CORILA

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SCIENTIFIC RESEARCH AND SAFEGUARDING OF VENICE

CORILA Research
Program 2003 results

Edit by
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UN TRAGUARDO RAGGIUNTO

Pierpaolo Campostrini
Direttore del CORILA

Questo volume è il terzo della serie, inaugurata nel 2002, che presenta l'insieme degli sviluppi delle ricerche promosse dal CORILA utilizzando i fondi della Legge Speciale per Venezia e conclude il suo Primo Programma di ricerca.

Nel primo volume la prefazione venne intitolata "Obbiettivi ambiziosi", in quanto sin dall'inizio eravamo consapevoli che eravamo di fronte ad una sfida per molti versi difficile. Vale la pena ricordarne qui brevemente i passaggi principali.

La struttura del Programma di ricerca e le sue modalità attuative furono stabilite ad inizio 2000, dopo un periodo iniziato già nel 1999 di colloqui ed incontri con diverse Pubbliche Amministrazioni, finalizzati a stabilire i principali "buchi" di conoscenza che le ricerche dovevano colmare. Infatti i risultati delle ricerche finanziate dalla Legge Speciale per Venezia devono essere "utili" alla Salvaguardia di Venezia e della sua laguna, in particolare aiutando il processo decisionale delle Amministrazioni che hanno compiti di intervento operativo.

Fu scelto di definire le "domande", cui i progetti di ricerca dovevano mirare a dare risposte; sulla base di un bando pubblico internazionale, furono selezionati i progetti più convincenti, che furono operativi all'inizio del 2001. Le ricerche sono durate sino a dicembre 2003 e qui vengono rappresentati appunto i risultati del terzo ed ultimo anno.

Il CORILA, attraverso i suoi organi ed avvalendosi di una piccola struttura operativa, ha coordinato il lavoro di 70 istituzioni di ricerca, di cui 18 straniere, con oltre 300 ricercatori che hanno prodotto oltre 3000 mesi/uomo di attività in tre anni. I Gruppi di ricerca hanno relazionato in maniera continua con il CORILA e comunque attraverso Rapporti semestrali, sia scientifici che tecnico-amministrativi. È stato costituito un sistema informativo che raccoglie tutte le informazioni prodotte, sotto forma di dati, documenti, immagini, ecc.

Sono stati tutti spesi, nei tempi previsti, gli oltre 12 miliardi di lire (oltre 6 milioni di Euro) che sono stati assegnati per lo svolgimento di queste ricerche. Per le piccole cifre della ricerca italiana, non è stato un piccolo finanziamento, né un piccolo programma. Ovviamente, solo in pochi casi, anche se significativi, possiamo mostrare una realizzazione "materiale", quale una complessa apparecchiatura funzionante in un laboratorio ed acquistata con quei fondi. La gran parte dei finanziamenti ha finanziato attività, in particolare quella dei giovani, fornendo loro la grande opportunità di un effettivo lavoro scientifico di alto livello sui temi lagunari, ed ora si rappresenta in "immateriale" conoscenza. Immateriale, ma non inutile, anzi.

Alcune ricerche hanno prodotto un interesse specifico di alcune Amministrazioni, i risultati di altre addirittura già indirizzato delle scelte operative. In molti casi, le ricerche sono state la base per ulteriori specifici approfondimenti. Se le "risposte" a quasi tutte le domande previste dal bando sono state date, non in tutti i casi esse sono definitive o non forniscono ulteriori spunti di riflessione. Qui non si tratta, è bene sottolinearlo, del "solito trucco" per cui il risultato della ricerca è semplicemente una ulteriore richiesta di ricerca: si sono conquistati traguardi importanti, si conosce di più e meglio, e questa conoscenza trova già oggi utile applicazione. D'altro lato, l'approfondimento delle conoscenze è davvero senza fine, ed in particolare le scienze ambientali, nella loro accezione più estesa, sono scienze giovani, dove molto possiamo attenderci dagli sviluppi futuri riguardo la nostra capacità di comprendere complessi dinamismi naturali.

Le lagune, quella di Venezia in particolare, sono un'ottima palestra per lo sviluppo di queste nuove conoscenze, mettendo insieme, in spazi e tempi tutto sommato limitati, una serie di processi "naturali" ed una quantità di forzanti antropiche, misurabili con relativa semplicità e confrontabili fra loro. Ciò nondimeno, viene richiesto al ricercatore il massimo dello sforzo per separare le diverse concause di fenomeni complessi: ciò richiede in alcuni casi l'uso di metodi sofisticati, magari testati in altri ambienti (anche "estremi" come l'Antartide). Richiede molto spesso la comprensione "interdisciplinare" di ciò che si sta esaminando, anche laddove si applicano gli strumenti più specialistici di una singola disciplina.

Forse questo, tra gli *obbiettivi ambiziosi* che ci ponevamo quattro anni fa, è quello di cui siamo più orgogliosi, anche se paradossalmente fra tutti è quello che resta ancora in buona parte da raggiungere. Nel nostro cammino, abbiamo fatto qualche passo reale di interdisciplinarietà. Abbiamo creato discussioni, consapevolezze, e fornito qualche strumento in più. Ciascun giovane specialista che si è formato nei differenti rami scientifici delle ricerche del CORILA, ne siamo certi, è maggiormente consapevole anche dei percorsi seguiti dai suoi colleghi di differente disciplina, li conosce, ha avuto modo di interagire con loro.

Le ricerche sono ora sottoposte a valutazione finale, sia da parte del CORILA attraverso panel ad hoc tramite il Comitato Tecnico Scientifico, che da parte degli organi competenti del MIUR, ma in molti casi le pubblicazioni che da esse sono risultate hanno già seguito l'usuale processo di *peer review* che ha aperto le porte di prestigiose riviste scientifiche internazionali.

Desideriamo comunque offrire la presente raccolta di pubblicazioni, che talvolta costituiscono l'"*extended abstract*" di lavori che saranno sottoposti in forma più completa al vaglio dei comitati editoriali di riviste specialistiche. Così rendiamo possibile una quasi immediata diffusione unitaria in un ambito vasto dei prodotti scientifici delle ricerche CORILA, con un linguaggio scientifico adatto ad un pubblico internazionale di specialisti. Ciò dimostra la vitalità e la competenza delle istituzioni scientifiche coordinate da CORILA e rende possibile il confronto internazionale.

È un obbligo gradito ringraziare chi ci ha dato fiducia ed incoraggiamento, spesso disponibile allo scambio di dati ed informazioni, a partire dal Ministro dell'Istruzione Università e Ricerca, il Magistrato alle Acque e il Consorzio Venezia Nuova, la Regione del Veneto e l'ARPAV, la Provincia di Venezia, il Comune di Venezia ed in particolare il Servizio Legge Speciale, il Centro Maree ed i Civici Musei, il Comune di Chioggia e gli altri Comuni lagunari, i Consorzi di Bonifica, l'APAT- Servizio Laguna di Venezia, la Sovrintendenza ai Beni Architettonici e culturali di Venezia. Dobbiamo essere grati al personale amministrativo e tecnico dei dipartimenti universitari e degli istituti CNR, che ha mantenuto la contabilità amministrativa assieme a quello del CORILA. Un ringraziamento del tutto particolare è esteso al Presidente e ai componenti del Comitato Tecnico Scientifico e del Consiglio di Amministrazione, per un impegno profuso con una passione che va al di là dell'obbligo del mandato.

Last but not least, un grazie alle persone che nel piccolo staff di CORILA hanno dimostrato non solo impegno, ma anche la capacità di costruirsi una professionalità di sapore nuovo e tra essi in particolare la dott.ssa Caterina Dabalà che ha curato con pazienza la messa insieme di questo libro.

A GOAL ACHIEVED

PIERPAOLO CAMPOSTRINI
Director of CORILA

This is the third volume in the series, begun in 2002, which presents research developments supported by CORILA using funds from the Special Law for Venice, and concludes the First Research Programme.

The title of the preface in the first volume was "Ambitious goals", since even from the beginning we realised that we faced a difficult challenge. It seems worth briefly reviewing the difficult passages here.

The structure of the Research Programme and the way it was to be carried out were established at the beginning of the year 2000, while meetings and interviews had begun in 1999 with the various sectors of the public administration to determine the main gaps in the knowledge that the research should fill. Indeed the research financed by the Special Law for Venice should be "useful" to the safeguarding of Venice and its lagoon, especially by supporting decision making by public authorities which have the operative responsibility for interventions.

It was decided to define the "questions", which the research projects should aim to answer, and the most convincing projects were selected on the basis of an international, public call for tender, becoming operative at the beginning of 2001. Research was carried out until December 2003 and the results which appear here are indeed the results of the third and final year of work.

CORILA, via its board and scientific committee and drawing upon a small operative structure, has coordinated the work of 70 research institutes, of which 18 were foreign, with over 300 researchers who produced over 3000 man-months of activities in 3 years. The research groups reported regularly to CORILA, including half-yearly scientific and technical-administrative reports. An information system was set up to collect all the information produced in the form of data, documents, images etc.

Within the expected timeframe, all allocated funds of over 12 billion lire (over 6 million Euro) were spent on research. Considering the level of Italian research funding, this was not a small financing, nor a small research programme. Obviously, in just a few cases, albeit significant, can we show a "material" achievement, such as the acquisition of sophisticated laboratory equipment. Most of the financing supported activities, especially those of young researchers, giving them a great opportunity in high level scientific pursuits on lagoon issues, and now constitutes an "immaterial" knowledge. Immaterial but certainly not useless.

Some research has already met with direct interest from individual administrations, the results of other projects have specifically guided specific operational decisions. In many instances, the research has been used as the basis for further specific investigation. If the "answers" of nearly all the questions posed in the Call have effectively been given, not in all cases are they definitive or they lead to further issues which need to be considered. It is important to note that this is not the "usual trick" where the research findings are simply a request to do further research: important goals have been reached, there are things that we know better and this knowledge can be usefully applied from today. On the other hand, extending knowledge is certainly endless, especially as regards environmental sciences, in their widest sense, which are truly a young branch in which we can expect much from future developments as regards our capacity to understand complex natural dynamics.

Lagoons, Venice's lagoon in particular, are an excellent training ground for developing these new types of knowledge, combining within a limited space and time, a series of "natural" processes with a quantity of anthropogenic forcing which are relatively simple to measure and comparable. The researcher, nonetheless, is expected to apply top efforts to separating the various and overlapping complex phenomena: in some cases this requires the use of sophisticated methods, which may have been tested in different environments (sometimes "extreme" like Antarctic) . Often this requires an interdisciplinary understanding of the subject under examination, even where one is applying the most specialised instruments of a single discipline.

This is perhaps the *ambitious goal* that we set ourselves 4 years ago that we are most proud of, even though it is paradoxically the one that is furthest from its final target. Along the way we have made a few truly interdisciplinary steps. We created additional discussions, awareness and particular instruments. Each young specialist that has been trained in the various scientific branches of CORILA research, we are sure, is now more aware also of the routes followed by her colleagues in different disciplines, knows them and has had an opportunity to interact with them.

The research has by now been subject to a final evaluation, both by CORILA via an ad hoc panel which constitutes the Scientific Committee, as well as by the competent bodies of MIUR, but in many cases the resulting publications have already passed through the process of *peer review* in prestigious international scientific journals.

We still wish to offer this collection of works, sometimes an "*extended abstract*" of works which will be subject, in their more complete form, to the review of specialist publications. It facilitates a near-immediate single distribution within a broad range of CORILA's scientific products, with an appropriate scientific language and an international readership of specialists. This demonstrates the vitality and competence of the scientific institutions coordinated by CORILA and makes international comparison possible.

It is a light and pleasant obligation to thank those who have trusted and encouraged us, for the exchange of data and information, starting with the Ministry for Education, Universities and Research, Magistrato alle Acque and Consorzio Venezia Nuova, Regione del Veneto and ARPAV, Provincia di Venezia, Comune di Venezia and especially the *Servizio Legge Speciale*, *Centro Maree and Civici Musei*, Comune di Chioggia and the other lagoon municipalities, Consorzi di Bonifica, APAT-*Servizio Laguna di Venezia*, Sovrintendenza ai Beni Architettonici e culturali di Venezia. We are also grateful to the technical and administrative staff of the university departments and CNR institutes who kept the administrative records alongside CORILA. A special thanks is extended to the President, to members of the Technical Scientific Committee and the Management Board, for profuse commitment and passion which extends beyond the obligations of the role.

Last but not least, thanks to the small staff at CORILA who have demonstrated not just commitment, but also the capacity to build a new type of professionalism and especially to dott.ssa Caterina Dabalà who patiently put together this book.

AREA 1
ECONOMICS

RESEARCH LINE 1.1
Economic evaluation of environmental goods

ELGIRA: SUPPORT SYSTEM FOR KNOWLEDGE BUILDING AND EVALUATION IN BROWNFIELD REDEVELOPMENT

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Riassunto.

La riqualificazione dei siti dismessi inquinati è oggi nella realtà nazionale e internazionale un tema economico-sociale e di pianificazione del territorio tra i più dibattuti. Nel '900 molte aree sono state abbandonate, in contesti urbani compatti e diffusi, a seguito di cambiamenti nell'economia della produzione e di welfare, riconversioni industriali, rilocalizzazioni produttive.

I cicli della dismissione rispondono a logiche locali e globali e i loro esiti sollevano problemi da entrambi i punti di vista: localmente richiedono la ridefinizione di regole che, con mitigazione del danno e assunzione di rischi, aiutino a restaurare il territorio e a definire nuove pratiche sociali secondo strategie sostenibili; in termini globali, ripropongono la città come "dispositivo che permetta di moltiplicare e organizzare l'interazione indiretta, a distanza", come sottolineato da A. Giddens. La complessità del tema sta in questo rapporto e nella capacità di catturarne i caratteri in processi di riqualificazione.

È in questa prospettiva che la ricerca ha inteso predisporre un sistema di aiuto alla riqualificazione dei siti inquinati: filiera di operazioni di cantiere, ma soprattutto dispositivo di conoscenza e valutazione continua in cui si alternano conoscenza esperta, strategie di stakeholder e algoritmi.

Abstract.

Both nationally and internationally, the redevelopment of brownfields is of late a matter of much intense discussion from a socio-economic and territorial planning point of view. The many changes in economy, production and welfare, industrial reorganization and production relocation during the last century gave rise to the abandonment of many inner- and outer-city areas.

Both local and global reasonings are responsible for the cycles of abandonment, which lead to problems from both points of view: at a local level these cycles necessitate a redefinition of regulations that may, via damage reduction and risk taking, help towards territorial renewal and the definition of new social practices according to sustainable strategies. In global terms, the town is thus reproposed as a "system whereby indirect interaction may be multiplied and organized at a distance", as

emphasized by A. Giddens. The complexity of the problem lies in this relationship and in the capacity to retain distinctive features within the redevelopment plan.

It is within this perspective that research was aimed at providing a support system for brownfield redevelopment: as a template for work sites, but above all as a tool for generating knowledge and continual evaluation whereby expertise, stakeholder strategies and algorithms would be alternated.

Fig. 1 – Brownfields. Porto Marghera, Venezia.

1. The research.

Research over the space of three years brought about ELGIRA[1], a system that aids those concerned in the processes of reclaim and redevelopment in working out a plan (both cognitive-based and procedural-based).

The conceptual structure of ELGIRA is made up of three interacting 'layers': the "cognitive logic" model, the "operational logic" model, and the "physical" model. The first takes the user 'critically' through the stages of the procedure, facilitating the evaluation of the appropriateness and efficacy of any analytical or planning choice, taking into account the context and the main economic, social, and environmental demands. The second layer concerns algorithms and information input and output

[1] ELGIRA is the acronym for Electra, Giuditta, REC and Aures, which are analytical evaluation models utilized in the first version of the procedure. The current version has been improved by new insertions, some of which are already complete and others in the process of completion. The choice of starting point has been facilitated via the creation of a database of reclaim techniques: the distinguishing of covered and uncovered surfaces; land usage and construction and renaturalization morphology; health hazard analysis optimisation via alternative models; the application of REC through reclaim 'processes' which are carried out either in sequence or in parallel; the analyses of land values leading to appropriate automaton rules that enable the capture of diffusion effects.

structures, which in the various modules constitute the procedure. The third transforms these processes in decisional maps[2] through specific software.

2. ELGIRA Logical Model.

ELGIRA is composed of modules that correspond to the same number of stages that characterize the process of reclaim and evaluation, and it is these stages that give structure to the procedure.

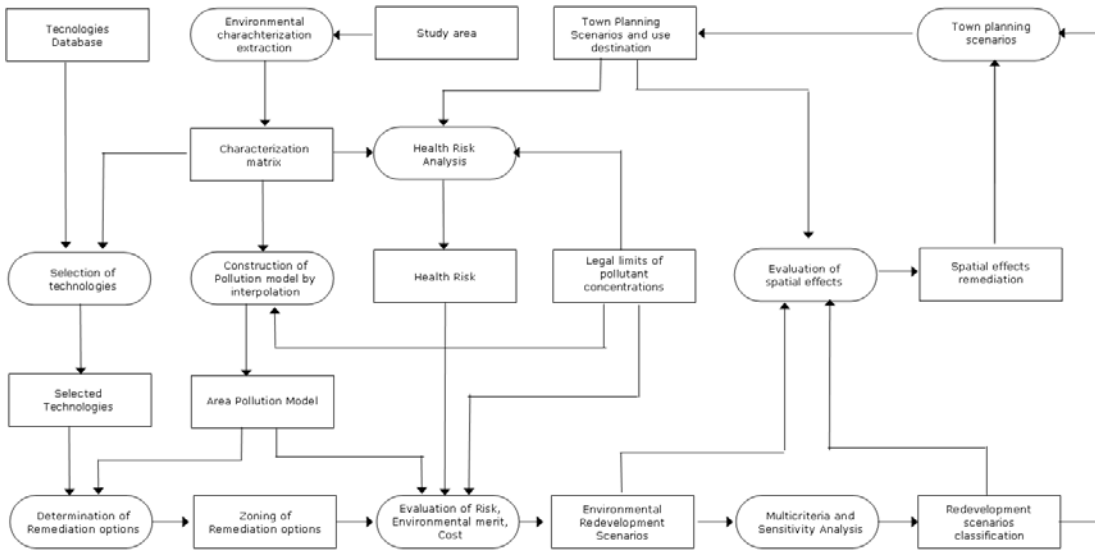

Fig. 2 – ELGIRA. Operative scheme.

The main stages are: characterization of the site; the preparation of a land pollution model; an environmental redevelopment scenario, and the evaluation of point and areal effects of the reclaim in question.

There are two distinct phases to scenario construction. The first phase concerns itself with urban redevelopment logic in general, when local and global factors operate together; and the second, operational, phase bases itself upon redevelopment hypotheses that embrace alternative reclaim processes and leads to the practical working phase of the project.

The model may be used ex-ante, as regards design or similar working phases, or ex-post in a learning situation. In the former case, it contributes to the assessment of overall acceptability, the technical/financial viability and the distributive equity in a reclaim project; in the latter, steps can be retraced in order to put to the test procedural reasoning.

So far research has concentrated on the ex-ante perspective.

[2] The mapping of a decision-making process in a simple 'interpreted' space.

2.1. Site characterization.

Site characterization involves the analyses of data concerning the state of land pollution. The numerous factors taken into consideration lead to a definition of the geographical characterization, i.e. the number of surveys and their respective locations (both of the land and water table), and the kinds of substances to be sought and analysed in each of these areas. The amount of detail included in the characterization generally depends on historical knowledge of the area (pre-existent industries, dumps, etc.) and on the availability of the resources necessary to the carrying out of the surveys, and later, laboratory analyses.

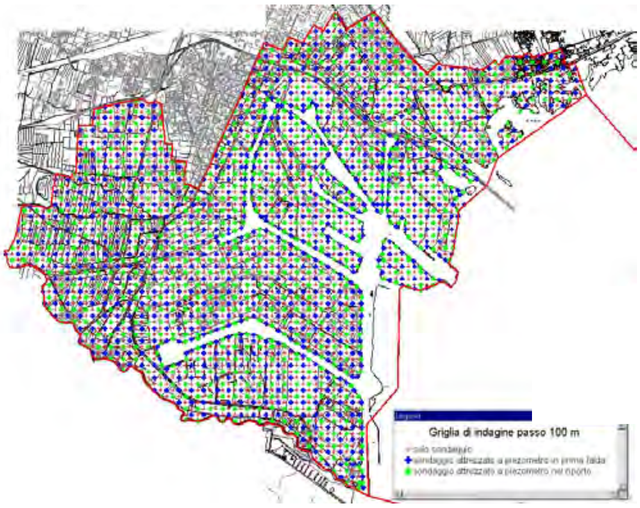

Fig. 3 – Porto Marghera, Site characterization (source: Comune di Venezia).

Detailed site characterization should lead into the next production of the model, complete with the state of land pollution as resulting from the surveys.

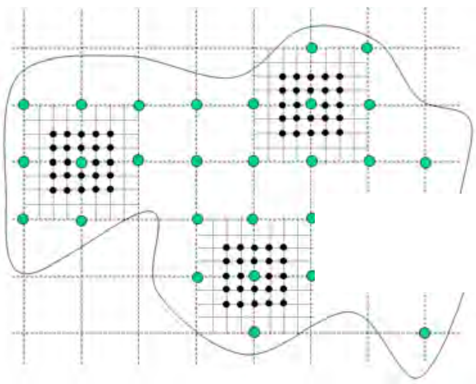

Fig. 4 – Site characterization, two levels of drilling.

One solution that is occasionally adopted is that of site characterization on two levels. The first level includes wide grid survey points of the whole area, which is then followed by the classification of the polluting agents and their respective level of concentration. This information, together with that concerning the historical background of the area, contributes to the definition of the second level of characterization, wherein the grid becomes narrower wherever a more detailed analysis may prove necessary. The results of the survey are then transmitted to an appropriate database and are then validated and utilized in the following stages of the evaluation process.

2.2. Soil pollution model.

The preparation of a soil pollution model goes necessarily hand in hand with environmental characterization. Utilizing special interpolation procedures, an ‘estimate’ is made of the concentration of pollutants in each point of the given area. This area, depending on the detection and interpolation techniques adopted, is then either divided into sub-areas of the same concentration level, or into regular cells of fixed dimension.

In the construction of a soil pollution model it is necessary to select the dimension (surface – 2D, or volume – 3D plus the interpolation algorithm (weighted average, benchmarking, kriging, etc.). The interpolation topology (areas, cells, etc.) will depend on the selected algorithm and subsequent choice of software.

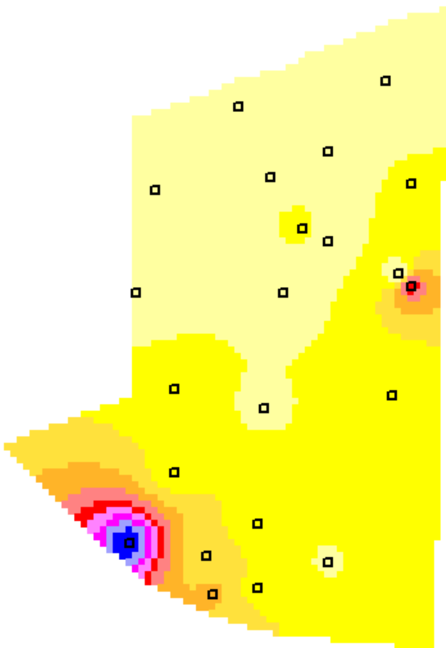

Fig. 5 – Two-dimensional interpolation with weighted average, related to the distance of drillings (in evidence with the black square cells).

A three-dimensional model of the soil is more effective as regards a description of the state of pollution, but is often difficult to build due to the dearth of information supplied by the surveys, and the lack of knowledge concerning both the deep geological structure of the terrain and the mechanisms of percolation between the substances and possible water tables[3] . To start with, in-depth pollution counts may be assessed via vertical interpolation techniques, after which a concentration value can be attributed to a single surface point. A similar two-dimensional model is applied to the water table layer.

The choice of interpolation algorithm depends on the range of pollutants and the kind of result that one hopes to obtain as regards precision of the estimate. It is difficult to establish quality ranking of the algorithms since their application also depends on the density of the sample points. A sophisticated algorithm may produce the same results as a simple weighted average. There is no such thing as a system that can estimate with certainty the presence of maximum pollution in a given area. However, apart from the making of a probability calculation, it is still very important to know the history of a site and therefore where exactly certain materials were treated, or substances or stockpiles offloaded.

ELGIRA at present utilizes software that was specifically designed for the use of interpolation algorithms of weighted averages.

The soil pollution model, therefore, enables us to produce not only two-dimensional or three-dimensional matrices of each substance (or family of substances[4]) which is present at a specific concentration level in a given area (cell or point), but also the two-dimensional or three-dimensional matrices or maps that are necessary in the evaluation process.

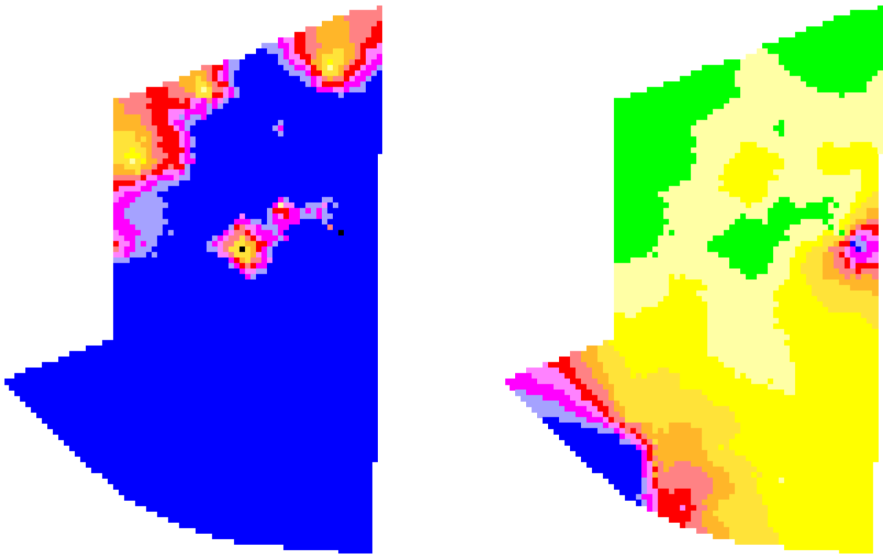

Fig. 6 – Application of a threshold to the interpolation according to the legal Italian limits of the substances concentration (D.M. 471/99), Residential destination (left), Industrial-Commercial destination (right). The shade from yellow to blue indicate an increase factor of limit overcoming. In the green area the concentration is under the limit.

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[3] In these cases it is often more effective to apply a "2½D" model, i.e. a 'layered' description of a determined thickness (50cm – 1.2 metres); each layer being considered independently from the others (the tables are represented in single strata) and each being subject to interpolation.

[4] Families of substances are groups of compounds that share the same chemical structure, elements and reaction; for this reason they may be treated with the same technology.

Useful maps are obtained through ‘threshold’ valuing of concentration levels in accordance with current regulations[5]. Complete matrices are used to produce sub-matrices by selecting the values that exceed the legal concentration limit. These are then visualized chromatically according to the degree of excess. The maps serve, therefore, to identify the ‘critical’ zones of pollutant distribution and are used in the ELGIRA procedure to determine volume and weights of the portions of land that are to be reclaimed and to assess the standardization of the families of substances according to zones. This operation helps in the ‘zoning’ of areas where specific reclaim technologies, either single or combined, are applied.

2.3. Risk analysis.

Health and environmental risk analysis in the area of intervention constitutes another fundamental phase of the procedure, and is closely connected to the final utilization and the prescriptive regulations of acceptable pollution levels (residual limits or risks admitted). At times it proves impossible to eradicate completely the pollutant concentration either for reasons of technological efficacy in the field of reclaim, or for lack of funding; in these cases there remains an amount of residual pollution concentration which must then be assessed both on health hazard and legal acceptability counts. This evaluation is in line with legal indications, and above all with the foreseen final utilization of the area. It may become of a critical feature due to the elements in consideration, such as duration of exposure, ingestion, etc., and the importance attributed to these factors by the subjects involved in the reclaim process, be they producers or consumers.

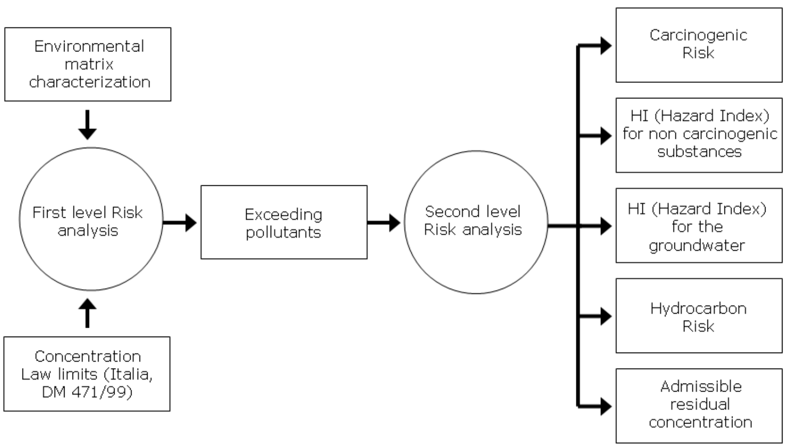

Fig. 7 – Risk analysis (two levels).

Health hazard is assessed within the ELGIRA procedure by a programme named Giuditta, which at present is being tested for efficacy by use of alternative software, such as Risc 4. Ecological risk analysis, whereas, is tested within the REC module.

[5] In Italy, the Environment Ministry decree no. 471 of 25October 1999: “a ruling that disciplines the criteria, procedures and modality inherent to the assurance of safety, reclaim and the environmental rehabilitation of polluted areas”

2.4. Model "zoning".

So as to improve the relationship between the reclaim technologies adopted and the substances to be treated[6] it is advisable to standardize treatment in correlation to substance families: same family, same treatment.

Spatial matrices revealing substances in the site (e.g. in zones where the legal limit has been exceeded) may be unified by identifying area and volume.

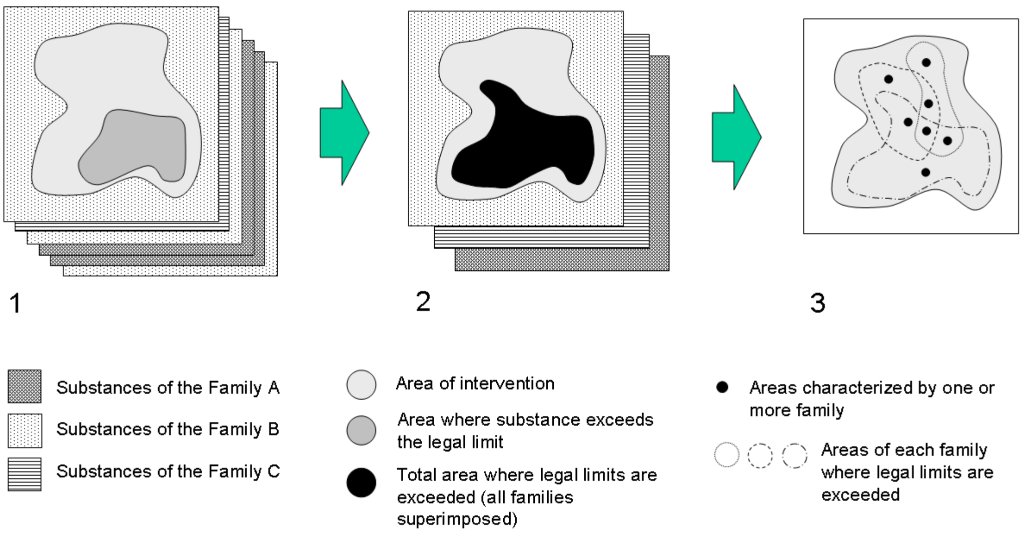

Fig. 8 – Zoning of pollutant model. Concentration maps of pollutants of the substances that refer to different families of pollutants (1); total area of the substances that refer to each family (2); final superimposition of the maps of each family (3).

Further processing is carried out via the spatial intersection of the areas (in volume) of each 'family' so as to attain one simple matrix (which can be represented either in a 2D or 3D map). This sort of identification is fundamental, in that to each of these portions it is (theoretical) possible to to apply one or more reclaim technologies.

2.5. Reclaim technologies.

It is indispensable, in the choice of a reclaim technology, to be in possession of a technological database. Each database has its own particular characteristics, which include application options and limits, depending on polluting agents in question, the contextual set-up, availability, performance, and cost. The construction of a database of this kind is always a useful resource of knowledge regarding possible contextual problems.

[6] In Italy, ministerial decree no. 471/99 defines polluting agents according to families. There exist, however, various clustering techniques.

Fig. 9 – Reclaim technologies. Mud treatment installation, Malcontenta, Venezia (Source: Alles S.p.A.).

With ELGIRA, a first selection is made according to specific requirements: the presence of polluting agents, available funding, and project and context limitations[7]. One valuable source of reference for an area test is the Master Plan for the Porto Marghera reclaim project. This association of technologies is then subjected to multi-criteria evaluation for choice, priority and assignment based on criteria of suitability[8]. It should be recalled here that a lexicographical procedure is adopted, in which multi-criteria assessment is carried out only for those technologies that have the necessary requirements for a given context. Environmental zoning, together with land utilization hypotheses are thus incorporated into the specific reclaim processes. Each process is defined according to the usage of either single or combined technologies whose time span is then determined by the redevelopment scenarios.

2.6. Redevelopment scenarios.

In this phase the reclaim scenarios are completed, the structural dimensions of which concern the use of the land, projects for the area, the reclaim process, and the setting up of the work site. These scenarios are assessed for *risk reduction*, *environmental merit*, and *overall cost.* The question of cost may be represented in terms of specific financial criteria, such as rates of return, the period of coverage, or suitable

[7] Criteria for choice of technological options include: site typology, process typology, condition of usage, state of the art, presence of treatment residue, contamination action typology, treated pollutants, and so on.

[8] Technological evaluation criteria options include: population exposure typology, events, responsiveness to unforeseen circumstances, reliability, effectiveness on specific pollutants, competitiveness, residue revaluation, treatment typology, reclaim costs, transport costs, environmental conformity, social acceptability, system performance, market availability, plant area requirements, etc.

cash-flow indices. Additional information may further enhance the scenario descriptions later, in the summary phase[9].

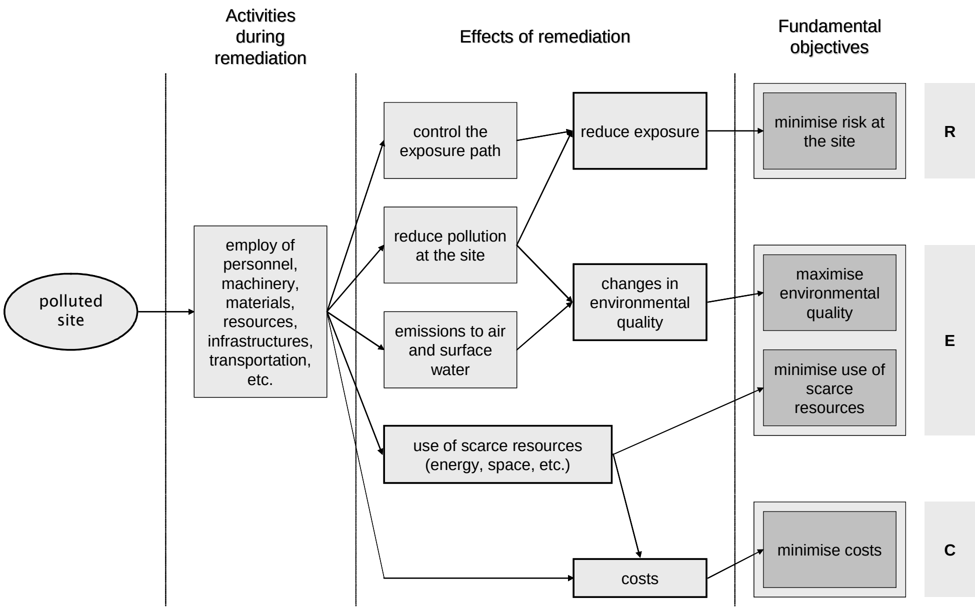

Fig. 10 – REC. Operative schema.

REC is the procedure by which a summary evaluation of the scenario is achieved. REC (Risk, Environment, Cost) is originally a Dutch-designed model that has been piloted in various European contexts. The principle objectives of the REC procedure are to a) minimise risk to persons, ecosystems and things within the site, b) to maximise the environmental quality of the area, c) to minimise the use of scarce resources during the reclaim operation, and d) to minimise financial costs.

2.7. Areal effects.

The redevelopment of a site (reclaim, new construction, upgrading, etc.) creates both point and areal effects on the open or built-up surroundings. These effects concern the variations within urban quality, accessibility, and the general real estate value of the area. In order to comprehend fully the consequences of a redevelopment intervention, the expectations and actions of the operators (housing and industrial) and the local population should be known.

[9] Additional information concerns, for instance, risk differentials (between the initial and the final states), pollutant concentration differentials, financial cost profiles for any single operation, and energy consumption.

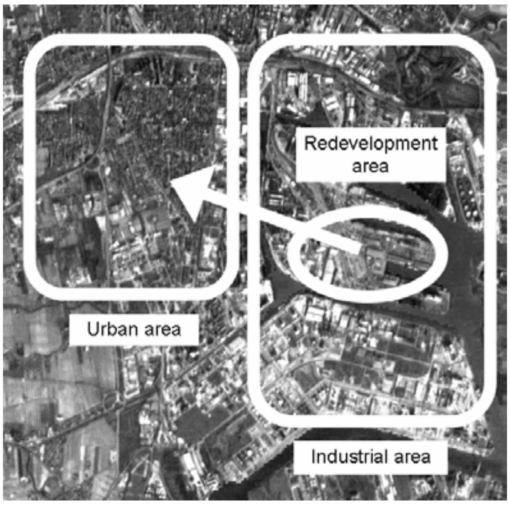

Fig. 11 – Areal effects of the redevelopment (Porto Marghera, Venezia).

This knowledge can be obtained using simulation models based on rules of diffusion, These rules may ensue from spatial models that have been tested in similar contexts, and which can return implicit pricing through edonic functions, or else from empirical studies on the expectations and actions of investors, city users, real estate agencies, public offices (e.g. the land register and the tax office), civic groups and various other subjects.

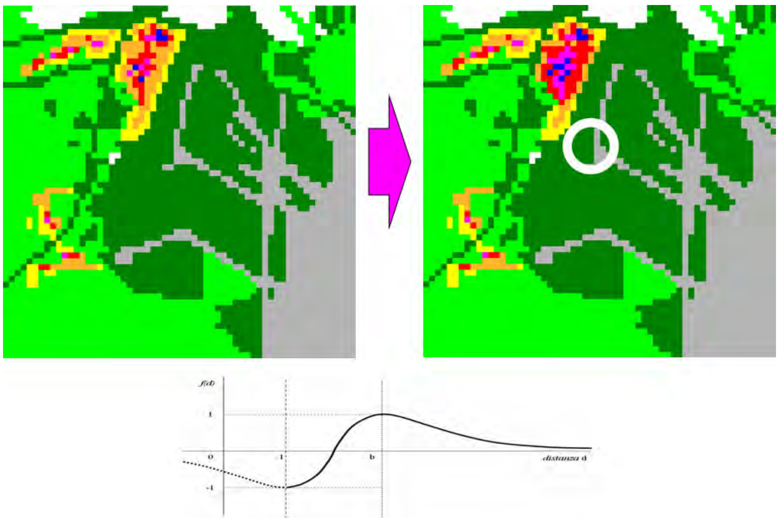

Fig. 12 – Simulation of the reclaim effect on the urban area real-estate values. Scenarios of Porto Marghera and the city of Marghera. The reclaimed area is marked by the white circle; real-estate values (shade from yellow to blue) before (left) and after (right) the redevelopment intervention. Application of a rule "increase-decrease" of a real-estate values, refer to the distance.

ELGIRA includes a procedure which was developed using cellular automaton technology. Two rules are applied: one concerning local interaction, and permits the simulating of the variation in value of the area in close proximity to the intervention; the second rule applies to remote considerations, capturing the effects of the reclaim at a distance. In both cases the effects follow specific 'regimes' that are dependent on the physical and social morphology of the territory in question.

2.8. Acceptability of redevelopment scenarios.

The scenarios created by the REC procedure are subjected to multi-criteria summary analyses with the aim of recognizing the leverage of negotiation between residual risk management, environmental merit, and financial costs. The financial costs could be transformed into economic cost by applying appropriate corrective factors. Current investigation regarding benefits will enhance evaluation from the economic viewpoint; a consideration only indirectly dealt with in the REC procedure. Discussion on redevelopment scenarios is enriched by one or more sensitivity analyses of variance of the matrix of effects and of possible trade-offs between risk, merit, and cost.

Conclusions. Test in the "43 hectare" area at Porto Marghera.

The model was applied to the '43 hectare' area in Porto Marghera, which belongs to the Venice Municipality and borders on the second Industrial Area. During the 1950s and 60s, the site was deployed as an industrial dumping area. The terrain is permeated by a wide variety of pollutants, including a considerable amounts of arsenic, lampblack, Polyciclic Aromatic Hydrocarbons (PAHs), zinc, and bauxite.

Fig. 13 – Porto Marghera. "43 hectare" area.

The matrix of environmental characterization supplied by surveys carried out by the Venice Municipality (Land Information System) is our main source of information. An estimate was made of the two-dimensional spatial distribution of approximately 40 substances. Maps of areas that approach the legal limit (DM 471/99) for their intended use, both residential (A) and commercial or industrial (B) highlight the presence of serious pollution in the southern part of the site. Here, the legal limits have in general been exceeded, and in particular (in the residential area) by as much as hundreds or even thousands of times for PAHs, and even more for the Polychlorobiphenyls (PCBs).

The test was carried out by hypothesising a commercial or industrial use of the area, as foreseen by the Porto Marghera Variant of the Venice Master Plan of 1999.

health hazard analyses were effectuated using the Giuditta software and identified just one area of exposure and nine exposure paths in the soil[10]. The results (summarized in the following table) reveal that cancerogenous risk emanating from the surface soil are extremely high both for workers and for future residents.

Tab. 1 – "43 ettari" area. Risk analysis results.

RISK	VALUE [adimensional]	EVALUATION (Ref. D.M. 471/99)
Cancerogenous risk from surface soil for workers	*$1{,}24 \cdot 10^{-3}$*	*100 times the legal limit*
Cancerogenous risk from surface soil for residents	*$4{,}78 \cdot 10^{-3}$*	*100 volte superiore al limite ammissibile*
Cancerogenous risk for the deeper soil levels and for the underground water tables	*Less than 1*	*Under the legal limit*
HI (Hazard Index = maximum daily intake for tolerable doses) for workers and adults	*Less than 1 for all the exposition paths*	*Under the legal limit*
HI (Hazard Index = maximum daily intake for tolerable doses) from the surface soil for children	*5,40 of which 1,32 from ingestion of arsenic, with the addition certain IPA (cadmium, selenium, lead, zinc, etc.)*	*5 times the legal limit*

The status of pollution , together with characteristics of the area suggest four reclaim techniques:

- *Thermic desorption in order to treat the IPA*
- *Soil washing for IPA and metals*
- *Capping as a less expensive solution*
- *Dumping as last solution destination for operational waste*

As regards pollution zoning and optimisation of the reclaim process five alternative reclaim options were taken into consideration:

1. *IPA thermic desorption and soil washing of IPA and metals*
2. *One soil washing line*
3. *Two soil washing lines*
4. *Capping*
5. *Dumping*

As required by the REC module, these options were evaluated for consumption costs and performance, so as to make an estimate of risk reduction, environmental merit and financial cost.

Evaluation results (in points for R and E, in Euro for C, and the percentage of the theoretical maximum) as represented in the figure below suggest that dumping offers the best option from the point of view of risk reduction; thermic desorption together

[10] Soil ingestion; skin contact; indoor inhalation of dust particles; outdoor inhalation of dust particles; indoor vapours rising from the surface soil; outdoor vapours rising from the surface soil; indoor vapours rising from the deeper soil levels; outdoor vapours rising from the deeper soil levels; washing of the soil towards the water table. Three paths concerning the free agent: indoor vapours from free agents; outdoor vapours from free agents; migration of dissolved substance towards the water table.

with soil washing is the most effective for environmental merit, and that capping is the least expensive solution.

Tab. 2 – “43 ettari” area. Final evaluation of the reclaim options.

	Reclaim options				
	Dumping	*Thermic desorption + soil washing*	*Soil washing (one line)*	*Soil washing (two lines)*	*Capping*
R (risk reduction)	28,40 (94 %)	21,49 (71 %)	21,00 (70 %)	20,49 (68 %)	12,19 (40 %)
E (environmental merit)	-1,32 (-13 %)	4,86 (49 %)	4,79 (48 %)	4,62 (47 %)	2,84 (29 %)
C (financial cost)	45’589’900 (± 1’578’200)	20’387’100 (± 682’200)	20’558’700 (± 693’200)	20’558’700 (± 693’200)	5’322’300 (± 155’800)

The final choice of option will depend on the modality and results of negotiations between R, E, and C.

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Bibliography.

Andreottola G., 2001. “Tecnologie di bonifica, criteri di selezione e analisi di rischio”, in C Gargiulo (a cura), *Processi di trasformazione urbana e aree industriali dismesse: esperienze in atto in Italia*, Atti del Convegno AUDIS 1999/2000, Venezia

Anselin L., 1992. SPACESTAT Tutorial. A workbook for using SpaceStat in the analysis of spatial data, NGCIA, Dept. of Geography, University of California, Santa Barbara

Beinat E., van Drunen M.A. (eds), 2001. *The REC decision support system for comparing soil remediation options. A methodology based on risk reduction, environmental merit and cost*, REC Consortium, Amsterdam

Benevolo L. (a cura), 1996. *Venezia. Il nuovo piano urbanistico*, Edizioni Laterza

Beretta G.P., 2001. “La caratterizzazione dello stato di contaminazione dei siti”, in C Gargiulo (a cura)

Cecchini A., 1999. *Meglio meno ma meglio. Automi cellulari e analisi territoriale*, Franco Angeli, Milano

Cecchini A., Viola F., 1990. *Ficties (Fiktive Stadte): Eine Stadtbausimulation* in *Wissenschaflichte Zeitschrift der Hochschule fu Architektur und* Bauwesen, Weimar Heft

Chiozzotto E., 2001. “Il caso di Porto Marghera”, in C Gargiulo (a cura), cit

Comune di Venezia, Direzione Centrale Ambiente e Sicurezza del territorio, 2001. *Accordo di programma per la chimica a Porto Marghera. Dpcm 12.02.99. Quadro conoscitivo di riferimento per la redazione del Master Plan per la bonifica delle aree contaminate di Porto Marghera* (a cura di E De Polignol, F Zanetti), Venezia

Comune di Venezia, 1996. La pianificazione urbanistica come strumento di politica industriale. La Variante al Prg per Porto marghera, *Urbanistica Quaderni* 9

Coses e Comune di Venezia, 1990. *Porto Marghera. Proposte per un futuro possibile*, Franco Angeli, Milano

Couclelis H., 1985. *Cellular Worlds: A Framework for Modelling Micro-Macro Dynamics*, Environment and Planning A, vol. 17

De Polignol E., 2001. "Un sistema di supporto alle decisioni in campo ambientale: il Sistema Informativo Ambientale Suolo del Comune di Venezia", in C Gargiulo (a cura), cit

Dennison M.S., 1998. *Brownfields redevelopment. Programs and strategies for rehabilitating contaminated real estate*, Government Institute, Rockville, MD

Fishman A., B.R. Amjad, 1997. "Acquisition considerations for brownfields properties", in in T S Davis, K D Margolis, *Brownfields. A comprehensive guide to redeveloping contaminated property*, Section of Natural Resources, Energy, and Environmental Law, American Bar Association (ABA), Chicago

Gargiulo C. (a cura), 2001. Processi di trasformazione urbana e aree industriali dismesse: esperienze in atto in Italia, AUDIS (Associazione Aree Urbane Dismesse), Venezia

Guarino G. e Zamparutti A. (a cura), 1998. "Quale futuro per le aree industriali inquinate? Un confronto tra alcuni casi italiani ed ester", *Osservatorio Veneto, Quaderno n. 1* (atti del Convegno: Piani e azioni di bonifiche per aree industriali inquinate 2-3 Ottobre 1998, Venezia)

Janssen R., van Herwijnen Marjan, Beinat E., 2001. *DEFINITE. Case studies and user manual*, Vrije Universiteit. Amsterdam

Landi G., Montini M., 1999. *La disciplina della bonifica dei siti inquinati. La normativa italiana a confronto con quella dei principali paesi europei e degli Usa*, Progetto Venezia 21, Rapporto di ricerca 01.99, Fondazione Eni Enrico Mattei, Venezia

Maggioni E., 1999. "Porto Marghera: bonifiche e riconversioni industriali, un progetto complesso*", Urbanistica Informazioni* 164, pp.23-24

Margolis K.D., Davis T.S., 1997. "Doing the brownfields deal", in T S Davis, K D Margolis

Maystre L.Y., Pictet J., Simos J., 1994. *Méthodes multicritères ELECTRE*, Presses Polytechniques et Universitaires Romandes, Lausanne

Mundy B., 1997. "Valuing brownfields", in TS Davis, KD Margolis

Patassini D., Cossettini P., De Polignol E., Hedorfer M., Paneghetti C., Rinaldi E., 2003. Contextual Knowledge Generated by a Decision Support System for Brownfield Development: The Case of Porto Marghera (Venice, Italy) in *D. Miller and D. Patassini (eds.), "Beyond Benefit Cost Analysis -- Accounting for Non-Market Values in Planning Evaluation", Ashgate, Aldershot, Hamps. (UK), in press*. Patchin PJ, "Contaminated properties – Stigma revisited", *The Appraisal Journal*, April, 1991

Provincia di Milano, Soc. URS Dames & Moore, 2002. "Manuale d'uso Giuditta 2.0"

Provincia di Venezia, www.provincia.venezia.it/proveco/rifiuti/chimica

Pugliese T., 2001. "Dai piani urbanistici alle politiche urbane: il caso di Porto Marghera a Venezia", in C Gargiulo (a cura), cit

Regione del Veneto, Comune di Venezia, 2002. Master Plan delle Bonifiche a Porto Marghera

Regione del Veneto, 1999. *PALAV. Piano d'area della laguna e dell'area veneziana*, Cierre Edizioni, Verona

Rinaldi E., 1998. *AuReS Automa Rendita Specializzato – MoDe Montagne del Degrado*, IUAV-DAEST, Venezia, Collana Stratema n. 3

Rinaldi E., 1999. *Automi cellulari per la simulazione di fenomeni dinamici. Una metodologia di progettazione*, in "Meglio meno ma meglio. Automi cellulari e analisi territoriale", a cura di Arnaldo Cecchini, Franco Angeli, Milano

Rinaldi E., Besussi E., Cecchini A., 1998, *The Diffused City of the Italian North-East: Identification of Urban Dynamics Using CA Urban Models*, in Computers, Environment and Urban Systems, vol. 22, n. 5

Russ T.H., 2000. *Redeveloping brownfields*, McGraw Hill, New York

Sichirollo S., 1997. *L'uso degli automi cellulari nello studio delle trasformazioni dei valori del mercato immobiliare*. *La città di Mestre*, IUAV-DAEST, Collana Tesi di laurea "Agostino Nardocci", Venezia

Simons R.A., 1998. *Turning brownfields into greenbacks*, Urban Land Institute (Uli), Washington

Succi S., 1991. *Automi cellulari: una nuova frontiera del calcolo scientifico*, Franco Angeli, Milano

Tobler W.R., 1979. *Cellular Geography*, in S. Gale, G. Olsson (eds.), "Philosophy in geography", Reidel, Dordrecht

White R., Engelen G., 1997. *Cellular automata as the basis of integrated dynamic regional modelling*, Environment and Planning B, vol. 24, n. 2

Wolfram S., 1986. *Theory and Applications of Cellular Automata*, World Scientific, Singapore

Wright J G, 1997. *Risks and rewards of brownfield redevelopment*, Lincoln Institute of Land Policy, Cambridge, MA

CONTAMINATION OF THE LAGOON OF VENICE: PEOPLE'S RISK PERCEPTION

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Riassunto.

La bonifica dei siti contaminati a Marghera presenta importanti opportunità sia per il settore privato che per quello pubblico. Molti di questi benefici non hanno un valore di mercato ed è quindi necessario ricorrere a metodi di valutazione non di mercato come il metodo della valutazione contingente e il metodo dell'analisi congiunta. Lo scopo di questo articolo è di fornire un'interpretazione critica, sulla base della letteratura esistente, dei risultati che si sono raggiunti con i focus group organizzati con la popolazione locale di Venezia e Marghera nel 2003 aventi lo scopo di indagare i temi che saranno affrontati nel questionario di valutazione economica dei benefici derivanti dalla bonifica. I risultati ottenuti offrono un quadro esaustivo della percezione del problema delle bonifiche da parte della popolazione, in particolare aiutano a individuare gli elementi importanti che la collettività considera nell'esprimere la disponibilità a pagare in relazione alle soluzioni proposte per il problema della contaminazione.

Abstract.

Remediation of contaminated sites in Marghera presents opportunities both to the public and to the private sector.. Most of these benefits do not have a market price, therefore requiring the use of non-market valuation tools like contingent valuation and conjoint analysis as part of the economic assessment of remediation options. The purpose of this paper is to give a critical interpretation, on the basis of the present literature, of the results obtained during our focus groups done in 2003 in Venice and Marghera, to better investigate the issues of our survey for the economic valuation of the benefits of the environmental remediation. The findings presented provide an overview of the perception of the problem by the public, and give an interesting insight in what has been considered more important by the public when we asked the participants about their WTP to pursue possible solutions to the problem.

1. Introduction.

Contaminated sites remediation presents opportunities both to the public and to the private sector: the benefits range from the reduction of health risks to benefits to the ecosystem. Remediation activities, combined with economic incentives, can improve the quality of life by changing the urban landscape, removing the contamination stigma, and possibly attracting other non-polluting industries to the region.

The results discussed in this paper are part of a broader research program pursuing the valuation of willingness to pay (WTP) for remediation both from the developers (supply side) and the residents (demand side). The "supply side" analysis of the remediation projects has been conducted in 2002, with the results reported in Alberini *et al.* (2003). In this paper we discuss the theoretical issues that were addressed when developing the draft questionnaire to elicit WTP from the "public side," and the results of focus group discussions finalized at the preparation of the questionnaire. These findings provide an overview of the perception of the problem by the public, and give an interesting insight in what has been considered more important by the public when we asked the participants about their WTP to pursue possible solutions to the problem. The work conducted so far and the survey we are working at have three main objectives. First, to generate data that will be used to express risk reduction after remediation in economic terms (monetarize the achieved reduction of risks). This information will be integrated with the results of other research activities of the WP3 related to the design of ELGIRA – a decision support system for rehabilitating contaminated real estate. Second, to make a contribution to the literature on the valuation of risk reduction from exposure to contamination. In particular, the national scope of the survey allows testing how knowledge of contamination affects risk perception and WTP for risk reduction. Finally, our results will be used to inform decision-makers of the public perception of health risks and preferences for the remediation measures in Marghera, enabling them to evaluate policy options according to the level of public support they enjoy. In the following sections we present the focus group methodology (section 2) and a review of literature on risk perception (section 3). In section 4 we will consider the problem of risk communication. Section 5 will clarify why the research has been restricted to the analysis of the health risks posed by contaminated sites. We will then move into the treatment of two crucial components in WTP evaluation when applied to our specific topic: latency, altruism (subsection 5.1) and familiarity (subsection 5.2). Results of perception of stigma effect are presented in section 6.

2. Focus groups and the concept of risk: theory and results.

Focus groups methodology is an important tool in questionnaire design and testing. It is attributed to Robert Merton, who started to adopt and develop this research tool in the '40s. A typical group has six to nine people, enough to keep the discussion flowing over a period of one-two hours. It is managed by an expert who encourages free-flowing discussion but keeps it focused. Focus groups are a research tool widely used in commerce, social sciences and increasingly in politics. They have been defined as the most important qualitative research procedure by Malhotra [1996]. The purpose of the focus groups, conducted in June and July 2003, was to reveal the extent to which the residents may be aware of the existence of contaminated sites, the risks they pose to health and ecosystems, and remediation measures. In particular, the findings of these focus group sessions helped us to determine what kind of information we need to supply about contaminated sites and their remediation in the questionnaire in order to familiarize the respondents with the issue. We tried to investigate these issues: how do people define contaminated sites? What are the main perceived exposure pathways? Does the stigma effect exist? A prerequisite for the design of our questionnaire was the need to gain an insight into the knowledge and understanding of the target audience. Prior to investigating the understanding of environmental risks we wanted to know something about people's understanding and their use of the concept of risk in general.

This is not as straight forward as it may appear, since it is often difficult to distinguish clearly between the concepts of risk and hazard, accident, catastrophe, disaster and crisis. Sometimes these concepts are used interchangeably, or accompanied by more or less precise definitions. Economists distinguish between risk and uncertainty. Risk refers to a situation where we can list all outcomes and assign probabilities to them. Uncertainty refers to situations where we may neither be able to list the outcomes, nor assign the probabilities. Among social scientists, "risk" is a fundamentally social construct and, as a minimum requirement, there is the need to take into account a number of additional qualitative characteristics in order to conceptualise hazards [Weyman and Kelly, 1999]. In our focus groups people used the word risk more in terms of hazards and less in terms of probabilities of danger. They also focused more on risks with higher probabilities instead of risks associated with lower probabilities. Only few people told us that: "risk is a probability"; "it represents an uncertain situation that could be positive or negative". In order to understand if people considered contaminated sites an important problem to be managed and resolved, we compared risks caused by environmental problems with other familiar risks people known and perceive relevant such as a car accident, home accident, meteorological risk, earthquake risk, etc. Our results demonstrated that residents were concerned with environmental contamination and the risks it posed: about 82% of our respondents said that they are worried about environmental pollution risks, and 76% of respondents considered industrial accident as a relevant risk. Moreover, they were aware of contaminated sites in general.

When we asked people to define a contaminated site they responded that a contaminated site was: i) a landfill, ii) land that has lost its pureness as a result of an adverse human intervention, iii) an abandoned factory, iv) a place that had suffered some negative modification from an initial state, v) a place completely unusable unless it is rehabilitated, vi) a place where there is an invisible hazard, and vii) a place where it is not possible to undertake the activities that people would like to. The high level of general awareness of contaminated sites, or more broadly, of the presence of contamination in the area, may affect the perception of the risks posed by such sites in two ways. On the one hand, the residents of areas adjacent to contaminated sites may fear the exposure to contamination more than the people that live far from such areas. On the other hand, the greater familiarity with the dangers can demystify contaminated sites and reduce the perception of dangers a contaminated site might not pose. Indeed, as pointed out by some participants in the focus groups in Marghera, contaminated sites may have a lot of potential for re-development into economically thriving areas and parks. The San Giuliano park was frequently cited as such an example.

3. Risk communication and risk ladder.

Great efforts have been dedicated by our research group to study and understand how to inform people about health and environmental risk and how to represent these risks in a simple way. We were aware that the way information on environmental and health issues is presented and the level of detail provided could influence people's understanding and valuation process. Prior to designing the section of the questionnaire that provides respondents with background information on contamination and health risks, we conducted a literature review. The results of this review are summarized below. The effect of information on consumers' choices has been a source of concern among economists and psychologists for several years. Viscusi and Magat [1987], in summarising their own research on product labelling and that of others with regard to risk communication state: "the existence of limitations on human cognitive capabilities makes the format and wording of labels particularly important". The process of estimating the value people place on environmental health risk necessarily involves communicating the risk to be valued in a proper manner. Applied researchers of stated preference methodology have recently begun to recognise that if the values obtained from such methodology are to be meaningful, great care must be taken to ensure that individuals have a reasonable understanding of the risks they are being asked to value.

Historically, risk is defined with reference to some objective numerical value, expressed in terms of the likelihood of the event's consequences, combined with some assessment of its severity. But numbers alone may not be sufficient to explain to people the real magnitude of risks, especially when they refer to very small quantities or are expressed in unfamiliar units. T. Barlow McDonald [2001] points out that several factors can contribute to successful risk communication. Among these factors we can list the technical, complex, and uncertain nature of risk information, a wide range of risk estimates, public distrust of regulatory agencies, varying definitions of risk, strong beliefs on the part of the public that are often difficult to change, and the public's general difficulties with comprehending probabilistic information.

Estimates of health risks related to pollution effects are even more troublesome because many environmental health risks have a long latency period , which creates significant challenges for the design of valuation instruments. Fischhoff [1990] believes that individuals perception of long-term risks poses particular difficulties for two reasons. Firstly, the decision maker does not receive immediate feedback as to how wise his decision was. Secondly, decisions about long term risks are spread out through time, making it difficult to link decisions with their consequences. Much of the early psychological research made use of probabilistic representations of risk, based upon utility assessment. These studies reveal that people experience difficulties in understanding and interpreting statistical probabilities. In an attempt to overcome such difficulties, and in recognition of the limitations of probabilistic information, a number of researchers have adopted the use of the qualitative, Likert type scales in their research. These scales typically require respondents to assess risk in terms of scale values. In this way, the risk reductions are represented in linear distance rather than an area within a circle. It seems plausible that people can more easily comprehend the magnitude of a risk change when the latter is represented as a simple linear distance, rather than as an area representation of a circle which involves two dimensions [Loomis *et al.*, 1993]. However, objections to such techniques have been raised, principally on the grounds that they are not well suited to the evaluation of very low probability risks.

Reviewing the Contingent Valuation health-related risk literature, we found out that there has been a lot of innovation in risk communication aides. Jones-Lee, Hammerton, and Phillips [1985] used darkened blocks on graph paper to portray the risk in 100.000 of death from transportation accidents. Risk ladders have been used by Mitchell and

Carson [1985] as well as Gerking *et al.* [1988]. In these ladders each step represented progressively higher and higher risks. As part of their effort to provide context on risk of death, Smith and Desvousges [1987] used both a risk ladder and three different pie charts. The pie charts are used to communicate changes in the probability of death due to hazardous waste under a series of programs. Loomis and duVair [1993] quote several shortcomings of the risk communication format used by Smith and Desvousges, arguing that risk ladders are a more appropriate risk communication device. More recently, Krupnick *et al.* [2000] used both audio and visual aids to communicate risk. Carson and Mitchell [2000] developed a risk ladder that portrayed risk as annual mortality per 100.000 people, and used various types of risks as anchors on the ladder. Considering what were the findings of the literature, we decided to adopt a framework similar to that of Carson and Mitchell [2000]. We find that the idea to give more emphasis to the lowest part of the ladder was particularly effective for explaining small risks such as the ones that originate from contaminated sites.

4. How people perceive contamination risks.

4.1. Health effects.

During the first focus groups round people seemed to be familiar with risks due to contaminated sites both to human health and to ecosystem. People were clear about the interdependency of the two forms of contamination, and were especially concerned with the threat to human health through contaminated food ingestion. The attention paid to sea-food contamination is a matter of high priority in the Venice lagoon, where legal and illegal fishing activities are particularly intense. Despite the previous acknowledgment, people seemed more concerned with human health than with the risks posed to the ecosystem. In particular, people fear more what we can define as “lethal” diseases, such as cancer, than the diseases with a lower probability of death. Once it has become clear that the respondents place a high priority on environmental risks mainly because of the potential health damage, we decided not to present questions about ecosystem risks in the second focus round. It has been therefore important to understand which particular health risks the public was more concerned with.

4.2. Environmental effects.

Although people seemed concerned with the environment, they clearly appeared more willing to support actions to protect their own health, than to reduce the treats posed by brownfields to wildlife and the ecosystems. This does not sound completely rational given that both contexts are closely linked. It is possible to explain this apparent logical incongruence assuming that people are reluctant to pay for pollution somebody else is liable for. Following this logic, the discussants would only wish to allocate scarce resources to addressing this problem. In this “relative scarcity” environment, people appear to have a high discount rate and a short run approach to remediation, preoccupied more with the avoidance of the risk of health damage at present than with leaving richer biodiversity for the future generations. This view is partially supported by our investigation, given that just one out of 67 people explicitly mentioned future generations as the main purpose of her WTP . The role played by different life discount rates should be a further field of investigation in a future questionnaire, that would present several remediation scenarios with different temporal health and ecosystem benefits.

5. Some crucial aspects influencing WTP for remediation.

5.1. Latency and Altruism.

Public policies addressing site contamination involve latencies between the time an investment is made and the time when the benefits (i.e., the reduction in health risks), are realized. We did not address this issue explicitly, but we asked which groups the respondents consider the most exposed to contaminants. Respondents are especially concerned with children's health and feel that children are more exposed to contamination from the sites than other high risk groups such as elderly people and people with a weak immune system. In future research we can investigate the temporal dimension of WTP to reduce risk by creating different versions of the questionnaire according to the period when benefits are realized. Altruism plays an important role in explaining the intrinsic nature of people's WTP for cleanup. A person may support a cleanup action out of concern for his or her own health and well-being, and/or out of concern for the future generations and residents of other parts of the country. If a person is not directly affected by the risks posed by contamination, why should he contribute? Altruism may be the answer. Altruism is usually defined as the consideration for other people without any thought of one's own direct benefit. During our two focus group rounds people manifested their willingness to pay under the condition that all stakeholders would contribute. In other words, they did not allow free riding behaviour, therefore manifesting some form of altruism. It is therefore possible to consider clean-up actions benefits either in a temporal dimension, either in a spatial one. Benefits have a temporal dimension because of the time mismatch between the investment period and the period in which people start to benefit from the actions undertaken. Contributors may prefer actions that will give short-run benefits foregoing better clean-up actions that would be enjoyed by their bequest. At the same time benefits have a spatial dimension, limited in our case to the Italian boundaries, and contributors may benefit differently depending on how far they live from contaminated areas. Considering the spatial dimension of altruism, the main task is to understand why people not directly threatened by the presence of a contaminated site in their surroundings should be rationally motivated in eliciting even a minimum WTP. Do they have a "warm glow" implicit purpose or do they have some other kind of "implicit benefit"? At the same time, with regard to the temporal dimension, do people contribute because they have a "real" bequest (or they have the option to have children, if still too young, i.e. students)? Are they fulfilled by an utility compensation thinking to leave future generation better off? Or, instead, do they feel the ethical need to compensate future generations for the environmental impact due to their present exploitation of the environment? These are important questions that need to be addressed, considering that altruism can explain some of the benefits provided by policy actions and therefore the amount people are willing to pay for them. A possible material internal return for people living far away from a contaminated site, derives from the fact that they can benefit from remediation when they avoid possible sources of contamination like the ingestion of food produced in contaminated areas or upstream contaminated water. Another source of spatial altruism can be the fear of future discovery of some form of contamination in one's own neighbourhood. People in this situation may pay today hoping for cooperation of other people in the future: they conceive their contribution as an insurance from future uncertainty. A different situation arises in the evaluation of intertemporal altruism. When a person individuates in children the most exposed class, it does not necessarily mean that she/he is willing to pay just in favour of future generations. A further indication could be the fact that the respondent has children, but even in this case his or her temporal altruism can not be taken for granted.

5.2. Familiarity and concern with health and ecosystems risks.

Familiarity with risk is one of the factors that influence risk perception, and it can also affect our estimation and decision process. Some studies [Teisl *et al.*, 2001] have highlighted that stated WTP for risk reductions can vary greatly according to familiarity with a particular risk. In contingent valuation (CV) methodology and in surveys in general, it is essential that the respondents understand the commodity as the researcher intends it. People could not have well defined preferences in an economic sense for goods with which they have no direct experience. There tends to be an inverse relationship between familiarity with the good and ability of respondents to answer meaningfully. Crucial for a CV survey is the information respondents have regarding the hypothetical commodity. Since the commodity being valued is normally a non-marketed good, respondents may not be very familiar with it. Studies show that responses to risk-income choices differ, whereas responses to risk-risk tradeoffs may be more stable, suggesting that persons who are unfamiliar with a disease cannot give valid and reliable answers to WTP questions [Mitchell and Carson, 1989]. There has been little empirical investigation on how risk perception might change over time as a function of social interaction, exposure or experience, where cognitive variables such as familiarity, perceived control or confidence might be hypothesised to be of salience.

Socio cultural insights highlight instances where familiarity has led to reduced levels of anxiety. As a source of cognitive bias, familiarity is said to operate at the level of personal experience, suggesting that, in the absence of negative outcomes, it can lead to reduce levels of caution. Direct experience of risk can either amplify or attenuate its perception through a feedback mechanism of reflexivity [Kasperson *et al.*, 1988]. If one faces the risk everyday with seeming impunity (that is, the risk appears to have a very low probability), the tendency is to become overconfident. In our specific case, the fact that, as people become more familiar with a situation, the perceived risk declines, seem to be not confirmed because our respondents are familiar with the risk associated with the presence of contaminated sites but they don't underestimate this risk. Familiarity in our context means that interviewees have been in touch with the problem of contamination living in an area close to the source of the matter. Therefore, familiarity does not necessarily imply that people have experienced symptoms of diseases associated with exposure to contamination. It has often emerged that people that are familiar with the situation are aware of the possible effects. These information and residents attention have been favoured by the big media resonance about the recent inquiry about suspect deaths with regard to Petrolchimico workers. The inquiry has increased public awareness of contamination. At the same time, it revealed the asymmetric information nature of the problem. Chemical managers knew about the health effects of some hazard substances treated in the Porto Marghera plants, but kept scientific data on exposure consequences hidden for at least twenty years. The awareness built up by the inquiry raised familiarity and, at the same time, distrust of the industry.

6. Public opinion about possible cleanup solutions and stigma.

The problems of land use after rehabilitation, and the perception of site cleanup operations by the local community are important aspects of remediation. We explored what people thought about site remediation and if it was true that stigma negatively influenced the local/regional property market. We provided the following definition of cleanup: "Environmental cleanup is the set of interventions used to eliminate pollution or to reduce pollutants concentration in soil, subsoil, water and groundwater, and to avoid human exposition to toxic substances in order to protect human health and ecosystem ". Then we asked people if they had ever heard about contaminated sites cleanup. Almost all participants said that they had heard of that before (94,4%). Moreover, respondents preferred remediation technologies that can remove pollution from the site in a definitive way but they don't think accurately about the costs and the intertemporal effects of these interventions. The concept of environmental stigma is often misunderstood and misused. Many posit that it is solely a residual effect that continues to affect a site's value even following the cleanup of contamination at the site. Others view it as an immeasurable effect on property value due to perceptions and fears of contamination [Jackson, 2003]. Stigma is an intangible abstract element that could influence market value, but, because it is based on people's perception, its real influence on value is not easily measurable. Patchin [1988] points out that stigma is a penalty imposed by the market that influences the economic value of a property where contamination is expected. Stigma can have an impact on the value of contaminated sites before, during and after the cleanup process. Moreover, it has been proved that it can influence the value of surrounding properties. The post-reclamation stigma is the residual value loss that is obtained after taking into account recovery, insurance and monitoring costs. Bond [2001] defines it as the difference between the value of a recovered site and the value of a "clean" site, without any precedent contamination.

One of the tangible effects of stigma is that people are particularly cautious in indicating that they are willing to live in a remediated area. According to Edelstein [2001], people distrust the effectiveness of remediation techniques, furthermore, even assuming that cleanup is certified at present, they have some distrust about their long run guarantees or the possible long-run health consequences of pollutants. During our focus groups we explicitly examined if the presence of stigma posed constraints to contaminated area redevelopment and reuse. This issue is particularly important for this kind of research because community's preferences and support must be taken into account to correctly address land planning after remediation. At the same time, people may be willing to pay more, when they are willing to reuse the area and trust the results of cleanup. To investigate people's perception of stigma properly, we asked our respondents if they would live in a remediated site. Most of the people we interviewed said that they would not live in cleaned up areas unless they had some financial incentives to live there (in particular lower housing prices). Working or shopping were considered as possible no risk alternatives to reuse these sites because of the limited time spent in those kinds of places. An interesting discussion has been fostered in one of our focus groups thanks to the participation of two young foreign people. They clearly had lower stigma-biases than the local participants and were more keen to settle in a remediated area. In particular, they brought up some examples of successful remediation stories in Belgium and France, where redevelopment action worked well supplying some of the most sought after real estate. A general problem that has emerged from participant's discussions is the distrust either in the institutions that manage/guarantee cleanup results, or in the scientific precautionary or legal thresholds. Nevertheless, it has to be kept in mind that our interviewees were really sensitive to environmental contamination due to the big turmoil after the judiciary enquiry about Porto Marghera scandal from 1998 to 2001, that strengthened the already widespread distrust in institutions.

Stigma apart, it turned out that respondents were particularly sensitive about future use scenarios when asked for their WTP. In addition to the usual distrust in government institutions about the future use of the taxes collected, a further uncertain variable has emerged. Who guarantees to the contributors that after cleanup the area would be dedicated to a particular use? The common fear of respondents is to not be able to enjoy the direct benefits from the remediated land direct use. Therefore, it will be necessary to add to WTP questions some information about the future use of the area. This could reduce the possible distrust bias in eliciting WTP.

Conclusions.

The research activities described in this report conclude the phase during which we explored risk perception by the public and drafted a questionnaire for valuing a risk reduction. Focus group discussions helped us to understand that participants had a well developed notion of health risk and their linkage to contamination. However, the understanding of what constitutes contaminated sites – the subject of our investigation – was vague. General ambient pollution, such as polluted water bodies and air, are frequently erroneously perceived as a possible form of a contaminated site. This implies that the questionnaire will need to include sufficient background information that would familiarize the respondents with a contaminated site and remediation issues.

People care about post-remediation land use. Not surprisingly, focus group discussions revealed that people are willing to pay a different amount for remediation depending on whether the cleaned up site is turned into a park, a residential or a commercial area. The stigma associated with the site after remediation also depends on the post-remediation land use. Focus group participants were generally sceptical of the reuse of remediated areas for residential purpose, although lower housing prices could induce them to live there. Commercial and recreational use of the remediated areas seemed generally more acceptable. In terms of the contribution to the literature, the focus group discussions have been structured to investigate the possible linkage between the WTP and altruism, stigma, and the public nature of environmental goods.

In the subsequent rounds of focus groups it will be important to assess how the latency of the benefits from cleanup, and how the different perceptions of respondents and their trust in the successful outcome of a project affect their WTP.

References.

Alberini A., Longo A., Tonin S., Trombetta F. and Turvani M., 2003. The Role of Liability, Regulation and Economic Incentives in Brownfield Remediation and Redevelopment: Evidence from Surveys of Developers, *Nota di lavoro* 7.2003, Fondazione Eni Enrico Mattei

Barlow McDonald T,. 2001. Valuing environmental health risks: a comparison of stated preference techniques applied to groundwater contamination, Dissertation submitted to the *Graduate School of the University of Massachusetts Amherst*

Bond S., 2001. Conjoint Analysis: Assessing Buyer Preferences for Property Attributes to Assist with the Estimation of Land Contamination Stigma, Paper presented to at the Conference of Pacific Rim Real Estate Society, Adelaide, 21-24 January, 2001

Carson R.T. and R. C. Mitchell, 2000. Public preference toward environmental risks: The case of trihalomethanes, discussion paper 2000-21, San Diego, California: University of California San Diego, Department of Economics

Eldestein M, 2001. Crying over Spoiled Milk: Contamination, Consumer Expectations and Environmental Stigma, in *Risk, Media and Stigma* (eds) Howard Kunreuther, James Flynn and Paul Slovic

Fischhoff B., 1990. Understanding long-term environmental risks, *Journal of Risk and Uncertainty*, 3, 315-330

Gerking S., M. De Haan, and W. Schulze, 1988. The marginal value of job safety: A contingent valuation study, *Journal of Risk and Uncertainty*, 1, pp 185-199

Jackson T.O., 2003. Appraisal Standards and Contaminated Property Valuation, *The Appraisal Journal*, Volume LXXI (2)

Jones-Lee M. W., M. Hammerton, and P. R. Philips, 1985. The value of safety: Results of a national sample survey. *The Economic Journal* 95: 49-72

Kasperson R, O. Renn, P. Slovic, H. Brown, J. Emel, R. Goble, J. Kasperson, and S. Ratick, 1988. The social amplification of risk: a conceptual framework, *Risk Analysis*, vol 8

Krupnick A.J., A. Alberini, M. L.Cropper, N. Simon, B. O' Brien, R. Goeree, and M. Heintzelman, 2000. Age, health and the willingness to pay for mortality risk reductions: A contingent valuation survey of Ontario residents. *Journal of Risk and Uncertainty*. Volume 24 2002, pp 161-86

Loomis, J.B., and P.H. duVair, 1993. Evaluating the effect of alternative risk communication devices on willingness to pay: Results from a dichotomous choice contingent valuation experiment, *Land Economics*, 69, (3), 287-298

Malhotra N.K., 1996. Marketing Research: An Applied Orientation, 2nd Edition, New Jersey: Prentice-Hall International

Mitchell R.C. and R.T. Carson, 1985. Not in My Backyard or the Economic Cost of Siting Opposition, invited paper presented at the annual American Economics Association Meeting, New York, December 1985

Mitchell R.C. and Carson, R. T., 1989. Using Surveys to Value Public Goods: The Contingent Valuation Method. Resources for the Future, Washington, DC

Patchin P.J., 1988. Valuation of Contaminated Properties, *The Appraisal Journal*, 10, pp 7-16

Smith V.K. and W. Desvousges, 1987. An empirical analysis of the economic value of risk changes, *Journal of Political Economy*, vol 95/1

Teisl M.F., B. Roe, K.J. Boyle, T.L. Riggs and M.J. Herrmann, 2001.Understanding how respondents view food safety risks: implications to the design of willingness to pay experiments, paper presented to AERE 2001 Summer Workshop "Assessing and Managing Environmental and Public Health Risks", Maine, June 13-15, 2001

Viscusi W.K., W. Magat and J. Huber, 1987. An investigation of the rationality of consumer valuations of multiple health risks. *Rand Journal of Economics*, 18, 465-479

Weyman A.K., and C.J. Kelly, 1999. Risk perception and risk communication: a review of literature. *Health and Safety Executive*, research report 248/99

AREA 2
ARCHITECTURE AND CULTURAL HERITAGE

RESEARCH LINE 2.1
Protection from high waters and architectural conservation

VENICE, ONE THOUSAND YEARS OF BUILDING AND THE PROTECTION FROM THE TIDES

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Riassunto.

La ricerca sviluppata nell'area tematica "Architettura e beni culturali", nella linea 2.1 "La difesa dalle acque e la conservazione dell'architettura", individuata nel primo triennio di ricerca CORILA è suddivisa in quattro settori principali, fondati su indagini di tipo storico, tecnico-analitico, di catalogazione: 1. La manutenzione dell'edilizia cittadina in età moderna, 2. Gli interventi di salvaguardia dalle acque nell'età della Repubblica, 3. La costruzione lagunare e l'acqua, 4. La catalogazione degli intonaci esterni della città.

Il lavoro, già reso noto con una nutrita serie di pubblicazioni, ha prodotto una vasta e sistematica raccolta di informazioni sulla storia e la costituzione fisica delle fabbriche lagunari, ed è stato condotto anche allo scopo di offrire nuovi strumenti e metodologie utili alla salvaguardia della città. Tutte le conoscenze relative alle problematiche esaminate sono state organizzate con strumenti informatizzati; i database prodotti sono stati concepiti come sistemi aperti, capaci di accogliere ulteriori immissioni di dati.

Abstract.

The research carried out on the subject matter of "Architecture and Cultural Heritage" within the research line titled "Protection from the waters and the preservation of Architecture", during the first three years of the CORILA research, is developed through four main sections, each based on historical, technical-analytical and compiling investigations: 1. Maintenance of city buildings in the Modern Age, 2. Protection from water's actions in the Age of the Republic, 3. The Lagoon building culture and water, 4. Cataloguing of the city's external plasters.

This work, already available in a series of publications, has yielded a wealth of systematic information on the history and physical structure of the Lagoon's constructions, and was carried out also with the aim of supplying useful new tools and methods for the preservation of the city. All the information collected with regard to the studied problems has been collated with the aid of computer-based instruments; the resulting databases have been organised as open systems, able to receive further inputs.

1. Introduction.

The relationship between the water and Venetian architecture is widely analysed in this research. The collection of information on the history and physical structure of the Lagoon's constructions, on some peculiar deterioration phenomena and ruination mechanisms affecting the whole construction complex of the Veneto Lagoon was carried out with the further aim of supplying the necessary know-how to improve the effectiveness of the protection and restoration of the Lagoon's buildings and of stimulating the perfecting of new executive methods and procedures that could be useful for the well thought-out and efficient solution of some problems that are currently being tackled with largely insufficient means and systems.

Several lines of research were investigated, each following multiple, intertwining and interconnected avenues of inquiry.

2.The maintenance of city building in the Modern Era.

The first research sector, addressed by the History of Architecture department, IUAV University, Venice, was dedicated to the study of maintenance works on city building in the Modern Era and was developed in two parts; the first part dealt with the creation of a database of skilled workers operating in the city between the XV and XVIII centuries, the second part dealt with the study of the archival collections of the *Commissarie* of the *Procuratie di San Marco de supra, de citra* and *de ultra.*

2.1 Database of the skilled workers operating in the city between the XV and XVIII centuries[1]*.*

A database of the skilled workers active in the city between the XV and XVIII centuries was created, as an instrument for the collection of all personal information on the skilled workers operating in the city, gleaned from published and unpublished archival documents and from publications, in order to have precise knowledge of the identity and specific role of the various masters working in the city's construction sites, as well as to understand the composition of the various teams or *botteghe* (workshops) and of their movements, cross-crafting and roles in the various projects. The database uses the collected information to create specific links between construction yards and skilled workers working therein, ore between the various skilled workers. The input cards contain details of names and patronymics, the date in which the person was present in the construction yard, roles, salaries received, bibliographic and archival sources, as well as other miscellaneous information concerning the skilled workers working in the city's various construction yards. The same is true also for the principals commissioning architectural works, and information of these is directly cross-referenced with the information pertaining to the construction yards, the skilled workers and attendance. The database is a system open to a continuous flow of future data input.

[1] Professor Manuela Morresi, together with Dr. Silvia Foschi, are responsible for the conception and scientific direction of this project, Nexus, Florence, is responsible for the programming of the database, together with Pierre Picotti, of IUAV's Bibliographic and documentary services office.

2.2 Examination of the "Commissarie" archival collection of the Procuratie di San Marco de supra, de ultra and de citra[2]*.*

A second research sector is dedicated to the analysis and historical study of Venetian construction and of the city's growth areas. This research was carried out using the archival collections of the *Procuratori* of *San Marco de citra, de supra* and *de ultra,* and aimed, on the one hand, at reconstructing the history and events related to the creation and structure of constructs such as the *rive*, the *fondamenta*, the expansions, etc., and, on the other hand, at determining the usual procedure adopted in the preservation works and in the transformations that were carried out, along the centuries, on a wide sample of Venetian residential buildings. The exam of the archival collections led to the preparation of about 800 computer cards ; the assessed materials concern both punctual urban and building interventions and general maintenance actions, with particular regard to the interventions for the protection of public spaces from the destructive actions of water. The analysis of the resolutions of the Senate led to an in-depth knowledge of the financing mechanisms for maintenance works and of the executive powers attributable to the various relevant offices appointed thereto. The analysis of the materials filed in the archival collections of the technical offices allowed the researchers to understand the details of the single interventions and to reconstruct the actual processes that led to the modification and transformation of the urban texture. The diachronic comparison of the various collected documents, finally, highlighted the change in intervention strategies and methods, as well as the technical-building evolution of the building science in Venice. Further, several very interesting details emerged on the maintenance and/or reconstruction of buildings belonging to the so-called "secondary building industry", involving several major architects: indeed, three previously unknown interventions by Jacopo Sansovino, in his capacity as *proto* of the *Procuratia de supra,* carried out on Santa Maria Formosa, on San Giacomo dell'Orio and on San Canciano between 1529 and 1570 were discovered.

3. Protection from the waters interventions in Venice in the Age of the Republic (XVI-XVIII centuries)[3]*.*

The main goal of the research carried out by the operating group was that of determining, through a systematic study of the documents stored in Venice's State Archive, the material actions and the technical and administrative procedures adopted in the Venetian age in order to protect the urban texture against the destructive action of the lagoon water.

The preliminary research activities concerned the reconstruction of an in-depth historiographical picture, on the basis of the existing studies and of the available literature, of the ordinary and extraordinary maintenance works carried out by the Republic of Venice in order to protect the city from the destructive effects of the water. The analysis and collection of data was aimed at directing the searches in the archives

[2] Professor Manuela Morresi, together with Paola Modesti and Gianmario Guidarelli, are responsible for the scientific direction of this project.

[3] Professor Donatella Calabi, together with Paola Antonio Brucculeri, Silvia Moretti, Elena Svalduz, Stefano Zaggia and Giulia Vertecchi, are responsible for the scientific direction of this project.

towards the document collections that could supply precise data and information on the actions that had been carried out. Then the research moved on to examine the archival collections of three offices entrusted with the control and maintenance of the urban area and of the lagoon's status, namely, the *Savi ed Esecutori alle Acque,* the *Giudici del Piovego* and the *Provveditori di Comun*. The jurisdiction, both judiciary and executive, of these three offices covered the whole of the activities for the management of public spaces and the "urban planning" control of the city. These offices were further supported by the highest government body, the Senate, which supplied planning and direction.

This area of the study did not entail any field or laboratory work, as the research concerned mainly the retrieval, reading and transcription of the relevant archival collections, mainly housed in Venice's State Archive, and the analysis of the existing literature.

The processing of the collected data included an historical-critical analysis of materials and their placement from a topographical point of view. One of the most difficult problems, indeed, was that of linking the toponymic terms used in the historical documentation with the present day cartographic maps.

The data collection was recorded on Access-based computer cards. In particular, the contents of the single documents were summarised and ordered by categories of information. The first part of the card, therefore, includes a series of fields concerning the materials' external data, namely, position in the archive, date, etc. The second block of information concerns, essentially, where the assessed action took place: fields were inserted for inputting the toponyms on the basis of both current and historical toponymy, including fields for GIS code input. Then there is a section meant for the recording of the relevant information: this section includes fields describing the type of action on the basis of a set nomenclature; there is also a free-text field, where extracts or summaries of the document can be typed in. The last part of the card is dedicated to drawings or graphs, if any, attached to the original document.

Generally speaking, the assessed materials concern both punctual urban planning and building actions and general actions of maintenance, with particular regard to the protection of public spaces from the destructive effects of water. The analysis of the senate's resolutions led to a deep understanding of the financing mechanisms for maintenance works and of the executive powers attributed to the various magistrates appointed thereto. The investigation of the material filed in the archival collections of the technical offices , on the other hand, also allowed the researchers to go into the details of the single interventions and to reconstruct the actual processes that led to the modification and transformation of the urban construct. The diachronic comparison of the various collected documents, finally, highlighted the change in intervention strategies and methods, as well as the technical-building evolution. Some critical data analyses have been collated into publications and reports that have been presented on the occasion of several international conferences.

Given the considerable amount of documentation existing within the single archival collections, and the huge information potential they bear, the results so far cannot but be incomplete, and are susceptible of further development.

4. Building on the Lagoon and water.

The second branch of the research aimed at assessing the techniques, procedures and building instructions applied within the context of the building tradition of the Lagoon, to protect buildings from water.

4.1 Dehumidification and desalinisation techniques applied to Venetian historic construction[4]*.*

The loss of static efficiency in Venetian buildings, due to old age, to the natural degradation of building materials and to improper maintenance, was further enhanced by the accumulation of damage due to water capillary migration and salt crystallisation. The deterioration affecting, to various extents, the lower part of the walls throughout the whole city complex is extremely widespread, and is due to capillary migration and to the consequent crystallisation cycles of salts coming from the salty water washing the lower brickwork of the constructions, but it can also be traced back to the effects of *acqua alta* (high tide) and of sea aerosols. Stones, structural tiles, bedding mortars and plasters in the lower part of the vertical walls are always affected, sometimes to such an extent that the bearing section of the brickwork is reduced, thus becoming a pre-existing cause of structural damage.

The research tried, on the one hand, to improve knowledge of the causes and mechanisms of the degradation of building materials, and, on the other hand, to analyse the systems that were adopted to oppose or solve the problems due to the constant presence of salt water, evaluating such problems both form the technical and the architectural compatibility points of view; indeed, the face reconstructions, the cut-and-sew substitutions, the mechanical and chemical barriers to prevent migration, the desalting of brickwork, etc., had never been systematically evaluated before. In particular, the research concentrated on the brickwork desalinisation technique, also through two main experimental applications and their variations, namely, the application of cellulose paste or absorbent clay compresses to the heated brickwork surface, together with intermittent soaking of the opposite face, and the percolation washing implemented through microcannules embedded in the wall structure. The research evidenced how, in order to oppose capillary migration, a cut and the insertion of a mechanical barrier in the lower part of the brickwork is the most efficient solution and how other techniques are decidedly less functional. The effectiveness of the desalinisation interventions, which would represent the best solution from the point of view of architectural compatibility, was shown to be difficult to obtain in practice and to be conditioned by the architectural-building characteristics of the constructions. The weak points of such operating methods were also studied: the long time required by washing operations might cause imbibition of the brickwork and trigger the rotting of the wooden floors at the wall/floor connection.

[4] Research co-ordinated by Prof. Paolo Faccio, IUAV, together with Andrea Briani and Alessia Vanin, and with Francesco Cainfrone of Metra Srl.

4.2 Bedding mortars: chemical-physical analysis[5]*.*

A part of the research is dedicated to the study of the bedding mortars of historical constructions, in order to ascertain their state of health. Bedding mortar, indeed, is the material which, within the context of the wall structure, has often the highest degree of deterioration, and which constitutes the weak point of the whole system.

Brickwork samples taken from monumental buildings, all constituted of air lime based mixes, with inerts belonging mainly to the granulometric classes of fine and medium sands, were subjected to complex chemical-physical analyses. Several different things emerged: the most important concern porosity of the mortars in relation with the various heights from which they were sampled: while the total porosity value remains mainly unchanged at the various sampling heights of a single mix, pore distribution changes significantly, as a consequence of salinity. There might be a reduction in pore diameter, due to the pore's partial occlusion by soluble salts, or a partial increase in pore dimensions (especially in mixes where pores were, on average, smaller), a phenomenon due to the breaking down and joining of internal vacuums derived from the salt crystallisation cycles. All the analysed mixes were free from disgregation due to freezing /thawing out alternation. In general, it turned out that mortars drawn from the lower levels are more friable than the previous ones. This fact may be explained by the higher influence of capillary migration processes and by the consequent salt crystallisation cycles at the lower levels. It was also noticed that, often, thickening (clast/matrix ratio) is higher in mortars located at lower heights, which could be an indication of the partial depauperation of mortars in the bonding phase, that, in turn, is also attributable to capillary migration phenomena. The dynamics interacting with the bedding systems are varied and lead to multiple consequences, and the collection of a series of systematic data allowed the creation of a precise characterisation of mixes and of their state of preservation.

4.3 Study methodology, using advanced analysis techniques for the evaluation of the protracted effectiveness of the conservative treatments of the stone materials[6]*.*

A specific sector of research dealt with the assessment of the effectiveness and duration of the consolidation and protection materials applied on the exposed stone materials in Venice. The most frequent treatment adopted in the last few decades for the restoration of external stones in urban architecture, with particular regard to stones presenting sculptures, reliefs, mouldings, coating slabs cut from Greek, oriental or Luni marbles, was based on the application of acrylic-silicone resins; such treatments are quite widespread, not only in the Lagoon area, but their endurance is not sufficiently known.

The research aimed at creating a model to determine the loss of effectiveness of consolidation and/or water repellent treatments, in order to perfect a procedure for the

[5] Research co-ordinated by Prof. Guido Biscontin, Ca' Foscari University, together with Guido Driussi and Zeno Morabito of Arcadia Ricerche Srl.

[6] Research co-ordinated by Prof. Fulvio Zezza, Architectural Construction Department, IUAV University, Venice, together with René Van Grieken, Department of Chemistry, University of Antwerpen, Belgium, and Fernand Auger, Laboratoire de Construction Civile et Maritime, Universitè de La Rochelle, France, and Prof. Eloisa Di Sipio and Emiliano Meda, engineer.

normalisation of analytical techniques' measures and thus contribute to the determination of the characteristics of the products eligible for the reduction or annulment of the effects of sea salts on the coastal environment. Two of the most important monuments of the city, namely, the Loggetta del Sansovino, located at the feet of San Marco's bell-tower, and the front of the Ca' D'Oro, were chosen as case studies. The research concentrated on the various forms of deterioration of the existing stones (macrocrystalline marbles, *pietra d'Istria*, ammonitic *Rosso*, Luni marbles, etc.) that had been subjected to consolidation and preservation treatments in the course of restoration works carried out in the past decades, and highlighted mainly the alterations linked to the various lithotypes' properties and to the exposure conditions. During the second phase of the research, carried out in the laboratory, the dynamics of the alteration were checked and interpreted. *In situ* measurements were related to measurements taken on healthy or deteriorated marble samples, treated with resins, subjected to accelerated artificial weathering cycles with salt fogs, all with the aim of establishing the endurance and loss of effectiveness of such treatments.

4.4 The "caranto": deposition environment and age[7].

A further sector of research was dedicated to the acquisition of information on the genesis and age of an altered level known as *caranto*.

This term, whose origin is uncertain, used to define strata with different compositions and texture that are found in the lagoon's subsoil (*caranto* usually indicates a yellowish clay, but the definition included also cemented sand or argillaceous slime levels) that exhibited higher bearing capacity than the lagoon's muds or the lower incoherent sediments; a key support function was and dtill is attributed to the *caranto* with regard to the lagoon's constructions. The *caranto*'s granulometric definition is vague, and its age had not been precisely determined either, as the lack of organogenic contents due to a subaerial environment had prevented its dating with traditional methods.

The research evidenced that this level, whose varied texture testifies to depositions linked to local hydrodynamic and morphologic conditions, is constituted of a carbonate-rich horizon, poor in humified organic substance. Its formation cannot be traced back to a single unconformity, but rather to a discontinuous and very reduced sedimentation sequence, characterised by occasional additions which, for different reasons in the different areas, justify the variable texture of the altered levels and the different ages of the organic findings included in the stratigraphic sequence. The various adopted approaches lead to the conclusion that the level known as *caranto* cannot be classified in a specific sediment category or with a specific mineralogical composition; that the *caranto* is constituted by the Ck pedogenetic horizon of a soil that formed between 12,000 and 5,700 years ago; that during the time necessary for the *caranto* to come into being, several sediment additions took place; and that the lack of the pedogenetic horizon demonstrates that the unconformity that formed at the same time as the *caranto* is at lest partly attributable to erosion phenomena.

[7] Research co-ordinated by Ms Rossana Serandrei Barbero of CNR-ISMAR, Venice, together with Claudio Bini, Maurizio Bonardi, Alberto Lezziero and Dr. Sandra Donnici (PhD).

5. The cataloguing of Venetian external plasters[8].

The last research sector, finally, was dedicated to the study of Venetian external plasters. The local building culture has always entrusted a building's external facing with precise protection tasks. The extreme thinness of the lagoon's construction's direct bearings, due to a quest for maximum lightness in building, commanded the implementation of every measure that could protect the walls; a reduction, albeit slight, of their section might trigger serious instabilities, with consequent dangerous accidents. Thus, the Venetian finishings and plasters have always been applied to the external fronts, apart from their indubitable aesthetic and formal value, also with the specific function of protecting the faces from external aggressions by shouldering the deterioration due to the combined action of weather and salt aerosols.

The studies carried out so far had shed partial light on the technical and formal evolution of such finishings and plasters, on their composition and deterioration. However, there were no quantitative details that might help to determine the type, stratification, distribution throughout the city and the conservation state of the external plasters.

5.1 The assessment of plasters[9].

Therefore, part of the research was dedicated to the systematic scouting and assessment of the historical external coatings of the city buildings. The cataloguing of Venetian external plasters had a double goal, namely, the collection of information for scientific purposes and the creation of an operating instrument. The cataloguing of plasters in the city of Venice led to the creation of a wide database pertaining to almost 15,000 buildings in the city's historical centre. Each building unit was assessed from the point of view of the type or types of plaster applied to its fronts, and photographic documentation was collected. Where the historical, pre-industrial era plasters still exist, the assessment went deeper, indicating the stratigraphic ratios of the external finishings and collecting a photo documentation of the details.

For easier recognition of the various kinds, plasters were subdivided into four classes (skim coats, frescoes, marmorinos and traditional plasters – as far as the historical ones are concerned), called chrono-typological classes, as they list plasters by technical-executive type and by date. Indeed, among the historical plasters are plasters dating back to the period between the XIV and the XIX centuries, while the non-historical plasters are plasters dated between the first 1900s and today.

The information obtained through field cataloguing has been input in a computer database and cross-referenced to a GIS map, for ease of consultation. This cataloguing campaign, while certainly time consuming, was indispensable in view of the future studies in the sector, and constitutes a basis for the processing of all the collected data. With the relevant computer program it is possible, for instance, to cross-reference data and obtain theme maps of single islands, *sestieri*, o even of the whole city, with the various types of plaster highlighted (for instance, marmorinos, or single-layer

[8] Research co-ordinated by Prof. Mario Piana.
[9] Assessment co-ordinated by architect Ms Alessandra Ferrighi.

marmorinos – the latter dating back to the XVI and XVII centuries – or single stratum marmorinos or on a cocciopesto substrate with abutting stringcourses, or with coloured bands, etc.).

The structure created for the assessment of plasters shall enable the use of GIS also as a future database for the city building industry, which is already organised and active in its fundamental aspects; this could be a starting point with all other information concerning the buildings (such as, for instance, the existing catalogues such as those concerning the city's Urban Sectors, or the paper catalogue organised by *insula* of building data, or such as future researches on the architectural heritage, or, again, type analyses on other materials, members or construction information, provisions and forecasts of the urban planning instrumentation, etc.) joined or cross-referenced here.

The cataloguing of external plasters shall offer, furthermore, important bonus results, even though they might not be immediately applicable, in view of their protection, restoration and enhancement. The computerised database, available to all public administration bodies (Municipality and Superintendence), shall be, in itself, a precious instrument, immediately available for control, management of the protection and planning of restoration actions on the historical building heritage. The offices entrusted with the control of such actions and with the issuing of authorisations and building licences shall be able to consult the database easily, to verify the consistency of the hypotheses contained in the plans with the protection laws, planning provisions and building regulations.

As against what was expected, the research on the cataloguing of external plasters has developed considerably. At the beginning, the program of activities had been created to collect information only on still existing historical plasters (from the XIV to the XIX century). The importance of this field and the possibility of creating a complete instrument for the knowledge and management of such information lead to the widening of the initial plan. Therefore, it has been decided that in the first three years the cataloguing activities would be extended to all the buildings of Venice's historical centre, for a total of almost 15,000 building units.

The general result is a systematic collection of information on the history and physical structure of the Lagoon's constructions, aimed also at supplying new methodologies that might be useful for the preservation of the city.

5.2 Chemical-physical analyses of plasters[10].

The drawing of samples of the most significant plasters and the subsequent chemical-physical analyses of the same aimed at defining the composition characteristics and the executive techniques used in the creation of the various categories of facing (*regalzieri* and mediaeval decorations, single-layer marmorinos or cocciopesto-based marmorinos, etc.) in order to ascertain the correspondence, if any, with the traditional, historical-aesthetic classification and the composition and dimensional characteristics of the raw materials used for the preparation of the various types of plasters. The drawn and analysed samples concern two classes of plasters, namely, mediaeval and Renaissance skim coats, and marmorinos, that were introduced

[10] Research co-ordinated by Prof. Lorenzo Lazzarini, Laboratory for the Analysis of ancient Materials – IUAV University, Venice, together with Fabrizio Antonelli and Stefano Cancelliere.

in Venice at the end of the XV century and that would be used until the XIX century. Such samples were subjected to analysis with a stereoscopic microscope, to carry out a preliminary morphological study, useful also to choose the orientation and modality of the inglobation/preparation of the thin sections; further, they were subjected to microscopic observation (MO) under transmitted polarised light and under reflected light of thin and stratigraphic polished sections, to X-ray diffractometric analysis (XRD; Cu Kα/Ni radiation at 40 Kv and 20 mA) of dusts of the as-drawn samples, for a qualitative and semi-quantitative analysis of the superficial layers of the finish (plaster and plaster finish) or of the preparatory layers (floating coat) of the samples. The microscopic examinations under polarised and reflected light have sometimes been documented by microphotographs with various degrees of magnification, while the diffractometric analyses were recorded on paper with the help of graphs. For both kinds of examinations, the Normal 12/83 and Normal 15/84 recommendations of the ICR of the Cultural Heritage Ministry, now UNI Cultural Heritage, were followed in studying the lithoid materials. In this instance, too, the final goal of this branch of the research was that of supplying useful direction and methodological criteria to direct future preservation and restoration works of the external coatings of the lagoon's buildings.

Bibliographies.

Bibliography of "The maintenance of city building in the Modern Era".

Foschi S., Morresi M., 2002. Data-Base "Venetian Skilled Workers" (maestranze veneziane) XV th-XVIIIth Centuries, in *Scientific Research and Safeguarding of Venice, CORILA Research 2001 results,* Venezia, pp. 109-123

Morresi M., 1999. Piazza San Marco. Istituzioni, poteri e architettura a Venezia nel primo Cinquecento, Electa, Milano

Morresi M., 2000. Jacopo Sansovino, Electa, Milano

Bibliography of "The maintenance of city building in the Modern Era".

Calabi D., 2003. Santa Maria Formosa: i campi, le calli, le rive, i pozzi. VII-XVIII secolo, in *Quaderni. Documenti sulla manutenzione urbana di Venezia*, n. 16

Calabi D., 2003. Definire il limite a Venezia in età moderna, in *Quaderni. Documenti sulla manutenzione urbana di Venezia*, n. 17 (dicembre 2003)

Moretti S., 2003. I limiti lagunari nella cartografia tra Cinque e Settecento. Aspetti giuridici, idromorfologici, semiologici, in *Quaderni. Documenti sulla manutenzione urbana di Venezia*, n. 17

Svalduz E.,2003. "Atorno questa nostra città": dai marginamenti cinquecenteschi alle Fondamenta Nuove, in *Quaderni. Documenti sulla manutenzione urbana di Venezia*, n. 17

Zaggia S., 2003. Il limite tra pubblico e privato nei processi di manutenzione urbana, in *Quaderni. Documenti sulla manutenzione urbana di Venezia*, n. 17

Moretti S., (in corso di pubblicazione). "Fondamenti sodi e non pensieri vani". Giuseppe Benoni ingegnere e architetto tra Venezia e Friuli nella seconda metà del Seicento a servizio della Dominante, in Giuliana Mazzi (a cura di), *Professioni: tra proto e architetto*, Venezia Marsilio

Moretti S., (in corso di pubblicazione). Domenicani dei Santi Giovanni e Paolo a Venezia nel XVI secolo: contraddizzione di un margine urbano,in Città e Ambiente sec. XVI-XX, atti del ciclo di convegni a cura di B. Marin, *Mélanges de l'Ecole Française de Rome. Italie et*

Mediterranée, Roma (in corso di stampa). Testo presentato al convegno: *Città e ambiente (secoli XVI – XX*) del ciclo «Città Capitali», Roma 22-23 febbraio 2002, organizzato dall'Università Roma Tre e dall'Ecole Française de Rome

Svalduz E., (in corso di pubblicazione). Al servizio del magistrato. I proti alle acque nel corso del primo secolo d'attività, in Giuliana Mazzi (a cura di), *Professioni: tra proto e architetto,* Venezia Marsilio

Zaggia S., 2002. «Far la città». Il ruolo dei Provveditori di Comun nell'evoluzione dell'ambiente urbano di Venezia. Strade, ponti, pozzi, case, in *Città e Ambiente sec. XVI-XX*, atti del ciclo di convegni a cura di B. Marin, *Mélanges de l'Ecole Française de Rome. Italie et Mediterranée,* Roma (in corso di stampa). Testo presentato al convegno: *Città e ambiente (secoli XVI – XX*) del ciclo «Città Capitali», Roma 22-23 febbraio 2002, organizzato dall'Università Roma Tre e dall'Ecole Française de Rome

Calabi D., 2004 (in corso di pubblicazione). L'organizzazione dell'edilizia cittadina pubblica e privata nella Repubblica Veneta tra XVI-XVIII secolo, in Atti del convegno internazionale di studi L'edilizia prima della Rivoluzione industriale. Secoli XIII-XVIII, Prato, 26-30 Aprile 2004

Moretti S. 2004 (in corso di pubblicazione). L'organizzazione di cantiere per la costruzione della chiesa, scuola e ospedale dei domenicani in un'area perimetrale e di valorizzazione immobiliare della città lagunare, San Giovanni e Paolo, in Atti del convegno internazionale di studi L'edilizia prima della Rivoluzione industriale. Secoli XIII-XVIII, Prato, 26-30 Aprile 2004

Svalduz E. 2004 (in corso di pubblicazione). L'organizzazione delle responsabilità e del lavoro di cantiere nella realizzazione delle Fondamente Nuove, in Atti del convegno internazionale di studi L'edilizia prima della Rivoluzione industriale. Secoli XIII-XVIII, Prato, 26-30 Aprile 2004

Bibliography of "The caranto*: deposition environment and age".*

Serandrei Barbero R., Donnici S., Lezziero A., Papa P., 2003. Il sottosuolo di Venezia e il suo ruolo nell' urbanizzazione. XIII settimana della cultura scientifica e tecnologica, *Ministero Istruzione, Università e Ricerca,* 31 Marzo-6 Aprile (Poster)

Bini C., Bonardi M., Donnici S., Lezziero A., Mozzi, Serandrei Barbero R., 2003. An overconsolidated paleosol layer underlying the Venice Lagoon: the Caranto. *XVI INQUA Congress, Reno, Nevada, USA, 23-30 Luglio* (Abstract)

Serandrei Barbero R., Bertoldi R., Canali G., Donnici S., Lezziero A. Paleoclimatic record of the past 20000 years in Venice (Northern Italy): Biostratigraphic evidences and chronology. (submitted for pubblication)

Canali G., Bertoldi R., Serandrei Barbero R., Pollen, 2004. Stratigraphy and new chronological data from the Upper Pleistocene-Holocene in old Arsenal and Northern lagoon of Venice. *Convegno AIQUA "La geologia del Quaternario in Italia: temi emergenti e zone d'ombra*", Roma 16-18 Febbraio 2004 (accepted)

Bibliography of "The cataloguing of Venetian external plasters".

Danzi E., Piana M., 2002. The Catalogue of the External Plasters in Venetian Building, in Scientific Research and Safeguarding of Venice, in *CORILA Research Program 2001 results*, Venezia, pp. 87-95

Ferrighi A., 2002. The Plasters database, in Scientific Research and Safeguarding of Venice, in *CORILA Research Program 2001 results*, Venezia, pp. 97-108

Piana M., 2003. L'uso di materiali e tecniche tradizionali, in *ΑΝΑΓΚΗ*, 37, atti del convegno Venice in Peril Found "L'altro novanta per cento: l'architettura minore a Venezia", pp. 65-74

Danzi E., Piana M.,2003. The Catalogue of Venetian exsternal plasters: medieval plasters, in *Atti del Workshop CORILA*, marzo 2003

Ferrighi A, 2003. The Cataloguing of Venetian exsternal plasters: the progress of research, in *Atti del Workshop CORILA*, marzo 2003

Piana M., Danzi E., De Zorzi S., Ferrighi A. Rinaldi E., 2003. Venezia organismi architettonici storici. Il censimento degli intonaci attraverso tecniche di rilievo e classificazione basata su strumenti GIS e WebGIS, in *Atti del convegno ASITA*, Verona, settembre 2003

Danzi E., Ferrighi A., Piana M., Campostrini P, De Zorzi S., Rinaldi E., 2005. Research for conservation of the Lagoon building culture: catalogue of the external plasterwork in Venetian buildings, in *Atti del convegno internazionale su Venezia, Cambridge – UK*, in corso di pubblicazione

AN INTEGRATED SYSTEM *DATABASE-GIS* FOR KNOWLEDGE OF VENETIAN ARCHITECTURE

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Riassunto.

Nell'ambito della ricerca *Venezia, un millennio di costruzioni e la protezione dalle "acque salse"*, è stato progettato e parzialmente implementato un sistema integrato *Database-GIS* basato sull'*interoperabilità* di diverse banche dati, che potrà consentire la gestione dell'informazione sull'architettura veneziana, nei suoi diversi aspetti ed elementi costituenti.

Il sistema è composto da un ambiente GIS e da vari Database, ciascuno afferente a tematiche diverse, che hanno in comune l'appartenenza allo scenario architettonico del Centro Storico veneziano.

Abstract.

Within the scope of the research project *Venice, a millennium of building and protection from "salt water"*, an integrated platform *Database-GIS (Geographical Information System)* has been designed and partially implemented. This system is based on the integration of various databases in order to manage information on Venetian Architecture, in its different aspects and constituent elements.

The system contains a GIS section as well as several databases, each one relating to different theme areas, which have in common a link within the architectural scenario of the Venetian Historical Centre.

1. Introduction.

The theme areas (which correspond in this research to specific survey sectors) addressed in the first phase of system development, are: *historical plasterworks, historical interventions in urban transformation* and *building restoration interventions.*

The system has been developed to include additional theme areas pertinent to urban elements of the city, for the management by local administrators, as well as private citizens, who can make use of additional, efficient tools for preserving buildings both public and private.

The system has been designed to permit the integration of several databases. It is possible to access, gather and synthesize information regarding buildings, spaces, elements, in its various aspects of structural constituents (walls, frameworks, foundations, coverings), and the urban areas (calli-streets, squares, fondamente-public quays, bridges, etc.) with which such buildings relate.

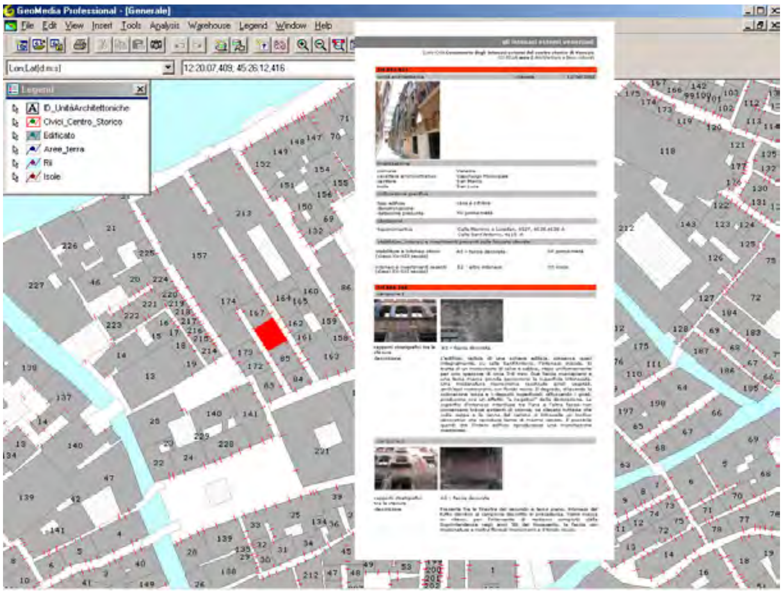

Fig. 1 – Database of historical plasterwork. Details from the GIS cartography with a *report* containing information about the building and the relative plasterwork.

For example, it is possible, indicating a building, to gather information on its conformation, outer covering, if it contains precious elements, if it has been recently restored, if has been conduct recent chemical – physic survey on their material, and more the urban works completed in the surrounding area. All the information provided is useful and necessary to evaluate responsibly, and in an integrated manner, new intervention projects related to the building.

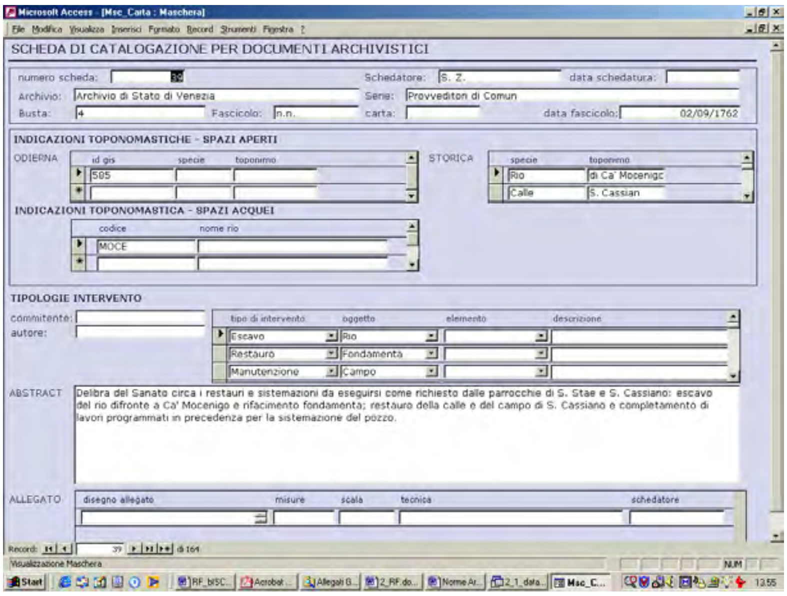

Fig. 2 – Database of historical urban intervention. Sample video for data entry.

The binding element – which makes even more efficient and useful the integration of the information – is the geographic space, specifically the spatial characteristics of the elements: the topographic position can be either the starting point or the arrival point for knowledge gathering.

Fig. 3 – Database of restoration interventions. Rilief module of wall panels used for testing.

2. Database-GIS System.

The GIS system has been designed on the basis of theme levels, this layout provides a clear scenario to which the various elements refer.

In addition to the base topographic level (buildings, public space, canals, etc.) there are distinct levels referring to specific themes: plasterworks (building iconography, chrono-typing of outer covering, surveying, scientific analysis, etc.), restoration (restored buildings) and urban space (urban intervention, also for different types).

Each information is connected to a referenced database, so as to provide *direct* knowledge of the information, that is starting from an element (building, plasterwork, restoration, urban object) contained in the specific database it is possible to determine its location within the city. By indicating a city element the system will provide details on the elements consistency, characteristics and history; as well as information about that element in the city context, for example, mapping of a plasterwork type within the city boundaries, the usage of a restoration technique, the urban works completed in a specific time frame.

In addition to the *direct* knowledge provided, it is as well available a *cross* knowledge view of the same information: for example, details are provided about restoration undertaken on a façade, regarding structural intervention on the building itself or on adjacent external spaces, about building regulations and permitted intervention – with a cost estimate for the entire city or the specific area –knowing the integrity of these elements, what is the effectiveness over time of a restoration technique used in certain buildings, and other articulated information.

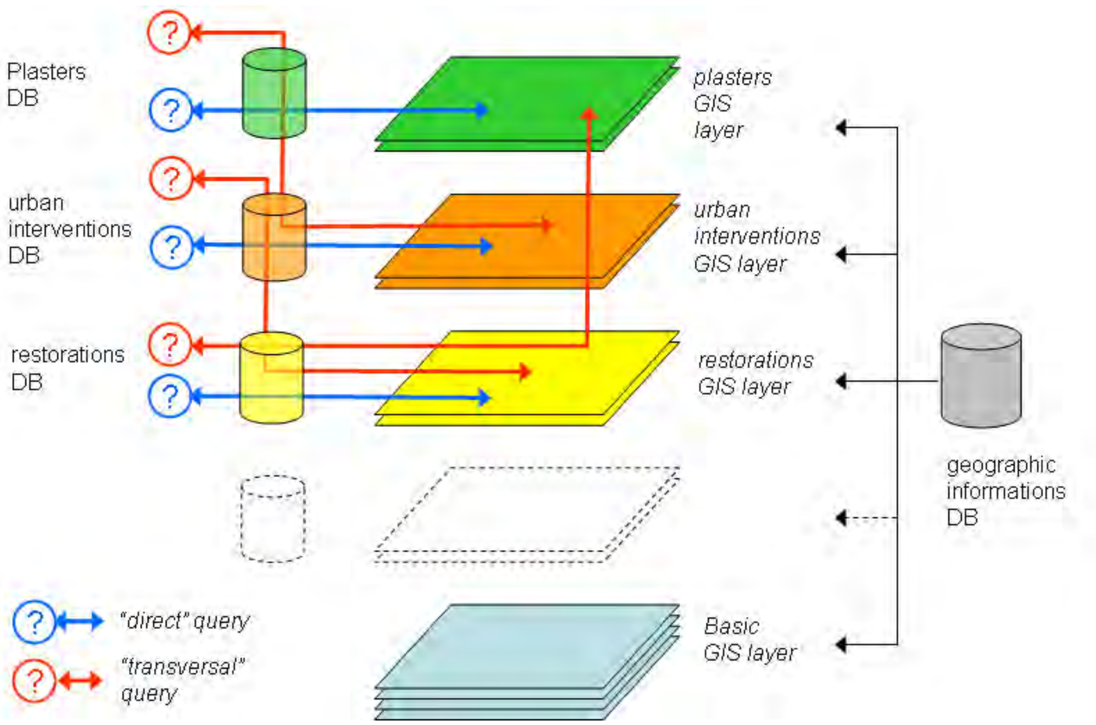

Fig. 4 – GIS-Database System for knowledge on Venetian architecture.

The integrated database system is made possible through respect of data structures defined for the database (they may be different, within certain limits, but compatible – considering the different information sources) and supported by communication interfaces.

The database environment must be able to interact with the GIS environment (a geographic database), in order to allow the user to navigate through the city topography, and to pass from an outer covering to a building structure and its restoration, to similar interventions within the rest of the city. Within the navigational path it is always possible to determine where you are positioned and the relationship between the actual exploration and the general city structure.

Bibliography.

Calabi D., 2003. Santa Maria Formosa: i campi, le calli, le rive, i pozzi. VII-XVIII secolo, in *Quaderni. Documenti sulla manutenzione urbana di Venezia*, n. 16

Calabi D., 2003. Definire il limite a Venezia in età moderna, in *Quaderni. Documenti sulla manutenzione urbana di Venezia*, n. 17

Danzi E., Ferrighi A., Piana M., Campostrini P, De Zorzi S., Rinaldi E., 2005. Research for conservation of the Lagoon building culture: catalogue of the external plasterwork in Venetian buildings, in *Atti del convegno internazionale su Venezia, Cambridge – UK*, in corso di pubblicazione

Danzi E., Piana M., 2002. The Catalogue of the External Plasters in Venetian Building, in *Scientific Research and Safeguarding of Venice. CORILA Research Program 2001 results*, Venezia, pp. 87-95

Danzi E., Piana M.,2004. The Catalogue of Venetian exsternal plasters: medieval plasters, in *Scientific Research and Safeguarding of Venice. CORILA Research Program 2002 results*, Venezia, pp. 65-77

De Zorzi S., Ferrighi A., Piana M., Rinaldi E., 2004. Catalogue of Venice External Plasterworks: WEB-GIS Tools, in *Scientific Research and Safeguarding of Venice. CORILA Research Program 2002 results*, Venezia, pp. 85-88

Ferrighi A, 2004. The Cataloguing of Venetian exsternal plasters: the progress of research, *Scientific Research and Safeguarding of Venice. CORILA Research Program 2002 results*, Venezia, pp. 79-83

Ferrighi A., 2002. The Plasters database, in *Scientific Research and Safeguarding of Venice. CORILA Research Program 2001 results*, Venezia, pp. 97-108

Moretti S., 2003. I limiti lagunari nella cartografia tra Cinque e Settecento. Aspetti giuridici, idromorfologici, semiologici, in *Quaderni. Documenti sulla manutenzione urbana di Venezia*, n. 17

Piana M., Danzi E., De Zorzi S., Ferrighi A. Rinaldi E., 2003. Venezia organismi architettonici storici. Il censimento degli intonaci attraverso tecniche di rilievo e classificazione basata su strumenti GIS e WebGIS, in *Atti del convegno ASITA*, Verona, settembre 2003

Svalduz E., 2004. L’organizzazione delle responsabilità e del lavoro di cantiere nella realizzazione delle Fondamente Nuove, in Atti del convegno internazionale di studi *L’edilizia prima della Rivoluzione industriale. Secoli XIII-XVIII*, Prato, 26-30 Aprile 2004

Svalduz E., 2003. “Atorno questa nostra città”: dai marginamenti cinquecenteschi alle Fondamenta Nuove, in *Quaderni. Documenti sulla manutenzione urbana di Venezia*, n. 17

Zaggia S., 2002. «Far la città». Il ruolo dei Provveditori di Comun nell’evoluzione dell’ambiente urbano di Venezia. Strade, ponti, pozzi, case, in *Città e Ambiente sec. XVI-XX*, atti del ciclo di convegni a cura di B. Marin, *Mélanges de l’Ecole Française de Rome. Italie et Mediterranée*, Roma (in corso di stampa). Testo presentato al convegno: *Città e ambiente (secoli XVI – XX*) del ciclo «Città Capitali», Roma 22-23 febbraio 2002, organizzato dall’Università Roma Tre e dall’Ecole Française de Rome

Zaggia S., 2003. Il limite tra pubblico e privato nei processi di manutenzione urbana, in *Quaderni. Documenti sulla manutenzione urbana di Venezia*, n. 17

AREA 3
ENVIRONMENTAL PROCESSES

RESEARCH LINE 3.1
Trends in global change processes

POLAR FORCING AND CLIMATE OSCILLATIONS: A LIKELY CONNECTION PATHWAY

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Riassunto.

L'articolo vuole mettere in evidenza l'esistenza di una possibile teleconnessione tra la variabilità di produzione di particolari acque polari con le pulsazioni che si osservano nell'oceano pacifico. Già si erano osservate correlazioni, anche se sporadiche, tra la variabilità interannuale della pressione atmosferica sopra l'Antartide, l'esistenza di una onda di pressione circumpolare antartica e il verificarsi di condizioni favorevoli ad eventi El Niño - ENSO. Per la prima volta, però, pur senza spingere la speculazione sulle possibili relazioni causa-effetto né sulle complesse dinamiche esistenti, si vuole sottolineare il carattere di condizioni di anticipo al verificarsi dell'importante fenomeno climatico.

Abstract.

The paper point out a possible "teleconnection" between characteristic new formed polar water and Pacific Ocean oscillations. Recently some correlations were found between atmospheric pressure variability over Antarctica and favourable conditions for El Niño – ENSO events. Now, for the first time, we present the existence of a strong signal in advance, even if at this stage, it is a speculating evidence, an important working hypothesis.

1. Introduction.

The Earth climate is regulated by a large number of complex interactions among atmosphere, oceans, ice regions, land and forests areas; all these subsystems constitute an interlinked ensemble that regulates itself via non-linear feedbacks [IPCC, 2001]. In this perspective the role of oceans is of paramount importance [Stommel, 1961], since they store heat through their high specific thermal capacity and move fresh water or, more generally, induce salinity anomalies, all around the world [Broecker, 1997]. Despite their recognized importance, the links between global change, ocean general circulation and climate oscillations are far from being completely understood. Several authors, indeed, stressed the possibility that climate warming may interfere with -and possibly reverse- regional [Bergamasco *et al.*, 2003] but also global thermohaline circulation (THC) [Manabe and Stouffer, 1993; Seidov *et al.*, 2001]. The THC of the global ocean is the major mechanism through which the oceans contribute to control the global radiation budget, and eventually also major climatic changes [Broecker, 1997; Bigg *et al.*, 2003]. The classical view of this circulation suggests that during winter of either polar hemisphere, both open-ocean deep convection and dense water formation via sea-ice formation in marginal seas produce dense, cold, saline waters that flow toward the equator and slowly upwell. Therefore, the densest waters ventilating the world ocean abyss are produced in the Northern and Southern extremes. The THC convection part is driven by the buoyancy loss in the open ocean caused by cooling [Marshall and Schott, 1999] and by densification due to salt release during sea-ice formation or sub-ice shelf accretion. In the Southern Ocean along Antarctic continental shelf break regions, dense plumes are formed and then slide down the continental slope all around the Antarctic coast [Orsi *et al.*, 1999]. Major sites are the Weddel and the Ross seas, where Antarctic Bottom Water (AABW) is formed by mixing and entrainment during this cascade events.

The understanding of their interactions and feedbacks on the global THC through the Antarctic Circumpolar Current (ACC) are crucial scientific issues to address in order to understand the physical and biogeochemical aspects of the global climate variability.

Another relevant aspect for the global climate is the formation and dispersion processes of the marine ice, since these are directly influencing the moisture ocean-atmosphere flux, both in the Antarctic and in the Arctic.

The effects of THC variability in these extreme regions – due to high non linear feedback mechanisms – are largely unknown [Hulme *et al.*, 1999] and are likely to generate concern for the environment in future scenarios [Rosenzweig, 1985]; with the aim of better understanding global climate evolution and narrowing uncertainties on predictions, modeling tools are becoming more and more adopted by the international scientific community [Haidvogel *et al.*, 2000; Bergamasco *et al.*, 2004a].

2. Current-meter analysis.

This note recalls a complete analysis of the evolution of the physical properties of a water column at the southern limit of the Ross Sea, Antarctica, recently published by [Bergamasco *et al.*, 2004b]. Data has been collected over a four year period (from January 1995 to July 1998 by means of an oceanographic mooring (named mooring "F") berthed a few miles north of the Ross Ice Shelf at a depth of 600 m on the continental shelf. The velocity and temperature measurements have been investigated seeking for ISW (Ice Shelf Water) outflows footprints. These outflows are irregular massive injections of cold water (with temperature below the surface freezing temperature) from below the Ice Shelf, flowing mainly across the cavity floor into the Ross Sea bottom layers.

The study evidenced a large number of DISW outflow events (Deep Ice Shelf Water, the coldest and densest fraction of the ISW, the actual main object of the present study), characterized by an inter-annual variability that could turn out to be an important co-factor in the variations in the planetary heat balance and climate instability. Differences in DISW outflow timings have been detected: in 1995-96 (Fig. 1) a jet-like behavior was dominating (each event was only a few days long), while in 1997-98 (see Fig. 2) few long and rather continuous cold water outflows were present.

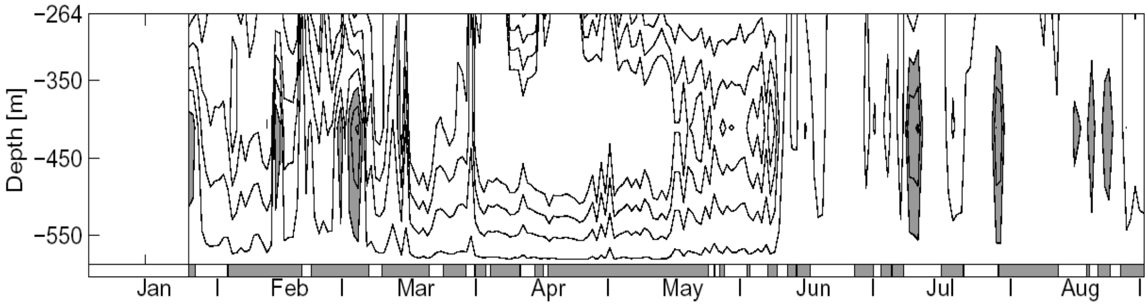

Fig. 1 – Evolution of water column vertical structure during 1996. Contour interval is 1°C, Temperature below –1.95°C is filled by light grey. Grey strip on bottom characterized outflow from below Ross Ice Shelf.

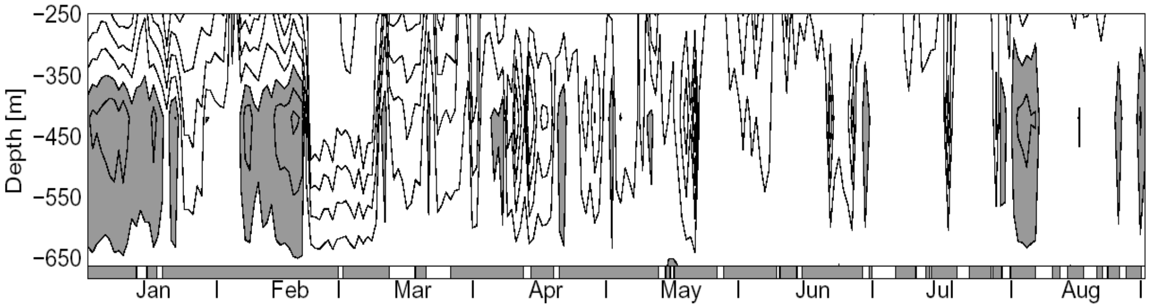

Fig. 2 – Evolution of water column vertical structure during 1997. Contour interval is 1°C, Temperature below –1.95°C is filled by light grey. Grey strip on bottom characterized outflow from below Ross Ice Shelf.

Moreover, in 1996 measurements (see again Fig. 1) evidenced a relatively long and warm period (about 110 days from March to July) characterized by the total absence of DISW outflow, this interval being more than twice longer with respect to any other warm period observed in the area during the early '80s.

3. Possible Teleconnections.

Recent studies [Kwok and Cosimo, 2002] showed that the climate of this region is strongly influenced by climate variations in the subtropical and tropical South Pacific, such as those associated with El Niño - Southern Oscillation (ENSO). While such "teleconnections" are responsible for much of the short-term variability in climate seen in this region, their role in driving longer-term (decadal to century scale) changes remains to be clarified. Normally, during ENSO (Fig. 3a) the persistent easterly trade winds push water toward the western Pacific (where the sea level is normally about 60 centimeters higher than that on the eastern side and the surface temperature is often above 28°C) and push down the thermocline (about 40 m deep in the eastern Pacific, 100-200 m deep in the west). When El Niño dominates, these winds die and results can be seen in Fig. 3b, clearly showing warmer temperatures in the eastern region during the 1997-98 event. Note the exceptionally warm surface waters in the eastern Pacific in November 1997, that influenced and interfered with the normal upwelling of cold deep water, therefore influencing the marine food chain and climate conditions of the region and of the planet.

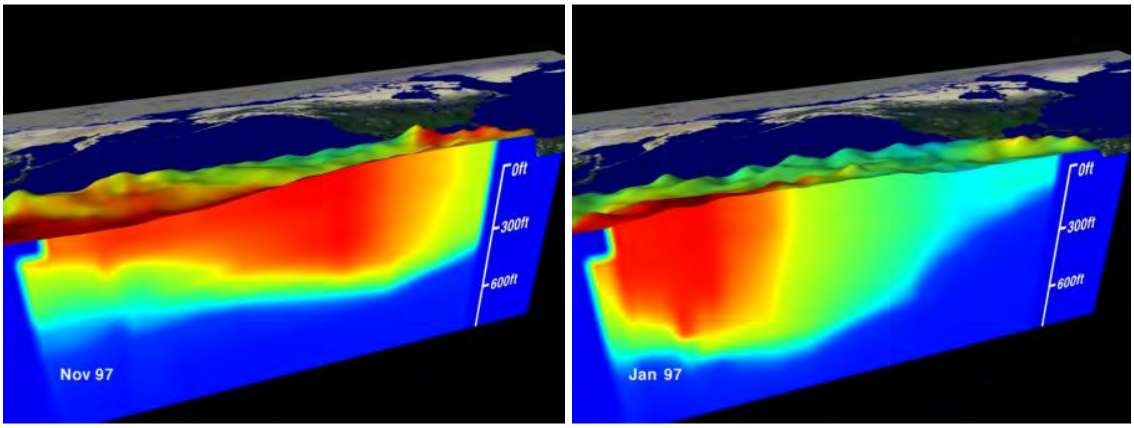

Fig. 3 – Ocean surface temperature anomaly along a tropical cross section during 1997 (Red is 30°C, blue is 8 °C; from http://www.solcomhouse.com/ElninoLanina.htm).

Conclusions.

Despite further investigations are needed in order to better understand the links induced by the ISW outflow variability and large scale climate connections, the Antarctica 1996 behavior led to a warmer winter and was actually preceding the ENSO by a few months, being the 1997-98 one of the most severe events in history as can be seen from Fig. 4 (see also [Kaplan A. *et al.*, 1998]).

This anomalous 4-months ISW "blocking" in the Antarctica region provided the surrounding region with an equivalent heating of approximate 100 W/m^2, that is capable of decreasing the water temperature up to half a degree in a water column 450 m depth. Since the Ross sea insists on the Pacific sector, some recent findings suggest that this signal could be an indication of future ENSO anomalies rather than vice-versa, and therefore it is worth to keep on investigating in this crucial area. This will be the focus of the activity of Polar DOVE, an international project funded by the Italian National Project in Antarctica, that will be lasting in the period 2004-2007, aiming to study the inter-annual variability of Deep Ocean Ventilation in southern polar region.

Acknowledgements.

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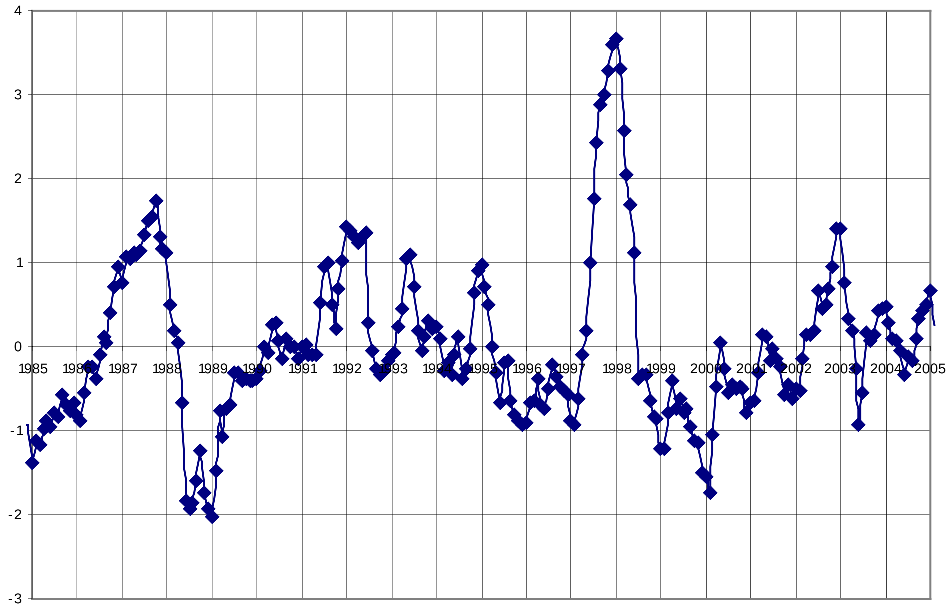

Fig. 4 – Temperature anomaly in 1997 (referred as NINO3), using data available at NOAA, NCEP, TUDELFT (e.g. http://www.ncdc.noaa.gov/paleo/ei/ or http://www.deos.tudelft.nl/altim/enso/).

References.

Bergamasco A., Carniel S. and Sclavo M., 2004a. Abstract S17/O07, in XXVIII SCAR Open Science Conference, M. Kunz-Pirrung & M. Reinke (Eds.) Bremen, Germany

Bergamasco A., Ardizzon G., Carniel S., Meloni R., Sclavo M., 2004b. The Ross Shelf cavity water exchange variability during 1995-1998. *Il Nuovo Cimento,* 27-3 C, 241-254. DOI: 10.1393/ncc/i2004/-10019-9

Bergamasco A., Filipetto V., Tomasin A., Carniel S., 2003. Northern Adriatic general circulation behaviour induced by heat fluxes variations due to possible climatic changes, *Il Nuovo Cimento*, 26-C (5), 521-533. DOI: 10.1393/ncc/i2003/-10005-9

Bigg G.R. , Jickells T.D., Liss P.S., Osborn T.J., 2003. The role of the oceans in climate. *Intern. J. of Climatology*, 23(10), 1127-1159

Broecker W.S., 1997. Thermohaline circulation, the Achille's heel of our climate system: will manmade CO_2 upset the current balance?, *Science*, 278 (5343), 1582

Haidvogel D.B., Arango H.G., Hedström K.S., Beckmann A., Malanotte-Rizzoli P., Shchepetkin A.F., 2000. Model evaluation experiments in the North Atlantic Basin: simulations in non-linear terrain-following coordinates. *Dyn. Atmos. Oceans*, 32, 239-281

Hulme M., Parry M., Rosenzweig C., Iglesias A., Fisher G., Livermore M., 1999. Climate change and world food security: a new assessment, *Global and Environmental Change*, 9, S51-S67

IPCC, 2001. Third assessment report: Climate Change 2001. A contribution of working group I, II and III to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge Univ. Press, UK, http://www.ipcc.ch

Kaplan A., Cane M.A., Kushnir Y., Clement A.C., Blumenthal M.B., 1998. Rajagopalan B.. Analyses of global sea surface temperature 1856 – 1991. *J. Geophys. Res.*, 103(C9), 18567-18590, 10.1029/98JC01736

Kwok R. and Cosimo J.C., 2002. Southern Ocean Climate and Sea Ice anomalies associated with the Southern Oscillation. *Jour. of Climate*, 15, n.5, 487-501

Manabe S. and Stouffer R.J., 1993. Century-scale effects of increased atmospheric CO_2 on the ocean-atmosphere system., *Nature,* 364 (6434), 215-218

Marshall J. and Schott F., 1999. Open Ocean convection: observations, theory and models. *Rev. Geophys,* 37, 1, 1-64

Orsi A.H., Johnson G.C., Bullister J.L., 1999. Circulation, mixing, and production of Antarctic Bottom Water, *Prog. Oceanogr.,* 43, 55-109

Rosenzweig C., 1958. Potential CO_2 induced climate effects on North American wheat-producing regions. *Climatic Change,* 7, 367-389

Seidov D., Barron E. and Haupt B.J., 2001. Meltwater and the global ocean conveyor: northern versus southern connections, *Global and Planetary Change,* 30 (issues 3-4), 257-270

Stommel H., 1961. Thermohaline Convection with Two Stable Regimes of Flow, *Tellus*, 13, 224-230

ON THE DYNAMICS OF THE ADRIATIC SEICHE

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Riassunto.

L'importanza delle sesse nella dinamica adriatica è notevole, considerando anche i livelli eccezionali che si possono raggiungere nel bacino settentrionale, dove è situata Venezia. Si usano qui sia schemi semplificati che modelli numerici dettagliati per mostrare come viene eccitata la sessa fondamentale e come può variare il suo sviluppo a seconda delle diverse condizioni meteorologiche.

Abstract.

The relevance of the seiche in the Adriatic dynamics is remarkable, with particular interest for the exceptional levels in the northern part and the Venice area. Both simplified schemes and detailed numerical models are used here to show how the basic, fundamental seiche is excited and how its development can be very different under various weather conditions.

1. Introduction.

Being a semi-enclosed basin, the Adriatic Sea shows conspicuous free oscillations ("seiches") after any external forcing event [Kesslitz, 1910]. It means that typically a windstorm from Southeast determines a water onset in the northern part (the "dead end") in a few hours, and at that point the whole Adriatic oscillates around its normal level with its proper period, slightly less than 22 hours.

These motions persist for many days, showing that the internal dissipation is moderate, and the outward radiation of energy is also slow.

Beyond scientific interest, the relevance of the above dynamics for the protection of Venice and all settlements around the northern Adriatic is evident. Not only surges are to be watched, but also their remnants in the following days: more subtle, the ordinary tide can enter on the problem, since what is observed is the addition of surge and astronomical oscillation.

It can occur that the first water onset "finds" ebbtide, and gives in total a level that is not dramatic, but the seiches that follow can "enter in phase" with tide, and give floods when the storm has passed (Fig.1).

The periodicity of 22 hours that was mentioned refers to the fundamental oscillation. There are higher harmonics, as it sounds obvious: making things clear, the main seiche involves the whole Adriatic Sea in a quarter-of-wave motion, with its maximum amplitude at the northern end and a "node" at the Otranto inlet, the strait towards the Ionian Sea. This latter basin is so deep and large to be considered an ideal ocean, so that at Otranto the level is unperturbed (the "node") [Robinson *et al.*, 1973].

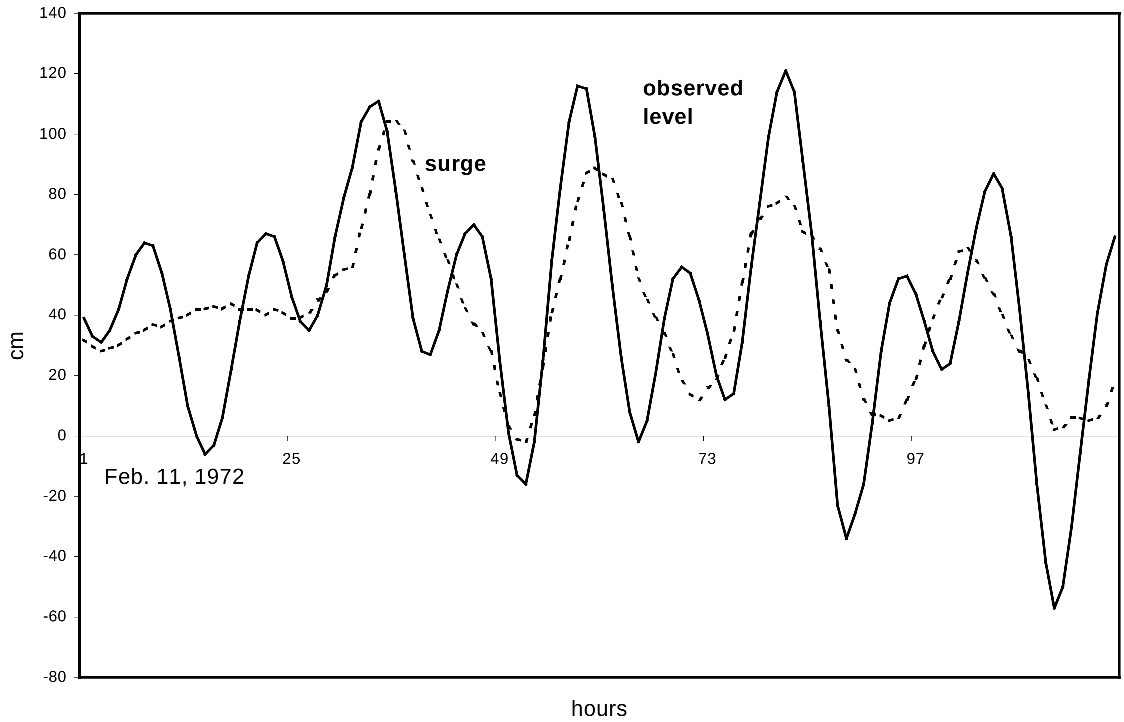

Fig. 1 – Surge and following seiches (dotted). Since seiches "enter in phase" with ordinary tide, the result (solid) gives more severe floods well after the first onset.

The following harmonics have a more complex pattern (with an increasing number of nodes and with substantial effects of the Earth rotation), but they are practically less relevant: considering the decade 1991-2000 at Venice, we found that a level "variance" of 34.3 squared centimeters of the basic seiche corresponds to a variance of 8.0 for the next one (about 11-hour period).

For the above reason, only the fundamental seiche will be considered here, i.e. what is observed, typically, when sirocco wind blows over a large part of the Adriatic Sea.

2. Simple scheme investigations.

Scientists always wish to describe physical processes with mathematical schemes, the more convincing they are, the more they are simple and elegant.

In fact, analytical solutions for the dynamics of geophysical systems can only be given if idealized morphologies are considered and many second-order factors are disregarded.

Support to this attitude is given by the following possibility to check all conclusions using detailed numerical models, thanks to the modern availability of high-speed computers.

This is in fact what is done here: a simple scheme for the Adriatic Sea permits analytical considerations that will be supported by detailed simulations.

Our Adriatic "box" is flat-bottom, straight shores and open on one side towards the Ionian Sea, a basin infinitely deep [Tomasin and Pirazzoli, 1999].

Since only qualitative conclusions are sought at this point, the sea depth is assumed unitary, and so are the horizontal dimensions ("length" and "width") and even the gravity acceleration. All kinds of dissipation are disregarded.

This very simple basin is stimulated by a constant wind blowing from the Ionian Sea, a wind that is "turned on" at time zero ("step function") when the Adriatic surface was flat and had no motion inside.

The depth-integrated and frictionless equations at this point are.

$$u_t = - z_x + w \qquad z_t = - u_x \tag{1}$$

where u is the transport along x (velocity times depth), z is the sea level, w is the wind stress component along x, t is time and subscript refer to differentiation. The variables u and z are functions of x and t, and so is w, but in fact it will be considered only a function of t, a step function (w = 0 for negative t, w = -1 for t > 0).

Boundary conditions are standard: no transport at the closed end, no change of level at the open end (Fig.2).

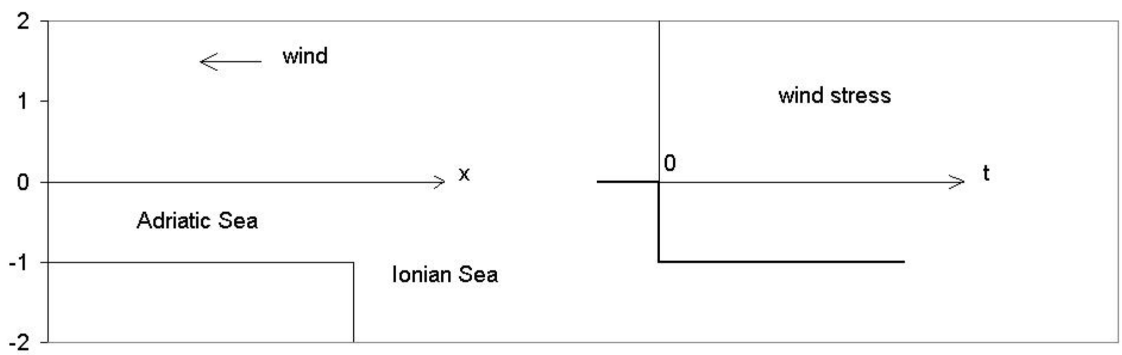

Fig. 2 – The simple scheme of the Adriatic Sea and of the wind "turned on" at t = 0.

The assumption of a continuous wind will first be considered.

Figures can help in following what happens: at the beginning, there is a motionless situation (Fig. 3.a), but the wind stress will act over the whole basin and in each point the u transport will steadily increase as long as the surface is flat.

But at the closed end the water will pile up, and a wave will leave towards the right, with unity speed (since both g and the depth are one), that will compensate the wind stress, and the transport will stop increasing in the points that are reached (Fig. 3.b).

At t=1, the wave has reached the open end, the sea is tilt, and the first equation says that there is no further acceleration: this would be the new equilibrium surface, should the wind blow forever (Fig. 3.c).

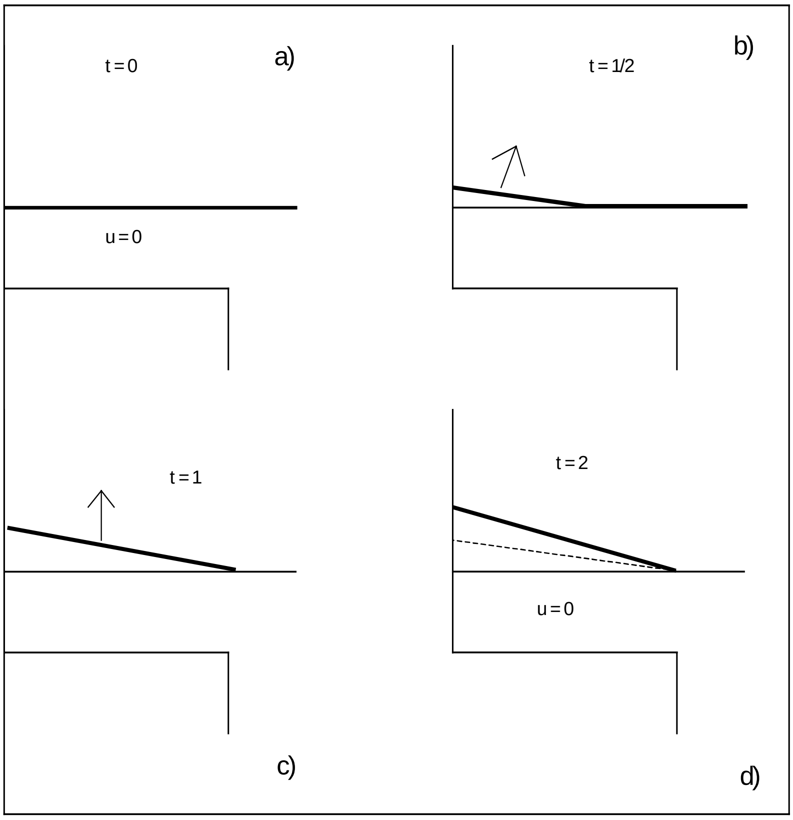

Fig 3 – Wind blowing forever excites the sea beyond the equilibrium level shown in c) and d). Afterwards, the sea, will oscillate between the flat condition and d). Continuous oscillations will start between figures (3.a) and (3.d), around the equilibrium surface.

But the transport u is not zero, it keeps bringing water to the left, and the sea moves to an "overshooting" beyond the equilibrium. At time 2 the maximum level is reached and the transport u is zeroed (Fig. 3.d, where the "equilibrium surface" is shown again).

A more stable foundation can be given to the above considerations if the technique of the Laplace transforms is used with respect to time: it is particularly useful when impulsive functions (like the step-shaped wind) are present.

Using this procedure one obtains

$$p\,U = -\,Z_x - 1/p \qquad p\,Z = -\,U_x \tag{2}$$

where the transform of any function g (t) is denoted by G (p).

Out of the rich analysis that is possible, the simple result is given here for the level z(t) at the closed end of the basin (where is Venice, in principle). For the transform it turns out:

$$Z\,(p) = (1/p)\tanh p \tag{3}$$

and the corresponding anti-transform [Abramowitz and Stegun, 1965] is an infinite sum of terms (Fig. 4.a), giving the oscillations described above, around an equilibrium level well above zero.

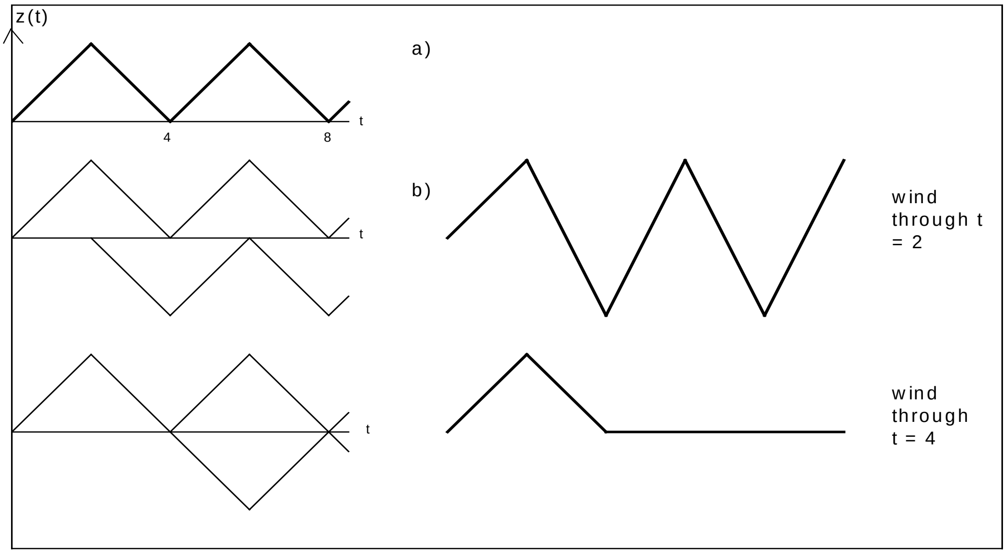

Fig. 4 – The effect of different durations of wind. In a) it blows forever, while in b) and c) it stops at different times. The corresponding effect is shown on the right side (as observed at the closed end).

Interesting variations can be considered at this point, showing that the simple expectation of the seiches can be deceiving. In fact, wind does not blow forever, and in the simple scheme considered here it will reasonably stop with a new step.

All the above treatment is linear (and this is sufficiently corresponding to real life), so that the stop of the forcing wind is just the arrival of a positive step function, and the above solution can be used, reversed, and summed to the first one.

It is shown what happens (Fig.4, b and c), in the scheme, when the wind stress stops at t = 2 or at t = 4.

The effect is impressive: in the two cases considered, the graph to the right gives the resulting sea level (as observed at the northern end of the sea), with very large seiches in the first case, and the absence of oscillations in the other one.

From the physical point of view, things are explained by the consideration that the stable wind gives positive work up to t = 2, but negative in the next two time steps, so that in one case (Fig. 4.b) all the advantage of the positive input is exploited, while in the other case the balance is zero. What happens in real life is usually some mixed solution: as outlined above, a forecaster must be warned about the various possibilities.

An important feature of the present work is the fact that a simple scheme like the one discussed so far is confirmed by detailed and rigorous numerical models, as shown below.

3. Numerical model investigations.

3.1. The SHYFEM model.

The Shallow-water HYdrodynamic Finite Element Model SHYFEM [Umgiesser, 1986; Umgiesser and Bergamasco, 1993], realized at ISMAR-CNR of Venice, has been used for the study in this work.

The 2-dimensional version of the model has been implemented to the Mediterranean Sea: it solves the well known shallow water equations through the finite element technique on a grid made out of triangular elements, variable in size and dimension.

The grid, represented in Fig. 5 is made out of 18626 elements: in the region of interest (the Adriatic Sea) the elements are very small with size of about 1.5 km, while the spatial resolution is kept coarser, about 35 km, in the other regions.

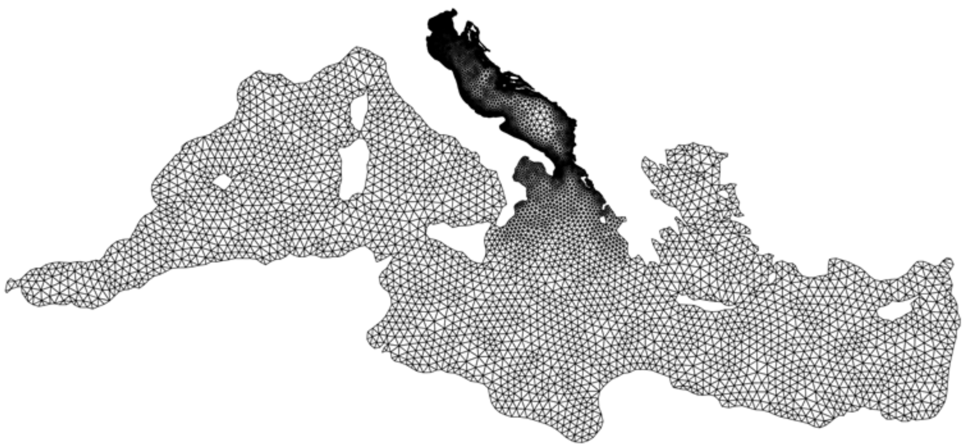

Fig. 5 – Grid of the hydrodynamic finite element model for the Mediterranean Sea.

The model uses finite elements for spatial integration and a semi-implicit algorithm for integration in time. The terms treated implicitly are the water level gradients, the Coriolis term and the bottom friction term in the momentum equation and the divergence term in the continuity equation. All other terms are treated explicitly.

The model solves the vertically integrated shallow water equations in their linearized formulation with levels and transports:

$$\begin{gathered}\frac{\partial U}{\partial t} - fV + gH\frac{\partial}{\partial x}\left(\zeta + \frac{p_a}{\rho_0 g}\right) - A_H\left(\frac{\partial^2 U}{\partial x^2} + \frac{\partial^2 U}{\partial y^2}\right) - \frac{1}{\rho_0}\left(\tau_{sx} - \tau_{bx}\right) = 0 \\ \frac{\partial V}{\partial t} + fU + gH\frac{\partial}{\partial y}\left(\zeta + \frac{p_a}{\rho_0 g}\right) - A_H\left(\frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2}\right) - \frac{1}{\rho_0}\left(\tau_{sy} - \tau_{by}\right) = 0 \\ \frac{\partial \zeta}{\partial t} + \frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} = 0\end{gathered} \tag{4}$$

where ζ is the water level, U and V the vertically-integrated velocities (total or barotropic transports), t the time, g is the gravitational acceleration, p_a the atmospheric pressure at the mean sea level ρ_0 is the water density, $H=h+\zeta$ the total water depth, h the undisturbed water depth, f the variable Coriolis parameter, τ_s the wind stress, τ_b the bottom stress and A_H the horizontal diffusion coefficient.

The bottom stress term is related to the water velocity:

$$(\tau_{bx}, \tau_{by}) = \rho_0 C_B |u| (u_x, u_y) \tag{5}$$

where u_x, u_y are the x, y components of the velocity and C_B is the bottom drag coefficient.

The wind stress can be computed in the quadratic formulation, from the wind field:

$$(\tau_{sx}, \tau_{sy}) = \rho_a C_D |u^w| (u_x^w, u_y^w) \tag{6}$$

where ρ_a is the density of air and water, respectively and u_x^w, u_y^w the wind components along x and y axis. C_D is a dimensionless drag coefficient that can be parametrized through different formulations.

The wind speed is directly specified for each element of the domain as the horizontal components of the wind velocity and it can vary both in space and time.

At the closed boundaries only the normal velocity is set to zero and the tangential velocity is a free parameter. This correspond to a full slip condition.

3.2. Reproduction of the seiches in the Adriatic Sea.

The principal seiche of the Adriatic Sea was simulated in an idealized numerical experiment, called simulation 0: the model was forced by a constant sirocco wind (with speed 10 m/s) and induced oscillations in different coastal locations of the Adriatic Sea were studied. Fig. 6 shows the computed sea level in Venice, Ancona, Split, Pescara, Brindisi, during the first 20 days of simulation: the effect of the constant sirocco wind is an oscillation of the sea level, more pronounced in the northern part (Venice) and much smaller in the southern part of the Adriatic (Brindisi). In the first hours the water level goes through a transient oscillation, due to the suddenly imposed wind forcing. After the first day, this oscillation is progressively smoothed and almost totally disappears after about 15 days, when a new equilibrium state is reached, with a sea level of +25 cm in Venice and of -9 cm in Brindisi, with respect to the initial state. In the above simple scheme, the southern end of the sea was assumed as unperturbed. The realistic description of the exchange with the Ionian Sea slightly modified this detail.

A harmonic analysis realized on the sea level results (Fig. 7) supplied the period of the modelled seiche: T_1 = 21.5 hours. This value agrees with the values computed from observed data, available in the literature [Defant, 1960].

In the simulation with idealized forcing (sirocco wind) only the main seiche of period T_1 is excited. The first harmonic seiche, of period T_2, very close to 11 hours, is very weakly visible in Fig. 7 at frequency 2.3 days^{-1}. It is generated by more complicated wind pattern and, in fact, it is clearly detectable in the sea level time series computed by the SHYFEM model in simulations with realistic forcing, not shown in this work.

After making sure that the SHYFEM model reproduces in a correct way the features of the Adriatic principal seiche, we tried to reproduce the interesting behaviour described above by a simple scheme. With this aim, two simulations were realized, called A and B, similar to simulation 0 previously described: at the beginning, the SHYFEM model was forced by a constant sirocco wind (speed 10 m/s), then the wind was switched off. In simulation A the wind was stopped after 21 hours, when the sea was as near as possible to the initial flat state, that is at the time when the sea level was at the lowest value. In simulation B, the wind was switched off when the sea was far from the initial equilibrium state, that is when the sea level was maximum. Fig. 8 shows the results of simulations A (top panel) and B (bottom panel): the modelled sea level in the same coastal stations of Fig. 6 is plotted.

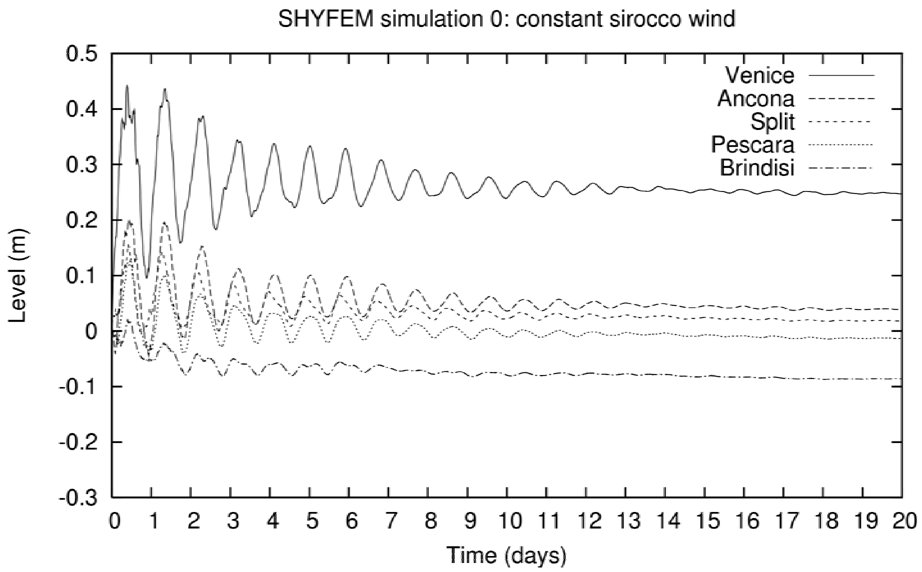

Fig. 6 – Sea level in Venice, Ancona, Split, Pescara, Brindisi, computed by the SHYFEM model in the simulation 0, with idealized atmospheric forcing (constant sirocco wind).

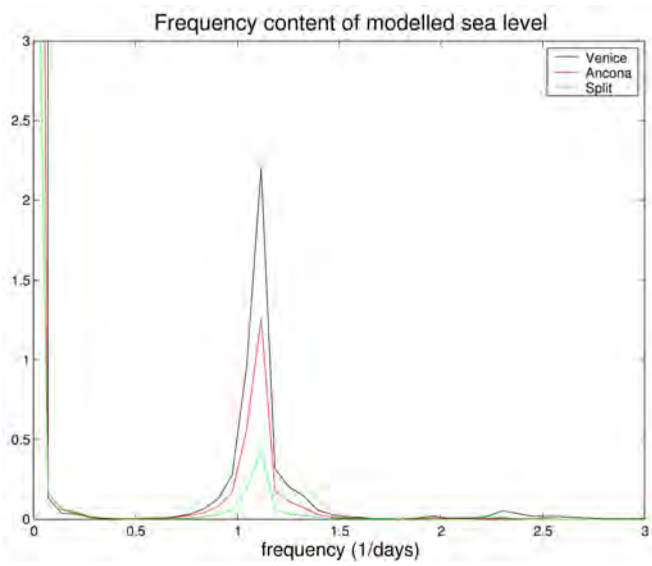

Fig. 7 – Harmonic analysis of the sea level calculated by the SHYFEM model in the simulation with idealized forcing (constant sirocco wind).

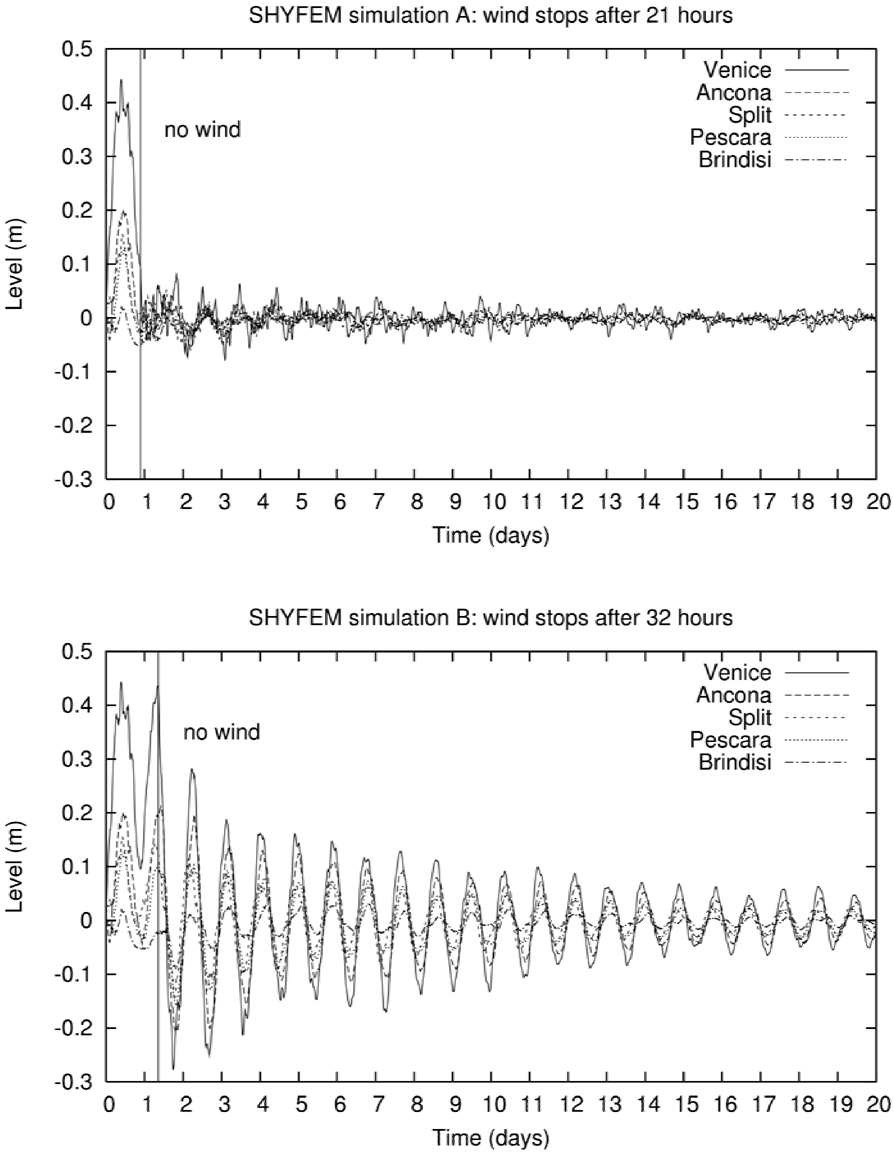

Fig. 8 – Sea level in Venice, Ancona, Split, Pescara, Brindisi, computed by the SHYFEM model. Top panel: simulation A. Constant sirocco wind for the first 21 hours, then no wind. Bottom panel: simulation B. Constant sirocco wind for the first 32 hours, then no wind. The vertical line indicates the exact moment in which the wind is switched off.

In both simulations, as expected, when the wind forcing effect disappears, the sea level oscillates around the initial equilibrium state $\zeta = 0$ in all stations, but the behaviour is completely different according to the time when the wind is switched off. As predicted by the theory, if the wind stops when the sea level is low (simulation A) the seiche is suddenly attenuated and disappears in a short time. The spurious oscillations visible in the top panel of Fig. 8 and remaining for many days, could be due to high frequency motions generated by the abrupt change in the meteorological forcing: they are probably meaningless in the discussion about the seiches. The sea level oscillations in Venice during the third day of simulation were considered as a measure of the different behaviours: during this day, the sea level computed in simulation A oscillates with an excursion of 13 cm between minimum and maximum values, partially enhanced by the spurious oscillations. This excursion is by a factor of 0.65 smaller than in simulation 0, with wind continuously blowing, when an oscillation with range of 20 cm has been found (see Fig. 6).

At the contrary, if the wind stops when the sea level is high (simulation B) the seiche is amplified, as shown in the bottom panel of Fig. 8. The sea level oscillations in Venice during the third day of simulation have an excursion of 53 cm, higher than the amplitude modelled in the case of constant wind by a factor 2.66. Even after 15 days, the sea level computed in simulation B, shows an oscillation of amplitude of about 11 cm, giving a picture of the sea state very different from the equilibrium reached at the same time, in the simulation with constant wind.

Conclusions.

Both analytical schemes and numerical models show that the development of the free oscillations of a basin that follow a surge strongly depend on the duration of the wind giving origin to the motion. The extreme possible values of the seiche amplitude are outlined.

References.

Abramowitz M. and Stegun I.A., 1965. "*Handbook of Mathematical Functions*", Dover Publications, New York

Defant A.,1960. "*Physical Oceanography*", Pergamon Press, New York.

Kesslitz W., 1910. Das Gezeitenphaenomen in Hafen von Pola. *Mitteilungen Geb. Seewesens*, Pola

Robinson A.R., Artegiani A., Tomasin A., 1973. Flooding of Venice: Phenomenology and prediction of the Adriatic storm surge. *Quarterly Journal of the Royal Meteorological Society*, 99, 688-692

Tomasin A. ad Pirazzoli P.A., 1999. The Seiches in the Adriatic Sea. *Atti dell'Istituto Veneto di Scienze, Lettere ed Arti*, Tomo CLVII, 299-316

Umgiesser G. ,1986. A model for the Venice Lagoon. Master thesis, University of Hamburg

Umgiesser G. and Bergamasco A., 1993. A staggered grid finite element model of the Venice Lagoon. In K. Morgan, E. Ofiate, J.P. and Zienkiewicz, O. , editors, "*Finite Elements in Fluids*", pages 659-668. Pineridge Press

SEASONAL FORECASTING OF PO RIVER DISCHARGES: A FUZZY NEURAL NETWORK MODEL

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Riassunto.

Sistemi non lineari sono ritenuti non predittibili a causa del loro comportamento caotico. Nel caso dei fenomeni idrologici, il caos non impedisce di effettuare previsioni a lungo termine grazie all'esistenza di una forzante esterna in grado di imporre il proprio ritmo alle fluttuazioni climatiche sulla Terra: il Sole. Dal momento che l'informazione utile proveniente dal sole è discreta nel tempo, solo previsioni interannuali sono possibili. Nel tentativo di incrementare la risoluzione delle previsioni alla scala stagionale, è stato messo a punto un sistema basato su reti neurali e fuzzy logic. I risultati ottenuti nel caso delle portate invernali del Po suggeriscono che indici di attività solare e indici di circolazione atmosferica possono essere utilmente impiegati per effettuare previsioni stagionali di variabili idrologiche.

Abstract.

Non-linear system are indexed as non predictable because of their chaotic behaviour. In the case of hydrological phenomena, chaos does not prevent long range forecasts thanks to the existence of an external forcing that can impose its rhythm on Earth's climate: the Sun. Because of the fact that useful information about solar activity is quite scarce in time, only inter-annual forecasts are possible: in order to increase hydrological predictions up to the desired seasonal scale an expert system based on a fuzzy neural network model has been built. The results obtained for the case of the wintertime Po River discharges are suggestive that indices of solar activity and proper indices of atmospheric circulation may be sufficient to obtain convincing long-term predictions of hydrological variables.

1. Introduction.

The nature of the climatic system, infinitely complex and non-linear, makes long-term predictions unreliable. Nevertheless, it exists the possibility of a conditioned prediction, bounded by the existence of one forcing in the complex tangle of the cause-effect relations that is strong enough to dominate all the other factors. This forcing is solar activity: the Sun as periodic or quasi-periodic system can force its rhythm on the Earth's climate system. The inviting prospective that emerges is that of the possibility of making long-term hydrological forecasts by coupling the information from solar activity [Landscheidt, 2000; Tomasino and Dalla Valle, 2000] and climatic regional details, such as atmospheric circulation [Hurrell, 1995]. Based exclusively on solar activity indices, predictions are feasible only within a little interval from critical points of solar cycles (maxima or minima): hence information about future hydrological patterns obtained by solar activity is quite scarce in time (every 2-3 years). In the attempt to extend the predictions up to the seasonal scale, given the uncertainty and ambiguity of the climate's evolution and the infrequency of critic points in solar activity, the most suitable approach seems that of the quantitative fuzzy neural network (*FNN*), that reconciles the ability of learning and reasoning in an environment of uncertainty and inaccuracy, taking advantages from the synergies that emerges from the coupling of neural networks [*NN*, Bishop, 1995] and fuzzy inference systems [*FIS*, Zadeh, 1965].

2. Description of the model.

The fuzzy system employed is a set of IF-THEN rules (Rj) defined as follow:

$$R_j\ :\ IF\ (x_1\ \ is\ \ F_1^{\ a})\ AND\ (x_2\ \ is\ \ F_2^{\ b})\ AND\ ...(x_n\ \ is\ \ F_n^{\ z}),\ THEN\ \ (y = v^{\,j}) \qquad (1)$$

where x and y are the input and the output of the fuzzy system, respectively, n is the number of input, F_i^k is the k^{th} fuzzy conditions of input i, and v^j is the j^{th} fuzzy consequence. The model is a modification of the classical integration of this fuzzy system with a forward three-layer artificial neural network, resulting on a five-layer fuzzy neural network (*FNN*), known as a Mamdani or zero-order Sugeno model, whose architecture is shown in Fig. 1. Essentially, all available data are fed into the network that through its supervised learning develops a relationship between the input and the output.

Data are directly input into the first layer (input layer), without any pre-processing: the first layer has as many nodes as the number n of inputs. The second layer (fuzzification layer) corresponds to the *IF* part of the inferential linguistic *IF-THEN* assumption (1): here each original input is transformed in the respective fuzzy variables. The membership functions (*MFs*) implemented in the model are of gaussian and sigmoid type and each input variable A_i has its own set of rules. This means that the number N_i, the type and the shape of the *MFs* associated to individual input node can be different: thus there are total $\sum N_i$ fuzzy modes in the fuzzification layer. The same transformation into fuzzy values is operated on the output variable. The third layer is the rule-antecedent layer, corresponding to the inference process that connects the *IF* part and *THEN* part of the fuzzy system. The second-to-third layer structure is not fully-connected [Zhang *et al.*, 2002]: each rule node is connected with n fuzzy modes, each of which belongs to an individual group of N_i fuzzy modes: in other words, each node of third layer is connected with just one node of each input fuzzy group. Thus total $\prod_{i=1}^{n} N_i$ nodes are created in the rule-antecedent layer. This allows the formal implementation of the *FIS* linguistic rule (1). The fourth layer is the rule-consequent layer, where each node corresponds to a rule of the fuzzy output set. During the initialisation, once the inputs and the output have been fuzzified, the network creates the structure of the second, third and fourth layer basing on the fuzzy sets: each rule-consequent node has its own subset of inference and rule-antecedent nodes and is then handled as independent. The result is somewhat similar to many parallel networks working together. The fifth layer is the defuzzification and output layer, where a single crisp value is calculated from the output fuzzy values using the 'centroid of area' method.

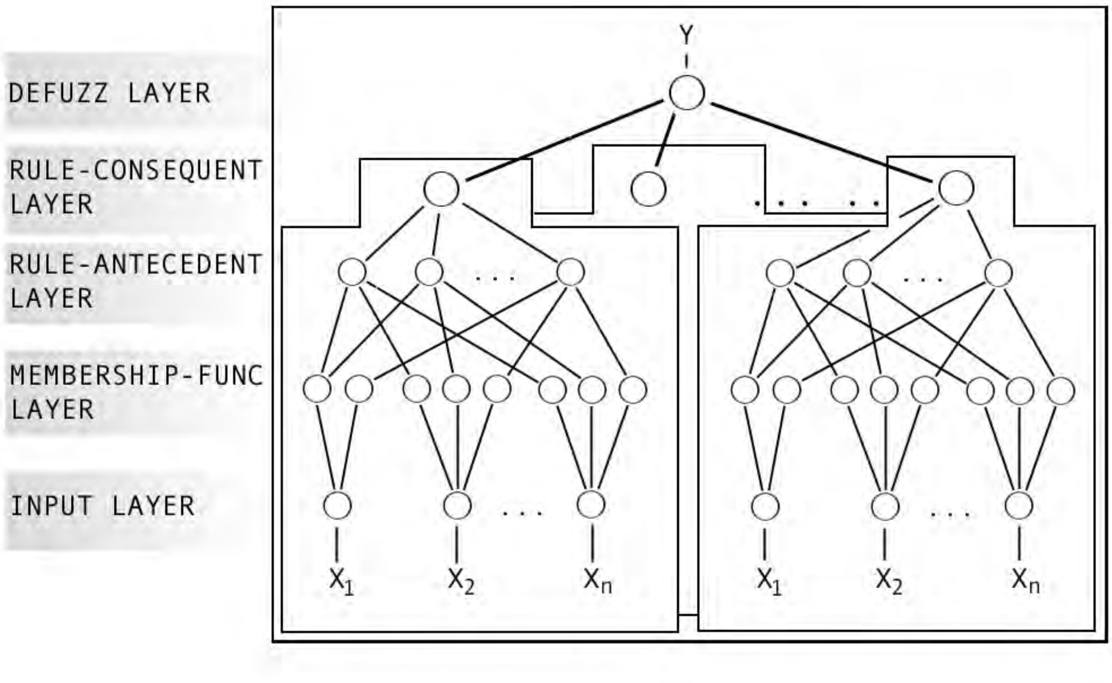

Fig. 1 – Architecture of the fuzzy neural network model.

As the complexity of a model, defined through the number of its parameters, increases, its ability of generalization intended as degrees of freedom falls down. Moreover in the case of a neural network, because of a high number of nodes in hidden layers the training procedure may get quite slow. This is the reason why a careful choice of the architecture of the model is required: in the *FNN* there are actually 108 nodes in the rule-antecedent layer. Generally, two linguistic labels (negative/low and positive/high) have been defined for each input.

The optimisation of the parameters is performed through supervised learning with the well known error back-propagation algorithm (*BP*), that guarantees low memory needs and high speed of optimisation but suffers of scarce robustness against local minima. In order to guarantee that not a local but the global minimum (or at least the best found) of the cost function is reached, random perturbations are induced on weights during the training phase when the learning rate reaches a critic value. In order to avoid overparametrizing, that means severe risk for overfitting, the well known method of early stopping was implemented in the model. Both *FIS* structure parameters (sigmoid and gaussian shape parameters) and *NN* parameters (connecting weights) are adjusted in the training of the *FNN*.

3. Results.

The model was used to estimate the wintertime (January-March average) discharge of the Po River using the following descriptors: the index of solar torque calculated by Landscheidt (1988); the wintertime North Atlantic Oscillation [Hurrel, 1995], that is the foremost source of variability in the North Atlantic sector; the Eastern Atlantic Pattern , as described by Wallace and Gutzler [1981]; the Euro-Atlantic Blocking, connected with the presence of a high pressure field over the Atlantic coast and the central European area [Pavan *et al*., 2000]; the air temperature measured at Trieste; the 9-year moving average of the wintertime Po River discharge. Results for training and validation datasets are reported in Fig. 2. The model seems to follow accurately the observed pattern for both the training and validation sets, proving itself efficient in predicting periods of maximum discharge. However, it overestimates low and medium flows, probably because of the defuzzification law implemented.

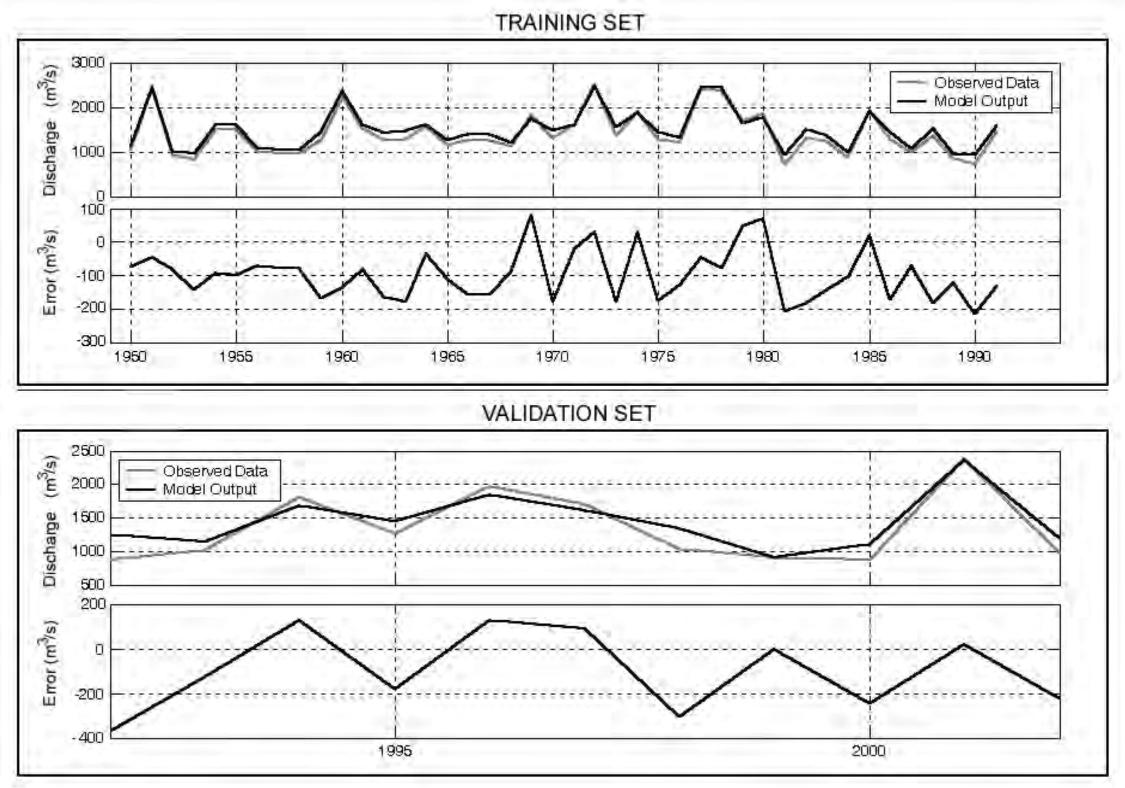

Fig. 2 – Observed data versus model output and error plots for training and validation set.

Fuzzy systems are particularly useful in the case of uncertainty and bounded conditioning [Horvitz and Suermondt, 1988], but the construction of a *FNN* model is not simple. To verify whether the application of the *FIS* gives better results than traditional regression models, the results of the *FNN* model were compared to the results of an ARMA and an ARMAX model. The ARMA and ARMAX models are built on the NNARMAX2 algorithm of the NNSYSID Toolbox [Nørgaard *et al*., 2002]. The regressors of the ARMA model are five past discharge values and two past residuals (ARMA(5,2)), as this is a common choice in hydrological analysis. The regressors of the ARMAX model are the input variables used in the *FNN*: one past value for each input variable, two past discharge values and two past residuals (ARMAX(2,[1],2)). The network architecture of the neural net model consisted of seven hidden "tanh" units and one linear output unit. The error distribution and error bars of the results of *FNN*, ARMA(5,2) and ARMAX(2,[1],2) models for training and validation sets are presented in Fig.3. The hypothesis of normal error distribution was verified for all the models using the Kolmogorov-Smirnov test and the Lilliefors test, whose results are also reported in Fig. 3. The acceptance of the hypothesis of normal error distribution allows one to test the goodness of fit of the models using the standard deviation of errors (SD). The ARMA(5,2) model gives the overall (training and validation sets) better performance (the SD of normalized error is 0.23), but closer investigation reveals that the SD of error of the validation set alone rises to 0.43 (Fig. 4). The ARMAX(2,[1],2) model produces an overall error with a SD of 0.70, while the distribution of the *FNN* overall error has a SD of 0.27 (0.33 for the validation set alone).

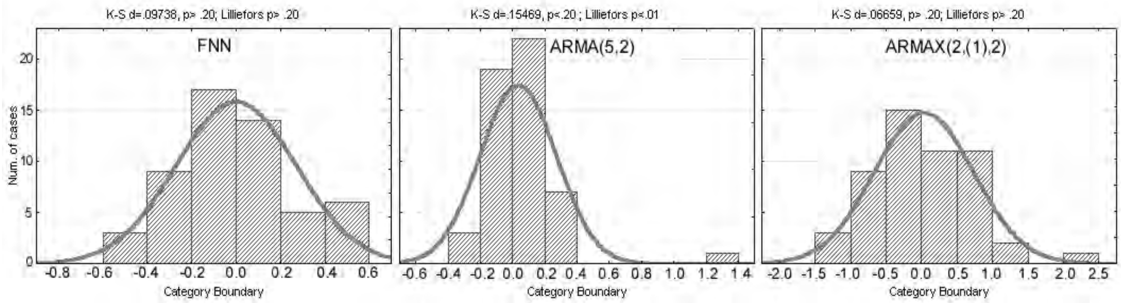

Fig. 3 – Error distributions and histograms of the FNN model, the ARMA(5,2) model and the ARMAX(2,[1],2) model: results of the Kolmogorov-Smirnov and Lilliefors tests for normality.

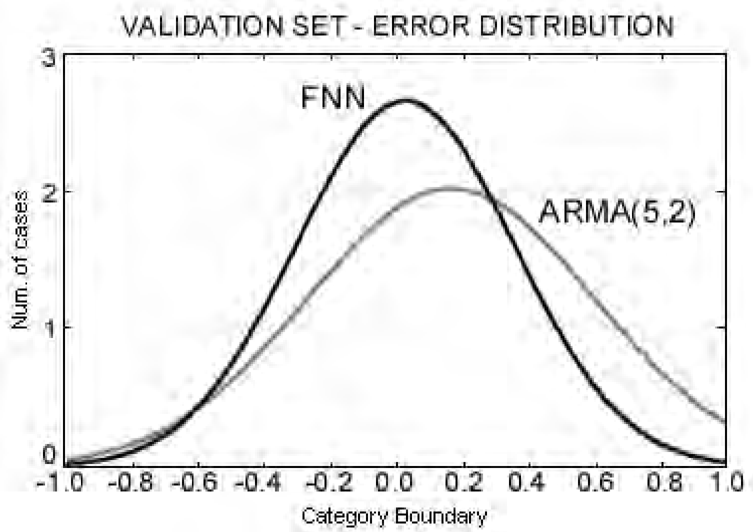

Fig. 4 – Error distributions of the FNN model and the ARMA(5,2) model for the validation set.

Conclusions.

In this research the use of a hybrid fuzzy neural system for the modelling and prediction of wintertime Po River discharges has been evaluated. The study case has been chosen thanks to the knowledge and to the good availability of data about this area: since the regional characterization proposed does not undermine the generality of the arguments treated in the paper, this method can reasonably be applied in other similar hydrological contests.

The model has proven high learning efficiency and good prediction accuracy: since high converging speed is not needed if dealing with long-term forecasting, the limitations due to the standard error back-propagation method implemented do not undermine the goodness of the model.

References.

Bishop C., 1995. Neural Network and pattern recognition. *Oxford University Press*

Horvitz, E. J. and Suermondt, J., 1988. Bounded conditioning: a flexible probabilistic inference algorithm. SMI-88-0212

Hurrell J. W., 1995. Decadal trends in the North Atlantic Oscillation: regional temperatures and precipitation. *Science* 269, 676–679

Landscheidt, T., 2000. River Po discharges and cycles of solar activity. *Hydrol. Sci. J.* 45(3), 491–493

Nørgaard M., Ravn O., Kjølstad Poulsen N., 2002. NNSYSID-Toolbox for system identification with neural networks. *Math. Comput. Modelling of Dynam. Syst.* 8(1), 1–20

Pavan V., Tibaldi S., Brankovic C., 2000. Seasonal prediction of blocking frequency: results from winter ensemble experiments. *Quart. J. Roy. Met. Soc.* 126, 2125–2142

Tomasino M., Dalla Valle F., 2000. Natural climatic changes and solar cycles: an analysis of hydrological time series. *Hydrol. Sci. J.* 45(3), 477–490

Wallace J. M., Gutzler D. S., 1981. Teleconnections in the geopotential height field during the Northern Hemisphere winter. *Mon. Weather Rev.* 109, 784–812

Zadeh L. A., 1965. Fuzzy Sets, *Information and Control*, 8, pp. 338-353

Zhang, L., Lijing, W., Yu, L., Pengyuan, Y., 2002. Quantitative fuzzy neural network for analytical determination, *Anal. Chim. Acta* 468, 105-117

SUBSIDENCE DUE TO PEATLAND OXIDATION IN THE VENICE LAGOON CATCHMENT

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Riassunto.

La Laguna di Venezia è caratterizzata da una morfodinamica apprezzabile non solo su periodi geologici ma anche in tempi storici e moderni. Un importante cambiamento nell’area meridionale lagunare si è verificato nel secolo scorso con la bonifica di vaste zone e la loro trasformazione in fertili territori agricoli. I suoli bonificati contengono elevati quantitativi di torbe che, a contatto con l’aria, si ossida rilasciando in atmosfera anidride carbonica e causando una continua perdita di massa dal terreno. La subsidenza antropica indotta da questo processo geochimico ha abbassato l’altimetria di molte zone ben al di sotto del livello medio del mare e della laguna, con problemi crescenti di rischio idrogeologico e maggiori costi di gestione della bonifica. La subsidenza in oggetto è stata quantificata in 1.5 m durante gli ultimi 70 anni, con una velocità attuale di abbassamento di 1.5-2 cm/anno. La reazione geochimica che controlla l’ossidazione della torba dipende principalmente dalla temperatura e dall’umidità del terreno. A questo riguardo le pratiche agronomiche ed il franco di bonifica giocano un ruolo assai importante. All’interno di un piccolo bacino (24 km^2) posto in prossimità del margine lagunare e ben delimitato dal punto di vista idrologico (Bacino Zennare) è stato allestito un campo sperimentale per la misura dei movimenti del terreno e delle principali grandezze idrologiche che controllano il processo di ossidazione. Le misure in-situ, integrate con dati telerilevati, hanno consentito la modellizzazione della subsidenza antropica e dei principali processi di interesse e l’individuazione di possibili strategie di mitigazione.

Abstract.

The Venice Lagoon is characterized by a fast morphodynamics appreciable not only over the geological scale but also in historical and modern times. The lagoon environment proves very sensitive to even minor modifications of the natural and anthropogenic controlling factors. An important human endeavor accomplished in the past century is the reclamation of the southernmost lagoon area that has been turned into a fertile farmland. The reclaimed soil is reach in organic matter (peat) that may oxidize with release of carbon dioxide to the atmosphere. The continuous loss of carbon is causing a pronounced settlement of the farmland that lies below the present sea/lagoon level. This enhances the flood hazard and impacts noticeably on the maintenance and operational costs of the drainage system. Total peatland subsidence is estimated at 1.5 m over the last 70 years with a current rate of 1.5-2 cm/year. The geochemical reaction is primarily controlled by soil water content and temperature, and is much influenced by agricultural practices, crop rotation, and depth to the water table. A small (24 km^2) controlled catchment located in the area has been instrumented for accurately monitoring the basic parameters and recording the ground motion. The in situ measurements have been integrated with the combined use of remote sensing data to help cast light on the process and identify the mitigation strategies.

1. Introduction.

According to some authors [Bortolami *et al.*, 1984; Brambati *et al.*, 2003] the Venice Lagoon was born about 6000 years and was much smaller than it appears today [Gatto and Carbognin, 1981]. The lagoon communicates with the Adriatic Sea through three inlets (Fig. 1) that were nine around 1000 AD. The original inflowing rivers, i.e. Adige, Bacchiglione, Brenta, Piave and Sile, were diverted to the sea by the "Serenissima" Republic to avoid the lagoon fill-in. More recently natural and anthropogenic land subsidence, mean sea level rise and deepening of a few channels for internal navigation have promoted a dominant marine-type environment [Gatto and Carbognin, 1981]. The southernmost part of the lagoon catchment was progressively reclaimed starting from the end of the XIX century and finishing in the late thirties (Fig. 1). As a major result the area was turned into a fertile farmland at present kept dry by a distributed drainage system that collects the water from a capillary network of ditches and canals and pumps into the lagoon or the sea. By its very origin this area lies below the sea level and progressively lowers in close connection with the agricultural practices on the reclaimed farmland. Anthropogenic land subsidence raises a number of serious environmental concerns and economical issues ranging from the enhanced risk of inundation during the frequent Adriatic winter storms, to a larger salt contamination from the intruding sea water [Tosi *et al.*, 2004], to the need for increasing the power of the pumping stations and the depth of the canal beds, i.e. the maintenance cost [Gambolati *et al.*, 2005a].

To study the land settlement that plagues this area of high economical value for the Venice watershed the VOSS (Venice Organic Soil Subsidence) project was undertaken with the primary objective to understand the process underlying the anthropogenic event, quantifying the past and present subsidence rate and advancing possible remedial measures without penalizing the economy of the area. The study, conducted in close collaboration with the Land Reclamation Authority (Consorzio di Bonifica) and the farmland owners, is focused on a hydrologically controlled catchment, the Zennare Basin, located just south of the Venice Lagoon and characterized by the presence of wide peat areas.

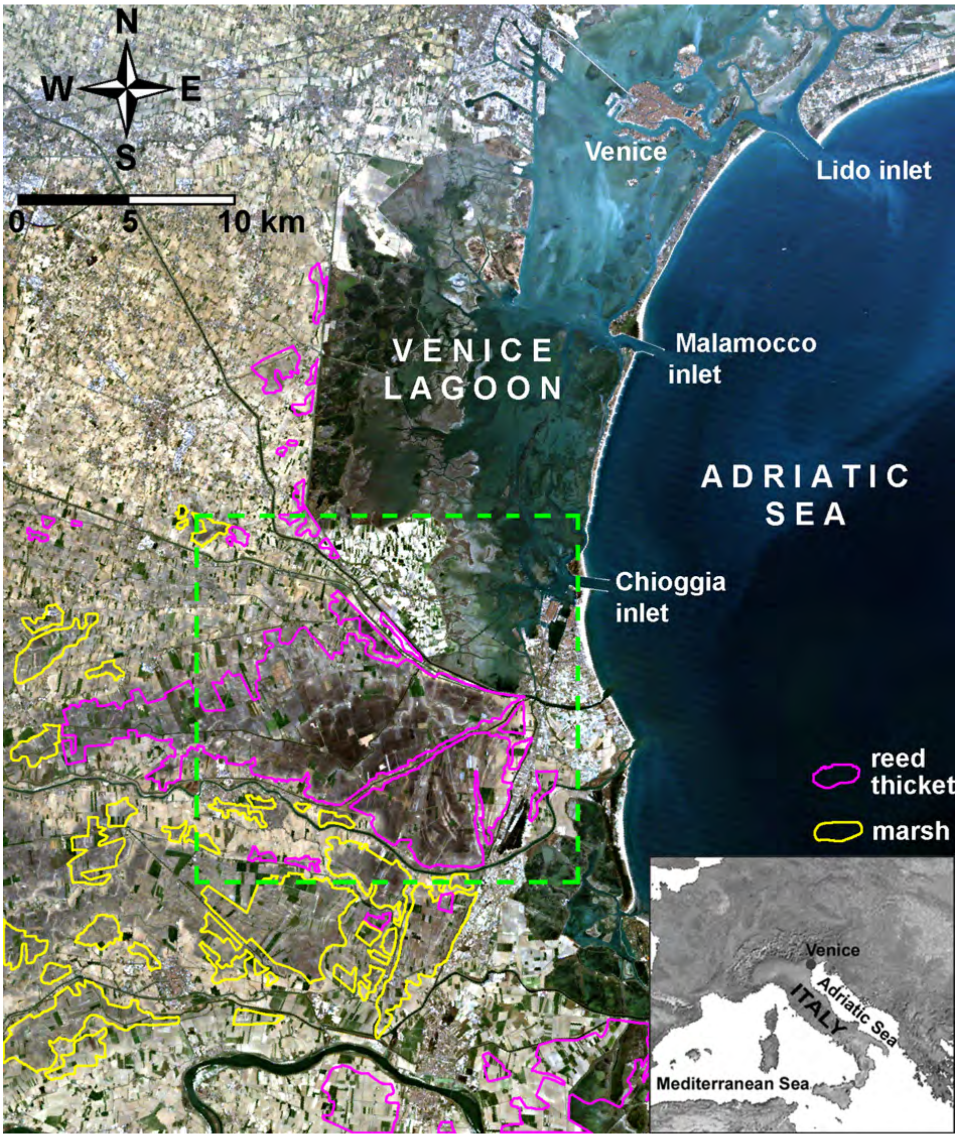

Fig. 1 – View of the Venice watershed with the map of the reedy and marshy areas drawn in 1833 during the Lombardo-Veneto kingdom and reclaimed in the past century. The green dashed box identifies the location of the map reported in Fig. 3 (after Gambolati *et al.* [2005b]).

2. Geochemical Land Subsidence.

Land subsidence is a major consequence of the oxidation of the soil organic fraction in the upper aerated agricultural zone and has been reported from other similar areas around the world as well [Stephens *et al.*, 1984; Rojstaczer and Deverel, 1995;

Nieuwenhuis and Schokking, 1997; Wösten *at al.*, 1997]. The geochemical reaction of interest can be represented as follows:

$$C_6H_{12}O_6 + 6O_2 = 6CO_2 + 6H_2O \tag{1}$$

The release of carbon dioxide to the atmosphere causes a soil mass loss which manifests itself as land subsidence. The organic soil is in the form of amorphous granular peat derived from the accumulation and decomposition of reeds (*Phragmites Australis*) grown in the ancient marshy area of the lagoon surroundings, where the above reaction could not occur due to anaerobic conditions. After reclamation, aerobic conditions were established in the upper soil (few tens of centimeters). Moreover the seasonal ploughing contributes to the exposition of new organic material to the atmosphere promoting new subsidence. The reaction is controlled by temperature and is limited by the presence of oxygen. Therefore, the lower the degree of water saturation in the subsoil and the higher the ambient temperature the faster the reaction rate. The depth of the subsurface water table affects the soil water content and the zone of aeration and hence the exposure of soil to oxygen. Since the water table is sensitive to the amount of precipitation, we can conclude that dry and hot seasons are most favorable to the occurrence. By contrast in winter soil oxidation slows down almost to zero. In light of the above we expect that anthropogenic land subsidence in the future might increase should the extreme climate events (i.e. hotter and dryer seasons) become more frequent, as the most recent meteorological records seem to indicate.

3. The VOSS Project.

The area under study was reclaimed from 1897 to 1937 and cumulative average settlement to date varies from 1.5 and 2 m (according to the thickness of the outcropping peaty layer) as is derived from indirect evidence including the protrusion of old structures from the ground (Fig. 2). Comparison of a 1983 DEM (Digital Elevation Model) of the area, obtained from aerophotogrammetry, and a 2002 kinematic DGPS (Differential Global Positioning System) campaign shows an average settlement rate of 2-3 cm/year, or more, over the last 20 years. Recent SAR (Synthetic Aperture Radar) surveys [Strozzi *et al.*, 2003] suggest that the areas where peat is not present are subject to natural subsidence only at a much smaller rate, estimated at a few mm/year [Gatto and Carbognin, 1981; Gambolati and Teatini, 1998; Kent *et al.*, 2002].

The areal extent of peatlands has been investigated using satellite data [Nicoletti *et al.*, 2003]. Several images from the IKONOS, ASTER, and LANDSAT-7ETM+ satellites, which combine high geometric (1 m^2 for IKONOS) and high spectral (6 bands for LANDSAT and 14 for ASTER) resolution, have been analyzed and calibrated against a detailed geomorphologic map of the study area and a large dataset of peat spectral signatures collected in situ using a portable spectrometer. The best results of the spectral analysis have been obtained from a density slice of the synthetic Brightness band obtained from the Tasseled Cap analysis of the LANDSAT data. Scenes collected between February and May provide the best data source as the farmland is already ploughed, so that no crop residues are present on the surface, and vegetation is only partially developed. The delineated peat areas well compare with a 1833 map of the local marshes drawn by government officials of the Lombardo-Veneto kingdom (Fig. 3).

Fig. 2 – Evidence of the anthropogenic land subsidence in the reclaimed area: (a) The protrusion of a sluice well above the bed of an old disappeared channel; (b) An old bridge hanging over the canal bank which settled by 1.5 m.

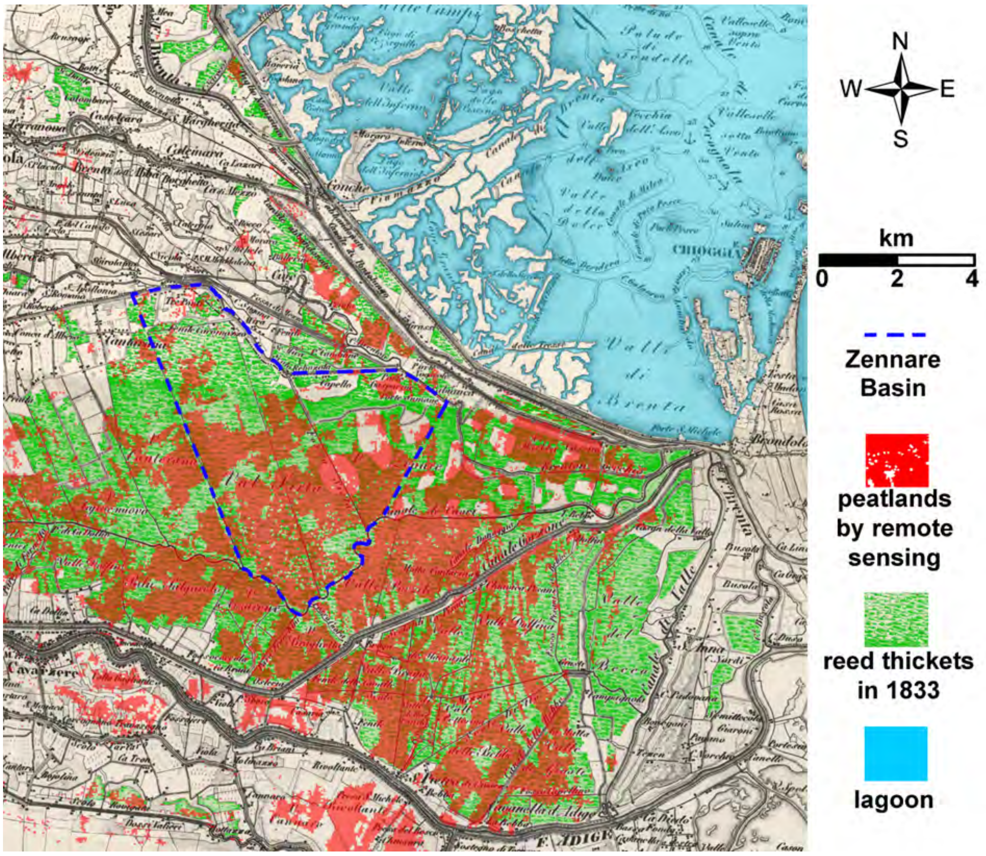

Fig. 3 – Peatland as derived from the spectral processing of the LANDSAT image of March 25, 2003, and superposed on the 1833 wet area. The boundary of the Zennare Basin is highlighted (after Gambolati *et al.* [2005b]).

A number of experimental fields have been instrumented in the Zennare Basin (Fig. 3), in the heart of the reclaimed farmland in the Venice watershed, to monitor the actual land settlement, help understand the process, and predict the future occurrence. The following devices were installed and operated for more than 2 years: rain gauges, anemometer, piezometers, soil temperature probes, tensiometers for capillary pressure, TDR probes for soil water content at 5 different depths, extensometer for land settlement, two NSS (Non Steady State) steel chambers for CO_2 fluxes [Hutchinson and Rochette, 2003] and a micrometeorological station based on the Eddy Covariance technique [Soegaard *et al.*, 2003]. The CO_2 fluxes are converted into an estimate of anthropogenic land subsidence η by the formula [Deveral and Rojstaczer, 1996]:

$$\eta = \frac{f_c}{\rho}\frac{p_c}{p_o} \qquad (2)$$

where:

- f_c is the carbon flux;
- ρ is the soil density (the peaty soil of the area has a ρ slightly larger than water);
- p_c is the percentage of carbon within the organic matter;
- p_o is percentage of organic matter within the soil (approximately equal to p_c).

The data from the NSS chambers, having footprints of a fraction of square meter (Fig. 4a), have been compared with records from the micrometeorological station, characterized by a footprint of the order of few hundreds of square meters. The average rates provided by these two techniques satisfactorily agree over the range 0.02-0.7 mg CO_2/m^2s, i.e. minimum (winter) and maximum (summer) value, respectively [Camporese *et al.*, 2004a]. From this data we readily obtain an estimate of the current anthropogenic land subsidence which ranges between 0.1 and 2 cm/year in winter and summer, respectively.

Experiences carried out with the extensometer (Fig. 4b) indicate that elastic soil deformations superpose on the long trend settlement (Fig. 4c) because of soil swelling (and subsequent shrinkage) that may occur in winter due to freezing and all year long due to rainfall [Camporese *et al.*, 2004b]. The peat soil expansion during a precipitation event can be experimentally related to groundwater table oscillations at a rate of 0.3-0.4 mm per 1 cm increase of the water table level. It is followed by a slower but completely reversible shrinkage (Fig. 4c). An original model fpr the simulation of the swelling/shrinking process in peat soil has been developed. Starting from the experimental observation that most of the deformations take place in the unsaturated zone, the model takes into consideration the variation of porosity with moisture content. A good agreement with published experimental data from laboratory analysis has been found. The model has been implemented into a Richards equation-based numerical code. This code has been applied for the simulation of the peat soil dynamics as measured in the Zennare Basin. The modelling results match very well with a large set of field data and demonstrate that the proposed model allows for an accurate reproduction of soil dynamics (Fig. 5).

On a larger scale (2 years) cumulative anthropogenic subsidence on the order of 2-3 cm is shown. Small or negligible rates characterize the summer and winter periods of the year 2002, when persistent and intensive rainfall events were recorded. Most of the settlement occurred in the very dry and hot summer of 2003. Application of a model developed by Stephens *et. al.* [1984], which relates the subsidence rate to soil temperature and groundwater table depth, allows for reasonably capturing the long term behavior of the settlement process (Fig. 4c).

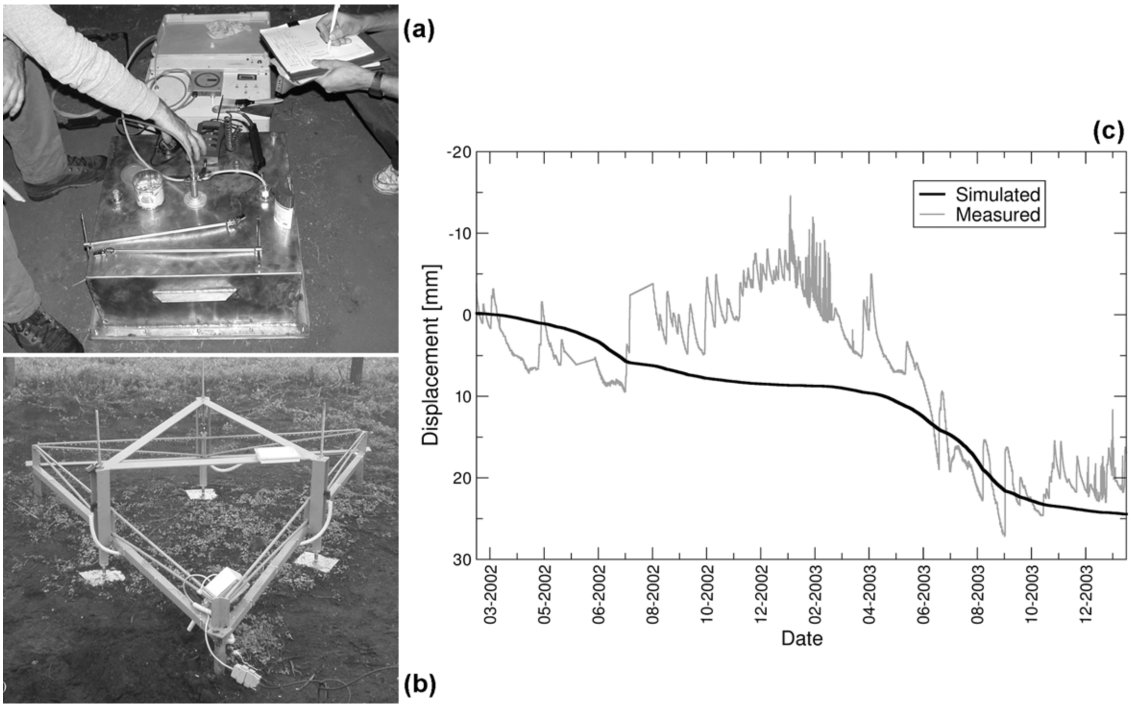

Fig. 4 – (a) NSS (Non Steady State) steel chamber used to measure the pointwise CO_2 released from the soil being oxidized. (b) Extensometer designed to measure the anthropogenic land subsidence due to peat oxidation. (c) Vertical displacement measured by the extensometer from February 2002 to January 2004 and compared with the prediction made by Stephens *et al.* [1984] formula which relates the reaction (and hence settlement) rate to temperature and depth to water table.

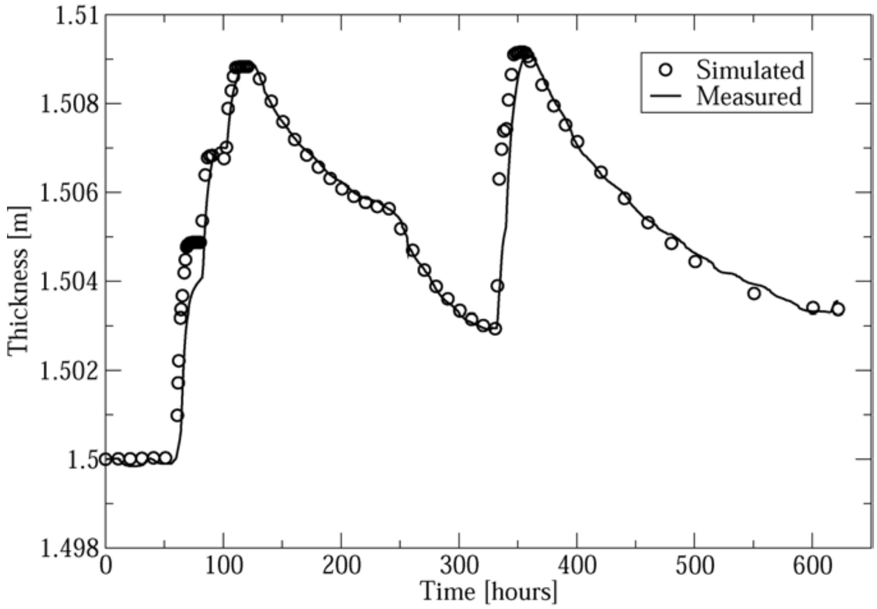

Fig. 5 – Measured and simulated reversible displacement of the peat surface over the period 08/10/2002 – 02/11/2002 (after Camporese *et al.* [2004b]).

4. Concluding Remarks.

Field experiments, data analysis, and modeling applications point to the following conclusions. The reclaimed farmland in the Venice watershed is subject to peat oxidation which has induced a cumulative anthropogenic subsidence between 1.5 and 2 m over the last century. Ground and remote sensed records provide evidence that land settlement has progressed at the rate of 2 cm/year or more during the last 20 years. The ad hoc extensometer exhibits a present trend of 1.5 cm/year while direct CO_2 measurements indicate up to 2 cm/year. These three independent measurement techniques agree very satisfactorily. Elastic reversible deformations related to soil freezing and rainfall may superpose on the long trend ground motion and make its pointwise interpretation very difficult.

If no remedial strategies are implemented in the near future and soil oxidation continues at the present rate, the entire peat layer is bound to disappear in about 50 years. This might cause an additional 75-100 cm of anthropogenic land subsidence with extremely negative consequences for the environment and the economy of the area. Since the process is accelerated during dry and hot summers, climate events, such as the 2003 summer, have a highly adverse impact. The extensometer data obtained in 2002 indicate that settlement can be mitigated by keeping a very low groundwater table depth. Scenarios using Stephens *et al.* model [1984] and calibrated on the available records suggest that, if the 2003 temperatures are projected into the future, the remaining peat layer will completely disappear in approximately 65 years for a constant water table depth of 60 cm. On the other hand, about 200 years would be needed to oxidize the peat if a more reduced water table depth of 20 cm is constantly maintained (Fig. 6).

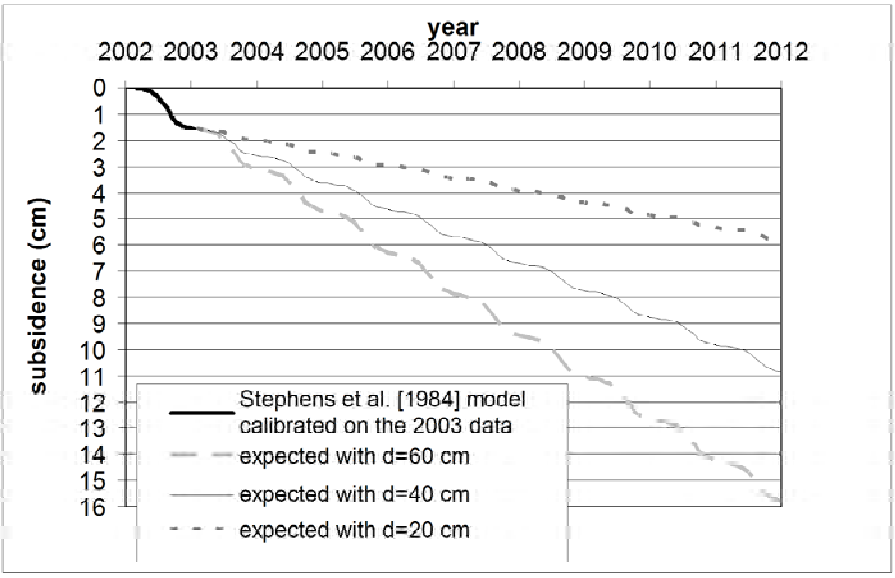

Fig. 6 – Expected land subsidence over the next decade as computed by the Stephens *et al.* [1984] model calibrated on the 2003 measurements collected at the Zennare Basin. The three scenarios assume the 2003 temperature and a constant water table depth of 20, 40, and 60 cm. Based on these data a 1 m thick peat layer would vanish in about 180, 90, and 65 years, respectively.

However, to become a management strategy of a practical use, shallow phreatic surface needs to coexist with the local agricultural practices. This can be achieved only if an accurate and timely control of the drainage system and the pumping station is planned, possibly with the aid of forecasting models, so that the water table depth can be kept at the minimum level consistent with the crop requirements. Introduction of different agricultural practices may also help reduce land settlement. For example, conservative tilling as a substitute to ploughing may help decrease the exposure of unmineralized peat to atmosphere while the introduction of cover crops may partially counterbalance the loss of organic material, as is also indirectly suggested in a much more general analysis of soil carbon sequestration at the global worldwide scale [Lal, 2004].

Acknowledgments.

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References.

Bortolami G., Carbognin L. and Gatto P., 1984. The natural subsidence in the Lagoon of Venice, Italy. In: Johnson A. I. *et al.* (Eds.), *Land Subsidence (Proc. III Int. Symp. on Land Subsidence)*, IAHS Publ. No.151, 777-784

Brambati A., Carbognin L., Quaia T., Teatini P. and Tosi L., 2003. The Lagoon of Venice: geological setting, evolution and land subsidence. *Episodes* 26, 264-268

Camporese M., Putti M., Salandin P. and Teatini P., 2004a. Spatial and temporal variability of CO_2 flux from a peatland south of Venice. In: J. Päivänen J. (Ed.), *Wide Use of Peatlands* (*Proc. XII Int. Peat Congress)*, Int. Peat Society Publ., Vol. 1, 117-123

Camporese M., Putti M., Salandin P. and Teatini P., 2004b. Modeling peatland hydrology and related elastic deformation. In: Miller C. T. *et al.* (Eds.), *Computational Methods in Water Resources*, Elsevier, Vol. 2, 1453-1464

Deverel S.J. and Rojstaczer S., 1996. Subsidence of agricultural lands in the Sacramento – San Joaquin Delta, California: role of aqueous and gaseous carbon fluxes. *Water Resour. Res.* 32(8), 2359-2367

Gambolati G. and Teatini P., 1998. Numerical analysis of land subsidence due to natural compaction of the Upper Adriatic Sea basin. In: Gambolati G. (Ed.) *CENAS, Coastline Evolution of the Upper Adriatic Sea due to Sea Level Rise and Natural and Anthropogenic Land Subsidence*, Kluwer Academic Publ., Water Science & Technology Library n.28, 103-132

Gambolati G., Putti M., Teatini P. and Gasparetto-Stori G., 2005a. Subsidence due to peat oxidation and its impact on drainage infrastructures in a farmland south of the Venice Lagoon. *Environ. Geol.* In press

Gambolati G., Putti M., Teatini P., Camporese M., Ferraris S., Gasparetto Stori G., Nicoletti V., Rizzetto F., Silvestri S. and Tosi L., 2005b. Peatland oxidation enhanced subsidence in the Venice watershed. *EOS Trans. AGU*. Submitted

Gatto P. and Carbognin L., 1981 The Lagoon of Venice: natural environmental trend and man-induced modification. *Hydrol. Sci. B.* 26, 379-391

Hutchinson G.L. and Rochette P., 2003. Non-flow-through steady-state chambers for measuring soil respiration: Numerical evaluation of their performance. *Soil Sci. Soc. Am. J.* 67, 166-180

Lal R., 2004. Soil carbon sequestration impacts on global climate change and food security. *Science* 304, 1623-1627

Kent D.N., Rio D., Massari F., Kukla G. and Lanci L., 2002. Emergence of Venice during the Pleistocene. *Quat. Sci. Rev.* 21, 1719-1727

Nicoletti V., Silvestri S., Rizzetto F., Tosi L., Putti M. and Teatini P., 2003. Use of remote sensing for the delineation of surface peat deposits south of the Venice Lagoon (Italy). In: *IGARSS 2003 - Int. Geoscience and Remote Sensing Symp.*, IEEE, CD-ROM, Vol. IV, 2881-2883

Nieuwenhuis H.S. and Schokking F., 1997. Land subsidence in drained peat areas of the Province of Friseland, The Netherlands. *Q. J. Eng. Geol.*, 30, 37-48

Rojstaczer S. and Deverel S.J., 1995. Land subsidence in drained histosols and highly organic mineral soils of California. *Soil Science Soc. of American J.* 59, 1162-1167

Soegaard H., Jensen N.O., Boegh E., Hasager C.B., Schelde K. and Thomsen A., 2003. Carbon dioxide exchange over agricultural landscape using eddy correlation and footprint modelling. *Agr. Forest Meteorol.* 113, 159-183

Stephens J.C., Allen L. H. and Chen E., 1984. Organic soil subsidence. In: Holzer, T.L. (Ed.), *Man-induced Land Subsidence*, Geological society of America Reviews in Engineering Geology, v. 6, 107-122

Strozzi T., Tosi L., Wegmüller U., Werner C., Teatini P. and Carbognin L., 2003. Land subsidence monitoring service in the Lagoon of Venice. In: *IGARSS 2003 - Int. Geoscience and Remote Sensing Symp.*, IEEE, CD-ROM, Vol. I, 212-214

Tosi L., Carbognin L., Teatini P., Rosselli R. and Gasparetto Stori G., 2000. The ISES project subsidence monitoring of the catchment basin south of the Venice Lagoon, Italy. In: Carbognin L. *et al.* (Eds), *Land Subsidence (Proc. VI Int. Symp. on Land Subsidence)*, La Garangola, Padova, Italy, Vol. II, 113-126

Wösten J.H.M., Ismail A.B. and van Wijk A.L.M., 1997. Peat subsidence and its practical implications: A case study in Malaysia. *Geoderma* 78, 25-36

RESEARCH LINE 3.2
Hydrodynamics and morphology

LONG-TERM MORPHOLOGICAL MODELLING OF THE BOTTOM EVOLUTION OF TIDAL BASINS

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Riassunto.

Lo scopo di questo contributo consiste nella valutazione della capacità di alcuni modelli morfodinamici a lungo termine di fornire, magari in modo semplificato, ma con una buona efficienza di calcolo, una previsione dell'evoluzione di una laguna a marea ad una scala temporale estesa sul lungo periodo. Per tale motivo, i processi fisici vengono rappresentati nelle loro proprietà medie intermareali, prescindendo dalle peculiarità pressoché istantanee legate alle caratteristiche idrodinamiche, ma integrando gli stessi processi su tempi molto più estesi.

Viene quindi sviluppato un modello morfologico uni-dimensionale, basato sul concetto di trasporto netto a lungo termine, per analizzare, attraverso la definizione di un coefficiente di dispersione intermareale, l'evoluzione di un canale rettangolare. Successivamente, e partendo dai medesimi presupposti, viene applicato un modello morfologico bi-dimensionale per riprodurre il comportamento di una laguna schematica ed analizzare le condizioni di instabilità che determinano la presenza di canali molto profondi che interessano le zone di bassofondali.

Abstract.

The aim of this paper consists on the application of some morphological models to the Venice Lagoon in order to simulate the behaviour of certain physical processes which are represented through their simplified long-term features, excluding their peculiarities related to the small-term scale events.

A one-dimensional long-term morphological model, based on the concept of net averaged sediment transport, is first developed to investigate the bottom evolution of a rectangular tidal channel. Subsequently, a two-dimensional long-term morphological model is applied to a simple tidal basin provided with a tidal inlet. The aim of the study is to simulate numerically the instability conditions that cause the presence of a deep channel in low flats.

1. *Introduction.*

The contents of this paper arise from the developments within the CORILA Project-Line 3.2, entitled "Analisi e monitoraggio dei processi morfologici nel sistema lagunare veneziano" (Analysis and monitoring of morphological processes within the Venice Lagoon system). In particular, this research line has been devoted to long term modelling which appears to be a good tool to investigate long-term evolution issues in order to manage the sedimentation process in a tidal basin. This approach permits to take into account all the processes having an impact on the tidal environment, both natural and anthropogenic.

In fact, tidal lagoons represent a peculiar feature of coastal environment where tidal oscillations, fluvial currents and wind waves, combined with geotechnical and biological phenomena, originate typical hydro-morphological processes. In the Venice Lagoon, in particular, natural morphodynamics, which also include the long-term effect of subsidence and eustatism, interacts with the consequences of human utilization, which makes the physical processes more and more complex.

The natural- or man-controlled morphodinamic behaviour of coastal and lagoon systems can be simulated through different types of model approaches, having their own area of applicability and covering a wide span of time and space scales (short- and long-term models). When dealing with physical processes which cause intertidal sediment transport, long-term models are found to be robust tools in simulating both tidal and wave effects. In particular, "conceptual models" incorporate many physical (and even biological) processes via a number of algebric or differential equations containing semiempirical coefficients, which can be calibrated by direct comparison with experiments or with specific short-term models.

The long-term models are in general elaborated through some subsequent aggregation processes, averaging the more general water flow and sediment transport equations over the spatial and the temporal scales statistically representative of the prevailing tidal and meteorological regime. However, as this computation requires a great deal of simplifications for expressing the averaged quantities, the residual terms arising from the averaging can be discussed in a "conceptual way". In fact, these residual terms contain a number of information about the hydrodynamic and the morphology of the system under investigation. These characteristics can be taken into account through a single parameter here called "transport concentration". This feature is in general the depth-integrated concentration averaged over a period of time (say, one year) statistically representative of the prevailing tidal and meteorological regime. Transport concentration represents the starting point of the one- and two-dimensional conceptual models here presented, which both consist on a number of modules that in the present configuration only include tidal currents and sediment transport. In particular, it will be analysed the long-term bottom evolutions of:

1. a rectangular tidal channel simulated by an intertidal morphodynamic one-dimensional model;
2. a rectangular tidal basin simulated by an intertidal morphodynamic two-dimensional model.

2. *One-dimensional empirical model.*

In this section a one-dimensional model of the bottom evolution of a tidal channel is presented and compared with laboratory data collected by Bolla Pittaluga [2003].

The one-dimensional long-term sediment transport T through any cross-section of a tidal channel A can be expressed in terms of long-term averaged concentration c, as the sum of a dispersive and an advective component (eulerian residual flow):

$$T = -DA\frac{dc}{dx} + cU_R A \pm \Delta T_R \quad (1)$$

where x is the longitudinal co-ordinate, D is the intertidal dispersion, U_R is the time averaged residual (eulerian) velocity and $\pm \Delta T_R$ is the long term transport, in the ebb- or flood-direction, depending on the non symmetrical tidal velocity. One can note that the advective component (cUA), which is usually caused by fluvial flows or by two dimensional circulations is nil in a closed channel while the term $\pm \Delta T_R$ is presumably very small for a sinusoidal forcing tidal. In fact, this term is due to the non symmetrical character of the tidal flow and is not proportional to the residual velocity U_R but depends on the difference $\pm \Delta U_{EF}$ between the residual velocity, respectively in ebb and flood conditions.

Therefore, as the advective transport can be considered not important in the long-term processes here simulated, we can consider the dispersive transport as the determining component of the tidal transport. We are focusing on the definition of an intertidal coefficient D, that depends on the spatial and temporal deviations of both the suspended sediment concentration and the water flow and incorporates different transport mechanisms, somehow related to the residual terms issuing from the averaging operations.

An attempt of theoretical derivation of the intertidal dispersion coefficient has been made [Dal Monte, 2005], by considering the transversal deviations from the average over the cross section, with an approach similar to Taylor's [1953]. In the present paper, some results derived from an empirical approach are shown, compared with the experimental data collected in the Laboratory of Genova [Bolla Pittaluga, 2003].

The main issue of such approach is based on the observation that for a tidal lagoon formed by a network of deep channels cut in broad and shallow areas, the dominant intertidal transport is due to the alternate "trapping and pumping" mechanism between channels and shoals during a tidal cycle [Schijf and Schönfeld, 1953].

This mechanism accounts for the fact that during flood conditions clear water enters from the sea basin into the lagoon through the channel, characterised by a sediment concentration smaller than in the shoals. Whereas, during ebb conditions, the sediments are more concentrated in the channels than in the shoals. Therefore, the flux of sediments is from the channels to the shoals in ebb conditions and from the shoals to the channels in flood conditions. Dronkers [1978] accounted for this behaviour by expressing the intertidal dispersion coefficient D as proportional to the squared maximum velocity in the channel:

$$D = f\left(\frac{A_c}{A_s}\right) \cdot U^2 = k_e \cdot U^2 \quad (2)$$

where f is a function of the ratio between the channel (A_c) and the shoal (A_s) cross section, respectively characterised by fast and slow flow. In our case the channel cross section is compact (no lateral shoals), but one can divide the channel cross-section into two flow zones, characterised by a current faster (fast flow section) and slower (slow flow section) than the averaged one, respectively. In fact, alternate transversal fluxes of water and sediments, between zones of fast and slow longitudinal velocity, take place also in a “compact section”. Therefore, when dealing with such a configuration the function f of eq. (2) is proportional to the ratio between the two flow zones. In the present paper, the function f is then considered to be a constant k_e which is computed by the calibration of the simulated results with the laboratory data.

Expression (2) of the intertidal dispersion coefficient is necessary for the computation of the dispersive transport T (eq. 1), that is considered to be the only component of the total net (long-term) sediment transport T in the model assumes the form:

$$\frac{\partial T}{\partial x} = \frac{\partial A}{\partial t} \tag{3}$$

where t is the long term time (order of the years).

Eq. (3) is solved by utilizing eqs. (1) and (2) and considering an expression for the long-term concentration in the channel $c(x,t)$ [Dal Monte and Di Silvio, 2003] provided by a monomial type formula [e.g. Engelund and Hansen, 1967]. The calibration of the model is carried on by assigning different values to the product ($k_e \cdot c_{\infty,0}$), where $c_{\infty,0}$ represents the sediment concentration in the sea (not measured in the “experiments”). The best value that gives a good agreement between the experimental data and the model output was found for $k_e \cdot c_{\infty,0} = 0.6\ s$. Fig. 1 shows the comparison between the bottom evolution (ratio between the bottom variation $\eta(x,t)$ and the initial depth D_0) of a tidal channel measured by laboratory data [Bolla Pittaluga, 2003] and computed through the empirical model.

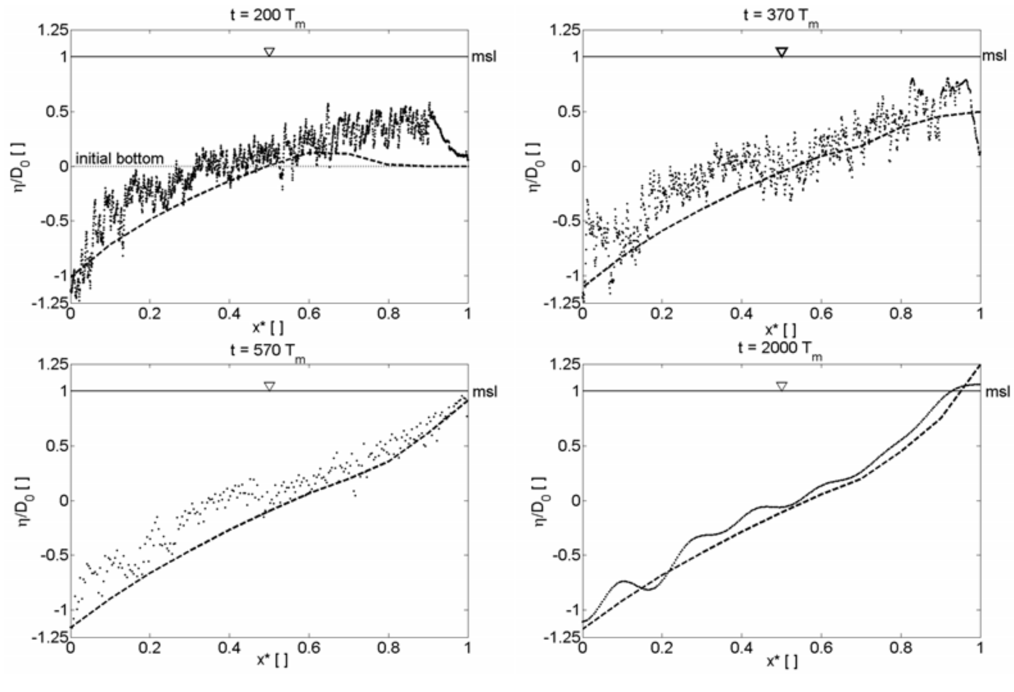

Fig. 1 – Comparison between the bottom profile of a tidal channel observed in laboratory (points) and modelled (broken line) at different time scales.

Starting from an initial flat bed profile, a slow evolution of the bed topography occurs due to the tidal effect. Sediments are scoured in the seaward portion of the channel, driven landward and deposited in the inner part of the channel. Finally, an equilibrium bed profile is reached, which is upward concave and slightly convex landward and shows the formation of a dry and wet region which eventually develops to a "beach". Apart from the initial period of adjustment (until about 200 tidal periods) the model results fit quite well with the laboratory bottom profile. Moreover, at equilibrium conditions, the model simulates the formation of a tiny beach at the landward end, due to the fact that, when the bottom of the channel reaches the mean sea level, the tidal amplitude still produces a water flow.

We must underline that, when computed in a theoretical way, the dispersion coefficient D appears to be much smaller than the value provided by calibration against the laboratory experiments. This means that apparently some other mechanisms of intertidal dispersion are not described by the crude physics employed up to now.

We are presently trying to single out and evaluate such mechanisms (and to include them in the dispersion coefficient D), by considering a finite propagation celerity of tidal wave and/or by distinguishing between "actual" concentration and "equilibrium" concentration in the short term model.

3. Two-dimensional morphological modelling.

In this section a two-dimensional conceptual model is proposed, aimed at simulating the morphodynamic evolution of natural tidal basin at long-term scale. The model shown is based on a simplification of the water flow equations for determining the instantaneous velocity field in flood conditions [Rinaldo *et al.*, 1999]. Moreover, it is defined an appropriate equilibrium concentration [Di Silvio and Padovan, 1998] and it is evaluated empirically an intertidal dispersion coefficient (see previous section).

3.1. Hydrodinamics.

As the intertidal dispersion coefficient depends on the maximum local velocity, the computation process starts from the computation of the flow field. In this case, the instantaneous velocity distribution at maximum flood conditions is considered. In a relatively "short" tidal lagoon, (with propagation time between inlet and lagoon basin smaller than a ¼ of a tidal period T_m) one can assume that, at maximum flood conditions, friction terms in the momentum equations dominate inertial effects and that the rate of the rising level $\partial\eta/\partial\tau$ is constant in each location of the lagoon (equals to the maximum rising rate in the sea).

The friction terms, under this hypothesis, have been linearised using the energy criterion [Fischer, 1979], which allows one to write the depth averaged velocity as:

$$\begin{cases} U = -\dfrac{h \cdot {C_h}^2}{\sqrt{U^2 + V^2}} \dfrac{\partial\eta}{\partial x} \\ V = -\dfrac{h \cdot {C_h}^2}{\sqrt{U^2 + V^2}} \dfrac{\partial\eta}{\partial y} \end{cases} \tag{4}$$

where (U,V) are the depth-averaged flow velocities in the (x,y) directions, $h=z_b - \eta$ is the local water depth, z_b and η is respectively the local elevation of the bottom and the water surface below the mean sea level.

The two-dimensional continuity equation can be written as:

$$\frac{\partial \eta}{\partial \tau} + \frac{\partial (hU)}{\partial x} + \frac{\partial (hV)}{\partial y} = 0 \qquad (5)$$

The system of eqs. (4) and (5) is numerically solved by a finite elements method using an "under-relaxation" approximation procedure for controlling the convergence.

3.2. Morphodynamics

The two-dimensional balance equations for the sediments are written as:

$$\frac{\partial T_x}{\partial x} + \frac{\partial T_y}{\partial y} = E \qquad (6)$$

where T_x and T_y are the long-term sediment transports (averaged over a long period of time) in the direction x and y respectively and E is the long-term rate of sediment removal from the lagoon surface.

The following expressions for the "net" sediment transport are obtained by averaging the suspended transport equations, over a long period of time:

$$\begin{cases} T_x = h \cdot \left(C \cdot \overline{U} - D_{xx} \dfrac{\partial C}{\partial x} - D_{yx} \dfrac{\partial C}{\partial y} \right) \\ T_y = h \cdot \left(C \cdot \overline{V} - D_{xy} \dfrac{\partial C}{\partial x} - D_{yy} \dfrac{\partial C}{\partial y} \right) \end{cases} \qquad (7)$$

where h is the averaged water depth and C the averaged sediment concentration over the water column. The terms of advective transport can be neglected in comparison with the intertidal dispersion phenomena, as previously assumed. The tensor of intertidal dispersion D_{ij} is expressed empirically by assuming a proportionality between the intertidal dispersion transport in the direction of $W = \sqrt{U^2 + V^2}$ and the squared velocity W^2 as explained in the one dimensional model.

The bottom erosion rate E in eq. (6) can be expressed by the following first-order reaction equation:

$$E = w \cdot (C_{eq} - C) \qquad (8)$$

where C_{eq} is the equilibrium concentration and w a flow-dependent parameter that, for fine particles, is equal to the fall velocity of the particle, but for simplicity here is considered to be constant.

Finally, the following expression of the water-depth long-term change is considered in order to simulate the bottom evolution of the tidal basin:

$$\frac{\partial h}{\partial t} = E + \alpha_e + \alpha_s \qquad (9)$$

where the eustatism α_e (rise of mean sea level) and the subsidence rate α_s (settlement of ground surface) are not accounted for in this initial phase of the investigation.

Fig. 2 shows the simulated evolution of a schematised tidal basin in 70 years. Marshes (which correspond to the red colour in Fig.2) originate near to the sediment sources, namely the lagoon inlets or the riverine outlets. When a string of marshes develops, the decrease of transmissivity represents a strong obstacle to the sediment transport from the source towards the shoals. Consequently, these shoals tend to become deeper and deeper and tend to form a pond.

After having attained almost their maximum elevation, marshes maintain constant their level. As soon as the cliff becomes too high, it collapses and consequently the marshes perimeter is destroyed. In other words, sediment deficit produces an erosion of the shoal near to the marsh, which, in its turn, causes the collapse of the marsh cliff.

After 100 years simulation, quasi-equilibrium conditions are reached, that are characterised by a concentration not really uniform but similar to the sea sediment concentration.

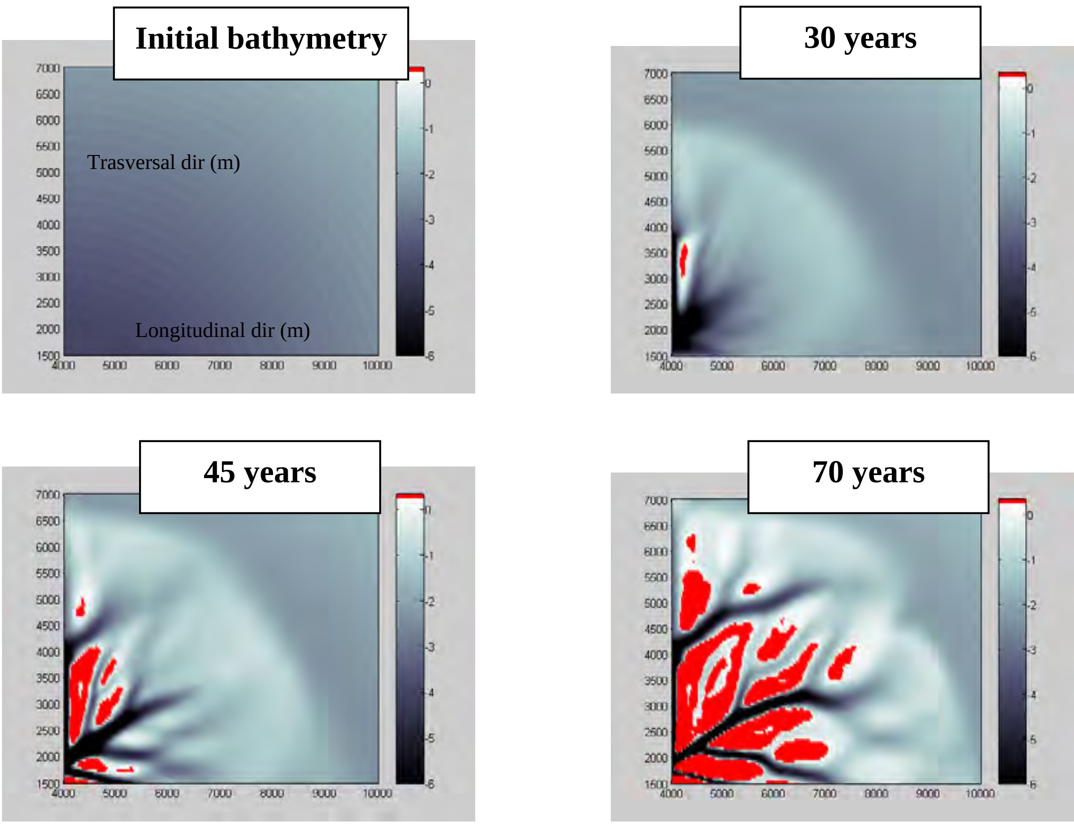

Fig. 2 – Bottom evolution and marshes formation of a tidal basin in the two-dimensional conceptual model. The red colour represents the marshes higher than 35 cm on the mean sea level.

Conclusions.

Long-term models result to be suitable to describe and to reproduce the behaviour of the three lagoon compartments (channels, shoals and salt marshes) under the action of tides, local wind, marine climate, riverine input and subsidence. In particular, one can describe the bottom evolution of a tidal basin at three different spatial scales, using 0-D, 1-D, 2-D and 3-D physical and conceptual models. These models still require the development of some aspects, both conceptual (e.g., the theoretical definition of the intertidal dispersion coefficient) and numerical (e.g., the bi-dimensional evolution of a tidal basin).

Some of this features will be investigated and completed in the future work and constitute an integral part of the CORILA Project-Line 3.18.

References

Bolla Pittaluga M., 2003. Long term morphodynamic equilibrium of tidal channels, Tesi di dottorato

Dal Monte L., 2005. Modellazione morfodinamica a lungo termine delle lagune a marea, Tesi di Dottorato, Università di Padova

Dal Monte L., G. Di Silvio, 2003. Ratio between channel-cross section and tidal prism in short lagoons: validity and limits of the “Law of Jarret”, 3^{rd} IAHR Symposium on River, Coastal and Estuarine Morphodynamics, 1-5 Sept., Barcelona, Spain

Di Silvio G. and A. Padovan, 1998. Interaction between marshes, channels and shoals in a tidal lagoon investigated by a 2-D morphological model. Proceedings of third international conference on hydro-science and engineering, III

Dronkers J., 1978. Longitudinal dispersion in shallow well-mixed estuaries, Vol. 3, 169, Coastal Eng. Conf.

Engelund F., E. Hansen, 1967. A Monograph on Sediment Transport in Alluvial Streams, Teknish Forlag, *Technical Press*, Denmark, Copenhagen, 62 pp

Fischer H.B., 1979. Mixing in inland and coastal waters, Academic Press, San Diego (483 pp.)

Rinaldo A., S. Fagherazzi, S. Lanzoni, M. Marani and W. E. Dietrich, 1999. Tidal networks 3. Landscape-forming discharges and studies in empirical geomorphic relationships. *Water Resources Research*, vol. 35, no. 12, pages 3919–3929, december

Schijf J.B., J.C. Schönfeld, 1953. Theoretical considerations on the motion of salt and fresh water, 321, Proc. Minnesota Int. Hydr. Cond. (IAHR/ASCE), Minneapolis, Minnesota,

Taylor G.I., 1953. Dispersion of soluble matter in solvent flowing slowly through a tube, Proc. R. Soc. London A, 219, 186-203

COUPLED RESPONSE IN THE GROUND OF THE VENICE LAGOON MARSHES INDUCED BY TIDE

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Riassunto.

Per descrivere l'evoluzione della pressione neutrale indotta dalle escursioni giornaliere di marea nelle barene della laguna di Venezia viene impiegato un approccio agli elementi finiti di tipo accoppiato, basato sulla teoria delle miscele. A tale scopo, il terreno che forma le barene viene schematizzato come un continuo elasto-plastico poroso e deformabile, in equilibrio termodinamico sia in condizioni di totale che di parziale saturazione. I risultati delle analisi numeriche sono confrontati con i risultati di una campagna di misure in sito condotta presso la barena S. Felice.

Abstract.

Pore pressure response in the ground forming the Venice lagoon marshes and wetlands under daily tide excursion is described using a coupled finite element approach based on the hybrid-mixture theory. To this end, the soil forming the marshes is assumed to be a deformable multiphase porous media, in a thermo-dynamic equilibrium state both in fully saturated and partially saturated conditions. The results of the finite element analyses are compared with accurate water pressure field measurements, carried out on the marsh S. Felice.

1. Introduction.

The landscape typifying the Venice lagoon, largely made up of marshes and wetlands (Fig. 1), is suffering an overall rapid deterioration, including dramatic changes in the sediment balance.

These shallow lands - formed throughout the Holocene epoch - as well as the Venetian ground at higher depths are composed of a predominant silt fraction irregularly combined with clay and/or sand thus, forming an erratic interbedding of various types of sediments [Cola and Simonini, 2002].

New research has been recently undertaken [Simonini and Cola, 2002] to characterize the hydro-geotechnical behaviour of the shallowest sediments of the marshes subject to tide fluctuation in the lagoon and to analyse and explain the evolution of marsh scarp instability, which is one of the most evident causes of the environmental damage occurring in the Venice lagoon.

Laboratory and field investigations, concentrated at the marsh S. Felice (Fig. 1), consisted of soil profile reconstruction, soil permeability and stiffness measurements and, moreover, monitoring for long periods the tide-induced pore pressure evolution in the marsh shallowest ground [Simonini and Cola, 2002].

Fig. 1 – Location of test site on the marsh S. Felice, in front to the Treporti village.

On the basis of the investigation results, a finite element model is now being calibrated and used to describe groundwater response during tide excursion.

Besides a description of site and laboratory investigation, the paper concerns with the preliminary numerical analyses performed so far using simplified marsh geometry and boundary conditions, to show the influence of permeability, skeleton stiffness and initial saturation degree on the overall pore pressure response.

2. Monitoring pore pressure evolution as a function of tide excursion.

Fig. 2 sketches a schematic layout of the pore pressure measurement system installed in the marsh S. Felice.

The pore pressure evolution was monitored using standpipe piezometers along with two verticals, as shown in Fig. 2.

The piezometers were provided by a special pore pressure transducer, equipped with a remote recording system and powered by battery. An additional pore pressure transducer measured the tide oscillation in the nearby channel.

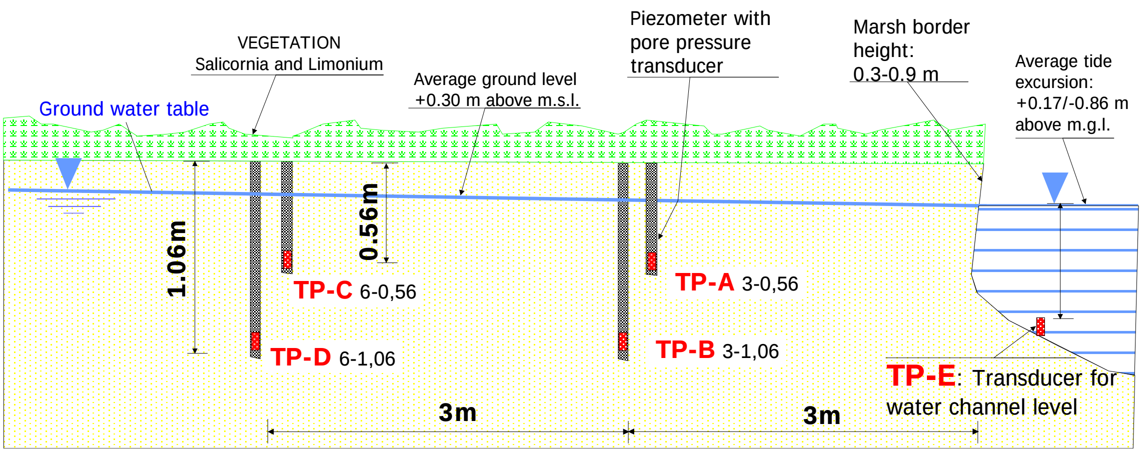

Fig. 2 – Layout of pore pressure transducers at the marsh border.

Water pressure was continuously measured during two periods, from 21th March to 24th April 2002 and from 29th May to 19th June 2002. All the measurements were then referred to the mean marsh ground level (m.g.l.) assumed at +0.30 m above mean sea water level (m.s.l.).

Fig. 3 shows the tide excursion and the pore pressure evolution measured in the ground over three days - from 23th to 26th March 2002 - during which the tide was characterized by two daily cycles not submerging the marsh surface. To note that, at the sigize tide, the marsh is flooded by a maximum head of 10 cm.

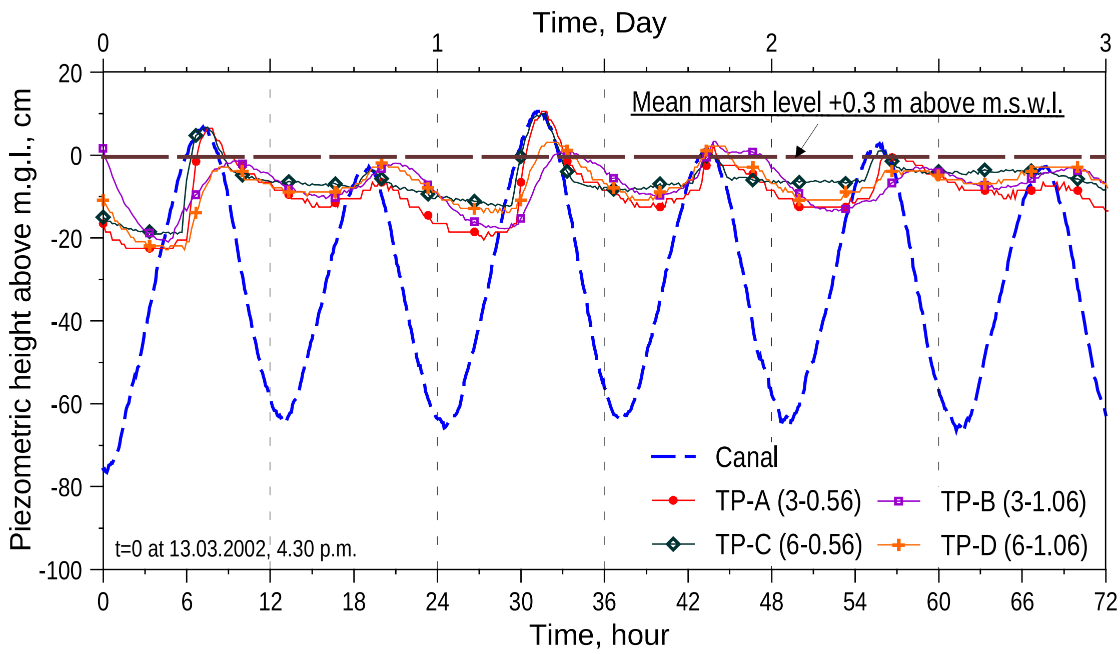

Fig. 3 – Tide excursion and induced pore pressure oscillations in the ground.

Interesting features to notice are:

- Significant damping and delay of the pore water response occurs especially at decreasing tide;
- Pore pressure is always positive up to a depth about 0.30 m below m.g.l., even if the tide approaches -0.80 m;
- Full soil saturation seems to occur when the marsh is flooded: in this case a sudden response of pore pressure transducers is observed indicating a fully coupled behaviour and no significant pore pressure damping;
- Significant hydraulic gradients and associated seepage forces can be hypothesised to act on the soil skeleton only within a small distance from the marsh boundaries.

It is important to note that the pore pressure evolution depicted in Fig. 3 is due to a selected short time interval, being the usual pore pressure trend in the range ±0.60 m above m.s.l,, with the oscillation amplitude typically controlled by the 28-day moon cycle. Occasionally high tides may rise up to 1-1.5 m above m.s.l.

Moreover, evapotranspiration and rain generally influence the marsh pore pressure response, but during the selected time interval shown in Fig. 3, air temperature was relatively constant and no vegetation was active: this provided negligible vapour exchange with the atmosphere.

3. Field equations.

The hydro-mechanical response of the ground is modelled using a finite element model for non-isothermal elasto-plastic multiphase geomaterials [Lewis and Schrefler, 1998, Sanavia *et al*., 2005]. The partially saturated porous medium is treated as a multiphase system composed of π = 1,…, k constituents with the voids of the solid skeleton (s) filled with water (w) and gas (g). The latter is assumed to behave as an ideal mixture of dry air (no-condensable gas, *ga*) and water vapour (condensable gas, *gw*).

At the macroscopic level the porous media is modelled as a deformable continuum in which each π-constituent has reduced density according with its volume fraction. The constituents are assumed to be isotropic, homogeneous, chemically non reacting and immiscible, with the exception of the latter for dry air and vapour.

Several phenomena are taken into account including water flow due to pressure gradient and capillary, heat conduction and convection, vapour diffusion and latent heat transfer, as a result of the phase-exchange of water inside the pores. Fluids, solid and thermal fields are coupled, all fluids being in contact with the solid.

All the constituents are taken to have the same temperature because the local thermal equilibrium between solid, gas and liquid phases is assumed. The state is described by the capillary pressure p^c, gas pressure p^g, temperature T and the displacements $\boldsymbol{u}$ of the solid matrix. In the partially saturated zone, the water is separated from its vapour by a concave meniscus (capillary water) and the water pressure p^w is in equilibrium with capillary and gas pressures according to the relationship $p^c = p^g - p^w$. The linear momentum balance equation in terms of total Cauchy stress σ assumes the form (ρ is the density of the mixture):

$$div\boldsymbol{\sigma} + \rho\mathbf{g} = \mathbf{0} \tag{1}$$

$$\rho = [1-n]\rho^s + nS_w\rho^w + nS_g\rho^g \tag{2}$$

with n the porosity and S_w and S_g the water and gas degree of saturation, respectively.

The total Cauchy stress can be decomposed into effective and pressure parts following the principle of effective stress

$$\boldsymbol{\sigma} = \boldsymbol{\sigma}' - [S_g p^g + S_w p^w]\mathbf{1} \tag{3}$$

where $\boldsymbol{\sigma}'$ is the modified effective Cauchy stress tensor, also called Bishop's stress tensor in soil mechanics and **1** is the second order identity tensor.

The mass conservation equation for the solid skeleton, the water and the vapour is

$$\begin{aligned} & n[\rho^w - \rho^{gw}]\frac{\partial S_w}{\partial t} + [\rho^w S_w - \rho^{gw}[1-S_w]]div\left(\frac{\partial \mathbf{u}}{\partial t}\right) + [1-S_w]n\frac{\partial \rho^{gw}}{\partial t} \\ & - div\left(\rho^g \frac{M_a M_w}{M_g^2}\mathbf{D}_g^{gw} grad\left(\frac{\partial p^{gw}}{\partial p^c}\right)\right) - div\left(\rho^w \frac{\mathbf{k}k^{rw}}{\mu^w}[grad\,(p^w) - \rho\mathbf{g}]\right) \\ & - div\left(\rho^{gw}\frac{\mathbf{k}k^{rg}}{\mu^g}[grad\,(p^g) - \rho\mathbf{g}]\right) - \beta_{swg}\frac{\partial T}{\partial t} = 0 \end{aligned} \tag{4}$$

where $\boldsymbol{k}$ is the intrinsic permeability tensor, k^{rw} the water relative permeability and μ^{w} the water viscosity.

The inflow and outflow have been described using Fick's law for the diffusion of vapour in the gas phase and by Darcy's law for water and the gas flows.

Similarly, the mass balance equation for the dry air is

$$\begin{aligned} & n\rho^{ga}\frac{\partial S_w}{\partial t}+\rho^{ga}[1-S_w]div\left(\frac{\partial \mathbf{u}}{\partial t}\right)+[1-S_w]n\left[\frac{\partial \rho^{ga}}{\partial t}+\frac{\partial \rho^{ga}}{\partial p^g}\right] \\ & -div\left(\rho^g\frac{M_aM_w}{M_g^2}\mathbf{D}_g^{ga}grad\left(\frac{p^{ga}}{p^g}\right)\right)-div\left(\rho^{ga}\frac{\mathbf{k}k^{rg}}{\mu^g}\left[grad\left(p^g\right)-\rho^g\mathbf{g}\right]\right) \\ & -\beta_s\rho^{ga}[1-n][1-S_w]\frac{\partial T}{\partial t}=0 \end{aligned} \tag{5}$$

The quantities S_w, S_g, k^{rw} and k^{rg} are defined at the constitutive level, as described in the following Section.

The energy balance equation is

$$\begin{aligned} & \left(\rho C_p\right)_{eff}\frac{\partial T}{\partial t}+\rho^wC_p^w\left[\frac{\mathbf{k}k^{rw}}{\mu^w}\left[-grad\left(p^g\right)+grad\left(p^c\right)+\rho^w\mathbf{g}\right]\right]grad(T) \\ & -div\left(\chi_{eff}\ grad(T)\right)-\rho^gC_p^g\left[\frac{\mathbf{k}k^{rg}}{\mu^g}\left[grad\left(p^g\right)-\rho^g\mathbf{g}\right]\right]grad(T) \\ & -\beta_s\rho^{ga}[1-n][1-S_w]\frac{\partial T}{\partial t}=-\dot{m}_{vap}\Delta H_{vap} \end{aligned} \tag{6}$$

where $\dot{m}_{vap}\Delta H_{vap}$ takes into account the contribution of evaporation and condensation.

4.1. Constitutive equations.

As previously introduced, the gas phase is a mixture of dry air and water vapour, both assuming to behave as ideal gases. According to the equation of the state of perfect gas (the Clapeyron equation) and Dalton's law, the pressure of dry air (*ga*), water vapour (*gw*) and moist air (*g*) are:

$$\begin{gathered} p^{ga}=\rho^{ga}RT/M_a, \qquad p^{gw}=\rho^{gw}RT/M_w, \\ p^g=p^{ga}+p^{gw} \end{gathered} \tag{7}$$

with $\rho^g=\rho^{ga}+\rho^{gw}$.

In the partially saturated zones, the equilibrium water vapour pressure p^{gw} can be obtained using the Kelvin-Laplace equation.

The elasto-plastic behaviour of the solid skeleton is described within the classical elasto-plasticity theory for geometrically linear problems. The yield function restricting the effective stress state is developed in the form of Drucker-Prager for simplicity. To solve the singular behaviour of the Drucker-Prager surface in the zone of the apex, return mapping and the consistent tangent operator is developed using the concept of multisurface plasticity. The return mapping algorithm and the consistent tangent moduli are developed in Sanavia *et al.* [2005] for the isotropic linear hardening/softening and volumetric-deviatoric non-associative plasticity.

4.2. Finite element formulation.

The finite element model is derived by applying the Galerkin procedure for spatial integration and the Generalised Trapezoidal Method for the time integration of the weak form of balance equations [e.g. Lewis and Schrefler, 1998].

In particular, after spatial discretisation within the isoparametric formulation, a non-symmetric, non-linear and coupled system of equation is obtained [Sanavia *et al.*, 2005].

After time integration, the non-linear system of equation is linearised, thus obtaining an equation system that can be solved numerically. Details concerning the matrices and residuum vectors of the linearised equations system can be found in Sanavia *et al*. [2005]. Owing to the strong coupling between the mechanical and pore fluid problem, a monolithic solution is preferred using a Newtonian scheme.

5. Results of numerical analyses.

The S. Felice marsh is a relatively narrow peninsula facing the S. Felice channel. Taking into account its relevant geometrical ratios, the marsh was modelled as a two-dimensional problem (Fig. 5). Assuming the symmetry of the vertical field, the inner boundary condition was characterized by no vertical restraints for the solid skeleton and no horizontal seepage flow across the symmetry axis (i.e. imposed fixed water head). A regular sinusoidal tide, composed of two daily ±42 cm amplitude oscillations, is applied at the channel side, thus reproducing lagoon tide cycles. The bottom of the marsh is impermeable whereas its top has no prescribed boundary values.

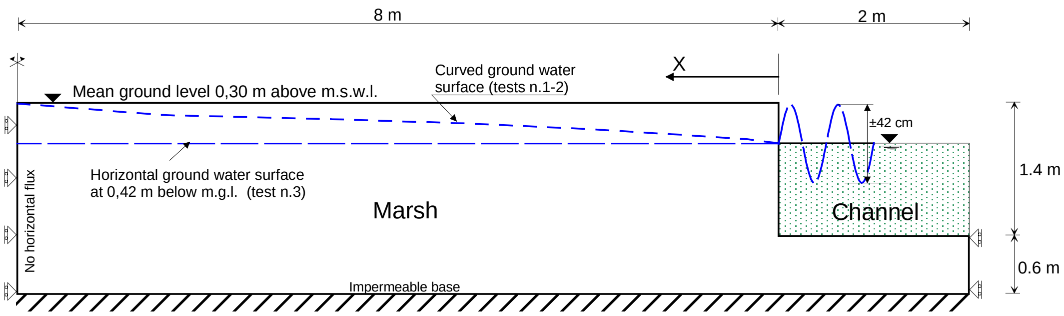

Figure 5 – Geometry reproduced by the numerical model.

The soil is assumed to be homogeneous and isotropic and characterized by the following mechanical properties: self unit weight = 19 kN/m^3, initial void ratio = 0,80, elastic modulus = 12 MPa, Poisson's ratio = 0,2, cohesion =10 kPa, effective friction angle =22° and dilatancy angle = 5°. These values of the material model parameters have been selected according to the results of mechanical tests carried out on Venice lagoon materials [Cola and Simonini, 2002].

The numerical model requires the initial distribution of the saturation degree S, which is particularly important because, even in the case of full saturation, small variations of saturation degree *S* may lead to important effects on material permeability and pore pressure evolution.

The initial S distribution is obtained by performing a pre-analysis with fixed initial boundary values, leaving the numerical analysis to run until the ground water pressure distribution becomes stable. Pre-analysis was performed by imposing water levels at 0.42 m below m.g.l. in the channel in correspondence to the symmetry axis at marsh surface: this may be justified by the outer marsh border being much more influenced by the tide's natural dewatering compared to the inner part of the marsh. At the end of the pre-analysis, S in the vadose zone resulted close to the unity (S=0.95÷0.98).

Assuming pre-analysis results as initial boundary conditions, two numerical analyses (referred here as test n.1 and n.2) were then performed, using two limit values of soil isotropic permeability, namely k = 10^{-6} and k = 10^{-8} m/s, which represent the highest and lowest in-situ values respectively [Simonini and Cola, 2002].

Figures 5a,b sketch the piezometric height evolution at five points located at an increasing distance from the marsh outer border (x = 0.2, 0.6, 1.0, 3.0 and 6.0 m) and at a depth of 0.42 m below m.g.l.

Some interesting observations can be drawn from these results:

- With lower permeability k =10^{-8} m/s (test n.2), only the soil closer to the channel experiences significant pore pressure oscillation and damping, the free water surface being totally stable at 1 m away from the outer boundary.
- With higher permeability k =10^{-6} m/s (test n. 1), the effect of tide excursion is still appreciable at a distance of x = 3 m from the channel (the damping is less than in the previous case) but vanishes completely at x = 6 m. This trend fits better the in-situ observations, suggesting that, even without any k >10^{-6} m/s being determined, the presence of some more permeable sandy laminations may effect an increase of seepage flow in horizontal direction.
- The damping effect on pore pressure response is much more pronounced in descending half cycle with respect to the ascending one: this non-symmetrical response, not usually modelled in transient seepage analyses in uncompressible porous medium, may be due to the influence of coupled actions of medium compressibility and seepage forces.
- Due to partial saturation, the soil is less permeable during the dewatering phase: as a consequence of this, the delay between minimum levels in the channel and minimum pore pressure in the soil is larger than the delay between peak values, even in analyses with higher permeability.

In order to verify the validity of assumed initial saturation conditions, an additional analysis (test n. 3) was performed assuming k = 10^{-6} m/s and the initial stable horizontal ground water surface, located at a depth of 0.42 m below m.g.l.

Fig. 6 compares the results of test n. 1 and n. 3. The influence of initial saturation on pore pressure evolution is clearly evident especially in the inner zone. In both cases, at the end of the daily cycle, the pore pressure does not reply the initial distribution: the tide-induced pore pressure decreases in tests n.1, while it increases in test n.3. This highlights the importance in selecting initial water pressure conditions and suggests that, to obtain a more proper response, the analysis should to reproduce several tide cycles, until pore pressure oscillations in the marsh become stable.

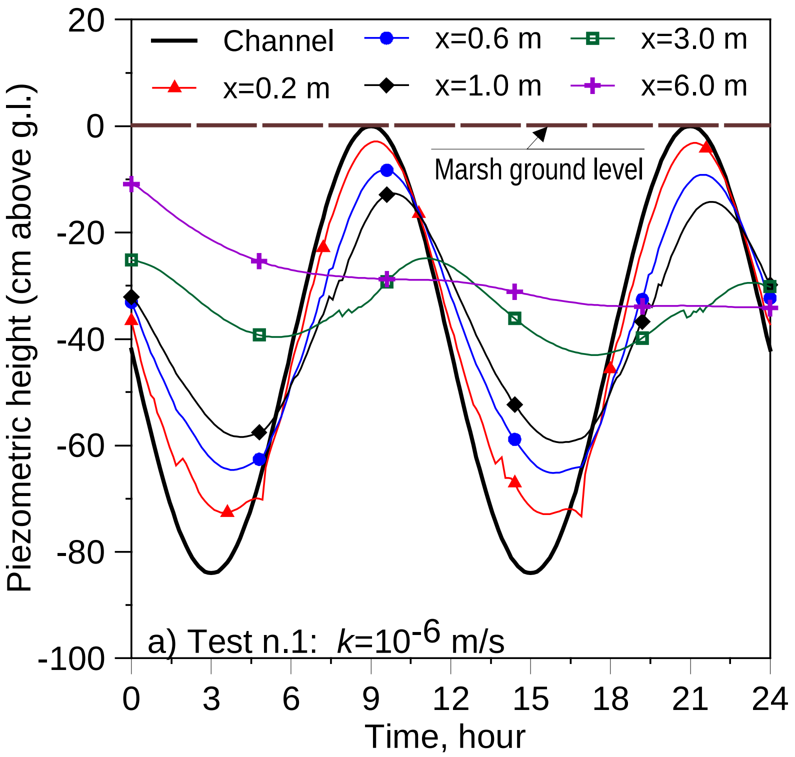

Fig. 5a – Piezometric height in channel and in the ground as predicted in test n.1.

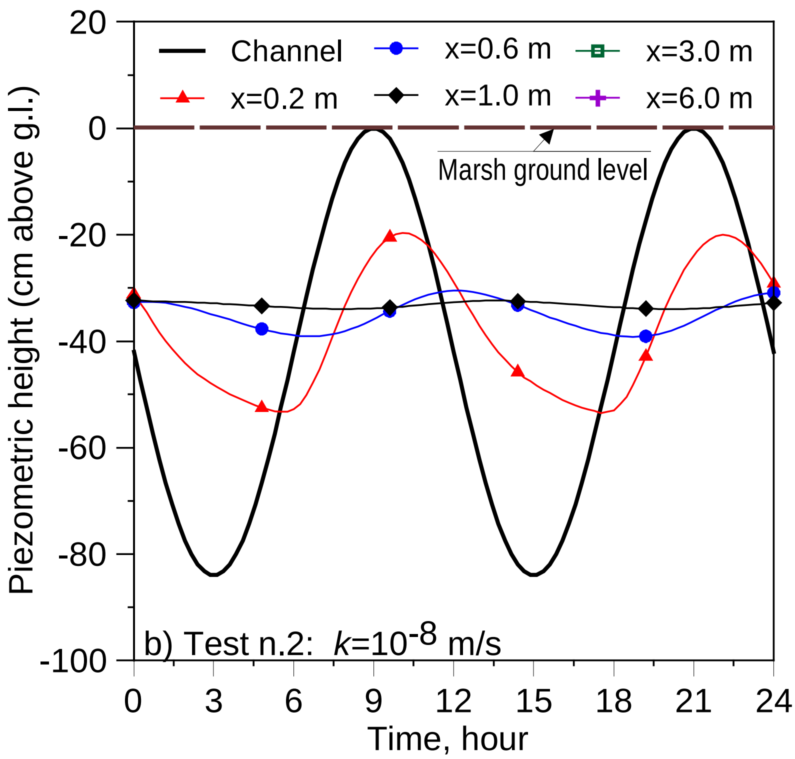

Fig. 5b – Piezometric height in channel and in the ground as predicted in test n. 2.

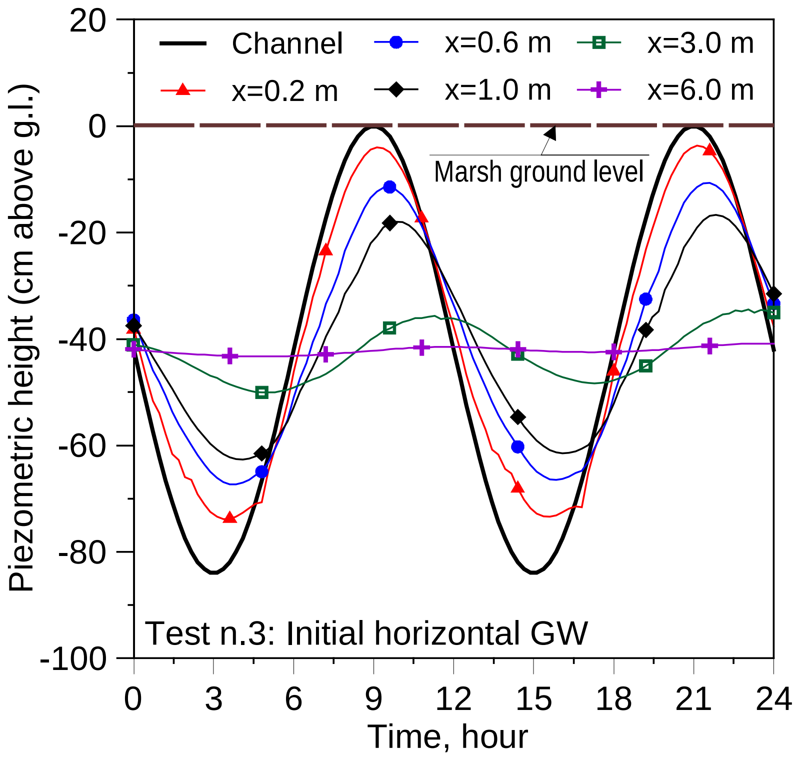

Fig. 6 – Predicted piezometric height in test n. 2 assuming initial horizontal ground water level.

Conclusions.

A complex boundary value problem has been studied by using a multi-phase coupled finite element approach, with the constitutive parameters of the soil material model selected on the basis of careful site and laboratory investigation.

From preliminary analyses carried out so far, the great difficulty in modelling such an extremely complex time-dependent pore pressure response was immediately evident, conditioned by many particular factors, among others the type of channel water oscillation amplitude, very low effective stresses, extremely small hydraulic gradients and partial soil saturation. Nevertheless, the numerical approach adopted here seemed capable of describing most of the relevant features of the problem, thus showing the great importance of coupling the seepage effect with soil skeleton deformability to explain the pore pressure evolution induced by lagoon tide cycles. The influence of initial boundary conditions on steady state response was also considered.

Future research will investigate in more details the observed behaviour, examining also the relevant effect of the permeability anisotropy, which plays a relevant role in this particular seepage problem.

References.

Cola S. and Simonini P., 2002. Mechanical behaviour of Venice lagoon silts as a function of their grading characteristics. *Canadian Geotechnical Journal*, Vol.39, pp. 879-893

Simonini P. and Cola S., 2002. Some pore pressure measurements at the marsh S. Felice in the Venice lagoon. In "*Scientific Research and Safeguarding of Venice. CORILA Research Program, 2001 results*". Istituto Veneto di Scienze, Lettere ed Arti, CORILA, Venezia

Lewis R.W and Schrefler B.A., 1998. The Finite Element Method in the Static and Dynamic Deformation and Consolidation of Porous Media, John Wiley

Sanavia L., Pesavento F., Schrefler B.A., 2005. Finite element analysis of non-isothermal multiphase geomaterials with application to strain localisation simulation, *Computational Mechanics*. Accepted for publication

HYDRODYNAMICS AND MORPHOLOGY CORILA 3.2

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Sommario.

Il progetto CORILA 3.2 si è occupato dei processi idrodinamici e morfologici che interessano la laguna di Venezia. Questo articolo presenta i temi principali della ricerca e tenta di dare una risposta ad alcune questioni che sorgono quando si studia la laguna di Venezia.

Sono state condotte delle indagini sul ruolo che gioca l’idrodinamica sulle variazioni geo-morfologiche, sulla batimetria, sull’erosione e su trasporto e deposizione di sedimento. Sono stati utilizzati i Foraminiferi come indicatori dei cambiamenti ambientali passati e presenti e sono state utilizzate delle tecniche di telerilevamento per studiare il fenomeno della subsidenza nella laguna di Venezia.

Sono state effettuate delle campagne di misura per studiare l’origine della sabbia in laguna. I risultati sono stati poi riprodotti con l’utilizzo di modelli. È stato adattato un modello idrodinamico per lo studio del trasporto di sedimento, ed è stato applicato ampiamente alla bocca di porto del Lido e al canale di Trerporti.

Abstract.

The CORILA project 3.2 has been dealing with the hydrodynamic and morphological processes ongoing in the Venice lagoon. This article presents the highlights of this research and tries to answer some questions that arise when studying the Venice Lagoon.

Investigations have been carried out on the role of hydrodynamics on geo-morphologic variations, bathymetry, erosion, transport and deposition of sediments. Foraminifera have been used as indicators of past and present environmental changes

and remote sensing techniques have been used to investigate the subsidence in the Venice lagoon.

Field campaigns have been carried out to study the origin of the sand in the lagoon. The findings have then been reproduced with modeling techniques. A hydrodynamic model of the lagoon has been adapted to be used for sediment transport studies, and has been extensively applied to the Lido inlet and the Treporti channel system.

1. Introduction.

Monitoring and managing a coastal ecosystem with a high anthropic influence, like the Venice lagoon, can only be achieved through a multidisciplinary approach. The CORILA project 3.2 *Hydrodynamics and Morphology* has been devised in order to answer the questions that are concerned with the Morphological transformations and its feedback on the Hydrodynamics.. It did this by collecting data and information and developing models and methodology that, hopefully, will also help to set up a management plan for the Venice Lagoon.

The main objectives of this project were:

- to build a state of the art data base of the Venice Lagoon that concerns the geo-morphologic and hydrodynamic characteristics, and of the processes that led to erosion and deposition in the past (time scale of centuries, datation of sediments), the recent past (time scale 10 years, comparison of maps) and the present (time scale 1 year, photo mapping of the lagoon);
- to develop a coupled mathematical model that is capable of describing the changes in the short and medium term and that accounts for the hydrodynamics, transport of sediments and re-suspension due to the wind and wave action on the lagoon.

These objectives have been achieved through:

- the evaluation of short- and medium-term evolutive trends concerning the processes of erosion and sedimentation, both natural and caused by human action;
- the estimate of fluxes of suspended sediments along the major channels;
- the evaluation of the impact of climate changes on the paleodepositional environments in order to obtain input data for the forecasting models;
- the investigation of the role of the hydrodynamics on geo-morphologic variations, bathymetry, erosion, transport and deposition of sediments;
- the increase in forecasting capabilities for the models dealing with hydrodynamics and transport and with the management of coastal ecosystems by collecting new data of physical, chemical, sedimentological and geo-morphological type;
- the indication of tools and methodologies suitable for an efficient management of the Venice Lagoon;
- the implementation and validation of a mathematical model that takes into account the action of tide, wind and waves on the morphological evolution;
- application of the model to different scenarios of the past and the future.

In the following an overwiev of the achievements is given and the results are presented. For more detail the bibliography section should be consulted.

2. Geomorphologic processes and sedimentological characterization of the Venice Lagoon bottom sediments.

2.1. Geomorphologic processes.

Physical and geomorphologic variations that occurred naturally in the lagoon of Venice since its formation have been recognized in the sedimentary layers underlying the Venetian basin.

It is however in recent times that the complex morphology and hydrodynamic of the lagoon have undergone extensive and increasing changes caused by natural processes and by the direct or indirect impact of man activities. The comparison of topographic and bathymetric maps dated 1931, of recent aerial photographs and of all available information on morphology and bathymetry of the lagoon [Bonardi, 1998] has allowed the identification and definition of morphological boundary variations, on a decadal scale, of salt marshes and soft inaccessible mud flats.

A detailed study of the BV (*Barena Vecchia*), BN (*Barena Nuova*) and BNW (*Barena North West*) of the Scanello area, chosen as a representative site of the geomorphologic changes and hydrodynamic processes presently affecting the Venice Lagoon, was carried out in order to better understand the erosion-transportation-sedimentation processes and the hydrodynamics interaction. The study that included detailed topographic and bathymetric surveys has indicated that the medium and short term erosion and deposition trends of the salt marshes under investigations seem to be strongly connected to local hydrodynamics.

Comparing historical topographic maps from 1931 to 1986 and air photos taken in 1961, 1968, 1987 and 1996, it has been possible to evaluate the spatial variations of the salt marshes. In a time span of about 70 years a maximum withdrawing of 58m of the edge lining the Burano Channel of *Barena Vecchia* was observed (Fig. 1), whereas a maximum accretion of 80m of the mud flat facing the north-eastern edge of *Barena Nuova* was calculated.

Furthermore, a series of GPS (Global Positioning System) surveys, conducted for 18 months between 1996 and 1997 and referred to the air photos taken in 1987, has led to the annual quantification of erosional processes (4m/year) occurring along the edges of *Barena Vecchia* and of the area extension of the salt marsh-mud flat limit at *Barena Nuova*. On the basis of textural and mineralogical analyses performed on the sediments from some cores taken in the Scanello area [Bonardi, 1998] we can suppose that the clayey silts eroded at the edge of *Barena Vecchia* settle down at the mud flat facing *Barena Nuova* concurring to expand its surface area.

Recently, in the framework of the morphological recovery activities of salt marshes performed by the Italian Ministry of Public Works, Water Authority of Venice by way of its concessionary Consorzio Venezia Nuova, the edges of the *Barena Vecchia* salt marsh have been marked out with containing piling. During a topographic survey performed in 2000 the reconstructed edges of *Barena Vecchia* were mapped; the restored south-western limits of the salt marsh actually lie approximately along the ones surveyed in 1996. The topographic survey was extended also to *Barena North West*, in order to find out if these restoration activities could interfere with the natural morphological trends of the adjacent mud flats and salt marshes.

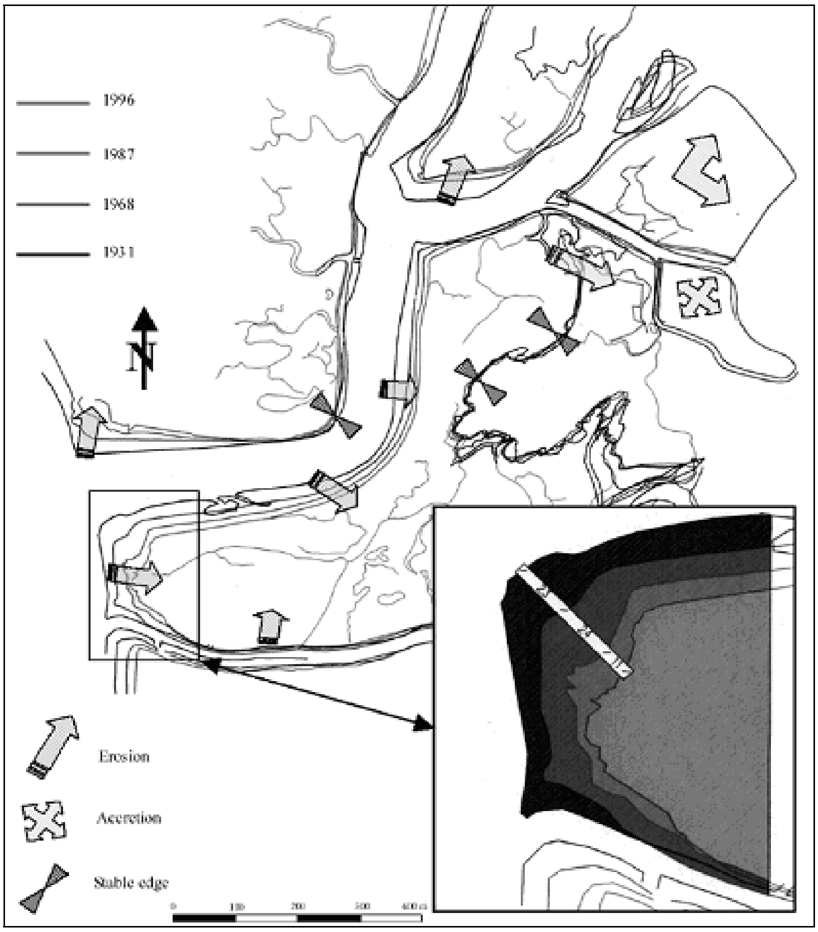

Fig. 1 – Comparison of *Barena Vecchia* (BV), *Barena Nuova* (BN) and *Barena North West* (BNW) edges between 1931 and 1996.

In 2002, a new series of GPS measures was so performed only at *Barena Nuova* and *Barena North West* (Fig. 2). *Barena Nuova* shows a general surface reduction even though it is very limited and meanly quantified in 0.50 m in the two years considered time span. A maximum shifting back of about 2m was observed at the south-western corner and in correspondence of the main tidal creeks. Nevertheless, it is important to note that between 2000 and 2002 at the salt marsh edge retreat there was a contemporaneous increase in its altitude, which varies between a minimum of about 2mm to a maximum of about 2cm, and deepening of the tidal creeks. *Barena North West* also suffers a general surface reduction, but it is greater than the one observed at *Barena Nuova*. In fact it retreated about 3.75m at its south-western corner and more than 7m along Scanello Channel (Fig. 2); however, a slight accretion of about 1m was observed along the north-western edge facing Scanello Channel. Even though altitude measures were not performed in 2000, it appears that a tidal creeks deepening is actually taking place on the edge facing *Barena Nuova* of this salt marsh.

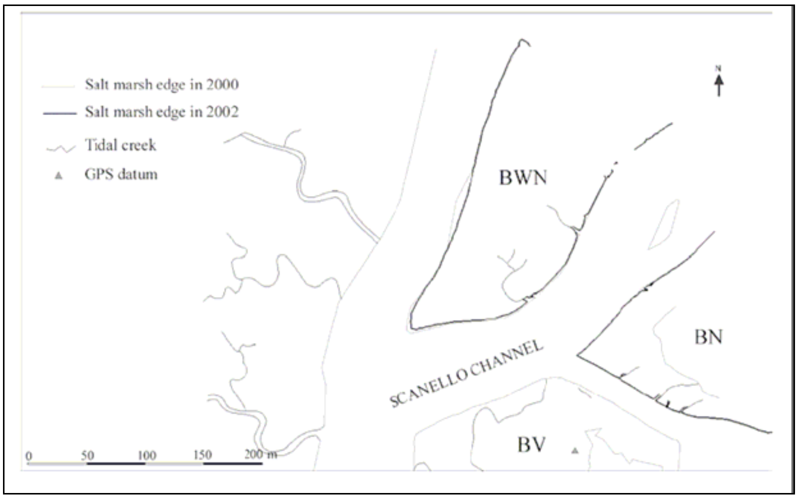

Fig. 2 – Comparison of *Barena Nuova* (BN) and *Barena North West* edges between 2000 and 2002.

2.2. Sedimentological characterization of the surficial sediment.

The geomorphologic study was later complemented with a comprehensive grain size, mineralogical and geochemical investigation of the bottom sediments of the Venetian basin .The characterization of the sediments is an important tool for the evaluation of the hydrodynamic processes. Hence, while the mineralogical composition of the bottom sediments is related to the ancient fluvial supply to the lagoon, which was different in the north and south lagoon areas; anomalous percentages of the mineral content may be considered a consequence of the hydrodynamic reworking processes. Textural characteristics also give important information about processes responsible for sediment erosion, transport and deposition. The study has provided an updated overview of the spatial textural, mineralogical and geochemical variations of the top lagoon sediments. It is based on more than one hundred analyzed samples taken in selected sites, which represent the various morphologies and hydrodynamic conditions of the lagoon system.

As already observed in many previous studies, our investigation indicates an overall similar mineralogical composition with distinct percentage changes from the northern sector of the lagoon, where carbonate-rich sediments prevail (Fig. 3), to the southern silicate-rich sector. This distribution mainly corresponds to the ancient fluvial input of the Piave and the Brenta-Bacchiglione river systems, from the north and the south respectively.

In particular, carbonate content shows dominant dolomite and subordinate calcite, whereas within silicates (quartz, k-feldspar and plagioclase) quartz is dominant. Clayey minerals (mica, chlorite, kaolinite, illite, hastingsite) show higher contents within the Brenta river deposits and in low energy areas, particularly landwards.

Geochemical analysis by ICP-MS (Induced Coupled Plasma Mass Spectrometry) on more than one hundred samples collected in proximity of the sites of the 1983 extensive sampling reported by Albani *et al.* [1995; 1998] and Albani and Serandrei Barbero [2001] was carried out for comparison in order to have some indication of possible heavy metal content variation during the past 20 years.

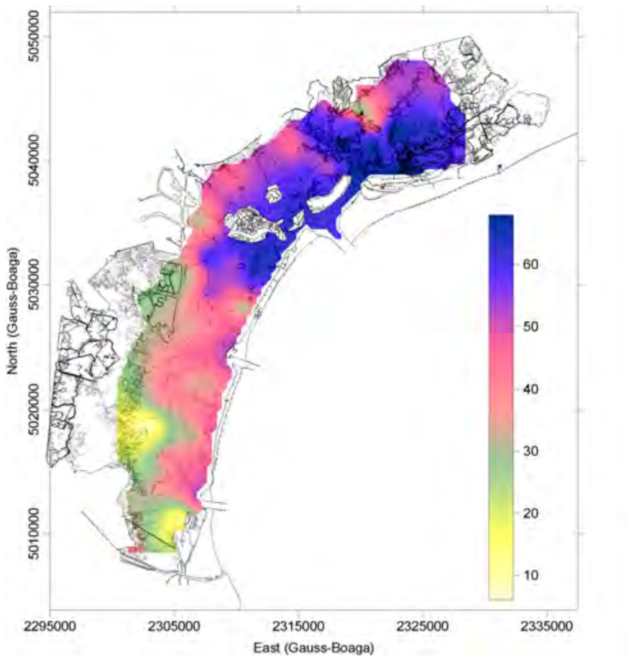

Fig. 3 – Spatial distribution of total carbonates (dolomite+calcite+ankerite+aragonite).

The geochemical data were elaborated [Bonardi and Bonsembiate, 2004] according to the method suggested by Albani *et al.* [1995] The analyzed elements have therefore been divided into two groups: 1) *natural elements* such as Si, Ti, Al, Fe, Mg, Ca, Na, K, Ni, Zr, and Ba of fluvial and coastal origin and *elements of anthropogenic origin* such as Cr, Cu, Zn, As and PB, the concentration of which could be linked mainly to industrial activities in the area of Marghera and Chioggia and to other past and present activities such as hospitals and glass industries (Sr, Y) in the area of Murano.

The analytical data obtained allowed the reconstruction of areal distribution of the heavy metals and gave an indication of restricted areas with abnormal concentration of heavy metals. The locations of these restricted areas and the fine texture of the sediments (clayey-silt and silty-clay) suggest an anthropogenic origin rather than due to transport, areas of provenance or local hydrodynamics. In fact it is the low hydrodynamic characteristic of these restricted areas that allows the concentration rather than the dilution with time of the heavy metals. The only exception to the above consideration is the Industrial Area of Porto Marghera where the concentration of heavy metals is spread over a large area, as indication of the intense environment use of the area during the past decades.

3. Foraminifera as indicators of past and present environmental changes.

Benthic foraminifera (Kingdom Protoctista, Phylum Granuloreticulosa, Class Foraminifera) have been often used to assess the level of environmental stress and pollution in coastal zones. They offer an effective and integrated view of the prevailing environmental conditions. For this purpose the total assemblage is considered, both biocenosis and tanatocenosis, as only the totality of the species present reflect the physical-chemical parameters prevailing, and is capable to recognize subtle but permanent changes in the environmental condition [Albani, 1993; Alve, 1995].

This methodology is of great value in a coastal setting such as the Lagoon where the level and direction of environmental stress can be determined and evaluated.

A complex sampling (733 samples, open dots in Fig. 4) of the Lagoon and the Gulf of Venice during the '80s has provided a baseline study of the distribution of benthic foraminifera (biotopes) [Albani *et al.*, 1984; 1991; 1998; Serandrei Barbero *et al.*, 1989; 1999], recent sediments and their geochemical characteristics [Albani *et al.*, 1995]. In particular foraminiferal biotopes identify, on the basis of the faunal similarities, the areas characterized by similar environmental conditions.

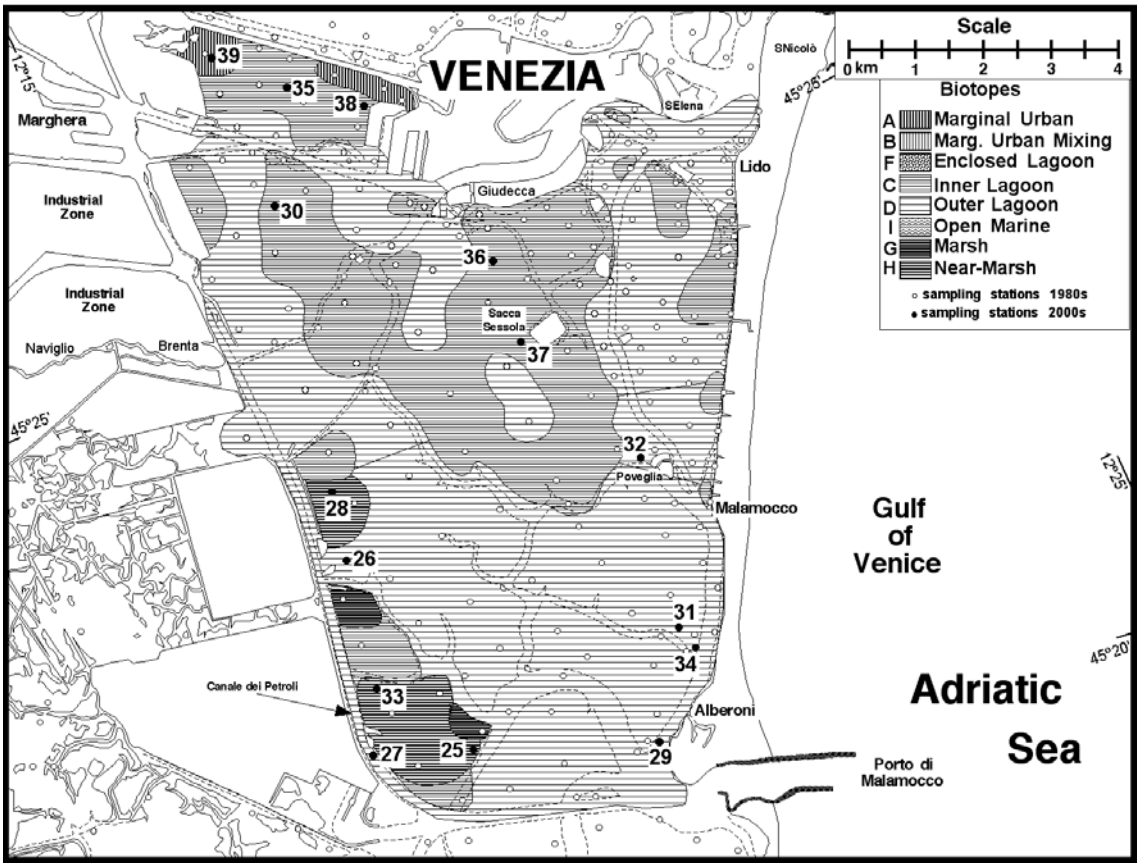

Fig. 4 – Central sector of the Lagoon of Venice with the 1983 biotopes distributions and the locations of the 2001 samples (solid dots).

The distribution of benthic foraminifera is mainly affected by the residence time of the water masses [Guelorget and Parthuisot, 1983]; some taxa reflect a relationship with the water level [Albani *et al.*, 1984; Hayward and Hollis, 1994; Petrucci *et al.*, 1983; Scott and Medioli, 1980] others the presence of fresh water [Donnici and Serandrei Barbero, 2005]. Changes in the level of abundance reflect the morphological evolution of the lagoon, as clearly shown by the study of palaeoenvironments [McClennen *at al.*, 1997; Reinhard *et al.*, 1994; Serandrei Barbero *et al.*, 1997; 2004].

During 2001 a set of 52 sampling sites, selected within the already identified biotopes (Fig. 4), have been analyzed using the same methodology adopted in the 1983 survey; the new quantitative data set was based on at least 300 individuals [Buzas, 1990; Serandrei Barbero *et al.*, 1997] of the fraction >0.125 mm. The 2001 numerical data set was added to the data from the 1983 study and the combined set was analyzed using cluster analysis (Pearson coefficient); this phase of the analytical process allowed the establishment of the level of similarity within the existing biotopes and establish the cluster links.

In addition, to assess the degree of environmental change, the quantitative data have been used for a comparative study between the 2001 and the nearby 1983 samples using the Kolmogorov-Smirnov statistical test, [Sneath and Sokal, 1981]. This non-parametric test compares the cumulative frequency values of two samples and records the value of the level of difference; the smaller the value the smaller is the difference and thus greater is the similarity of the two samples. The combination of the Kolmogorov-Smirnov test, which determines the level of similarity between each pair [Albani *et al.*, 1998], and the cluster links determines not only the degree, but also the direction of the change, if any.

The comparative study between the faunal distributions of the base-line 1983 and the 2001 samples, using the cluster analysis and the Kolmogorov-Smirnov indices, shows areas of environmental stability, although with a slight decrease of the residence times. These are linked to the maintenance dredging of the channel in response to the navigational needs. The purification plant, operating since 1986, has improved the conditions in areas where industrial and urban stress predominated, shown by the decrease of faunas tolerant of such conditions, whereas no improvement is recorded in areas with local pollution sources such as at Tronchetto and off the island of S. Michele (stns 6 and 38). In addition, new areas with high environmental stress are noted in the northern sector of the Lagoon. Along the Canale dei Petroli the collapse of some intertidal morphologies (Fig. 5) appears to be related to the local predominance of more marine conditions.

But the biological description of an environment also consents the interpretation and the measurement of its physical aspects. The quantitative analysis of benthic communities in sedimentary sequences, revealing the presence of *ecological transitions*, shows environmental changes occurred and provides the conventional radiocarbon ages BP through the ^{14}C analyses on shells buried in the sediment during deposition.

Recent researches have shown the variability of lagoon conditions, testimonied by the channel migration, made evident by the ancient buried channel beds [McClennen *et al.*, 1997], the presence of the shoreline in areas lying inside the lagoon [Serandrei Barbero *et al.*, 2001] and evidence of ancient marsh, sometimes with human remains, today buried [Serandrei Barbero *et al.*, 1997; 2004]. Temporal and spatial variability in environmental conditions leads to a wide range in sediment accumulation rates, the importance of which is vital for today's lagoon morphologies to survive.

Within the different sediment areas identified with foraminiferal biotopes were therefore drilled 26 sediment cores about 1 m deep to verify the persistence of biotopes present in the current lagoon system. Rich organogenic deposits, on which 57 radiocarbon datings were performed, allowed verifying previous biofacies and their age, obtaining mean sediment accumulation rate, in the presence of constant biofacies, or the age of the event that changed the deposition environment, in the presence of surface erosion or of evident discontinuities in the sediment sequence. Sediment accumulation rates are considered constant in the sedimentary sequence in which *ecological transitions* are not present.

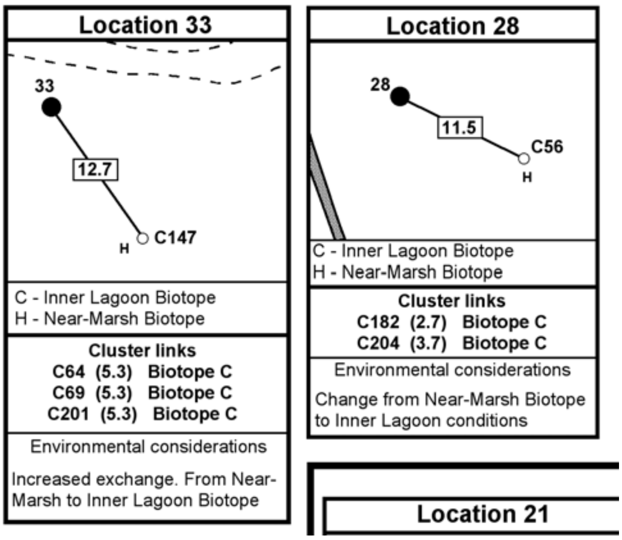

Fig. 5 – Relationships between the 2001 faunas (solid dots) and the 1983 faunas (open dots) for the changed morphologies. The Kolmogorov-Smirnov indices are also shown (smaller the value, smaller the difference or higher the similarity). The cluster links are derived from the combined cluster analysis of the total fauna.

A sediment accumulation rate of 0.5 mm/year was obtained from the 57 radiocarbon datings obtained from organogenic materials in the lagoon sedimentary sequence. Different results are obtained considering two different periods:

- between about 2500 and 1500 years BP the accumulation rate is 1 mm/year.
- between 1500 years BP and present the accumulation rate is 0.4 mm/year.

Cores taken at the continental margin of the lagoon have often reached the continental environment before the lagoon settling: the lagoon: in these marginal areas the age of marine transgression occurred between 2117 and 1620 years BP.

Cores 2, 8 and 14 give no evidence of *ecological transitions* and sediments have been deposited at a constant accumulation rate of 0.5 mm/year. *Ecological transitions* present in cores 39 and 53 show the presence of marsh dating back to 1887 and 820 years BP, respectively. The sedimentation rate is equal to 0.8-0.9 mm/year for marsh and much less (0.2-0.3 mm/year) in the following environment of marsh edge or subtidal zone. The *ecological transition* present in core 29 drilled to a 90-cm depth, allowed dating the ancient coastline back to 3180 years BP, which afterwards migrated to its present position.

4. The application of sar interferometry for ground vertical displacement of small islands in the Venice Lagoon.

Repeat-pass spaceborne Synthetic Aperture Radar (SAR) interferometry is a powerful technique for the observation of land surface deformation at mm resolution, as demonstrated in the Venice area by Tosi *et al.* [2002] and Strozzi *et al.* [2001b].

In order to provide land displacement rates in small islands of the Venice Lagoon not covered by traditional surveys (levelling and differential GPS), SAR-based monitoring techniques, i.e. differential SAR interferometry [Strozzi *et al.*, 2001a] and interferometric point target analysis [IPTA, Werner *et al.*, 2003], were performed.

The validation of the SAR interferometric displacement rates performed in the framework of the ISES and VENEZIA Projects [Carbognin and Tosi, 2003; Carbognin *et al.*, 2004] through levelling and differential GPS surveys in areas where data from all techniques are available demonstrated a mm/year accuracy of the vertical displacement rates.

First, a time series of six interferometric radar images of the European Remote Sensing Satellites ERS-1 and ERS-2 from 1993 to 2000 was considered. In order to generate a displacement map with reduced errors, the six INSAR images were combined [Strozzi *et al.*, 2001b]. The INSAR map shows information over the major urban areas, with a few scattered points in other regions.

Then, IPTA has been applied with 59 ERS-1/2 SAR images between 1992 and 2000. Point targets with valuable information are scattered over villages, suburban areas, and isolated structures. Deformation time series, as indicated for two points in Fig. 6, are available from IPTA.

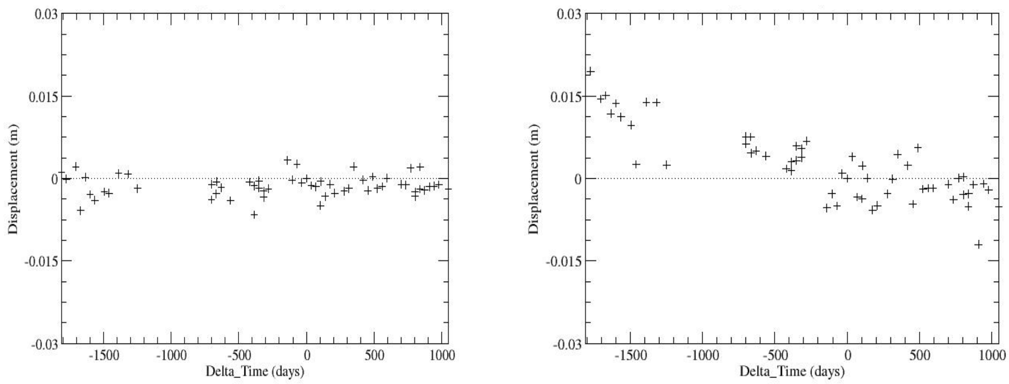

Fig. 6 – Deformation time series from IPTA for two points target located in Murano Island for the time period from 1992 to 2000.

This analysis of ground vertical displacement with SAR interferometry demonstrated a general land stability of Murano Island, with maximum sinking rates of less than 2 mm per year.

In conclusion, the application of SAR-based monitoring techniques appears an important tool capable of providing data for the morphodynamics study of the lagoon setting.

5. The origin of the sand – Field work.

This study comprised a coupled programme of numerical modelling, laboratory experimentation, and field surveying in order simulate the factors leading to the evolution of muddy tidal flats in northern Venice Lagoon for purposes of prediction and management. This study has resulted in 7 scientific publications, 3 Ph.D theses (two completed; one in progress), 1 M.Sc. thesis (completed), 1 Tesi di Laurea (completed), and 4 B.Sc. theses (completed). The most important aspects of the study are the predictive calibrated sediment transport model of Venice Lagoon (SEDTRANS05), the discovery that sand is a vital component to the protection and development of salt marshes in Venice Lagoon as it forms the foundation on which marshes grow, and also provides protection from wave erosion at the margins.

We have collected over 512 line km of bathymetric data and digital sidescan, 258 bottom sediment samples, 6 days of current speed, depth and turbidity data at 6 key sites in the Burano canal system (burst sampled at 4 Hz), 3 days of hourly ADCP profiles (Fig. 7) across Burano, Scanello, Treporti and S. Felice canals from which residual transports of sediment have been estimated, and wave attenuance data across three profiles of submerged beaches. Analyses are still underway and include the updating of the cohesive sub-routine of SEDTRANS05 (and the production of a scientific paper on the model), the application of SEDTRANS05 to the Po delta plume for the 2000 event (and scientific publication), the production of a bathymetric chart based on a compiled data set, the production of a bottom character map based on the sidescan data (and production of review paper) and the application of the O'Brien relationship to the Lido-Treporti-Burano canal system.

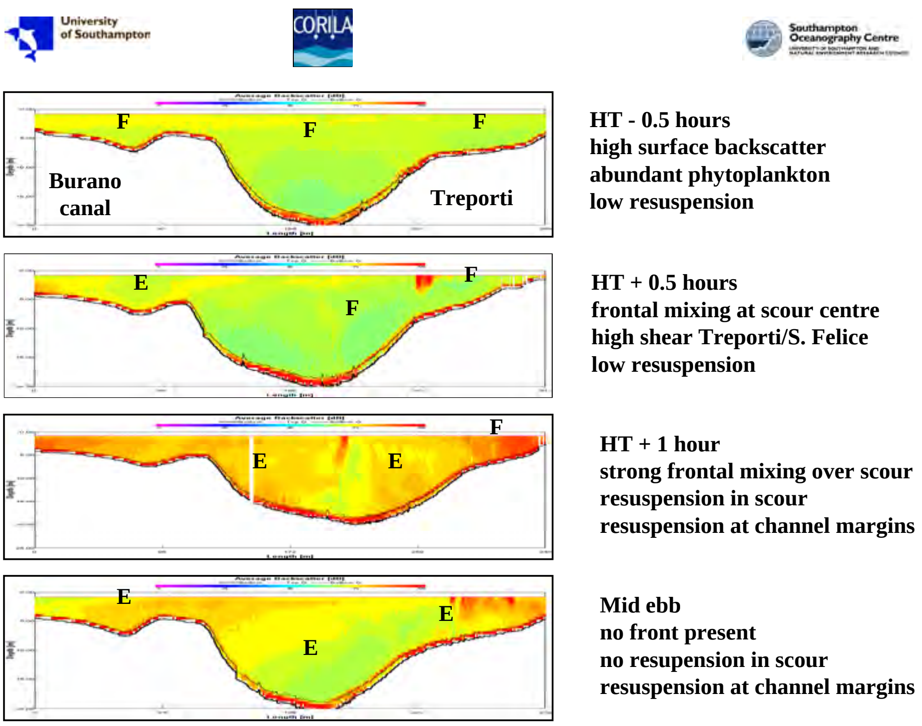

Fig. 7 – ADCP profiles across Treporti canal though the scour hole at the Burano-Treporti-S. Felice triple junction.

Four field surveys were undertaken in this project (two summer and two winter, for a total of about 40 days field surveying) in order to map the Lido-Treporti-Burano canal system and to characterise the dominant morphological features within this system: As well, to provide a data set for numerical model simulation and calibration. SEDTRANS96 has been linked to the hydrodynamic model of Venice Lagoon

[Umgiesser, 2000; Umgiesser *et al.*, 2004] and the sedimentation sub-routines have been advanced on the basis of our field results. The new version, called SEDTRANS05, will be used for both sand and fine-sediment transport in the future. As well, a number of significant discoveries have been made which will help understand the morpho-dynamical evolution of northern Venice Lagoon. These are:

- submerged beaches form a significant part of the margins to the canal system. These beaches attenuate wave motion and thus protect the marshes from erosion. The beaches are composed of fine sand in dynamic equilibrium with the passage of waves, and also host colonies of *Cymadocea* that attenuate wave energy. The origin of the fine sand is unknown, but is thought to come from reworking of the canal bed and perhaps from the Lido entrance;
- active scours occur at the triple junctions of canals and are up to 18 m deep. They form through turbulence induced at the fronts between ebbing water masses and are thus a source of mobile material to the system;
- there is strong headward residual transport of suspended sediment in the study region caused largely by the residual circulation of tidal waters. Such residuals do not favour a loss of material from the lagoon and may, in part, explain the local growth of tidal flats; and
- the grain size trends (fining headwards) and the orientation of megaripples within the Lido entrance favour a movement of sand as bedload into the lagoon. This contrasts with initial model results that indicate a net export of sand from the lagoon.

The overall conclusion of this work is that knowledge of the origins, transport pathways and depo-centres of sand is vital to the understanding of the evolution and well-being of the lagoon.

6. The origin of the sand – Modelling.

In this part of the project the model SEDTRANS96 and the model SHYFEM have been applied to the lagoon of Venice to look for the reasons of erosion and deposition and to study the origin of the sand that can be found in the lagoon.

6.1. Exploring the bottom stress variability in the Venice Lagoon.

The Venice Lagoon is a complex system when speaking in terms of hydrodynamic and bio-chemical processes. Narrow channels determine the tidal propagation and the large tidal flats represent a delicate ecosystem that is susceptible to erosion. Moreover, climatic changes seem to have a high impact on the delicate equilibrium that has been formed in the last centuries. The possible global sea level rise will have a higher impact on the Venice Lagoon and the island of Venice than on any other coastal zone in the Mediterranean.

In order to preserve the delicate lagoon ecosystem a modeling approach that combines hydrodynamics, waves and the sediment dynamics of the Venice Lagoon is highly desirable. This model could be used to estimate the actual loss or gain of sediments from the lagoon to the Adriatic Sea and the importance of the various forcing factors that influence these dynamics.

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As a preliminary step towards this direction, a framework of numerical models has been implemented and applied to the Venice Lagoon. The models consist of a state of the art hydrodynamic model for shallow areas and lagoons and a last generation wave model. With these models the bottom stress distribution during typical strong meteorological situations is studied.

Results show a good agreement of the computed bottom stress patterns and the empirical erosion and deposition rates found in the lagoon. The areas where wave action is responsible for sediment re-suspension are identified; they consist basically in the large shallow areas that are spread out all over the lagoon. This makes the wave action the most important erosion mechanism in the lagoon during typical strong winds.

During a tidal cycle the bottom stress distribution due to currents only appears to be non negligible only during maximum flood or ebb tide. (The following pictures refer to the latter situation). Values appear to be higher in correspondence of deeper channels, those hydrodynamically more active. The situation does not change significantly when the wind forcing is switched on, except that now the values at the inlet is increased and some shallow areas are showing some evidence of increased stress. As an example, we present here results of Scirocco wind forced situation (Fig. 8a) where the bottom stress is computed only from currents.

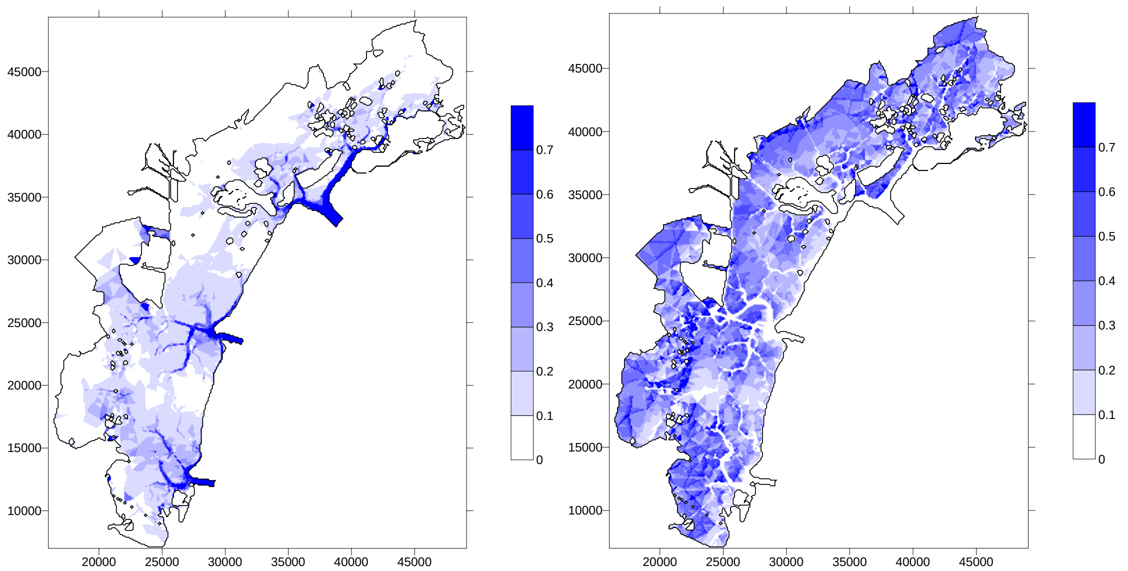

Fig. 8 – Bottom shear stress (N/m^2) induced by currents only (top panel, a) and waves only (bottom panel, b) and during a Scirocco event.

Fig. 8b presents the bottom stress taking into account only the wave contribution. The scale presents a maximum value of 0.7 N/m^2 as this value is considered to be the threshold above which cohesive sediments may be mobilized in the Venice Lagoon [Amos *et al.*, 2004].

Comparing the two figures, the bottom stress induced only by currents is maximum along the deepest channels, i.e., where the hydrodynamics is more active. In the case where only waves have been taken into account, the channels show very low values, reflecting the fact that in deep regions wave effects are negligible. On the other hand, the shallower parts exhibit values higher than 0.7 N/m^2. Therefore, generally speaking, the two pictures are in a way complementary: where wave effects are higher, current effects are weaker.

Three scenarios of future climatic changes are simulated: an increase in the amplitude of the tidal oscillation, a global sea level rise and the combination of both. The results show that the most vulnerable parts of the lagoon are the flat regions close to the deeper channels. The erosion of these channel borders could be the cause of the filling of the deeper channels that then would need artificial dredging.

6.2. Modeling sand transport in the Venice Lagoon inlets.

The lagoons developing along the coast of sedimentary zones are in an unstable situations. If not destroyed by the sea, they tend to be filled up by the sediment flow from the sea or from the rivers ending into the lagoon. Geomorphological variations have been naturally occurring in the Venice Lagoon since its formation. In the past the large sediment discharge from the main lagoon tributaries threatened to transform the lagoon into a marshland. Then the increase in the lagoon depth, due to subsidence and eustatic water level rise, and in recent times the impact of anthropic activities have reversed the lagoon's natural tendency to silt up transforming it slowly into a more sea-like environment.

To understand the sediment dynamics in the Venice Lagoon it is necessary to analyze the hydrodynamic behavior of the three inlets. The aim of this study was to describe the sediment transport in the Venice Lagoon in order to evaluate the sediment exchanges between the sea and the lagoon through the three inlets of Lido, Malamocco and Chioggia.

Up to now numerical models of sediment transport have not been applied extensively in the Venice Lagoon, therefore a lack of knowledge concerning sediment erosion, resuspension, transport and sedimentation remains. This work represents a first attempt to evaluate the role that the hydrodynamics plays in the sediment processes occurring at the three inlets.

A sediment transport model Sedtrans96 coupled to a hydrodynamic model has been applied to the Venice Lagoon in order to evaluate the sediment exchanges between the sea and the lagoon through the three inlets of Lido, Malamocco and Chioggia. At the three inlets the sediments are mostly non-cohesive and therefore the transport model has been applied uniquely to this sandy sediment type.

To evaluate the influence of the wind (in this case consisting of bora and scirocco) the simulations have been carried out both with the tidal forcing only and with the tide-wind combined action. Two different sets of simulations have been setup. In the first the models have been applied for 12 hours time and the basin was forced with idealized wind and tide values; in the second set the simulations have been extended to one year and carried out with a real time series of in-situ wind and tide elevation measurements.

The sediment suspension and transport have been evaluated through two sections per inlet in order to calculate the mass balance and the bottom thickness variation caused by erosion and deposition processes.

From the modeling analysis at the inlets of Malamocco and Chioggia a tendency of erosion has been calculated (Fig. 9) and this situation shows a good agreement with the empirical data collected during the last 20 years. As far as the Lido inlet is concerned, a clear tendency of erosion or deposition is more difficult to see and further work has to be carried out.

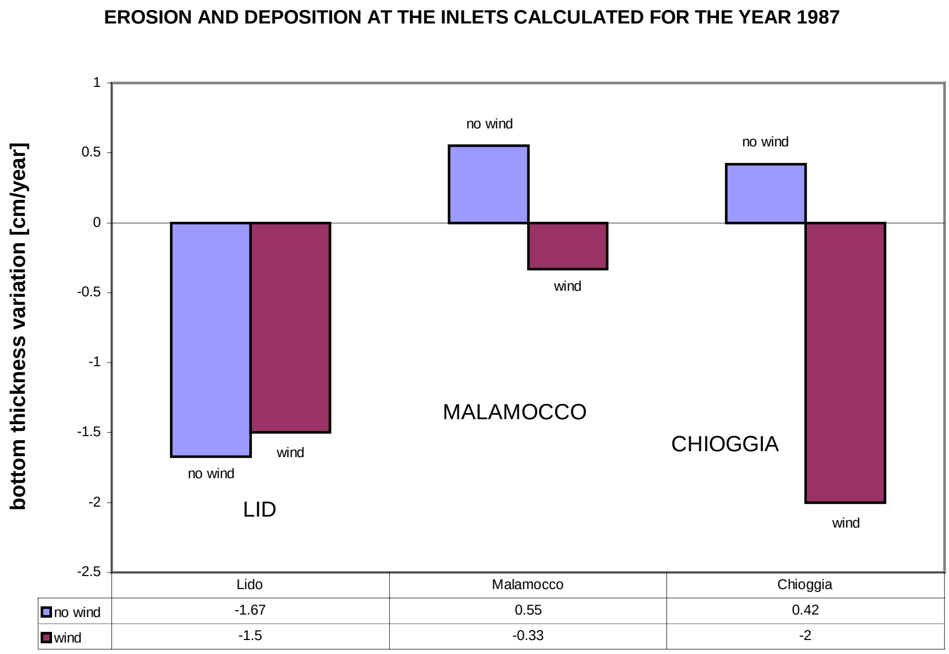

Fig. 9 – Bottom thickness variation rate calculated by the model in the simulations over the whole year 1987 with real forcing data. The positive values represent the deposition and the negative represent the erosion. The rate is in cm/year.

6.3. Modeling sand transport in a canal system, northern Venice lagoon.

The dominant factor governing the long-term evolution of a coastal lagoonal system is the stability and evolution of its barrier island system which is controlled by the availability and supply of sand. The fact that Venice is located within a lagoon immediately illustrates the dominating role of sand in the evolution of this coastal setting. The string of barrier islands and beaches fronting Venice Lagoon attest to the supply and longshore transport of sand from fluvial point sources in the NE, as well as artificial replenishment. Indeed much of the shelf off Venice is composed of sand (sculpted into megaripples) indicative of high-energy events in the past high in sand content.

Submerged beaches form a significant part of the margins to the canal system. These beaches attenuate wave motion and thus protect the marshes from erosion. The beaches are composed of fine sand in dynamic equilibrium with the passage of waves, and also host colonies of *Cymadocea* that attenuate wave energy. The origin of the fine sand is unknown, but is thought to come from reworking of the canal bed and perhaps from the Lido entrance.

However, the origin of the sands close to the inlets is still unclear: are they from ancient deposits cropping out in the lagoon and continuously reworked by the tidal action or are they transported into the lagoon from the Adriatic Sea through the inlets.

The origin of the sands in the Venice lagoon has therefore been the subject of extensive field surveying in parallel with numerical modeling. Three transects along Treporti and Burano canals were conducted from which 33 bottom sediment samples were collected. These samples were analysed for grain size and sorting to examine any trends in the granulometry of these sediments that might shed light on transport paths (Fig. 10).

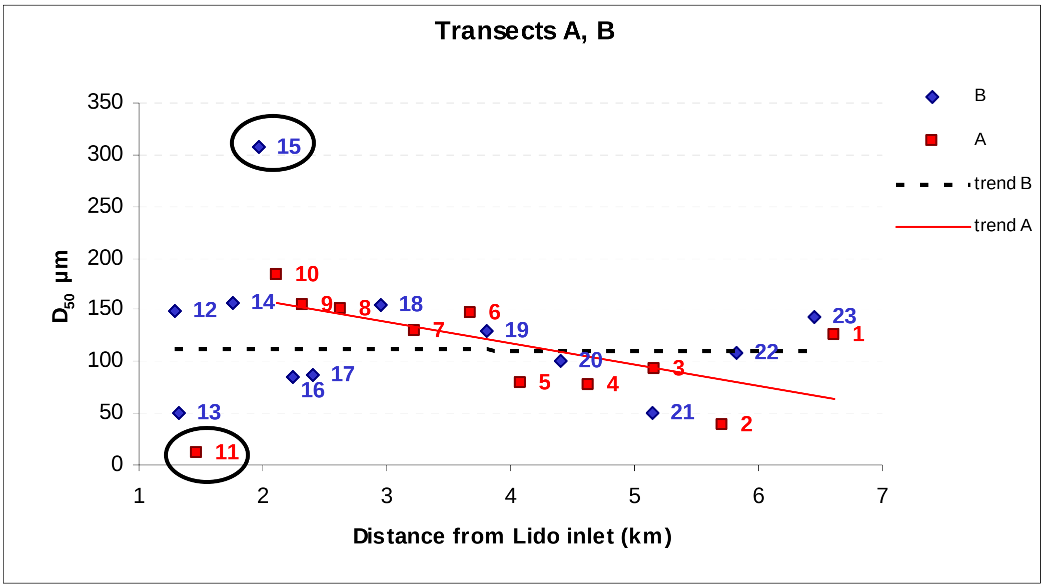

Fig. 10 – Grain size distribution in transect A and B. Two outliers have been eliminated (samples 11 from A and 15 from B).

The modeling study consists of two parts: the sediment transport model SEDTRANS96 was used with a finite–element, hydrodynamic model (SHYFEM) to simulate sand transport in Treporti canal. A type of linked box model was created by combining elements of the main model and subsequently computing water and sediment fluxes for the so-created boxes. Several grain size classes were simulated; the distribution before and after the simulation were examined. A variety of wind regimes were used to force the tidal flows, as well as a full year of measured tidal and wind data. Only a part of the Venice lagoon was covered by the simulation: a major channel running from the Lido inlet north towards the northern lagoon.

The total transport through all of the sections was computed for 1987 (a normal year in Venice lagoon). Sediment mass balance was determined and the resulting trends of erosion and deposition were computed. There were no trends in the median grain diameter and sorting of bottom samples from Treporti canal; all sands were fine (120 microns, one outlier of 300 micron was removed).

The absence of a trend in grain size suggests that there is no significant import of sand to the lagoon through the Lido inlet. The results from the simulations seem therefore to confirm the hypothesis of reworking of sand within the lagoon. The computed erosion is some cm/year diagnostic of channel scouring and enlargement with time. The Treporti canal is subject to strong current velocities of around 1 m/s which hold fine sand in suspension and thus prevent sedimentation.

Conclusions.

The CORILA project 3.2 on Hydrodynamics and Morphology has collected valuable data needed for an insight into the transformations ongoing in the Venice Lagoon. The project was an interdisiplinary approach: geomorphological methods have been used to characterize the sediment characteristics of the lagoon, and Foraminifera have been used as indicators of past and present environmental changes. Remote sensing has been used to investigate the subsidence in the Venice lagoon.

Field campaigns have been carried out to study the origin of the sand in the lagoon. The findings have then been reproduced with modeling techniques. A hydrodynamic model of the lagoon has been adapted to be used for sediment transport studies, and has been extensively applied to the Lido inlet and the Treporti channel system.

Summarizing, the three year project has been a great success, bringing together scientists from different disciplines and working on a common goal: to better understand the morphological and hydrodynamic processes of the Venice Lagoon.

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References.

Albani A.D., 1993. Use of benthonic foraminifera to evaluate the environmental characteristics of Port Hacking; significance for coastal engineering works and pollution. In G. McNally, M. Knight, & R. Smith (Eds.), Collected Case Studies in Engineering Geology, Hydrogeology and Environmental Geology. Geological Society of Australia: Sydney, pp. 134

Albani A.D., Favero V., Serandrei Barbero R., 1984. Benthonic foraminifera as indicators of intertidal environments. *Geo-Marine Letters*, 4, 43-47

Albani A.D., Favero V. and Serandrei Barbero R., 1991. The distribution and ecological significance of recent Foraminifera in the lagoon South of Venice (Italy).*Rev.Esp. Micropaleontologia* 23, 29 - 45

Albani A.D., Rickwood P.C., Favero V. and Serandrei Barbero R., 1995. The geochemistry of recent sediments in the Lagoon of Venice: environmental implications. *Istituto Veneto Scienze, Lettere ed Arti, Atti* 153, 153 - 239

Albani A.D., Favero V. and Serandrei Barbero R., 1998. Distribution of Sediment and Benthic Foraminifera in the Gulf of Venice, Italy. *Estuarine, Coastal and Shelf Science* 46, 251 - 265

Albani A.D. and Serandrei Barbero R., 2001. The distribution of surface sediments in theLagoon of Venice (Italy) in the 1980s. *Atti dell'Istituto Veneto di Scienze, Lettere ed Arti*, 159, 363-378

Alve E., 1995. Benthic foraminiferal responses to estuarine pollution: a review. *Journal of Foraminiferal Research* 25: 190-203

Amos C.L., A. Bergamasco, G. Umgiesser, S. Cappucci, D. Cloutier, L. DeNat, M. Flindt, M. Bonardi and S. Cristante, 2004. *The stability of tidal flats in Venice Lagoon - the results of in situ measurements using two benthic, annular flumes*. Journal of Marine Systems, Vol. 51, 211-241

Bonardi M., 1998. Studio dei processi evolutivi di alcune barene della Laguna di Venezia (Bacino Nord) relazione alle variazioni del livello marino. *Rapporto Finale, Consorzio Venezia Nuova, pp.65*

Bonardi M. and Bonsembiate N., 2004: Caratteristiche geochimiche dei sedimenti superficiali della laguna di Venezia. *CORILA, Progress Report*

Buzas M., 1990. Another look at confidence limits for species proportions. *Journal of Paleontology* 64, 842-843

Carbognin L., Tosi L., 2003. Il progetto ISES per l'analisi dei processi di intrusione salina e subsidenza nei territori meridionali delle province di Padova e Venezia. 96pp, 12 tavv. f.t., Grafiche Erredici, Padova

Carbognin L., Teatini P., Tosi L., 2004. Eustacy and land subsidence in the Venice Lagoon at the beginning of the new millennium. *Journal of Marine Systems*, doi:10.1016/j.jmarsys.2004.05.021, 51(1-4), 345-353

Donnici S., Serandrei Barbero R., 2005. I foraminiferi di ambiente vallivo della Laguna di Venezia. *Lavori Soc. Ven. Scienze Naturali,* in stampa

Guelorget O., Perthuisot J.P., 1983. Le domaine paralique. *Travaux du laboratoire de geologie,* 16. Presses de l'ecole normale superieure, Paris, 136 pp

Hayward B.W., Hollis C.J., 1994. Brackish foraminifera in New Zeeland: a taxonomic and ecologic review. *Micropaleontology* 40 (3): 185-222

McClennen C.E., Ammerman A.J., Shock S.G., 1997. Framework Stratigraphy for the Lagoon of Venice, Italy: Revealed in New Seismic-Reflection Profiles and Cores. *Journal of Coastal Reseasrch* 13, 745-759

Petrucci F., Medioli F.S., Scott D.B., Pianetti. F.A., Cavazzini R., 1983. Evaluation of the usefulness of foraminifera as sea level indicators in the Venice Lagoon (N. Italy). *Acta Naturalia* 19: 63-77

Reinhardt E.G., Patterson R.T., Schröder-Adams C.J., 1994. Geoarchaeology of the ancient harbour site of Caesarea Maritima, Israel: evidence from sedimentology and paleoecology of benthic foraminifera. *Journal of Foraminiferal Research* 24(1): 37-48

Scott D.B., Medioli F.S., 1980. Living vs. total foraminiferal populations: their relative usefulness in paleoecology. *Journal of Paleontology* 54, 814-831

Serandrei-Barbero R., Albani A., Bonardi M., 2004. Ancient and modern salt marshes in the Lagoon of Venice. *Palaeogeography, Palaeoclimatology, Palaeoecology* 202, 229–244

Serandrei Barbero R., Albani A.D. and Favero V., 1989. Distribuzione dei foraminiferi recenti nella laguna a Nord di Venezia. *Boll. Soc. Geol. It.* 108, 279 - 288

Serandrei Barbero R., Albani A., Zecchetto S., 1997. Palaeoenvironmental significance of a benthic foraminiferal fauna from an archaeological excavation in the Lagoon of Venice, Italy. *Palaeogeography, Palaeoclimatology, Palaeoecology,* 136, 41-52.

Serandrei Barbero R., Carbognin L., Taroni G. and Cova E.,1999. Distribution of Recent Benthic Foraminifera in the Southern Basin of the Venice Lagoon (Italy): Statistical Evaluation of Taxa Significance. *Micropaleontology* 45, 1 - 13

Serandrei Barbero R., Lezziero A., Albani A., Zoppi U., 2001. Depositi tardo-pleistocenici ed olocenici nel sottosuolo veneziano: paleoambienti e cronologia. *Il Quaternario,* 14 (1), 9-22

Sneath P.H.A., Sokal R.R., 1981. Numerical taxonomy, W.H. Freeman & Co, San Francisco, p. 573

Strozzi T., Wegmüller U., Tosi L., Bitelli G., Spreckels V., 2001a. Land Subsidence Monitoring with Differential SAR Interferometry. *PE&RS*, 67: 1261-1270

Strozzi T., Tosi L., Wegmüller U., Teatini P., Carbognin L., 2001b. Thematic and land subsidence maps of the Lagoon of Venice from ERS SAR interferometry. CORILA Research Program 2001 Results (ed. by P. Campostrini), IVSLA Venezia, 345-355

Tosi L., Carbognin L., Teatini P., Strozzi T., Wegmüller U., 2002. Evidences of the present relative stability of Venice, Italy, from land, sea and space observations. *Geophysical Research Letters,* 29: 10.1029/2001GL013211

Umgiesser G., Melaku Canu D., Cucco A., Solidoro C., 2004. A finite element model for the Venice Lagoon. Development, set up, calibration and validation. *Journal of Marine Systems,* Vol. 51, 123-145

Umgiesser G., M. Sclavo, S. Carniel and A. Bergamasco, 2004. Exploring the bottom stress variability in the Venice Lagoon. *Journal of Marine Systems,* Vol. 51, 161-178

Umgiesser G., 2000. Modeling residual currents in the Venice Lagoon, in interactions between estuaries, coastal seas and shelf seas, Ed. T. Yanagi, 107-124

Werner C., Wegmüller U., Strozzi T., Wiesmann A., 2003. Interferometric Point Target Analysis for Deformation Mapping. In: Proceedings of IGARSS'03, Toulouse, France, 21-25 July

Bibliography.

Amos C.L., G. Umgiesser, P. Reed, G. Munford and J. Lea, 2004. *The residual tidal circulation of water, sediment and organics in northern Venice lagoon, Italy*. In: Scientific research and safeguarding of Venice. Proceedings of the annual meeting of the CORILA Research program 2002 results, Volume II, Campostrini (ed), CORILA, Venezia, 189-202

Amos C.L., Umgiesser G., Bonardi M. and Capucci S., 2002. Sedimentation mechanism in northern Venice Lagoon. In "*Scientific research and safeguarding of Venice - CORILA Research Program 2001 results*", by Campostrini P. (ed), Istituto Veneto di Scienze Lettere ed Arti, La Garangola, Padova, 315-332

Bonardi M., Cucco A., Schiozzi L., Tosi L., Sitran R. and Scroccaro I., 2003. Morphodynamics processes in the Lagoon of Venice: the Scanello salt marsh area. In "*Scientific research and safeguarding of Venice - CORILA Research Program 2001 results*", by Campostrini P. (ed), Istituto Veneto di Scienze Lettere ed Arti, La Garangola, Padova, 301-313

Cappucci S., C.L. Amos, T. Hosoe and G. Umgiesser, 2004. SLIM: a numerical model to evaluate the factors controlling the evolution of intertidal mudflats in Venice Lagoon, Italy. *Journal of Marine Systems,* Vol. 51, 257-280

Coraci E., G. Umgiesser, M. Sclavo and C.L. Amos, 2004. *Modeling sand transport in the Venice lagoon inlets*. In: Scientific research and safeguarding of Venice. Proceedings of the annual meeting of the CORILA Research program 2002 results, Volume II, Campostrini (ed), CORILA, Venezia, 157-173

Schiozzi L., Bonardi M. and Basu A., 2003. A critical evaluation of heavy metals contamination of Venice Lagoon bottom sediments. In "*Scientific research and safeguarding of Venice - CORILA Research Program 2001 results*", by Campostrini P. (ed), Istituto Veneto di Scienze Lettere ed Arti, La Garangola, Padova, 333-343

Solidoro C., D. Melaku Canu, A. Cucco and G. Umgiesser, 2004. A partition of the Venice Lagoon based on physical properties and analysis of general circulation. *Journal of Marine Systems*, Vol. 51, 147-160

Strozzi T., Tosi L., Wegmüller U., Teatini P., Carbognin L. and Rosselli R., 2003. Thematic and land subsidence maps of the Lagoon of Venice from ERS SAR interferometry. In "*Scientific research and safeguarding of Venice - CORILA Research Program 2001 results*", by Campostrini P. (ed), Istituto Veneto di Scienze Lettere ed Arti, La Garangola, Padova, 345-355

Thompson C.E.L., C.L. Amos and G. Umgiesser, 2004. *A comparison between fluid shear stress reduction by halophytic plants in Venice Lagoon, Italy and Rustico Bay, Canada - analyses of in situ measurements*. Journal of Marine Systems, Vol. 51, 293-308

SPATIAL VARIATIONS OF THE SURFICIAL SEDIMENT CHARACTERISTICS OF THE LAGOON OF VENICE, ITALY

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Riassunto.

In questo lavoro sono riportati i risultati di uno studio effettuato sui sedimenti superficiali della laguna di Venezia. Il lavoro rientra nell'ambito del progetto CORILA Linea 3.2 ed ha lo scopo di determinare le caratteristiche granulometriche, mineralogiche e geochimiche dei sedimenti lagunari come parte complementare alle indagini geomorfologiche intese a determinare il legame esistente tra la dinamica dei flussi nel comprensorio lagunare e la risposta morfologica della laguna stessa.

Le diverse mappe tematiche prodotte hanno evidenziato le variazioni areali dei vari parametri tessiturali, mineralogici e geochimici dei sedimenti di fondo.

I risultati ottenuti hanno messo in evidenza alcune variazioni di tessitura e di composizione mineralogica e geochimica dei sedimenti di alcune aree lagunari, in molti casi correlabili alle attività antropiche recenti, in altri imputabili a variazioni delle condizioni idrodinamiche per cause naturali o antropiche.

In particolare dal punto di vista granulometrico è stato evidenziato un maggior contenuto medio di limo nel settore nord della laguna rispetto a quello centrale e meridionale, mentre, per quanto concerne la distribuzione mineralogica è stata riscontrata una prevalenza di silicati nel bacino sud e carbonati in quello nord. I minerali che maggiormente riflettono queste differenze composizionali sono la dolomite nel settore settentrionale ed il quarzo in quello meridionale.

I dati geochimici relativi ai campioni dei sedimenti superficiali hanno permesso la rappresentazione della distribuzione areale della concentrazione dei metalli pesanti. In particolare i risultati ottenuti hanno permesso di individuare aree puntuali, dove la concentrazione dei metalli pesanti si differenzia notevolmente dalla norma. Il carattere locale e la loro ubicazione in zone a granulometria fine (argille limose, limi argillosi) fa pensare si tratti di accumuli di origine antropica formati direttamente in situ, non legati quindi a processi di trasporto o a particolari condizioni idrodinamiche locali.

Abstract.

We report the results of a detailed sedimentological study carried out on surficial sediments of the Lagoon of Venice within the framework of the CORILA Project, Linea 3.2: Idrodinamica e Morfologia della Laguna di Venezia. Aim of the study was the description of the textural, mineralogical and geochemical characteristics of the surficial sediments as part of a more general study on the link between past and present

geomorphological processes and the reaction of the geomorphological features of the lagoon to the different hydrodynamic fluxes.

The spatial variations of the textural, mineralogical and geochemical parameters are indicated in the thematic maps produced. These maps also indicate areas of the lagoon where the mean value of these parameters may be correlated to recent human activities and areas more influenced by natural or man-induced hydrodynamic conditions.

In particular the mean silt content is higher in the Northern sector of the lagoon, while the mean sand content increases towards the Southern section.

Among the major mineral species present in the top sediments, carbonates prevail in the North lagoon, while silicates are more abundant in the South lagoon.

The spatial distribution maps of the geochemical data show several areas of the lagoon of limited size, where the heavy metal concentration is higher than the mean values. The heavy metal content mean value in these areas, characterized by fine textures, mainly silty clay, may suggest an anthropogenic origin rather than a natural enrichment due to transport processes or to the effects of local hydrodynamics.

1. Introduction

The morphological and geological configurations of the Lagoon of Venice are extremely detailed and complex, due to the modifications caused by natural events and/or, in recent times, by human interventions [Gatto *et al.*,1981; Bonardi *et al.*, 1997; Tosi, 1994]. Accurate and detailed description of the geomorphological, sedimentological and hydrodynamic aspects of certain areas of the lagoon is therefore quite difficult due to the constant impact of human activities. Several sub-depositional environments can be recognized in the lagoon, at the local scale, for the erosion/deposition processes, and for the transport and redistribution of the sediments [Bonardi *et al.*, 2003].

Within the framework of the CORILA Project, Research Line 3.2: Hydrodynamics and Morphology, a detailed sedimentological investigation of the top sediments was undertaken as part of a multidisciplinary study aimed at obtaining new insights of recent and present morphodynamic processes in the Lagoon of Venice. The main aim of this study was to provide an updated overview of the spatial textural, mineralogical and geochemical variation of the bottom sediments of the Venice Lagoon.

In addition, the characterization of the top sediments provides important indications of the past and present evolutionary processes that have, in the past, contributed to the present lagoon ecosystem. The textural, mineralogical and geochemical characteristics give useful information about the erosion, transport and deposition processes linked to the ancient fluvial supply to the lagoon, which was different in the Northern and Southern sectors of the lagoon. Geochemical parameters may indicate areas of the lagoon where the heavy metal content has abnormal levels above the mean, as indication of the impact of human activities. The study is based on more than one hundred analyzed samples of sediments taken in selected areas representative of the different morphologies and hydrodynamic conditions of the lagoon system.

2. Study area

The Lagoon of Venice is a shallow aquatic ecosystem, presently characterized by a network of channels, creeks, tidal flats, and mud flats, and other features that reflect strong hydrodynamics and morphological variability, often linked to past and present human interventions. We can regard the Venice Lagoon today as a very complex ecosystem, due to the interaction between natural evolution and human intervention. The surficial sediments carry the imprints of the different past fluvial supplies and of the reworking caused by the ancient and present lagoon hydrodynamics. The lagoon morphology is strictly linked to the flux dynamics. During historical times the major tributaries were diverted into the sea, outside the lagoon, and several other human interventions were carried out with the consequence that the lagoon morphology and hydrodynamics were modified and, in same cases, sediment distribution changed [Favero *et al.*, 1988; Bonardi *et al.*, 1997; 2003; Barillari, 1975; 1978; 1981]. The areal and alti-bathymetric variations of tidal channels, inlets, marshes, mud flats etc. depend on the local and more general hydrodynamics. It is, in fact, possible to differentiate the lagoon into three main basins: the northern basin, North of the city of Venice, where the deposits of the Piave and Sile rivers prevail, the southern basin, South of the Malamocco inlet, characterized by the sedimentation from the Brenta and Bacchiglione rivers, and the central basin, between the city of Venice and the Malamocco inlet, with prevalent Brenta river sediments reworked by the hydrodynamics [Jobstraibizer and Malesani, 1973].

3. Materials and Methods.

More than one hundred samples, collected in proximity of the sites of the 1983 extensive sampling reported by Rickwood *et al.* [1992] and by Albani *et al.* [1995; 2001], for comparison and in order to obtain some indication of possible heavy metal content variation during the past 20 years, were analyzed and their textural, mineralogical and geochemical characteristics determined. Three groups of samples (Fig.1) were considered for this study over the entire lagoon: 53 samples collected with a stainless steel Van Veen grabber, 26 long cores obtained with a custom made PVC corer 10cm in diameter and 100cm long, and 30 grab samples, here indicated as Bonardi-Basu 1996 [Schiozzi *et al.*, 2003], for a more detailed Northern sector investigation. Of the 26 short cores only the average of the analytical data of the top 15cm were considered for this surficial sediment characterization. Textural, mineralogical and geochemical analyses were carried out on each sample.

The sandy fraction (2mm-0.0625mm) previously separated from the >2mm fraction, was analyzed by sieving, while pelite was analyzed by a Fritsch, Analysette 20 Photo Sedimentograph analyzer.

Mineralogical phases were determined on the < 0.0625mm fraction by X-ray powder diffraction (XRD) on a Philips PW 1800/10 diffractometer, following standard procedures.

Geochemical analyses of the 30 grab samples were performed on fractions <2mm, by total digestion with a mixture of hydrofluoric, nitric and perchloric acid; samples were treated after a series of controlled drying was done to desiccate them and then diluted with hydrochloric acid. The solutions obtained were analyzed by mean of a Perkin-Elmer Optima 3000 ICP Optical Emission Spectrometer. Geochemical analyses of 53 sample grabs and of the top 15 cm of each of the 26 cores were obtained using an ICP-MASS, Model HP 4500 Series 500 Shield Torch System.

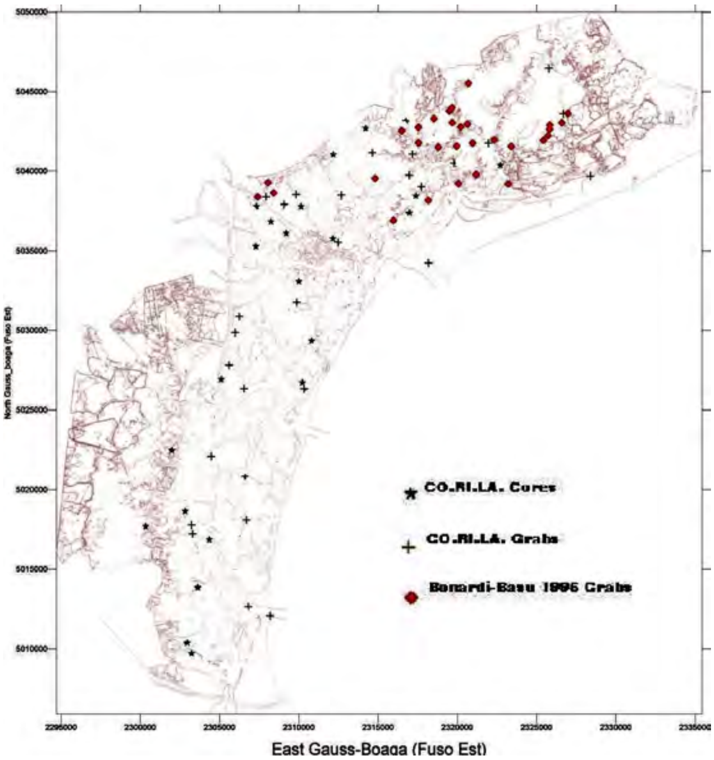

Fig. 1 – Sampling locations.

Surfer v.8 software was used to create variogram maps to show spatial differences in sediment parameters. Data were gridded using the Kriging method.

4. Results and Discussion.

4.1. Grain-size distribution.

For this work the textural composition of the samples was based on the Folk grain-size classification. The textural data indicate that bottom sediments of the Venetian lagoon are of medium-fine size and consist mainly of silty-sand, sand-silt, and silt. The textural distribution reflects the energy of the local hydrodynamics: the coarser sediments, mainly sands, are mostly located at the lagoon’s inlets, along the principal tidal channel, where the tidal energy and waves are stronger.

The finer sediments, silt and clay, instead are concentrated mainly in the more internal areas of the lagoon, where the flux energy is lower and diminishing allowing the deposition of the fine suspended fraction. The average values of grain size fractions for all the grab samples and for the top 15cm of the sediment cores, are given in Fig. 2 for the North, Central and South sectors of the lagoon.

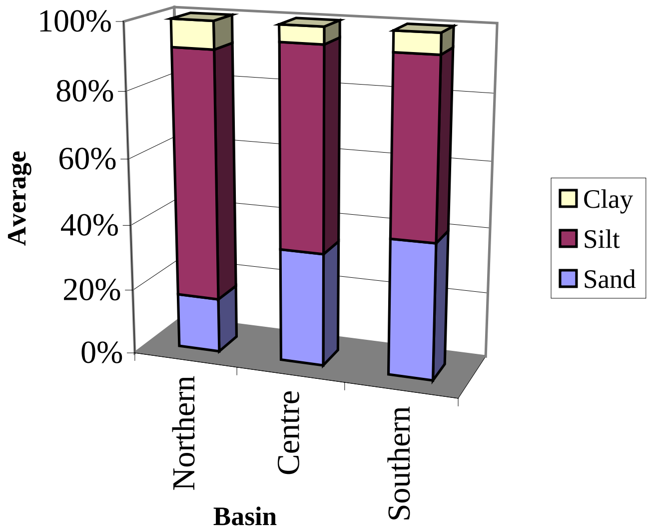

Fig. 2 – Average grain size contents for the three basins.

It is quite evident that the relative percentage of sand increases from the Northern to the Southern basin of the lagoon, while the relative percentage of silt decrease. Spatial distributions of sand, silt and clay are given in Figs. 3, 4, 5 respectively.

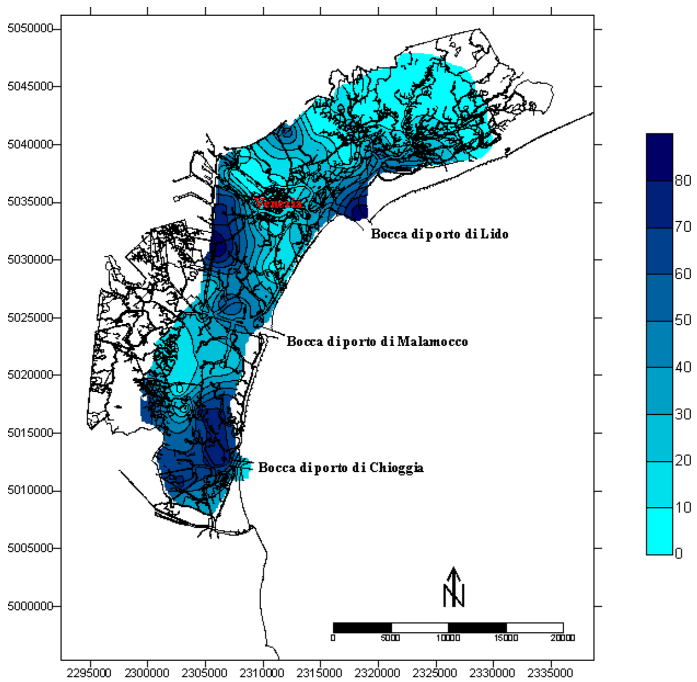

Fig. 3 – Spatial distribution of Sand (%).

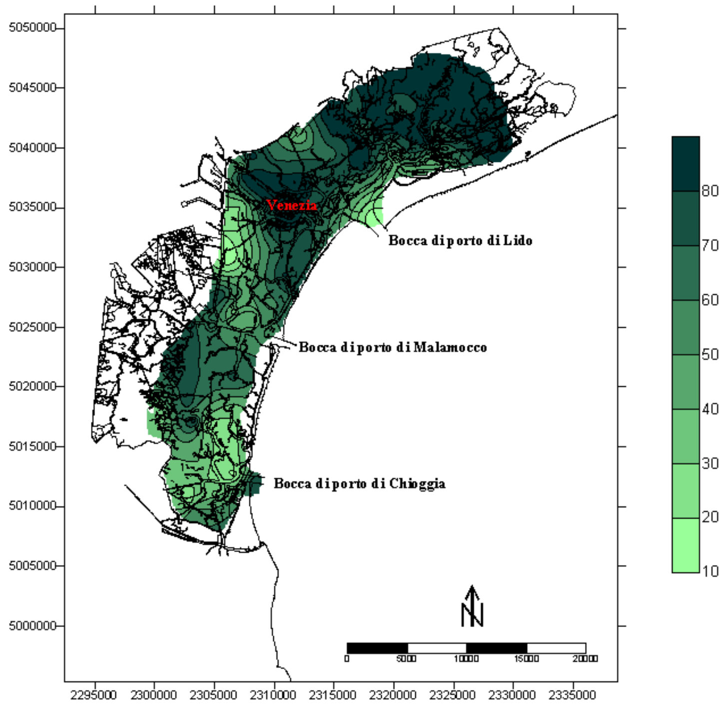

Fig. 4 – Spatial distribution of Silt (%).

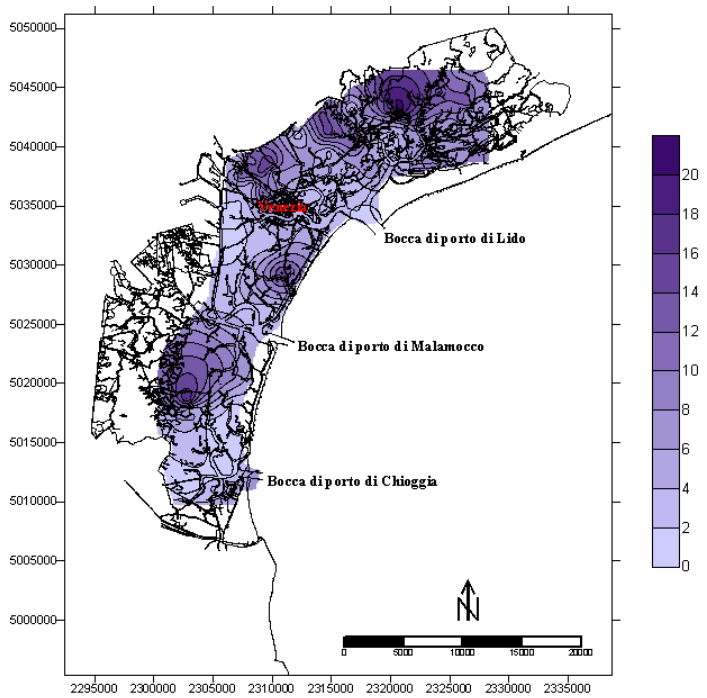

Fig. 5 – Spatial distribution of Clay (%).

4.2. Mineralogy.

The mineralogical analyses of the sediments and the spatial distribution of the major components (carbonates, silicates and clayey minerals) indicate an overall fairly similar composition of the bottom sediments for the entire lagoon [Bonardi and Bonsembiate, 2004]. The main detected minerals are: dolomite, calcite, quartz, feldspars (k-feldspar+plagioclase), chlorite and mica, while kaolinite, ankerite, aragonite and hastingsite are present in low percentages.

In general, carbonates (dolomite, ankerite, calcite, and aragonite) are more abundant in the northern sector of the lagoon, whereas silicates (quartz+feldspars) prevail in the southern sector. In the central sectors the relative percentages of carbonates and silicates are very similar. The opposite trend of carbonates and silicates is shown in Fig. 6a, 6b. Dolomite and ankerite are constantly the most abundant components of the carbonates, while quartz is the main component among the silicates. Fig. 7 shows the spatial distribution of quartz with a very distinct increase toward the mainland, particularly in the central and southern sectors. Feldspars (Fig. 8) are mainly present in the southern sector with a maximum in the area west of Chioggia. Dolomite (Fig. 9) prevails in the northern sector while the highest concentration of the clay minerals (Fig.10) is located towards the mainland in the southern sector and in a limited area of the northern sector.

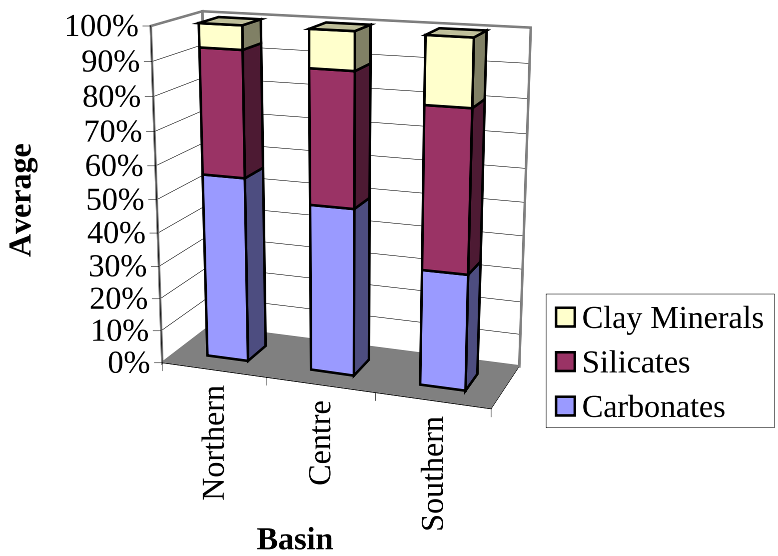

Fig. 6a – Average mineralogical composition.

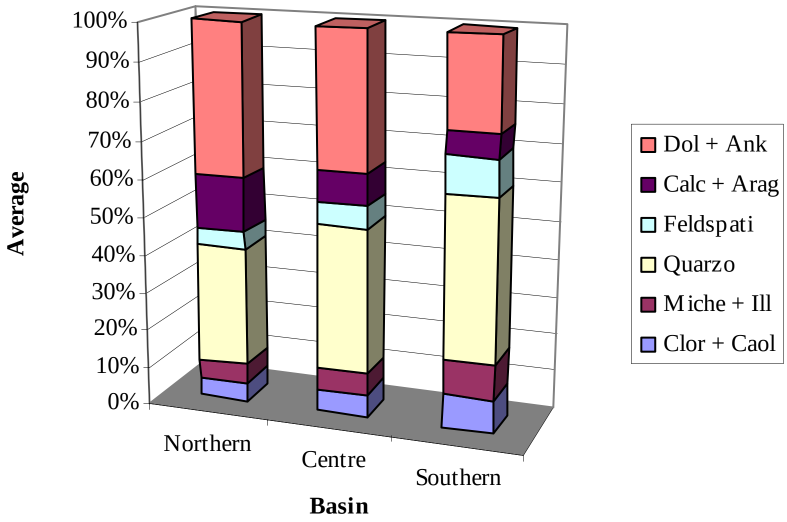

Fig. 6b – Average mineral content.

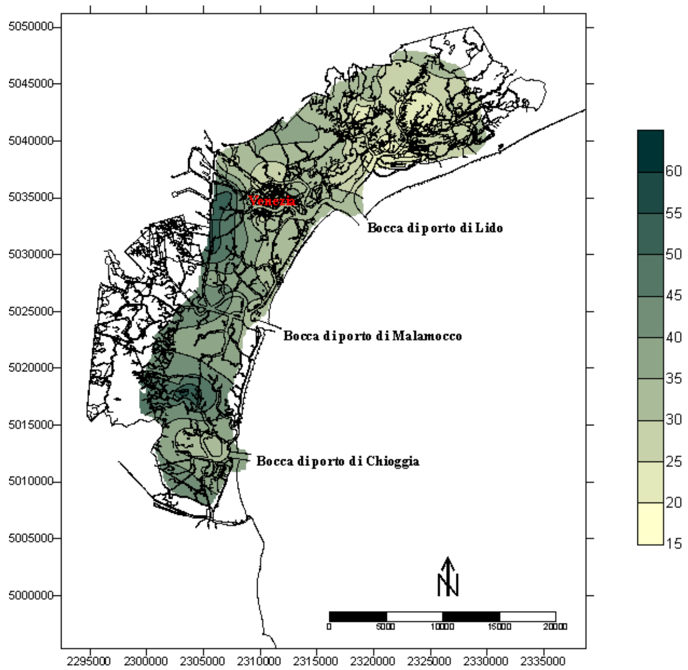

Fig. 7 - Spatial distribution of Quartz (%).

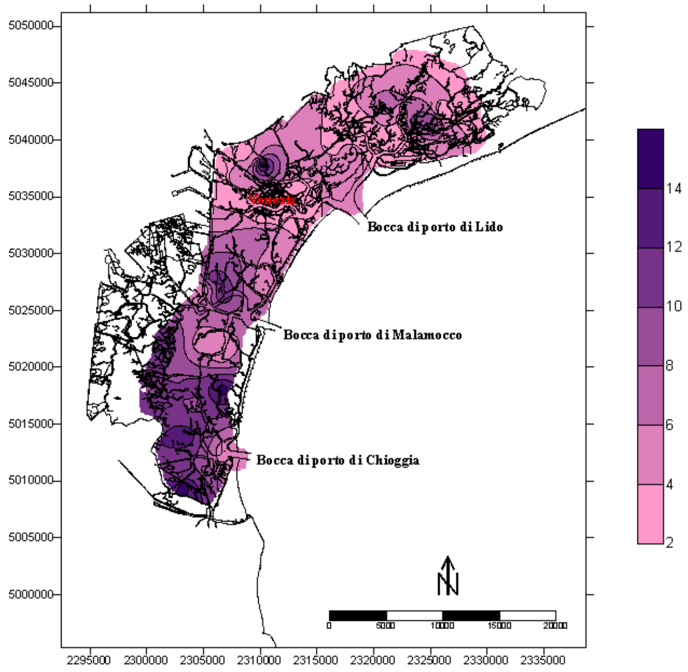

Fig. 8 – Spatial distribution of Feldspars (%).

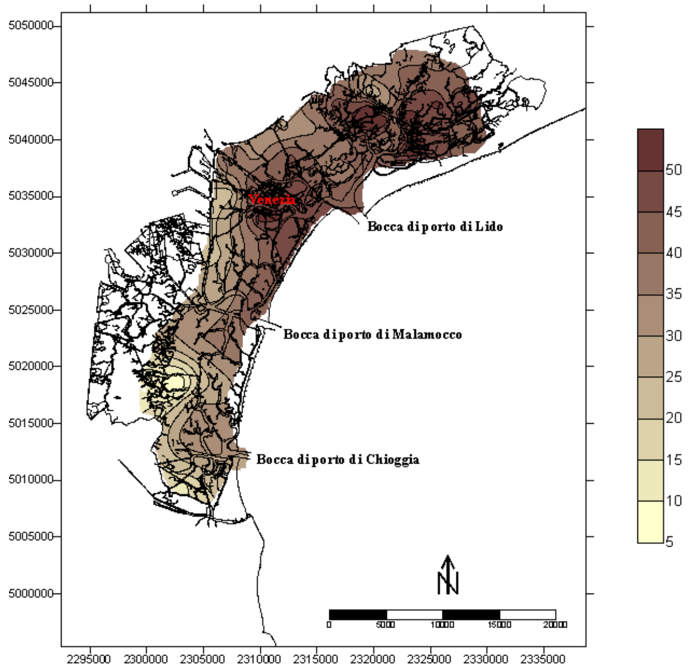

Fig. 9 – Spatial distribution of Dolomite (%).

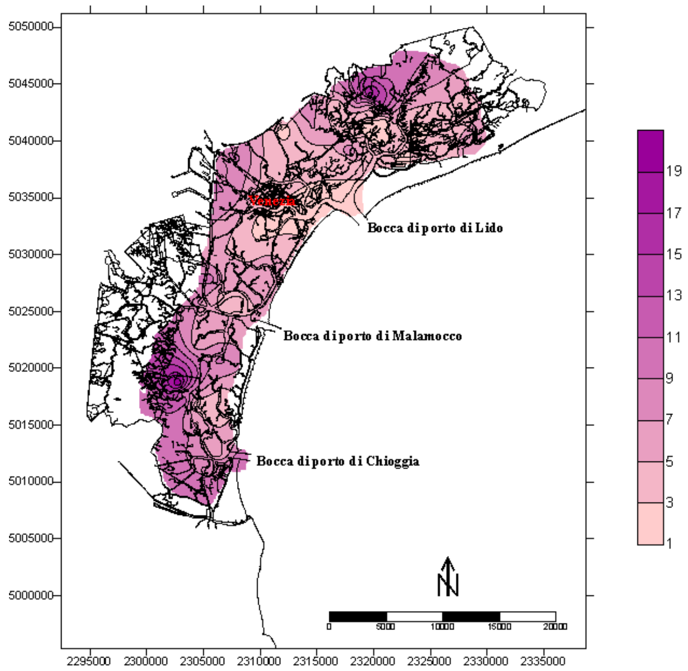

Fig. 10 – Spatial distribution of Clay minerals (%).

4.2. Geochemistry.

The geochemical data obtained for the surficial sediments have allowed the production of thematic maps showing the spatial variation of the major heavy metal concentrations. In these maps, areas of limited extension are indicated where the heavy metal concentration is higher than the average.

The confined areas of these concentrations, the fine texture of the sediments (silty clay and/or clayey silt) and their location close to industrial areas of Marghera, Chioggia and Murano suggest an anthropogenic origin, rather than caused by local hydrodynamics [Frignani *et al.*, 1997; Bellucci *et al.*, 2002; Schiozzi *et al.*, 2003, Bonardi and Bonsembiate, 2004]. In fact, the limited water circulation and sediment transport typical of these areas with high concentration of certain heavy metals suggest a link to past and present industrial activities. Some examples of spatial distribution of heavy metal concentration are given in Figs 11,12,13,14.

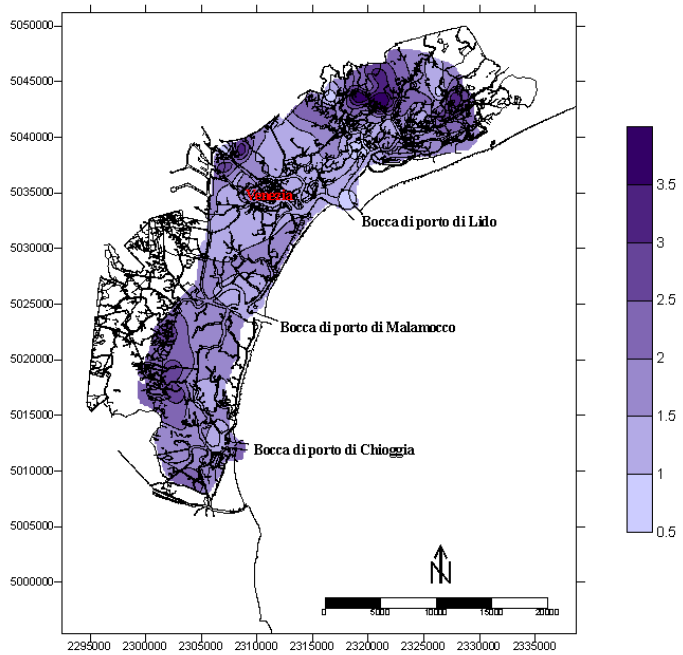

Fig. 11 – Spatial distribution of Fe (%).

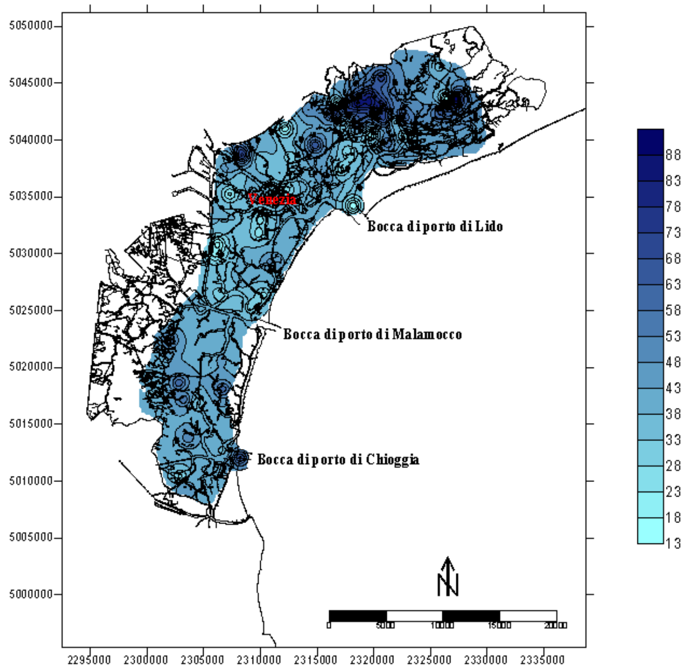

Fig. 12 – Spatial distribution of Cr (ppm).

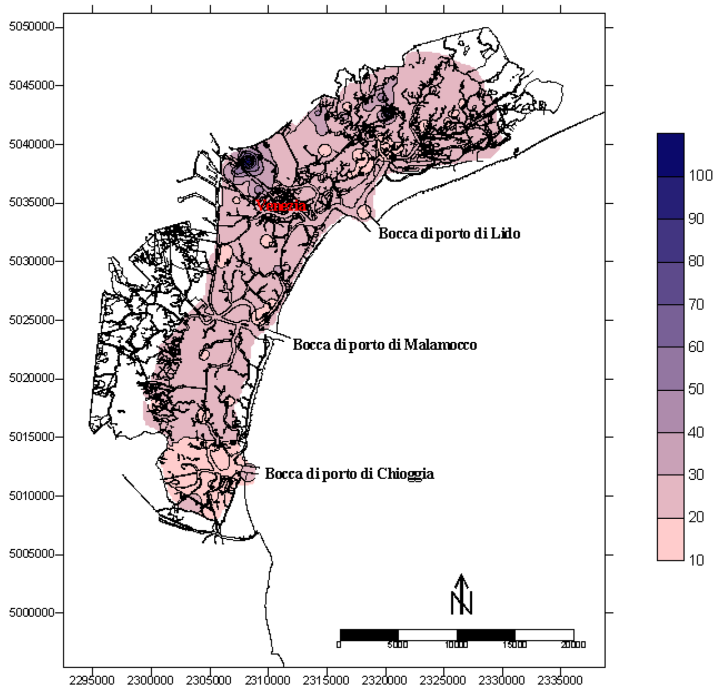

Fig. 13 – Spatial distribution of Pb (ppm).

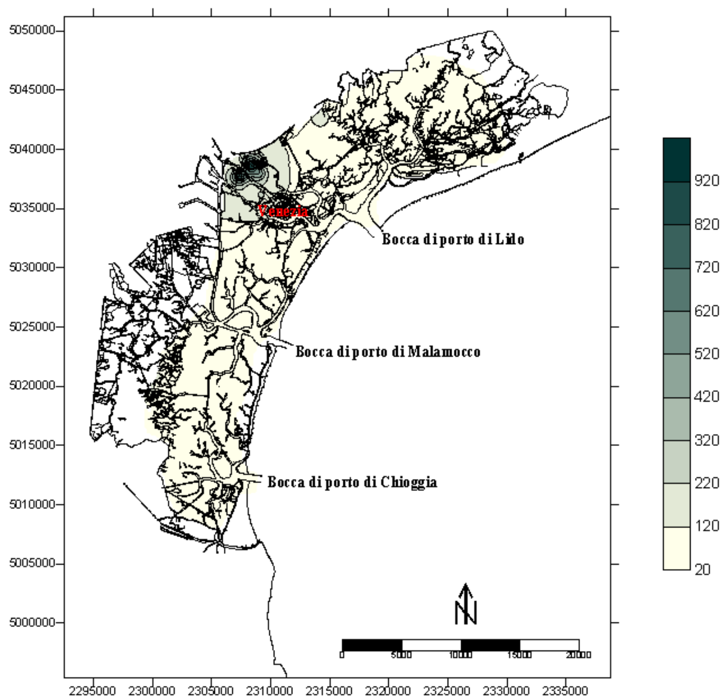

Fig. 14 – Spatial distribution of Zn (ppm).

4. *Conclusions.*

From the sedimentological investigation of more than one hundred surficial sediments, collected from selected areas representative of the different morphological characteristics and hydrodynamics conditions of the lagoon systems, the following conclusions can be drawn. The textural analysis has confirmed that clayey silt deposits prevail in the Venetian ecosystem. The coarser sand deposits are confined mainly at the inlets and along the major tide channels, whereas the finer silty clay sediments are found in the watershed areas between different basins, not reached by the tidal currents and where the energy of transport is low.

The comparison of the surficial sediment mean mineralogical composition has given a good indication of how the major mineralogical components, such as quartz, feldspar, dolomite, mica and chlorite, can be used to differentiate the Northern, Central and Southern basins and the areas of provenance. In fact, on the basis of the average petrographic characteristics, it is possible to distinguish the mainly silicatic northern basin of the Brenta-Bacchiglione river system from the carbonate rich basins of the Piave-Sile river system, with a silicates/carbonates ratio increasing from north to south.

The recognized regional differences may be also due to the anti-cyclonic Adriatic current [(Zore and Gacic, 1987; Orlic *et al.*, 1992] that, by entering the lagoon through the Lido and Malamocco inlets, may have contributed to the mixing of the more carbonate-rich sediments of the northern sector with those silicate-rich of the southern sector and may have prevented the expansion to the North of the Po River delta sediments. The Central and Southern sectors, although rich in silicates, present a high content of carbonates, in part probably of marine origin.

The general distribution of the major and trace elements in the Venetian Lagoon, is strictly related to the lithology of the areas of provenance, as indicated by the geochemical analysis of the selected samples, and therefore to the granulometric and mineralogical compositions of the deposits.

The samples with a discrepancy between mineralogical composition and abnormally high content of heavy metals are, as expected, located in areas with intense past and/or present human impact.

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References

Albani A.D. and Serandrei Barbero R., 2001. The distribution of surface sediments in the Lagoon of Venice (Italy) in the 1980s. *Atti dell'Istituto Veneto di Scienze, Lettere ed Arti*, 159, 363-378

Albani A.D., Rickwood P.C., Favero V. e Serandrei Barbero R., 1995. The geochemistry of recent sediments in the Lagoon of Venice: environmental implications. *Atti dell'Istituto Veneto di Scienze, Lettere ed Arti*, 153, 235-321

Barillari A., 1975. Prime notizie sulla distribuzione dei sedimenti superficiali nel bacino settentrionale della Laguna di Venezia. *Memorie Biogeografiche Adriatiche*, 9 (supp.):13-32

Barillari A., 1978. Prime notizie sulla distribuzione dei sedimenti superficiali nel bacino centrale della Laguna di *Venezia. Atti dell'Istituto Veneto di Scienze, Lettere ed Arti*, 136: 125-134

Barillari A., 1981. Prime notizie sulla distribuzione dei sedimenti superficiali nel bacino centrale della Laguna di Venezia. *Atti dell'Istituto Veneto di Scienze, Lettere ed Arti*, 139: 87-109

Bellucci L.G., Frignani M., Paolucci D., Ravanelli M., 2002. Distribution of heavy metals in sediments of the Venice Lagoon: the role of the industrial area. *The Science of Total Environment* 295, 35-49

Bonardi M. and Bonsembiate N., 2004: Caratteristiche geochimiche dei sedimenti superficiali della laguna di Venezia. *CORILA, Progress Report*

Bonardi M., Canal E., Cavazzoni S., Serandrei Barbero R. e Tosi L., 1997. Sedimentological, archaeological and historical evidences of paleoclimatic changes during the Holocene in the Lagoon of Venice (Italy). *World Resource Review,* 9, 4, 435-446

Bonardi M., Cucco A., Schiozzi L., Tosi L., Sitran R. and Scroccaro I., 2003. Morphodynamics processes in the Lagoon of Venice: the Scanello salt marsh area. In "*Scientific research and safeguarding of Venice - CORILA Research Program 2001 results*", by Campostrini P. (ed), Istituto Veneto di Scienze Lettere ed Arti, La Garangola, Padova, 301-313

Favero V., Parolini R. and Scattolin M. (eds), 1988. Morfologia storica della laguna di Venezia. Arsenale Editrice, Venezia

Frignani M., Bellocci L.G., Langone L., Mintau H., 1997. Metal fluxes of the sediments of the northern Venice Lagoon. *Marine Chemistry*, 56, 275-292

Gatto P. and Carbognin L., 1981. The Lagoon of Venice: natural environmental trend and man-induced modification. *Hydrological Sciences Bulletin*, 26 (4), 379-391

Jobstraibizer P. and Malesani P., 1973. I sedimenti dei fiumi veneti. *Memorie della Società Geologica Italiana*, 12, 411-452

Orlic M., Gacic M. and La Violette P.E., 1992. The currents and circulation of the Adriatic Sea. *Oceanologica Acta*, 15,2,109-124

Rickwood P.C., Albani A.D., Favero V.M. e Serandrei Barbero R., 1992. The geochemistry of unconsolidated sediments from the Gulf of Venice, Italy. Technical Contribution Series. 3. Centre for Marine Science, University N.S.W., Sidney

Schiozzi L., Bonardi M. and Basu A., 2003. A critical evaluation of heavy metals contamination of Venice Lagoon bottom sediments. In "*Scientific research and safeguarding of Venice - CORILA Research Program 2001 results*", by Campostrini P. (ed), Istituto Veneto di Scienze Lettere ed Arti, La Garangola, Padova, 333-343

Tosi L., 1994. L'evoluzione paleoambientale tardo quaternaria del litorale veneziano nelle attuali conoscenze. *Il Quaternario*, 7(2), 589-596

Zore Armanda M. and Gacic M., 1987. Effects of bura on the circulation in the North Adriatic. *Annales Geophysicae*, 5B, (1), 93-102

FORAMINIFERA AS PROXY RECORD OF MARGINAL ENVIRONMENTS: THE AGE OF THE SEDIMENTS OF THE VENICE LAGOON

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Riassunto.

Negli ambienti marginali l'associazione a foraminiferi bentonici è in grado di evidenziare, attraverso la distribuzione areale dei biotopi, le aree sottoposte a diverso regime chimico-fisico. Nelle sequenze sedimentarie, i diversi regimi chimico-fisici succedutisi nel tempo sono evidenziati da *transizioni ecologiche* nella comunità a foraminiferi bentonici. L'esame quantitativo del contenuto di foraminiferi bentonici in 89 campioni provenienti da 26 carote profonde circa 1 m eseguite nella Laguna di Venezia, ha permesso di evidenziare le *transizioni ecologiche* presenti nelle successioni sedimentarie. L'analisi statistica, sviluppata sui dati quantitativi relativi al contenuto percentuale dei vari taxa nei diversi campioni, ha riconosciuto la presenza di cinque diversi biotopi indicativi di morfologie pregresse. Le 57 analisi radiometriche ottenute dal materiale organogeno presente nei sedimenti hanno fornito le età convenzionali BP dei principali eventi riconosciuti: il litorale identificato a 90 cm di profondità, è stato per la prima volta datato ed ha fornito un'età pari a 3180 anni BP; le barene sepolte hanno fornito età diverse, comprese tra 820 e 1887 anni BP; nei sondaggi effettuati nella laguna interna, che hanno raggiunto il substrato continentale, l'ingressione lagunare risulta essersi verificata in epoca storica o protostorica, avendo fornito età comprese tra 820 e 2403 anni BP; l'età lagunare più antica (3437 anni BP) è stata ottenuta su gusci di organismi lagunari presenti a 90 cm di profondità nel sondaggio 2, interamente compreso entro depositi lagunari. L'età dei depositi è legata alla loro profondità dal tasso di accumulo il cui valore medio, comprensivo di subsidenza ed eustatismo, negli ultimi 2500 anni risulta pari a 0,5 mm/anno. Risultati diversi si ottengono considerando due diverse fasce di età: tra circa 2500 e 1500 anni BP il tasso di accumulo risulta di 1 mm/anno; tra 1500 anni BP e il presente il tasso di accumulo risulta di 0,4 mm/anno.

Abstract.

Benthic foraminiferal assemblages, based on the distribution of biotopes, can delineate areas of different chemical and physical conditions and, in the sedimentary sequences, changes in environmental conditions are reflected in the *ecological transitions* of the benthic foraminifera. From 89 samples, obtained from 26 cores about 1 metre long, the quantitative analyses of the foraminiferal assemblages have recognized a number of *ecological transitions* in the sedimentary sequences of the

Lagoon of Venice. The statistical analysis based on the percentage of each foraminiferal species present in each sample has recognised five different biotopes indicative of older lagoonal morphologies. In addition, 57 radiometric determinations on organic material present in the sediments have yielded the conventional BP ages of the major events. The littoral deposits, identified at a depth of 90 cm, were dated for the first time, giving an age of 3180 years BP, while the various buried saltmarshes have given different ages ranging from 820 to 1887 yBP. In the inner portion of the Lagoon the cores, reaching the continental deposits, indicate that the earliest lagoonal deposits are from historic or protohistoric times with ages from 820 to 2403 yBP. The oldest age (3437 yBP) was obtained using shell of lagoonal organisms found at 90 cm of depth at location 2, entirely within the lagoonal deposits. The age of the sediments and their depth are related to the rate of deposition whose average value, comprehensive of subsidence and eustatism, appears to be for the last 2500 years about 0.5 mm/year. However if different time intervals are considered such depositional rates vary from 1mm/year, for the period between 2500 and 1500 yBP, and 0.4 mm/year from 1500 yBP to the present.

1. *Introduction.*

Benthic foraminifera, shell bearing unicellular organisms of the class Foraminifera [Loeblich and Tappan, 1992], in marginal areas with freshwater and/or industrial inputs, are affected by three main factors: residence time or confinement [Guelorget and Perthuisot, 1983], degree of mixing of the freshwater inputs [Donnici and Serandrei Barbero, 2005] and stress levels due to domestic and industrial pollution [Albani, 1993; Alve, 1995]. Within the Lagoon of Venice a five years study has identified the chemical and physical characteristics of some lagoonal areas controlled by their distance from the entrances and the degree of pollution [Ramasco, 1991].

During the 1980s 600 samples of bottom sediment were collected. The foraminiferal biotopes delineated the extent of the *biofacies* present in areas with different chemical and physical conditions [Albani *et al.*, 1991; Serandrei Barbero *et al.*, 1989 and 1999] that reflect the present hydrological conditions, practically unchanged since the 1960s and the subtidal or intertidal morphologies [Albani *et al.*, 1984; Hayward and Hollis, 1994; Petrucci *et al.*, 1983; Scott *at al.*, 1991; Serandrei Barbero *et al.*, 1997 and 2004a].

Furthermore, in a sedimentary sequence the benthic communities may reveal *ecological transitions* that, if present and in accordance with sediment characteristics, indicate past hydrodynamic conditions and changed morphologies. Recent studies [Serandrei Barbero *et al.*, 2001 and 2004a; McClennen *et al.*, 1997; Mozzi *et al.*, 2003] have recognised several *ecological transitions* and thus highlighted the relatively short duration of the lagoonal morphologies shown by buried palaeochannels, littoral deposits in areas of the inner Lagoon and buried saltmarshes, often associated with ancient human settlements. The ages of the various horizons, made possible by the presence of organic remains, may establish the rate of deposition, considered constant in sequences lacking *ecological transitions.*

The foraminiferal *biofacie*s of the various successive environments were determined in 26 cores obtained from various parts of the Lagoon (Fig.1). From 57 samples, radiometric ages (AMS) were obtained using the shells of the benthic fauna.

The various rates of sedimentations, which include subsidence and eustatism and previously defined as variable and site dependent [Bortolami *et al.*, 1977], were calculated.

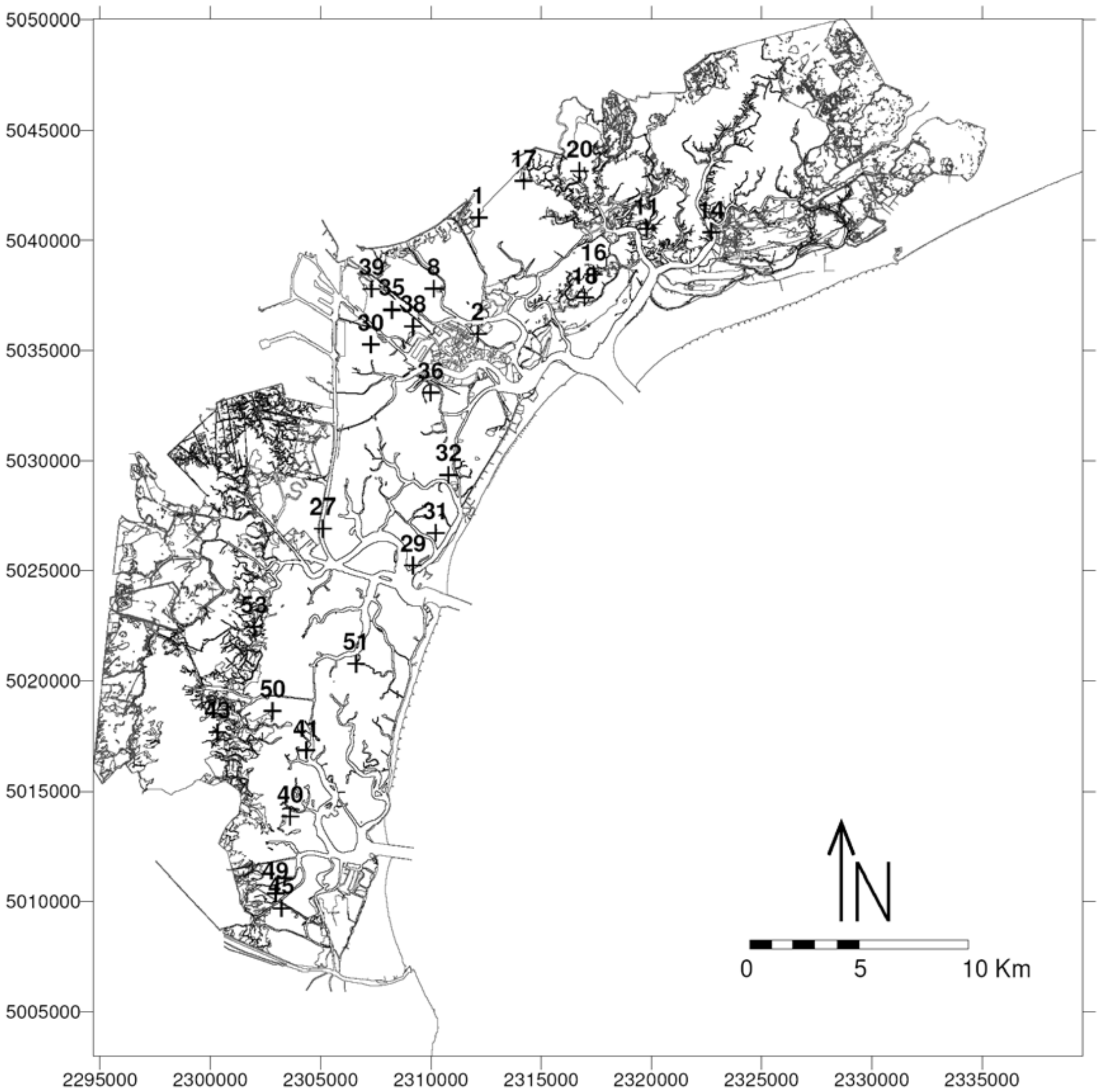

Fig. 1 – Location of the 26 cores in the Lagoon of Venice

2. Materials and Methods.

The identification of the *biofacies* is based not only on the direct observations and on the local morphological factors but also on a five year study based on monthly data of the physical and chemical parameters along a transect that included anthropogenic and different residence time conditions [Ramasco, 1991]. This study has identified the parameters that characterize the industrial and antropic lodes and also both the transition areas and those with natural conditions. The lagoonal characteristics thus defined and the monitoring of the living foraminiferal faunas [Donnici *et al.*, 1997] have made possible the correlation between the physical and chemical regimes with the various biotopes [Serandrei Barbero *et al.*, 2004b].

The 26 cores, 10 cm in diameter and about 1 metre in length, were obtained from areas characterized by different *biofacies*. The lithology consists of muds, sands and clays with occasional peat horizons. Samples were selected from the top, middle and bottom levels of each core with additional samples from horizons containing changes in faunal content. From the total 88 samples 9 were found to be sterile.

The samples were dried and their weight determined, washed on a sieve of 0.063 mm opening to disperse the silt-clay fractions, dried at 50 °C and then weighted again to determine the amounts of silt-clay present. The size fractions greater that 0.125 mm were analysed for foraminiferal content. In the lagoonal environment, characterised by ample variations in environmental parameters, the various individuals reach the reproductive maturity later than those living in the marine environment and therefore their full development is reached by individuals with greater dimensions. For this reason foraminiferal studies conducted in the Lagoon of Venice since the early 1960s have considered the fractions greater than 0.125 mm.

In the 79 samples the total foraminiferal fauna (living and dead) was examined and at least 300 individual were identified and counted [Buzas, 1990; Serandrei Barbero *et al.,* 1997] following the Loeblich and Tappan [1987] classification. The total assemblage integrates the seasonal variations and the short but not permanent environmental changes and the biotopes represent the prevailing local physical and chemical conditions [Scott and Medioli, 1980].

The numerical data formed by the percentage of each species with respect to the total foraminiferal assemblage present in each sample was used for the cluster analysis to determine the biotopes and for the correspondence analysis [Davis, 1986], which is particularly useful with this type of data.

From the fractions greater than 0.5 mm fragments of lagoonal molluscs were used to obtain a conventional age (yBP). The age determinations were carried out on 57 samples at the laboratories of the Australian Nuclear Science and Technology Organization (ANSTO) using the Accelerator Mass Spectrometry (AMS), which requires few mg of carbon and a small analytical time [Tuniz *et al.*, 1998]. In case of continental deposits, without shell fragments, such analyses were performed on peat remains.

3. *Results.*

The foraminiferal content of the 88 analyzed samples is shown in Tab. 1. The numerical data set was analysed by the multivariate correspondence analysis, which groups on one cartesian plane the similar samples and the species determining such similarity. The first two resulting values, the components X1 and X2, define the 71% of the total variability.

The component X1 (Fig. 2) is defined with 94% by *Trochammina inflata*, a taxon typical of intertidal conditions while *Ammonia beccarii* and *Haplophragmoides canariensis* have a limited weight, 2% and 1.5% respectively. All other species have no effect.

Tab. 1 – Taxa found on the 79 samples containing foraminiferal faunas. Average, maximum, minimum values and number of samples containing each taxon are shown.

Foraminiferal species	average	max.	min.	occur.
Saccamina difflugiformis (Brady, 1879)	0.3	0.3	0.3	1
Miliammina fusca (Brady, 1870)	1.3	4.0	0.3	4
Acostata mariae (Acosta, 1940)	0.3	0.3	0.2	5
Haplophragmoides canariensis (d'Orbigny, 1939)	0.8	3.8	0.2	14
Ammobaculites agglutinans (d'Orbigny, 1846)	1.1	9.1	0.2	62
Trochammina inflata (Montagu, 1808)	13.2	96.2	0.2	35
Gaudryina silvestrii (Bronniman, Whittaker and Valleri, 1992)	0.3	0.3	0.3	1
Eggerella scabra (Williamson, 1858)	4.7	22.4	0.2	15
Textularia agglutinans d'Orbigny, 1839	0.2	0.2	0.2	1
Spirillina vivipara Ehremberg, 1843	0.3	0.4	0.2	3
Massilina disciformis (Williamson, 1858)	0.2	0.3	0.2	3
Quinqueloculina agglutinata Cushman, 1917	0.3	0.3	0.2	3
Quinqueloculina candeiana d'Orbigny, 1839	0.2	0.3	0.2	2
Quinqueloculina elegans (Williamson, 1858)	0.4	1.0	0.2	10
Quinqueloculina ferussacii d'Orbigny, 1826	0.2	0.3	0.2	4
Quinqueloculina seminulum (Linnè, 1758)	1.8	10.6	0.2	31
Quinqueloculina subpolygona Parr, 1945	0.8	0.8	0.8	1
Triloculina trigonula (Lamarck, 1804)	0.3	0.3	0.3	1
Sigmoilina grata (Terquem, 1878)	0.2	0.2	0.2	1
Lagena laevis (Montagu, 1803)	0.3	0.3	0.3	1
Fissurina lucida (Williamson, 1848)	0.3	0.5	0.2	6
Brizalina spathulata (Williamson, 1858)	1.5	1.5	1.5	1
Brizalina striatula (Cushman, 1922)	0.3	0.5	0.1	6
Valvulineria perlucida (Heron-Allen & Earland, 1913)	8.1	22.0	0.7	74
Helenina anderseni (Warren, 1957)	0.3	0.3	0.2	4
Rosalina bradyi (Cushman, 1915)	0.6	1.0	0.2	2
Cibicides lobatulus (Walker & Jacob, 1798)	0.3	0.3	0.3	1
Haynesina paucilocula (Cushman, 1944)	11.3	56.5	1.5	76
Nonion politum (d'Orbigny, 1826) syn. N.citai (di Napoli)	0.3	0.3	0.2	2
Buccella frigida granulata (Di Napoli Alliata, 1952)	0.5	1.2	0.1	12
Buccella pustulosa Albani e Serandrei Barbero, 1982	0.3	0.4	0.2	4
Trichohyalus lacunae (Silvestri, 1950)	0.3	0.3	0.2	4
Ammonia beccarii (Linnè, 1758)	62.6	94.8	4.0	78
Cribrononion advenum (Cushman, 1922)	0.6	1.0	0.3	2
Cribrononion granosum (d'Orbigny, 1846)	8.9	51.7	0.2	74
Cribrononion lagunensis Albani e Serandrei Barbero, 1982	0.7	2.6	0.1	52
Cribrononion simplex (Cushman, 1933)	0.5	1.0	0.2	9
Cribrononion translucens (Natland, 1938)	1.1	3.0	0.2	62
Cribrononion venetum Albani, Favero e Serandrei Barbero, 1991	0.5	2.0	0.2	16
Elphidium complanatum (d'Orbigny, 1839)	0.7	1.5	0.3	3
Elphidium crispum (Linnè, 1758)	0.2	0.3	0.2	3
Elphidium depressulum Cushman, 1933	1.0	8.7	0.2	49
Elphidium macellum (Fichtel & Moll, 1798)	0.3	0.3	0.3	3

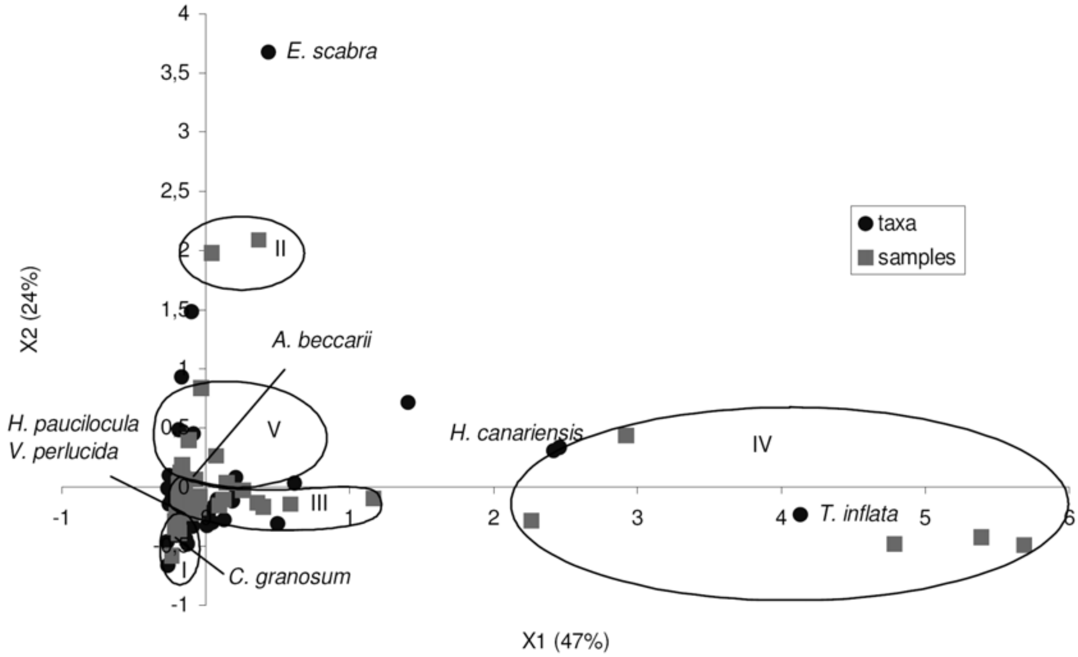

Fig. 2 – In the correspondence analysis diagram, with the resulting first values X1 and X2, the points relative to the species and those related to the samples are shown. Cluster analysis (c-means) recognize five groups with similar faunal content.

The second component X2 is controlled by *Eggerella scabra* for the 83%, a taxon typical of a detaic environment, while the effect of *Cribrononion granosum*, *Valvulineria perlucida* and *Haynesina paucilocula* are limited to 8%, 2% and 2% respectively.

Tab. 2 – Groups of similar samples and associated biotopes identified by cluster analysis (c-means) using the results of the correspodence analysis. Each sample is identified by the number of the core (C) and by the depth in centimetres.

Cluster I, Brackish Biotope: 11C-14, 17C-11, 20C-10, 20C-48, 20C-89, 35C-19, 38C-13, 49C-55
Cluster II, Deltaic Biotope: 40C-5, 41C-10
Cluster III, Intermediade Lagoon Biotope: 1C-10, 1C-30, 1C-50, 2C-10, 2C-30, 8C-13, 8C-55, 8C-142, 14C-43, 16C-10, 16C-130, 17C-95, 17C-120, 18C-85, 20C-115, 27C-15, 27C-35, 27C-58, 29C-55, 29C-93, 30C-22, 31C-145, 35C-35, 36C-15, 38C-40, 39C-8, 39C-30, 40C-65, 43C-7, 43C-77, 45C-15, 49C-7, 53C-8, 53C-20
Cluster IV, Intertidal Biotope: 39C-53, 39C-62, 39C-68, 50C-8, 50C-30
Cluster V, Outer Lagoon Biotope: 2C-60, 2C-90, 11C-50, 11C-70, 11C-96, 14C-13, 14C-132, 16C-80, 17C-70, 18C-15, 18C-122, 29C-12, 30C-30, 31C-11, 31C-60, 31C-15, 32C-80, 32C-123, 35C-105, 36C-63, 36C-125, 38C-68, 40C-42, 41C-55, 41C-100, 45C-50, 49C-133, 51C-9, 51C-52, 51C-134

The cluster analysis (c-means) recognised five groups (Tab. 2), which indicate the presence in some cores of *ecological transitions* and thus a change in environmental conditions.

The *ecological transitions*, if present as in cores 29 and 31, were dated by AMS. In all other cores dating was carried out on levels with sufficient organic remains. From a total of 57 determinations the rate of sedimentation for the last 3000 years was calculated (Tab. 3).

4. *Discussion.*

In the quaternary venetian sediments a decreasing sedimentation rate, comprehensive of eustatism, deep subsidence and compaction, has been calculated: the curve of the rate of accumulation of uncompacted sediments [Massari *et al.*, 2004] shows a value less than 1.69 mm/y for the Upper Pleistocene and Holocene, in agreement with the rate of 1.3 mm/y for the Holocene [Bortolami *et al.*, 1977] and similar to the value for the historic period in the northern lagoon [Serandrei Barbero *et al.*, 1997] while, during the last 5000 years, on the saltmarshes of the northern lagoon the sedimentation rate 1.2 mm/y was calculated [Serandrei Barbero *et al.*, 2004a].

In the long term the accumulation rate is related to the formation of space where deposition may occur, which also depends from the subsidence of various origins and from the sea level rise. However it depends primarily from the availability of sediments, which can be drastically reduced during a transgressive phase or due to the lack of terrigenous material caused by the redirection of the rivers once entering in the Lagoon [Favero *et al.*, 1988]. Furthermore the rate of accumulation is controlled by the bottom morphology and by its location. On several saltmarshes the rate of sedimentation, during the period 1993 – 1995, has been quantified as 0.3 – 2.3 cm/y, a rate free of the effect of the eustatism, with the high value during storm or high tide events [Day *et al.*, 1995].

Significative *ecological transitions* are absent in cores 2, 8, 11, 16, 18, 20, 32, 36, 38, 41, 49 and 51 thus the subtidal environment of deposition has remained constant within the last 2500 years (Tab. 3) with an average rate of sedimentation of the order of 0.5 mm/y. However, if the rates are considered for specific intervals of time, an average value of 1 mm/y (0.6-1.7 mm/y) is obtained for the period 2500-1500 yBP and 0.4 mm/y for the last 1500 years. The highest values of the lower sequences at cores 18, 41 and 49 are probably due to the presence of a sediment active littoral morphology, which has later migrated to its present position.

Cores 14, 29, 31, 39, 50 and 53 show the presence of *ecological transitions*. In cores 14, 39, 50 and 53 the *ecological transitions* are due to the presence of saltmarshes of different age. Even in these intertidal environments a decrease of the rate of sedimentation is noted with the decrease of age: in core 39 the saltmarsh of 1887 yBP shows a rate of 0.8 mm/y for the period 1887-1714 yBP. A rate of 0.2-0.6 mm/y is noted for the saltmarshes from cores 14, 50 and 53 with a respective age of 690, 842 and 820 yBP. In core 29 the *ecological transition* is due to the appearance of littoral indicators of 3000 yBP, in agreement with Favero and Serandrei Barbero [1980]. In core 31 the *ecological transition* is linked to the presence of a channel, which is responsible for the relatively high (7.5 mm/y) sedimentation rate.

Tab. 3 – Rates of sedimetation in different time intervals. The depositional environments are obtained from the analyses of the biofacies and their comparison with present day assemblages.

core	depth interval (cm)	age interval (years BP)	deposition rate (mm/y)	environment of deposition	average deposition rate (mm/y)
1C	lagoon floor - 50	present - 1035	0.7	subtidal / alluvial	0.7
2C	lagoon floor - 30 30 - 90	present - 1010 1010 - 3437	0.3 0.3	subtidal subtidal	0.3
8C	lagoon floor - 142	present - 2451	0.5	subtidal	0.5
11C	lagoon floor - 50 50 - 96	present - 1900 1900 - 2558	0.3 0.7	subtidal subtidal	0.4
14C	lagoon floor - 43 43 -132	present - 690 690 - 2337	0.6 0.5	intertidal subtidal	0.5
16C	lagoon floor - 45 45 -130	present - 1480 1480 - 2486	0.3 0.8	subtidal subtidal	0.5
17C	lagoon floor - 70	present - 2000	0.3	subtidal / alluvial	0.3
18C	lagoon floor - 50 50 - 122	present - 1630 1630 - 2080	0.3 1.6	subtidal subtidal	0.6
20C	lagoon floor - 48 48 - 115	present - 1860 1860 - 2433	0.2 1.2	subtidal subtidal	0.5
27C	lagoon floor - 58	present - 2403	0.2	subtidal / alluvial	0.2
29C	lagoon floor - 93	present - 3180	0.3	subtidal / littoral	0.3
30C	lagoon floor - 30 30 - 60 60 - 99	present - 241 241 - 2923 2923 - 3029	1.2 0.1 3.5	subtidal swamp swamp / alluvial	1.2
31C	lagoon floor - 90 90 - 145	present - 1170 1170 - 1243	0.7 7.5	subtidal tidal channel or littoral	1.2
32C	lagoon floor - 30 30 - 80 80 - 123	present - 730 730 - 1933 1933 - 2204	0.4 0.4 1.6	subtidal subtidal subtidal	0.6
35C	lagoon floor - 50 50 - 105	present - 979 979 - 1069	0.5 6.1	subtidal subtidal / alluvial	1.0
36C	lagoon floor - 125	present - 1570	0.8	subtidal	0.8
38C	lagoon floor - 40 40 - 68	present - 2016 2016 - 2518	0.2 0.6	subtidal subtidal	0.3
39C	lagoon floor - 53 53 - 68	present - 1714 1714 - 1887	0.3 0.8	subtidal intertidal	0.4
40C	lagoon floor - 42	present - 871	0.5	subtidal	0.5
41C	lagoon floor - 55 55 - 100	present - 1566 1566 - 1834	0.4 1.6	subtidal subtidal	0.5
43C	lagoon floor - 140	present - 2117	0.7	subtidal / alluvial	0.7

Tab. 3 – Rates of sedimetation in different time intervals. The depositional environments are obtained from the analyses of the biofacies and their comparison with present day assemblages (cont.).

core	depth interval (cm)	age interval (years BP)	deposition rate (mm/y)	environment of deposition	average deposition rate (mm/y)
45C	lagoon floor - 50	present - 1160	0.4	subtidal	0.6
	50 - 93	1160 - 1611	1.0	subtidal	
	93 - 112	1611 - 1932	0.6	subtidal / alluvial	
49C	lagoon floor - 30	present - 1290	0.2	subtidal	0.6
	30 - 133	1290 - 1866	1.7	subtidal	
50C	lagoon floor - 30	present - 842	0.3	intertidal	0.5
	30 - 108	842 - 2026	0.6	subtidal / alluvial	
51C	lagoon floor - 52	present - 1370	0.3	subtidal	0.5
	52 - 134	1370 - 2548	0.7	subtidal	
53C	lagoon floor - 20	present - 820	0.2	intertidal	0.6
	20 - 124	820 - 1883	0.9	subtidal / alluvial	

The cores 1, 17, 27, 30, 35, 43, 45, 50 and 53, located near the continental margin of the Lagoon, have reached the pre-lagoonal substrate, whose age is between 905 yBP (age of the peat at base of core 1) and 2117 yBP (age of the peat at base of core 43). In case of core 30, however, the establishment of the present Lagoon, over an older marsh of 3000 yBP was dated at 240 yBP. The ages of the more internal areas of the Lagoon appear, in fact, always younger than those of the central portions, which show an age of 4670 ± 70 yBP in the historic centre of Venice [Serandrei Barbero *et al.*, 2001] and 5064 ± 130 yBP in the northern sector of the Lagoon [Serandrei Barbero *et al.*, 2004a].

In cores 1, 17 and 27 the age of the basal sediments of the Lagoon, obtained from lagoon molluscs as 1035, 2278 and 2403 yBP respectively, appears to be older than the ages of the continental deposits, obtained from peat remains and of the order of 905, 1869 and 1620 yBP. This discrepancy is due to the *reservoir effect* [Zoppi *et al.*, 2001], which can produce differences of up to 1000 years based on organisms characterized by different physiologies.

In all these marginal cores the rate of sedimentation, even with the degree of approximation due to the reservoir effect, is generally between 0.2 and 0.9 mm/y. Only core 30 shows a higher value, for the last 240 years, of 1.2 mm/y. This more active sedimentation is reflected by the presence of sands, probably from a channel deposit.

In the cores 35, 45, 50 and 53, where the rate has been determined for different time intervals, high values of the order of 0.6 to 1.0 mm/y are obtained at the base of the sequence (time interval 1600 to 820 yBP) while at the top of the sequence the sedimentation rates are never greater than 0.2-0.4 mm/y during the last 820 years.

Conclusions.

In marginal settings such as the Lagoon of Venice, the rate of sedimentation is strongly controlled by the local morphology; in a sedimentary sequence different morphologies are often present and are due to the migration of morphological units such as channels and saltmarshes. This constantly changing environment is related to variations in sediment inputs, in transport conditions, in redepositional processes and in changes in eustatism.

These changes are reflected in the sedimentary sequences by the presence of *ecological transitions* in the foraminiferal *biofacies*. The main *ecological transitions* noted in the 26 cores are: 1) the pre-lagoonal deposits located close to the continental margins of the Lagoon; 2) the presence of ancient saltmarshes buried under subtidal deposits; 3) a buried shoreline inside the middle part of the present lagoon.

The ^{14}C chronology obtained from shell material present in the different biofacies establishes a time sequence for these events: the littoral sediments, found in core 29 at 90 cm depth has been dated for the first time at 3180 yBP; the buried saltmarshes shown by the biofacies in cores 14, 39, 50 and 53 have given different ages ranging from 870 to 1887 yBP. The cores from the inner part of the Lagoon, which have reached the continental substrate, indicate that the lagoonal environment was established in historic or protohistoric times, between 820 and 2403 yBP. The oldest lagoonal deposit (3437 yBP), was obtained from shells found at 90 cm depth and wholly within lagoonal sediments.

The age of the deposits is related to the rate of sediment accumulation; from the 57 age determinations on organic remains the average rate of accumulation, inclusive of eustatism and subsidence, is 0.5 mm/y. However, if different time intervals are selected, the rates become:

1 mm/y for the period 2500-1500 yBP
0.4 mm/y from 1500 yBP to the present

The rates therefore appear to be halved in historic time with respect to the previous millennium.

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References.

Albani A.D., 1993. Use of benthonic foraminifera to evaluate the environmental characteristics of Port Hacking; significance for coastal engineering works and pollution. In G. McNally, M. Knight, & R. Smith (Eds.), *Collected Case Studies in Engineering Geology, Hydrogeology and Environmental Geology*. Geological Society of Australia: Sydney, pp. 134

Albani A.D., Favero V., Serandrei Barbero R., 1984. Benthonic foraminifera as indicators of intertidal environments. *Geo-Marine Letters*, 4, 43-47

Albani A.D., Favero V. and Serandrei Barbero R., 1991. The distribution and ecological significance of recent Foraminifera in the lagoon South of Venice (Italy). *Rev. Esp. Micropaleontologia* 23, 29 - 45

Alve E., 1995. Benthic foraminiferal responses to estuarine pollution: a review. *Journal of Foraminiferal Research* 25: 190-203

Bortolami G.C., Fontes J.Ch., Markgraf V., Saliege J.F., 1977. Land, Sea and Climate in the Northern Adriatic region during Late Pleistocene and Holocene. *Palaeogeography, Palaeoclimatology, Palaeoecology* 21, 139-156

Buzas M., 1990. Another look at confidence limits for species proportions. *Journal of Paleontology* 64, 842-843

Davis J.C., 1986. Statistics and Data Analysis in Geology. *John Wiley and Sons*, New York, 646 pp

Day J.W., Are D., Rismondo A., Scarton F., Cecconi G., 1995. Relative Sea Level Rise and Venice Lagoon Wetlands. Proceedings of *Medcoast 95* Conference, Terragona (Spagna) 24-27/10/95, 636-647

Donnici S., Serandrei Barbero R. and Taroni G., 1997. Living benthic foraminifera in the Lagoon of Venice (Italy). Populations dinamycs and its significance. *Micropaleontology* 43, 440 - 454

Donnici S., Serandrei Barbero,R., 2005 . I foraminiferi di ambiente vallivo della Laguna di Venezia. *Lavori Soc. Ven. Scienze Naturali,* in stampa

Favero V., Parolini R., Scattolin M., 1988. Morfologia storica della Laguna di Venezia. Comune di Venezia, Assessorato all'Ecologia, *Collana Ambiente* 3, 79 pp

Favero V., Serandrei Barbero R., 1980. Origine ed evoluzione della Laguna di Venezia - bacino meridionale. *Lavori Soc. Ven. Scienze Naturali* 5, 49 - 71

Guelorget O., Perthuisot J.P., 1983. Le domaine paralique. *Travaux du laboratoire de geologie*, 16. Presses de l'ecole normale superieure, Paris, 136 pp

Hayward B.W., Hollis C.J., 1994. Brackish foraminifera in New Zeeland: a taxonomic and ecologic review. *Micropaleontology* 40 (3): 185-222

Loeblich A.R., Tappan H., 1987. Foraminiferal genera and their classification. Van Nostrand Reinhold Company, New York, 970 pp

Loeblich A.R., Tappan H., 1992. Present status of foraminiferal classification. In: Studies in Benthic Foraminifera (edsY. Takanayagi and T. Saito), Proceedings of the *Fourth International Symposium on Benthic Foraminifera,* Sendai 1990 (Benthos '90), Tokai University Press, Tokyo, Japan, 93-102

McClennen C.E., Ammerman A.J., Shock S.G., 1997. Framework Stratigraphy for the Lagoon of Venice, Italy: Revealed in New Seismic-Reflection Profiles and Cores. *Journal of Coastal Research* 13, 745-759

Massari F., Rio D., Serandrei Barbero R., Asioli A., Capraro L., Fornaciari E., Müllenders W., Raffi I., Vergerio P.P., 2004. The environment of Venice in the past two million years . *Palaeogeography, Palaeoclimatology, Palaeoecology,* 202, 273-308

Mozzi P., Bini C., Zilocchi L., Beccatini R., Mariotti Lippi M., 2003. Stratigraphy, palaeopedology and paynology of Late Pleistocene and Holocene deposits in the landward sector of the lagoon of Venice (Italy), in relation to the Caranto Level. *Il Quaternario, Italian Journal of Quaternary Sciences*, 16, 1bis, 197-214

Petrucci F., Medioli F. S., Scott D.B., Pianetti. F.A., Cavazzini R., 1983. Evaluation of the usefulness of foraminifera as sea level indicators in the Venice Lagoon (N. Italy). *Acta Naturalia* 19: 63-77

Ramasco, C., 1991. Qualità delle acque del Bacino Centrale della Laguna di Venezia. *CNR-ISDGM Technical Report* 161, 54 pp

Scott D.B., Medioli F.S., 1980. Living vs. total foraminiferal populations: their relative usefulness in paleoecology. *Journal of Paleontology* 54, 814-831

Scott D.B., Suter J.R., Kosters E.C., 1991. Marsh foraminifera and arcellaceans of the lower Mississippi Delta: Controls on spatial distributions. *Micropaleontology* 37, 373-392

Serandrei Barbero R., Albani A., Bonardi M., 2004a. Ancient and modern salt marshes in the Lagoon of Venice. *Palaeogeography, Palaeoclimatology, Palaeoecology* 202, 229–244

Serandrei Barbero R., Albani A., Bonardi M., Donnici S., 2004b. Foraminiferal biotopes as environmental monitoring indicators: a comparison with the 1983 foraminiferal faunas. In "*Scientific Research and Safeguarding of Venice. Research Programme 2001-2003, Volume II, 2002 results*". CORILA, 175-188 pp, Venezia

Serandrei Barbero R., Albani A.D. e Favero V., 1989. Distribuzione dei foraminiferi recenti nella laguna a Nord di Venezia. *Boll. Soc. Geol. It.* 108, 279 - 288

Serandrei Barbero R., Albani A., Zecchetto S., 1997. Palaeoenvironmental significance of a benthic foraminiferal fauna from an archaeological excavation in the Lagoon of Venice, Italy. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 136, 41-52

Serandrei Barbero R., Carbognin L., Taroni G. and Cova E., 1999. Distribution of Recent Benthic Foraminifera in the Southern Basin of the Venice Lagoon (Italy): Statistical Evaluation of Taxa Significance. *Micropaleontology* 45, 1 - 13

Serandrei Barbero R., Lezziero A., Albani A., Zoppi U., 2001. Depositi tardo-pleistocenici ed olocenici nel sottosuolo veneziano: paleoambienti e cronologia. *Il Quaternario*, 14 (1), 9-22

Tuniz C., Bird J.R., Fink D., Herzog G.F., 1998. Accelerator mass spectrometry: ultrasensitive analysis for global science. CRC Press, Boca Raton. FL (USA), 371 pp

Zoppi U., Albani A., Ammerman A., Hua Q., Lawson E.M., Serandrei Barbero R., 2001. Preliminary evaluation of the reservoir effect in the lagoon of Venice. *Radiocarbon*, 43 (2A), 489-494

SAR INTERFEROMETRY FOR GROUND VERTICAL DISPLACEMENT OF SMALL ISLANDS IN THE VENICE LAGOON: THE CASE OF MURANO ISLAND

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Riassunto.

La conoscenza della dinamica dei movimenti verticali del suolo assume un ruolo fondamentale nello studio dei processi geomorfologici ed in particolare nella valutazione delle cause dell'erosione o dell'accumulo dei sedimenti. La sopravvivenza di strutture morfologiche lagunari, quali le barene e le velme, oltre che ai fenomeni di erosione imputabili al moto ondoso e alle correnti, è subordinata alla loro altimetria rispetto al livello del mare che, per periodi brevi, risente principalmente del processo di subsidenza e secondariamente dell'eustatismo. Variazioni di quota del piano campagna rispetto al livello del mare, anche piccole, possono innescare i processi di erosione o accumulo di sedimenti.

Con lo scopo di determinare i tassi dei movimenti verticali del suolo in aree insulari della Laguna di Venezia non coperte dai rilievi topografici tradizionali (livellazioni e GPS differenziale), è stata effettuata l'analisi di immagini SAR, acquisite dai satelliti ERS-1 e ERS-2, attraverso interferometria differenziale (INSAR) e l'analisi dei riflettori puntuali (IPTA). In questo lavoro è riportato l'esempio dell'Isola di Murano.

Abstract.

Our knowledge of the dynamics of vertical ground movements plays a fundamental role in the study of the geomorphological processes, particularly for determining sediment deposition and erosion causes. The conservation of lagoon morphological structures such as salt marshes and tidal flats, besides erosion due to waves and currents, depends on their surface height with respect to the sea level that, for short periods, is primarily related to the land subsidence process and secondarily to eustasy. Ground vertical variations with respect to the sea level, even if small, can, in fact, trigger sediment erosion and deposition processes.

To determine land displacement rates in small islands of the Venice Lagoon not covered by traditional surveys (levelling and differential GPS), SAR-based monitoring techniques, i.e. differential SAR interferometry (INSAR) and interferometric point target analysis (IPTA) from ERS-1 and ERS-2 satellites, were performed. We will use the Murano Island for our example in this contribution.

1. Introduction.

Repeat-pass spaceborne Synthetic Aperture Radar (SAR) interferometry is a powerful technique for the observation of land surface deformation at mm resolution, as demonstrated in the Venice area by Tosi *et al.* [2002] and Strozzi *et al.* [2003]. In the SAR interferometric approach two satellite radar images are combined to exploit the phase difference of the signals. The interferometric phase is sensitive to both surface topography and coherent displacement along the look vector occurring between the acquisitions of the interferometric image pair. The basic idea of differential SAR interferometry (INSAR) [Strozzi *et al.*, 2001a] is to subtract the topography related phase from the interferogram to derive a displacement map. Important problems for SAR interferometry are decorrelation and heterogeneity of atmospheric path delay. Temporal decorrelation occurs from changes in the scatterer characteristics, for instance over vegetation, and leads to incomplete spatial coverage. Spatial decorrelation prevents interpretation of the interferometric phase for extended targets in pairs with long baselines. Techniques for overcoming these problems have been developed and can be applied for a specific case depending on the availability of a Digital Elevation Model (DEM), on the characteristics of the SAR data with respect to spatial baseline, acquisition time difference and coherence, on the displacement rates and shapes, on the land cover, and on the topography. Interferometric Point Target Analysis (IPTA) [Werner *et al.*, 2003] makes interpretation of the phase values only on reflectors with a scattering behavior corresponding to that of a point target, to avoid geometric decorrelation, and that are persistent over the whole observation time period, to avoid temporal decorrelation. In this way more acquisitions may be included in the analysis to increase accuracy, temporal sampling, and spatial coverage.

2. The application of SAR interferometry in the Venice Lagoon.

In this project we used SAR interferometry to measure the ground vertical displacement of areas of the Venice Lagoon not covered by traditional surveys (levelling and differential GPS) i.e. small islands. The validation of the SAR interferometric displacement rates performed in the framework of the ISES and VENEZIA Projects [Carbognin and Tosi, 2003; Carbognin *et al.*, 2004] through levelling and differential GPS surveys in areas where data from all techniques are available demonstrated a mm/year accuracy of the vertical displacement rates.

First, a time series of six interferometric radar images of the European Remote Sensing Satellites ERS-1 and ERS-2 from 1993 to 2000 was considered. In order to generate a displacement map with reduced errors, the six INSAR images were combined [Strozzi *et al.*, 2001b]. The map presented in Fig. 1 shows information over the major urban areas, with a few scattered points in other regions. Then, IPTA has been applied with 59 ERS-1/2 SAR images between 1992 and 2000. Point targets with valuable information are scattered over villages, suburban areas, and isolated structures (Fig. 2a). Deformation time series, as indicated for one point in Fig. 2b, are available from IPTA. This analysis of ground vertical displacement with SAR interferometry demonstrated a general land stability of Murano Island.

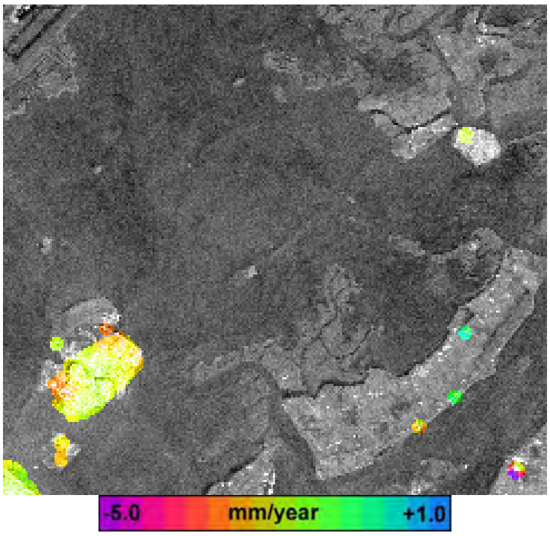

Fig. 1 – Land subsidence map for the Lagoon area in the north-east of Venezia (Murano Island) over the time period 1993-2000 from INSAR. Background is an averaged ERS backscattering intensity image.

a) b)

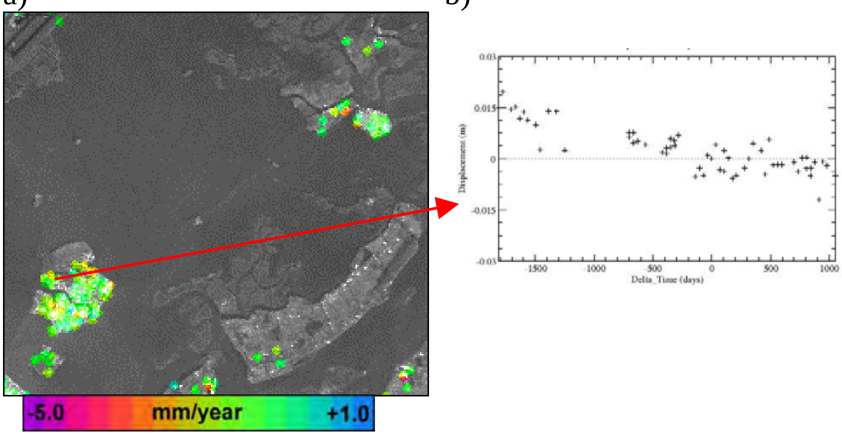

Fig. 2 – a) Land subsidence map for the Lagoon area in the north-east of Venezia (Murano Island) over the time period 1992-2000 from IPTA. Background is an averaged ERS backscattering intensity image. b) Deformation time series from IPTA for the indicated point target for the time period from 1992 to 2000.

Conclusions.

The application of differential SAR interferometry (INSAR) and Interferometric Point Target Analysis (IPTA) in small island of the Venice Lagoon provided new data regarding the ground vertical movements of areas never investigated in the past. In particular, in the case of Murano Island, the analysis of ground vertical displacement with SAR interferometry shown a general land stability with maximum sinking rates of less than 2 mm per year. The application of SAR-based monitoring techniques appears as an important tool capable of providing data for the morphodynamics study of the lagoon setting.

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References.

Carbognin L., Tosi L., 2003. Il Progetto ISES per l'analisi dei processi di intrusione salina e subsidenza nei territori meridionali delle province di Padova e Venezia. 96 pp, 12 tavv. f.t., Grafiche Erredici, Padova

Carbognin L., Teatini P., Tosi L., 2004. Eustacy and land subsidence in the Venice Lagoon at the beginning of the new millennium. *Journal of Marine Systems*, doi:10.1016/j.jmarsys.2004.05.021, 51(1-4), 345-353

Strozzi T., Wegmüller U., Tosi L., Bitelli G., Spreckels V., 2001a. Land Subsidence Monitoring with Differential SAR Interferometry. *Photogrammetric Engeneering & Remote Sensing*, 67: 1261-1270

Strozzi T., Tosi L., Wegmüller U., Teatini P., Carbognin L., 2001b. Thematic and land subsidence maps of the Lagoon of Venice from ERS SAR interferometry. CORILA Research Program 2001 Results (ed. by P. Campostrini), IVSLA Venezia, 345-355

Strozzi T., Tosi L., Wegmüller U., Werner C., Teatini P., Carbognin L., 2003. Land Subsidence Monitoring Service in the Lagoon of Venice. International Geoscience and Remote Sensing Symposium 2003, Toulouse, France, 21-25 July 2003, Vol. I: 212-214

Tosi L., Carbognin L., Teatini P., Strozzi T., Wegmüller U., 2002. Evidences of the present relative stability of Venice, Italy, from land, sea and space observations. *Geophysical Research Letters,* 29: 10.1029/2001GL013211

Werner C., Wegmüller U., Strozzi T., Wiesmann A., 2003. Interferometric Point Target Analysis for Deformation Mapping. In: *Proceedings of IGARSS'03*, Toulouse, France, 21-25 July

THE ORIGIN OF THE SAND IN THE VENICE LAGOON

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Sommario.

Questo studio comprende l'applicazione di modelli numerici, osservazioni in campo ed analisi di laboratorio al fine di descrivere la dinamiche che regolano l'evoluzione delle piane tidali della parte nord della Laguna di Venezia. Tali informazioni serviranno a predire l'evoluzione morfologica ed a pianificare la gestione di queste aree. Gli aspetti più importanti di questo studio sono lo sviluppo di un modello di trasporto dei sedimenti per la Laguna di Venezia (SEDTRANS05) e la scoperta dell'importanza delle sabbie nella difesa e nello sviluppo delle barene in Laguna di Venezia, costituendo il basamento su cui le barene crescono, e fornendo protezione dall'erosione delle onde.

Quattro campagne di osservazione sono state svolte durante questo progetto (2 in estate e due in inverno per un totale di 40 giorni di osservazioni) al fine di mappare il sistema di canali Lido-Treporti-Burano, caratterizzandone anche le formazioni morfologiche, e creare un data set per l'applicazione e la calibrazione dei modelli matematici. Durante le osservazioni in campo sono stati raccolti più di 512 km di dati batimetrici e digital sidescan, 258 campioni di sedimento, 6 giorni di misure di velocità della corrente, profondità e torbidità in 6 stazioni nell'area dei canali di Burano (burst sampled at 4 Hz), 3 giorni di profili orari di misure ADCP lungo i canali Burano, Scanello, Preporti e S. Felice, in cui i trasporti residui di sedimenti sono stati stimati, e 3 misure di attenuazione delle onde lungo 3 profili di spiagge sommerse.

L'analisi dei dati prevede la produzione di una carta batimetrica e di una mappa di distribuzione dei sedimenti (basata sui dati di sidescan) e l'applicazione della relazione di O'Brien nella zona dei canali Lido-Treporti-Burano. Sulla base delle informazioni raccolte il modello di trasporto dei sedimenti SEDTRANS96 è stato migliorato e successivamente accoppiato al modello idrodinamico della laguna di Venezia SHYFEM [Umgiesser, 2000]. La nuova versione del modello, SEDTRANS05, verrà utilizzata in futuro per simulare il trasporto di sabbie e sedimenti fini.

Abstract.

This study comprised a coupled programme of numerical modelling, laboratory experimentation, and field surveying in order simulate the factors leading to the evolution of muddy tidal flats in northern Venice Lagoon for purposes of prediction and management. The most important aspects of the study are the predictive calibrated sediment transport model of Venice Lagoon (SEDTRANS05), the discovery that sand is a vital component to the protection and development of salt marshes in Venice Lagoon

as it forms the foundation on which marshes grow, and also provides protection from wave erosion at the margins.

We have collected over 512 line km of bathymetric data and digital sidescan, 258 bottom sediment samples, 6 days of current speed, depth and turbidity data at 6 key sites in the Burano canal system (burst sampled at 4 Hz), 3 days of hourly ADCP profiles across Burano, Scanello, Treporti and S. Felice canals from which residual transports of sediment have been estimated, and wave attenuance data across three profiles of submerged beaches. Analyses are still underway and include the updating of the cohesive sub-routine of SEDTRANS05, the production of a bathymetric chart based on a compiled data set, the production of a bottom character map based on the sidescan data and the application of the O'Brien relationship to the Lido-Treporti-Burano canal system.

Four field surveys were undertaken in this project (two summer and two winter, for a total of about 40 days field surveying) in order to map the Lido-Treporti-Burano canal system and to characterise the dominant morphological features within this system: As well, to provide a data set for numerical model simulation and calibration. SEDTRANS96 has been linked to the Umgiesser [2000] hydrodynamic model of Venice Lagoon and the sedimentation sub-routines have been advanced on the basis of our field results. The new version, called SEDTRANS05, will be used for both sand and fine-sediment transport in the future.

1. Introduction.

The main objectives of line 3.2 were:

(1) to build a data base on the processes leading to erosion and deposition over time scales varying from centuries to years; and

(2) to develop a coupled mathematical model capable of describing these changes in short and medium time scales.

The time-scale for this work was 3 years from 2001-2004. Objective (1) was largely undertaken by SOC under the direction of Professor C. L. Amos, objective (2) was undertaken under the direction of Dr. G. Umgiesser at CNR-Grandi Masse. The two objectives were strongly linked through joint effort and regular consultation and is a good example of a fully-integrated field-laboratory-modelling study. These activities were supplemented by collaboration with the EURODELTA team (COMDELTA Conference, May, 2003) who undertook key high-resolution seismic profiles in the region, the BIOFLOW Conference (August, 2004) concerned with bio-roughness, flume optimisation, and biostabilization of tidal flats, and the EUROSTRATAFORM Programme which has had a strong presence in the N. Adriatic (Po delta) since 2000 (and will provide calibration data for the Po delta simulation).

It was not possible, given the time-frame of this study, to study of the entire Lagoon. Consequently, attention was focussed on the Lido-Treporti-Burano canal system where a number of key questions were defined based on previous studies of the region largely undertaken by CNR and in the F-ECTS project [Bergamasco *et al.*, 2003]. Perhaps the most important question to resolve was the apparent growth of the tidal flats in this region [Cappucci, 2002] which contrasted with losses of tidal flats elsewhere [Carbognin and Cecconi, 1997]. In this study, we proposed to examine the balance of fine sediment within the main channel (Scanello) which feeds an actively accreting tidal flat (Palude della Centrega) in an attempt to understand why this region is accreting and which factors are important in this accretion, and to update the defining equations governing the sediment budget. Fine sediment behaviour over tidal flats is reviewed by Van Straaten and Keunen [1957] and more recently by Perillo [1995]. Initial sensitivity analyses using a very simple box model of Palude della Centrega suggest that the evolution of the flats (trapping efficiency) is controlled by the balance between wave erosion during Bora events and tidal sedimentation during fine weather [Cappucci *et al.*, 2004]. This balance is strongly affected by (1) turbidity of the waters flooding the tidal flats, (2) by sea grass density, which suppresses wave action and tidal flow, and (3) by biostabilization due to microphytobenthos which enhances stability. We also know that even in regions dominated by fine-grained sediments there is a large bedload component. In Venice, Flindt *et al.* [1997] discovered large quantities of macrophytes (Ulva and Chaetomorpha) moving throughout the lagoon close to the bed at current speeds as low as 0.02 m/s. These macrophytes induce a solid-transmitted stress to the bed [Amos *et al.*, 2000a; 2000b] that can cause scouring below the fluid-transmitted stress threshold. Laboratory studies of this mechanism were used to quantify the magnitude and character of the solid-transmitted stress, which has been incorporated in SEDTRANS05 [Levy, 2000].

The objectives of (1) were achieved through four field surveys to Venice (August, 2001; February, 2003; February, 2004 and June, 2004) over a total period of 40 days. These surveys are briefly described below.

2. Field campaigns.

2.1. Field campaign of August, 2001.

The major activities revolved around data collection in order to resolve the issues described above. In particular, this comprised:

- a detailed bathymetric survey at the confluence of Burano and Treporti canals in a region of active scouring. This was completed with the discovery that active scour to 18 m depth was taking place at most triple junctions of the canal system. Resuspension was evident on ADCP profiles at tidal fronts evident on early ebbing tides, which develop at the confluence of ebbing tidal masses that move at different velocities. The bottoms of the scours are sandy/gravelly and are a source of sand to the canal system.
- A detailed ADCP survey of the Treporti region was undertaken to determine the origin, nature and causes of a tidal front at the confluence of Burano and Treporti canals. The results are presented in Reed [2001] and Tremblay [2002].
- CTD profiles and sampling of the water column were made throughout the canal system Treporti-Burano-San Felice in order to define the character of the water masses and the distribution of chlorophyll and sediment in suspension.
- A reconnaissance sidescan sonar survey (Marine Electronics model 1640) of the Lido entrance was made to determine the net transport of sand and the morphology of the bedforms are the entrance. The results are presented in Chick [2002].

- ADCP profiles at key sections of the canal system to determine the mass balance of water, sediment and chlorophyll (recommended by M Bonardi). Results are presented in Amos *et al.* [2004].
- SIS (Sediment Imaging System) survey was carried out on newly-discovered submerged beaches (Palude della Centrega). The results are presented in Munford [2002].
- The mass balance of water/sediment/chlorophyll at Scanello and Burano for purposes of calibration of the box and 2-D numerical simulations were calculated. The results are presented in Amos *et al.* [2004].

The most important discovery of the survey was the existence of submerged beaches of fine sand surrounding Palude della Centrega. These beaches attenuate waves and protect the marshes from wave erosion due to the presence of Cymadocea beds on the outer submerged beach. The sheltering role of plants in Venice Lagoon has been studied by Thompson *et al.* [2004]. The beach is made of well-sorted fine sand and is located on a shoulder of the eroded palude surrounding the margins of Palude della Centrega. We observed that ship wakes were strongly attenuated by the presence of this beach, and in particular over the Cymadocea beds. We have undertaken a detailed survey of the morphology of these beaches, as well as the grain size of the material, and have undertaken measures of wave attenuance and sand resuspension over them. We propose that this morpho-dynamical feature results in natural protection of the palude from wave erosion. We also noted that remedial works to protect the palude from erosion near Scanello have removed this submerged beach and appear to have increased the potential of erosion, not reduced it.

The tidal front off Treporti has been well monitored and linked to the scouring of the tidal channel to a depth of 18 m. The 3-D structure of the water masses at the confluence of Treporti and Burano canal have been mapped in detail (Fig. 1) and forms the basis of a completed M.Sc thesis (Lea, 2002). The thesis also provides calculations of the mass balance of water through the canal system and shows a very strong flood-dominance in Treporti-San Felice as well as Burano canal, and a strong ebb dominance in Scanello. This shows that the accreting tidal flats of western Centrega are supplied by water and sediment that flows in through San Felice and across eastern Centrega. The passage of the majority of the ebbing waters is unknown, but must be to the west and north of the island of Burano and over Palude del Monte.

A calibration of the ADCP backscatter to suspended sediment and chlorophyll was attempted but showed a high degree of scatter. This is considered the result of the high phytoplankton content of the water masses and low sediment content.

The sidescan survey of Lido showed a well-developed suite of sand waves and megaripples in the centre of the channel. These bedforms are flood oriented even on an ebbing tide, thus indicating a migration of sand into the lagoon.

We noted a series of turbid fronts in Burano canal generated by the outflow of waters from the canals entering from Palude di Burano and Centrega. These fronts existed on both the flood and ebb tides, and show that Burano is a conduit of sediment derived from the adjacent paludi and is not the source to the tidal flats. The 14-hour time-series at the mouth of Scanello canal [see Amos *et al.*, 2004] shows that it strongly exports material from Palude della Centrega to the Burano canal. SIS surveys of the mouth of Scanello canal show that there is a significant bedload component to this export. We think that it is largely macrophyte debris.

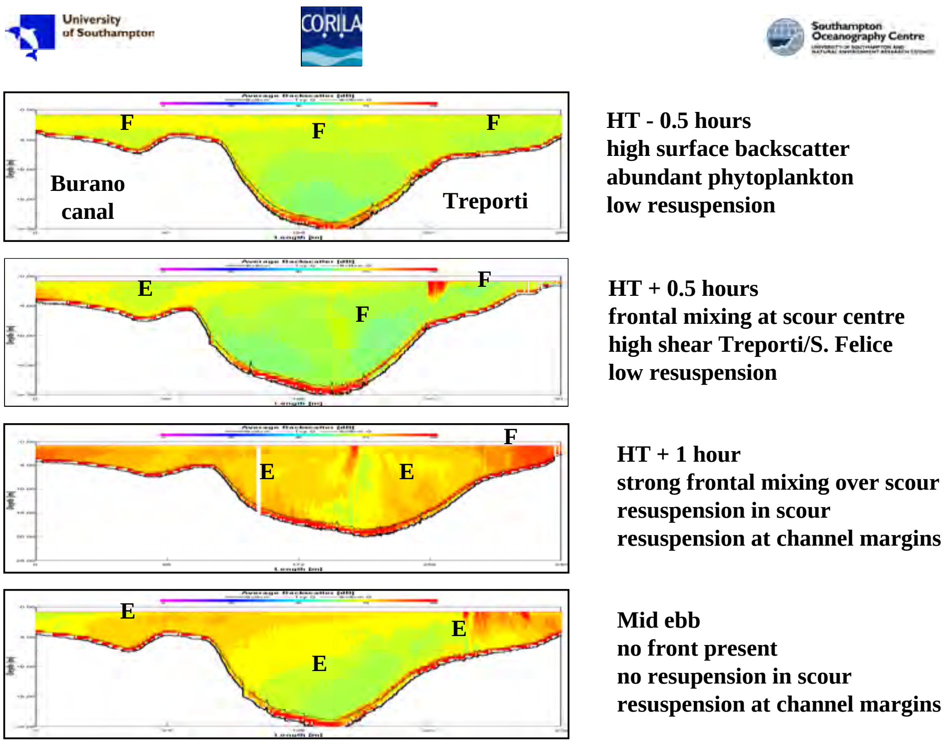

Fig. 1 – ADCP profiles across Treporti canal though the scour hole at the Burano-Treporti-S. Felice triple junction.

The floating aggregates come from Palude dei Laghi. There are two possible explanations for their origin: the first explanation is that they result from eutrification of biofilms at the centre of this palude. This happens on neap tides when evaporation leads to high salinities and strong bacterial reduction. The free methane so produced increases buoyancy and so they are floated off the bed during the build-up of subsequent spring tides. A second explanation is that they are produced by free oxygen due to high photosynthesis of microalgae that dominate the biofilm of the tidal flats. When low water coincides with solar noon this effect is maximised. During the periods of intense sun-light the biofilm becomes buoyant and thus resuspended on a flooding tide. The aggregates were seen floating in the canals surrounding Palude dei Laghi during ebbing tides only, and could be traced only as far as Burano canal where they were quickly broken down by boat traffic whereupon they sank. Unfortunately, the aggregates were absent from all surveys in this project.

2.2. Field Campaign of February, 2003.

A 10-day operation based at Mazzorbetto was undertaken with input from Drs. C.L. Amos, G. Umgiesser, P.L. Friend and G. Maillet. As well, Dott. T. Missaen (BSRG) joined us for 1 week in order to prepare for the COMDELTA conference and to discuss sites for the high-resolution seismic survey. The boats of CORILA and D. Tagliapietra were used throughout. Conditions were calm and clear for the entire survey. The following activities were undertaken:

(1) A survey was undertaken to map the bathymetry of the Burano-Treporti canal system. A total of 220 line km of data were collected. As well, as digital sidescan was used to collect imagery of the bed at key sites from which the extensive distribution of fine sand was evident. The survey was concentrated upon the triple junctions of Scanello, Treporti and Torcello.
(2) Valeport 808 sensors were placed synoptically in the three canals of the triple junctions in order to examine the mechanisms leading to scouring. Good data were collected at Scanello and Torcello and will be combined with results from Reed [2001] and output from the Umgiesser [2000] model to prepare a publication on this mechanism.
(3) Two profiles were established to examine wave attenuance and sand resuspension at two profiles of submerged beaches in Burano canal: La Madonnina, and at the confluence of Burano and S. Felice canals. Attenuance of 13 vaporetto bow waves were logged and will be combined with results from Munford (2002) for preparation of a publication on this phenomenon.
(4) 33 bottom samples were collected along two transects from Lido to Treporti (Fig. 2B) in order to determine the size trends along the canal, and to attempt to relate these to flow magnitude in the form of a Tesi di Lauria (Universita di Ca' Foscari). A decrease in grain size was evident landwards, but this trend was not related to local flow conditions. Further studies of the mineralogy will be undertaken to determine the source of the sand (by R. Helsby).

2.3. Field Campaign of February, 2004.

A 10-day operation was undertaken based at Mazzorbetto. Those present were Drs. C.L. Amos, G. Umgiesser and Dott.ssa R. Helsby. The small boat of the camping was used for sampling and the boat of D. Tagliapietra was used for surveying. The following activities were undertaken:

(1) A bathymetric and sidescan survey was undertaken of Burano-Treporti to supplement data collected in 2001. This survey included the addition of a new 3-D Marine Electronics scanning sonar (model 4640) as well as was limited due to boat breakdown and bad weather. A total of 80 line km of survey was completed before the onset of bad weather. However, 225 bottom samples were collected from the rivers, canals, and beaches of the northern Lagoon.
(2) Sampling of the Lido entrance and the flood and ebb tidal deltas was carried out (92 samples, Fig. 2) in order to fit within the grid of samples described by Tosi (pers. comm.). Samples will be analysed for grain size (using the SOC sedimentation column) and mineralogy [after Gazzi *et al.*, 1973] and form the basis of a Ph. D. thesis (R. Helsby). The results will be used within the trend analysis model of Gao and Collins [1994], through application of the statistical model of Welje [1995], and through mineralogical indexes from Gazzi *et al.* [1973] to determine the net sand transport pathways within the Lido entrance.
(3) Sampling of the Cavallino-Lido-Pellestrina-Chioggia shoreline was undertaken at 1 km intervals to examine the trends in longshore transport and to examine the impact of beach replenishment at Cavallino on the trends of Gazzi *et al.* [1973]. Samples were collected from the sediment surface at the top of the swash zone.

(4) Sampling of the Tagliamento, Piave and Brenta rivers was undertaken as "source signatures" for sand within northern Venice lagoon.

The locations of samples collected during this survey and shown in Fig. 2.

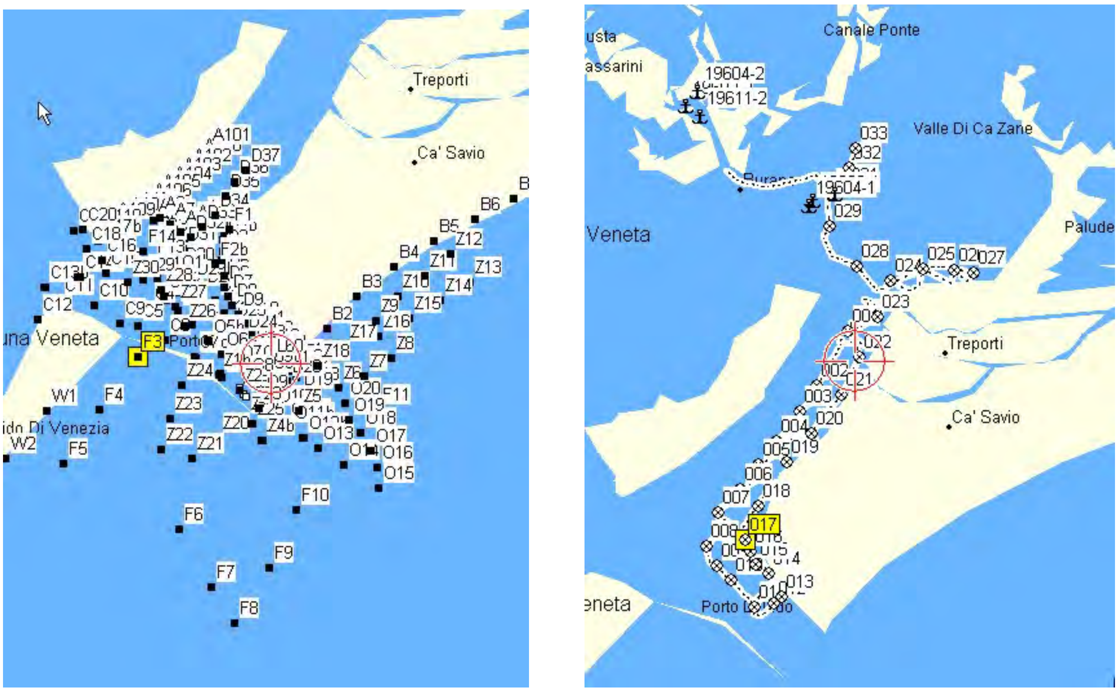

Fig. 2 – (A) The samples collected for analysis of grain size and mineralogy near the Lido entrance during the February, 2004 campaign. (B) 33 samples collected within the Treporti canal (also shown are the 6 current meter sites at Scanello and Torcello).

2.4. Field Campaign of May, 2004.

A 10-day field campaign was undertaken based at Foresteria – CNR-IBM. The survey was coordinated by C.L. Amos, G. Umgiesser and with input from R. Helsby. The boat of D. Tagliapietra was used throughout and was moored at the "pontone" of CNR-Grandi Masse on the Grand Canal. The weather throughout was cool but clear and breezy which was ideal for surveying. The purpose of this campaign was to collect bathymetric data and sidescan sonograms from the Lido entrance and the flood and ebb tidal deltas in the regions from which bottom samples were collected. The survey and sampling programme were coordinated throughout with discussions with L. Tosi and A. Mazzoldi in order to link with the next round of CORILA projects.

The survey boat was equipped with (1) a GPS system linked to Mapsource for positioning and line surveying; (2) A Lowrance (200kHz) echosounder linked to GPS and logged at 1 Hz; (3) a Fishfinder (200 kHz) echosounder logged at 1 Hz; (3) a digital sidescan sonar logged continuously; and (4) a digital 3-D swath sonar seeping at a rate of .2 Hz. A total of 212 line km of survey data was collected (see Fig. 3).

Fig. 3 – A summary of the survey lines undertaken during the February, 03 and May, 04 field campaigns. A total of 512 line km of survey were carried out.

3. Results.

The results of this research will be used to upgrade SEDTRANS to include some important advances. One of them will be an **erosion threshold** which will vary with eroded depth according to the internal friction angle of bed sediments, and according to the history of deposition and consolidation. Previous versions held this threshold constant. Work by Cappucci *et al.* [2004] has shown that friction angle (is the most important parameter controlling bed stability in Venice Lagoon and varies between 10 and 30^o. The higher the friction angle the more stable is the sediment. Evidence shows that it not monotonic with depth, but shows variations reflecting depositional history (Fig. 4).

Overall, it decreases to zero with depth in parallel with bulk density. A synthesis of data from Venice Lagoon shown in Fig. 5 illustrates that it is within other data worldwide and varies as a function of excess density:

$$\tau_c = 5 \times 10^{-13}(\rho_b\text{-}1100)^4 \text{ Pa} \qquad (1)$$

The minimum density of 1100 kg/m^3 is the value normally associated with the transition from mobile fluid muds to stationary fluid muds.

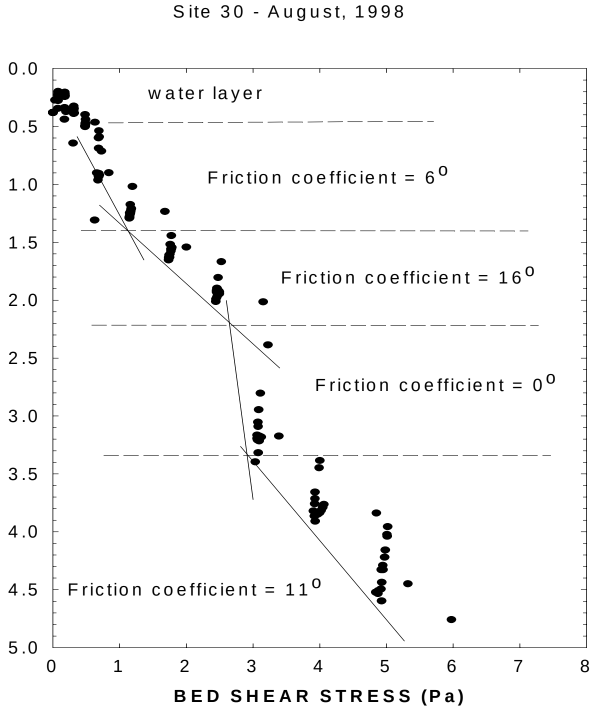

Fig. 4 – An example of bed strength changes with depth, evident by the changes in friction angle – sample taken from palude della Centrega during F-ECTS campaign.

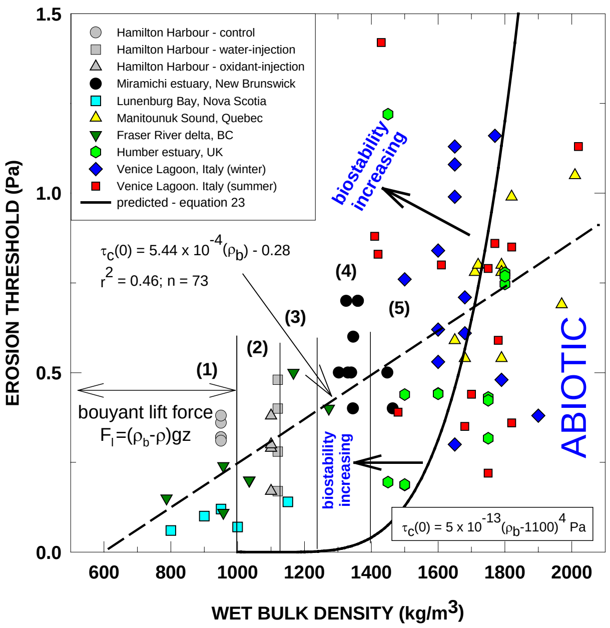

Fig. 5 – A summary of erosion thresholds from Venice Lagoon (summer and winter) compared with those from other studies worldwide.

An erosion rate (Em) taken from Amos *et al.* [2004] who showed:

$$Em = \chi\tau s\beta \text{ kg/m}^2\text{/s} \tag{2}$$

where the mean summer and winter values of χ and β were 0.0029 and 0.99, and 0.0012 and 2.13 respectively. The function is applicable to stresses above the critical. In practice, erosion decreases in an exponential fashion as the eroded depth exposes material of higher threshold, and ceases as eroded depth reaches the failure envelope [Parchure and Mehta, 1979].

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The **deposition threshold** (τd) has in the past been considered constant. However, it has been found by Bagnold [1941] that the maximum settling rate of particles (Ws) in suspension is equal to the upward instantaneous velocity (w'). In practical terms this is expressed as:

$$W_s = 0.8U_* \tag{3}$$

where U_* is the mean shear velocity of the flow. As it is proportional to the mean flow velocity ($U = \rho U_*^2$), it follows that the stress history is the dominant factor controlling settling character. Partheniades [1971] expressed the population of material in suspension as a Gaussian distribution and that any drop in stress will cause settling of that part of the population where $W_s > U_*$. The ratio of the material remaining in suspension to that deposited is called "the degree of retention". This ratio is finite above the traditional critical threshold whereupon all material in suspension will be deposited in time. This phenomenon is particularly important in Venice lagoon where suspension is caused by short-lived events such as the Bora and Sciroco. This representation allows material to deposit immediately after the passage of peak conditions thus increasing significantly the trapping efficiency [sensu Schubel and Kennedy, 1984] of the lagoon. Measurements of W_s vary between 2-4 x 10^{-4} m/s. (see Fig. 6).

The concentration in suspension under still-water conditions is strong exponential function of time in the form:

$$C(t) = C_o \exp^{-kt} \tag{4}$$

where C_o is a starting concentration and k is a decay constant. According to this formulation, W_s must remain constant throughout settling. Note the continuity of results between summer and winter surveys shown in Fig. 6 and the correspondence with results from other estuarine sites worldwide.

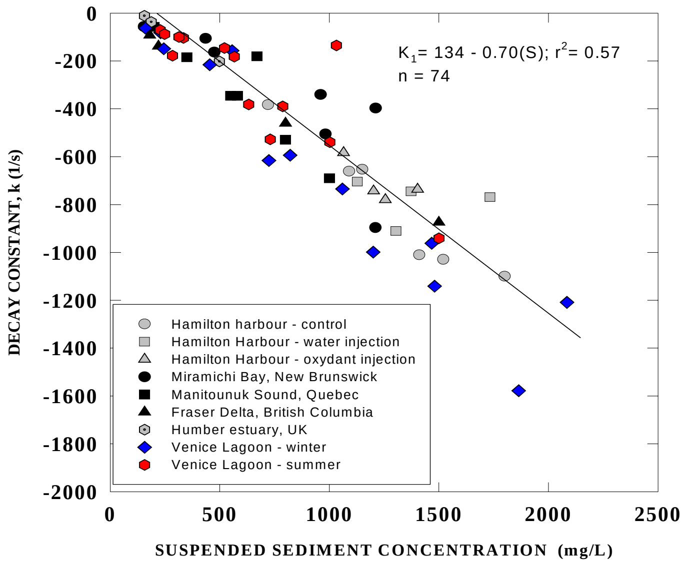

Fig. 6 – The still-water concentration decay constant plotted against initial sediment concentration. Note the strongly linear relationship diagnostic of a constant particle settling rate. Also note that the results from Venice Lagoon are similar for summer and winter seasons and fit with other examples worldwide.

Salinity dependence on W_s will be incorporated to simulate flocculation at the salt-water boundary. Data from Dyer [1984] will be used for this purpose. As well, the limits for free settling, flocc settling and hindered settling will be incorporated.

The upgrades to SEDTRANS are presently being implemented and tested. The final version will be coupled to the hydrodynamic model of the N. Adriatic and tested against data collected for the 2000 Po river flood event (courtesy of EUROSTRATAFORM).

Conclusions.

The tidal flats in the northern part of Venice Lagoon differ significantly in the accumulation and erosion rates from those south of Venice. The northern marshes are more stable and exhibit high sedimentation rates while those to the south are subject to erosion. Our results to date suggest that the major difference between the two regions is sediment texture. The region to the north is dominated by sandy sediment; the region to the south is largely silt/clay. The origin of the sand is unknown. We speculate it is derived from reworking of ancient barrier islands which have been mapped to occur in the northern regions [Bonardi and Tosi, 1995].

High-resolution seismic surveys conducted by Missaen et al. during the COMDELTA workshop showed the presence of internal cross-stratification similar to sand ridges on the Scotian Shelf. These features are undergoing scouring in the region of S. Antonio canal and may be a source of sand (see Fig. 7)

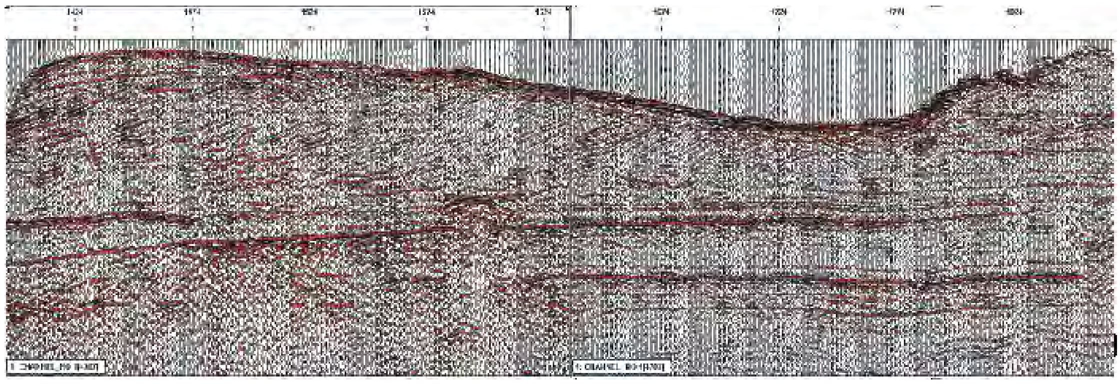

Fig. 7 – A high resolution seismic section along Burano canal from the scour pit off S. Antonio canal (far left). The sand ridge showing cross-bedding is evident in the figure and is thought to be supplying sand to the system through reworking. (image courtesy T. Missaen, BGSR and P. Simpkin, IKB).

We propose that the sand in the northern lagoon enhances preservation of the tidal flats in two ways: (1) it provides a stable base on which the mudflats can accumulate. This is a fundamental mechanism of tidal flat progradation that has been documented since the pioneering work of Evans [1965]; and (2) through the creation of submerged beaches around the tidal flats. We have found and mapped submerged beaches throughout Burano and San Felice canals and are best developed off Baccan (Lido). They are characterised by well-sorted fine sand that extends from the mid water level to the channel margin. They have a shore parallel bar often colonised by the seagrass *Cymadocea nodosi.* We observed that boat wakes break on this bar and are strongly dissipated through sand resuspension across the beach.

The submerged beaches thus appear to act as a natural defense against wave erosion. We have collected preliminary data on wave propagation across the sandy beach off Baccan, and the dissipation of wave energy through bottom drag over the various bed roughnesses of the region. Our results show significant wave energy loss and sand resuspension. We thus propose: (1) to map the distribution of submerged beaches in detail and to determine the composition, size, and source of the sand; (2) to monitor wave energy dissipation (both boat wakes and natural waves) across the submerged beaches in order to define a characteristic drag coefficient suitable for modelling; (3) to link sand resuspension to wave energy dissipation and evaluate the results within the context of the Rouse parameter for prediction purposes; (4) to define bed roughness as a 1-D spectrum to be defined from ultrasonic profiles of bed elevation across the sandy beaches. This will provide a quantitative measure of complex roughness (patchy plants and bare flats for example) that will be valuable in assigning drag coefficients within numerical tidal and wave models.

We propose to undertake this research with emphasis on the mouths of Venice Lagoon (principally Lido). In this way, our results will be directly relevant to the estimation of the residual transport of sand within the mouths. We will deploy benthic landers equipped with pressure sensors (for wave height), 2-D flow sensors (for nearbed wave/tidal flows), acoustic profilers (to monitor bed level changes and sand in suspension), and sector scanning sonars (to map bedform evolution and migration). We will deploy three arrays across Baccan and evaluate changes in wave energy (αH^2) in relation to bed type between arrays. We will link these arrays to a series of 5 self-logging pressure transducers which will allow us to monitor wave energy dissipation at 8 sites across the tidal flats. The sites will be chosen based on a detailed sidescan mosaic of Baccan/Lido (using a high-resolution digital sidescan 670 kHz evaluated in Venice February, 2003), and a detailed calibrated bathymetric survey of the region.

Wave/current/turbidity data will be logged at 4 Hz, which will provide adequate resolution on wave/bed interactions over single waves (which is essential in a complex wave climate). While ship waves produce a regular wave train, natural waves are complex, short crested and behave as second-order forms. Because of this, we will monitor near-bed wave motion at 25 Hz using a Nortec ADV and evaluate the turbulent spectra under various states of natural waves during Bora and Scirroco events and define the bed shear stresses using TKE and Reynolds Stress methods. We envision that wave energy contribution to bed stress may regarded as a spectrum in which energy input will be within the lower frequencies (> 1 second) and energy dissipation within the higher (inertial sub-range) frequencies. The distribution of sand through the water column under waves will be monitored using the RD Instruments Pulse-coherent ADCP, which logs 3-D velocity and backscatter within the bottom boundary layer a 1 cm intervals and at 2 Hz. Pumped samples will be used to calibrate the backscatter to sand in suspension.

Sand transport through the inlets of Venice Lagoon takes place as traction, saltation and suspension. Traction/saltation are extremely difficult to measure but are usually manifested by migrating bedforms (ripples, megaripples and sand waves). Suspension is manifested in two forms: vortex separation over a rippled bed (resulting in a Rouse Profile), and as sheet flow; the greatest sand transport rates occurs as sheet flow. In the first case, sand is largely distributed throughout the benthic boundary layer in a fashion governed by ($\frac{W_s}{\beta\kappa U_*}$, where W_s is sand settling rate, β is an empirical coefficient dependent on sorting, κ is von Karmans constant and U_* is the bed friction velocity which is strongly dependent on bed roughness). For sheet flow, sand is restricted to the near-bed in a region (10 cm) of high excess pore pressure. The onset of sheet flow is strongly related to grain size and independent of flow Reynolds number. In order to simulate sand transport the following MUST be known:

- what bedforms are present in the inlets under the spectrum of flow conditions
- what are the stability phases (wave/current regimes) for the various bedform types recognized
- what is the form drag associated with each bedform type (needed for accurate estimations of U_*)
- what are the sand transport rates for the spectrum of flows for
    - traction
    - traction/saltation
    - suspension
    - sheet flow

We propose to answer all of these questions through a series of deployments of an instrumented, multi-parameter, benthic lander – AQUILA. The benthic lander is an automatic, self-logging system which records flow conditions (waves and tidal currents) within the benthic boundary layer. It has an array of flow sensors to monitor the flow velocity gradient from which estimates of U_* will be made. As well, turbulence will be logged (at 25 Hz) using a Nortec ADV, and the Reynolds Stress and bed stress evaluated using the TKE method. Sand transport will be evaluated using (1) 4 OBS sensors at various heights within the benthic boundary layer, (2) using a sector scanning sonar (SSS) to monitor bedform type and migration rate, and (3) a profiling sonar (SIS) to monitor bed roughness, ripple migration and sand in suspension/sheet flow. Sand traps will also be placed at 5 heights on AQUILA in order to calibrate the acoustical and optical sensors.

Seabed samples will be collected at all sites and analyzed for grain size and settling velocity using the SOES sedimentation column. A digital, high-resolution sidescan survey of the survey sites will be undertaken in order to map the detailed bathymetry and bottom type. AQUILA will be deployed at no less than 4 locations in each inlet (dependent on grain size) and for periods no less than 12 hours. Field surveys of sidescan and ADCP profiles of across the inlets will be made throughout the AQUILA deployments in order to put the punctual measurements into the context of the entire channel width.

The deliverables will be:

- Time-series plots of the data collected
- Evaluation of bed roughness and U_* based on a time-varying drag coefficient
- Definition of threshold conditions for the various phases of sand transport and bedform stability phase diagrams
- Definition of sand transport rates as a function of U_* for the four phases of sand transport
- Residual sand transport rates for the duration of the survey periods.
- The value of β will be determined from these measurements and used to compare the estimated Roussian profiles with actual examples.

The long-term evolution of the canal systems of Venice Lagoon can be expected to move towards an equilibrium condition between the tidal prism (the mean volume of water between high and low and the cross-sectional area of the channel through which the tidal prism flows. This relationship (the O’Brien relationship) is found to be almost linear and applicable to sandy tidal entrances worldwide. This relationship will be evaluated for the Lido-Treporti-Burano canal system once the bathymetric maps have been produced. The tidal prisms for about 20 sections will be derived from the Umgiesser [2000] model. If the canal system falls along the O’Brien relationship then the canal system may be considered as stable in the long term. Conversely, if the canals are either too large or too small then erosion or deposition may be expected in order to move to equilibrium. The results of this evaluation will provide a long-term “calibration” for the numerical model predictions.

In conclusion, the most important findings concerning the morpho-dynamical evolution of northern Venice Lagoon are:

(1) submerged beaches form a significant part of the margins to the canal system. These beaches attenuate wave motion and thus protect the marshes from erosion. The beaches are composed of fine sand in dynamic equilibrium with the passage of waves, and also host colonies of *Cymadocea* that attenuate wave energy. The origin of the fine sand is unknown, but is thought to come from reworking of the canal bed and perhaps from the Lido entrance;

(2) active scours occur at the triple junctions of canals and are up to 18 m deep. They form through turbulence induced at the fronts between ebbing water masses and are thus a source of mobile material to the system;
(3) there is strong headward residual transport of suspended sediment in the study region caused largely by the residual circulation of tidal waters. Such residuals do not favour a loss of material from the lagoon and may, in part, explain the local growth of tidal flats; and
(4) the grain size trends (fining headwards) and the orientation of megaripples within the Lido entrance favour a movement of sand as bedload into the lagoon. This contrasts with initial model results that indicate a net export of sand from the lagoon. The overall conclusion of this work is that knowledge of the origins, transport pathways and depo-centres of sand is vital to the understanding of the evolution and well-being of the lagoon.

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References.

Amos C.L., Bergamasco A., Umgiesser G., Cappucci S., Cloutier D., Flindt M. Denat L. and Cristante S., 2004. The stability of tidal flats in Venice Lagoon – the results of *in situ* measurements using two benthic flumes. *Journal of Marine Systems Special Issue*

Amos C.L., Sutherland T.F., Cloutier D. and Patterson S., 2000a. Corrasion of a remoulded cohesive bed by saltating littorinid shells. *Continental Shelf Research* 20: 1291-1315

Amos C.L., Cloutier D., Cristante S. and Cappucci S., 2000b. The Venice Lagoon Study (F-ECTS) Field Results – February, 1999. Geological Survey of Canada open File Report 3904

Bagnold R.A., 1941. The Physics of Blown Sand and Desert Dunes. Publ. Chapman & Hall, London: 265p

Bonardi M. and Tosi L., 1995. Caraterizzazione e differenzazione mineralogical dei levelli sabbiosi tardo quarternari del litorale veneziano. *Italian Journal of Quaternary Sciences* 8(2): 315-322

Cappucci S., 2002 The Stability and Evolution of an Intertidal Flat in Venice Lagoon, Italy. Unpublished Ph.D. Thesis, Southampton University, 132p

Cappucci S., Amos C.L., Hosoe T. and Umgiesser G., 2004. Factors controlling the evolution of intertidal mudflats in Venice Lagoon, Italy. *Journal of Marine Systems Special Issue*

Carbognin L. and Cecconi G., 1997. The Lagoon of Venice, Environmental Problems and Remedial Measures. Meeting on Environmental Sedimentology, Venice: 71p

Chick K., 2002. The distribution of bedforms in Lido inlet and sand transport rates, Venice Lagoon. Unpublished B.Sc. Thesis, Univesity of Southampton, 88p

Dyer K.R., 1984 Coastal and Estuarine Sediment Dynamics. Publ. John Wiley & Sons, Chichester, 342p

Evans G., 1965. Intertidal flat sediments and their environments of deposition in the Wash. *Quarterly Journal of Geological Society of London* 121: 209-245

Flindt M., Salomonsen J., Carrer M., Bocci M. and Kamp-Nielsen L., 1997. Loss, growth and transport dynamics of Chaetomorpha aerea and Ulva rigida in the Lagoon of Venice during an early summer field campaign. *Ecological Modelling* 102: 133-141

Gao S., and Collins M.B., 1994. Analysis of grain size trends, for defining sediment transport pathways in marine environments. Journal of Coastal Research 10(1): 70-78

Gazzi P., Zuffa G.G., Gandolf G. and Paganelli L., 1973. Provenienza e dispersione litoranea delle sabbie delle spiagge adriatiche fra le foci dellIsonzo e del Fogilia: inquadramento regionale. *Memorie della Societa Geologica Italiana* 12: 1-37

Lea, J. 2002. The residual tidal circulation of water, sediment and organics in Northern Venice Lagoon, Italy. Unpublished B. Sc. Thesis. University of Southampton

Levy A., 2000. The effects of the macrophytes on bed stability. Unpublished M. Sc. Thesis, Acadia University, Canada

Munford G., 2002. The role of submerged beaches in the salt marsh protection of Venice Lagoon. Unpublished B.Sc. Thesis. University of Southampton, 63p

Parchure, T.M. and Mehta, A.J. 1979 Erosion of soft cohesive sediment deposits. *Journal of Hydraulic Engineering* 111, 1308-1325

Partheniades E., 1971. Erosion and deposition of cohesive materials. In, *River Mechanics V.* II. (H.W.Shen, ed.): 25-91

Perillo, G. 1995. Geomorphology and Sedimentology of Estuaries. *Developments in Sedimentology* 53. Publ. Elsevier Science: 471p

Reed P., 2001. An ADCP survey of a tidal front in the northern Venice Lagoon. Unpublished M.Sc. Thesis. University of Southampton

Schubel J.R. and Kennedy V.S., 1984. The estuary as a filter: an introduction. Kennedy, V.S. (ed), The Estuary as a Filter. Publ. Academic Press, Orlando: 1-11

Thompson, C.E.L., Amos, C.L. and Umgiesser, G. 2004 A comparison between fluid shear stress reduction by halophytic plants in Venice Lagoon, Italy and Rustico Bay, Canada – analyses of in situ measurements. *Journal of Marine Systems, Special Issue*

Tremblay, G. 2002. Dynamique sedimentaire du canale Burano, Lagune de Venise. Unpublished B.Sc. thesis, Univerity of Quebec a Rimouski, 24p

Umgiesser G., 2000. Modelling residual currents in the Venice Lagoon. In. *Interactions between estuaries, coastal seas and shelf seas*. T. Yanagi (Ed). Publ. Terra Scientific Publishing Company: 107-124

Van Straaten, L. and Keunen, M.J.U. 1957. Accumulation of fine grained sediments in the Dutch Wadden Sea. *Geologie en Mijnbouw*: 239-354

Weltje G.J., 1995. Unravelling mixed provenance of coastal sands: The Po Delta and adjacent beaches of the Northern Adriatic Sea as a test case. In: Oti, M.A. and Postma, G. (eds), Geology of Deltas, Balkema, Rotterdam: 181-202

MODELING SAND TRANSPORT IN A CANAL SYSTEM, NORTHERN VENICE LAGOON

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Riassunto.

L'origine delle sabbie nella laguna di Venezia è stata oggetto di un'estesa indagine sperimentale portata avanti in parallelo all'applicazione di modelli numerici. All'interno dei canali di Treporti e Burano sono stati definiti tre transetti, lungo i quali sono stati prelevati 33 campioni di sedimento. Su questi campioni sono state effettuate analisi granulometriche al fine di evidenziare eventuali trend di granulometria utili alla comprensione dei processi di trasporto.

Lo studio modellistico è stato suddiviso in due parti: il modello di trasporto di sedimenti SEDTRANS96 è stato utilizzato con il modello idrodinamico SHYFEM per simulare il trasporto di sabbia all'interno del canale di Treporti. In seguito è stato creato un modello a box attraverso cui sono stati calcolati i flussi di acqua e sedimento. È stato simulato il comportamento di diverse granulometrie utilizzando sia differenti regimi di vento e marea ideali, sia i dati reali di un anno tipo per la laguna di Venezia (il 1987). Oltre al trasporto è stato successivamente effettuato un bilancio di sedimenti per avere una stima di erosione e deposizione.

I risultati dell'analisi granulometrica hanno evidenziato che nel canale di Treporti non si trova un trend granulometrico e la sabbia risulta di granulometria fine (106 µm). Tale assenza di trend suggerisce che non vi è un trasporto significativo di sabbia attraverso la bocca di Lido verso l'interno della laguna. I risultati ottenuti con le simulazioni sembrano confermare l'ipotesi di rimaneggiamento della sabbia all'interno della laguna stessa. L'erosione calcolata è di alcuni cm/anno, ciò è indicativo di un'erosione e allargamento del canale nel tempo. Il canale di Treporti è soggetto ad una forte velocità di corrente che portando le sabbie fini in sospensione ne impedisce la deposizione.

Abstract

The origin of the sands in the Venice lagoon has been the subject of extensive field surveying in parallel with numerical modeling. Three transects along Treporti and Burano canals were conducted from which 33 bottom sediment samples were collected. These samples were analysed for grain size and sorting to examine any trends in the granulometry of these sediments that might shed light on transport paths.

The modeling study consists of two parts: the sediment transport model SEDTRANS96 was used with a finite–element, hydrodynamic model (SHYFEM) to

simulate sand transport in Treporti canal. A type of linked box model was created by combining elements of the main model and subsequently computing water and sediment fluxes for the so-created boxes. Several grain size classes were simulated; the distribution before and after the simulation were examined. A variety of wind regimes were used to force the tidal flows, as well as a full year of measured tidal and wind data. Only a part of the Venice lagoon was covered by the simulation: a major channel running from the Lido inlet north towards the northern lagoon.

The total transport through all of the sections was computed for 1987 (a normal year in Venice lagoon). Sediment mass balance was determined and the resulting trends of erosion and deposition were computed.

There were no trends in the median grain diameter and sorting of bottom samples from Treporti canal; all sands were fine (106 microns, one outlier of 300 micron was removed).

The absence of a trend in grain size suggests that there is no significant import of sand to the lagoon through the Lido inlet. The results from the simulations seem therefore to confirm the hypothesis of reworking of sand within the lagoon. The computed erosion is some cm/year diagnostic of channel scouring and enlargement with time. The Treporti canal is subject to strong current velocities of around 1 m/s which hold fine sand in suspension and thus prevent sedimentation.

1. Introduction.

The Venice lagoon is an extremely complex ecosystem. In this environment the sand transport has an important role for the morphological transformations.

The coastal lagoon development is closely connected to the barrier islands system formation due to the long-shore currents. The sandy sediment is transported along the seacoast to form a shore spits that are transformed into barrier islands.

The type of coastal setting and its morphological manifestation is governed by the relative proportions of sand to mud [EMPHASYS Report, 2000]. When mud dominates, then fringing tidal flats and wetlands dominate the coastal landscape and barrier islands are largely absent; when sand dominates, then beaches, barriers and lagoons dominate. The fact that Venice is located within a lagoon immediately illustrates the dominating role of sand in the evolution of this coastal setting.

Submerged beaches form a significant part of the margins to the canal system. These beaches attenuate wave motion and thus protect the marshes from erosion. The beaches are composed of fine sand in dynamic equilibrium with the passage of waves, and also host colonies of *Cymadocea* that attenuate wave energy. The origin of the fine sand is unknown, but is thought to come from reworking of the canal bed and perhaps from the Lido entrance.

This work aims to give a contribution to these questions. Here a sediment transport model has been applied, together with a hydrodynamic model to study the sand transport in one of the major channels in the lagoon, close to the northernmost inlet. The model has been set up as a box model, and the net transport of the sandy material and the mass balance has been determined. With the knowledge of these parameters, and with a field campaign that analyzed the grain size trend in this channel, it was possible to make some first hypothesis on the origin of the sand in the lagoon.

2. Methods.

2.1. Field campaign.

2.1.1. Sampling.

A field campaign was carried out in the Treporti channel (northern part of the Venice Lagoon, see Fig. 1), in order to study the grain size distribution and, in a second step, to test the output of a sediment transport model.

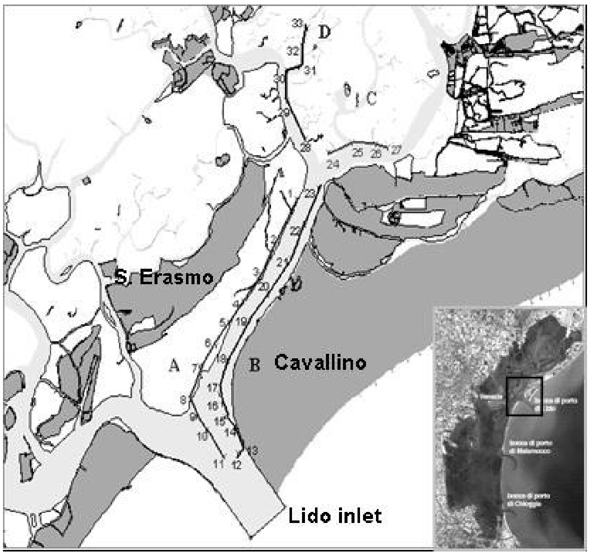

Fig. 1 – Overview of the sampling area.

The sampling area was subdivided in four transects; thirty-three samples were taken. Samples 1 to 11 were taken in the shallower area north of the main channel (transect A) and samples 12 to 23 were taken in the deepest part of the channel (transect B). Other samples were taken in the Burano and the S. Felice channel, but were not used in this analysis (transects C, D).

The sediment samples were taken with a medium van Veen grab. This instrument during its operation, disturbs the samples which makes it difficult to extract only the superficial level (0-3 cm) and it does not allow to either measure vertical variations of the sediment characteristics nor to sample deeper levels. Therefore, in most cases, the samples were diluted which prevented an accurate determination of color and appearance.

2.1.2. Granulometric analysis.

The granulometric composition of the Treporti channel was determined using two different methods. For sandy fractions of four sieve sizes (500, 250, 125, 63 µm) were used. In this work the sheet-flow effect has not been considered. The weight of the sieves has been measured with an analytic balance and the percentage with respect to the total weight of sandy sediment fraction has been determined. For fine sediments the

Sedigraph 5000D Micromeritics was employed. This instrument computes the grain size by estimating the transmittance produced by an X ray beam which crosses the sediment scattered in the water.

The classification of fine and coarse sediments followed the Wentwort scale [1922] which puts the limit between sand and mud at 63 µm and the limit between mud and clay at 4 µm.

2.2. *Modeling.*

Two numerical models have been applied to the Treporti channel in order to study the mobility of the sediments found in the experimental phase. The models used were the hydrodynamic model SHYFEM and the sediment transport model SEDTRANS96.

2.2.1. Hydrodynamic model (SHYFEM).

The hydrodynamic data used in the simulations with the sediment transport model have been derived from the numerical model SHYFEM, developed at ISMAR-CNR of Venice. SHYFEM is a finite element program that can be used to resolve the hydrodynamic equations in shallow water. The program uses finite elements for the spatial resolution of the equations and an effective semi-implicit time resolution algorithm, which makes this program especially suitable for the application to complicate geometry and bathymetry.

The subdivision of the system in triangles, varying in form and size, allows the simulation of shallow water flats, tidal marches that in tidal cycle may be covered with water during high tide and then fall dry during ebb tide.

The equations used in the model are the well known vertically integrated shallow water equations in their formulation with water levels and transports:

$$\frac{\partial U}{\partial t} - fV + gH\frac{\partial \varsigma}{\partial x} + RU + X = 0 \tag{1}$$

$$\frac{\partial V}{\partial t} + fU + gH\frac{\partial \varsigma}{\partial y} + RV + Y = 0 \tag{2}$$

$$\frac{\partial \varsigma}{\partial t} + \frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} = 0 \tag{3}$$

where ζ is the water level, u, v the velocities in x and y directions, U, V the vertical integrated velocities.

$$U = \int_{-h}^{\varsigma} udz \qquad V = \int_{-h}^{\varsigma} vdz \tag{4}$$

g the gravitational acceleration, $H = h + \zeta$ the total water depth, h the undisturbed water depth, t the time and R the friction coefficient. The terms X, Y contain all other terms that may be treated explicitly by the semi-implicit algorithm like the wind stress or the non-linear terms. [Umgiesser *et al.*, 2004].

The grid of the Venice lagoon model is constructed by a subdivision of the area into 4000 nodes and almost 8000 triangular elements to describe the lagoon’s geometry and bathymetry. Thanks to the flexible size of the elements it is possible to have a higher spatial resolution for the three inlets and the small channels.

2.2.2. The wave model.

Resuspension of sediments due to wind-generated waves is an important source of sediment to the water column. The wave sub-model utilizes empirical formulations which provide approximate estimates of significant wave height and period. This model does not take into account refraction, dispersion or wave breaking effects.

The formulation of the significant wave height (H_{m0}) and period (T_p) is based on the well know empirical prediction equations for shallow water [U.S. Army Engineer Waterways Experiment Station, 1984]:

$$\frac{gH_{m0}}{U_A^2} = 0.283\tanh\left[0.530\left(\frac{gh_a}{U_A^2}\right)^{3/4}\right]\tanh\left[\frac{0.00565\left(\frac{gX}{U_A^2}\right)^{1/2}}{\tanh\left[0.530\left(\frac{gh_a}{U_A^2}\right)^{3/4}\right]}\right] \tag{5}$$

$$\frac{gT_p}{U_A} = 7.54\tanh\left[0.833\left(\frac{gh_a}{U_A^2}\right)^{3/8}\right]\tanh\left[\frac{0.0379\left(\frac{gX}{U_A^2}\right)^{1/3}}{\tanh\left[0.833\left(\frac{gh_a}{U_A^2}\right)^{3/8}\right]}\right] \tag{6}$$

where U_A is the wind speed [m/s], g is the gravity [m^2/s], h_a is the averaged water depth along the fetch and X is the wind fetch [m]. h_a is the weighted average of the element water depth along the fetch using the each element part of the fetch distance as the weights. Using the averaged water depth along the fetch it could appear that the calculated wave height is higher than the real depth. To avoid this overestimation the wave height has been limited to the breaking wave height $H_{br} = 0.78h$ with h the element depth.

This empirical formulation assumes that the wind blows with essentially constant direction, over a fetch for sufficient time to achieve steady-state fetch limited values.

2.2.3. Transport model (SEDTRANS96).

The processes of sediment erosion, transport and deposition essentially occurs in the bottom boundary layer which forms the interface between the seabed and the water column. These processes greatly affect seabed stability, the dispersal of particulate material and benthic communities.

SEDTRANS96 is a two-dimensional computer model that can be used to predict the transport rate and direction of sand or mud under either steady currents or combined waves and currents outside the breaking zone. SEDTRANS96 adopts the Grant and Madsen [1986] continental shelf bottom boundary layer theory (GM86 hereafter) to predict bed shear stresses and the velocity profile in the bottom boundary layer. The model uses the algorithms of Einstein-Brown [Brown, 1950] and Yalin [1963] for bedload prediction. The methods of Engelund and Hansen [1967] and Bagnold [1963] are used to determine total load transport (bedload plus suspended load). At the present, SEDTRANS96 uses the median grain size of bottom sediment in its calculations and does not deal with the effect of grain size distribution. The prediction of cohesive sediment transport adopts a new algorithm proposed by Li and Amos [1997] [Li and Amos, 2001].

2.2.3.1. Calculation of critical shear stresses

As bed shear stress increases, sediment particles will first be entrained from their inert positions and then go through three distinctive modes of transport, bedload, suspension and sheet-flow transport. In this work the sheeflow effect has not been considered. From bottom conditions the critical shear stresses and critical shear velocity are computed for every transport mode.

BEDLOAD TRANSPORT:

$$\tau_{cr} = \vartheta_{cr}(\rho_s - \rho)gD \qquad \text{[Pa]} \tag{7}$$

The Yalin's metod according to Miller *et al.* [1977] has been used to obtain the dimensionless critical Shields parameter ϑ_{cr}:

$$\log \vartheta_{cr} = 0.041 (\log Y)^2 - 0.356 \log Y - 0.997 \qquad Y < 100 \tag{8}$$

$$\log \vartheta_{cr} = 0.132 \log Y - 1.804 \qquad 100 < Y < 3000 \tag{9}$$

$$\vartheta_{cr} = 0.045 \qquad \text{[m s}^{-1}\text{]} \tag{10}$$

$$u^*_{cr} = \sqrt{\frac{\tau_{cr}}{\rho}} \tag{11}$$

where τ_{cr} the critical shear stress, u^*_{cr} is the critical shear velocity, ϑ_{cr} is the Shields parameter, Y is the Yalin parameter that is defined as $\left[(\rho_s - \rho)gD^3/\rho\nu^2\right]^{0.5}$, ρ is the fluid density, ρ_s is the sediment density, g is the gravity acceleration, , D is the (median) grain diameter, and ν is the Kinematic fluid viscosity

SUSPENSION TRANSPORT: In this case the settling velocity W_S [Gibbs *et al.*, 1971] of a sediment grain of diameter D is first calculated:

$$W_s = \frac{\left\{-3\mu + \left[9\mu^2 + \left(gD^2/4\right)\rho(\rho_s - \rho)(0.0155 + 0.0992D)\right]^{0.5}\right\}}{\left[\rho(0.0116 + 0.0744D)\right]} \qquad \text{[m s}^{-1}\text{]} \tag{12}$$

where μ is the dynamic viscosity of the transporting fluid.

The critical shear stress τ_{crs} is than computed from Bagnold [1966]:

$$\tau_{crs} = 0.64\rho W_s^2 \qquad \text{[kg m}^{-1}\text{ s}^{-2}\text{]} \tag{13}$$

$$u^*_{crs} = 0.8W_s \qquad \text{[m s}^{-1}\text{]} \tag{14}$$

These critical values are compared with the bottom stress value produced by flow conditions in order to determine the start and duration of three transport modes. After that SEDTRANS96 computes transport rates only when the bottom stress goes past one of the critical values.

2.2.3.2. Calculation of flow conditions in the boundary layer.

Through the bottom boundary layer theory of waves and currents the model computes the velocity profile and the bottom stress. The model uses the Grant & Madsen method (1986) to estimate the friction factor and the combined-flow stress. This method determines first the bottom boundary layer velocity profile and than the shear velocity is calculated in this way:

$$u^*_{cw} = u^*_w C_r^{0.5} \qquad [\text{m s}^{-1}] \tag{15}$$

where C_r is the relative strength ratio of wave to current, estimated through:

$$C_r = \left[1 + 2\left(\frac{u^*_c}{u^*_w}\right)^2 \cos\phi_b + \left(\frac{u^*_c}{u^*_w}\right)^4\right]^{0.5} \tag{16}$$

φ_b is the angle between wave and current in the boundary layer. The wave shear velocity u^*_w is obtained by:

$$u^*_w = \left(C_r f_{cw} u_b^2 / 2\right)^{0.5} \qquad [\text{m s}^{-1}] \tag{17}$$

The friction factor f_{cw} can than be obtained by iteration from:

$$\frac{1}{\left(4 f_{cw}^{0.5}\right)} + \log\left[\frac{1}{\left(4 f_{cw}^{0.5}\right)}\right] = \log\left(\frac{C_r u_b}{\omega z_0}\right) + 0.14\left(4 f_{cw}^{0.5}\right) - 1.65 \tag{18}$$

where $z_0 = \dfrac{k_b}{30}$ is the bottom roughness.

The procedure described above is repeated three times, using different roughness heights, to obtain various friction factors and shear velocity.

a. At the first step SEDTRANS96 uses the grain roughness height $k_g = 2.5D$ to estimate the friction factor and skin-friction velocities ($u^*_{cs}, u^*_{ws}, u^*_{cws}$);

b. At the second step the sum of predicted bedload roughness height and the grain roughness height is used to obtain bedload friction factor and bedload shear velocities ($u^*_{cb}, u^*_{ws}, u^*_{cwb}$);

c. At the third step the model derives the ripple roughness height $k_r = 27.7\eta(\eta/\lambda)$ which is added to the grain roughness height and bedload roughness height to give the total roughness height. Through this value the model computes the total friction factor and total bed shear velocities (u^*_c, u^*_w, u^*_{cw}).

2.2.3.3. Duration of transport.

SEDTRANS96 calculates the time during a wave cycle when the respective threshold criteria are exceeded. A vectorial sum is used to obtain the instantaneous combined shear stress τ_{cws} from:

$$\tau_{cws}(t)^2 = \left[\tau_{ws}\cos(\omega t) + \tau_{cs}\cos(\phi_b)\right]^2 + \left[\tau_{cs}\sin(\phi_b)\right]^2 \qquad (19)$$

where φ_b is the angle between τ_{cs} and τ_{ws}. The duration of bedload transport t_b is obtained by solving the following equation:

$$\left[\tau_{ws}\cos(\omega t_b) + \tau_{cs}\cos(\phi_b)\right]^2 + \left[\tau_{cs}\sin(\phi_b)\right]^2 \geq \tau_{crb}^2 \qquad (20)$$

The same procedures are repeated using τ_{crs} to derive the time for suspended load transport.

2.2.3.4. Sediment transport.

The model calculates sediment transport only if the flow velocity at the seabed exceeds one of the critical values. The instantaneous sediment transport is integrated though a wave cycle to obtain the time-averaged net sediment transport rate. Five transport algorithms are available in SEDTRANS96 (Engelund-Hansen total load equation, Einstein-Brown bedload equation, Bagnold total load equation, Yalin bedload equation, cohesive sediment transport*)*. In this work, the Engelund-Hansen algorithm is used. The original Engelund–Hansen equation was based on unidirectional flume experiment data and was derived for dune-covered beds with mean grain size larger than 150 µm. This equation modified for continental shelf conditions reads:

$$q = 0.05 u_{100}^2 \rho^2 u_*^3 / D(\Delta\rho g) \qquad [\mathrm{m\ s^{-1}}] \qquad (21)$$

where q is the volume rate of sediment transport per unit width of bed, $\Delta\rho = (\rho_s - \rho)$ and u_* is a general form skin-friction shear velocity.

2.2.4. Application of models.

The Treporti area was subdivided into 4 boxes delimited by 8 sections, using the existing grid of the finite element model in order to compute the hydrodynamic data necessary for the transport simulations (Fig.2).

The hydrodynamic input parameters needed for SEDTRANS96 were the flow conditions on every node of each section. These were computed through several simulations with SHYFEM. All simulations were carried out with a time step of 300 s. The hydrodynamic model was calibrated prior to this study, and all parameters (bottom friction, etc.) have been adopted in these simulations. Further details can be found in De Pascalis [2003].

Two sets of simulations were generated. In the first set simulation idealized wind and tidal regimes were used during a 12 hour period:

- tide ± 40 cm
- tide and bora (speed 15 m/s, direction 45° N)
- tide and scirocco (speed 10 m/s, direction 135° N)

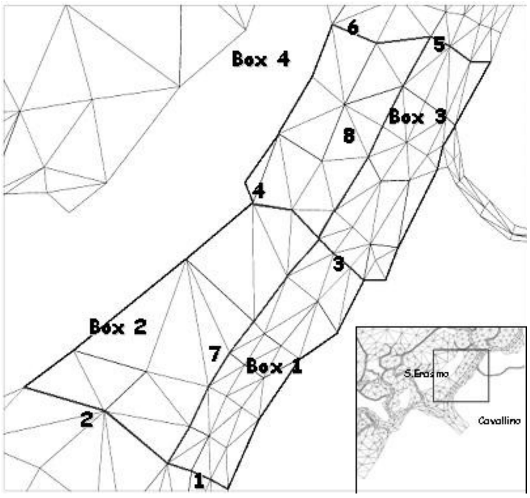

Fig. 2 – Finite element grid and box model of the studied area.

In the second simulation a entire year (1987) of real tidal and wind data were used. The wind field statistics during the year 1987 is shown in Fig.3.

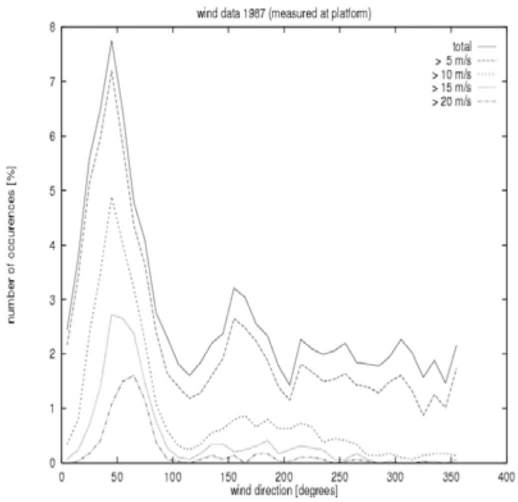

Fig. 3 – Wind distribution of year 1987.

Two peaks can be distinguished clearly: the first one, between 40-70° N, represents the bora events, frequently during the winter season. The second peak, with direction 140-170° N, represents the scirocco wind that blows mostly during summer [Coraci *et al.*, 2004].

The sediment transport model has been run for several grain size distributions (500, 250, 200, 150 µm). The Engelund-Hansen algorithm ($q = 0.05u_{100}^2 \rho^2 u_*^3 / D(\Delta\rho g)$) was used because this method is valid for grain sizes greater than 150 µm and was therefore able to cover nearly all the grainsizes found in the Treporti channel. The total transport through all sections was computed with the 12 hour simulations and for the year 1987 which seemed to be representative of Venice lagoon. A mass balance was carried out and the bottom variation in each box due to erosion and deposition was computed.

3. Results.

3.1. Granulometric Analysis.

The frequency histograms of the granulometric class distribution show that 90% of the samples have an uni-modal distribution (Fig. 4).

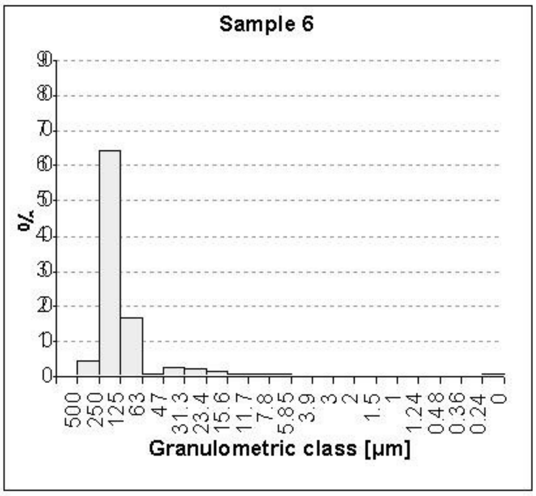

Fig. 4 – Unimodal distribution example of the grain size distribution in the Treporti channel.

For that reason the median is taken as the representative parameter of average grain size, and this value has been used in the model applications.

In order to classify the several typologies of sediments in the Treporti channel, all samples are subdivided on the basis of the Shepard diagram [Shepard, 1954] which distinguishes between contents of sand, mud and clay (Fig.5).

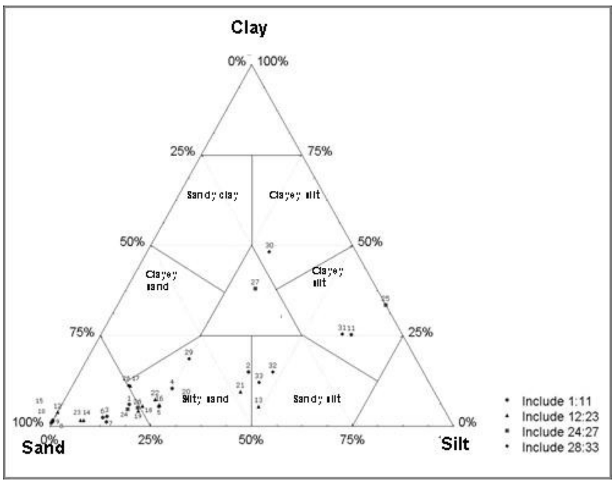

Fig 5 – Shepard diagram of the sediment composition in the four transects.

The sample distribution in this diagram shows that the grain texture is dominated by two main classes: sand and muddy sand. To understand which is the granulometric trend in the Treporti channel several statistic parameters were calculated: median, sorting and skewness. The median values of transects A and B in the Treporti channel are shown in Fig. 6.

These samples were analysed to gain information on the grain size trend along the transects. Two outliers were eliminated from the transects (one from each transect, outliers are shown in Fig. 6).

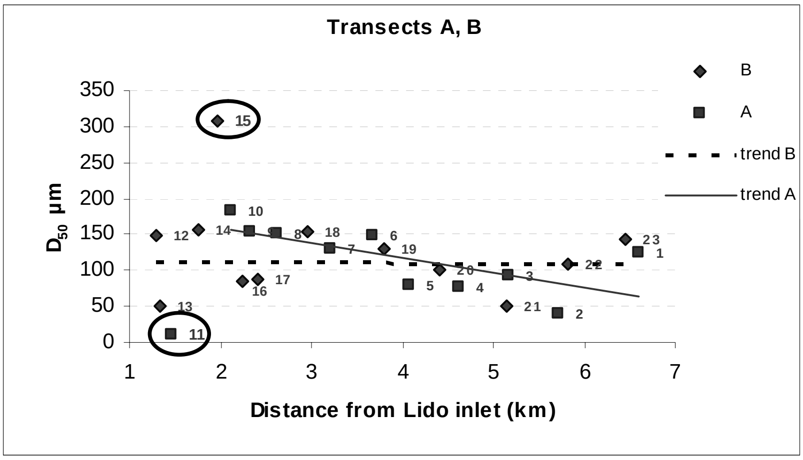

Fig 6 – Grain size distribution in transect A and B. Two outliers have been eliminated (samples 11 from A and 15 from B).

Results show that in the shallow area of the channel, where current is weaker (transect A), the mean diameter decreases entering the lagoon. In the deepest area of the channel (transect B), no granulometric trend could be found. The average value of the grain size in the Treporti channel is 106 µm.

3.2. Idealized simulations.

Results of simulations with idealized conditions are shown in this section. As mentioned above, in the hydrodynamic model application, during 12 hours, three cases have been considered (tide without wind, with bora and with scirocco). In these cases the idealized wind fields used have been kept constant over the Venice lagoon.

Maximum transport rates were predicted for the finest sand fraction (150 µm). In the case of tide only, the sediment transport occurs mainly in the sections with high current speed (1 and 3). The net transport, over a complete tidal cycle, is directed towards the open sea (Fig. 7).

When the tidal forcing is supplemented by bora winds, the sediment transport changes radically. In sections 1, 3, 5 (deep channel) the maximum transport is directed towards the lagoon. For the other sections (shallow part), the transport is lower and directed towards the sea (Fig. 8).

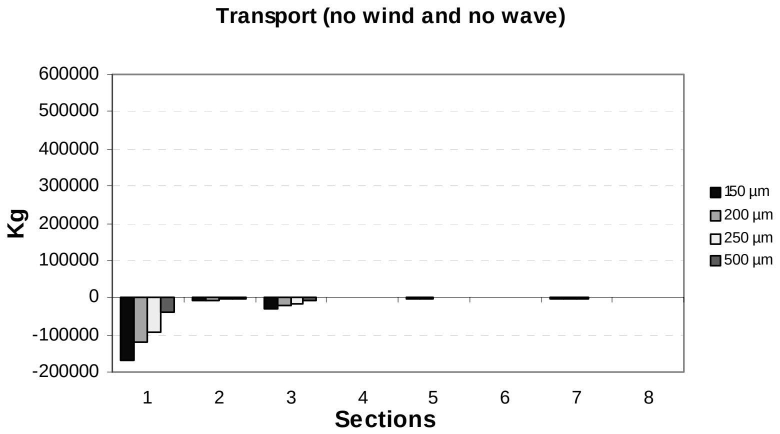

Fig. 7 – Sediment transport through eight sections during 12 hours and only tidal forcing.

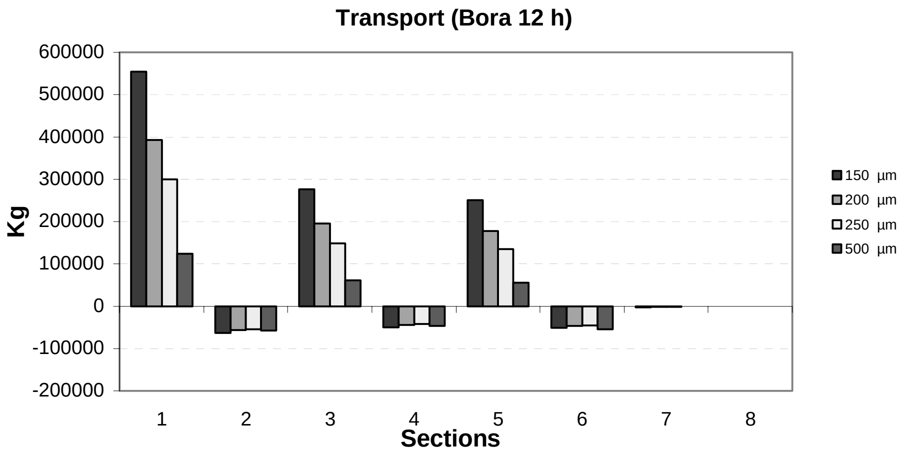

Fig. 8 – Sediment transport through eight sections during 12 hours and bora wind forcing.

In the final case, a sirocco wind forcing has been simulated. In this scheme it can be shown [Umgiesser, 2000; Solidoro *et al.*, 2004] that the wind pushes the water from the southern part into the northern part inducing the water to exit through the Treporti channel and the Lido inlet. However, Fig. 9 shows that in sections 1, 3, 5 the transport is positive and entering the Venice lagoon.

This paradox can be explained by the fact that during this situation the out-flowing phase is about 1 hour longer than the inflowing phase, which is more vigorous. Therefore, on average, the water flow is directed outward, but the sediment transport, much more sensitive to variations in high currents, shows an inward transport of sediments (Fig. 9).

The other sections (in the shallow part of the channel) show nearly no transport of sediments.

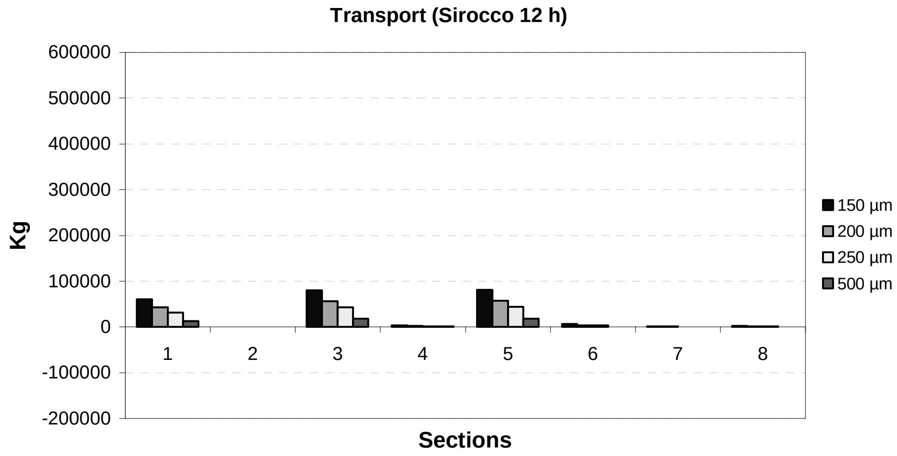

Fig. 9 – Sediment transport through eight sections during 12 hours and sirocco wind forcing.

3.3. Simulation of one year (1987).

The results of the year 1987 simulation may be considered as the most representative of the average lagoon sediment transport because the forcings are derived from real measurements (wind and tide). The transport through the 8 sections and the mass balance between the 4 boxes are shown in Fig. 10.

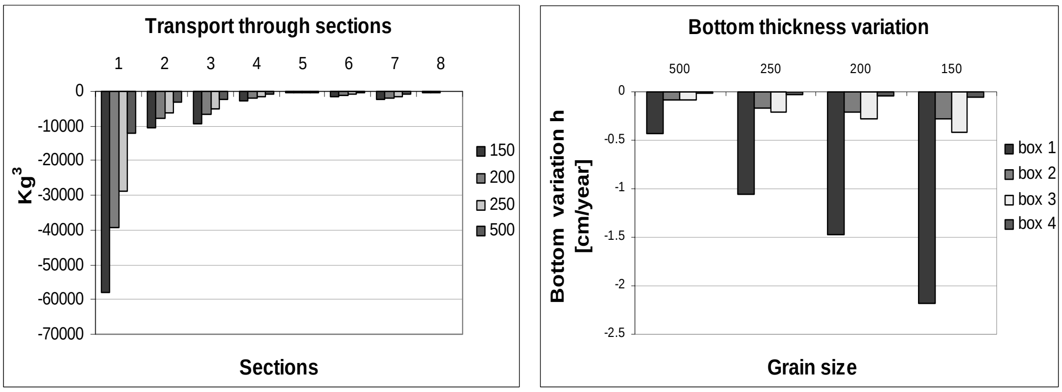

Fig. 10 – Simulations results of year 1987 for the Treporti channel. Transports through sections (left) and bottom thickness variation (right).

The bottom thickness variation is negative in all boxes showing erosion, which is higher for boxes closer to the inlet and for smaller grain sizes. This behavior, and the computed order of erosion of some cm/year, is in agreement with data and observations. The sediment transport through the Treporti channel during 1987 can be seen to be directed outward towards the Adriatic sea.

Conclusions.

The results obtained by application of the models during a tidal cycle show that the sediment transport is inversely proportional both to the grain size and to the distance from the Lido inlet. For the case of only tidal forcing the sediment transport is directed towards the sea [Umgiesser, 2000; Solidoro *et al.*, 2004].

In the bora case, the sediments of the Treporti channel show a net import into the lagoon, while in the shallow areas close to S. Erasmo the transport is directed towards the sea. This is due to the overall effect that the bora wind has on the circulation of the lagoon. The bora is most effective in pushing water to the south in the area north of S. Erasmo, since this area is very shallow (around 1.5 m). Therefore the water that must be replaced in the Northern lagoon can only be imported through the Treporti channel, the only deep channel leading north. This explains the ingoing northward flow in the Treporti channel, which is mostly governed by the basin wide circulation, and the southward flow in the shallower parts which are more influenced by the direct forcing of the wind.

When the sirocco wind blows over the lagoon the residual water circulation is directed out of the Lido inlet to the sea but this residual circulation is in contrast with the sediment transport results. In fact in all sections the sediment transport, resulting from all simulations, is directed into the lagoon. As explained before, observing the time series of currents it is possible to see that this is due to a slight difference of velocity between the two tidal phases. The incoming tidal phase is shorter and faster than the outgoing one. The high velocities of incoming phase cause an inward oriented sediment transport.

In order to obtain more information about the morphological variation into the Venice lagoon, the granulometric analysis results have been compared with the modelling results of the one year simulation. During the year 1987 the transport is directed outward of the lagoon in both the deeper channel and the shallow flats. This situation is comparable to the situation of no wind, where also the transport through all sections was directed outward.

The results obtained from granulometric analysis show the absence of a clear trend of the grain size distribution in the Treporti channel. This situation is compatible with the model results that show a sediment transport from the lagoon out into the Adriatic Sea. If there were a preferential transport of the sand from the Adriatic Sea into the lagoon, then we would expect a granulometric trend from coarse grain sizes in the vicinity of the inlets to finer grains the further we enter the lagoon, especially because the average grain diameter at the mouth of the Lido inlet is about 230 microns. However, the absence of any trend in the Treporti channel does not sustain the hypothesis that the sand is actually being imported from the sea through the Lido inlet. On the contrary, the absence of any trend and the results from the modeling sustains the hypothesis that the sand we find in the Treporti channel is actually part of an older sand barrier inside the lagoon and has therefore already been reworked. Moreover, the channel shows a trend of erosion which is in the order of 1.5 cm/year. This trend is confirmed by bathymetry charts and latest measurements [Amos *et al.*, tThis volume].

The shallow flats to the north of the Treporti channel show a landward trend from coarse to fine sands. The erosion is much less (2 mm/year), and seems basically stable. There seems therefore to exist two different mechanisms of sand transport in the area between the Cavallino sand barrier island and S. Erasmo: The first is a continuous erosion which is taking place in the deeper channel. This erosion prevents the accumulation of sand entering the lagoon from the Adriatic Sea and no sorting of the grain size takes place. The sand that can be found in the Treporti channel would therefore be sand already inside the lagoon, before the actual barrier islands have been formed and is now uncovered by the eroding currents.

On the other hand, the shallow flats close to the S. Erasmo island do show a grain size trend. Since the net erosion is close to zero this might lead to the conclusions that this trend is sustained by the alternation of sand intrusion and deposition and sand export and erosion of the flats. In this way the grain size trend could be explained.

The Treporti canal is subject to strong current velocities of around 1 m/s which hold fine sand in suspension and thus prevent sedimentation. The net transport of the suspended sand (averaged for 1987) is directed southwards towards the mouth of the lagoon. Thus the northern lagoon appears to be losing sand rather than gaining it. This is contrary to the mass movement of fines which moves largely landwards due to the strong flood-dominant residual currents. It is not known if the sand is transported out of the lagoon through Lido inlet, or if it is accumulating on the flood-tidal deltas and sand bars attached to S. Erasmo island. Studies undertaken by Chick [2002] suggest that sand moves landwards through the Lido inlet and thus a zone of convergence is expected where the canals of S. Nicolò, Treporti and Lido converge.

To resolve this concept of convergence, and indeed to undertake a sand budget estimate for the lagoon, further sampling of the bottom sediments and an extension of the model is underway. As well, a mineralogical study on the sediment samples has been undertaken to find out more about the origin of the sand in the northern lagoon and the Treporti channel [Amos *et al.*, 2004]. These studies will give us more insight in the processes that govern the sediment dynamics in the Venice lagoon.

References

Amos C. L., Helsby R., Umgiesser G., Mazzoldi A. and Tosi L., 2005. Sand transport in northern Venice lagoon. This volume

Amos C.L., Umgiesser G., Helsby R.A. and Friend P.L., 2004. Final Report - CORILA 3.2 – Idrodinamica e morfologia della laguna di Venezia (VELMA). *In Scientific Research and Safeguarding of Venice.* Volume II, CORILA, Venice: 189-202

Bagnold R.A., 1963. Mechanics of marine sedimentation. In: Hill, M.N. (Ed.), The Sea, 3. *Wiley-Interscience, New York*, 507-527

Bagnold R.A., 1966. An approach to the sediment transport problem from general physics. *US Geological Survey Professional Paper*, 4421, 37p

Brown C.B., 1950. In: Rouse, H. (Ed.), Engineering Hydraulics. *Wiley, New York*, 1039

Chick K., 2002. A sidescan survey of Lido Entrance, Venice Lagoon. Unpublished B.Sc. thesis, University of Southampton

Coraci E., G. Umgiesser, M. Sclavo and C.L. Amos, 2004. Modeling sand transport in the Venice lagoon inlets. In: *Scientific research and safeguarding of Venice. Proceedings of the annual meeting of the CORILA Research program 2002 results*, Volume II, Campostrini (ed), CORILA, Venezia, 157-173

De Pascalis F.,2003. Applicazione di un modello di trasporto di sedimenti ai canali principali della laguna di Venezia: il canale di Treporti. *Master thesis. Università Ca’Foscari Venezia*

EMPHASYS Consortium. 2000. A Guide to Prediction of Morphological Change within Estuarine Systems. *MAFF Project FD1401 Publication*: 53p + Appendixes

Engelund F., Hansen E., 1967. A monograph on sediment transport in alluvial streams. *Teknisk Vorlag, Copenhagen Denmark*, 62p

Gibbs R.J., Mathews M.D., Link D.A., 1971. The relation-ship between sphere size and settling velocity. *Journal of Sedimentary Petrology* 41, 7-18

Grant W.D., Madsen O.S., 1986. The continental shelf bottom boundary layer. *Annual Review of fluid Mechanics* 18, 265-305

Li M.Z., Amos C.L., 1997. SEDTRANS96: Upgrade and calibration of the GSC sediment transport model. *Geological Survey of Canada Atlantic Open File Report* 3512, 140p

Li M.Z., Amos C.L., 2001. SEDTRANS96: the upgraded and better calibrate sediment transport model for continental shelves. *Computers & Geosciences* 27, 619-645

Miller M.C., McCave I.N., Komar P.D., 1977. Threshold of sediment motion under unidirectional currents. *Sedimentology,* 24, 507-527

Shepard, F.P., 1954. Nomenclature based on the sand-silt-clay ratios. *J. Sedim. Petrol.,* 24, n. 3, 151-158

Solidoro C., D. Melaku Canu, A. Cucco and G. Umgiesser, 2004. A partition of the Venice Lagoon based on physical properties and analysis of general circulation. *Journal of Marine Systems*, Vol. 51, 147-160

U.S. Army Engineer Waterways Experiment Station, 1984. Shore Protection Manual. *U.S. Government Printing Office,* Washington DC, U.S

Umgiesser G., 2000. SHYFEM Finite element model for coastal Seas - User manual

Umgiesser G., Melaku Canu D., Cucco A., Solidoro C., 2004. A finite element model for the Venice Lagoon. Development, set up, calibration and validation. *Journal of Marine Systems,* 51, 123-145

Wentworth C.K., 1922. A scale of grade and class terms for clastic sediments*. J. Geol.* 30, 377-392

Yalin M.S., 1963. An expression for bedload trasportation. *Journal of Hydraulica Division, Proceedings ASCE 89 (HY3)*, 221-250

RESEARCH LINE 3.3
Efficiency of lagoon metabolism

ASSEMBLAGES AND ECOLOGICAL ROLE OF DIATOMS IN THE SURFACE SEDIMENT OF THE VENICE LAGOON

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Riassunto.

La necessità di avere validi strumenti di valutazione dello stato ecologico degli ambienti marini e di transizione ha indotto molti ricercatori a finalizzare la propria attività verso la definizione di indici di qualità ambientale. In questo contesto è già ampiamente diffuso l'utilizzo delle diatomee bentoniche, soprattutto per il monitoraggio dei corsi d'acqua dolce. Al fine di verificare il ruolo di tali organismi negli ambienti di transizione e la possibilità di elaborare un indice che descriva questi ecosistemi, sono stati raccolti, nell'ambito di due diverse campagne di campionamento, campioni degli strati superficiali (0.5 cm) di sedimento, in aree sempre sommerse.

Il set di dati, costituito dai risultati raccolti in tre stazioni campionate con cadenza mensile, da luglio 2001 a giugno 2002, ed in 84 siti studiati durante l'estate 2003, ha, principalmente, lo scopo di descrivere le variazioni spazio-temporali dell'abbondanza e della composizione tassonomica delle Bacillariophyceae bentoniche. La loro variabilità spazio temporale è risultata scarsa se confrontata con quella delle forme microalgali planctoniche. Nel complesso, le abbondanze sono variate tra 0.26 e 5.65 x 10^6 cells cm^{-3} e le specie più diffuse sono state *Amphora exigua* Gregory, *Amphora veneta* Kützing, *Cocconeis molesta* Kützing, *Navicula lanceolata* Kützing, *Nitzschia lanceolata* Smith, *Nitzschia microcephala* Grunow e *Thalassiosira* sp. Il confronto tra biomassa e abbondanza ha consentito di ottenere interessanti informazioni sulla struttura di comunità in relazioni alle condizioni ambientali, distinguendo le aree soggette a maggior impatto antropico da quelle meno interessate da alterazioni fisico-chimiche. La definizione di un indice quantitativo di qualità ambientale è, tuttavia, ancora prematura.

Abstract.

In recent years the international research efforts have been focused on the set up of environmental indicators to assess water quality and to apply correct management policies. Diatom-based indices have been widely used to monitor freshwaters. To extend the use of benthic microalgae as ecological indicators of coastal waters, surface sediment samples were collected during two sampling campaigns (from July 2001 to June 2002 in three sites and during summer 2003 in 84 sites), and abundance and the taxonomic composition were investigated.

The benthic Bacillariophyceae spatial and temporal distribution showed poor fluctuations, if compared with the phytoplankton changes in the same areas. In general diatom abundance varied between 0.26 e 5.65 x 10^6 cells cm^{-3} and rhapid taxa were the

most abundant as per number of cell and of species. Centric diatoms, in particular *Thalassiosira* sp., were widespread near the mainland, south of the translagoon bridge. The abundance-biomass curves gave interesting qualitative information on the community structure and the ecosystem condition, distinguishing the areas most affected by the anthropic impact from the least disturbed ones. However, these data are not sufficient to set up a quantitative environmental index.

1. Introduction.

Benthic microflora plays an important ecological role, as primary producer, in shallow-waters where macrophytes lack. Some studies highlight the importance of the microphytobenthos as sediment stabilizer [MacIntyre *et al.*, 1996; Austen *et al.*, 1999] and, recently, particular attention has been paid to the use of benthic diatoms to set up trophic indices [Prygiel *et al.*, 1999; Hill *et al.*, 2000]. These organisms seem to be more suitable, as ecological indicators, than phytoplankton, because they are less affected by temperature and wave motion [Facca *et al.*, 2002 and references therein].

The Venice lagoon has undergone important changes in the last ten years: the eutrophication effects, such as *Ulva rigida* C. Agardh blooms and dystrophic crises, have progressively disappeared and *Tapes philippinarum* Adams & Reeve spread in the areas free of macrophytes. In these new conditions, the ecosystem equilibrium has changed and the sediment resuspension increased [Sfriso *et al.*, 2003; Sfriso *et al.*, 2004 and references therein].

The present results aim at describing the benthic diatom distribution in an area where microalgae are the main primary producers as macrophytes are seldom present. The datasets let us update previous investigations on the seasonal variations [Facca *et al.*, 2002; Facca *et al.*, 2004], adding information on the whole spatial distribution in the lagoon and interesting conclusions on the community structure and its relationships with some environmental parameters.

2. Material and Methods.

The diatom assemblages were investigated in the 5 mm thick top sediment layer. Sediment sub-samples were taken by means of syringes with the point removed, from sediment cores, collected by means of a Plexiglas core (d: 10 cm). Predefined volume caps (0.7-0.8 cm^3) were used to obtain a quantitative reference (data are expressed as number of cells per cm^{-3} of wet sediment). Two-three sub-samples were separately preserved with 12 cm^3 of hydrogen peroxide (10 vol. FU) for 24 hours and then diluted with synthetic seawater till the inverted light microscope determination according to the Uthermohl’s method [1958]. The diatom taxonomic identification was carried out according the texts by Peragallo and Peragallo [1897-1908], Vanlandingham [1967-79] and Tomas [1997].

The difference (W) between the biomass (B) and the abundance (A) was calculated according to the formula

$$W = \left[\sum_{i=1}^{S} \left(B_i - A_i \right) \right] / 50 \cdot \left(S - 1 \right) \quad (1)$$

where S was the number of species [Clarke and Warwick, 1994].

2.1. Study area.

Sediment samples were collected during two different sampling campaigns: the first one was carried out monthly in three sites (SN= San Nicolò located at the Lido inlet, TR= Tresse located close to the Porto Marghera industrial area, CE= Celestia located near the Venice historical centre) during the period July 2001 - June 2002 and the second one in 84 sites north of the Malamocco inlet during summer 2003.

All sites were located off the main canals in submerged areas (mean water depth ca. 130 cm).

3. Results and Discussion.

The benthic Bacillariophyceae abundance presented a spot distribution (Fig. 1). The highest values were observed in areas where the wave motion was scarce and mainly wind- and tide-induced. The maximum (Tab. 1) occurred near Burano-Torcello wetlands, but only four values, among the considered samples, exceeded 2 x 10^6 cells cm^{-3}. Most of the samples were comprised between 0.26 and 0.9 x 10^6 cells cm^{-3} and they occurred south of Venice historical centre and north of Burano-Torcello wetlands.

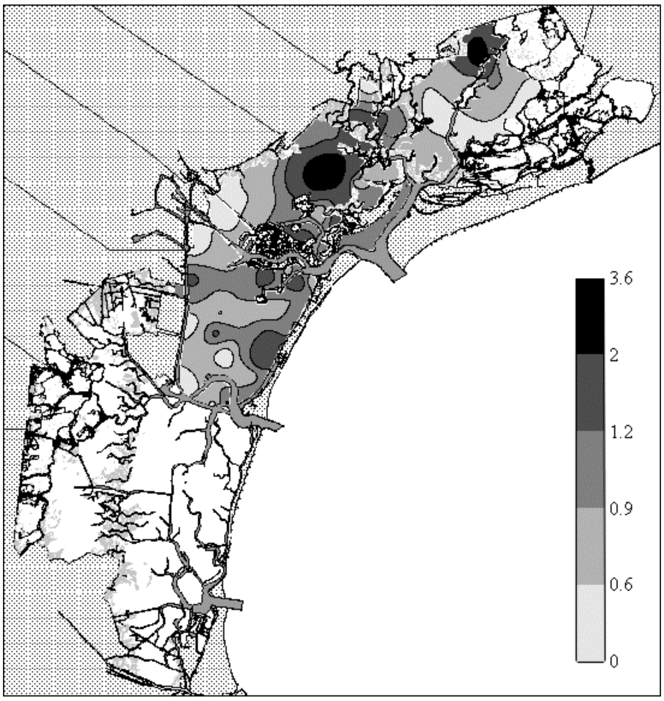

Fig. 1. – Distribution of benthic Bacillariophyceae abundance (10^6 cells cm^{-3}).

On the whole, the mean abundance was lower than the seasonal trend mean values observed during the present (Tab. 1) and past [Facca *et al.*, 2002; Facca *et al.*, 2004] investigations. However that sampling campaign, carried out in a limited period, cannot provide a complete idea of the diatom abundance, although it was observed that the benthic Bacillariophyceae seasonal trends seldom reflect temperature and light variations. At St. TR, for example, the maximum value occurred in October (Fig. 2) whereas at Sts. SN and CE it was recorded in March.

Tab. 1 – Basic descriptive statistic of diatom cell abundance, biomass (carbon content) and Shannon diversity (H').

	San Nicolò (SN)			**Tresse (TR)**		
	10^6 cells cm^{-3}	µg C cm^{-3}	H'	10^6 cells cm^{-3}	µg C cm^{-3}	H'
Mean	1.07	24.9	2.76	2.51	107	3.12
Std. Dev.	0.81	9.30	1.09	1.29	63.1	0.86
Min	0.42	13.5	0.93	1.13	43.5	1.62
Max	3.11	45.4	3.71	5.65	228	4.36
	Celestia (CE)			**Map**		
	10^6 cells cm^{-3}	µg C cm^{-3}	H'	10^6 cells cm^{-3}	µg C cm^{-3}	H'
Mean	1.35	67.7	3.33	1.00	96.0	2.86
Std. Dev.	0.79	62.0	0.55	0.54	86.4	0.75
Min	0.48	17.3	2.31	0.26	8.06	1.00
Max	3.20	191	4.21	3.60	609	3.93

In fact, it must be taken into account that the abundance seasonal fluctuations were poor. Moreover, if compared with the phytoplankton, the benthic diatom community can be considered almost stable. The map supplies information, above all, on the taxonomic composition as it allows to compare a high number of sites and to catalogue a lot of species.

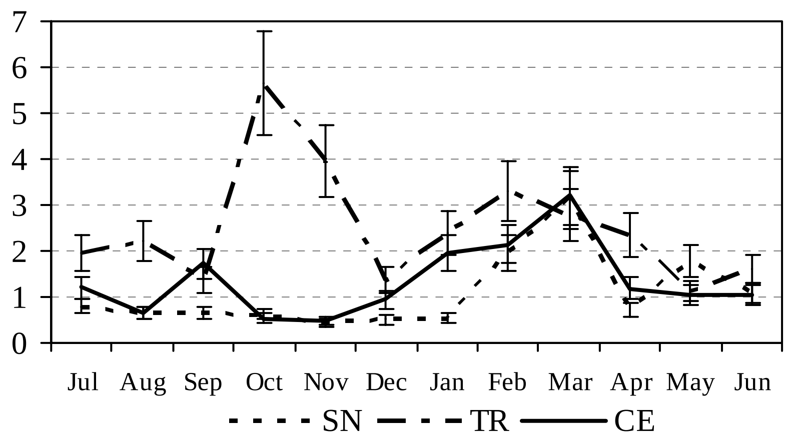

Fig. 2 - Benthic diatom cell abundance seasonal trends (106 cells cm-3).

Among the 122 taxa identified, 40 were found only in the samples of the map, 30 were recorded only during the seasonal campaigns and 52 constituted a common background. The most widespread and abundant species belonged to the genera

Amphora, *Navicula*, *Nitzschia* and *Thalassiosira*. In particular *Nitzschia frustulum* Grunow represented 57% of the community in September at St. CE, 80% in late winter and spring at St. SN and 72% in autumn at St. TR. In the other periods, at Sts. TR and CE, *Thalassiosira* sp. was quite important (20-30% of total abundance), whereas at St. SN *Cylindrotheca closterium* Reimann & Lewin and *Navicula lanceolata* Kützing prevailed. In the map samples, *Amphora exigua* Gregory, *Amphora veneta* Kützing, *Cocconeis molesta* Kützing, *Navicula lanceolata* Kützing, *Nitzschia lanceolata* Smith and *Nitzschia microcephala* Grunow constituted a constant community fraction. Some species were very abundant in some areas and completely absent in other zones, such as *Cocconeis scutellum* Ehrenberg, which exceeded 70% of the community near Sant'Erasmo, and *Thalassiosira* sp., which was dominant (up to 80%) close to the industrial zone.

The community structure was studied through the abundance-biomass curves [Clarke and Warwick, 1994] which give information on the opportunistic species (r-selected species characterised by small size cells) presence and abundance. The biomass-abundance difference (W) allowed to gain some qualitative indications on the environmental conditions (Fig. 3).

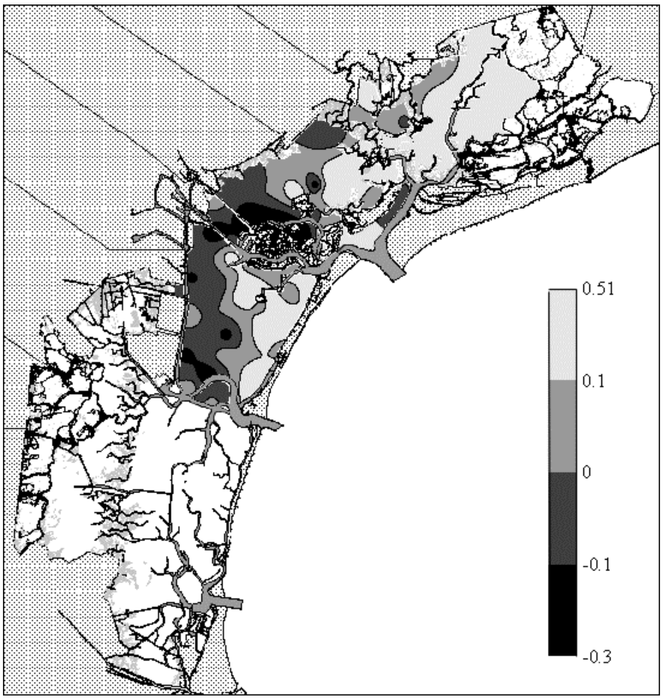

Fig. 3 – Biomass-Abundance difference (W) distribution.

In the shallow protected areas of the northern basin and near the port entrances, the community was characterised by large size diatoms and high diversity. On the contrary, close to Venice historical centre and near the mainland, few small species were found. That distribution distinguishes the areas, where the anthropic impacts are the most intense, from the least disturbed zones. However it must be noticed that the r-selected species abundance was not so high as expected (the opportunistic species are, in general, more abundant than the conservative, or k-selected, ones). This is probably due to the frequent sediment resuspension phenomena which have affected this area since the late '90s as consequence of catching the clam *T. philippinarum* [Sfriso *et al.*, 2003; Sfriso *et al.*, 2004 and references therein]. The frequent disruption of the 20-30 cm sediment top layers favours the resuspension of microalgae and their spreading seaward because of tidal currents. The consequence is a depletion of the surface layer and an increase of benthic microalgae in the water column.

4. Conclusion.

The benthic Bacillariophyceae abundance resulted to be low in the areas where the sediment resuspension is mainly caused by clam catching activities and ship transits. In those areas, the sediment perturbation is so strong that the microphytobenthos cannot contribute to the sediment stability, and cannot form the mucilaginous mat that some authors consider very important to reduce the erosion [Austen *et al.*, 1999]. The displacement of the benthic diatoms toward the water column also favours a decrease of diversity. In fact, the community was mainly constituted by small species and the Shannon index was lower than in the protected areas. This probably due to the different ability of species to create mucilaginous aggregates, which settle more rapidly than others. The study of the benthic diatom community structure gave interesting information on the conditions of the environment, not only on its trophic state, but also the general characteristics of the ecosystem. In fact, the comparison between abundance, biomass and diversity allows to distinguish the lagoon areas according to the different degrees of chemical and/or physical disturbance. This method, which allows only a qualitative indication of the state of the environment, does not provide exhaustive data to classify the different sites, nevertheless it represents a starting point.

References.

Austen I., Andersen T.J. and Edelvang K., 1999. The influence of benthic diatoms and invertebrates on the erodibility of an intertidal mudflat, the Danish Wadden Sea. *Estuarine Coastal and Shelf Science*, 49, 99-111

Clarke K.R. and Warwick R.M., 1994. Change in marine communities: an approach to statistical analysis and interpretation. Plymouth Marine Laboratory, Plymouth, UK, 144 pp

Facca C., Sfriso A. and Socal G., 2002. Temporal and spatial distribution of diatoms in the surface sediments of the Venice lagoon. *Botanica Marina*, 45, 170-183

Facca C., Sfriso A. and Ghetti P.F., 2004. Abbondanza e diversità del fitoplancton e delle diatomee bentoniche in laguna di Venezia. *Biologia Ambientale*, 18(2), 19-24

MacIntyre H L., Geider R.J. and Miller D.C., 1996. Microphytobenthos: the ecological role of the "Secret Garden" of unvegetated, shallow-water marine habitats. I. Distribution, abundance and prymary production. *Estuaries*, 19, 186-201

Hill B.H., Herlihy A.T., Kaufmann P.R., Stevenson R.J., McCormick F.H. and Burch Johnson C., 2000. Use of periphyton assemblage data as an index of biotic integrity. *Journal of the North American Benthological Society*, 19, 50-67

Prygiel J., Whitton B.A., and Bukowska J. (eds), 1999. Use of Algae for Monitoring Rivers III. Agence d'Eau Artois-Picardie, Douai, France, 271 pp

Peragallo M. M. H., and Peragallo M., 1897-1908. Diatomées marines de France et des districts maritimes voisins. MJ. Tempere, Grez-sur-Loing, pp. 492, 135 plates

Sfriso A., Facca C. and Ghetti P.F. 2003. Temporal and spatial changes of macroalgae and phytoplankton in a Mediterranean coastal area: the Venice lagoon as a case study. *Marine Environmental Research*, 56, 617-636

Sfriso A., Facca C., Ceoldo S. and Ghetti P.F., 2004. Variazioni delle concentrazioni di nutrienti e dei flussi di sedimentazione nella parte centrale della laguna di Venezia. *Biologia Ambientale*, 18(2), 11-18

Tomas C.R., 1997. Identifying Marine Diatoms and Dinoflagellates. Academic Press, San Diego pp. 598

Uthermöhl H., 1958. Zur Vervollkomnung der quantitativen Phytoplankton-Methodik. *Mitt. int. Verein. Limnol. 9*: 1-38

Vanlandingham S.L., 1967-79. Catalogue of the Fossil and Recent Genera and Species of Diatoms and Their Synonyms. J. Cramer, Valduz. 8 vol. pp.4654

SEDIMENTATION RATES, EROSIVE PROCESSES, GRAIN-SIZE AND SEDIMENT DENSITY CHANGES IN THE LAGOON OF VENICE

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Riassunto.

Questo lavoro riporta alcuni risultati sui processi di sedimentazione ottenuti per la laguna di Venezia sin dalla fine degli anni '90. In questo periodo i tassi di sedimentazione sono aumentati fino a ca. un ordine di grandezza e le acque sono divenute molto torbide. La pesca alle vongole ha avuto conseguenze drammatiche sia sulla ri-sospensione dei sedimenti sia sulla perdita della frazione granulometrica più fine. Attualmente la composizione granulometrica e la densità dei sedimenti superficiali è molto cambiata e processi erosivi sono in atto nelle aree lagunari affette da attività di pesca alle vongole e soggette ad elevati correnti mareali. Nelle aree a bassa turbolenza o colonizzate dalle fanerogame marine si hanno invece fenomeni di sedimentazione. Le fanerogame marine, infatti favoriscono la sedimentazione delle particelle fini e in tal modo contrastano l'erosione. Presso le aree assegnate dalle Amministrazioni locali per l'allevamento delle vongole non si sono osservati significativi cambiamenti dei tassi di sedimentazione né fenomeni erosivi.

Abstract.

In this paper are summarized the main results on sedimentation processes obtained in the Venice lagoon since the late '90s. Sedimentation rates, in that period increased markedly (up to one order of magnitude) and water became very turbid. The effect of clam fishing on sediment re-suspension and the loss of the finest sediment fraction from the surface sediment was dramatic. At present marked changes of surface sediment grain-size and density have favoured erosive processes in all the areas affected by clam fishing and flooded by intense tidal streams. On the contrary sedimentation occurs in areas which are not affected by water turbulence or are colonised by seagrasses. No significant environmental impact was recorded near the areas especially devoted to clam farming by the local Administrations.

1. Introduction.

In late 15 years the Venice lagoon, and in particular its central basin, has been affected by strong environmental transformations mainly due to the reduction of the macroalgal biomass and the spread of the non indigenous Manila clam *Tapes philippinarum* Adams and Reeve [Sfriso and Marcomini, 1996; Sfriso *et al.*, 2003a;

2003b; 2004a; 2004b; 2004c; Facca *et al.*, 2002a; 2002b; Pessa and Sfriso, 2002; Secco *et al.*, 2004].

Clam harvesting with hydraulic and mechanical dredges [Pranovi and Giovanardi, 1994; ICRAM, 1994; Orel *et al.*, 2000] severely damaged the upper 20-30 cm surface sediment. Because indiscriminate clam-fishing has been going on since the early ‘90s the sediment texture has been severely damaged. The finest material keeps being re-suspended and removed and tidal and wind actions help the erosive processes and changes both in the water transparency, sedimentation rates, granulometry and density of the surface sediments [Sfriso, 2000].

Such effects have been monitored since the beginning by utilizing sedimentation devices fixed in the surface sediments. Sediment granulometry has been measured by sorting the finest sediment fraction (<63 μm) and the sediment density has been also determined.

This paper aims at reviewing the results obtained during those investigations showing the changes both on sediment re-suspension/sedimentation rates and the amount of dry sediment per volume unit (dry density) and granulometry of the surface sediments. Moreover, data recorded before the clam spreading in the lagoon (late ‘80s) and during the period of intense clam harvesting (1994-2004) have been compared. In the latter period some changes in the lagoon bathymetry have been also measured in order to assess the magnitude of sediment losses.

2. Materials and methods.

2.1. The study area.

Studies have been carried out in the whole lagoon although the central basin, where the most significant changes occurred, was the most frequently monitored.

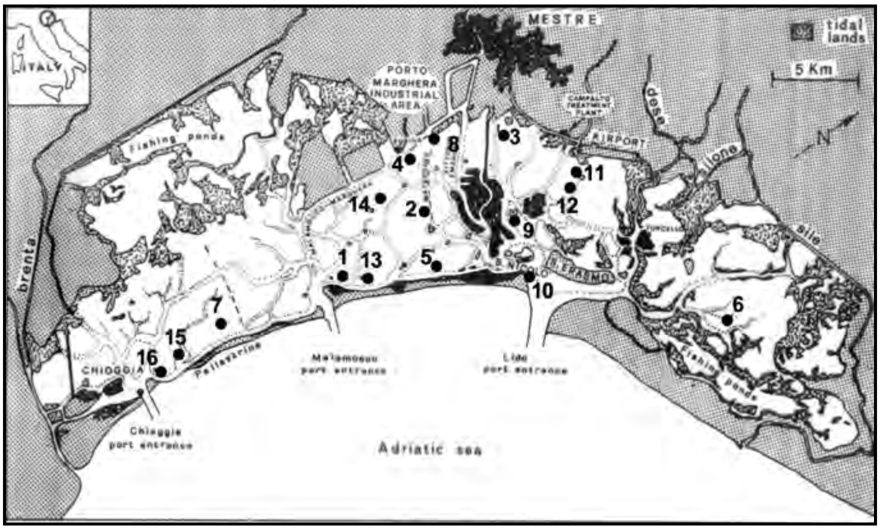

Fig. 1 – Map of the Venice lagoon and sampling stations.

About 16 stations placed in the whole lagoon (Fig. 1) have been monitored for sediment rates determination during the whole year and some of them (Alberoni, Sacca Sessola, San Giuliano and Fusina) have been sampled again during the following years. In ca. 13 of those stations bathymetric changes have also been monitored every three months for one year by sampling sediment erosion/sedimentation processes.

The results obtained by mapping the surface sediment grain-size and the amount of dry sediment per volume unit (dry density) in ca. 31-55 stations homogeneously spread in the central lagoon have been also reported (Fig. 2).

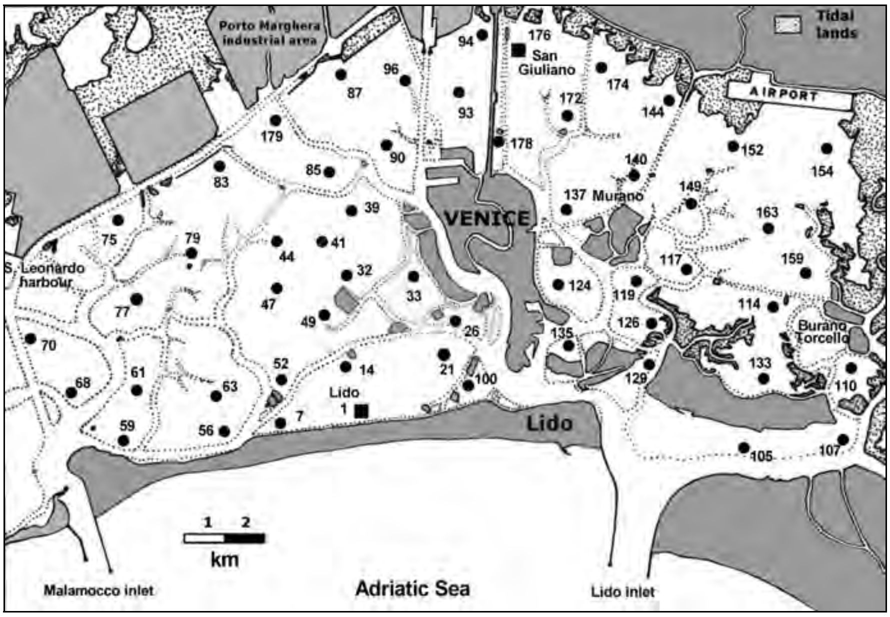

Fig. 2 – Stations of the central lagoon sampled for grain-size and dry sediment determination.

2.2. Sediment traps.

In the selected stations, home-made sediment traps (base: 20x20 cm; mouth: 15x15 cm; height 10 cm) designed for shallow bottoms [Sfriso *et al.*, 1992] were placed onto the sediment surface. They were covered with a 1-cm mesh net to prevent the re-suspension of the settled particles and the penetration of benthic fish and macrofauna for spawning. Traps were emptied every 15-30 days depending on sedimentation rates. The settled particulate matter (SPM) was carefully homogenised and two volumetric sample aliquots (ca. 100 g) were stored in polyethylene boxes. One aliquot was wet processed for the determination of the fine (<63 μm) fraction percentage and the sediment dry density. The other aliquot was frozen, lyophilised and weighed for the determination of the SPM amount and rate per square meter unit on a daily, monthly and yearly basis.

2.3. Physico-chemical determinations.

The amount of dry sediment per volume unit (dry density = g dwt cm^3) was calculated by drying ca. 30 g of homogenised sediment at 110 °C in volumetric containers up to constant weight. The sediment and SPM percentage of fine fraction was obtained by wet sieving ca. 50 g of lyophilised samples through 63 µm mesh sieves by the Endecotts LTD, London, England. All dry density and grain-size measurements were duplicated and significant differences between the study periods were tested according to one-way ANOVA.

2.4. Sedimentation devices.

Stainless steel or polyethylene disks (i.d. ca. 25 cm) kept by a metallic pole (diameter: ca. 2 cm, height: ca. 2 m) partly infixed in the sediment were placed onto the bottom surface of each station in order to monitor the bathymetric changes and the erosion/sedimentation trends. Measurements were carried out every three months for one year by means of an equaliser which was threaded by divers on the pole above-ground part. The equaliser had a spirit-level, fixed screws calibrated with the disk on the bottom surface and screws to be adjusted to the bottom variations. Bottom changes were obtained by measuring the different heights between the fixed and the adapted screws placed at the edges of the equaliser, with a precision of ±1 mm. Obviously, measurements around the disk could be very different (up to 2-3 cm) because the bottom surface is not homogeneous. Therefore, the final value (erosion or sedimentation) was the mean of 8 measurements obtained by moving the equaliser around the pole at a distance of ca. 50 cm from the pole in order to avoid recording cavitation effects due to currents and fish holes below the disk. Each set of eight measurements was reported as a couple of values measured at the opposite edges of the equaliser. Mean values were calculated and one-way ANOVA was applied to the different sets of measurements to disclose significant bathymetric changes.

3. Results and Discussion.

3.1. Settled Particulate Matter (SPM) rates.

The mean SPM rates recorded in the study areas are summarized in Tab. 1. They ranged from 38 kg dwt m^{-2} y^{-1} at Lido in 1997-98 to 1485 kg dwt m^{-2} y^{-1} at San Nicolò in 2001-02. However, the most interesting results come from the stations Alberoni, Sacca Sessola, San Giuliano and Fusina (Fig 3). Samplings were carried out in 1989-90 when the lagoon was covered by an extraordinarily high biomass of *Ulva rigida* C. Ag. and were performed again in 1992-93, during the reduction of the macroalgal coverage, and in 1998-99, in the period of intense clam harvesting.

At Alberoni SPM rates ranged from ca. 41 kg dwt m^{-2} y^{-1} (113 g m^{-2} d^{-1}) in 1989-90 to ca. 228 kg dwt m^{-2} y^{-1} (626 g m^{-2} d^{-1}) in 1998-99. At Sacca Sessola SPM rates changed from ca. 65 kg dwt m^{-2} y^{-1} (177 g m^{-2} d^{-1}) in 1889-1990 reaching ca. 269 kg dwt m^{-2} y^{-1} (737 g m^{-2} d^{-1}) in 1992-93, and ca. 760 kg dwt m^{-2} y^{-1} (2082 g m^{-2} d^{-1}) in 1998-99. A similar change was recorded at San Giuliano (from 140 kg dwt m^{-2} y^{-1} in 1989-90 to 721 kg dwt m^{-2} y^{-1} in 1998-99), whereas at Fusina, an area strongly influenced by the water turbulence caused by the transit of cargos along the Malamocco-Marghera canal, the SPM increase was negligible (from 825 kg dwt m^{-2} y^{-1} in 1992-93 to ca. 952 kg dwt m^{-2} y^{-1} in 1998-99).

Tab. 1 – SPM rates in 16 areas of the Venice lagoon. In the stations Alberoni, Sacca Sessola, San Giuliano and Fusina samplings were carried out in different years.

SPM Rates

			kg dwt m^{-2} y^{-1}	g dwt m^{-2} d^{-1}			
			total	**mean**	**ratio**	**max**	**min**
1	Alberoni	1989-90	**41**	**113**		350	41
		1998-99	**228**	**626**	**5.5**	1704	145
2	Sacca Sessola	1989-90	**65**	**177**		454	20
		1992-93	**269**	**737**		2583	24
		1998-99	**760**	**2082**	**11.7**	3607	1153
3	San Giuliano	1989-90	**65**	**177**		454	20
		1992-93	**269**	**737**		2583	24
		1998-99	**760**	**2082**	**5.1**	3607	1153
4	Fusina	1992-93	**825**	**2260**		3609	494
		1998-99	**952**	**2609**	**1.2**	3889	1679
5	Lido	1997-98	**38**	**103**		407	6
6	Palude Maggiore	1997-98	**148**	**405**		748	27
7	Fossa della Magra	1997-98	**135**	**370**		540	176
8	Trezze	2001-02	**1173**	**3214**		4960	1453
9	Celestia	2001-02	**840**	**2302**		4399	164
10	S. Nicolò	2001-02	**1485**	**4852**		5224	2190
11	Dama Nord canale Carbonera	2001-02	**270**	**735**		1707	145
12	Canale Carbonera (Briccola 19)	2001-02	**735**	**2014**		3566	413
13	Ottagono Abbandonato Alberoni	2001-02	**119**	**325**		1028	41
14	S. Marco in Boccalama	2001-02	**282**	**772**		1765	104
15	Casoni Canale Bombae	2001-02	**266**	**729**		1056	275
16	Ottagono Ca' Roman	2001-02	**257**	**705**		3162	230

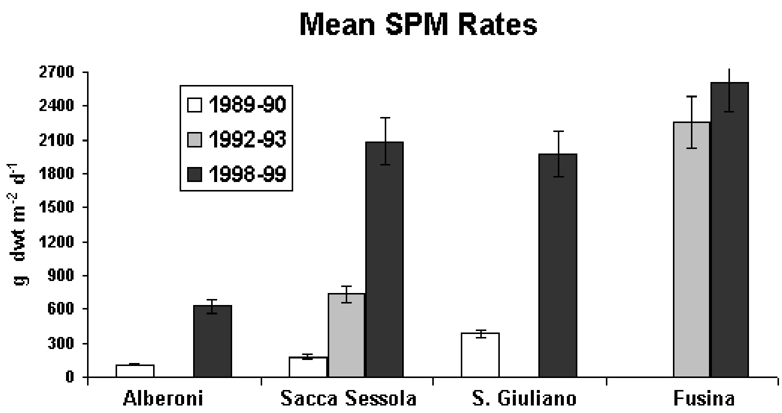

Fig. 3 – SPM rates in four stations of the central lagoon.

Very interesting are also the SPM rates recorded in 1997-98 at the Lido (st. 5), Palude Maggiore (st. 6) and Fossa della Magra (st. 7). In that case SPM rates are relatively low because of the peculiarity of the chosen areas: inside an *Ulva rigida* C. Ag. population in the Lido watershed (Lido station), inside a *Zostera marina* L. bed in the Pellestrina watershed (Fossa della Magra) and in a clam fishing free area in the northern lagoon where water turbulence is low (Palude Maggiore).

The last six stations (st. 11 to st. 16) were monitored to record the effect of clam fishing. In fact, sts. 12, 14, 16 are strongly influenced by that activity. On the contrary fishing is scarce at sts. 11, 13, 15. Stations 11 and 12, placed in the northern lagoon show the most significant differences (ANOVA: $p< 3.95E-04$). In fact at st.11 the SPM was ca. 270 kg dwt m^{-2} y^{-1} whereas at st. 12 the SPM reached ca. 735 kg dwt m^{-2} y^{-1}. Similarly, in the central lagoon the SPM found at st. 13 was ca. half (119 kg dwt m^{-2} y^{-1}) the one (ca. 282 kg dwt m^{-2} y^{-1}) found at st. 14 (ANOVA: $p<0.012$). The results found in the two areas placed in the southern lagoon (sts. 15 and 16) do not show any particular difference because the sampling areas have been selected inside a *Zostera marina* bed (st. 15) and in proximity of a clam-farm (st. 16). In that case the impact of seagrass uprooting, clam seedling and harvesting was strongly reduced with null effect on an annual basis.

3.2. Physico-chemical determinations.

The grain-size determination shows that the finest sediment fraction increased from st. 1 near the Malamocco mouth to sts. 3 and 4 near the mainland. Marked differences were found between 1989-90 and 1998-99 (Fig. 4a), especially at st. 1 (from 20% to 43%, one-way ANOVA: $p< 2.94E-13$), st. 3 (from 99% to 89%, ANOVA: $p< 7.07E-10$) and st. 4 (from 95% to 81%, ANOVA: $p< 2.54E-12$).

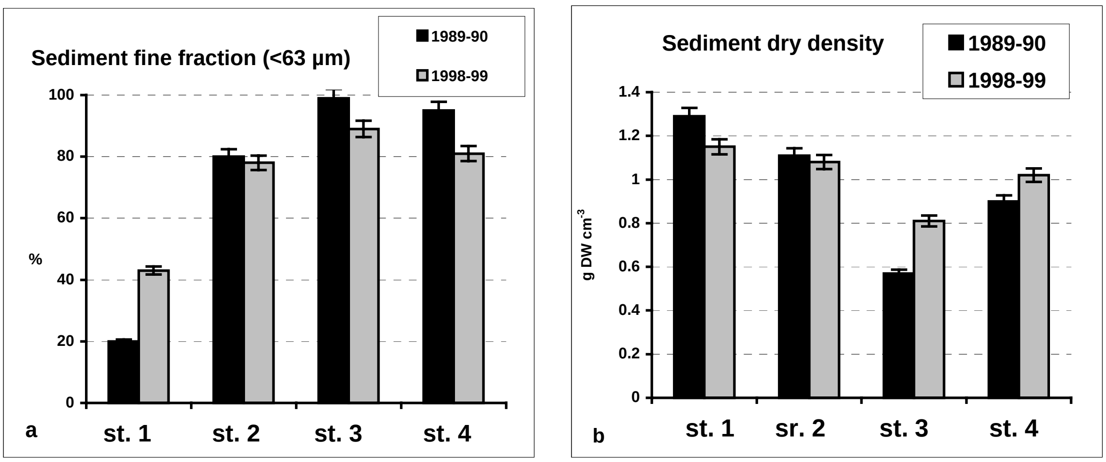

Fig. 4 – Comparison of granulometry (a) and sediment dry density (b) in the surface sediment of the study areas in the periods before (1989-90) and after (1998-99) the starting of clam fishing.

On the contrary, the sediment dry density (Fig. 4b) decreased from st. 1 towards st. 3, where the highest difference was found (from 0.57 to 0.81 g dwt cm^{-3}, ANOVA: $p< 1.94E-12$). A significant decrease was also found at st. 1 (from 1.29 to 1.15 g dwt cm^{-3}, ANOVA: $p < 1.6E-11$) whereas at st. 4 the dry density increased (from 0.90 to 1.02 g dwt cm^{-3}, ANOVA $p < 1.45E-04$). At st. 2 no significant changes were found.

However, changes of the surface sediment granulometry and dry density are in Figures 5 and 6, where the values monitored in summer 1987, 1998 and 2002 are reported.

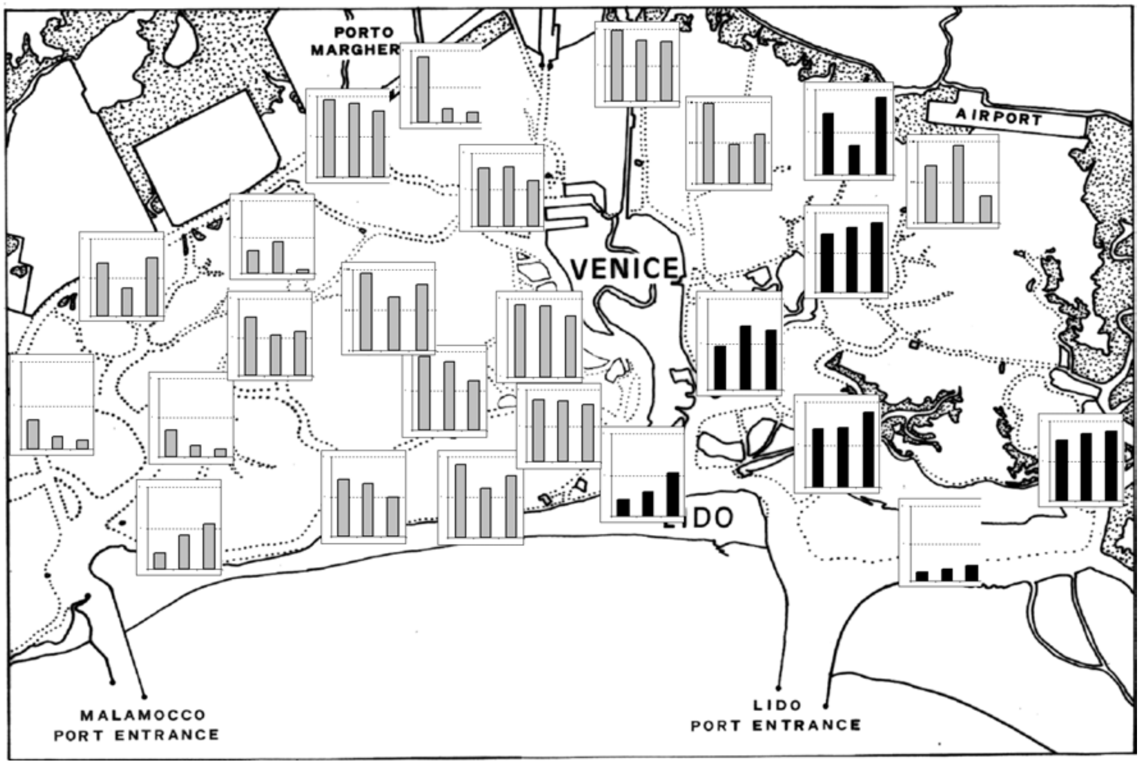

Fig. 5 – 1987, 1998, 2002 percentages of the finest fraction in the surface sediments. Histograms show a per cent scale ranging from 0 to 100% of fine sediment (fraction <63 µm). Black histograms show an increasing trend and grey histograms a decreasing trend.

In Fig. 6 it can be observed that from 1987 to 2002 most of the central lagoon south of Venice was affected by a loss of the finest sediment whereas the lagoon north of Venice showed an opposite trend, although clam harvesting was intense also in that area. That is due to the different behaviours of the finest sediment after re-suspension. South of Venice the sediment is moved away by the intense water turbulence which affects the area crossed by deep canals such as the “Malamocco-Marghera Canal”, whereas north of Venice it settles again because islands and salt marshes naturally hamper water turbulence.

Some exceptions occur especially near the Malamocco inlet where bottoms are colonised by seagrasses. In fact seagrass leaves favouring the settlement of the finest material contrast erosive processes.

A similar but opposite result (Fig. 6) was found by recording the sediment dry density changes. In fact it increases in the areas where sandy sediment increases and vice versa.

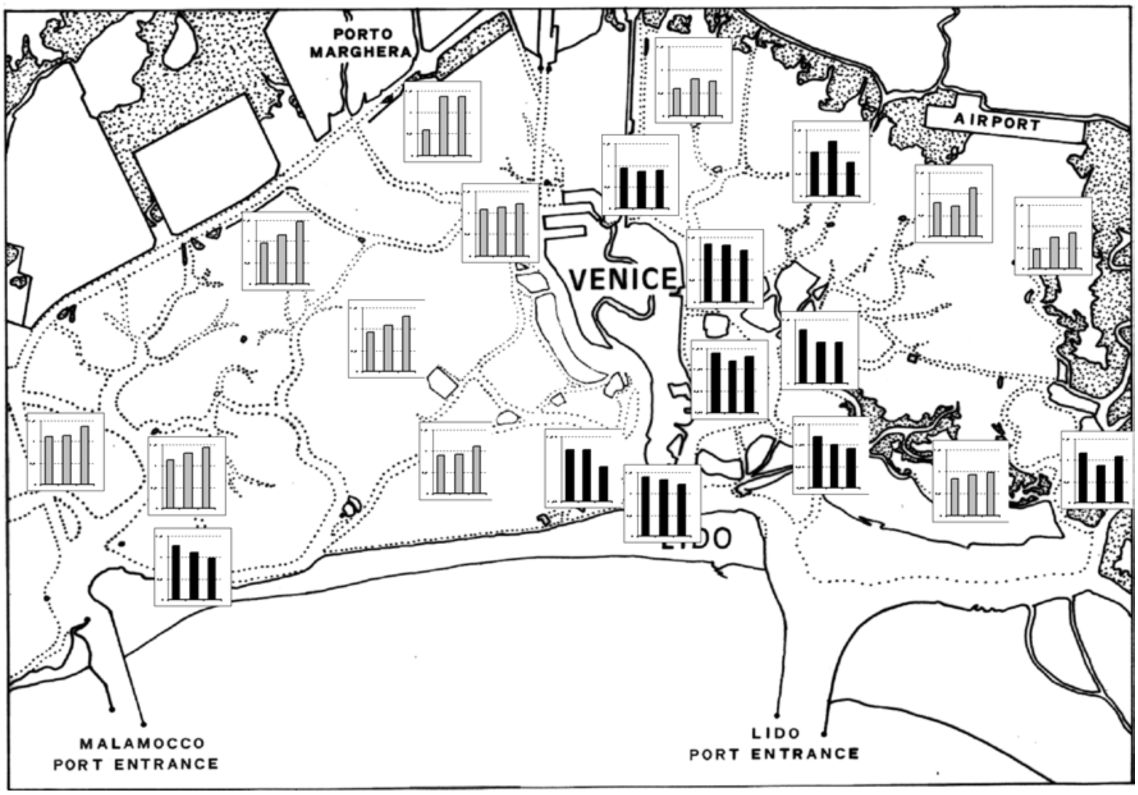

Fig. 6 – Dry density in the surface sediments in 1987, 1998, 2002. Histograms show a density scale of 0.5, 1.0, 1.5 g dwt cm^{-3}. Black histograms show a decreasing trend and grey histograms an increasing trend.

3.3. Bathymetric changes.

Traps supply information on the amount of fine sediments which after re-suspension settles on the lagoon bottoms and on the changes of SPM rates. Granulometry and dry density measurements corroborate the information on the fine sediment loss or settlement, but they do not supply any information on the lagoon bathymetric changes. Bathymetry was measured using sedimentation devices fixed on the surface sediments with a frequency of three times per month in order to detect the erosive or sedimentation tendency of the study areas.

Tab. 2 shows the measurements carried out in 13 stations of the lagoon. The values are very different depending on the lagoon basin and the station location. In general there is an erosive tendency in the areas affected by clam fishing or close to canals or areas with strong streams (sts. 2, 3, 4, 8, 9, 15) and a sedimentation tendency in the stations north of Venice (sts. 11, 12) where water turbulence is low. The stations colonised by seagrasses always showed a null sedimentation rate (sts. 1, 10, 13, 16) or a bathymetric decreasing trend. In the last years the area of S. Marco in Boccalama (st. 14) suffered a marked bathymetric loss which uncovered the ruins of an ancient Venetian island. Unfortunately archaeological excavations which started after the beginning of the sampling campaign affected the bathymetric measurements invalidating the data obtained.

Tab. 2 – Bathymetric changes in 13 areas of the Venice lagoon. Measurements were carried out every three months and the reported data are the mean of 8 measures. The last value is the final result after one year.

Bathymetric changes in some areas of the Venice lagoon

	Areas		**spring**	**summer**	**autumn**	**winter**	**spring**
					cm		
1	Alberoni	1998-99	-	-0.3	0.0	1.4	**-0.1**
2	Sacca Sessola	1998-99	-	-0.4	-1.8	-0.7	**-0.5**
3	San Giuliano	1998-99	-	-0.6	-0.3	-1.1	**-1.5**
4	Fusina	1998-99	-	-1.2	-1.5	-2.9	**-3.6**
8	Trezze	2001-02	-	0.8	-0.5	-2.1	**-0.9**
9	Celestia	2001-02	-	-0.2	0.1	-0.5	**-0.8**
10	S. Nicolò	2001-02	-	1.0	-1.0	-2.0	**0.6**
11	Dama Nord canale Carbonera	2001-02	1.9	1.1	1.5	**0.6**	-
12	Canale Carbonera (Briccola 19)	2001-02	2.3	2.5	4.1	**7.7**	-
13	Ottagono Abbandonato Alberoni	2001-02	1.6	1.6	1.7	**2.9**	-
14	S. Marco in Boccalama	2001-02	-1.1	-0.3	1.7	**3.5**	-
15	Casoni Canale Bombae	2001-02	0.7	-0.2	0.7	**-2.4**	-
16	Ottagono Ca' Roman	2001-02	3.7	5.0	3.3	**2.7**	-

Conclusions.

All the data presented in this paper and collected since the late '80s show that a marked and progressive increase of sediment re-suspension and removal affects the shallow bottoms of the Venice lagoon. The SPM has increased up to one order of magnitude and water turbidity, at present, hampers the bottom visibility in most of the central and northern lagoon basins. Concurrently, the surface sediment continuously disturbed by clam fishing activities, suffers a loss of the finest fraction, especially south of Venice and in the areas near the Malamocco-Marghera canal or close to the mainland. On the contrary it is on the increase north of Venice, where water turbulence is weak and in the areas colonised by seagrasses which favour sedimentation and contrast the erosive processes. Sediment density, which depends on the grain-size sediment composition, showed an opposite trend. The loss of the finest sediment fraction recorded in many areas accelerated the bathymetric increase and the marine evolution of the lagoon. These results are validated also by a recent map of sedimentation/erosion processes in the Venice lagoon resulting from the analysis of the ^{7}Be concentrations of atmospheric origin in the surface sediments [Degetto, 2000]. Moreover a study on the sediment displacement to the Venice lagoon inlets [Coraci *et al.*, 2004] confirms an erosive tendency also at Malamocco and Chioggia inlets, although no estimations are reported. At the Lido inlet results are not clear.

The present work outlines also the key role played by seagrass beds in order to favour sedimentation rates and contrast erosive processes. In fact, the areas populated by seagrasses showed alternate periods of erosion and sedimentation depending on the growth cycle of those plants. In the presence of a well developed above-ground part composed by thousands of standing leaves per square meter, whose height can exceed one meter, the settlement of fine particles is favoured. The sediment settlement opposes the sediment loss occurring during the winter period when the number of leaves and their height is strongly reduced and the final sediment balance is null.

Finally, the SPM rates and the bathymetric changes recorded since the beginning of clam spreading and fishing in the southern lagoon show that the conversion from free clam-fishing to clam farming can be a valid solution to contrast the loss of the finest material from the shallow lagoon bottoms.

Aknowledgements.

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References

Coraci E., Umgiesser, M., Sclavio, M., Amos, C. L., 2004. Modeling sand transport in the Venice lagoon inlets, in "*Scientific Research and Safeguarding of Venice. CORILA. Research Programme 2001-2003. 2002 Results*", by Campostrini Paolo, Venice

Degetto S., 2000. Project 2023 – sub-project B: Radiochemical research on the recent sediments of the Venice lagoon - B3 - Radiochemical procedure for the determination of the loss of suspended particulate matter at the lagoon mouths of the Venice lagoon (In Italian). CNR - ICIS, Magistrato alle Acque - Consorzio Venezia Nuova, Venezia, Final Report

Facca C., Sfriso A., and Socal G., 2002a. Temporal and spatial distribution of diatoms in the surface sediment of the central part of the Venice Lagoon. *Bot. Mar.*, 45 (2), 170-183

Facca C., Sfriso A., and Socal G., 2002b. Changes in abundance and composition of phytoplankton and microphytobenthos due to increased sediment fluxes in the Venice lagoon, Italy. *Estuar. Coast Shelf Sc.,* 54, 773-792

ICRAM - Istituto Centrale per la Ricerca Scientifica e Tecnologica Applicata al Mare, 1994. Preliminary investigation on the hydraulic dredge (turbosoffiante) employment for fishing bivalves in lagoon environments (in Italian*). Quaderni* N.7, Nicema, Roma

Orel G., Boatto V., Sfriso A., and Pellizzato M., 2000. Fishing sources management plan for the lagoons of the Venice Province (in Italian), Provincia di Venezia, Benevento, Sannioprint

Pessa G., and Sfriso A., 2002. Effect of *Tapes philippinarum* fishery on sediment fluxes, erosion/deposition processes and on the seaweed and seagrass distribution in free lagoon areas and in areas close to clam farms (in Italian), Final Report

Pranovi F., and Giovanardi O., 1994. The impact of hydraulic dredging for short-necked clams, *Tapes* spp., on an infaunal community in the lagoon of Venice. *Sci. Mar.*, 58, 345-353

Secco T., Pellizzato F., Sfriso A., and Pavoni B., 2004. The changing state of contamination in the lagoon of Venice. Part 1. Organic pollutants. *Chemosphere,* 58, 279.-290

Sfriso A., 2000. Water and sediment eutrophication and pollution in the central part of the Venice lagoon (in Italian) - Final Report. In "*Project 2023 - Subproject D*". Magistrato alle Acque - Consorzio Venezia Nuova, Venezia

Sfriso A., Pavoni B., Marcomini A., Raccanelli S., and Orio A. A., 1992. Particulate matter deposition and nutrient fluxes onto the sediments of the Venice lagoon. *Environ. Technol.*, 13, 473-483

Sfriso A., Marcomini A., 1996. Decline of *Ulva* growth in the lagoon of Venice. *Bioresource Technol*., 58, 299-307

Sfriso A., Facca C., and Ghetti P.F., 2003a. Temporal and spatial changes of macroalgae and phytoplankton in a Mediterranean coastal area: The Venice lagoon as a study case. *Mar. Environ. Res*., 56, 617-636

Sfriso A., Facca C., Ceoldo S., Silvestri S., and Ghetti P.F., 2003b. Role of macroalgal biomass and clam fishing on spatial and temporal changes in N and P sedimentary pools in the central part of the Venice lagoon. *Oceanol. Acta*., 26, 3-13

Sfriso A., Favaretto M., Ceoldo S., Facca C., and Marcomini A., 2004a. Organic carbon changes in the surface sediments of the Venice Lagoon., *Environ. Int.*, in press

Sfriso A., Ceoldo S., Facca C., and Marcomini A., 2004b. Recording the occurrence of trophic level changes in the lagoon of Venice during the '90s. *Environ. Int*., in press

Sfriso A., Facca C., and Marcomini A., 2004c. Sedimentation rates and erosion processes in the lagoon of Venice. *Environ. Int.*, in press

EFFECTS OF TEMPERATURE AND SALINITY ON THE BIOLOGICAL RESPONSE OF MUSSEL (*M. galloprovincialis*)

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Riassunto.

Questa ricerca si propone di valutare gli effetti della variazione di alcuni parametri ambientali naturali, quali temperatura e salinità, sulle risposte biochimiche, cellulari e fisiologiche del mollusco bivalve *Mytilus galloprovincialis*.

Le indagini sono state effettuate su due popolazioni soggette ad un diverso impatto antropico: una proveniente da un sito caratterizzato da un inquinamento prevalentemente industriale (Tresse) e l'altra da un'area relativamente pulita e considerata come riferimento (S. Nicolò). Le risposte degli organismi sono state valutate dopo un'esposizione di breve e media durata (3 e 6 giorni) a due diverse temperature (15°C – 20°C) e salinità (26 PSU – 36 PSU), valori compresi negli intervalli di variabilità normalmente registrati in laguna di Venezia, con lo scopo di confrontare l'eventuale difformità nelle risposte tra le due popolazioni e la sensibilità dei diversi indici applicati.

I risultati hanno evidenziato una sostanziale differenza tra le due popolazioni al tempo zero (indicative di un livello base di stress diverso) e una disomogeneità della rispettive risposte biologiche in relazione al tipo di trattamento effettuato e al tempo di esposizione. Tra i diversi indici testati, quello fisiologico è risultato il più sensibile alle variazioni di temperatura e salinità.

Abstract.

In this study the effects of temperature and salinity on some stress indices were evaluated in mussels (*M. galloprovincialis*) from the Lagoon of Venice (Italy). The aim was to detect and evaluate possible response modulation between organisms from two differently polluted sites.

In the first experiment sets, mussels were exposed to water temperatures of 15°C and 25°C, in the second ones to salinity of 26 PSU and 36 PSU. Organisms were sampled after 3 and 6 days and their biological response evaluated at biochemical (aldehyde deidrogenase and catalase activities), cellular (neutral red retention test) and physiological (survival in air) level.

The results showed that the applied biomarkers were suitable, as a whole, to make clear the unlike well being of mussels of different origin.

Aldehyde deidrogenase activity resulted always insensitive to temperature, and to salinity in the most polluted organisms. Enzyme response was always influenced by

different time exposure of both temperature and salinity, except for salinity in less polluted mussels.

Catalase activity was always unaffected by salinity, and by temperature in the less polluted mussels. This enzyme activity was influenced by time exposure of both temperature and salinity in the polluted mussels, thus showing the different behaviour of the two populations.

Neither temperature nor salinity, nor time of exposure (except for salinity in the less polluted mussels) influenced the results from the neutral red test.

Survival in air was always controlled by temperature, salinity, and time of exposure.

1. Introduction.

The lagoon of Venice is a complex coastal ecosystem, characterised by frequent variations of natural parameters such as temperature, salinity, oxygenation, food supply related to both seasonal and tidal cycles. Moreover, numerous and various anthropogenic activities, located within or nearby the lagoon, concurred to the present spread of various xenobiotics in both lagoon waters and sediments. Agriculture draining from the mainland, industrial drainpipe from the estate of Porto Marghera, sewage and urban runoff from both highly populated surroundings and historical centre of Venice, waste discharge into the canals by the glassworks of Murano are the main causes of pollution in this peculiar environment.

In the last few years various field studies were carried on in the lagoon using the biomarker approach with the aim to contribute at evaluating the environmental health of the lagoon [Livingstone and Nasci, 2000; Lowe and Da Ros, 2000; Nasci *et al.*, 2002; 2004]). The results of these investigations showed that both anthropogenic and natural stressors are important factors in drawing biological responses in appropriate organisms that can be potentially regarded as “sentinel” or “early warning signals” in the monitoring of the environmental quality in the lagoon of Venice. In this context, it is important not only to discriminate between effects elicited by natural stressors and those ones due to xenobiotics, but also to evaluate the possible dissimilar modulation in the response to natural stressors by organisms native of differently polluted sites.

In this investigation, mussels (*Mytilus galloprovincialis)*, well-known bioindicators of the water column quality [Goldberg *et al.*, 1978; Bayne *et al.*, 1979], were use to test the effects of temperature and salinity. Mussels were native of two differently impacted sites of the lagoon: Tresse, characterized by industrial pollution and S. Nicolò considered as reference site.

The mussel response was evaluated by various biomarkers. At biochemical level, catalase and aldheyde dehydrogenase activities were measured in digestive gland. Catalase is an antioxidant enzyme, detoxifying oxyradicals, which can be increased by stress conditions [Livingstone *et al.*, 1993]. Aldheyde dehydrogenase is involved in the oxydative biotransformation of endogenous and xenobiotic compounds to more soluble and excretable products, and is inducible by exposure to pollutants [Forlin *et al.*, 1995]. At cellular level, neutral red retention time was measured in hemocytes. This assay has been widely employed to evaluate the condition of the lysosomal membranes, by considering the retention time of neutral red dye into the lysosomal compartment before it leaches into the cytoplasm, the elapsing time being a measure of the membrane stability [Lowe *et al.*, 1995]. As for the physiological parameters, survival in air was used as simple but effective test to determine pre-existing stress [Eertman *et al.*, 1993].

2. Materials and Methods.

2.1. Experimental procedure for temperature.

In June 2002 mussels of 3-4 cm length size were collected at S. Nicolò (T=23.5°C, S=34.7 PSU) and Tresse (T=25.3, S=31.3 PSU), transferred to the laboratory, and placed in 120 l aerated aquaria at same salinity of 35.8 ± 0.8 PSU and at two different temperature of 15°C and 25°C. For each sampling stations a first group of mussels was left untreated and immediately processed (time 0). Two experimental groups, placed respectively at 15 °C and 25 °C, were fed with a commercial food mixture for filtering marine invertebrates (Liquid Fee) every second day, sampled after 3 and 6 days, and subsequently processed. Seawater in tanks was changed every third day and kept constantly aerated.

2.2. Experimental procedure for salinity.

In July 2002 mussels of 3-4 cm length size were collected at S. Nicolò (T=25.4°C, S=36.5 PSU) and Tresse (T= 28.7°C, S=32.4 PSU), transferred to the laboratory, and placed in 120 l aerated aquaria at same temperature (24.0 °C ± 0.5°C) and at two different salinities of 26 PSU and 36 PSU. For each sampling stations a first group of mussels was left untreated and immediately processed (time 0). Two experimental groups, placed respectively at 26.0 ± 0.5 PSU and 36.0 ± 0.5 PSU, were fed with a commercial food mixture for filtering marine invertebrates (Liquid Fee) every second day, sampled after 3 and 6 days, and subsequently processed. Seawater in tanks was changed every third day and kept constantly aerated.

2.3. Sample processing and biomarker analyses.

Fifty animals from each experimental group were sacrified.

As for biochemical analyses, activities of aldehyde dehydrogenase (ADH) and catalase (CAT) were measured on S9 fraction of 5 pooled samples, each made up of 4 digestive glands. Aldehyde dehydrogenase activity (ADH) was determined by measuring the increase of absorbance at 340 nm, due to the NAD reduction [Förlin *et al.*, 1995]. Catalase activity was measured at 240 nm, by the decreasing of the absorbance due to the H_2O_2 consumption [Aebi, 1974].

Neutral red retention time (NRR) was evaluated individually on the hemocytes of 10 animals, according to Lowe *et al.* [1995]. After incubation with neutral red dye, hemocytes were inspected under a microscope after a time interval of 1 hour, the aim being to assess the percentage of destabilised haemocytes [Lowe and Pipe, 1994; Ringwood *et al.*, 1998].

Survival in air was determined on 20 individuals. Mussels were damp dried with paper tissue and the tray was placed in a constant temperature room of 18°C [Eertmann *et al.*, 1993]. Daily recordings were made of the number of the animals alive. Animals were considered dead when shell-gape occurred and an external stimulus (prodding tissues with a probe and/or squeezing of the valves) didn't generate any response. Dead animals were removed immediately.

2.4. Statistics.

Statistical analysis was carried out with the aid of the STATISTICA package (software Statistica 5.5 - Statsoft). The normally distributed data, but with non homogeneous variances, of biochemical and cellular parameters were statistically compared using the non-parametric Kruskall – Wallis test. LT50 (lethal time for the 50% of the sample) was calculated for Survival in air according to the method of Kaplan and Meier [1958], and the resulting survival curves were compared using the Gehan and Wilcoxon test [Gehan, 1965].

3. Results and discussion.

Several studies have elucidated how the biological response of sentinel organisms can be affected not only by chemical pollutants but also by a number of natural stressors such as temperature, salinity, hypoxia, food availability and reproductive cycle [Depledge and Lundenbye, 1996; Ringwood *et al.*, 1998; Sheehan and Power, 1999; Nasci *et al.*, 2000]. Particularly in monitoring environmental quality by biomarker evaluation, the effects of natural stressors have to be carefully taken into account, especially in estuarine environments such as lagoons, where the natural variability of these parameters could led to misunderstanding of results [Nasci *et al.*, 2000; 2004]. The results of temperature and salinity experiments are presented in Figure 1 and Figure 2 respectively. As for ADH activity (Fig. 1a), in the temperature experiment the two mussel populations are quite different at time 0, indicating a different level of stress. Mussels from Tresse showed significant higher values, according with a previous seasonal study performed in 2002 in the same sites [Nasci *et al.*, 2004]. Whilst in the natives to S. Nicolò the enzymatic level after 3 and 6 days increased both at 15°C and 25°C, the organisms from Tresse showed a significant decrease only at 15°C. This result could represent an adaptive behaviour for Tresse mussels to an environment characterised by warmer water in comparison with S. Nicolò [Sfriso *et al.*, 2003]. An opposite trend is evidenced in the salinity experiment (Fig. 2a). After 3 days of treatment the mussels from Tresse showed a significant depression of the enzymatic activity only in sample treated with 36 PSU, whereas the levels decreased significantly also in those ones exposed to 26 PSU only after 6 days of treatment. The population from S. Nicolò revealed a marked increase of the enzymatic levels only in 6 days at 26 PSU treatment. Mussels from Tresse, the most inner site, resulted to be more influenced by salinity variation, whereas those ones from S. Nicolò, the area closer to the sea, more adapted at 36 PSU.

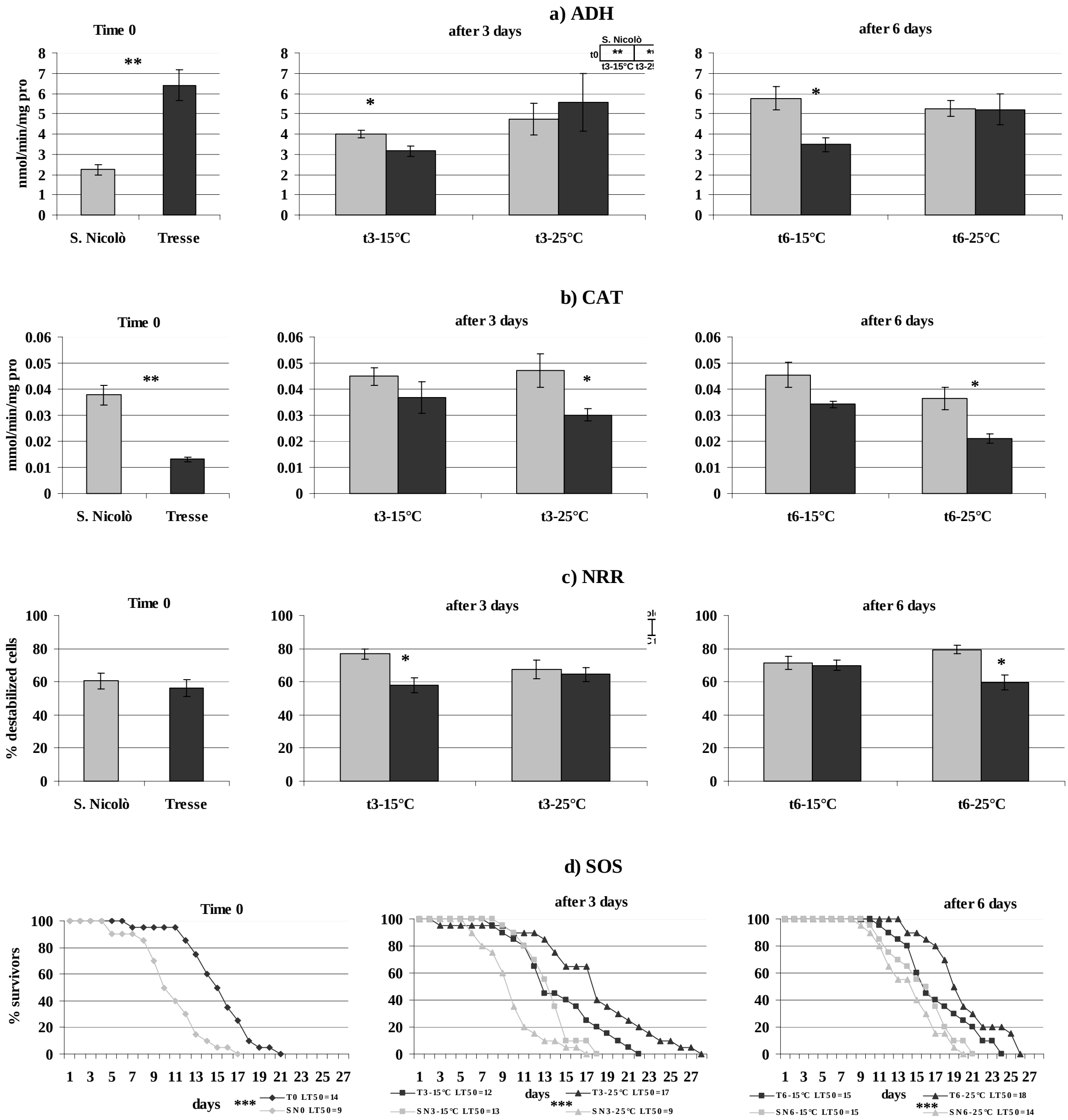

Fig. 1(a-d) – Temperature experiment. Aldehyde deidrogenase activity (ADH) (nmol/min/mg prot.), catalase activity (CAT) (mmol/min/mg prot) (mean ± st. err, n = 5), neutral red retention test (NRR) (% destabilized cells) (mean ± st. err, n =10 and survival test (% survivors) (n=20) in *M. galloprovincialis* collected from two areas of the Lagoon of Venice and treated for 3 and 6 days at 15°C (respectively t3-15°C and t6-15°C) and 25°C (respectively t3-25°C and t6-25°C). Statistical comparison (Kruskal – Wallis test, Gehan & Wilcoxon test only for survival in air):
* = p≤ 0.05; ** = p≤ 0.01; *** = p≤ 0.001; n.s. = not significant.

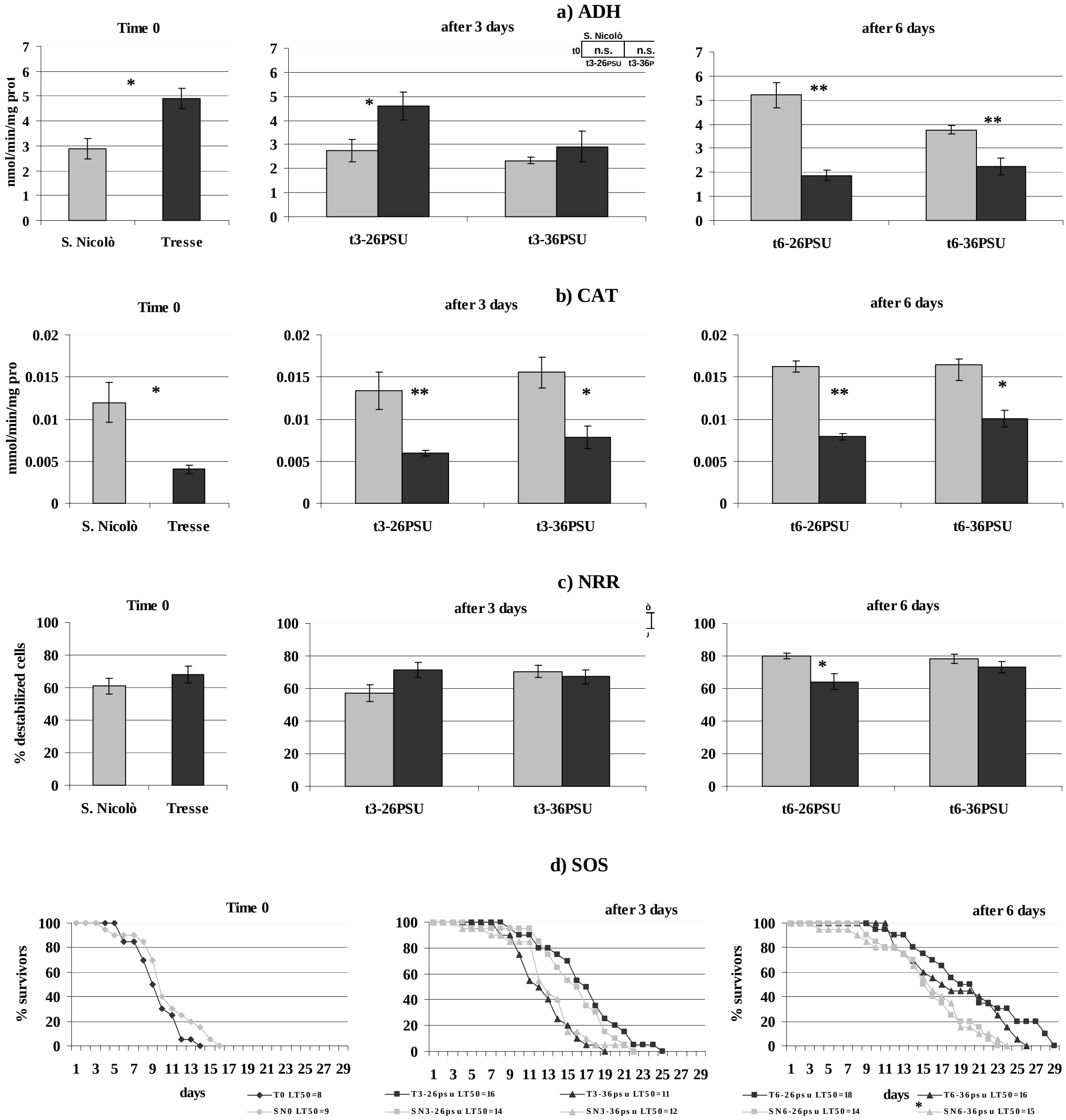

Fig. 2 (a-d) – Salinity experiment. Aldehyde deidrogenase activity (ADH) (nmol/min/mg prot.), catalase activity (CAT) (mmol/min/mg prot) (mean ± st. err, n = 5), neutral red retention test (NRR) (% destabilized cells) (mean ± st. err, n =10 and survival test (% survivors) (n=20) in *M. galloprovincialis* collected from two areas of the Lagoon of Venice and treated for 3 and 6 days at 26 PSU (respectively t3-26 PSU and t6-26 PSU) and 36 PSU (respectively t3-36 PSU and t6-36 PSU). Statistical comparison (Kruskal – Wallis test, Gehan & Wilcoxon test only for survival in air):
* = p≤ 0.05; ** = p≤ 0.01; *** = p≤ 0.001; n.s. = not significant.

The CAT activity showed significant higher levels in mussel from S. Nicolò in comparison with Tresse at time zero (Fig. 1b). This data agreed with those recorded in the same population in a previous seasonal study performed in 2002 [Nasci *et al.*, 2004]. Also in this case, the peculiar environmental conditions at Tresse (e.g. high food availability as Particulate Organic Carbon) [Sfriso *et al.*, 2003], could have influenced enzyme induction more than in S. Nicolò, located by the sea inlet, where the water is less enriched with suspended particulate food. Temperature resulted ineffective in influencing the activity of this enzyme in mussels from S. Nicolò. Differently, a significant increase in the enzymatic levels has been detected in mussels from Tresse, after both exposure times both at 15°C and 25°C, although less important at the highest temperature. As for the salinity experiment, the levels of CAT activity were similar among the S. Nicolò samples, whereas those form Tresse showed significant higher values both at 26 PSU and 36 PSU than the controls (Fig. 2b). The higher pollution in Tresse area may account for this different response behaviour: mussels, more stressed by chemical contamination, resulted more susceptible to variation of environmental parameters.

The effect of temperature on neutral red retention test indicated a marked destabilisation of the lysosomal membrane at 15°C after 3 days of treatment in mussels from S. Nicolò, whereas no variation was recorded at Tresse (Fig. 1c). After 6 days of exposure a significant destabilisation at 25°C was observed in mussels from S. Nicolò, whereas at 15°C in those ones from Tresse. In the salinity experiment no variations with respect to control at time 0 were recorded after 3 days, and after 6 days only mussels from S. Nicolò exhibited a significant increase of the lysosomal destabilisation both at 26 and 36 PSU (Fig. 2c). A study performed on *Ostrea edulis* from the south coast of UK revealed that the haemocytes were more stable at temperature and salinity of 15-20°C and 25-32 PSU, respectively [Hauton *et al.*, 1998]. Ringwood *et al.* [1998] reported that lysosomal integrity in digestive cells was not affected by either short – term (18 hr – 4 days) or long–term (7–14 days) variation in salinity during laboratory experiments and the destabilisation indices were similar to those of deployed and native oyster from reference sites characterised by a wide range of salinities (10 –30 PSU). Statistical differences were never recorded in the lysosomal destabilisation of mussel from Tresse and S. Nicolò, collected at time 0, although the lysosomes of Tresse mussels resulted more destabilized then S. Nicolò ones. A previous seasonal study on *M. galloprovincialis* collected from the same sites in 2002, revealed a marked worse situation in mussels from Tresse [Nasci *et al.*, 2004]. Studies carried out in the lagoon of Venice in 1992 -1993 evidenced a better neutral red retention capability in mussels from relatively unpolluted areas, with respect to more contaminated sites [Lowe *et al.*, 1995; Lowe and Da Ros, 2000]. In the present investigation, results showed significant differences between the two sites in samples exposed for 3 days at 15°C and for 6 days at 25°C, with lower destabilisation values for Tresse, possibly due to a more elevated adaptive capacity to wide temperature variations in these mussels. Similarly, in the salinity experiment, the sample from S. Nicolò, exposed at 26 PSU for 6 days, showed a marked increase of the cellular destabilisation in comparison with Tresse, reflecting the lower capacity to adapt to low salinities for those outer mussels. Also De Lorenzi [2001] found no significant differences in the neutral red retention capacity between two populations of *M. galloprovincialis* from differently impacted areas of the lagoon after treating for 7 days at 26 and 36 PSU.

The survival in air test is a physiological stress index sensitive to generic stress conditions suffered previously by the organism [Eertman *et al.*, 1993; Viarengo *et al.*, 1995]. In all experiments similar effects for mussels from both sites were recorded, i.e. an increase of the survival capacity in the exposed samples with respect to the controls both after 3 and 6 days (Fig. 1d, 2d). It is well known that temperature and salinity affect deeply this physiological response, which is related to mussel metabolism [de

Zwaan and Wijsman, 1976]. Eertman *et al.* [1993] demonstrated that *M. edulis*, exposed to high levels of chemical contamination, show a reduced survival capacity. Viarengo *et al.* [1995] showed *M. galloprovincialis*, after been treated with contaminants (30mM Cu^{++} in the form of copper chloride aqueous solution, 6mM Aroclor 1254 in dimethyl sulfoxide), to lower its LT50 values more than unexposed controls. Similar results are recorded for *M. edulis* [de Zwaan *et al.*, 1995] and in *M. trossulus* [Thomas *et al.*, 1998]. The time 0 survival in air resistance was significant higher in mussels from Tresse than S. Nicolò only in temperature experiment. Similar results have been already reported for mussels and clams from the lagoon [Marin *et al.*, 2001; De Lorenzi, 2001, Nasci *et al.*, 2004]. It has been suggested that the high levels of particulate organic matter and nutrients in the water of the most contaminated area of Tresse [Sfriso *et al.*, 2003] may account for particularly favourable trophic conditions for the native bivalves, making them more resistant to air exposure. Under anaerobic condition, the metabolism of the mussel turns into anaerobic pathways, and the glycogen becomes its only or main source of energy [de Zwaan and Wijsman, 1976]. Therefore, a polluted but high trophic environment may supply these organisms with energetic content to increase their fitness, despite the stress due to the high chemical contamination.

In Tab. 1-2 the main effects of temperature, salinity and the exposure time on the biological response are reported. The results, as a whole, showed that all biomarkers were suitable to make clear the unlike well being of mussels of different origin.

Tab.1 – Effects of temperature and exposure time on response of biomarkers as given by Kruskall-Wallis analyses.

TRESSE	**Temperature**	**Time**
ADH	n.s.	*
CAT	*	***
NR	n.s.	n.s.
SOS	*	**

S. NICOLO'	**Temperature**	**Time**
ADH	n.s.	**
CAT	n.s.	n.s.
NR	n.s.	*
SOS	***	***

Tab. 2 – Effects of salinity and exposure time on response of biomarkers as given by Kruskall-Wallis analyses.

TRESSE	**Salinity**	**Time**
ADH	n.s.	*
CAT	n.s.	**
NR	n.s.	n.s.
SOS	***	***

S. NICOLO'	**Salinity**	**Time**
ADH	**	n.s.
CAT	n.s.	n.s.
NR	n.s.	***
SOS	**	***

ADH activity resulted insensitive to temperature in both populations, whereas salinity affected this enzyme in the less polluted mussels. Also the exposure time to different temperatures and salinity is always an important factor affecting the enzyme response (except for salinity in the less polluted mussels).

CAT activity showed to be influenced by temperature only in the most polluted mussels, exhibiting possible adaptive mechanisms to warmer temperature, whereas salinity does not affect the enzyme response in both populations. Previous studies reported a decrease of the antioxidant defence system associated with a higher level of lipid peroxidation in mussels during winter whereas an opposite trend was evidenced in spring-summer [Viarengo *et al.*, 1991; Regoli, 1998]. Moreover, the results of a study on the effects of environmental parameters such as temperature, pH, oxygenation, water type and substrate on the biomarkers response in the freshwater clam *Corbicula fluminea* showed no significant effect of temperature on CAT activity in clams exposed for 5 days to 10°C and 20°C [Vidal *et al.*, 2002]. Exposure time to different temperatures and salinities affected always the response in the most polluted mussels, revealing the presence of a different behaviour between the two populations.

Neutral red retention test resulted always insensitive to both temperature and salinity. This result is in agreement with the findings of Ringwood *et al.* [1998] in oysters *C. virginica* showing that neither short – term (18 hr – 4 days) nor long – term (7 – 14 days) variation in salinity affected significantly lysosomal integrity of oysters. Morover, in the same study was shown that lysosomal destabilisation was not affected by environmentally relevant temperatures. Also Moore *et al.* [1980] found no significant changes in lysosomal enzyme activities in mussel *M. edulis* acclimated to a high salinity (33 PSU) and then transferred to low salinity (15 PSU).

Exposure time to different temperatures and salinities influenced the biomarker response in the less polluted organisms, showing again a different behaviour of the two populations. As a conclusion, the lysosomal destabilisation test, being insensitive to natural stressors such as salinity and temperature, but sensitive to pollutants [Moore, 1985; Regoli, 1992; Lowe and Pipe, 1994; Ringwood *et al.*, 1998] may be considered a good biomarker of anthropogenic effects.

Survival in air resulted always significantly influenced by both temperature, salinity and time exposure. In general, the survival in air response in mussels shows seasonal variation [Eertman and de Zwaan, 1994]. The seasonal pattern, which is in agreement with the glycogen content cycle, is related to the reproductive process, which is activated by the increase of seawater temperature [Seed, 1975]. Eertman *et al.* [1993] found that the survival time in air of mussels was not significantly affected after 7 days of exposure, or longer, to lowered salinities. Therefore, the marked influence of salinity in our results may be due to the short term exposition.

Conclusions.

Each biomarker evaluated in this investigation was suitable to demonstrate the different well being of mussels native to differently impacted areas of the lagoon of Venice.

Mussel response to changes in temperatures and salinities was sometimes different between the two groups. In particular, whereas survival in air resulted always significantly affected by both temperature and salinity, catalase activity showed to be influenced by temperature only in the most polluted mussels, aldehyde dehydrogenase activity was affected by salinity in the less polluted mussel, and neutral red retention time resulted insensitive to both environmental parameters.

Exposure time showed to be an important factor affecting the survival in air, the neutral red retention in the less polluted mussels, and the biochemical indices in the most polluted organisms.

References

Aebi H., 1974. Catalase. In: *Methods of Enzimatic Analysis*. Bergmeyer, H.U. (ed.). London, Academic Press, 671-684

Bayne B.L., Moore M.N., Widdows J., Livingstone D.R., Salked P., 1979. Measurement of the response of individuals to environmental stress and pollution: studies with bivalve molluscs. *Phil. trans. R. Soc. Lond. B.*, 286, 563-581

De Lorenzi A., 2001. Monitoraggio e bioindici in *Mytilus galloprovincialis* nella valutazione di stress antropogenico e naturale. Tesi di laurea, Università degli studi di Padova

de Zwaan A., Cortesi P., Cattani O., 1995. Resistance of bivalves to anoxia as a response to pollution-induced environmental stress. *The science of the total environment*, 171, 121-125

de Zwann A., Wijsman T.M.C., 1976. Anaerobic metabolism in bivalvia (Mollusca). Characteristics of anaerobic metabolism. *Comparative Biochemistry and Physiology*, 54B, 313-323

Depledge M.H., Lundebye A., 1996. Physiological monitoring of contaminant effects in individual rock crabs, *Hemigrapsus Edwardsi*: the ecotoxicological significance of variability in response. *Comparative Biochemistry and Physiology*, 113C, 277-282

Eertman R.H.M., de Zwaan A., 1994. Survival of the fittest: resistance of mussels to aerial exposure. In: *Biomonitoring of Coastal Waters and Estuaries*. Edites by Kramer K.J.M.,RC Press, Boca Raton, FL, 269-282

Eertman R.H.M., Wagenvoort A.J., Hummel H., Smaal A.C., 1993. “Survival in air” of the blue mussel *Mytilus edulis* L. as a sensitive response to pollution-induced environmental stress. *Journal of Experimental Marine Biology and Ecology*, 170, 179-195

Förlin L., Lemaire P., Livingstone D.R., 1995. Comparative studies of hepatic xenobiotic metabolizing and antioxidant enzyme in different fish species. *Marine Environmental Research*, 39, 201-204

Gehan E.A., 1965. A generalized Wilcoxon test for comparing arbitrarily singly-censored samples. *Biometrica*, 52, 203-223

Goldberg E.D., Bowen V.T., Farrington J.W., Harvey G., Martin J.H., Parker P.L., Risebrought R.W. Robertson W., Schneider E., Gamble E., 1978. The mussel watch. In: *Environmental Conservation*, the Foundation of Environmental Conservation. La Jolla C.A., 5, 101-125

Hauton C., Hawkins L.E., Hutchinson S., 1998. The use of the neutral red retention assay to esamine the effects of temperature and salinity on haemocytes of the European flat oyster *Ostrea edulis* (L.). *Comparative biochemistry and Physiology Part B*, 119, 619-623

Kaplan E.L., Meier P., 1958. Nonparametric estimation from incomplete observations. *Journal of American Statistics Association*, 53, 457-481

Livingstone D.R., Lemaire P., Matthews A., Peters L., Bucke D., Law R.J., 1993. Pro-oxidant, Antioxidant and 7-Ethoxyresorufin o-Deethylase (EROD) activity responses in liver of dab (*Limanda limanda*) exposed to sediment contaminated with hydrocarbons and other chemicals. *Marine Pollution Bulletin*, 26 (11), 602-606

Livingstone D.R., Nasci C., 2000. Biotransformation and antioxidant enzymes as potential biomarkers of contaminant exposure in goby (*Zosterissor ophiocephalus*) and mussel (*Mytilus galloprovincialis*) from the Venice Lagoon. In: *The Venice Lagoon Ecosystem. Inputs and Interactions between Land and Sea*. Lasserre, P., Marzollo, A. (Eds), UNESCO, Paris and The Parthenon Publishing Group, Lancs and N.Y. Press, 357-373

Lowe D.M., Da Ros L., 2000. Cellular biomarkers of contaminant exposure and effect in mussel (*Mytilus galloprovincialis*) and goby (*Zosterissor ophiocephalus*) from the Venice Lagoon. In: *The Venice Lagoon Ecosystem. Inputs and Interactions between Land and Sea*. Lasserre, P., Marzollo, A. (Eds), UNESCO, Paris and The Parthenon Publishing Group, Lancs and N.Y. Press, 375-385

Lowe D.M., Fossato V.U., Depledge M.H., 1995. Contaminant - induced lysosomal membrane damage in blood cells of mussel *Mytilus galloprovincialis* from the Venice Lagoon: an *in vitro* study. *Marine Ecology Progress Series*, 129, 189-196

Lowe D.M., Pipe R.K., 1994. Contaminant induced Lysosomal membrane damage in marine mussel digestive cells: an *in vitro* study. *Aquatic Toxicology*, 30, 357-365

Marin M.G., Nesto N., Da Ros L., 2001. Evaluation of biological stress indices in *Tapes philippinarum* from the Lagoon of Venice through monitoring of natural populations and transplantation experiments. In: *Mediterranean Ecosystems: Structures and Processes*, F.M. Faranda, G. Spezie (eds). Springer – Verlag Italia: 91-94

Moore M.N., 1985. Cellular responses to pollutants. *Marine Pollution Bulletin*, 16, 134-139

Moore M.N., Koehn R.K., Bayne B.L., 1980. Leucine aminopeptidase (aminopeptidase I) , n-acetyl-β-hexosaminidase and lysosomes in the mussel, *Mytilus edulis* L., in response to salinity changes. *J. Exp. Zool*., 214, 239-249

Nasci C., Da Ros L., Nesto N., Sperni L., Passarini F., Pavoni B., 2000. Biochemical and histochemical response to environmental contaminants in clam, *Tapes philippinarum*, transplanted to different polluted areas of Venice Lagoon, Italy. *Marine Environmental Research*, 50, 425-430

Nasci C., Nesto N., Bertoldo M., Da Ros L., 2004. Evaluation of biomarker responses in bivalves from the Venice Lagoon: seasonal study and transplantation experiment. In: *Scientific Research and Safeguarding of Venice. CORILA Research Program 2001-2003 2002 results*, Campostrini P. (Ed). Istituto Veneto di Lettere Scienze ed Arti, 243-257

Nasci C., Nesto N., Monteduro R.A., Da Ros L., 2002. Field application of biochemical markers and a physiological index in the mussel, *Mytilus galloprovincialis*: transplantation and biomonitoring studies in the lagoon of Venice (NE Italy). *Marine Environmental Research*, 54, 811-816

Regoli F., 1992. Lysosomal responses as a sensitive stress index in biomonitoring heavy metal pollution. *Marine Ecology Progress Series*, 84, 63-69

Regoli F., 1998. Trace metals and antioxidant enzyme in gill and digestive gland of the Mediterranean mussel *Mytilus galloprovincialis*. *Arch. Environ. Contam. Toxicol*., 34,48-63

Ringwood A.H., Conners D.E., Hoguet J., 1998. Effects of natural and anthropogenic stressors on lysosomal destabilization in oysters *Crassostrea virginica*. *Marine Ecology Progress Series*, 166, 163-171

Seed R., 1975. Reproduction in *Mytilus* (Mollusca; Bivalvia) in European waters. *Pubbl. Staz. Zool. Napoli*, 39 (Suppl.), 317-334

Sfriso A., Facca C., Ghetti P.F., 2003. Temporal and spatial changes of macroalgae and phytoplankton in a Mediterranean coastal area: the Venice lagoon as a case study. Marine Environmental Research, 56, 617-636

Sheehan D., Power A., 1999. Effects of seasonality on xenobiotic and antioxidant defence mechanisms of bivalve molluscs. *Comparative Biochemistry and Physiology, C*, 123, 193-199

Thomas, R.E., Brodersen, C., Babcock M.M., Carls, M.G., Rice, S.D., 1998. Lack of physiological responses to hydrocarbon accumulation by *Mytilus trossulus* after 3 to 4 years chronic exposure to spilled Exxon Valdez crude oil in Prince William Sound. *Comp. Biochem. Physio*l, 122, 153-163

Viarengo A., Canesi L., Pertica M., Livingstone D.R., 1991. Seasonal variations in the antioxidant defence systems and lipid peroxidation of the digestive gland of mussel. *Comparative Biochemistry and Physiology*, 100C, 187-190

Viarengo A., Canesi L., Pertica M., Mancinelli G., Accomando R., Smaal A.C., Orunesu M., 1995. Stress on stress response: a simple monitoring tool in the assessment of a general stress syndrome in mussels. *Marine Environmental Research*, 39, 245-248

Vidal M.L., Bassères A., Narbonne J.F., 2002. Influence of temperature, pH, oxygenation, water-type and substrate on biomarker responses in the freshwater clam *Corbicula fluminea* (Müller). *Comparative Biochemistry and Physiology Part C*, 132, 93-104

SET UP OF BIVALVE EMBRYOTOXICITY TEST USING *Mytilus galloprovincialis* AND C*rassostrea gigas* FOR EVALUATING SEDIMENT QUALITY IN THE LAGOON OF VENICE

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Riassunto.

Durante il progetto Co.Ri.La è stato messo a punto un metodo ecotossicologico sensibile basato sui primi stati vitali dei molluschi bivalvi, seguendo i protocolli standard internazionali. È stata valutata la possibilità di utilizzare, per i saggi di tossicità, organismi provenienti da popolazioni naturali lagunari della specie autoctona *Mytilus galloprovincialis.* Al fine di validare questo metodo per la laguna di Venezia, è stato intrapreso un percorso iterativo a vari livelli, che include la messa a punto, la valutazione della riproducibilità intralaboratorio, della sensibilità e della capacità discriminatoria verso alcune sostanze pure e verso campioni ambientali.

La valutazione della sensibilità verso una sostanza tossica di riferimento (il rame), ha evidenziato una discreta replicabilità e ripetibilità del metodo.

Per la valutazione della tossicità di elutriati preparati da sedimenti di quattro stazioni della laguna di Venezia, è stata utilizzata, accanto al mitilo, anche l'ostrica *Crassostrea gigas,* largamente impiegata a livello internazionale e facilmente reperibile in allevamenti specializzati. I risultati di due campagne di campionamento hanno mostrato che i metodi sono in grado di discriminare tra sedimenti a diversa tipologia e grado di contaminazione.

Questi test, applicabili insieme ad altri test di tossicità come il test Microtox o ai test di spermio ed embrio tossicità con il riccio di mare *Paracentrotus lividus,* possono contribuire ad evidenziare possibili effetti negativi per il biota dovuti agli inquinanti accumulati nei sedimenti e in seguito rilasciati nella colonna d'acqua, e ad identificare siti lagunari rappresentativi di condizioni patologiche nel funzionamento dell'ecosistema.

Abstract.

A sensitive ecotoxicological method based on early life stages of bivalve molluscs was set up, according to international standard methods, during the CORILA Project. The possibility of using the autochthonous mussel *Mytilus galloprovincialis* from natural populations of the Lagoon of Venice in toxicity bioassays was investigated. In order to validate this method for the Lagoon, iterative steps including set-up, evaluation

of reproducibility, sensitivity and discriminatory capacity towards some pure substances and environmental samples were preliminarily performed.

Evaluation of sensitivity towards a toxicant reference (copper) evidenced acceptable replicability and repeatability.

Jointly to the mussel, the oyster *Crassostrea gigas,* internationally employed and easily found from hatchery industries, was used to test elutriates prepared from sediments collected at four sites of the Lagoon of Venice. Results of two sampling campaigns revealed that the methods are able to discriminate among sediments at different types and levels of contamination.

These tests, applicable together with more standardised toxicity bioassays such as Microtox test or sperm cell toxicity test and embryo toxicity test with the sea urchin *Paracentrotus lividus*, contribute to put in evidence possible negative effects for biota due to pollutants accumulated into sediments and released in the water column, identifying the sites of the Lagoon representative of pathological conditions for functioning.

1. Introduction.

The use of biological indicators is becoming of increasing importance in evaluating the quality of sediments and their potential effects on the environment [US EPA and US ACE, 1998]. The choice of bioindicators is based on reliable scientific knowledge and often on the availability of standardized procedures [Giesy and Hoke, 1989; Lamberston *et al.*, 1992]. The search for the most representative species for specific areas of concern and specifically designed for estuarine conditions should aim at indigenous species instead of surrogate species [Chapman and Wang, 2002]. Bivalve molluscs are considered the best candidates among marine organisms [ICES, 1997; His *et al.*, 1999; Nendza, 2002], since gametes are available for many months of the year in the Mediterranean [Valli, 1971; Da Ros *et al.*, 1985].

The request of effective bioindicators by national law (D.lvo 152/99 and integrations) and European Water Framework Directive (2000/60/CE), particularly for transitional environments, led our research group to set up bioassays based on bivalve embryos development, according to existing standard methods [US EPA, 1995; ASTM, 1998; RIKZ, 1999].

The possibility of using *Mytilus galloprovincialis*, the species of Mytiloida most diffused in the lagoon of Venice [Cesari, 1994] was investigated during this project. To evaluate the real applicability of this test for the Lagoon, iterative steps including set-up, choice of population, evaluation of reproducibility, sensitivity and discriminatory ability towards some pure substances and environmental samples were carried out. As for previous and parallel researches on sea urchin tests [Volpi Ghirardini *et al.*, 2005a; 2005b], for this test an experimental design based on Quality Assurance/Quality Control procedures (QA/QC) was adopted too, in order to set the methodological basis for an reliable use of these bioassays in biomonitoring. The intralaboratory reproducibility of method was evaluated using copper as reference toxicant, testing sensitivity of embryos from natural and hatchery populations of the Lagoon from November 2002 to May 2003. The sensitivity of method was yet verified testing three highly toxic pesticides (Carbofuran, Atrazine, Malathion) [Losso *et al*., 2004a] for which literature data on molluscs were available only for some species of oysters. The last step regarded the evaluation of the applicability of method to environmental samples. Both elutriates and pore water from sediments of four sites of the Lagoon were used as test matrices for such fundamental research. Elutriates give information about the potential effects of pollutants which are made available in the water column as a consequence of sediment resuspension (dredging, fishing gear, etc); the application of bivalve embryos to elutriate is recommended by standard guidelines [ICES, 2003]. Pore water represents the main exposure way for most sediment-dwelling organisms, giving information on toxicity due to the soluble fraction of contaminants; the use of bivalve test on pore water is recommended by guidelines for monitoring marine and estuarine environments [US EPA, 2000]. Jointly to the autochthonous *M. galloprovincialis*, samples were tested also with the embryotoxicity test with the oyster *Crassostrea gigas.* This species is internationally used in embryotoxicity bioassays and easily found from hatchery industries.

2. Materials and Methods.

2.1. Animal sampling.

Adults of *M. galloprovincialis* were sampled from natural and hatchery populations from the Lagoon of Venice. Samples were collected monthly from October 2002 to May 2003, according to the length of the reproductive period described for the populations of the North Adriatic Sea [Valli, 1971; Da Ros *et al.*, 1985]. Natural and hatchery sites were very close, located near the sea inlet of Malamocco and far from point-sources of pollution. Adults from natural populations were collected during high tide from artificial substrates 1.5-2 m deep, using a rake with a net. Adults from hatchery populations (Mitilpesca s.r.l., Venice, Italy) were collected using a similar method, sampling them from January when the animals reached full maturity. Moreover, in order to compare lagoonal and open sea populations, sampling was also performed in a site (N 45° 18’ 53’’, E 12° 30’ 30’’) some miles off the sea inlet.
Adults were transported to the laboratory in refrigerated containers, were cleaned and stored at 4°C until testing.

Conditioned adults of *C. gigas* were purchased from Guernsey Sea Farm Limited hatchery (Guernsey, UK).

2.2. Embryotoxicity test.

The embryotoxicity tests with *M. galloprovincialis* and *C. gigas* were performed according to the method proposed by His *et al.* [1997] (Fig. 1), based on the standard protocol of US EPA [1995]. Adults were induced to spawn by thermic stimulation (temperature cycles at 18°C and 28°C). Gametes of good quality derived from the best males and females were selected and filtered at 32 μm (sperm) and 100 μm (eggs) to remove impurities. Eggs (1000 mL) were fertilised by injecting 10 mL of sperm; fecundation was verified by microscopy. Egg density was determined by counting four subsamples of known volume. Fertilised eggs, added to test solutions in order to obtain a density of 70 eggs ml^{-1}, were incubated for 48h at 18°C for *M. galloprovincialis* and

24h at 24°C for *C. gigas* and then fixed with buffered formalin. A number of 100 larvae was counted, distinguishing between normal larvae (D-shape) and abnormalities (malformed larvae and pre-larval stages). The acceptability of test results was based on negative controls for a percentage of normal D-shape larvae ≥ 80% [His *et al*., 1999].

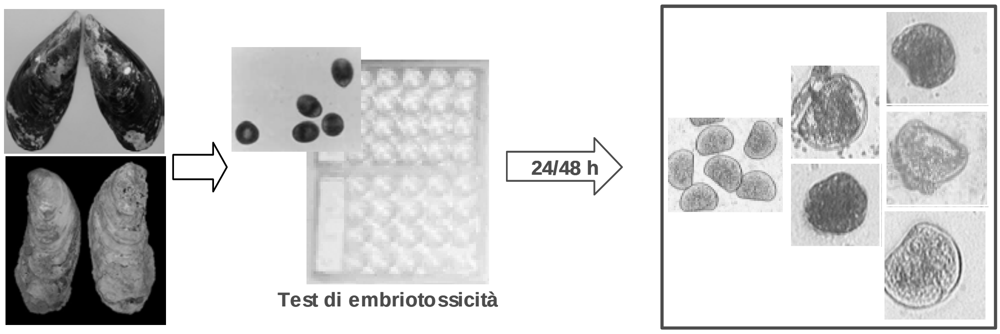

Fig. 1 – Phases of embryotoxicity test with *M. galloprovincialis* and *C. gigas*. From left to right: adults for emission; exposure of fertilised eggs; toxicity endpoints (normal D-shape; trochophora stage; D-shape malformations).

Three replicates for each pure toxicant and environmental sample were tested. EC50 values with 95% confidence limits were calculated using the Trimmed Spearman-Karber statistical method [Hamilton *et al*., 1978].

2.3 Chemicals.

Dilution water (for test solutions and gametes) was artificial sea water reconstituted according to ASTM [1998] at salinity of 34 ppt.
Copper solutions were prepared starting from a standard solution for atomic spectroscopy (1000 mg l^{-1}) composed of copper nitrate in nitric acid 0.5 M (Baker, Deventer, Holland).

To evaluate the possible influence of confounding factors in elutriate and pore water toxicity, ammonia and sulphides were analysed for each environmental sample. Concentrations of sulphides and total ammonia were measured with a spectrophotometer (mod.DR/2010, HACH, Loveland, CO, USA) using the methylene blue method (USEPA SM 4500-S2 D) for sulphides and the salicylate method [Reardon *et al*., 1966] for total ammonia.

2.4 Sediment sampling and preparation of matrices for testing.

Four sampling sites (Fig. 2) covering varying types and levels of contamination were selected in coordination with other research groups (CORILA Project, Line 3.3. ‘‘Efficiency of the lagoon metabolism’’). The sites (SE, SN, CEL, TR) were located in zones influenced by anthropogenic activities, in shallows characterized by bare substrates. One station (SE) was close to the island of Sant’Erasmo, in an area characterized by fast water turnover, due to the proximity of the Lido sea inlet, and presumably also by a minimum degree of contamination. This site is classified as a high-quality site (class A for both organic and inorganic micropollutants) according to current quality criteria used to classify dredged sediments in the Lagoon of Venice [Losso *et al*., 2004b]. For this reason, this site was chosen as a possible reference. The second site, Celestia (CEL), was located between the island of Murano on the northeastern side of the city of Venice. The site receives untreated municipal wastewater (from Venice city centre) and may also be affected by contamination from industrial sources, due to the vicinity of Murano, where several glass factories are located. The contamination level of the area near the site is medium for heavy metals (class B) and higher for organic micropollutants (class C) [Volpi Ghirardini *et al*., 2003]. The third station (TR) was located off Tresse, an artificial island composed of rubble dredged from the Industrial Zone channels near Porto Marghera. This site had already been investigated from a chemical point of view, and had revealed high contamination levels of both heavy metals and organic micropollutants (class C) [Volpi Ghirardini *et al*., 2003]. A fourth station, San Nicolò (SN), located in the proximity of the Lido sea inlet, presumably characterised by a minimum degree of contamination, was added at the second sampling as possible reference, since SE revealed high toxicity in the first sampling [Losso *et al*., 2004b; Volpi Ghirardini *et al*., 2004].

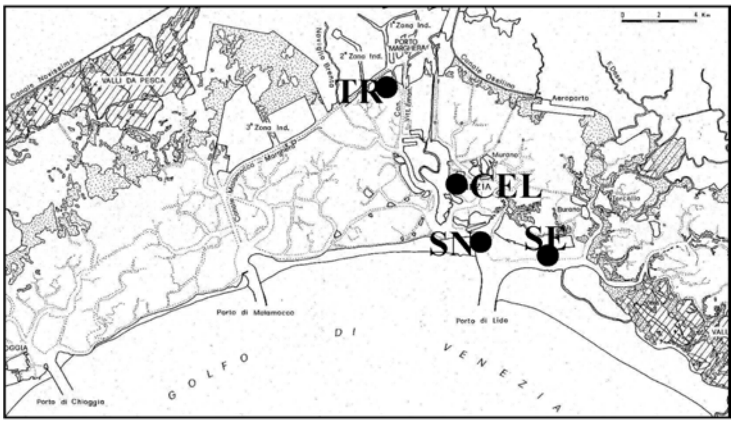

Fig. 2 – Location of sampling stations.

Core sediment samples were collected in November 2001 and in April 2003. At each site, the area (a circle approximately 30 meters across, with a central point fixed by geographical co-ordinates), and sample dimensions (8 and 16 sediment cores for depths of 20 and 5 cm, respectively) were defined, and integrated sampling (with cores equally distributed in the area) was carried out in order to take into account any spatial microvariability in pollution/bioavailability, according to the scheme reported in Volpi Ghirardini *et al.* [2005b]. Samples were collected using an 8-cm-diameter Plexiglas corer.

For elutriate preparation, a slurry with a 1:4 sediment:water (dry weight/volume) ratio was stirred (230 rpm) at 4°C in the dark for 24 h using a Jar test (Vittadini, Milan, Italy). After stirring, the sediment/water mixture was allowed to settle for 1 h. The unsettled portion (due to the high clay content of lagoonal sediments) was centrifuged (Beckman ultracentrifuge) at about 7700 g for 15 min at 4°C [Volpi Ghirardini *et al*., 2003]. The resulting elutriate was frozen until use.

For pore water extraction, international guidelines [Carr *et al.*, 2001] were used as reference to set up the procedure for the Lagoon. Pore water was obtained after sediment homogenization and treatment in an atmospheric controlled glove-box and by centrifuging sediment at about 13.500g for 30 min at 4°C (Beckman ultracentrifuge). Filtration was avoided according to more recent literature [Carr and Chapman, 1995; US EPA, 2001].

3. *Results and discussion.*

3.1. Reference toxicant (copper).

Experiments performed during November 2002 with two batches of natural populations and one operator highlighted good replicability of methods. Indeed, EC50 values with 95% confidence limits for copper for batch A were 11.4 µg/L (10.9-11.9) for the first replicate, 12.0 µg/L (11.6-12.5) for the second and 13.0 µg/L (12.7-13.3) for the third, with a mean of 12.3 µg/L (11.8-12.8) and a standard deviation of 0.8. EC50 values for batch B were 12.3 µg/L for the first replicate, 10.5 µg/L (9.9-11.1) for the second and 10.4 µg/L (9.9-11.0) for the third, with a mean of 12.5 µg/L (12.3-12.8) and a standard deviation of 1.1.

The repeatability of the method was shown by experiments performed with natural populations from November 2002 to May 2003 (Fig. 3), using two operators and 10 batches of organisms: the EC50 mean value with standard deviation for copper was 18.1±5.5 µg/l (CV=31%, n=10).

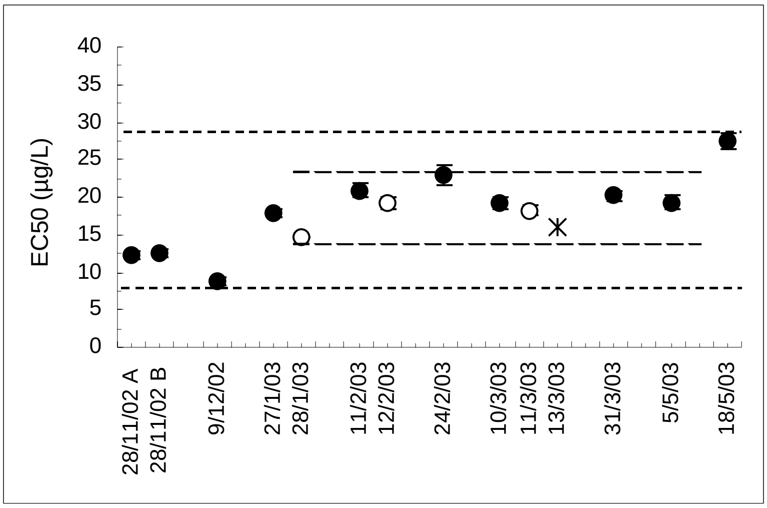

Fig. 3 – Control chart for embryotoxicity test using copper as reference toxicant. Black: results of natural populations; white: hatchery populations; star: marine populations. Dotted lines: acceptability ranges, considering start and end of reproductive period (thicker) and central reproductive alone period (tighter dots).

Considering all experiments performed during the reproductive period, with two operators, 14 organism batches and 3 different sampling populations (natural, hatchery, open sea) a reference control chart was constructed (Fig. 3). The mean EC50 value with standard deviation for copper was 17.8±4.7 µg/l (CV=27%, n=14). As a preliminary evaluation, embryotoxicity with autochthonous populations of *M. galloprovincialis* showed acceptable intralaboratory reproducibility.

A first optimal range (two standard deviations from the mean EC50 value) in which the EC50 should fall in subsequent tests was defined, using all data, with lower and upper control limits of 8.3 and 27.2 µg/l, respectively (thicker lines in Fig. 3). Considering only the central reproductive period, when the sensitivity of gametes may have been less variable, the range narrowed from 14 to 23 µg/l. Considering only the data included into this range, a better intralaboratory reproducibility can be obtained (CV=12%, n=10).

3.2. Elutriates from lagoonal sediments.

Embryotoxicity results for elutriates are shown in Fig. 4. In the first sampling campaign, the bivalve embryotoxicity method was preliminarily applied only to CEL and SE stations. The mussel evidenced low toxicity for CEL station both for the core–top 20 cm and the core-top 5 and the oyster revealed not significant toxicity for the core-top 20 cm and a toxicity for the core-top 5 comparable with that shown by mussel. High toxicity was shown by both test for the site SE, chosen as a possible reference on chemical-based criteria: for *M. galloprovincialis* the toxicity of core-top 20 and 5 were comparable (EC50 ± SD of 28.7% ± 6.4 and 38.3% ± 2.4, respectively), whereas for *C. gigas* the core-top 5 were more toxic (EC50 ± SD =31.6% ± 1.6) than the core-top 20 (percentage of effect=39%). In the second sampling campaign, the mussel showed negligible toxicity for SE, CEL and SN core-top 20 and a noticeable toxicity for TR core-top 20; oyster confirmed these data even if a lower toxicity was revealed by TR core-top 20. All samples from 5 cm depth registered not significant toxicity for *C. gigas* and low toxicity for *M. galloprovincialis*.

Results with bivalve embryotoxicity tests confirmed some evidences revealed by embryotoxicity test with *P. lividus*: also the sea urchin toxicity test showed higher toxicity in the first sampling campaign and, particularly, in SE core-top 5 (EC50 ± SD = 39.7 ± 1.8%), which represented an unexpected hot spot of toxicity [Losso *et al*., 2004b; Volpi Ghirardini *et al*., 2004].

In order to verify if possible confounding factors could contribute to toxicity of elutriates, as suggested by literature regarding the quality evaluation of marine and coastal sediments [Ankley *et al*., 1990; Carr *et al*., 1996; Whiteman *et al*., 1996; Phillips *et al*., 1997], chemical analyses of sulphide and ammonia were made on elutriates and a comparison between chemical concentration in elutriates and sensitivity limits of method towards ammonia and sulphide was carried out. Sulphide concentrations in elutriates ranged from 0 to 0.078 mg/L and were lower than the NOEC value of 0.1 mg/L recommended by ASTM [1998] for bivalve embryotoxicity tests. For ammonia, elutriates showed concentrations of total ammonia ranging from 0.07 to 4.57 mg/L and therefore lower than NOEC value of 4.7 mg/L (at pH 7.8-8.1) recommended for bivalve embryotoxicity test [ASTM, 1998].

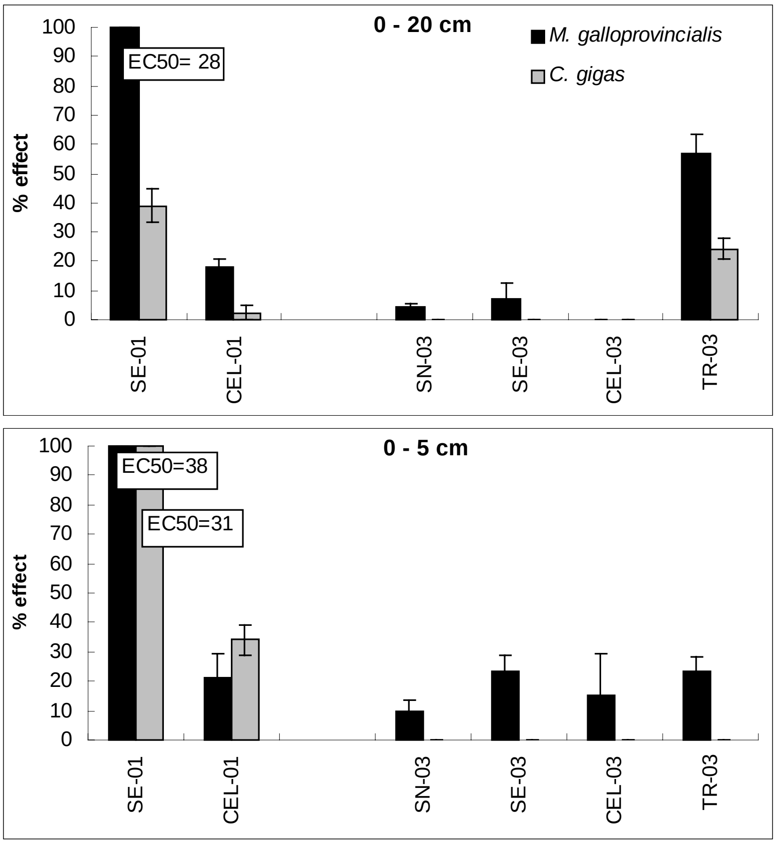

Fig. 4 – Embryotoxicity results for elutriates from the core–top 20 cm (above) and the core–top 5 cm (below).

3.3. Pore waters from lagoonal sediments.

Pore water tests were carried out in the second sampling campaign, after a first application to available samples from the first campaign (data not reported). Only core-top 20 cm in the investigated sites allowed to obtain an adequate volume of pore water for testing and stations comparison (Fig. 5). Pore waters showed a noticeable toxicity in all stations, higher than that showed by correspondent elutriates; indeed, all pore water samples (with the exception of SE in oyster test) showed a toxicity expressible in Toxicity Units (TU50). Oyster and mussel showed comparable results only for station CEL, their responses differing among other stations: oyster test showed a sensitivity higher than mussel test in station SN (TU50 = 2.0 and 1.1, respectively) and TR (TU50 = 9.3 and 3.2, respectively); on the contrary, oyster test showed a toxicity lower than mussel test for station SE, making not possible EC50, and consequently TU50, calculation.

Also for pore waters the possible contribution of confounding factors as sulphide and ammonia was investigated. Sulphide concentrations in elutriates ranged from 0 to 0.052 mg/L and were lower than the NOEC value of 0.1 mg/L recommended by ASTM [1998] for bivalve embryotoxicity tests. Total ammonia concentrations ranged from 0.6 to 5.3 mg/L and could contribute to toxicity of TR; anyway, further investigations are necessary in order to discriminate between natural and anthropogenic origin of ammonia.

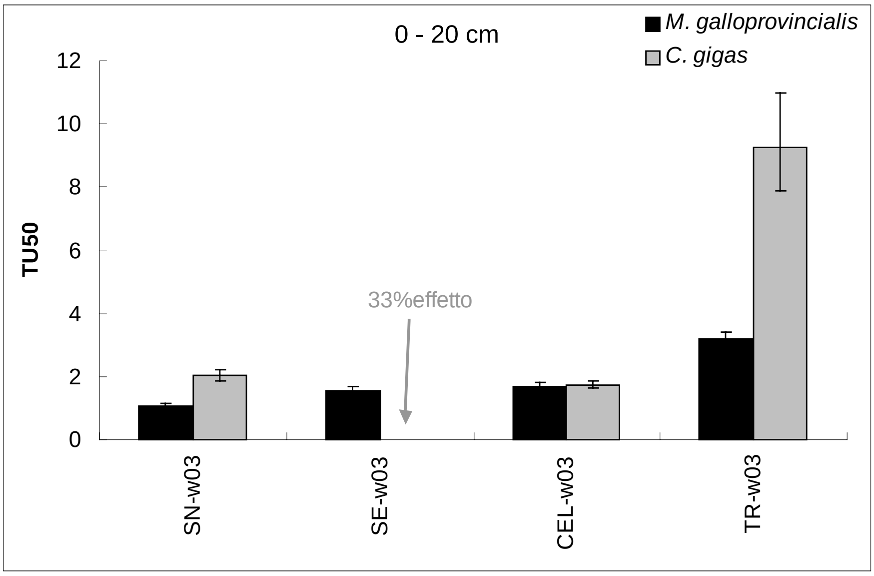

Fig. 5 – Embryotoxicity results for pore waters from the core–top 20 cm for the second sampling campain.

Conclusions.

During the Co.Ri.La project, the set up of a sensitive bioassay with bivalves was carried out, using species representative for the lagoonal environment. A preliminary validation of embryotoxicity test using *M. galloprovincialis* for the Lagoon of Venice was performed. The use of a reference toxicant (copper) provided preliminarly acceptable intralaboratory reproducibility (EC50 mean value with standard deviation of 17.8±4.7 µg/l, CV=27, n=14), when some variables such as different operators, different organism batches and sampling populations (natural, hatchery, open sea) were changed. Good quality of gametes and the long reproductive period (from November to May) were shown by natural lagoonal populations; these characteristics were not found in the hatchery populations.

The application of embryotoxicity tests using both autochthonous populations of the mussel *M. galloprovincialis* and conditioned oysters of the species *C. gigas* to elutriates obtained from four stations of the Lagoon of Venice revealed that the method is able to discriminate among sediments at different types and levels of contamination. Results also showed an hot spot of subchronical toxicity in a site (S. Erasmo) previously classified as a high-quality site (class A) for both organic and inorganic micropollutants. First applications of both bivalve methods to pore waters was surely promising due to little volumes necessary for testing and a negligible contribution of confounding factors.

In conclusion, embryotoxicity test with bivalves represents a new tool to introduce in a battery of bioassays for the quality assessment of the Lagoon of Venice. An ecotoxicological approach is revealed to be useful to put in evidence possible negative effects for biota due to pollutants accumulated into sediments and to identify sites inside the Lagoon characterized by pathological conditions for functioning.

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References.

Ankley G.T., Katko A. and Arthur J.W., 1990. Identification of ammonia as an important sediment-associated toxicant in the Lower Fox River and Green Bay, Winsconsin. *Environ. Toxicol. Chem*., 9, 313-322

ASTM., 1998. *Standard guide for conducting static acute toxicity tests starting with embryos of four species of saltwater bivalve molluscs*. E 724-98: 21pp

Carr R.S. and Chapman D.C., 1995. Comparison of methods for conducting marine and estuarine sediment porewater toxicity tests – extraction, storage and handling techniques. *Arch. Environ. Contam. Toxicol*., 28: 69-77

Carr R.S., Long E.R., Windom H.L., Chapman D.C., Thursby G., Sloane G.M. and Wolfe D.A., 1996. Sediment quality assessment studies of Tampa Bay, Florida. *Environ. Toxicol. Chem.*, 7, 1218-1231

Carr R.S., Nipper M., Adams W.J., Berry W.J., Burton Jr G.A., Ho K., MacDonald D., Scroggins R. and Winger P.V., 2001. Summary of the SETAC technical workshop: *Porewater toxicity testing: biological, chemical, and ecological considerations with a review of methods and applications, and recommendations for future areas of research.* 18-22 March 2000; Pensacola, FL. Society of Environmental Toxicology and Chemistry (SETAC). Pensacola, FL. 38p

Cesari P., 1994. *I molluschi della laguna di Venezia*. Arsenale ed., Verona, Italy. 189 pp

Chapman P.M. and Wang F., 2002. Assessing sediment contamination in estuaries. *Environmental Toxicology and Chemistry*, 20(1), 3-22

Da Ros L., Bressan M. and Marin M.G., 1985. Reproductive cycle of the mussel (*Mytilus galloprovincialis* Lmk) in Venice lagoon (North Adriatic). *Bol. Zool.*, 52, 223-229

Giesy J.P. and Hoke R.A., 1989. Freshwater sediment toxicity bioassessment: rationale for species selection. *J. Great Lakes Res.*, 15, 539-569

Hamilton M.A., Russo R.C. and Thurston R.V., 1978. Trimmed Spearman-Karber method for estimating median lethal concentrations in toxicity bioassays. *Environ. Sci. Technol.*, 12, 714-720

His E., Seaman R.N.L. and Beiras R., 1997. A simplified bivalve larval bioassay method for seawater quality assessment. *Water Research*, 31, 351-355

His E., Beiras R. and Seaman M., 1999. The assessment of aquatic contamination: bioassays with bivalve larvae. *Advances in Marine Biology*, 37, 1-178

ICES International Council for the Exploitation of the Sea., 1997. *Report of the ICES Advisory Committee on the Marine Environment.* ICES Cooperative Research Report 222**,** 12-20

ICES. International Council for the Exploration of the Sea., 2003. Report of the ICES Advisory Committee on the Marine Environment, 2003. ICES Cooperative Research Report, Copenhagen, 16-20 June 2003

Lamberston J.O., De Witt T.H. and Swartz R.C., 1992. *Assessment of sediment toxicity to marine benthos*. In: Burton G.A.Jr (ed) "Sediment toxicity assessment" Lewis Publ., 183-211

Losso C., His E., Ghetti P.F. and Volpi Ghirardini A., 2004a. Sensitivity of embryotoxicity test with *Mytilus galloprovincialis* (LMK) towards some compounds of environmental interest (copper and pesticides). *Environmental Technology*, 25(7): 841-846

Losso C., Arizzi Novelli A., Picone M., Marchetto D., Pessa G., Molinaroli E., Ghetti P.F. and Volpi Ghirardini A., 2004b. Evaluation of sediment resuspension effects on toxicity: preliminary results from the Lagoon of Venice. *Journal of Marine Systems*, 51: 281-292

Nendza M., 2002. Inventory of marine biotest methods for the evaluation of dredged material and sediments. *Chemosphere*, 48(8), 865-883

Phillips B.M., Anderson B.S. and Hunt J.W., 1997. Measurement and distribution of interstitial and overlying water ammonia and hydrogen sulfide in sediment toxicity tests. *Mar. Environ. Res.*, 44, 117-126

Reardon J., Foreman J.A. and Searcy R.L., 1966. New reactants for the colorimetric determination of ammonia. *Clinica Chimica Acta*, 14(3), 203-205

RIKZ., 1999. Marine oyster *Crassostrea gigas* embryo-larvae mortality and development sediment toxicity test. Standard operating procedure. Specie-05. RIKZ/AB-99.118x

US EPA., 1995. *Short-Term Methods for Estimating the Chronic Toxicity of Effluents and Receiving Waters to West Coast Marine and Estuarine Organisms*. EPA/600/R-95/136, Cincinnati, Ohio, U.S

US EPA and US ACE., 1998. *Evaluation of Dredged Material Proposed for Discharge in Waters of the US – Testing Manual*. US Environmental Protection Agency and US Army Corps of Engineers. EPA/823-B-94/002, Washington, DC

US EPA., 2000. *Estuarine and coastal marine waters: bioassessment and biocriteria technical guidance.* U.S. Environmental Protection Agency, Office of Water, 4304 Washington, D.C. 20460. EPA-822-B-00-024

US EPA., 2001. *Methods for collection, storage and manipulation of sediments for chemical and toxicological analyses: technical manual.* Office of Science & Technology Office of Water. U.S. Environmental Protection Agency, Washington, D.C. 20460. EPA-823-B-01-002

Valli G., 1971. Ciclo di maturità sessuale in *Mytilus galloprovincialis* Lmk di Duino (Trisete). *Bol. Pesca Piscic.Idrobiol.*, 26 (1-2), 260-265

Volpi Ghirardini A., Arizzi Novelli A., Losso C. and Ghetti P.F., 2003. Sea urchin toxicity bioassays for sediment quality assessment in the Lagoon of Venice (Italy). *Chemistry and Ecology*, 19(2-3), 99-111

Volpi Ghirardini A., Arizzi Novelli A., Losso C., Marchetto D., Picone M. and Ghetti P.F., 2004. *Sediment quality assessment in the lagoon of Venice using a battery of toxicity bioassays*. In Scientific Research and Safeguarding of Venice, Research Programme 2001-2003, Volume II, 205-213

Volpi Ghirardini A., Arizzi Novelli A., Losso C. and Ghetti P.F., 2005a. *Sperm cell and embryo toxicity tests using the sea urchin Paracentrotus lividus (LmK)*. In: Techniques in Aquatic Toxicology, volume 2, ed G.K. Ostrander, CRC press: 147-168

Volpi Ghirardini A., Arizzi Novelli A. and Tagliapietra D., 2005b. Sediment toxicity assessment in the Lagoon of Venice (Italy) using *Paracentrotus lividus* (Echinodermata: Echinoidea) fertilization and embryo bioassays. *Environmental International*, in press

Whiteman F.W., Ankley G.T., Kahl M.D., Ra, D.M. and Balcer M.D., 1996. Evaluation of interstitial water as a route of exposure for ammonia in sediment tests with benthic macroinvertebrates. *Environ. Toxicol. Chem.*, 15, 794-801

AN INVESTIGATION ON HEAVY METAL AND ARSENIC CONTAMINATION IN THE VENICE LAGOON: A SPECIATION APPROACH

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Riassunto.

Sono sinteticamente presentati i risultati di uno studio sulla contaminazione da metalli pesanti e da arsenico nella laguna di Venezia, ottenuti nell'ambito del Primo Programma di Ricerca CORILA. Lo studio è stato focalizzato sulla speciazione dei metalli che, rispetto alla determinazione delle concentrazioni totali, è in grado di fornire informazioni più significative riguardo a biodisponibilità, mobilità, destino e bioaccumulo degli inquinanti considerati nell'ecosistema acquatico.

Abstract.

This paper presents a synthesis of the results of a study on heavy metal and arsenic contamination in the lagoon of Venice, obtained in the framework of the First Research programme of CORILA. The study has focused on metal speciation which, compared to the determination of total concentrations, can provide more significative information on the bioavailability, mobility, fate and bioaccumulation of the considered pollutants in aquatic ecosystems.

1. Introduction.

Metal pollution can influence negatively the efficiency of the lagoon metabolism and cause serious problems to the community of organisms living therein. These pollutants are persistent and can accumulate under various forms in environmental compartments that can act as sinks, such as bottom sediments, and in aquatic organisms.

The lagoon of Venice has been the object in past years of a number of studies and monitoring programs that allowed for the achievement of a sufficient level of knowledge on metal contamination and for the identification of the most polluted areas. These studies, however, have rarely taken into consideration the various forms under which metals are present, and have mostly focused on the determination of total metal concentrations in the different environmental matrices.

As a consequence, there is a lack of knowledge on metal pollution in terms of bioavailability, mobility, distribution and transformation.

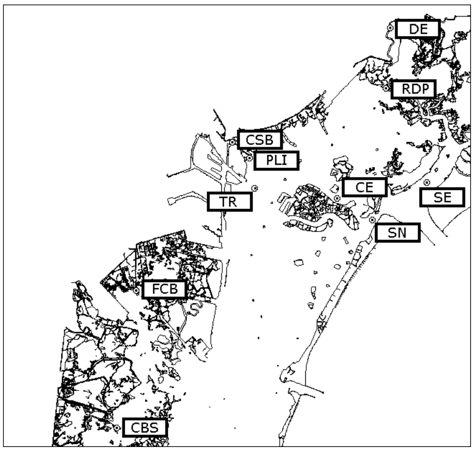
This research was aimed at acquiring knowledge on the relationships between the chemical forms of metals and their bioavailability, on metal mobility among the various biotic and abiotic compartments, on the pathways of introduction in the food chain and on bioaccumulation mechanisms. A particular attention was posed to arsenic, which has been the subject of a debate about the potential risks posed by its rather high levels found in some parts of the lagoon of Venice. Arsenic can be found in aquatic ecosystems under a variety of chemical species, each having different toxicity and environmental behaviour. The quantification of the different species can thus provide more useful information, with respect to total concentrations, about the toxicological risk and about the transformations and the metabolism of this element in the environment.

An analytical approach based on metal speciation was chosen and used throughout this study as a tool to evaluate metal bioavailability and to investigate the mechanisms of bioaccumulation.

To this purpose, a procedure of geochemical speciation of metals in sediments based on sequential extractions has been optimized. It permitted to partition metals in five fractions, corresponding to the main forms of association found in sediments, each characterized by a different possibility of release to the overlying water column or uptake by organisms.

Arsenic speciation required the development of a suitable and rather complex analytical procedure, based on the hyphenated techniques HPLC-ICP-MS, which allowed for the quantification of the main arsenic species present in aquatic organisms: the most toxic ones, arsenite and arsenate, the less toxic species monomethylarsonic acid (MMA) and dimethylarsinic acid (DMA), and the more complex compounds like arsenobetaine (AB), arsenocholine (AC) and arsenosugars, which are considered non-toxic.

The optimized procedures were then used to characterize metal pollution in different sites of the Venice lagoon, with different levels and typology of metal contamination, selected on the basis of previous knowledge and on the distribution and population dynamics of the two species selected as bioindicators, a water column and a benthic one (the mollusc *Mytilus galloprovincialis* and the polychaete *Hediste diversicolor*, respectively). Sampling sites are shown in Fig. 1.



<u>Mussels</u>:
TR= Tresse
CE= Celestia
SN= S.Nicolò
SE=S.Erasmo

<u>Polychaetes:</u>
FCB=Fine Canale Bondante
DE=Dese
RDP=Ramo dei Passarini
CBS=Canale della Bastia
CSB=Canal Salso-Canale Brentella
PLI=Pili

Fig. 1 – Map of the lagoon of Venice with sampling sites.

2. Metal speciation in sediments and bioaccumulation in aquatic organisms.

In general, sediments collected at the site of S. Nicolò, which was opportunely selected as a reference site, presented lower metal levels. On the other hand, higher concentrations for most metals, in particular Cd, Zn, Hg, Cu, Cr and Pb, were found at the site of Tresse, situated in proximity of the industrial area of Porto Marghera, and at the site of Celestia, which can be affected by pollution sources of urban origin as well as by the activities of the glass industry of Murano island. Also the sites of Pili and Canal Salso-Brentella, both located near Porto Marghera, showed higher concentrations of some elements, indicative of a contamination of anthropogenic origin.

Metal partitioning among the geochemical phases of sediments showed a limited spatial and temporal variability. However, in the most polluted sites a higher relative abundance in the non-residual phases was found for the metals of anthropogenic origin. In general, an important portion of the total content was found in potentially bioavailable fractions for the most toxic metals, except for chromium.

In the sites indicated in Fig. 1 specimens of *M. galloprovincialis* were collected in the course of four seasonal samplings (October 2001, February, July 2002 and October 2002), whereas the samples of *H. diversicolor* were collected in July 2002. Sediments samples were collected at the same sites in October 2001 and July 2002.

The differences between metal concentrations in mussels from the four selected sampling sites were not as relevant as observed for sediments. The sites of Tresse and Celestia showed in general higher levels of Cd and, to a lower extent, of Cu, Zn and Pb, with respect to S. Nicolò and S. Erasmo, chosen as reference sites. Samples from these sites, on the other hand, showed significantly higher levels of As in samples collected in February 2002.

For most elements a clear seasonal trend was observed, with a maximum in February, a minimum in July and intermediate levels in the two October samplings. The observed differences can be ascribed to various factors, among which the reproductive cycles of organisms can play an important role; mussel spawning, in fact, is likely to have occurred in the period between the February and July samplings.

Another finding related to the physiology and metabolic activity of the organisms is the higher metal bioaccumulation in the digestive gland of mussels, with respect to the remaining soft tissues, except for Zinc. Fig. 2 shows the data for the sampling of October 2002.

Compared to mussels, polychaetes showed some marked differences among sites, particularly for Pb, Fe, Al, Cd and Cu. In general, the highest concentrations were observed at the sites Canal Salso-Brentella and Pili, located near the industrial area. Zn showed a lower variability, thus confirming the results of previous studies. As and Ni had significantly lower concentrations only at the site of Dese (Fig. 3). The concentrations of most elements were comparable to those measured in mussels, with the exception of Cu and Fe. Nonetheless, the different habitats and feeding strategies of these organisms must be taken into account.

As observed in many studies regarding aquatic ecosystems, metal concentrations in sediments can be sparingly related to those found in organisms. In a complex system such as the lagoon of Venice the evaluation of the relationships between contamination in the abiotic and the biotic compartment may be even more difficult.

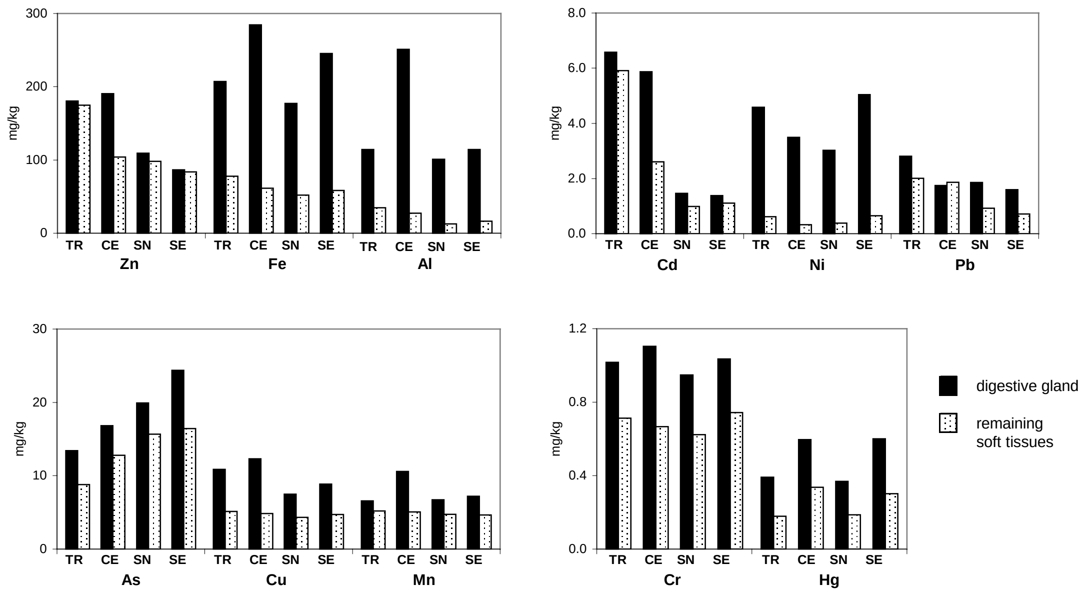


Fig. 2 – Comparison between metal concentrations (mg/kg dry weight) measured in the digestive gland and in the remaining soft tissues of mussels collected in October 2002.

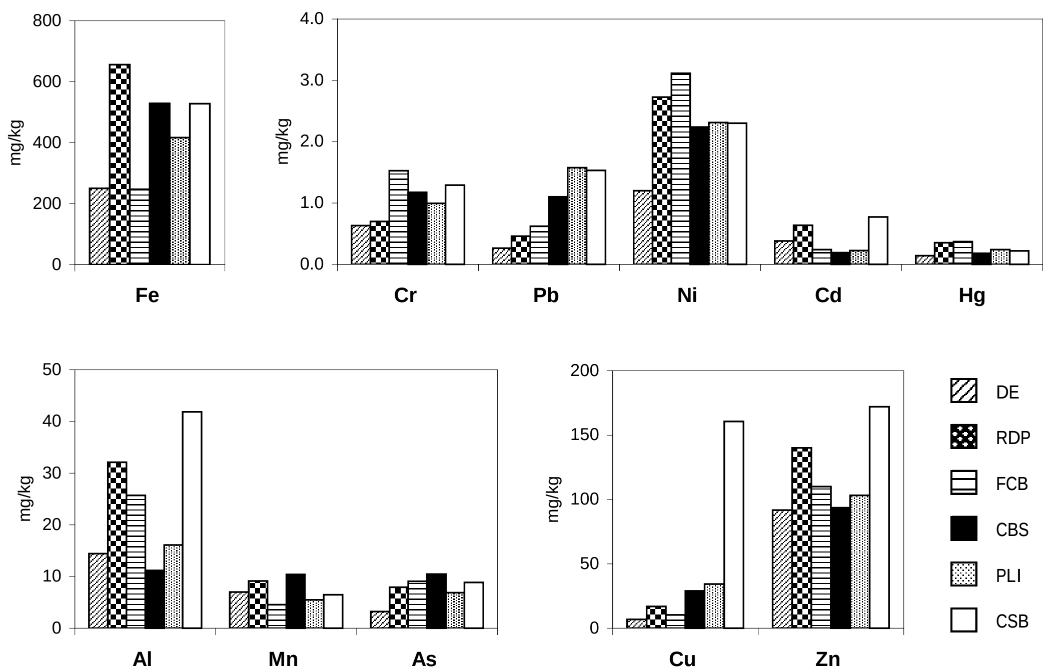


Fig. 3 – Metal concentrations determined in polychaete samples (mg/kg dry weight).

The approach based on geochemical speciation appears more suitable for this purpose; for Cu and Cd, for example, a significant correlation seemed to exist between the content in mussels and that measured in non-residual geochemical phases. However, due to the relatively low number of sampling sites examined, these results can allow only for the drawing of provisional conclusions, but can provide a valuable basis for the setting up of future investigations.

3. Arsenic speciation.

Mussel tissues contained various arsenic compounds, most of which were organic species, with a prevalence of arsenobetaine and of the arsenosugar AR2 (1-[5-deoxy-5-(dimethylarsinoyl)-β-ribofuranosyloxy]-3-‘glycerophosphoryl’-2-hydroxypropane), that is non-toxic species.

Though displaying different levels of total arsenic, mussel samples from the various sites of the lagoon showed comparable patterns of arsenic species. The variability among seasonal sampling was rather limited as well.

It can be noticed that inorganic arsenic was mostly undetectable. Significant levels of arsenite and arsenate (about 8% on a whole) were found only in mussels collected at S. Nicolò in February 2002, and were concentrated in the digestive glands of the specimens (Fig. 4).

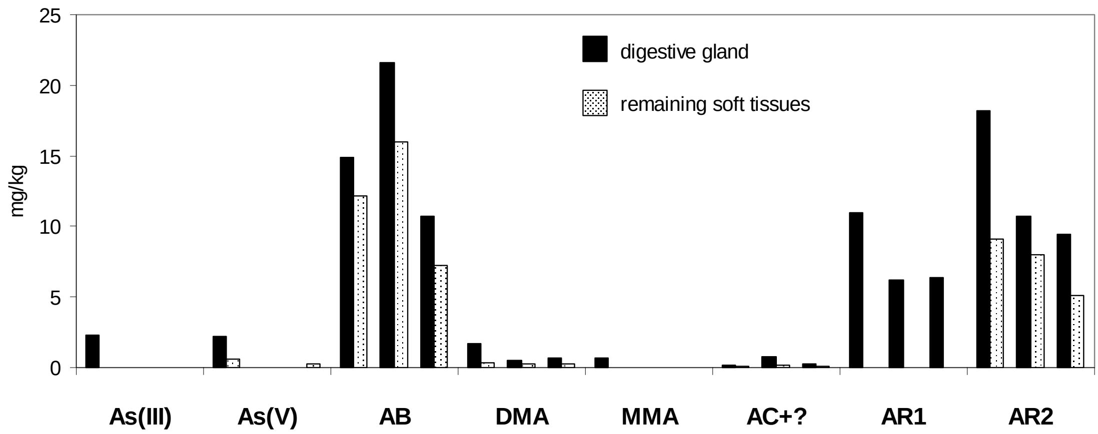


Fig. 4 – Distribution of arsenic species in the digestive gland and in the remaining soft tissues of mussels collected at the site of S. Nicolò in February 2002. Concentrations are expressed in mg/kg dry weight.

This organ, as already mentioned, presented in general higher amounts of arsenic, with a preferential accumulation of some species, such as the arsenoriboside AR1 (2,3-dihydroxypropyl 5-deoxy-5-(dimethylarsinoyl)-β-ribofuranoside). These features, which are linked to the metabolic pathways of arsenic in the examined organisms, point out the need for further investigations involving species belonging to different levels of the trophic chain, in order to get a deeper knowledge into the processes involved in the metabolism of arsenic in the lagoon ecosystem.

In addition to the arsenic species detected in mussels, polychaetes showed the presence of other compounds, among which a third arsenosugar. The prevailing species were nontheless arsenobetaine and the arsenosugars AR1 and AR2. Though at very low levels (below 2%, except at the site of Dese), inorganic arsenic was detected in most polychaete samples, probably because of the different habitat and feeding strategy of these organisms, for which arsenic uptake may occur through the ingestion of sediment particles.

Conclusions.

The results obtained in this study allowed for a characterization of metal contamination in the selected areas of the lagoon of Venice, by using speciation techniques as a tool to evaluate metal bioavailability and bioaccumulation.

The set-up and application of arsenic speciation procedures provided an update of the current knowledge on arsenic contamination, since information about the presence and levels of arsenic species in lagoon organisms was not formerly available. The most toxic forms, As(III) and As(V), were mostly undetectable and, in any case, far below the 10% of total content estimated by the *US Food and Drug Administration.*

These results constitute a first step for understanding the processes involved in arsenic metabolic and detoxification pathways in the lagoon environment, as well for assessing the risk posed to aquatic organisms and to human health.

Bibliography.

Argese E., C. Bettiol, A. Cedolin, S. Bertini, E. Delaney, 2003. Speciation of heavy metals in sediments of the lagoon of Venice collected in the industrial area. *Annali di Chimica - Journal of Analytical and Environmental Chemistry* 93, 329-336

Argese E., C. Bettiol, C. Rigo, S. Bertini, S. Colomban and P.F. Ghetti. Distribution of arsenic compounds in *Mytilus galloprovincialis* of the Venice lagoon (Italy). *The Science of the Total Environment* (in press)

Bryan G.W., W.J. Langston, 1992. Bioavailability, accumulation and effects of heavy metals in sediments with special references to UK estuaries: a review, *Environ. Pollut.*, 76, 89-131

Cullen, W.R. and Reimer, K.J., 1989. Arsenic Speciation in the Environment. *Chemical Reviews* 89, 713-764

Edmonds, J.S. and Francesconi, K.A., 1992. Arsenic metabolism in aquatic ecosystems, in "*Metal metabolism in Aquatic Environments"*, by Langston W.J. and M.J. Bebianno, London

Falk K. and Emons H., 2000. Speciation of arsenic compounds by ion-exchange HPLC-ICP-MS with different nebulizers. *Journal of Analytical Atomic Spectrometry* 15, 643-649

Larsen E.H., Pritzl G., Hansen S.H., 1993. Arsenic Speciation in Seafood Samples With Emphasis on Minor Constituents: an Investigation Using High-performance Liquid Chromatography With Detection by Inductively Coupled Plasma Mass Spectrometry. *Journal of Analytical Atomic Spectrometry* 8, 1075-1084

Shibata Y. and Morita M., 1992. Characterization of organic arsenic compounds in bivalves. *Applied Organometallic Chemistry* 6, 343-349

Tessier A., P.G.C. Campbell, 1987, Partitioning of trace metals in sediments: relationships with bioavailability, *Hydrobiologia*, 149, 43-52

Volpi Ghirardini A., L. Cavallini, E. Delaney, D. Tagliapietra, P.F. Ghetti, C. Bettiol, E. Argese, 1999. H. diversicolor, N. Succinea and P. Cultrifera (polychaeta: nereididae) as bioaccumulators of Cadmium and Zinc from sediments: preliminary results in the venetian lagoon (Italy), 1999, *Toxicological and. Environmental Chemistry*, 71, 457-474

IMPOSEX IN *Hexaplex trunculus* FROM THE LAGOON OF VENICE: ROLE OF ORGANOTIN COMPOUNDS AND PRELIMINARY STUDY ON PCBS, PAHS AND ORGANOCHLORINE PESTICIDES

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Riassunto.

Il fenomeno dell'imposex, che consiste nell'imposizione di caratteri sessuali maschili, come pene e vaso deferente, nelle femmine di molluschi gasteropodi a sessi separati, è stato osservato in molte specie e la sua comparsa è stata originariamente messa in relazione con la presenza di composti organostannici rilasciati dalle vernici antivegetative. In questo lavoro sono stati raccolti dei dati preliminari per iniziare uno studio sul possibile coinvolgimento anche di PCB, pesticidi clorurati e IPA nello sviluppo dell'imposex in organismi appartenenti alla specie *Hexaplex trunculus* prelevati in Laguna di Venezia.

Abstract.

The phenomenon of imposex, consisting of a superimposition of male sexual characteristics, such as penis and vas deferens, on female of gonocoric gastropods, has been observed in many species and at the beginning correlated to the presence of organotin compounds released from antifouling paints. In this study, preliminary data were obtained on the possible concurrent involvement of PCBs, organochlorine pesticides and PAHs in the imposex development in *Hexaplex trunculus* from the Lagoon of Venice.

1. Introduction.

Imposex, i.e. the superimposition of male sexual characteristics, such as penis and vas deferens, on female of dioecious gastropods, is a well documented example of endocrine disruption.

At the beginning, imposex development was correlated to the presence of tributyltin (TBT) released from antifouling paints, but the involvement of other compounds was suggested: triphenytltin (TPhT) causes the same effect as TBT in the gastropods *Thais clavigera* and *Thais bronni* [Horiguchi *et al.*, 1997], and induces imposex in the freshwater ramshorn snail *Marisa cornuarietis* [Schulte-Oehlmann *et al.*, 2000]; copper and environmental stress can induce the development of imposex in *Lepsiella vinosa* [Nias *et al.*, 1993].

The exact biochemical mechanisms at the basis of imposex development is not clear, but different hypotheses were reported: 1) TBT can act as a competitive inhibitor of aromatase, the enzyme that converts androgen hormones to estrogens [Bettin *et al.*, 1996]; 2) TBT appears to inhibit the conjugation of androgens which would normally deactivate these steroid hormones [Ronis and Mason, 1996]; 3) TBT can act as a neurotoxin that co-localizes in the ganglia which produce the Penis Morphogenic Factors, which is a neuropeptide hormone that normally induces male differentiation in mollusks [Oberdörster and McClellan-Green, 2002].

Recently, some authors have suggested the role of PCBs, PAHs and some organochlorine pesticides as endocrine disruptors [Bonefeld-Jørgensen *et al.*, 2001, Kelce *et al.*, 1995, Santodonato, 1997].

In this work a preliminary study was conducted about the involvement of organic and organochlorine compounds, along with organotin compounds (OTCs), in the imposex development in organisms belonging to the species *Hexaplex trunculus*. For this purpose, specimens of *Hexaplex trunculus* were analysed in order to determine the contents of organotin compounds, PCBs, organochlorine pesticides and PAHs.

Aims of this work were: 1) to monitor concentration levels of organotin compounds in *Hexaplex trunculus* sampled in various stations of the Lagoon; 2) to preliminarily understand how *Hexaplex trunculus* can handle organotin compounds to form metabolites in visceral coil and in the rest of soft body; 3) to study a possible relationship between organotin contamination and imposex degree; 4) to obtain data on PCBs, organochlorine pesticides, and PAHs as possible promoters of imposex.

2. Materials and methods.

2.1 Sampling

Organisms belonging to the species *Hexaplex trunculus* were sampled in four stations, two inside the Lagoon, namely S. Nicolò del Lido and S. Maria del Mare, and three on the seaward side, namely Lido Mare, Malamocco, and Chioggia (Fig. 1).

After sampling, organisms were carried to the laboratory and frozen until biological analysis.

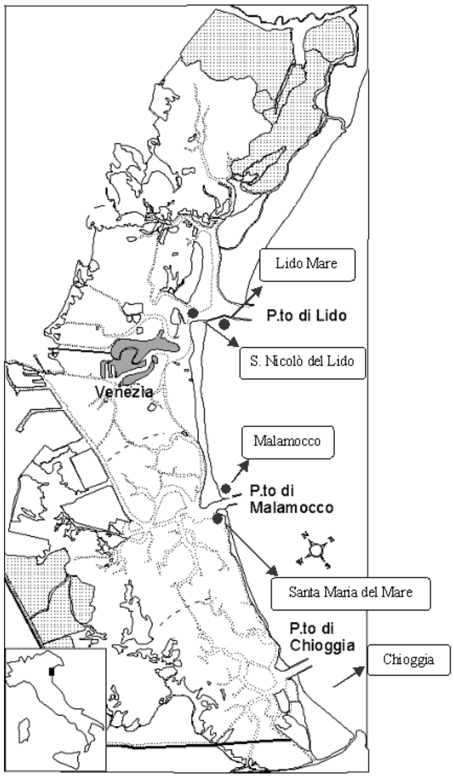

Fig. 1 – Map of the Lagoon of Venice and sampling stations [from Pellizzato *et al.*, 2004].

2.2 Biological analysis

Length, height, and width of shells were recorded.

After thawing, shells were cracked in a vice, mantle was longitudinally cut, and pallial oviduct was exposed.

Penis length was measured and Relative Penis Size Index (RPSI) calculated as follows [Bryan *et al.*, 1986]:

$$\mathrm{RPSI} = \frac{(\text{female penis length})^3}{(\text{male penis length})^3} \times 100 \qquad (1)$$

Sex and stage of imposex of every specimen were recognized.

Imposex degree determination was conducted on the basis of Vas Deferens Sequence Index (VDSI) proposed by Axiak *et al.* (1995) for *Hexaplex trunculus*.

These authors divided imposex development in eight stages:

- Stage 0: normal female,
- Stage 1: female shows an incipient penis behind the right ocular tentacle,
- Stage 2: a small penis with penis duct is present,
- Stage 3: penis duct continues in a portion of vas deferens,
- Stage 4: the vas deferens reaches the vaginal opening,
- Stage 4.3: the vas deferens passes the vaginal opening,
- Stage 4.7: the vas deferens runs along capsule gland for 30% of its length,
- Stage 5: no vulva is visible.

VDSI was calculated as average stage of imposex of the population.

Organisms were divided in two part, visceral coil and the rest of soft body, and from 4 to 6 organisms of same sex and stage of imposex were pooled and frozen until chemical analyses.

2.3 Chemical analyses

2.3.1 Organotin compounds analysis

The analytical procedure, as reported in Bortoli *et al.* [2003], is characterized by five steps: 1) extraction of organotin compounds from the matrix by means of a methanolic solution of tropolone; 2) derivatization with Grignard reagent, Pentylmagnesium bromide; 3) extraction of pentilated organotin compounds with n-hexane; 4) purification of the extract on a Florisil column; 5) injection of the extract in HRGC-LRMS. Analysed organotin compounds are: tributyltin (TBT), dibutyltin (DBT), monobutyltin (MBT), triphenyltin (TPhT), diphenyltin (DPhT), and monophenyltin (MPhT).

2.3.2 Analysis of PCBs, PAHs and organochlorine pesticides

The analytical procedure performs the contemporaneous purification of the extract and separation of compounds in two fractions, one containing PCBs and a part of organochlorine pesticides, the other containing PAHs and the rest of pesticides [Raccanelli *et al.*, 1994].

Both fractions are injected in HRGC-ECD to quantify PCBs and organochlorine pesticides and only the second one is injected in HRGC-LRMS to quantify PAHs.

Analysed organochlorine compounds are: PCB 18, PCB 54, PCB 28, PCB 52, PCB 155, PCB 101, PCB 77, PCB 123, PCB 118, PCB 153, PCB 105, PCB 138, PCB 126, PCB 185, PCB 156, PCB 157, PCB 180, PCB 198, PCB 169, PCB 170, PCB 194, PCB 209, α-HCH (hexachlorocyclohexane), HCB (hexachlorobenzene), γ-HCH, *o,p'*-DDE, *p,p'*-DDE, *o,p'*-DDD, *p,p'*-DDD, *o,p'*-DDT, *p,p'*-DDT. PAHs analysed are: naphthalene, 2-methylnaphthalene, 1-methylnaphthalene, acenaphthylene, acenaphthene, fluorene, phenanthrene, anthracene, fluoranthene, pyrene, benz[a]anthracene, chrysene, benz[k]fluoranthene, benz[a]pyrene, dibenz[a,h]anthracene, benz[g,h,i]perylene.

3. Results and discussion.

Data on S. Nicolò del Lido, S. Maria del Mare, Chioggia, and Malamocco stations are reported in Pellizzato *et al.* [2004]. Lido Mare station provided new data in order to improve the research on imposex and organotin contamination.

From RPSI values it is possible to observe differences between the stations. VDSI, on the contrary, provides no differentiation. Organisms from S. Nicolò del Lido (RPSI=36.2) are the most imposex affected, specimens from Chioggia (RPSI=1.03) and Malamocco (RPSI=1.06) are the least. VDSI values were about 4.5 for every station except for Chioggia, where a value of 3.6 was found.

In Fig. 2 OTC concentrations are reported and a trend similar to that obtained with RPSI data is observed. S. Nicolò del Lido is the most polluted station, and Chioggia and Malamocco the least, whereas the contamination in the other stations is intermediate.

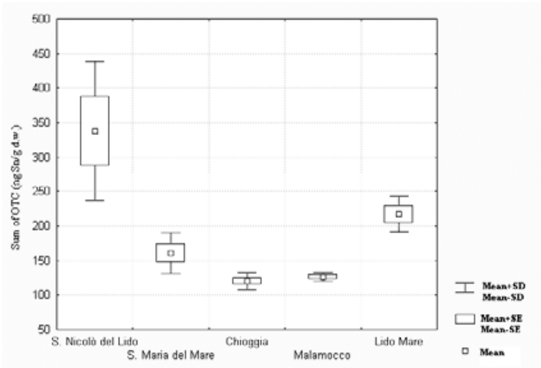

Fig.2 – ΣOTC concentrations in the entire organism of sampled *Hexaplex trunculus*.

Differences were observed between OTC levels in visceral coil and in the rest of soft tissue: concentrations of DBT and MBT were higher in the first (33÷221 ng Sn g^{-1} and 34÷167 ng Sn g^{-1} respectively) than in the second (28÷161 ng Sn g^{-1} and 15÷70 ng Sn g^{-1} respectively) , while TBT was similar in the two parts of the body.

Because the main source of TBT is food, the first part of the organism that enter in contact with this compound is the visceral coil, where enzymes of the cytochrome P450 system are present. The fact that this enzymatic complex is able to de-alkylate TBT into DBT and MBT can explain the different partitioning of these contaminants in the visceral coil and the rest of soft body.

A relationship was investigated between OTC levels in tissues of *Hexaplex trunculus* and the phenomenon of imposex: considering imposex degree, a slight increase of organotin compound concentrations at increasing VDS is observed only in the rest of soft body in three stations (Fig. 3). Probably, visceral coil has reached a saturation level and differences between stages cannot be seen.

Considering female penis length, a good correlation was found with OTC content in tissues. The best fit was obtained with a sigmoidal dose-response curve (Fig. 4), [Pellizzato *et al.*, 2004]:

$$y = \frac{a}{1 + e^{-\frac{(x - x_0)}{b}}} \tag{2}$$

where: x_0 is x value at mid-curve,

a is amplification parameter corresponding to maximum value of y,

b is steepness of curve up to saturation plateau.

No female with stage of imposex below three were found in this study and the trend of the sigmoidal curve in the lower part is unknown.

As the variance of penis length is not completely explained by organotin compounds concentrations, the involvement of other contaminants in the development of penis was hypothesized.

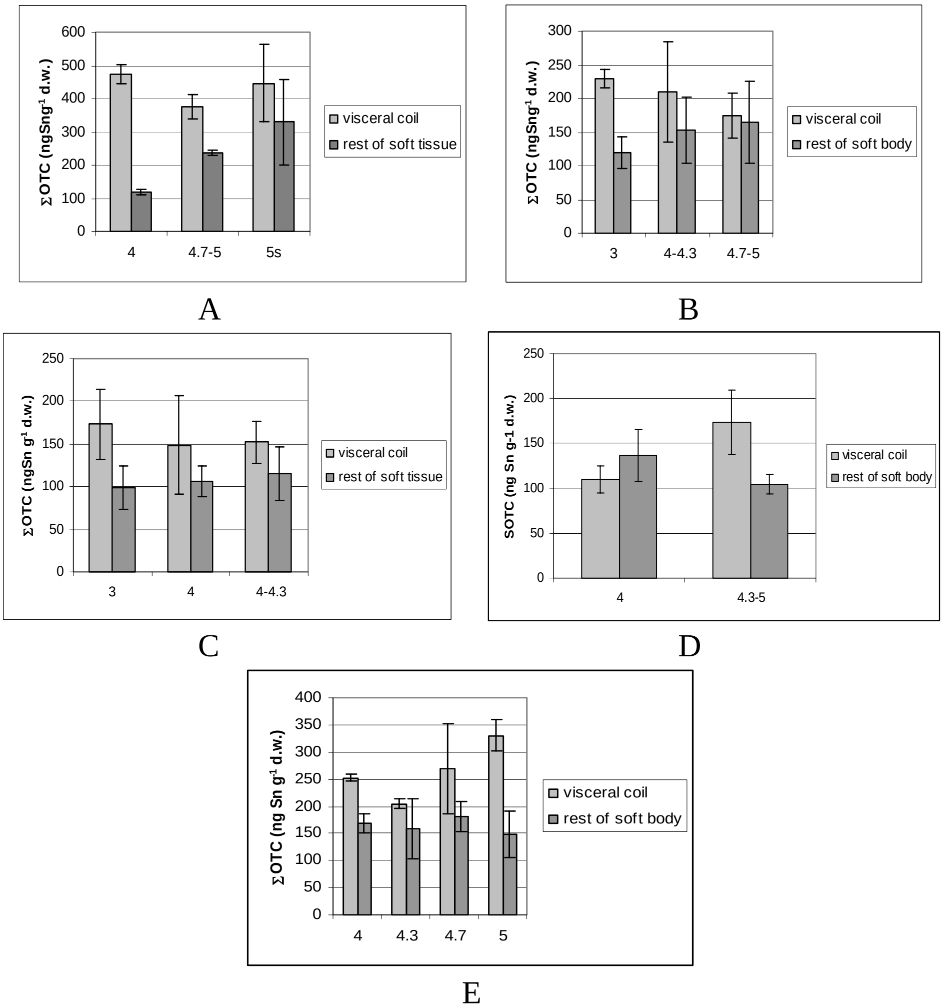

Fig. 3 – Comparison between ΣOTC content in visceral coil and in the rest of soft body (A: S. Nicolò del Lido; B: S. Maria del Mare; C: Chioggia; D: Malamocco; E: Lido Mare).

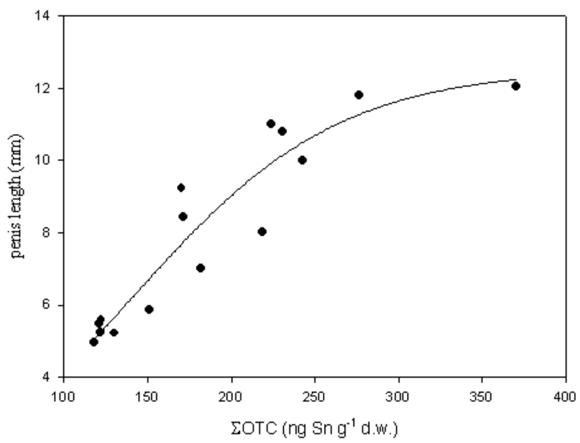

Fig.4 – Relationship between average penis length and total organotin content in entire organisms of each pool (n=15, r = 0.942, P < 0.05, a=12±1, b=61±15, x_0=142±13).

Analyses on PCB, organochlorine pesticide and PAH content in the same organisms were conducted.

Statistical elaborations of data on these pollutants are in progress. From preliminary results it is possible to observe an involvement of PCBs, organochlorine pesticides and PAHs in the promotion of the phenomenon of imposex and a model is being built to investigate their actual role in the development of penis in females.

4. Conclusions.

The obtained biological and chemical data are evidence for the importance of using imposexed organisms to bio-monitor contamination by organotin compounds in aquatic environments.

The relationship found between OTC levels in the tissues of organisms and female penis lengths need more data to build up a dose-response model, particularly because points in the lower part of the sigmoidal curve are missing. In order to understand the trend of the curve in the lower part, a sampling in a protected area with no or little contamination will be necessary.

A study examining the role of PCBs, organochlorine pesticides, and PAHs in the development of imposex is in progress.

References.

Axiak V., Vella A.J., Micallef D., Chircop P., Mintoff B., 1995. Imposex in *Hexaplex trunculus* (Gastropoda: Muricidae): first results from biomonitoring of tributyltin contamination in the Mediaterranean. *Marine Biology*, 121, 685-691

Bettin C., Oehlmann J., Stroben E., 1996. TBT - induced imposex in marine neogastropods is mediated by an increasing androgen level. *Helgoländer Meeresuntersuchungen* 50, 299-317

Bonefeld-Jørgensen E.C., Andersen H.R., Rasmussen T.H., Vinggaard A.M., 2001. Effect of highly bioaccumulated polychlorinated biphenyl congeners on estrogen and androgen receptor activity. *Toxicology* 158, 141-153

Bortoli A., Troncon A., Dariol S., Pellizzato F., Pavoni B., 2003. Butyltins and phenyltins in biota and sediments from the Lagoon of Venice. *Oceanologia* 45, 7-23

Bryan G.W., Gibbs P.E., Hummerstone L.G., Burt G.R., 1986. The decline of the gastropod *Nucella lapillus* around south-west England: evidence for the effect of tributyltin from antifouling paints. *Journal of Marine Biological Association of the UK* 66, 611-640

Horiguchi T., Shiraishi H., Schimizu M., Morita M., 1997. Effects of triphenyltin chloride and five other organotin compounds on the development of imposex in the rock shell, *Thais Clavigera. Environmental Pollution* 95, 85-91

Kelce W.R., Stone C.R., Laws S.C., Gray L.E., Kemppainen J.A., Wilson E.M., 1995. Persistent DDT metabolite p,p'-DDE is a potent androgen receptor antagonist. *Nature* 375, 581-585

Nias D.J., McKillup S.C., Edyvane K.S., 1993. Imposex in *Lepsiella vinosa* from Southern Australia. *Mar Pollut Bull* 26, 380-384

Oberdörster E., McClellan-Green P., 2002. Mechanisms of imposex induction in the mud snail, *Ilyanassa obsoleta*: TBT as a neurotoxin and aromatase inhibitor. *Marine Environmental Research* 54, 715-718

Pellizzato F., Centanni E., Marin M.G., Moschino V., Pavoni B., 2004. Concentrations of organotin compounds and imposex in *Hexaplex trunculus* from the Lagoon of Venice. *Science of the Total Environment* 332, 89-100

Raccanelli S., Pavoni B., Maroli L., Sfriso A., 1994. One step clean-up and separation of chlorinated, aliphatic and polycyclic aromatic hydrocarbons in environmental samples, prior to gas chromatographic quantification. *Toxicology and Environmental Chemistry* 45, 121-137

Ronis M.J.J., Mason A.Z., 1996. The Metabolism of Testosterone by the Periwinkle (*Littorina littorea*) *In Vitro* and *In Vivo*: Effects of Tributyl Tin. *Marine Environmental Research* 42, 161-166

Santodonato J., 1997. Review of the estrogenic and antiestrogenic activity of polycyclic aromatic hydrocarbons: relationship to carcinogenicity. *Chemosphere* 34, 835-848

Schulte-Oehlmann U, Tillmann M, Markert B, Oehlmann J, Watermann B, Scherf S., 2000. Effects of endocrine disruptors on prosobranch snails (Mollusca: Gastropoda) in the Laboratory. Part II: Triphenyltin as a Xeno-Androgen. *Ecotoxicology* 9, 399-412

A METHODOLOGY FOR ESTIMATING ECOLOGICAL RISK FROM THE BIOACCUMULATION OF POPS IN A MARINE FOOD WEB (LAGOON OF VENICE, ITALY)

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Riassunto.

Gli inquinanti organici altamente tossici e persistenti (POP) presenti nei sedimenti della laguna di Venezia tendono a bioconcentrarsi ed a biomagnificare lungo la rete trofica raggiungendo alte concentrazioni ai livelli più alti della rete trofica, e causando potenziali effetti avversi per la comunità acquatica. In questo lavoro viene proposta una metodologia per stimare il rischio ecologico, basata sulla procedura dell'US-EPA. Sulla base di un modello di rete trofica lagunare, che include fitoplancton, zooplancton, organismi bentonici e pesci, è stato stimato il bioaccumulo dei POP in sei sub-aree lagunari, applicando il modello Food Chain. Il bioaccumulo stimato è stato confrontato con dati sperimentali di concentrazione nei tessuti. Gli effetti ecologici sono stati caratterizzati utilizzando l'approccio delle Tissue Screening Concentration (TSC), calcolate moltiplicando i criteri di qualità ambientali per i fattori di bioaccumulo. Infine, il rischio è stato stimato dividendo il bioaccumulo stimato in TEQ per il TSC per la 2.3.7.8. TCDD. I gruppi trofici principalmente soggetti al rischio sono I filtratori bentonici ed onnivori predatori, mentre le aree lagunari nelle quali il rischio è risultato più alto sono quelle maggiormente interessate da scarichi industriali e civili. Nella comunità dei pesci le forme giovanili sono quelle risultate più a rischio.

Abstract.

The highly toxic and persistent organic micropollutants (i.e. POPs) stored in the Venice lagoon sediments tend to bioconcentrate and biomagnificate through the food web reaching high concentrations at the top level of the food web, that results in potential risk for the aquatic communities. In this paper, a methodology to estimate ecological risk was proposed, according to the procedure developed by the US-EPA. On the basis of a food web model for the Venice lagoon, including phytoplankton, zooplankton, benthic organisms and fish, POPs bioaccumulation was estimated in six sub-areas of the lagoon by applying the Food Chain bioaccumulation model, The estimated bioaccumulation was compared with observed concentrations in organism tissues. The ecological effects were characterized by the Tissue Screening Concentrations, calculated by multiplying the literature ambient quality criteria (AQC) by the bioconcentration factor (BCF). Finally, risk was estimated by ratioing the estimated bioaccumulation reported as total TEQ by the Tissue Screening Concentration for the 2,3,7,8 TCDD (TEF = 1). The trophic groups of major concern were benthic filter feeders and omnivorous predators, while the lagoon area with higher risk were

those affected by both industrial and urban discharges. Within the fish community, the highest risk was found for juveniles and for species at the top levels of the food web.

1. Introduction.

Polychlorinated dibenzo-p-dioxins and furans (PCDD/Fs), and dioxin-like polychlorobiphenils (PCBs), are POPs showing high toxicity and bioaccumulation potential [Office of Water, Office of Solid Waste, 2000]. They tend to biomagnify into the higher levels of the aquatic food web, posing also a threat to human health. The occurrence of high concentrations of organochlorines in sediments, water and biota of a coastal area such as the lagoon of Venice, highlighted by studies conducted in the 1997-2002 period [Venice Water Authority, 2002; 2000a], raised the question whether bioaccumulation of PCDD/Fs and PCBs congeners could pose a potential ecological risk for the aquatic food web.

A screening ecological risk assessment based on PCDD/F experimental tissue concentrations in fish, shellfish and piscivouros wildlife in the lagoon of Venice was carried out on the basis of experimental data [Wenning *et al.*, 2000].

In this paper we presents a methodology to estimate the ecological risk [Risk Assessment Forum, 1998] from modelled bioaccumulation of PCBs and PCDD/Fs in organisms distributed over six lagoon sub-areas.

The main objectives of this work were 1) to apply a simple bioaccumulation model to the lagoon food web addressing the spatial variability of sediment contamination, and 2) to estimate the risk for the aquatic food web, and to identify the lagoon sub-areas at potential risk.

2. Methods.

The Ecological Risk Assessment (ERA) methodology was developed according to the ERA procedure proposed by US-EPA [Risk Assessment Forum, 1998], which includes three steps: Problem Formulation, Analysis Phase, and Risk Characterization.

In the Problem Formulation phase, a food web model recently proposed by Pranovi et al. [Pranovi *et al.*, 2003] for the lagoon of Venice was identified. In the exposure characterization phase, a steady state partitioning bioaccumulation model [Gobas, 1993] was applied to estimate the PCDD/Fs and PCBs congeners concentration in organism tissues. Effects were estimated by a “tissue residue” approach, estimating a no-effect tissue residue for 2,3,7,8 TCDD by the Tissue Screening Concentration method [Shephard, 1998], on the basis of international Ambient Quality Criteria.

Finally, the ecological risk for all components of the aquatic food web was assessed by the Hazard Quotient method [Jones *et al.*, 1999], comparing the exposure concentration expressed as 2,3,7,8 TCDD toxicity equivalents by the corresponding Tissue Screening Concentration.

2.1. Problem formulation.

2.1.1. Food web model.

The application of the Food Chain (FC) model [Gobas, 1993] required the definition of a detailed food–web model, which was adapted (i.e., simplified) from the food-web model recently proposed by Pranovi et al. [Pranovi *et al.*, 2003]. The species and trophic groups were selected according to functional (i.e. primary producers, primary, secondary and tertiary consumers, decomposers) and structural (e.g. plankton, benthos) role in the ecosystem, feeding strategies (e.g. filter-feeders, detritivorous) and commercial importance.

The selected food-web model includes 14 trophic groups, each representing one or more taxa. The plankton group allocates phytoplankton and zooplankton, while benthic species are grouped into three macro-groups according to feeding strategies (i.e. filter feeders, detritivorous, omnivorous-predators).
Finally, fish groups allocate “necton carnivorous benthic-feeders” that includes *Solea* sp. and *Sepia* sp., and the taxa *Mugilidae* (family), *Atherina boyeri, Zosterisessor ophiocephalus, Sparus aurata,* and *Dicentrarchus labrax*.

2.2. Exposure characterization

2.2.1. Experimental database.

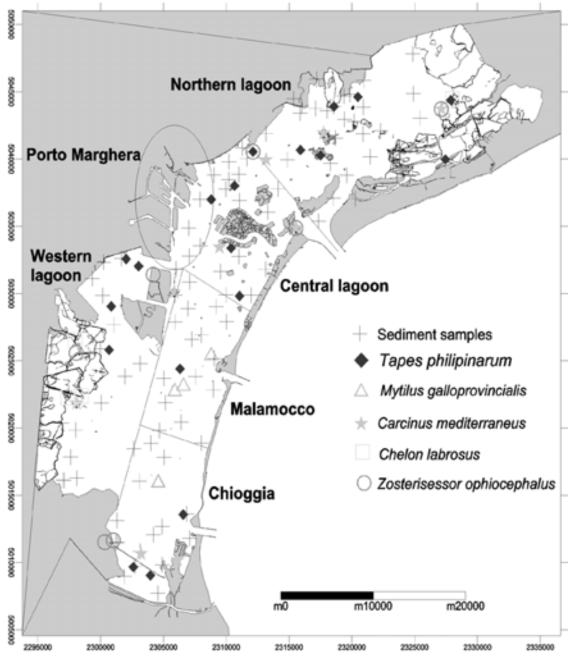

Fig. 1 – Distribution of sediment and organism sampling stations over the whole lagoon, with the indication of the six sub areas.

The database applied in this work consisted of selected 2,3,7,8 substitutes PCDD/F congeners (2,3,7,8-TCDD, 1,2,3,7,8-PCDD, 1,2,3,4,7,8-HCDD, 1,2,3,7,8,9-HCDD, 1,2,3,6,7,8-HCDD, 1,2,3,4,6,7,8-HpCDD, 1,2,3,4,6,7,8,9-OCDD, 2,3,7,8-TCDF,

1,2,3,7,8-PCDF, 2,3,4,7,8-PCDF, 1,2,3,4,7,8-HCDF, 1,2,3,7,8,9-HCDF, 1,2,3,6,7,8-HCDF, 2,3,4,6,7,8-HCDF, 1,2,3,4,6,7,8-HpCDF, 1,2,3,4,7,8,9-HpCDF, 1,2,3,4,6,7,8,9-OCDF) and PCB congeners (PCB #77, 81, 105, 114, 118, 123, 126, 156, 157, 167, 169, 170, 180, 189) concentration in sediments and organisms [Venice Water Authority, 2000a] (Fig. 1).

The database included concentrations of PCDD/Fs and PCBs in 95 sediment samples and in tissue of 5 typical lagoon organisms, namely *Mitylus galloprovincialis* (6 samples), *Tapes philipinarum* (23 samples), *Carcinus mediterraneus* (9 samples), *Chelon labrosus* (6 samples) and *Zosterisessor ophiocephalus* (8 samples) (Fig. 1).

The sediments, and organisms data were grouped into six homogeneous lagoon sub-areas (i.e. Northern lagoon, Central lagoon, Porto Marghera industrial district, Malamocco, Chioggia, and Western lagoon), shown in Fig. 1, according to the lagoon hydrodynamics and the concentrations of the considered persistent organic pollutants in the environmental matrices (e.g. sediments) [Venice Water Authority, 2000b].

Tab. 1 presents the UCL 95% concentrations as TEQ of PCBs and PCDD/Fs in sediment and organisms.

Tab. 1 – Experimental concentrations of PCDD/Fs and PCBs in abiotic samples (TEQ UCL 95%) and in biotic samples (TEQ maximum concentration), in each lagoon sub-area (Fig. 1).

Parameters		**Northern lagoon**	**Central lagoon**	**Porto Marghera**	**Malamocco**	**Chioggia**	**Western lagoon**
Pollutants concentration in abiotic matrices							
PCDD/Fs sediments	ng/kg d.w. (TEQ)	3.9	14	11	9.8	4.3	25
PCBs sediments	μg/kg d.w. (TEQ)	1.1E-03	7.4E-04	1.2E-03	1.1E-03	1.6E-03	3.6E-03
Pollutants concentration in biotic matrices							
PCDD/Fs Tapes philipinarum	μg/kg w.w. (TEQ)	1.5E-04	5.9E-04	6.2E-04	1.7E-04	3.4E-04	1.4E-03
PCDD/Fs Mytilus galloprovincialis	μg/kg w.w. (TEQ)	NA	8.7E-05	NA	2.1E-04	2.1E-04	NA
PCDD/Fs Carcinus mediterraneus	μg/kg w.w. (TEQ)	1.7E-03	6.6E-03	NA	NA	1.7E-03	3.4E-03
PCDD/Fs Chelon labrosus	μg/kg w.w. (TEQ)	3.5E-04	NA	NA	NA	NA	7.6E-04
PCDD/Fs Zosterisessor ophiocephalus	μg/kg w.w. (TEQ)	4.4E-04	1.0E-03	NA	NA	6.4E-04	4.4E-04
PCBs Tapes philipinarum	μg/kg w.w. (TEQ)	3.1E-04	4.5E-04	4.8E-04	1.2E-04	5.2E-04	5.0E-04
PCBs Mytilus galloprovincialis	μg/kg w.w. (TEQ)	NA	3.2E-04	NA	1.0E-03	3.7E-04	NA
PCBs Carcinus mediterraneus	μg/kg w.w. (TEQ)	3.9E-03	4.5E-03	NA	NA	2.3E-02	4.0E-03
PCBs Chelon labrosus	μg/kg w.w. (TEQ)	8.6E-04	NA	NA	NA	NA	9.1E-04
PCBs Zosterisessor ophiocephalus	μg/kg w.w. (TEQ)	2.0E-01	4.3E-03	NA	NA	7.8E-03	2.4E-03

d.w.: dry weight basis; w.w.: wet weight basis; NA: not available; TEQ: Toxicity Equivalents; PCB: polychlorbiphenils; PCDD/F: polychloro dibenzo dioxins/furans.

2.2.2. Estimation of bioaccumulation by FC bioaccumulation model.

The *Food Chain* (FC) bioaccumulation model, developed by Gobas [Gobas, 1993], was applied to estimate the bioaccumulation through the food web of PCDD/Fs and PCBs congeners in each of the aforementioned sub areas (Fig. 1). The FC model is a steady state partitioning model estimating the bioaccumulation of hydrophobic substances through an aquatic food-web, composed by plankton, benthic organisms, and fish. According to the model equations reported in Tab. 2, for plankton and benthos only chemicals partitioning between organisms and water (or sediments), respectively [Gobas, 1993], was considered. Besides, for fish a kinetic equation was applied, including the uptake of chemicals from gills (i.e. k_1) and food (i.e. k_D), as well as elimination through gills (i.e. k_2), faeces (i.e. k_G), metabolic transformation (i.e. k_M), and body growth (i.e. k_G). The kinetic constants were calculated from parameters such as the weight of fish, the pollutants K_{OW}, and the water temperature.

Tab. 2 – Food Chain bioaccumulation model equations.

Trophic group	**Equations**	
Plankton	$\mathbf{C_P = L_P \times K_{OW} \times C_{WD}}$	
Benthos	$\mathbf{C_B = (L_B/OC) \times C_S}$	
Fish	$\mathbf{C_F = (k_1 \times C_{WD}+k_D \times \Sigma P_i \times C_{D,i})/(k_2+k_E+k_M+k_G)}$	
Parameter	**Description**	**Measurement unit**
C_S	Observed concentration in sediments	μg/kg
C_{WD}	Truly dissolved concentration in water	μg/L
OC	Organic carbon fraction in sediments	kg/kg
K_{OW}	Octanol/water partitioning constant	unitless
C_P	Estimated concentration in plankton	μg/kg
C_B	Estimated concentration in benthos	μg/kg
C_F	Estimated concentration in fish	μg/kg
P_I	Diet fraction constituted by the prey i	%
$C_{D,I}$	Estimated concentration in diet	μg/kg
L_P	Lipid fraction in plankton	kg/kg
L_B	Lipid fraction in benthos	kg/kg
L_F	Lipid fraction in fish	kg/kg
k_1	Uptake rate constant through gills	1/kg day
k_D	Uptake rate constant through diet	kg food/kg fish/day
k_2	Elimination rate through gills	l/day
k_E	Faeces excretion rate constant	l/day
k_M	Metabolic rate constant	l/day
k_G	Growth dilution rate constant	l/day

In order to estimate the pollutant bioaccumulation into food web organisms, UCL (Upper Confidence Limit) 95% of mean [Gilbert, 1997] was calculated for sediment concentration of PCB and PCDD/F congeners in each sub-area. Environmental properties of the sub areas (i.e., water temperature, organic carbon fraction in sediments) were taken from previous studies [Venice Water Authority, 2000a; Venice Water Authority, 2000b; Bianchi *et al.*, 1999], while organism characteristics (i.e. lipid fraction and body weight) were calculated from experimental data [Venice Water

Authority, 2000a] or collected from scientific literature [Gobas, 1993; Pastor *et al*., 1996; Ribeiro *et a.l*, 2001; Santhina *et al*., 1999; Anthony *et al*., 2000; Robaina *et al*., 1995; Kucklick and Baker, 1998; Goerke and Weber, 2001; Lotufo *et al*., 2001; Van Hattum and Montanes, 1999; Cope *et al*., 1999; Kidd *et al*., 1998; Peres and Oliva-Teles, 1999]. The K_{OW} and Henry constants values of the congeners were calculated by applying the EPI Suite Software [US-EPA, 2000].

Finally, due to the lack of data concerning the dissolved concentration of pollutants in water, the truly dissolved contaminant concentration in water (i.e. C_{WD}) was estimated in each sub-area from the UCL 95% [Gilbert, 1987] sediment concentration by applying the first level of the fugacity Mackay model [Mackay, 1991], taking into account the partitioning between sediment and water.

2.2.3 PEC estimation.

Subsequently, a TEQ concentration from the estimated PCDD/F and dioxin-like PCB congener concentrations were obtained, by applying the Toxic Equivalent Factors [Van den Berg *et al.*, 1998]. The estimated bioaccumulation expressed as 2,3,7,8-TCDD Toxicity Equivalents (i.e., TEQs) represented the Predicted Exposure Concentration, or PEC, which was applied to estimate the ecological risk for the aquatic organisms in the Risk Characterization phase.

2.3. Effect characterization.

Effects were characterized by the Tissue Screening Concentration (TSC) approach [Shephard, 1998]. The TSC approach permitted to estimate the contaminant concentration in organism tissues related with adverse effects. The TSCs were calculated by multiplying a Bioaccumulation Factor (BAF) and an Ambient Quality Criteria (AQC) according to the eq. 1.

$$TSC = AQC \text{ x } BAF \tag{1}$$

The BAFs were calculated from bioaccumulation estimated by Food Chain model, while the AQC were collected from international guidelines [Canadian Council of Ministers of the Environment, 1999; 2002].

According to the exposure characterization approach, where PCDD/Fs and dioxin-like PCB congener bioaccumulation was expressed as 2,3,7,8 TCDD equivalent (i.e., TEQ), the TSC was calculated for the 2,3,7,8 TCDD.

2.4. Risk characterization.

Results obtained from exposure and effects characterization were used in the last step of the ERA procedure in order to estimate risk for the food web associated to the sediment and water contamination. In this work ecological risk was estimated by the Hazard Quotient (HQ) approach [Jones *et al.*, 1999], a standard approach usually applied in screening risk assessment. The HQ was calculated by comparing the exposure concentration (Predicted Environmental Concentration, PEC) and the no effect concentration (Predicted No Effect Concentration, PNEC), both expressed in Toxic Equivalents (TEQ), according to the following equation:

$$\text{Hazard Quotient} = \text{PEC} / \text{PNEC} \tag{2}$$

The PNEC represents the highest pollutant concentration correlated with no adverse effects; when PEC > PNEC (i.e. HQ > 1), it is likely that adverse effect might occur, the likelihood increasing with increasing HQ value. However, this ratio has no statistical meaning, rather indicating a rank of risk in different areas and for different assessment endpoints.

3. Results and discussion.

3.1 Exposure characterization.

3.1.1 Bioaccumulation model results and estimates corroboration.

The application of the Food Chain model [Gobas, 1993] permitted to estimate the PCDD/F and PCB congeners concentration in the organism tissues of the lagoon food web. Generally bioaccumulation resulted higher for fish, especially juveniles, mainly because of the lower body weight. As example, the bioaccumulation of PCB 126 in Northern lagoon is presented (Fig. 2).

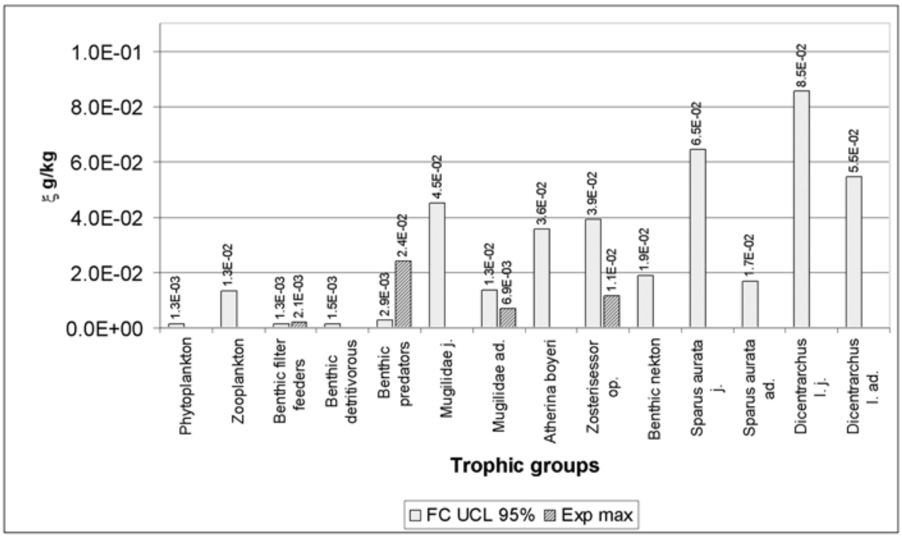

Fig. 2 – Estimated bioaccumulation from UCL 95% sediment concentration (FC UCL95%, plain bars), and the maximum observed concentrations (Exp max, dashed bars) of the congener PCB 126 in the 5 organisms (*Tapes philipinarum* and *Mitylus galloprovincialis*; *Carcinus mediterraneus; Chelon labrosus*; *Zosterisessor ophiocephalus*) sampled in Northern Lagoon sub area.

The bioaccumulation model results obtained from UCL 95% concentration in sediment were compared with experimental maximum tissues concentrations (Tab. 1) in five typical organisms of the Venice lagoon, such as *Tapes philipinarum*, *Mytilus* *galloprovincialis*, *Carcinus mediterraneus*, *Chelon labrosus*, and *Zosterisessor ophiocephalus*.

As far PCBs are concerned, the concentrations for benthic organisms were under-predicted or over-predicted to an extent lower than one order of magnitude. As far as fishes are concerned, model results showed an overestimation of one order of magnitude.

Taking into consideration the PCDD/Fs congeners bioaccumulation, the concentrations were considerably overestimated for all the trophic groups, but especially for fish, with differences between observed and estimated values is in the range of 1-2 orders of magnitude. Similar results were obtained by Carrer *et al.* [2000] for the bioaccumulation of 1,2,3,4,6,7,8 HpCDD and OCDD in nekton detritivorous.

The overestimated bioaccumulation for PCDD/F congeners may be explained with the higher depuration rates (i.e., the sum of all the depuration mechanisms of fish: metabolism, excretion, and growth) in fish of the PCDD/Fs compared to PCBs [Gobas, 1990].

3.2 Effects characterization.

Taking into account the equation 1, a the Tissue Screening Concentration for 2,3,7,8-TCDD was estimated from the product of the Ambient Quality Criteria (AQC) by Bioaccumulation factor (BAF).The BAF for the food web trophic groups were calculated from the previously estimated bioaccumulation. The Water Quality Criteria (i.e., a provisional value) and the Sediment Quality Criteria were collected from the CCME (The Canadian Council of Ministers of the Environment) guidelines [Canadian Council of Ministers of the Environment, 1999; 2002] and then reported in Tab. 3, together with the estimated Bioaccumulation factors (BAF) and the resulting Tissue Screening Concentrations.

The BAFs for 2,3,7,8-TCDD were calculated as mean value for the whole lagoon, according to the procedure proposed by the US-EPA in “Bioaccumulation testing and interpretation for the purpose of sediment quality assessment - status and needs” [Office of Water, 2000].

The BAF was calculated as the ratio of the contaminants concentration in organism’s tissues, estimated from UCL 95% pollutants concentration in sediments, and the UCL 95% contaminant concentration in the exposure matrices (water for phytoplankton, zooplankton and fish; sediment for benthos).

The TSCs (Tab. 3) are generally comprised in the range of $1x10^{-2} – 1x10^{-3}$ μg/kg on wet weight basis.

3.3 Risk characterization.

Results obtained in the exposure and effect characterization phases, i.e., Predicted Exposure Concentration and Predicted No Effect Concentration, were compared according to the Hazard Quotient approach [Jones *et al.*, 1999] in order to estimate risk for the lagoon food web.

The HQ was calculated for each lagoon sub-area, by comparing the modelled bioaccumulation (i.e., by the FC model using the UCL 95% TEQ sediment concentration (Tab. 1)) of PCB and PCDD/F congeners for each trophic group, with the 2,3,7,8-TCDD Tissue Screening Concentration (Tab. 3):

$$HQ_{ij}\ (\text{PCDD/Fs + dioxin-like PCBs}) = TEQ_{ij}\ (\text{PCDD/Fs + dioxin-like PCBs}) / TSC_j \quad (3)$$

where: i = lagoon sub area ($1 \leq i \leq 6$);
j = trophic group ($1 \leq j \leq 13$).

Tab. 3 – Tissue Screening Concentration (TSC) for the examined food-web trophic groups calculated from the product of Ambient Quality Criteria, and bioaccumulation factors estimated by Food Chain model, taking into account the UCL 95% concentrations in sediment and water.

Trophic group	**Ambient Quality Criteria**	**BAF[c] 2,3,7,8 TCDD**	**TSC[d] 2,3,7,8 TCDD**
Phytoplankton	0.38E-7[a]	31,500	0.0012
Zooplankton	0.38E-7	315,000	0.0120
Benthic filter-feeders	0.00085[b]	0.36	0.0003
Benthic detritivorous	0.00085	0.43	0.0004
Benthic omnivorous-predators	0.00085	0.80	0.0007
Mugilidae juveniles	0.38E-7	1,080,000	0.0410
Mugilidae adults	0.38E-7	335,000	0.0128
Atherina boyeri	0.38E-7	863,000	0.0328
Zosterisessor ophiocephalus	0.38E-7	958,000	0.0364
Nekton	0.38E-7	470,000	0.0178
Sparus aurata juveniles	0.38E-7	1,600,000	0.0597
Sparus aurata adults	0.38E-7	420,000	0.0159
Dicentrarchus labrax juveniles	0.38E-7	2,100,000	0.0803
Dicentrarchus labrax adults	0.38E-7	1,300,000	0.0526

[a] Water Quality Criteria (μg/L wet weight basis); CCME
[b] Sediment Quality Criteria (μg/kg dry weight basis); CCME
[c] BAF: Bio Accumulation Factor
[d] TSC: Tissue Screening Concentration (μg/kg wet weight basis); Shephard, 1998

The Hazard Quotients obtained from the modelled bioaccumulation using the UCL 95% concentration in sediments are reported in Table 4. However, the HQ values are affected by the overestimation of the PCDD/F bioaccumulation, resulting in an overestimation of risk. The risk estimated by comparing the observed concentrations in organism tissues (Tab. 1) by the TSC for 2,3,7,8-TCDD (Tab. 3) in Central lagoon and Western lagoon sub-areas, (i.e. Central lagoon Obs. (i.e., meaning observed) and Western lagoon Obs.), respectively highlighted that there's a good agreement between risk from modelled bioaccumulation and observed bioaccumulation for benthic organism. On the contrary, the HQs for fish calculated from observed bioaccumulation were from 1 to 2 orders of magnitude lower than HQs calculated from modelled bioaccumulation suggesting an overestimated risk for fish in Tab. 4. Nonetheless, the analysis of the Hazard Quotients allowed the lagoon sub-areas ranking on the basis of risk magnitude, as well as the identification of the most probable adversely impacted trophic groups.

Tab. 4 – Hazard Quotient (HQ) estimated for total PCDD/Fs and PCBs congeners in the six lagoon sub-areas from the bioaccumulation estimated applying the UCL 95% contaminant concentration in sediments. In Central lagoon Obs. and Western lagoon Obs. colums are shown HQs estimated taking into account the observed concentrations in organism tissues rationed by 2,3,7,8-TCDD.

Trophic groups	**Northern lagoon**	**Central lagoon**	**Central lagoon *Obs.*[a]**	**Porto Marghera**	**Malamocco**	**Chioggia**	**Western lagoon**	**Western lagoon *Obs.a***
Phytoplankton	1.3	5.4		4.3	3.8	2.2	3.2	
Zooplankton	1.3	5.4		4.3	3.8	2.2	3.2	
Benthic filter feeder	5.0	20.5	3.47	16.5	14.5	8.3	12.3	6.33
Benthic detritivorous	5.0	20.5		16.5	14.5	8.3	12.3	
Benhtic predators	5.0	20.5	16	16.5	14.5	8.3	12.3	11
Mugilidae juveniles	1.1	2.0		3.3	3.2	1.9	2.4	
Mugilidae adults	1.0	3.1		3.0	3.1	1.9	2.2	0.13
Atherina boyeri	1.0	3.3		3.1	3.1	1.9	2.3	
Zosterisessor ophiocephalus	1.0	2.7	0.14	2.8	3.0	1.8	2.1	0.078
Benthic nekton	1.0	3.2		3.1	3.1	1.9	2.3	
Sparus aurata juveniles	1.0	3.1		3.0	3.1	1.9	2.2	
Sparus aurata adults	1.0	2.9		2.9	3.1	1.8	2.1	
Dicentrarchus labrax juveniles	1.0	2.7		2.8	3.0	1.8	2.1	
Dicentrarchus labrax adults	0.9	2.3		2.6	3.0	1.8	1.9	

[a]: HQs estimated from observed concentrations in organism tissues (Tab. 1)

According to the risk estimated from UCL 95% pollutants concentration in sediments, the sub-areas showing the highest risk (i.e. HQ higher than 1 for all trophic groups) are Central lagoon, Porto Marghera, and Malamocco, which are located in the Central lagoon (Fig. 1), affected mainly by industrial and urban treated and untreated wastewater discharges.

The trophic groups which were most likely exposed to ecological adverse effects were those organisms living in direct contact with sediment, i.e. benthic groups.

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References.

Anthony A.J., Roby D.D. and Turco K.R., 2000. Lipid content and energy density of forage fishes from the northern Gulf of Alaska. *Journal of Experimental Marine Biology and Ecology,* 248(1), 53-78

Bianchi F., Acri F., Alberghi L., Bastianini M., Boldrin A., Cavalloni B., Cioce F., Camosci A., Rabitti S., Socal G., and Turchetto M.M., 1999. Biological variability in the Venice lagoon. In: "*The Venice lagoon ecosystems. Inputs and interactions between land and sea*", by P. Lesser and A. Marzotto, Parthenon Publishing Press

Canadian Council of Ministers of the Environment, 1999. Canadian Environmental Quality Guidelines (water, sediment, and tissue) for dioxins and furans (first draft). September 1999, Winnipeg, Canada

Canadian Council of Ministers of the Environment, 2002. Canadian Environmental Quality Guidelines, summary tables. Updated. In: "*Canadian environmental quality guidelines"*, 1999, Canadian Council of Ministers of the Environment, Winnipeg, Canada

Carrer S., Halling-Sørensen B., Bendoricchio G., 2000. Modelling the fate of dioxins in a trophic network by coupling an ecotoxicological and an Ecopath model. *Ecological Modelling* 126:201–223

Cope W.G., Bartsch M.R., Rada R.G., Balogh S.J., Rupprecht J.E., Young R.D., and Johnson D.K., 1999. Bioassessment of mercury, cadmium, polychlorinated biphenyls, and pesticides in the upper Mississippi river with zebra mussels (*Dreissena polymorpha*). *Environmental Science and Technology,* 33, 4385-4390

Gilbert R.O., 1987. Statistical methods for environmental pollution monitoring. Van Nostrand Reinhold. New York, NY

Gobas F.A.P.C., 1990. Bioaccumulation of some polychlorinated dibenzo-p-dioxins and octachlorodibenzofuran in the Guppy (*Poecilia reticulata*). Chemosphere 20(5), 495-512

Gobas, FAPC, 1993. A model for predicting the bioaccumulation of hydrophobic organic chemicals in aquatic food-webs: application to Lake Ontario. *Ecological Modelling* 69, 1-17

Goerke H. and Weber K., 2001. Species-specific elimination of polychlorinated biphenyls in estuarine animals and its impact on residue patterns. *Marine environmental research*, 51, 131-149

Jones D.S., Barnthouse L.W., Suter G.W., Efroymson R.A., Field J.M., and Beauchamp J.J., 1999. Ecological risk assessment in a large river-reservoir: 3. Benthic invertebrates. *Environmental Toxicology & Chemistry* 18, 599-609

Kidd K.A., Hesslein R.H., Ross B.J., Koczanski K., Stephens G.R., and Muir D.C.G., 1998. Bioaccumulation of organochlorines through a remote freshwater food web in the Canadian Arctic. *Environmantal Pollution*, 102, 91-103

Kucklick J.R. and Baker J.E., 1998. Organochlorine in Lake Superior's Food Web. *Environmental Science and Technology* 32, 1192-1198

Lotufo G.R., Landrum P.F., and Gedeon M.L., 2001. Toxicity and bioaccumulation of DDT in freshwater amphipods in exposures to spiked sediments. *Environmental toxicology and chemistry,* 20: 810-825

Mackay D, 1991. Multimedia environmental models – The Fugacity Approach. Lewis Publishers

Office of Water, Office of Solid Waste, 2000. Bioaccumulation Testing And Interpretation For The Purpose Of Sediment Quality Assessment: Status and Needs. EPA-823-R-00-001. U.S. Environmental Protection Agency, Washington, DC

Pastor D, Boixb J, Fernández V, Albaigés J, 1996. Bioaccumulation of Organochlorinated Contaminants in Three Estuarine Fish Species (*Mullus barbatus, Mugil cephalus and Dicentrarcus labrax*). *Marine Pollution Bulletin* 32(3), 257-262

Peres H. and Oliva-Teles A., 1999. Effect of dietary lipid level on growth performance and feed utilization by European sea bass juveniles (*Dicentrarchus labrax*). *Aquaculture* 179(1-4), 325-334

Pranovi F., Libralato S., Raicevich S., Granzotto S., Pastres R., and Giovanardi O., 2003. Mechanical clam dredging in Venice lagoon: ecosystem effects evaluated with a trophic mass-balance model. *Marine Biology* 143(2), 393-403

Ribeiro J., Correia C., Monteiro P., Coelho R., Lino P., Bentes L., Gonçalves J.M.S., and Erzini K., 2001. Study of the ichthyofauna of the Ria Formosa coastal lagoon (Southern Portugal, Algarve): preliminary results. Tenth European Congress of Ichthyology, 3rd - 7th September 2001. Prague, Czech Republic

Risk Assessment Forum, 1998. Guidelines for Ecological Risk Assessment. EPA/630/R-95/002F. Final Report. U.S. Environmental Protection Agency, Washington, DC

Robaina L., Izquierdo M.S., Moyano F.J., Socorro J., Vergara J.M., Montero D., and Fernández-Palacios F., 1995. Soybean and lupin seed meals as protein sources in diets for gilthead seabream (*Sparus a*urata): nutritional and histological implications. *Aquaculture* 130(2-3), 19-223

Santinha P.J.M., Medale F., Corraze G., and Gomes E.F.S., 1999. Effects of the dietary protein: lipid ratio on growth and nutrient utilization in gilthead seabream (*Sparus aurata* L.). *Aquaculture Nutrition*, 5, 147-156

Shephard B.K., 1998. Quantification of Ecological Risks to Aquatic Biota from Bioaccumulated Chemicals. Proceedings, National Sediment Bioaccumulation Conference, Bethesda, Maryland, USA, September 11-16 1996, 2-31 – 2-52

US-EPA, 2000. Office of Pollution Prevention Toxics and Syracuse Research Corporation. On-Line EPIWIN™ User's Guide (v3.10). U.S. Environmental Protection Agency, 2000

Van Hattum B. and Cid Montanes J.F., 1999. Toxicokinetics and bioconcentration of polycyclic aromatic hydrocarbons in freshwater isopods. *Environmental Science and Technology*, 33: 2409-2417

Van den Berg M., Birnbaum L., Bosveld A.T.C., Brunstorom B., Cook P., Freely M., Giesy J.P., Handberg A., Hasewaga R., Kennedy S.W., Kubiak T., Larsen J.C., van Leeuwen F.X.R., Liem A.K.D., Nolt C., Peterson R.E., Poellinger L., Safe S., Schrenk D., Tillitt D., Tysklind M., Younes M., Waern F., Zacharewski T., 1998. Toxic equivalency factors (TEFs) for PCBs, PCDDs, PCDFs for humans and wildlife. *Environmental Health Perspective* 106, 775-792

Venice Water Authority – Consorzio Venezia Nuova, 2000a. M*apping the pollutants in the lagoon bottom sediment* (In Italian). Final Report. Consorzio Venezia Nuova, Venice, Italy

Venice Water Authority, 2000b. Project 2023, Line E-C: Assessment of Venice lagoon's contamination transfer into the food web and risk assessment for the human health. Final report. Venice, Italy

Venice Water Authority, 2002. Monitoring Venice lagoon's waters (In italian). Report, December 2002, Venice, Italy

Wenning R., Dodge D., Peck B., Shearer K., Luksemburg W., Della Sala S. and Scazzola R., 2000. Screening-level ecological risk assessment of polychlorinated dibenzo-p-dioxins and dibenzofurans in sediments and aquatic biota from the Venice lagoon, Italy. *Chemosphere* 40:1179-1187

RESEARCH LINE 3.4
Chemical contamination

TRACE METAL AND ORGANIC POLLUTANT FLUXES IN THE VENICE LAGOON

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Riassunto.

In questo lavoro sono state studiate, per oltre un anno, le concentrazioni di elementi in tracce, policlorobifenili (PCB) e idrocarburi policiclici aromatici (PAH) nella fase gassosa e nel PM_{10} presso tre siti localizzati nei pressi della laguna (sorgenti; "industriale", "marina, "rurale"). La concentrazione totale media di PAH, calcolata come somma di 16 composti, è rispettivamente circa tre e cinque volte maggiore presso il sito "industriale" e "rurale" rispetto a quello "marino". Presso la stazione influenzata direttamente da sorgenti industriali è stata osservata la più alta concentrazione media annuale di PCB totali (somma di 54 congeneri) con valori tre e cinque volte maggiori rispetto alle concentrazioni riscontrate alle stazioni "marina" e "rurale". Analogamente, presso lo stesso sito, sono state rilevate le concentrazioni atmosferiche maggiori di elementi in traccia (Fe, Al, Mn, V, Cd) nella frazione di aerosol PM_{10}.

Per valutare il contributo delle differenti sorgenti alla contaminazione dell'atmosfera della laguna di Venezia sono stati stimati i flussi orizzontali di PAHs, PCBs ed elementi.

Abstract.

Concentrations of trace elements (PM_{10}), gas-phase polychlorinated biphenyls (PCBs) and polycyclic aromatic hydrocarbons (PAH) were studied over one year at two sites of the Venice lagoon (MARINE, INDUSTRIAL) and at a mainland station (RURAL). Average ∑PAH concentrations, calculated as sum of 16 PAHs, at MARINE are about three and five times lower than those at INDUSTRIAL and RURAL sites respectively.

The highest annual average concentration of ∑PCBs was observed at the station directly influenced by "INDUSTRIAL" sources with values about 3 and 1.5 times higher compared to the concentrations found at the stations where "MARINE" sources and "RURAL" were respectively sampled from.

The atmospheric concentration of trace elements (Fe, Al, Mn, V, Pb, Cd) show the highest concentrations at INDUSTRIAL site.

To evaluate the contribution from different sources to the Venice Lagoon air, horizontal fluxes of PAHs, PCBs and elements have been obtained.

1. Introduction.

The Venice Lagoon is the largest lagoon and one of the most important wetland sites in the Mediterranean Sea. It is a unique ecosystem where the mingling of human activity and natural ecology has been enduring, complete, complex, and profound. Many sources contribute to the input of pollutants into the Lagoon of Venice. In particular, the contribution of industrial activities has been intensively studied in the past [Donazzolo *et al.*, 1984; Martin *et al.*, 1994; Frignani *et al.*, 1997; Scarponi *et al.*, 1998; Moret *et al.*, 2001] but very little is known about the role of the aerosol on chemical contamination of the Venice ecosystem. In recent decades, however, the study of the transport and fate of persistent organic pollutants in the environment has been improved by including the surface microlayer, where gas and material transfer between the bulk water and atmosphere takes place by complex physic-chemical processes. The surface microlayer has a unique chemical composition, composed of a high content of lipids, fatty acids and proteins which leads to its capacity for accumulating hydrophobic organic pollutants [Wurl and Obbard, 2004]. It can also act as source of contamination because chemicals accumulated in the microlayer may be transferred to the air via bursting of bubbles; this process is strongly influenced by the surface properties, the vapour pressure and the structure of the compounds, the presence of surfactants and suspended particles [Cini *et al.*, 1994; Oppo *et al.*, 1999].

The aim of this study was to investigate previously insufficiently assessed processes that contribute to the input of pollutants into the water of the Lagoon of Venice. Attention was particularly focused on i) the role of aerosol and ii) the role of the microlayer and sub-superficial waters in the contamination of the Venice Lagoon.

2. Experimental.

Aerosol sampling was performed at two sites of the Venice Lagoon and one site in the Euganei hills (Fig. 1). The first site (St. 1; MARINE) was located at the Northern inlet of the lagoon (N 45°25’21.8’’ E 12°26’12.2’’) on the light house, at a height of 15 m; samples were collected when the wind blew from the southeast which we assume carried predominantly “marine” aerosols. The second sampling site (St. 2; INDUSTRIAL) was south of the industrial zone of Porto Marghera and the urban area of Mestre (N 45°25’38.5’’ E 12°12’47.6’’); samples were collected when the wind blew from the northeast which we hypothesize is dominated by “urban” and “industrial” aerosols. The third site (St. 3; RURAL) was located on Monte Grande, in the Euganei hills, which is about 460 m above sea level and about 50 Km from Venice (N 45°21’43.0’’ E 11°40’ 22.4’’); samples were collected when the wind blew from the northeast which we suppose carried aerosols from no particular direct local sources.

Samplings were performed every 15-days from March 2002 to June 2003.

For organic analysis hi-vol samplers were equipped with a quartz fibre filter (QFF) for collecting “particulate” phase compounds and a polyurethane foam plug (PUF) for retaining “gas-phase” compounds. The average operative flux was about 0.34 m^3 min^{-1} but due to different meteorological conditions, collected volumes varied during the study between 50 m^3 and 2074 m^3. Every month a calibration was done to check the flow rates. Sampled QFFs and PUFs were separately Soxhlet extracted with a *n*-

pentane: dichloromethane (2:1, *v/v*) mixture, a labelled ^{13}C solution of PCB and PAH for quantification was added afterwards. The purified (by alumina and florisil) extract volumes were reduced to 100 μl and analysed by HRGC-LRMS.

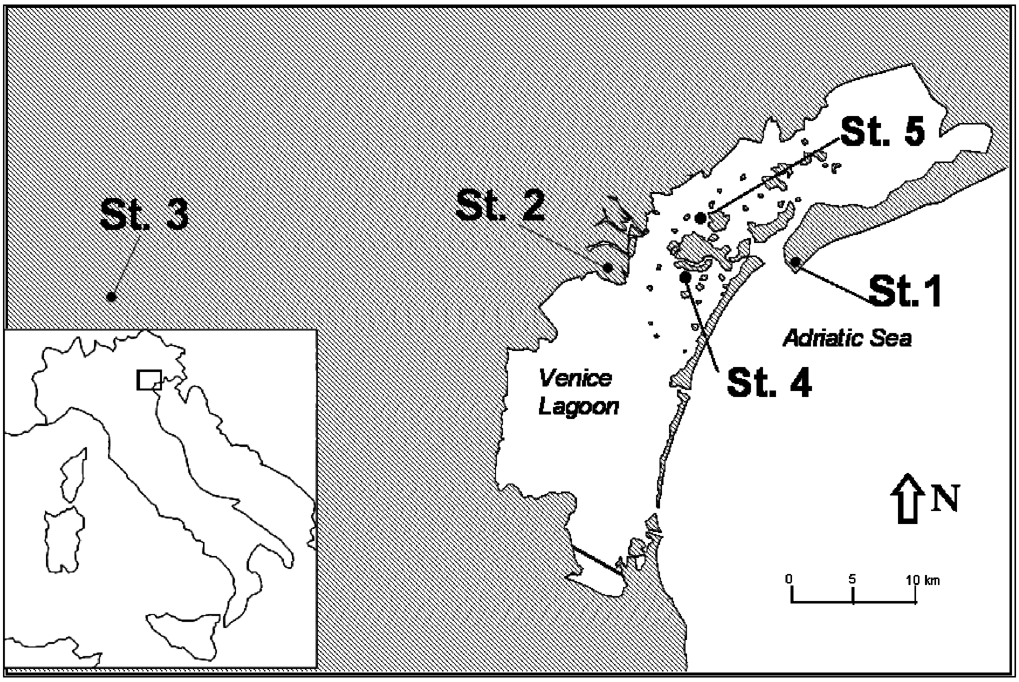

Fig. 1 – Map of the sampling stations.

For elemental analysis samples were collected on cellulose membranes cleaned with acidified water before use. Sampling was performed by a six-stage cascade impactor mounted on high volume pumps equipped with PM10 size-selective inlets.

Cellulose filters used for the sampling of aerosol were weighed before and after sampling, to assess the amount of particulate matter collected; they were mineralized in an acid mixture using a microwave digestion system. Elemental analysis was carried out by ICP-SFMS (Element 2, Finnigan Mat). The accuracy and repeatability of the analytical method were controlled using a certified reference material (urban particulate matter SRM 1648, NIST). Blanks deriving from filters and handling were estimated for each campaign by exposing cleaned membranes for a few minutes without activating the pump. Quantification was carried out by the multiple standard addition method.

Sea microlayer (SML) and sub-superficial water (SSW) samples were collected from July 2001 until June 2003 at two different sites of the Venice Lagoon, namely near Sacca Sessola Island (St. 4) and close to Tessera Island (St. 5). Station 4 was located in the central part of the lagoon, about 3 km south of the city Venice and 7 km west of the industrial plants of Porto Marghera. This area has a low depth and is surrounded by a small network of navigable channels directly connected with the Lido inlet which are not intensively travelled. Station 5 is about 3 km to the north Venice urban area and has a depth similar to Station 4, but is crossed on one side by the highly frequented Tessera channel (average depth 2.5 meters), which connects by boat the international airport 'Marco Polo' to the city of Venice. On the east side, this area is surrounded by the mainland, and the presence of the Osellino channel, which collects municipal and industrial sewage effluents and discharges, increasing the urban inputs to this zone.

Five sampling campaigns were performed at each station under calm sea conditions. SML and SSW samples were simultaneously collected by the Multi-Use Microlayer Sampler (MUMS) [Cincinelli *et al*., 2001], an autonomous floating device electrically powered and radio-controlled. The MUMS collected the microlayer water with a rotating Pyrex glass drum (mean thickness: < 50 μm) and a Mylar scraper removed it from the glass surface.

3. Results and discussion.

Maximum, minimum and average concentrations of elements, gas-phase ∑PCB (sum of 54 congeners) and ∑PAH (sum of the 16 identified compounds) obtained in this study are summarized in Tab. 1a. The highest annual average concentration of ∑PCBs was observed at St. 2, which is directly influenced by the industrial plants. The concentrations of samples at station 2 were about 3 times higher than the values at St. 1 and about 1.5 times higher those that at St. 3. Measured concentrations are found to differ by about one order of magnitude from one congener to another. The highest concentrations, falling in the pg m^{-3} range, are observed for the tri-CBs; PCB#18, PCB#28+31, the tetra-CBs; PCB#52, PCB#49, PCB#95, the penta-CBs; PCB#84+90+101, PCB#110, the hexa-CBs; PCB#153 and PCB#138.

The lowest annual average ∑PAH concentrations were detected at St.1 (2.3 ± 2.6 ng m^{-3}), with values of about three and five times lower than those obtained at St.2 (6.4 ± 4.0 ng m^{-3}) and St.3 (11.4 ± 5.4 ng m^{-3}) respectively. The concentrations of single PAH compounds, falling in the pg m^{-3}, are observed to differ by about one order of magnitude from one compound to another. The results indicate the 3-ring PAHs as those mainly present in the gas phase.

The PM_{10} concentration of crustal trace elements, such as Fe, Al and Mn show the highest concentrations in particles with an diameter greater than 3 μm (34, 40 and 0.75 mg/g for Fe, Al and Mn respectively). This distribution is quite typical for elements whose origin is principally related to natural sources [Chow, 1995]. Elements related to anthropic sources (for example V, Pb, Cd) are associated preferentially with the fine particles, the highest concentration is in particles smaller than 1.5 μm (65, 680 and 450 μg/g for Cd, Pb and V respectively). The lowest annual average concentrations of the Fe and Mn were detected at St.1, with values of about 2 times lower than those obtained at St.2. The highest annual average concentration of of the V and Cd was observed at St. 2. The concentrations of samples at station 2 were about 2-3 times higher than the values at St. 1 and St. 3.

Maximum, minimum and average concentrations of ∑PAHs and ∑PCBs in the dissolved and particulate phases in subsurface water and the microlayer at stations 4 and 5 are listed in Tab.1b.

Tab. 1a – PM10 trace elements (ng m-3), gas-phase ∑PAH (ng m-3) and ∑PCB (pg m-3) concentrations.

	St. 1			St. 2			St. 3		
	average	**max**	**min**	**average**	**max**	**min**	**average**	**max**	**min**
ΣPAH	2.3	11	0.48	6.4	15	2.3	11	22	5.1
ΣPCB	109	184	56	340	485	183	220	600	44
Fe	139.6	192.4	77.5	278.4	374.5	200.9	128.3	275.0	55.0
Al	139.9	217.0	70.4	390.7	143.7	615.5	190.4	285.3	55.6
Mn	5.0	7.2	3.4	12.8	24.9	8.1	6.8	11.3	4.8
V	5.4	10.0	3.9	10.3	13.6	8.1	3.9	13.2	0.7
Pb	10.4	15.1	5.8	14.7	19.8	9.8	15.9	20.6	10.7
Cd	0.32	0.97	0.08	0.95	1.68	0.20	0.30	0.53	n.d.

Tab. 1b – ∑PAH and ∑PCB concentrations (ng l^{-1}) in dissolved and particulate SSW and SML.

	St. 4											
	'DISSOLVED' SSW			'PARTICULATE' SSW			'DISSOLVED' SML			'PARTICULATE' SML		
	average	**max**	**min**	**average**	**max**	**min**	**average**	**max**	**min**	**average**	**max**	**min**
ΣPAH	8,78	11,28	6,31	8,12	9,22	5,68	15,08	20,52	8,32	106,46	158,09	59,39
ΣPCB	0,547	0,871	0,261	0,356	0,769	0,122	0,6	1,084	0,343	1,629	3,498	0,901

	St. 5											
	'DISSOLVED' SSW			'PARTICULATE' SSW			'DISSOLVED' SML			'PARTICULATE' SML		
	average	**max**	**min**	**average**	**max**	**min**	**average**	**max**	**min**	**average**	**max**	**min**
ΣPAH	75,13	25885	7,96	19,44	45,15	7,95	54,22	138,3	10,06	58,69	162,93	30,31
ΣPCB	0,467	0,899	0,233	0,599	1,215	0,226	0,584	1,002	0,37	3,466	9,929	0,346

Total PAH concentrations are higher at station 5 than at station 4 in all matrices but the former sampling site shows the strongest yearly variations. At station 4, dissolved concentrations in SML (15.08 ± 5.06 ng/l) are higher than in SSW (8.78 ± 2.61 ng/l) whilst at station 5 this behaviour is not always observed and average concentrations were 54.22 ± 59.49 ng/l in dissolved SML and 75.13 ± 108.22 ng/l in dissolved SSW. At both sites the PAH content in the particulate phase is more enriched in SML than in SSW, but generally it is greater at station 4 (SSW: 8.12 ± 1.42 ng/l; SML: 106.46 ± 44.51 ng/l) than at station 5 (SSW: 19.44 ± 15.46 ng/l; SML: 58.69 ± 58.40 ng/l). Lighter PAH (3 rings) are predominantly in the dissolved phase, while heavier PAH (more than 3 rings PAH) are predominant in the particulate phase.

Total PCB concentrations in dissolved SSW and SML are rather similar at station 4 (547 ± 302 pg/l; 600 ± 340 pg/l respectively) and at station 5 (467 ± 264 pg/l; 584 ± 266 pg/l respectively). Conversely, particulate PCB concentrations are about double at station 5 compared to station 4 in both SSW (599 ± 398 pg/l and 356 ± 238 pg/l respectively) and SML (3466 ± 3765 pg/l; 1629 ± 1072 pg/l respectively).

At both stations PCB congeners are present at the pg/l level and the predominant ones are PCB#84+90+101, PCB#110, PCB#153 and PCB#138.

4. PCB fluxes.

To evaluate the contribution of different sources to the contamination of the atmosphere of the Venice Lagoon, instant horizontal fluxes (F_{inst}) have been estimated at every station. They represent the total amount of PCBs, PAHs and elements horizontally transported by air masses from the selected direction, per unit of time (s) and unit of vertical area (m^2). Instant fluxes have been calculated considering the compound concentrations ([C]) and the average wind speed ($\bar{u}$, m s^{-1}) over the sampling period:

$$F_{inst}=[C]\ \bar{u} \tag{1}$$

The average wind speeds have been calculated taking in to account only air masses whose speed and direction were in agreement with sampler set up values.

Since the compounds (PCB, PAH, elements) loading entering the Lagoon of Venice atmosphere depends on their concentrations in the aerosol and the frequency of wind from the direction selected at each station, mean daily fluxes over each sampling campaign have been experimentally calculated taking into consideration the ratio between the selected wind duration and the sampling duration. At every station, the estimated value of actual annual flux (f_{act}, mg m^{-2} y^{-1}) has been obtained as a sum of daily fluxes over the year, from 1/6/2002 to 31/5/2003. When no experimental data were available approximated values of daily fluxes have been calculated as the arithmetical mean of previous and successive daily fluxes.

$$f_{act} = \sum_i \left[\text{daily } f_{act}\right]_i \left[\text{campaign duration}\right]_i \tag{2}$$

where *i* = number of (effective and approximated) campaigns.

The highest PCBs instant flux has been detected at St. 2 (1912 pg $m^{-2}s^{-1}$), the lowest one at St. 3 (80 pg $m^{-2}s^{-1}$). The maximum instant flux at St. 1 (641 pg m^{-2} s^{-1}) was comparable with the lowest one found at St. 2 (603 pg $m^{-2}s^{-1}$).

Horizontal instant fluxes have shown the same temporal trend observed for ∑PCBs concentrations, with greater values during warmer seasons and lower values in cold months. The comparison of St. 1 and 2 average fluxes values (358 pg m^{-2} s^{-1} and 1222 pg m^{-2} s^{-1} respectively) shows that the contribution to contamination of the Venice Lagoon atmosphere from urban and industrial sources is only 4 times greatest than those from marine sources. Estimated annual fluxes at St. 1 and 2, which are mainly linked to the contamination of the lagoon atmosphere, are 1.31 mg m^{-2} y^{-1} and 10.9 mg m^{-2} y^{-1} respectively. Results obtained show that the largest contribution to the PCB contamination of the lagoon of Venice atmosphere derives from the urban and industrial sources, which is about 8 times greater than the marine source.

The St.1 shows the lowest PAH mean horizontal flux (7.56 ng m^{-2} s^{-1}) and St.3 the highest (21.72 ng m^{-2} s^{-1}), which is very close to the value obtained for St. 2 (21.19 ng m^{-2} s^{-1}). The seasonal trend of instantaneous fluxes reflects the trend of PAH concentrations: at St. 1 and St. 2 they are higher during the colder months, whilst at St. 3 site the highest concentrations occur over the summer seasons.

The estimated PAH annual flux is about 9 times greater at St. 2 (193.5 mg m^{-2} y^{-1}) than at St. 1 (20.6 mg m^{-2} y^{-1}); at both stations the highest contribution (79 % and 76% respectively) of the annual flux is present during the coolest months, which are considered as from October to April.

The mean daily fluxes of metals reaching the lagoon of Venice by aerosol are reported in Tab. 2. The estimated mean daily fluxes of all metals is about 2-3 times greater at St. 2 than at St. 1 and St. 3.

Tab. 2 – Mean daily metal fluxes determined at the sampling sites.

Site	**Flux, mg/m^2/day**						
	Al	**Fe**	**Mn**	**Cd**	**Cu**	**Pb**	**V**
St. 1	11.7	9.3	2.0	0.055	0.36	0.55	0.31
St. 2	39.1	26.1	4.8	0.101	0.78	1.07	1.17
St. 3	11.1	8.2	2.6	0.020	0.67	0.57	0.21

Conclusions.

PM_{10} trace elements, gas-phase PAH and PCB concentrations were investigated for about a year at three sites of the Venice Lagoon that aresubjected to different sources. The station near to the industrial zone of Porto Marghera and the urban area of Mestre showed the highest annual mean concentration of ∑PCBs, ΣPAHs and elements related to anthropic sources (for example V, Pb, Cd).

To evaluate the role and contribution of aerosols to the transport of contaminants to the Venice atmosphere, horizontal fluxes of elements, PAHs and PCBs have been calculated. They have been obtained by considering the concentration in air and the mean wind speed over each sampling period.

The results show that the PCB flux from the MARINE site is about 1/8 of that from the URBAN and INDUSTRIAL sites. So for the study on the chemical contamination of the Venice atmosphere the PCB flux derived from marine source has to be considered.

The estimated annual flux of PAHs is about 9 times greater at the INDUSTRIAL site than at the MARINE site.

The estimated mean daily fluxes of all metals are about 2-3 times greater at the INDUSTRIAL site than at the MARINE and RURAL sites. So for the study on the chemical contamination of the Venice atmosphere we must take into account the elemental, PCB, PAH fluxes derived from marine sources as well as the continental input.

Acknowledgements.

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References.

Chow J.C., 1995. Measurement methods to determine compliance with ambient air quality standards for suspended particles. *Journal of the Air and Waste Management Association*, 45, 320-382

Cincinelli A., Stortini A.M., Perugini M., Cecchini L., Lepri L., 2001. Organic pollutants in sea-surface microlayer and aerosol in the coastal environment of Leghorn – (Tyrrhenian Sea). *Marine Chemistry*, 76, 77-98

Cini R., Desideri P., Lepri L., 1994. Transport of organic compounds across the air/sea interface of artificial and natural marine aerosols. *Analytica Chimica Acta*, 291, 329-340

Donazzolo R., Orio A., Pavoni B., Perin G., 1984. Heavy metals in sediments of the Venice Lagoon. *Oceanologica Acta*, 7, 25-32

Frignani M., Bellucci L.G., Langone L., Muntau H., 1997. Metal fluxes to the sediments of the northern Venice Lagoon. *Marine Chemistry*. 58, 275-292

Martin J.M., W.W. Huang, and Y.Y. Yoon, 1994. Level and fate of trace-metals in the Lagoon of Venice (Italy). *Marine Chemistry*, 46, 371-386

Moret I., Piazza R., Benedetti M., Gambaro A., Barbante C., Cescon P., 2001. Determination of polychlorobiphenyls in Venice Lagoon sediments. *Chemosphere*, 43, 559-565

Oppo C., Bellandi S., Degli Innocenti N., Stortini A.M., Loglio G., Schiavuta E., Cini R., 1999. Surfactant components of marine organic matter as agents for biogeochemical fractionation and pollutant transport via marine aerosol. *Marine Chemistry*, 63, 235-253

Scarponi G., Turetta C., Capodaglio G., Toscano G., Barbante C., Moret I., Cescon P., 1998. Chemometric studies in the Lagoon of Venice, Italy. 1. The environmental quality of water and sediment matrices. *Journal of Chemical Information and Modeling*, 38, 552-562

Wurl O., Obbard J.P., 2004. A review of pollutants in the sea-surface microlayer (SML): a unique habitat for marine organisms. *Marine Pollution Bulletin*, 48, 1016-103

NEW EXPERIMENTS ON SEDIMENT BIOTURBATION AND PERSPECTIVES FOR MODELLING THE BIOPHYSICAL TRANSPORT OF CONTAMINANTS

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Riassunto.

Vengono discussi i risultati degli esperimenti sulla bioturbazione eseguiti in corrispondenza di due siti della laguna centrale nel periodo 28/10-13/11/2002 e confrontati con le informazioni ottenute l'anno precedente. Come futura applicazione, viene presentato un nuovo modello in grado di descrivere il comportamento dei contaminanti nella colonna sedimentaria e lo scambio di soluti all'interfaccia acqua-sedimento.

Abstract.

The results of new bioturbation experiments, carried out at two sites of the central Venice Lagoon in the period 28 October-13 November 2002, are presented and discussed in comparison with the information obtained in the past. A new model, designed to describe the fate of chemicals in the sedimentary column and the exchange of solutes at the sediment-water interface, is described in the perspective of a future utilisation.

1. Introduction.

Hydrophobic organic and metal contaminants are strongly associated with the particle fraction of sediments and partition only weakly into porewaters and overlying waters [Reible *et al.*, 1996]. The possible transport pathways of contaminants from bed sediments to bottom waters include particle resuspension, diffusion, advection, and processes mediated by organic colloidal material and benthic organisms. Recent studies in laboratory microcosms involving different organisms demonstrated that bioturbators also affect fluxes entering the sediment and, as a consequence, contaminant accumulation [Ciutat, 2003; Ciutat *et al.*, 2004]. In general, activities that result in particulate contaminant transport are generally responsible of the largest fluxes through the water sediment interface. However, besides sediment resuspension, contaminant migration is likely to be dominated by the indirect action of the normal life-cycle activities of benthic organisms (i.e. bioturbation).

Bioturbation is defined as the sediment processing by animals during burrowing, sediment ingestion, defecation, tube building and biodeposition. The net result is the vertical and horizontal movement of particles and porewaters, which mix the upper sediment column and cause changes of both the contaminant distribution within the sediment (i.e. the concentration-depth profile) and the output of interstitial fluids with their load of dissolved species. The first effect can be distinguished according to the time scale considered: the long term mixing can be represented by a unique diffusive-type coefficient derived by the integrate effect of many bioturbation processes over time, whereas short term experiments can differentiate between mechanisms and rates of bioturbation-related material displacement by various organisms [Gerino *et al.*, 1994; Mugnai *et al.*, 2003].

In the Venice lagoon, previous measures of bioturbation with conservative tracers (luminophores) showed the presence of different types of biological transport within the upper sediment: biodiffusion, bioadvection and downward non local mixing [Mugnai *et al.*, 2003]. The aim of this paper is to comment on the results obtained from new experiments at two selected sites of the central lagoon in the perspective of the assessment of sediment bioturbation effects from the point of view of both the particle-mediated transport of contaminants within the sediment and the exchange across the sediment-water interface.

2. Materials and methods.

Two new experiments were carried out between October 28 and November 13, 2002 at the same sites selected for 2001 experiments (Fig. 1). At each site four tubes were inserted into the bottom, one of them - the control - full of sediment without macrofauna. The luminophores, fluorescent particles 63-350 μm in diameter, were supplied as tracer pulse inputs at the sediment surface. Eventually, the tubes were recovered and the sediment sliced in sections 0.5 to 5 cm thick. Sediments were then lyophilized, sub-sampled and counted for fluorescent dyed particles with a UV microscope. Results are expressed as concentration-depth profiles of luminophores normalized against total tracer inventories.

3. Results and discussion.

Tracer depth distributions (Fig. 2) are a function of the type of mixing, which in turn depends on the macrofauna community at the experimental site. In particular, when the tracer distribution shows a maximum at the surface and the concentration decreases almost exponentially with depth, the pattern is typical of biodiffusive mixing [Guinasso and Schink, 1975; Cochran, 1985; Wheatcroft *et al.*, 1990]. This is produced by organisms that move sediment particles in a random manner over short distances. On the contrary, tracer peak values in the subsurface sediment, associated with absence of tracers at the sediment surface, can be explained by the bioadvective part of the conveying process [Robbins *et al.*, 1979; Fisher *et al.*, 1980; Rice, 1986; Gerino *et al.*, 1994]. Another type of non-local transport, called regeneration, is characterized by deeper tracer peaks originated by the subsequent filling of burrows with surface sediment [Gardner *et al.*, 1987]. Because of this, the luminophore profiles are assumed to represent the records of biodiffusion, bioadvection and regeneration.

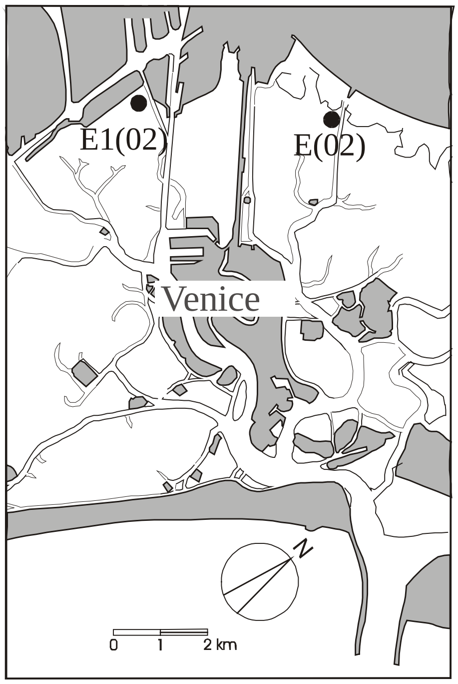

Fig. 1 – Study area and experimental sites.

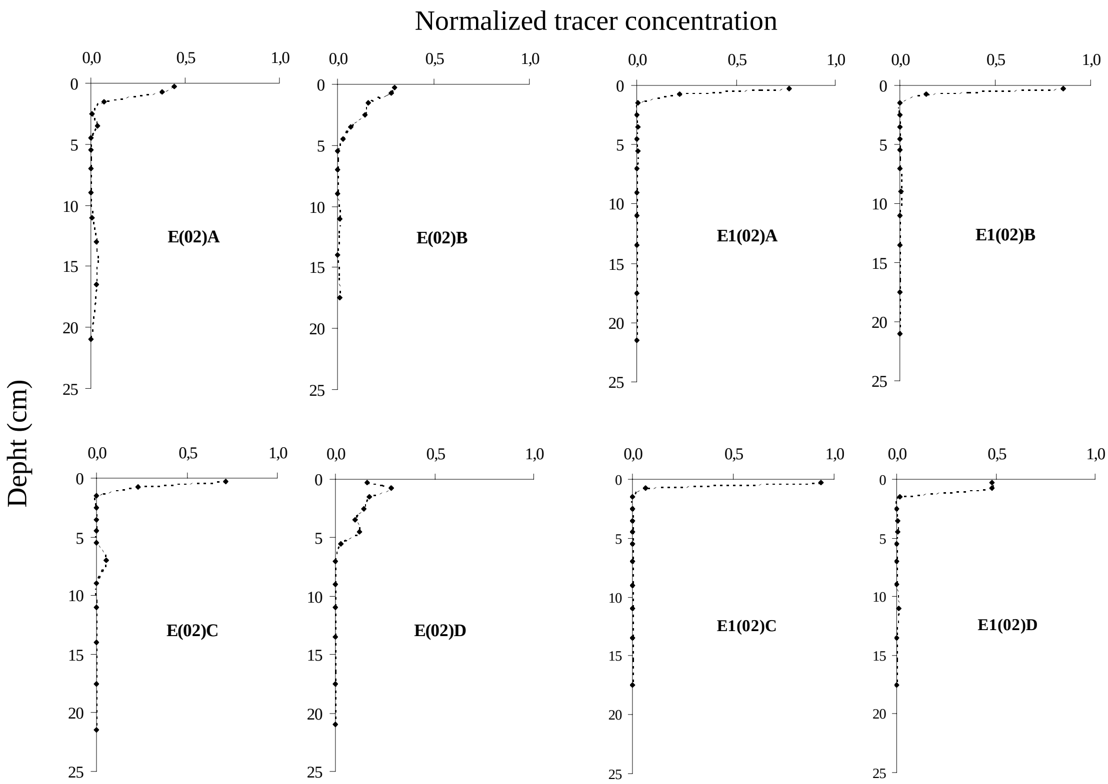

Fig. 2 – Depth profiles of luminophores at the two experimental sites.

When two or three tracer peaks are present in the subsurficial sediment, with a low or zero concentration at the interface, the upper accumulation can be assigned to conveyor effects, when they are present in the cores. The enlargement of the corresponding peak is interpreted as biodiffusion. Other deeper tracer accumulations should result from regeneration effects. Finally, when the tracer accumulates in the subsurface sediment with a maximum still present at the top, the choice between bioactivities at work, conveying or regeneration, is made according to the invertebrate community composition.

Site E1 is not characterized by the deep tracer accumulation that, on the contrary, can be clearly identified in the experimental cores of site E, as well as in its control. At this latter location multiple tracer peaks can be found, with a great heterogeneity in both shape of the profiles and depths of peak tracer accumulation. This pattern is similar to that observed at the same site in the previous experiments [Mugnai *et al.*, 2002]. The subsurficial peak found in the control core (E(02)C) can be originated by a rapid colonization of organisms that produce the same type of mixing as in the test tubes. Previous experiments at site E1 showed in all cases a well defined subsurficial peak, attributable to conveying processes [Mugnai *et al.*, 2002]. This type of mixing appears to be less effective in this new experiment (carried out in autumn instead of summer), as the tracer remained confined at the interface, except for a small downward migration in E1(02)D.

Experimental distributions were simulated by a biodiffusive-bioadvective transport-reaction model under non steady state boundary conditions with the addition of a non-local component [Mugnai *et al.*, 2002; 2003], formulated as follows:

$$\frac{\partial C}{\partial t} = D_b \frac{\partial^2 C}{\partial z^2} - V\frac{\partial C}{\partial z} + K(z,t) - R(z,t) \text{ with } \quad R = K\frac{z_2 - z_1}{0.5}$$

where C is the tracer concentration normalized against its inventory, t is the time (y), D_b is the biodiffusive mixing rate ($cm^2\ y^{-1}$), V is the bioadvective transport rate ($cm\ y^{-1}$) and z (cm) is depth. R is the removal function that determines the fraction of tracer displaced from the surface by regeneration, whereas K (y^{-1}) represents the "injection function" that simulates the deposition of tracer elsewhere in the sediment column [Smith *et al.*, 1986/87; Boudreau, 1997]. The depths z_1 and z_2 are those of the upper and lower limits of the regeneration zone. Regeneration is thus quantified by a flux of sediment "injected", called Removed Sediment (RS, $g\ cm^{-2}\ y^{-1}$) calculated from K, z_1, z_2, the bulk dry density ($g\ cm^{-3}$) and the thickness of the supplied frozen cake.

The parameters of the model are obtained through a best fit to the experimental profiles using the ordinary least square method. This allowed the estimate of D_b (1.1-25.0 $cm^2\ y^{-1}$), V (0-16.0 $cm\ y^{-1}$) and K (4-36.5 y^{-1}), that account for the rates of biodiffusion, bioadvection and non-local injection of tracer caused by regeneration, respectively. The series of parameters obtained for each experimental core and control, including the amount of sediment per unit area removed by non local-transport (RS), are reported in Tab. 1.

In order to assess the trend of mixing at the two sites in different seasons (summer 2001 and autumn 2002), the mean values of the parameters were calculated and plotted in Fig. 3.

Tab. 1 − Bioturbation coefficients and RS values from model simulations relative to 2002 experiments. E(02)C and E1(02)C are the control cores.

Core	D_b $cm^2\ y^{-1}$	V $cm\ y^{-1}$	K y^{-1}	z_1 cm	z_2 cm	RS $g\ cm^{-2}\ y^{-1}$
E(02)A	4.4	6.0	4.0	3	4	1.205
E(02)B	25.0	4.0	8.0	2	4	2.409
E(02)C	1.8	3.0	5.5	6	7	1.643
E(02)D	4.0	16.0	36.5	2	5	10.950
E1(02)A	1.9	1.4	-	-	-	-
E1(02)B	1.3	1.5	-	-	-	-
E1(02)C	1.1	0	-	-	-	-
E1(02)D	2.0	9.0	-	-	-	-

It appears evident that at E1 both biodiffusive and bioadvective processes are less effective in the autumn 2002 experiment, as well as regeneration at site E. This could be ascribed to the effect of lower temperature, since the previous experiments were carried out in summer. The biodiffusive component, in spite of a great heterogeneity, increases its importance at site E in the last experiment, whereas E1 shows an opposite pattern. Furthermore, regeneration processes were absent at E1 in both experiments. This can be attributed to differences in benthic community composition between the two experiments. In particular, we expect that at site E1(01) conveyor-belt organisms are less represented in autumn 2002 than in summer 2001. The analyses of biological samples, collected at the same sites during both experiments, will verify this hypothesis.

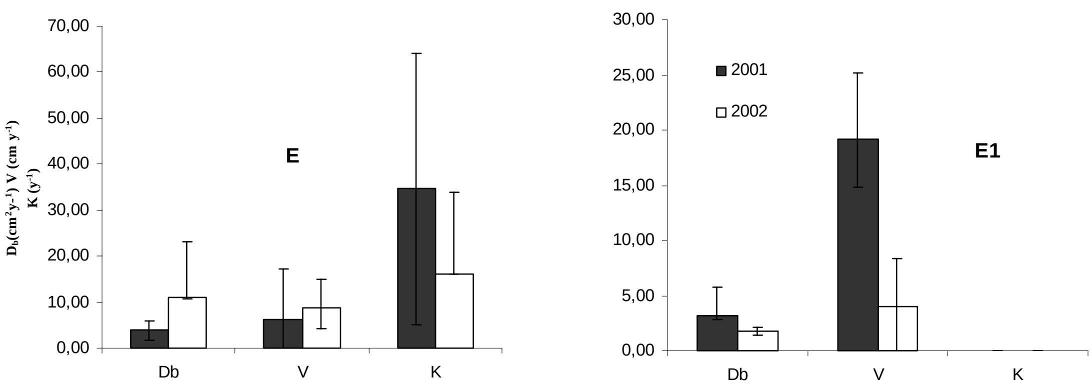

Fig. 3 – Comparison of mixing parameters (mean ± standard deviation) obtained from the experiments. Data relative to summer 2001 are from Mugnai *et al.* [2002]. Note the difference between the y axes.

4. Model development.

In order to describe the fate of particulate contaminants (e.g. anthropogenic metals) within sediments over a long period of time, it is necessary to include all transport processes in a single model, coupling biological and physical transports. So far, literature coupled classical models dealing with bioturbation effects on tracers and other particle-specific compounds in sediments predominantly use diffusion-like transport to describe the downcore distributions. Other types of biological transports, interpreted as non-local mixing, also exist in specific models like transition matrix description [Shull, 2001], lattice automaton functional models [François *et al.*, 1997] and non-local 1-D models [Boudreau, 1986; 1997].

Biological non local transports include convoying and regeneration processes. Bioadvection is only the convoying process component of the that quantifies the burial velocity. The second component is deposition, at the surface, of faecal pellets derived from ingestion at depth in the sediment. This mechanism appears to be particularly important in a model designed to describe pollutant fluxes because it causes the renewal of the particles at the sediment-water interface and, as a consequence, new free adsorption sites are put in contact with the bottom waters. The complete convoying process is able to create a cyclic transport between the sediment at depth and the surface that should be included in new models to accurately predict pollutant fluxes and distributions. The downward non-local mixing, also named regeneration, is often the most variable process in space and time and may dominate the biological transports [Mugnai *et al.*, 2002].

To describe the fate of metals in the sediment and their vertical distributions, a bio-physical model, which includes all the biological transports of particulate and dissolved tracers and exchanges between these two phases is required. Therefore, a model has been developed that includes biodiffusion, convoying (bioadvection plus deposition of matter at the surface) and downward non-local mixing. The chemical processes driving metal behaviours within the sediment are taken into account with a simplified approach, using an equation that includes the equilibrium constant and a reaction rate. The former is calculated from dissolved and particulate metal concentrations measured in sediment, whereas the latter is calibrated by fitting the model output to the metal concentration-depth profile. This model runs with different inputs of dissolved and particulate materials that can be constant, variable or episodic.

To apply a mechanistic bio-physical transport model to metal profiles, some preliminary steps need to be accomplished: (i) verification of accuracy and stability of the solutions; (ii) running the model with different coefficients to determine the coherence of the output with what is known about the organism behaviours and to provide a quantitative verification; (iii) calibration, where the intensities of the different mixing coefficients (biodiffusion and non-local mixing) are estimated to fit a conservative tracers distributions from laboratory or in situ experiments. This step requires the use of tracers, luminophores or microspheres, that provide profiles representative of the biological transport processes; (iv) validation, through the simulation of diverse metal profiles with the transport coefficients obtained from calibration. The consistency of the model output with the measured metal distribution in the sediment column accounts for the contribution of the transport processes involved in the formation of the concentration-depth profile. In other words, a good fit between the model output and the measured metal downcore distribution provides both evidence of the relative importance of the transport processes in the metal profile generation and an estimate of how realistic the description of the coupled biological and physical transport is.

The biodiffusion/conveying part of the model was validated using laboratory experiments with constant cadmium sources in the overlying water, pulse inputs of microspheres, and tubificids in the sediment [Delmotte *et al.*, 2003; submitted]. The model accurately reproduced both the particulate and dissolved metal profiles.

The complete model will be tested for the Venice Lagoon with data that must be specifically collected in the prosecution of the research. At the same time, the interpretation of the results of the benthic chamber experiments carried out so far, and the collection of new data, will allow the definition of the role of bioturbation in contaminant sediment-water exchanges.

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References.

Boudreau B.P., 1986. Mathematics of tracer mixing in sediments: II Nonlocal mixing and biological conveyor-belt phenomena. *American Journal of Science*, 286, 199-238

Boudreau B.P., 1997. Diagenetic models and their implementation. Springer-Verlag, Berlin

Ciutat A., 2003. Impact de la bioturbation des sédiments sur les transferts et la biodisponibilité des métaux - Approches expérimentales. *Sciences du vivant, Géosciences, Sciences de l'Environnement.* Bordeaux, Bordeaux I

Ciutat A., Gerino M., Mesmer-Dudons N., Anschutz P. and Boudou A., 2004. Cadmium bioaccumulation in Tubificidae from the overlying water source and effects on bioturbation. *Ecotoxicology and Environmental Safety*, in press

Cochran J.K., 1985. Particle mixing rates in sediments of the eastern equatorial Pacific: evidence from ^{210}Pb, $^{239,240}Pu$ and ^{137}Cs distributions at MANOP sites. *Geochimica et Cosmochimica Acta*, 49, 1195-1210

Delmotte S., 2003. Modelization du transport bio-physique des elements particulaires au sein du sediment: developpement du modele, measures et application aux traceurs conservatifs et aux metaux. *Memoire de DEA.* Universites Paul Sabatier Toulouse III, 34 pp

Delmotte S., Ciutat A., Sauvage S., Boudou A. and Gerino M. Modelling the transport of conservative tracer and cadmium in sediment by tubificids. *Water Research*, submitted

Fisher J.B., Lick W.J., McCall P.L. and Robbins J.A., 1980. Vertical mixing of lake sediments by tubificid oligochaetes. *Journal of Geophysical Research*, 85,3997-4006

François F., Poggiale J.C., Durbec J.P. and Stora G., 1997. A new approach for the modelling of sediment reworking induced by a macrobenthic community. *Acta Biotheoretica*, 45, 295-319

Gardner L.R., Sharma P. and Moore W.S., 1987. A regeneration model for the effect of bioturbation by fiddler crabs on ^{210}Pb profiles in salt marsh sediments. *Journal of Environmental Radioactivity*, 5, 25-36

Gerino M., Stora G. and Durbec J.P., 1994. Quantitative estimation of biodiffusive and bioadvective sediment mixing: in situ experimental approach. *Oceanologica Acta*, 17, 5, 547-554

Guinasso Jr. N.L. and Schink D.R., 1975. Quantitative estimates of biological mixing rates in abyssal sediments. *Journal of Geophysical Research*, 80, 3032-3043

Mugnai C., Frignani M., Gerino M., Sauvage S. and Bellucci L.G., 2002. Bioturbation in the Venice Lagoon and its possible role on sediment-water interactions. In "*Scientific Research and Safeguarding of Venice*. *CORILA Research Program 2001 results.*" by P. Campostrini. Venezia. pp. 437-445

Mugnai C., Gerino M., Frignani M., Sauvage S. and Bellucci L.G., 2003. Bioturbation experiments in the Venice Lagoon. *Hydrobiologia*, 494, 245-250

Reible D.D., Popov V., Valsaraj K.T., Thibodeaux L.J., Lin F., Dikshit M., Todaro M.A. and Fleeger J.W., 1996. Contaminant fluxes from sediment due to tubificid oligochaete bioturbation. *Water Research*, 30, 704-714

Rice D.L., 1986. Early diagenesis in bioadvective sediments: relationships between the diagenesis of beryllium-7, sediment reworking rates, and the abundance of conveyor-belt deposit-feeders. *Journal of Marine Research*, 44, 149-184

Robbins J.A., McCall P.L., Fischer J.B. and Krezoski J.R., 1979. Effect of deposit feeders on migration of ^{137}Cs in lake sediments. *Earth and Planetary Science Letters*, 42, 277-287

Shull D.H., 2001. Transition-matrix model of bioturbation and radionuclide diagenesis. *Limnology and Oceanography*, 46, 905-916

Smith J.N., Boudreau B.P. and Noshkin V., 1986/87. Plutonium and ^{210}Pb distributions in northeast Atlantic sediments: subsurface anomalies caused by non-local mixing. *Earth and Planetary Science Letters*, 81, 15-28

Wheatcroft R.A., Jumars P.A., Smith C.R. and Nowell A.R.M., 1990. A mechanistic view of the particulate biodiffusion coefficient: step lengths, rest period and transport directions. *Journal of Marine Research*, 48, 177-207

BENTHIC FLUXES OF TRACE METALS AND ORGANIC LIGANDS IN THE LAGOON OF VENICE

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Riassunto.

Sono stati esaminati gli scambi di elementi in traccia all'interfaccia acqua sedimento in due siti della zona centrale della Laguna di Venezia (Tresse e Campalto) per valutare la loro mobilità ed il loro comportamento geochimico. Sono stati effettuati due esperimenti di circa 60 ore mediante camere bentiche monitorate per pH, ossigeno disciolto, salinità e temperatura. L'andamento temporale della concentrazione dei metalli nella camera bentica è stato esaminato in relazione ai cambiamenti di pH e ossigeno disciolto. E' stato inoltre stimato il flusso derivante dalla diffusione molecolare dei metalli mediante l'esame della loro distribuzione nelle acque interstiziali.

Il contenuto di Cu, Fe, Mn e Zn è stata determinato mediante ICP-SFMS e l'intervallo della concentrazione (min-max in nmol l^{-1}) era 12.7-38.7, 4.5-29.7, 211-576, 79.5-329.0 rispettivamente per Cu, Fe, Mn e Zn. Nei due esperimenti sono stati determinati flussi dal sedimento all'acqua per lo Zn (62 e 67 pmol/cm^2/h) ed il Mn (19 e 12 pmol/cm^2/h), mentre per il ferro il flusso era dall'acqua verso il sedimento (–3.5 e -6.3 pmol/cm^2/h). Il comportamento del rame era differente nei due esperimenti.

Per valutare il ruolo del complessamento sulla mobilità dei metalli, è stato determinato il flusso di leganti organici del rame. I risultati hanno mostrato la presenza di due classi di leganti: one più forte con una concentrazione stabile (17.3±4.4 nmol/l) ed uno più debole a concentrazione più elevata che cambiava tra 44 and 170 nmol/l.

Abstract.

Exchanges of trace elements at the water sediment interface were examined at two sites in the central part of the Venice lagoon (Tresse and Campalto) to assess their mobility and geochemical behaviour. Two experiments of approximately 60 hours were carried out using a benthic chamber monitored for pH, dissolved oxygen, salinity, and temperature. The temporal trend of metals inside the benthic chamber was examined in relation to changes of pH and dissolved oxygen. Diffusive metal fluxes were also assessed by determination of the vertical distribution of metals in pore water.

Cu, Fe, Mn, and Zn were determined by ICP-SFMS and the concentration ranges (min-max in nmol l^{-1}) were 12.7-38.7, 4.5-29.7, 211-576, 79.5-329.0 for Cu, Fe, Mn and Zn respectively. Fluxes from the sediment to the water were determined for Zn (62 and

67 pmol/cm^2/h), Mn (19 and 12 pmol/cm^2/h) in both the experiments whilst negative fluxes were determined for iron (–3.5 and -6.3 pmol/cm^2/h). The copper behaviour was different for the two experiments.

To assess the effect of complexation on the metal mobility, fluxes of copper complexing ligands were also determined. Results showed the presence of two classes of ligands: one strong copper complexing ligands with an equilibrium concentration (17.3±4.4 nmol/l) and one weaker class present at higher concentration changing between 44 and 170 nmol/l.

1. Introduction.

The lagoon has been subject to important anthropogenic inputs of various origin (domestic, agricultural and industrial) that have progressively deteriorated the quality of the lagoon ecosystem. Significant amounts of these pollutants are accumulated in sediments, which may constitute a potential source of secondary pollution. Elements are temporarily stored in sediments and diagenetic processes can lead to their remobilisation to the overlying water. In this context the sediment-water interface represents an important boundary layer, with the greatest gradients in chemical and physical properties. Fluxes of elements through this interface affect element concentrations in both pore water and bottom water [Warnken *et al.*, 2001].

On the other hand, complexation is one of the factors controlling metal geochemistry and bioactivity. There is evidence that sediments can act as a source of metal complexing ligands [Skrabal *et al.*, 2000], in particular sulphur species [Luther *et al.*, 1986] and thiol compounds [Luther and Church, 1988]. As thiol compounds form stable complexes with metals, especially copper [Leal and van den Berg, 1998], it is likely that the thiols are part of the pool of complexing ligands thereby potentially controlling metal concentrations and distribution.

The purpose of this work was to understand and quantify the inputs of trace metals from sediments to overlaying waters in the Venice lagoon. The processes of remobilisation was studied using benthic chamber experiments.

Here we present results of experiments carried out in the central part of the Venice lagoon to investigate the benthic fluxes of metals (Cu, Fe, Mn, and Zn), thiols and copper binding ligands in shallow waters. Porewaters from sediment cores were also used to provide supporting information about fluxes.

2. Experimental.

Two experiments were carried out using benthic chambers in contaminated sites of central lagoon (Fig. 1): 1) Canale delle Tresse, near the industrial area of Porto Maghera (October 2002), and 2) the Campalto area (May 2003) (Fig. 1). The benthic chambers had a volume of 90L and contained a multi-parameter probe (mod. 556, YSI) to monitor pH, dissolved oxygen, salinity, and temperature . Water samples were collected every 3-4 hours over approximately 50-60 hours. by means of a peristaltic pump and filtered by a cartridge filter (0.20 μm).

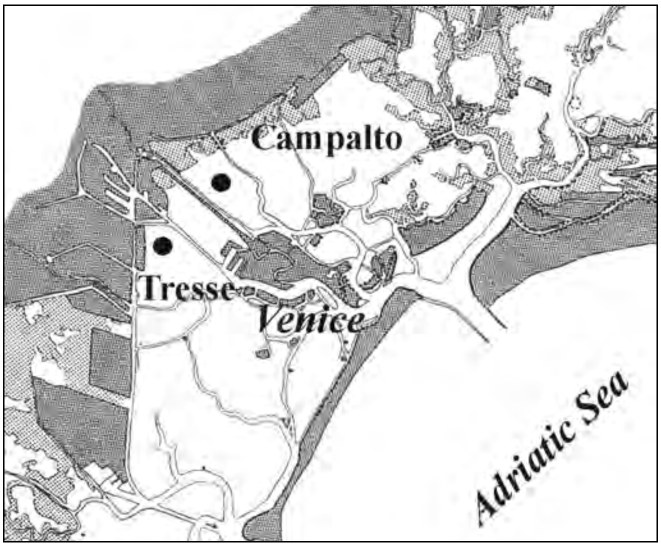

Fig. 1 – Locations of benthic chamber experiments.

Two sediment cores were collected by piston corer in June 2003 (one at each site) to extract pore water to estimate the diffusive benthic fluxes by an independent procedure. Ambient overlying water was also collected at two different depths (subsurface and bottom water). The cores were sealed and placed in a glove box conditioned with nitrogen and and sliced at interval of 0.5-1 cm , with greater detail at the top of the sediment core. Fractions were centrifuged to extract the pore water which was then quickly filtered in inert atmosphere.

Total dissolved metal concentrations were determined by Inductively Coupled Plasma-Sector Field Mass Spectrometry [Turetta *et al.*, 2004] in medium resolution mode ($m/\Delta m=3000$) by direct introduction using a microconcentric nebulizer and a Teflon spray chamber. Each sample was 10-fold diluted using ultrapure water and acidified with UPA grade HNO_3 (1:10 v:v). To correct measurements for instrumental changes in sensitivity, an internal standard containing In, Sc, Y and W (1 ng ml^{-1}) was added. Quantification was carried out by a matched calibration method with multiple-standard additions to one sample aliquot. The accuracy of the measurements was determined using a certified reference material (CRM-CASS-4).

Dissolved copper concentrations were also determined by adsorptive cathodic stripping voltammetry on acidified to pH 2.5 and UV-digested samples. A 10 ml sample aliquot was adjusted to pH 8.0 by boric buffer and 25 µl of Salycilaldoxime (SA) was added to a final concentrations of 0.01 M (buffer) and 30 µM (SA). The solution was deaerated by purging for 5 min with nitrogen. Voltammetric parameters for copper were: deposition time of 30 s at -1.1 V whilst stirring; 8 s equilibration at -0.1 V; a square wave potential scan was applied from -0.1 to -0.8 V using a frequency of 50 Hz, step height 2.5 mV and a pulse height of 25 mV. The calibration was carried out through standard additions method.

The concentration of copper complexing ligands was determined as before [Campos and van der Berg, 1994; Laglera and van der Berg, 2003]: 130 ml of sample was transferred to a Teflon bottle, buffered at pH 8.0 and adjusted at 10 µM SA. The sample was divided in 12 aliquots of 10 ml each which had been spiked with copper to give a concentration range of 0 to 200 nM and equilibrated overnight. The titration was followed by CSV with an adsorption potential of -0.1 V for 60 s and scan parameters as for dissolved copper. The sensitivity was calibrated by two additions of copper to the last aliquot where the copper concentration was > than the natural ligand concentration, and the peak height was recorded immediately to minimise equilibration with the unknown ligands.

3. Fluxes at the sediment-water interface.

The benthic flux of an analyte at the sediment-water interface is defined as the mass of that analyte migrating per unit of sediment surface and per unit of time. The following equation was used to calculate the flux [Zago *et al.*, 2000]. The benthic flux was calculated from:

$$F_i = \frac{\Delta C_i H}{\Delta t_i} \qquad (1)$$

where i is the time interval, Δt_i the elapsed time (h), ΔC_i is the concentration change (pmol cm^{-3}) and H the chamber height (cm). F_i is expressed as pmol cm^{-2} h^{-1}. A positive flux means a migration out of the sediments.

The benthic fluxes were calculated from the data reported in table 2. Because the chamber volume changed during the experiment from the initial value of 90 l to the final of 60 l, the mass of metals contented into the chambers were used to calculate fluxes. The calculation of metal fluxes on the basis of point-to-point variations contributes to an apparent high variability of the results because determination of trace components are subjected to a relatively high uncertainty. To reduce the effect of the uncertainty of the data, the mean variation of amount of trace elements inside the chambers as a function of time during the experiment was obtained from the slope of the regression line for the plot pmol vs. hours. The fluxes were then calculated by the equation:

$$F_m = \frac{R}{S} \qquad (2)$$

where F_b is the mean benthic flux during the experiment, R is the slope of the regression line in pmol/h and S is the sediment surface covered by the chamber. Positive fluxes result from an increase in concentration in the water with time; whereas negative fluxes result when the concentration in water decreases with time.

4. Diffusive fluxes.

Estimates of the molecular diffusion of metals and thiols across the sediment-water interface were obtained using the following equation [Berner, 1980]

$$F_d = -\phi D_s \frac{\delta C}{\delta x} \qquad (3)$$

where F_d = the diffusion flux of the species (pmol cm^{-2} h^{-1});
ϕ = the porosity of the sediment;

D_s = the diffusion coefficient of the bulk sediment (10^{-6} cm^2 s^{-1});
$\delta C/\delta x$ = concentration gradient of the species from the sediment-water interface to a depth of 1-2 cm (pmol cm^{-4}).

The sediment diffusion coefficient (D_s) was calculated using

$$D_s = \frac{D_0}{1 + n(1-\phi)} \tag{4}$$

where n depends on the sediment and species and was assumed as 3 [Irversen and Jorgensen, 1993], D_0 is the diffusion coefficient of the species at infinite dilution [Li and Gregory, 1974] and ϕ is the porosity of the sediment. The flux value, D_s, includes tortuosity (non radial diffusion) and molecular diffusion within the porewaters and does not account for other processes such as adsorption, resuspension and bioturbation [Berner, 1980].

5. Result and discussion.

The variation in the temperature, oxygen and pH in the benthic chambers are shown in Fig. 2. Both chambers went sub-oxic (40% or less) after about 12-15 h. The pH gradually dropped from 8 to 7.6 at Tresse and 7.8 to 7.3 at Campalto. The consumption rates of oxygen were calculated using Eq. 1, the flux was initially 95 for Tresse and 173 nmol cm^{-2} h^{-1} for Campalto whilst it decreased after the first 25 h to ~25 nmol cm^{-2} h^{-1}.

Particulate matter (PM) and POC showed a rise at the beginning, followed by a gradual decrease through the remainder of the experiment finally reaching a concentration similar to the initial value. This return to the starting condition suggests that sediment resuspension caused by the positioning of the chamber caused the resuspension of PM and POC. DOC was nearly constant, showing an overall decrease of about 10 % at both sites over the duration of the experiment.

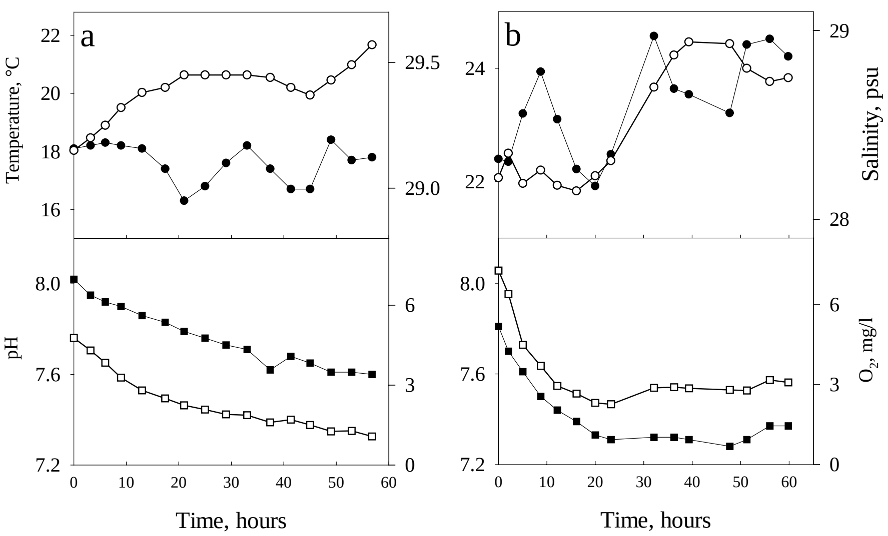

Fig. 2 – Temperature (●), salinity (○), pH (■) and oxygen (□), inside the chambers during the experiments; (a) = Tresse and (b) = Campalto.

The decrease in the oxygen concentration was not matched by a similar decrease in DOC thus suggesting that most of the change in the oxygen concentration was due to benthic processes not immediately affecting the DOC concentration in the overlying waters.

In agreement with the hydrological characteristics of the lagoon, Campalto presented a lower salinity with respect to Tresse. In both cases the salinity variations were not correlated to the tide level and were very low with respect to what expected in the two areas. Therefore, we can assume that the chambers were well sealed and that the salinity variations could derive from intrusion of water through the sediment during the sample collection. Due to the low depth of the lagoon in the studied areas, the temperature inside the chamber showed the day/night variation, characteristic of the autumn and spring period.

5.1. Trace elements.

The concentration of dissolved elements Cu, Fe, Mn, and Zn during the experiments are shown in Figs. 3a and b for Tresse and Campalto respectively. The results highlight the re-suspension of sediments and pore-water during the chamber settling, in both the experiments showed a significant increase in concentration of Cu, Fe and Zn and an increase in the suspended particulate matter at the beginning of the experiments. However, the metal concentrations did not show significant correlation with PM, indicating that the behaviour of these metals is less controlled by the suspended particulate matter than by chemical or biological processes at the benthic interface.

The mean benthic fluxes, Fm, were calculated using Equ. 2. Values are reported in Tab. 1.

Tab. 1 – Measured flux (F_m - pmol cm^{-2} h^{-1}) from the benthic chambers and the modelled flux (F_d - pmol cm^{-2} h^{-1}) from porewater data.

	Cu	**Fe**	**Mn**	**Zn**
Tresse				
F_m	-0.00±0.07	-3±11	19±6	62±1
F_d	- 0.03±0.07	29±36	45±37	-0.4±0.8
F_m/F_d	0.037	-0.12	0.42	-155
Campalto				
F_m	1.3±0.1	-6±17	12±37	67±9
F_d	- 0.02±0.03	96±80	102±68	0.001±0.001
F_m/F_d	-65	-0.07	0.12	67000

Metal concentrations in these areas are comparable to those found in the northern lagoon (copper concentration was 8-21 nM) [Martin *et al.*, 1994] and, though the concentration in the central lagoon is strongly changing with sampling sites, the values here reported are comparable with those previously detected (copper=7.5-14 nM) [Capodaglio *et al.*, in preparation].

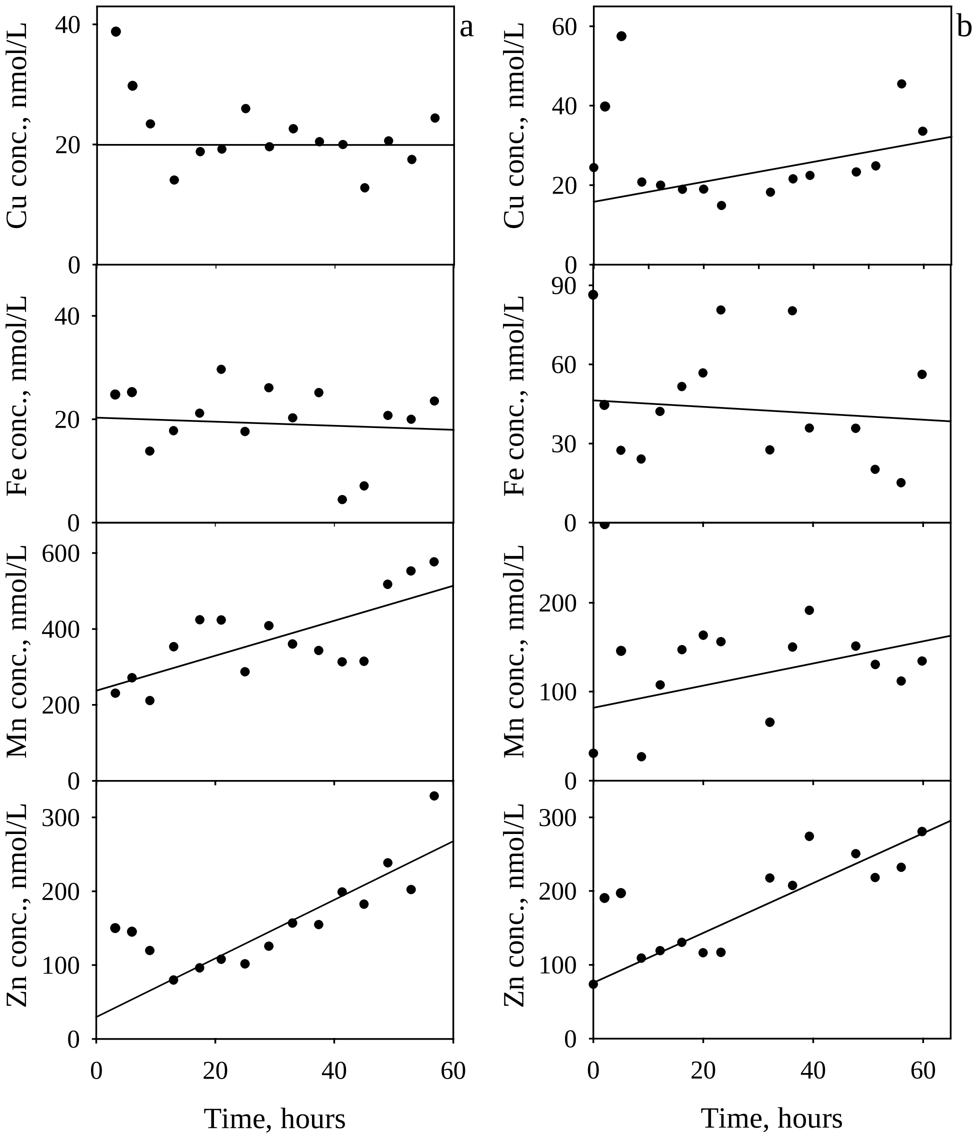

Fig. 3 – Concentration trend of Cu, Fe, Mn and Zn during the (a) Tresse and (b) Campalto experiments.

Positive fluxes were detected for manganese and zinc in both the areas, whereas they were negative or nil for Cu and Fe. Manganese and iron, though both are elements whose geochemical behaviour is driven by oxido-reductive processes, present remarkably different fluxes: the manganese fluxes were 19 and 12 pmol/cm^2/h for Tresse and Campalto, respectively, the iron fluxes were negative in both cases (–3.5 and -6.3 pmol/cm^2/h respectively).

The concentrations of Cu, Fe, Mn, Zn in porewater are shown in Fig. 4. In general, data underlined that their vertical distribution was less regular in the Tresse area as a consequence of clam fishing. Very different distributions for the four elements were observed in the porewater: the manganese and iron distribution showed a peak value at a sediment depth depending on their redox characteristics, the manganese maximum was located within 1 cm from the sediment interface, whereas the iron maximum was at 2-3 cm depth (Fig. 4). In general, the metal concentrations in porewater were at least 1 or 2 order of magnitude higher than those in the overlying water.

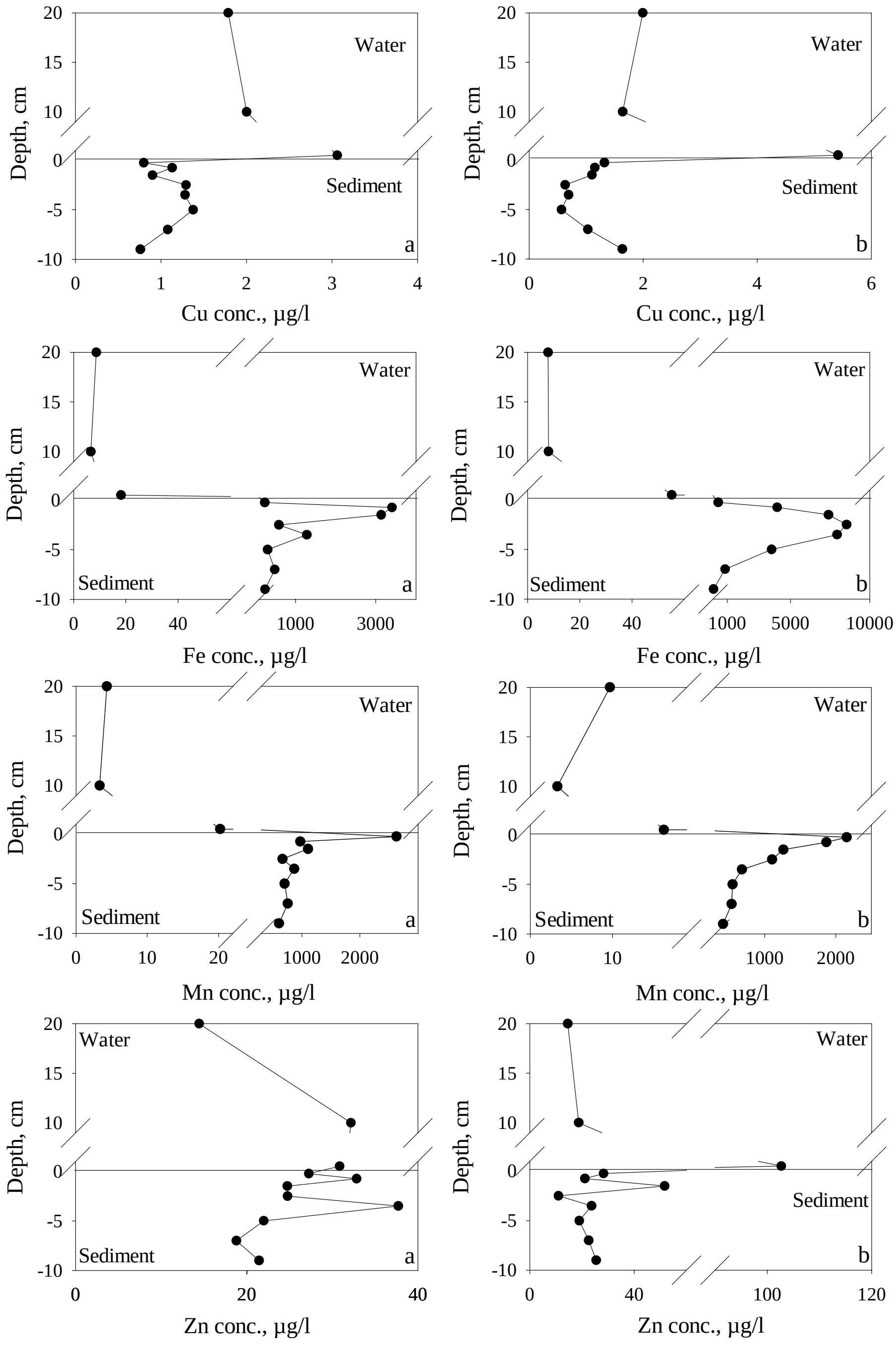

Fig. 4 – Concentration of Cu, Fe, Mn and Zn in Tresse (a) and Campalto (b) pore-water.

Copper and zinc presented their maxima in the water near the water-sediment interface (0-1 cm over the sediment surface) whilst their concentrations in the porewater were comparable to those of the lagoon waters at the same site. The reason for the strong increase at the sediment surface is unclear. It is likely that copper and zinc are associated with an organic or sulphidic fraction at the solid phase, and transfer of solids from deeper part of the sediment due to physical or bio-turbation processes in direct contact with oxygenated water may be responsible for their remobilization.

The fluxes calculated by the benthic chamber data (F_m) are compared to those obtained from the porewater data (F_d) (Tab. 1). The F_m value for zinc was greater than F_d, while it was significantly lower for iron and manganese. The ratio F_m/F_d for zinc (diffusion enhancement) was higher than 100 at both sites being about 0.1 for Fe and lower than 0.5 for Mn. The F_m/F_d ratio for copper differed at the two sites. However, it can be emphasized that the diffusive flux was undetectable in both experiments. The data suggest that transport of copper and zinc by molecular diffusion plays a negligible role in the metal cycle due to the small concentration gradient in the deeper porewaters. However, chemical or biochemical processes at the sediment level may be responsible for the remobilisation of zinc after the biodiffusion or, as reported by Mugnai *et al.* [2002], bioadvective processes provide to transfer deep sediment to the surface.

For iron and manganese the molecular diffusion seem to contribute significantly to the transport from deep sediments to the benthic interface; however, the remarkable low net fluxes detected by the benthic chambers indicate a probable re-precipitation of Mn(VI) and Fe(III) oxides within the chambers.

5.2. Organic complexation of copper.

The organic ligands complexing copper were determined by titration and data were fitted to a two-ligand model because the titration curves showed curvature, in agreement with the theory [Campos and van der Berg, 1994; Laglera and van der Berg, 2003]. The calculated ligand concentrations is shown in Fig. 5. The titrations showed that copper speciation was predominantly controlled by the a strong ligand (L1) at low copper concentrations, excess copper being bound to a weaker ligand as the copper increased during the titrations, saturating L1. The conditional stability constants of L1 and L2 complexes were log K'_{CuL1} =14.5. ± 0.4 and log K_{CuL2} =12.7 ± 0.3 at Tresse, and log K_{CuL1} = 13.8 ± 0.3 and log K_{CuL2} = 12.4 ± 0.2 at Campalto.

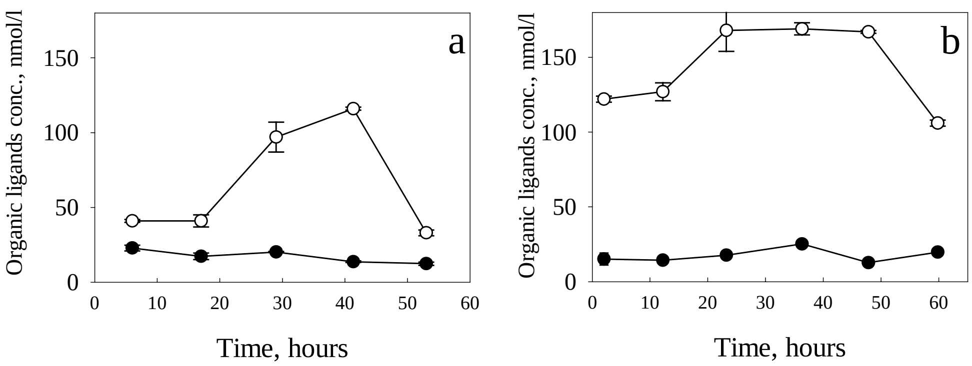

Fig. 5 – Plots showing the concentration of the two classes of ligands complexing copper, ● [L_1] and ○ [L_2], during the (a) Tresse and (b) Campalto experiments.

The copper concentration was similar to that of L1 at both sites. Therefore, L1 was nearly saturated and some of the copper was bound to L2. The concentration of L1 was about 20 nM at both sites and did not showed a systematic trend as a function of time, thus suggesting that this was L1 equilibrium concentration.

The equilibrium concentrations of copper and L1 were similar and it is possible that the two are related: either because copper is kept in solution at the level of L1 as a result of removal by scavenging until L1 stabilises the remaining copper, or L1 is stabilised from photochemical or bacterial breakdown by complexation with copper, or both. The concentration of L2 increased from 40 to 120 nM at Campalto, and from 120 to 160 nM at Tresse, before dropping to the original level near the end of the experiment.

Few data are available for the chemical speciation of copper, comparable concentration of L1 and L2 were determined at sites very closed to these considered here [Capodaglio *et al.*, in preparation]. The ligand concentrations and complex stabilities are similar to those found in estuarine waters, for instance in the river Scheldt [Laglera and van der Berg, 2003]. Guanabara Bay, a shallow lagoon adjacent to Rio de Janeiro, had copper complexing ligands at greater concentrations of 40 – 300 nM and log K'_{CuL} values of 9.6 to 12.4 [van der Berg and Rebello, 1986].

6. Conclusions.

The results obtained in the two areas show that trace elements can be remobilised from the sediment to the water by re-suspension and/or sub-oxygenation. Some preliminary conclusions can be drawn from the data.

Despite the differences in the concentrations observed at the two sites studied, the benthic fluxes of total dissolved Cu, Fe, Mn, and Zn were not significantly affected by differences between the two sites, but are apparently controlled by chemical and diffusive processes.

At the beginning of the experiment, the benthic flux of the trace elements was often positive, possibly due to remobilisation caused by the settling of the benthic chambers. Therefore, the sediments may be considered a source of trace elements for the water column following physical perturbations. Sediment re-suspension affects the mobility of a larger part of the metals, while; the mobility due to chemical or/and diffusive processes seems to be quite different even for elements with similar geochemical characteristics.

The speciation data show that copper is complexed by organic ligands present in excess the metal concentration. In spite of the high ligand concentrations, there was only little release of copper from the sediments, probably because the copper occurs there also bound by organic matter which itself is associated with the sediments.

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References

Berner R.A., 1980. *Early Diagenesis, A Theoretical Approach*. Princeton University Press, Princeton

Campos M. and van den Berg C.M.G., 1994. Determination of Copper Complexation in Sea-Water by Cathodic Stripping Voltammetry and Ligand Competition with Salicylaldoxime. *Analytica Chimica Acta*, 284, 481-496

Capodaglio G., Barbante C., Turetta C. and Cescon P. Trace metal speciation in the Lagoon of Venice. Relation with the water/particulate partition., in preparation

Iversen N. and Jorgensen B.B., 1993. Diffusion-Coefficients of Sulfate and Methane in Marine-Sediments - Influence of Porosity. *Geochimica et Cosmochimica Acta*, 57, 571-578

Laglera L.M. and van den Berg C.M.G., 2003. Copper complexation by thiol compounds in estuarine waters. *Marine Chemistry*, 82, 71-89

Leal M.F.C. and van den Berg C.M.G., 1998. Evidence for strong copper(I) complexation by organic ligands in seawater. *Aquatic Geochemistry*, 4, 49-75

Li Y.H. and Gregory S., 1974. Diffusion coefficients of ions in seawater and in deep-sea sediments. *Geochimica et Cosmochimica Acta*, 38, 703-714

Luther G.W., Church T.M., Scudlark J.R. and Cosman M., 1986. Inorganic and Organic Sulfur Cycling in Salt-Marsh Pore Waters. *Science*, 232, 746-749

Luther G.W. and Church T.M., 1988. Seasonal Cycling of Sulfur and Iron in Porewaters of a Delaware Salt-Marsh. *Marine Chemistry*, 23, 295-309

Martin J.M., Huang W.W. and Yoon Y.Y., 1994. Level and Fate of Trace-Metals in the Lagoon of Venice (Italy). *Marine Chemistry*, 46, 371-386

Mugnai C., Frignani, M., Gerino, M. and Bellucci, L.G., 2002. Bioturbation in Sediments of the Venice Lagoon and its Possibile Role on Water-Sediment interations. In: *Scientific Research and Safeguarding of Venice*. P. Campostrini Ed., Istituto Veneto di Scienze Lettere ed Arti, pp. 437-446

Skrabal S.A., Donat J.R. and Burdige D.J., 2000. Pore water distributions of dissolved copper and copper- complexing ligands in estuarine and coastal marine sediments. *Geochimica et Cosmochimica Acta*, 64, 1843-1857

Turetta C., Cozzi G., Barbante C., Capodoglio G., Cescon P., 2004. Trace Elements Determination in Seawater by ICP-SFMS coupled with a Micro-Flow Nebulization/Desolvation System. *Anal. Bioanal. Chem.*, 380, 258–268

van den Berg C.M.G. and Rebello D.L., 1986. Organic-copper interactions in Guanabara Bay, Brazil. An electochemical study of copper complexation by dissolved organic material in a tropical bay. *Science of the Total Environment*, 58, 37-45

Warnken K.W., Gill G.A., Griffin L.L., Santschi P.H., 2001. Sediment-water exchange of Mn, Fe, Ni and Zn in Galveston Bay, Texas. *Marine Chemistry*, 73, 215-231

Zago C., Capodaglio G., Ceradini S., Ciceri G., Abelmoschi L., Soggia L., Cescon P. and Scarponi G., 2000. Benthic fluxes of cadmium, lead, copper and nitrogen species in the northern Adriatic Sea in front of the River Po outflow, Italy. *Science of the total environment*, 246, 121-137

ISOTOPIC COMPOSITION AND CONCENTRATION OF LEAD ON AEROSOLS IN THE REGION OF VENICE

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Riassunto.

È stato effettuato uno studio per stimare la composizione isotopica del piombo nell'atmosfera dell'area veneziana per valutare se l'impronta isotopica può essere usata per identificare l'origine dell'aerosol. Le misure mostravano che la concentrazione di piombo diminuiva da 10.4 ng/m^3 nell'aprile 2001 a 6 ng/m^3 un anno dopo. La concentrazione era più del doppio di quella determinata durante il 1998 (19 ng/m^3) da Bollhofer and Rosman [2002] mettendo in evidenza la progressiva diminuzione di concentrazione del Pb nell'aerosol della regione.

I risultati mettevano in evidenza una significativa differenza nella composizione isotopica del Pb in funzione delle dimensioni delle particelle, dei siti ed del periodo di campionamento. I campioni prelevati a Venezia durante il 2001 e 2002 avevano una composizione isotopica simile mentre i campioni prelevati durante il 1998 erano significativamente meno radiogenici. Questo cambiamento può essere dovuto alla riduzione del contributo da piombo derivante dalle benzine facendo, pertanto, diventare più evidente il contributo derivante da altre sorgenti. Un esame più approfondito di questi risultati insieme con i dati di composizione isotopica del piombo ottenuti in regioni vicine consentirà una migliore comprensione delle sorgenti.

Abstract.

The study was carried out to assess the isotopic composition and concentration of Pb in the air in the Venice region to investigate if isotopic signatures could be used to identify the origin of the aerosols. Measurements at Venice showed the Pb concentration falling from 10.4 ng/m^3 in April 2001 to 6 ng/m^3 one year later. Concentrations were more than double those detected during the 1998 (19 ng/m^3) by Bollhofer and Rosman [2002] giving strong evidence of a declining Pb concentration in the region.

The results show significantly different isotopic compositions of the Pb as a function of particle size, the sampling sites and sampling period. The samples collected at Venice during 2001 and 2002 had a similar isotopic composition whilst samples collected in the same way in 1998 were significantly less radiogenic. This shift may be due to the reduction in the contribution from gasoline Pb allowing the signatures of other sources to become more obvious. A closer examination of these data coupled with

published isotopic data on Pb sampled in nearby regions will give a better understanding of the sources.

1. *Introduction.*

It has recently become apparent that aerosol have a central role on transport of natural and pollutant components both at local that at large scale level.

Previous scientific research on the Lagoon of Venice showed that several processes contribute substantially to the input of pollutants into this delicate environment such as atmospheric transport, remobilization of sedimented pollutants and fresh waters draining from the catchment basins. We know very little about the atmospheric contribution of trace elements and of organic pollutants to the contamination of the Venice Lagoon [Bellucci *et al.*, 1999; Jimenez *et al.*, 1998].

The aerosol contribution to the transport of micropollutans in the environment is frequently not considered in proportion to its importance. There is evidence that transport of pollutants by aerosols can reach also remote areas as well polar regions, however, effects of aerosols in urban areas are of particular importance [Miller *et al.*, 2001].

Because its extreme mobility, to define the aerosol origin is complex and tracers are necessary for this purpose. Studies showed that lead isotopic composition can be conveniently used as a tracer of atmospheric transport, its origin and paths [Bollhofer and Rosman, 2001]. Lead concentrations and isotopic ratios have been measured on aerosols collected in the vicinity of Venice. The purpose of these measurements was to use Pb isotopes to indicate the possible sources of these aerosols.

2. Methods.

2.1. Sampling Sites and Aerosol Collection.

Aerosol samples were collected in four sites reported in Fig. 1 by high-volume impactors, fitted with PM_{10} size selective inlets. Particles with aerodynamic diameters <10µm were classified into six size intervals with cutoff aerodynamic diameters of 7.2, 3, 1.5, 0.95, 0.49 and <0.49 µm. Sampling campaign were carried out between July 2001 and December 2003, 6 samples were collected at the Lido ~9km East of Venice, when winds blew from the Adriatic Sea in a southeasterly direction. When winds were northeasterly, urban and industrial sources were collected at Moranzani, ~8km west of Venice (3 samples). Terrestrial sources were collected at Tessera, ~6km north of Venice (3 samples), and pollutants from no specific sources were collected at Teolo, in the Euganei hills ~50 km west of Venice (6 samples). Further description of the sampling devices and collection, the sites, and relation to the major wind systems are given by Gambaro *et al.* [2002] and Capodoglio *et al.* [2003].

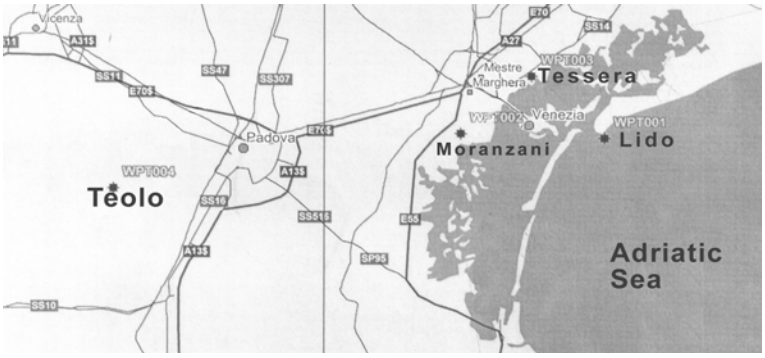

Fig. 1 – Venice and surrounding area. Sampling sites are indicated.

2.2. Filter Handling Procedure.

After sampling in Italy, the filters were cut into sectors and stored in petri dishes. A quarter of each slotted filter (stages with cutoff aerodynamic diameters of 7.2, 3, 1.5, 0.95, 0.49 µm), a sixth of each backup filter (cutoff aerodynamic diameters of <0.49 µm), and corresponding field blanks, were sent to Curtin University in Perth, Australia. These samples were kept refrigerated at -18^{o}C until they were analysed.

At Curtin, preparation of filters for isotopic analysis was carried out inside a HEPA-filtered clean-air laboratory using ultra-clean procedures. The samples were chemically processed in 15 ml PFA Teflon beakers (with screw top lids) which were numbered and dedicated either to isotopic composition (IC) or concentration (isotope dilution, ID) measurements.

Total aerosols were collected in Venice on 37 mm Teflon filters prepared and analysed using methods described by Bollhofer *et al.* [1999].

2.3. Chemical Processing.

The analyses were carried out at Curtin University in Perth, Western Australia. From each slotted filter, a 4 cm long section of the fifth strip (counted from the edge) was taken for analysis. Also, a 4 cm x 1 cm strip of the backup filter (taken from the centre) was analysed. Samples were leached in warm 0.2M HBr (~5 ml) for one hour and then a 10% aliquot of this solution was taken for concentration measurement by isotopic dilution mass spectrometry (IDMS). Pb was separated from this solution using anion exchange chemistry. Samples were loaded on Bio-Rad anion AG1x8 (100-200 mesh) ion exchange columns in 0.2 M HBr. Following a wash with 0.2 M HBr the Pb was eluted with 1 M HNO_3. The extraction efficiency of the separation was measured to be 96%. Following the addition of 4 µL of a phosphoric acid/silica gel ionisation enhancer (needed for TIMS) the solution was evaporated to dryness overnight on a hotplate.

A Pb blank for the chemical processing of the samples was measured with each batch of samples analysed and was typically 120 pg. This represented a contribution of < 0.2% of the Pb analysed in samples other than the field blanks, where the chemical blank was generally <13%. The field blanks supplied from each site contained varying amounts of Pb. The average isotopic ratios for the filter media was $^{206}Pb/^{207}Pb = 1.16 \pm 0.02$, $^{208}Pb/^{207}Pb = 2.42 \pm 0.02$ (uncertainties are 2 sd of the values).

2.4. Isotope Dilution Mass Spectrometry.

The amount of Pb in each sample was measured by isotope dilution mass spectrometry [Webster, 1960]. Samples were spiked with tracer enriched to 99.6% in the ^{204}Pb isotope. Three spike solutions were employed, with concentrations 23.3 ± 0.1 ppb (by weight) and 8.08 ± 0.04 ppb for samples, and concentration 1.50 ± 0.02 ppb for blanks. All uncertainties shown are 95% confidence limits on accuracy.

Samples were loaded on zone-refined rhenium single filament ion sources, together with a phosphoric acid/silica gel ionisation enhancer. The measurements were carried out using a VG354 (Fison Instruments, UK) isotope ratio thermal ionisation mass spectrometer. The ions were measured using either a 4 cup Faraday multi-collector array for typical samples or a Daly detector for blanks. Measurements were corrected for fractionation by 0.12 ± 0.05% per mass unit for measurements on the Faraday Cups and 0.24 ± 0.06% per mass unit for measurements on the Daly collector. This correction is based upon two decades of Pb measurement on the VG354 mass spectrometer at Curtin. During the project 23 samples of NIST 981 were analysed, which after correction yielded $^{206}Pb/^{207}Pb = 0.9147 \pm 0.0004$, $^{208}Pb/^{207}Pb = 2.3693 \pm 0.0006$ and $^{206}Pb/^{204}Pb = 16.94 \pm 0.01$ (uncertainties shown are 2 * standard deviation of the 23 measurement). These values deviate from the NIST certified values by 0.01%, -0.05% and 0.01% respectively.

3. Results and Discussion.

Data for both the isotopic composition and the amount of Pb fractioned into the six size interval diameters are shown in Tables 1a, 1b, and 1c. On each stage are shown data for the two collection periods in July 2001, two in March 2002, and two in October/November/December 2002. Data are also given in Tab. 2 for total aerosol collection using samplers located on Venice for 12 months from April 2001.

The volumes of air passing through the impactor are provided with the data and these were used to determine the Pb concentration in the various size fractions. The data were also combined to give the total isotopic composition and concentration of Pb at each location for the different periods.

The data are also plotted in Figures 2, 3 and 4. The $^{206}Pb/^{207}Pb$ ratios and the Pb concentrations are shown. Note that the scale for concentration axis is coarser for the July #2 period where the concentrations were significantly higher. The isotopic ratios are plotted on the same scale in all graphs to facilitate comparison; however the precision of these measurements is significantly better than the size of the symbols.

Tab. 1a – Isotopic composition and concentration of Pb at three sites near Venice in July 2001.

Aerosol collection July 2001												
site & sampling period	particle size (µm)	Pb206/204 #	± *	Pb206/207 #	± *	Pb208/207 #	± *	Pb on stage (ng)‡#	± *	Volume ** (m^3)	Pb Concentration # (ng/m^3)	± *
Lido period 1	7.2 - 10	18.12	0.03	1.1574	0.0007	2.434	0.002	217	9	963	0.23	0.01
	3 - 7.2	18.16	0.02	1.1615	0.0006	2.437	0.001	658	23	963	0.68	0.02
	1.5 - 3	18.09	0.02	1.1596	0.0006	2.435	0.001	721	25	963	0.75	0.03
	0.95 - 1.5	18.10	0.05	1.1578	0.0007	2.437	0.001	2200	74	963	2.28	0.08
	0.49 - 0.95	18.14	0.02	1.1600	0.0006	2.435	0.001	2341	80	963	2.43	0.08
	<0.49	18.27	0.02	1.1684	0.0006	2.436	0.001	4140	220	963	4.3	0.2
	Total ++			1.1629	0.0006	2.436	0.001				10.7	0.3
Lido period 2	7.2 - 10	18.07	0.07	1.1614	0.0007	2.436	0.001	192	7	521	0.37	0.01
	3 - 7.2	18.12	0.02	1.1601	0.0006	2.434	0.001	847	29	521	1.62	0.05
	1.5 - 3	18.08	0.02	1.1584	0.0006	2.432	0.001	1421	48	521	2.73	0.09
	0.95 - 1.5	18.08	0.02	1.1571	0.0006	2.433	0.001	3948	131	521	7.6	0.3
	0.49 - 0.95	18.11	0.02	1.1598	0.0006	2.433	0.001	4660	154	521	8.9	0.3
	<0.49	18.15	0.03	1.1614	0.0006	2.431	0.001	7344	547	521	15.6	0.8
	Total ++			1.1599	0.0006	2.432	0.001				36.8	0.9
Teolo period 1	7.2 - 10	18.55	0.02	1.1834	0.0006	2.447	0.001	592	20	1845	0.32	0.01
	3 - 7.2	18.20	0.02	1.1634	0.0006	2.435	0.001	1787	59	1845	0.97	0.03
	1.5 - 3	18.10	0.02	1.1588	0.0006	2.432	0.001	2915	97	1845	1.58	0.05
	0.95 - 1.5	18.11	0.02	1.1600	0.0006	2.433	0.001	5288	175	1845	2.87	0.09
	0.49 - 0.95	18.15	0.02	1.1622	0.0006	2.434	0.001	9162	582	1845	5.0	0.3
	<0.49	18.24	0.02	1.1669	0.0006	2.435	0.001	13861	667	1845	7.5	0.4
	Total ++			1.1640	0.0006	2.434	0.001				18.2	0.5
Teolo period 2	7.2 - 10	18.12	0.05	1.1608	0.0007	2.436	0.001	301	11	865	0.35	0.01
	3 - 7.2	18.09	0.02	1.1590	0.0006	2.433	0.001	1573	52	865	1.82	0.06
	1.5 - 3	18.08	0.02	1.1581	0.0006	2.431	0.001	2134	71	865	2.47	0.08
	0.95 - 1.5	18.07	0.02	1.1579	0.0006	2.431	0.001	3303	109	865	3.8	0.1
	0.49 - 0.95	18.10	0.02	1.1592	0.0006	2.431	0.001	5820	191	865	6.7	0.2
	<0.49	18.12	0.02	1.1601	0.0006	2.429	0.001	11911	1159	865	13.8	1.3
	Total ++			1.1594	0.0007	2.430	0.001				29	1
Moranzani period 1	7.2 - 10	18.15	0.02	1.1626	0.0006	2.435	0.001	749	25	1627	0.46	0.02
	3 - 7.2	18.17	0.02	1.1626	0.0006	2.437	0.001	2692	88	1627	1.65	0.05
	1.5 - 3	18.14	0.02	1.1613	0.0006	2.436	0.001	2813	92	1627	1.73	0.06
	0.95 - 1.5	18.17	0.02	1.1631	0.0006	2.438	0.001	7504	246	1627	4.6	0.2
	0.49 - 0.95	18.22	0.02	1.1665	0.0006	2.439	0.001	8552	280	1627	5.3	0.2
	<0.49	18.18	0.02	1.1688	0.0006	2.440	0.001	14429	707	1627	8.9	0.4
	Total ++			1.1659	0.0006	2.438	0.001				22.6	0.5
Tessera period 2	7.2 - 10	18.19	0.02	1.1632	0.0006	2.434	0.001	534	19	684	0.78	0.03
	3 - 7.2	18.16	0.02	1.1630	0.0006	2.434	0.001	1970	66	684	2.9	0.1
	1.5 - 3	18.18	0.02	1.1611	0.0006	2.436	0.001	2494	83	684	3.6	0.1
	0.95 - 1.5	18.16	0.02	1.1639	0.0006	2.435	0.001	6026	199	684	8.8	0.3
	0.49 - 0.95	18.23	0.02	1.1646	0.0006	2.437	0.001	7937	262	684	11.6	0.4
	<0.49	18.17	0.02	1.1630	0.0006	2.430	0.001	14806	783	684	21.6	1.1
	Total ++			1.1634	0.0006	2.433	0.001				49.3	1.3

‡Amount of Pb on complete stage, estimated from the analysis of ~3% of a complete filter. Assumptions made are that the total exposed areas are 504 cm^2 for the backing filter and 120 cm^2 for the stages containing collection strips.

** Integrated volume of air passed through the filter system. The uncertainty in this quantity is not known, but must be added to the values shown on the concentration when quoting the accuracy on the concentration of Pb in the air.

* All uncertainties shown are 95% confidence intervals for the mean.

The values shown are all corrected for both the chemical processing and residual Pb present in the filters (filter blank). The isotopic ratios have also been corrected for these blanks.

Table 1b – Isotopic composition and concentration of Pb at three sites near Venice in March 2002.

Aerosol collection March 2002												
site & sampling period	particle size (µm)	Pb206/204 #	± *	Pb206/207 #	± *	Pb208/207 #	± *	Pb on stage (ng)‡#	± *	Volume ** (m^3)	Pb Concentration # (ng/m^3)	± *
Lido period 1	7.2 - 10	18.16	0.02	1.1602	0.0006	2.438	0.001	283	10	3207	0.09	0.00
	3 - 7.2	18.14	0.02	1.1609	0.0006	2.437	0.001	1031	34	3207	0.32	0.01
	1.5 - 3	18.13	0.02	1.1610	0.0006	2.435	0.001	3349	110	3207	1.04	0.03
	0.95 - 1.5	18.14	0.02	1.1598	0.0006	2.436	0.001	9836	324	3207	3.1	0.1
	0.49 - 0.95	18.13	0.02	1.1607	0.0006	2.436	0.001	8877	292	3207	2.77	0.09
	<0.49	18.11	0.02	1.1599	0.0006	2.436	0.001	7988	563	3207	2.5	0.2
	Total ++			1.1603	0.0006	2.436	0.001				9.8	0.2
Lido period 2	7.2 - 10	18.32	0.08	1.1684	0.0007	2.444	0.001	224	8	2215	0.10	0.00
	3 - 7.2	18.30	0.02	1.1710	0.0006	2.447	0.001	1159	38	2215	0.52	0.02
	1.5 - 3	18.22	0.03	1.1650	0.0006	2.441	0.001	1207	40	2215	0.54	0.02
	0.95 - 1.5	18.17	0.02	1.1639	0.0006	2.439	0.001	4465	147	2215	2.02	0.07
	0.49 - 0.95	18.24	0.02	1.1672	0.0006	2.442	0.001	5436	178	2215	2.45	0.08
	<0.49	18.36	0.02	1.1735	0.0006	2.448	0.001	9746	508	2215	4.4	0.2
	Total ++			1.1694	0.0006	2.444	0.001				10.0	0.3
Teolo period 1	7.2 - 10	18.35	0.02	1.1587	0.0006	2.436	0.001	1414	51	1507	0.94	0.03
	3 - 7.2	18.21	0.02	1.1589	0.0006	2.435	0.001	2423	86	1507	1.61	0.06
	1.5 - 3	18.17	0.02	1.1585	0.0006	2.433	0.001	3364	115	1507	2.23	0.08
	0.95 - 1.5	18.12	0.02	1.1594	0.0006	2.433	0.001	7624	254	1507	5.1	0.2
	0.49 - 0.95	18.19	0.03	1.1581	0.0006	2.436	0.001	6393	215	1507	4.2	0.1
	<0.49	18.27	0.02	1.1646	0.0006	2.441	0.001	10027	834	1507	6.7	0.6
	Total ++			1.1606	0.0006	2.437	0.001				20.7	0.6
Teolo period 2	7.2 - 10	18.15	0.03	1.1627	0.0006	2.438	0.001	212	7	1382	0.15	0.01
	3 - 7.2	18.17	0.02	1.1624	0.0006	2.440	0.001	830	28	1382	0.60	0.02
	1.5 - 3	18.19	0.02	1.1624	0.0006	2.442	0.001	1113	37	1382	0.81	0.03
	0.95 - 1.5	18.18	0.02	1.1619	0.0006	2.441	0.001	3440	118	1382	2.49	0.09
	0.49 - 0.95	18.18	0.02	1.1627	0.0006	2.440	0.001	4100	135	1382	2.97	0.10
	<0.49	18.19	0.02	1.1634	0.0006	2.441	0.001	7344	547	1382	5.31	0.40
	Total ++			1.1628	0.0006	2.441	0.001				12.3	0.4
Moranzani period 1	7.2 - 10	18.16	0.02	1.1631	0.0006	2.440	0.001	1560	52	3781	0.41	0.01
	3 - 7.2	18.16	0.02	1.1634	0.0006	2.439	0.001	4711	155	3781	1.25	0.04
	1.5 - 3	18.16	0.02	1.1636	0.0006	2.438	0.001	4848	160	3781	1.28	0.04
	0.95 - 1.5	18.27	0.05	1.1628	0.0007	2.440	0.001	8801	295	3781	2.33	0.08
	0.49 - 0.95	18.20	0.02	1.1659	0.0006	2.440	0.001	14434	475	3781	3.8	0.1
	<0.49	18.26	0.02	1.1681	0.0006	2.444	0.001	28281	1256	3781	7.5	0.3
	Total ++			1.1660	0.0006	2.441	0.001				16.6	0.4
Tessera period 2	7.2 - 10	18.17	0.02	1.1690	0.0008	2.439	0.002	434	15	4063	0.11	0.00
	3 - 7.2	18.03	0.02	1.1657	0.0006	2.440	0.001	2603	86	4063	0.64	0.02
	1.5 - 3	18.24	0.02	1.1669	0.0006	2.439	0.001	4244	140	4063	1.04	0.03
	0.95 - 1.5	18.32	0.02	1.1683	0.0006	2.439	0.001	9709	319	4063	2.39	0.08
	0.49 - 0.95	18.27	0.02	1.1679	0.0006	2.438	0.001	17252	578	4063	4.2	0.1
	<0.49	18.21	0.02	1.1651	0.0006	2.437	0.001	3639	261	4063	0.90	0.06
	Total ++			1.1675	0.0006	2.438	0.001				9.3	0.2

♦ ** # refer to Tab. 1a.

A comparison of the isotopic data for all locations is shown on three-isotope plots in Figures 5, 6 and 7 which correspond to the July 2001, March 2002 and Oct/Nov/Dec 2002 sampling periods respectively. Additional data for Venice during 1998, taken from Bollhofer and Rosman [2002], are also shown.

Tab. 1c – Isotopic composition and concentration of Pb at three sites near Venice during Oct/Nov/Dec 2002.

Aerosol collection October/November/December 2002												
site & sampling period	particle size (µm)	Pb206/204 #		Pb206/207 #		Pb208/207 #		Pb on stage (ng)‡#		Volume ** (m3)	Pb Concentration # (ng/m3)	
			± *		± *		± *		± *			± *
Lido period 1	7.2 - 10	18.095	0.019	1.1581	0.0006	2.4382	0.0013	315	11	2140	0.147	0.005
	3 - 7.2	18.060	0.018	1.1560	0.0006	2.4359	0.0012	1402	46	2140	0.655	0.021
	1.5 - 3	18.069	0.018	1.1578	0.0006	2.4360	0.0012	1840	60	2140	0.860	0.028
	0.95 - 1.5	18.143	0.018	1.1620	0.0006	2.4390	0.0012	4830	157	2140	2.257	0.073
	0.49 - 0.95	18.202	0.018	1.1646	0.0006	2.4408	0.0012	4650	151	2140	2.173	0.071
	<0.49	18.182	0.019	1.1638	0.0006	2.4387	0.0012	6541	313	2140	3.029	0.146
	Total ++			1.1623	0.0006	2.4388	0.0012				9.122	0.182
Lido period 2	7.2 - 10	18.143	0.204	1.1683	0.0010	2.4443	0.0020	1543	55	496	3.114	0.110
	3 - 7.2	18.203	0.021	1.1656	0.0006	2.4426	0.0013	323	11	496	0.652	0.022
	1.5 - 3	18.183	0.020	1.1631	0.0006	2.4405	0.0013	440	15	496	0.889	0.030
	0.95 - 1.5	18.182	0.019	1.1649	0.0006	2.4395	0.0012	1470	48	496	2.964	0.097
	0.49 - 0.95	18.220	0.019	1.1653	0.0006	2.4385	0.0012	1258	41	496	2.537	0.083
	<0.49	18.307	0.077	1.1657	0.0007	2.4401	0.0014	2142	116	496	4.322	0.233
	Total ++			1.1659	0.0007	2.4408	0.0014				14.478	0.290
Teolo period 1	7.2 - 10	18.862	0.019	1.2026	0.0006	2.4561	0.0013	1029	34	1629	0.632	0.021
	3 - 7.2	18.210	0.019	1.1632	0.0006	2.4418	0.0012	1562	51	1629	0.959	0.032
	1.5 - 3	18.187	0.018	1.1632	0.0006	2.4402	0.0012	1631	54	1629	1.001	0.033
	0.95 - 1.5	18.153	0.018	1.1603	0.0006	2.4398	0.0012	2687	88	1629	1.649	0.054
	0.49 - 0.95	18.128	0.018	1.1612	0.0006	2.4365	0.0012	4167	136	1629	2.558	0.083
	<0.49	18.177	0.018	1.1632	0.0006	2.4371	0.0012	7043	338	1629	4.324	0.208
	Total ++			1.1646	0.0007	2.4391	0.0012				11.123	0.236
Teolo period 2	7.2 - 10	18.155	0.018	1.1622	0.0006	2.4393	0.0012	1221	40	7914	0.154	0.005
	3 - 7.2	18.160	0.018	1.1629	0.0006	2.4404	0.0012	5644	184	7914	0.713	0.023
	1.5 - 3	18.185	0.018	1.1637	0.0006	2.4429	0.0012	7843	255	7914	0.991	0.032
	0.95 - 1.5	18.165	0.018	1.1629	0.0006	2.4414	0.0012	21102	686	7914	2.666	0.087
	0.49 - 0.95	18.131	0.018	1.1612	0.0006	2.4384	0.0012	20459	665	7914	2.585	0.084
	<0.49	18.078	0.018	1.1577	0.0006	2.4346	0.0012	37133	1930	7914	4.692	0.244
	Total ++			1.1605	0.0006	2.4381	0.0013				11.802	0.275
Moranzani period 1	7.2 - 10	18.135	0.021	1.1627	0.0006	2.4412	0.0012	1802	59	5160	0.349	0.011
	3 - 7.2	18.132	0.018	1.1622	0.0006	2.4391	0.0012	4226	138	5160	0.819	0.027
	1.5 - 3	18.120	0.022	1.1637	0.0006	2.4398	0.0012	5296	172	5160	1.026	0.033
	0.95 - 1.5	18.103	0.021	1.1633	0.0006	2.4386	0.0012	13435	436	5160	2.604	0.085
	0.49 - 0.95	18.186	0.018	1.1647	0.0006	2.4380	0.0012	14587	474	5160	2.827	0.092
	<0.49	18.167	0.018	1.1633	0.0006	2.4372	0.0012	35197	1689	5160	6.821	0.327
	Total ++			1.1635	0.0006	2.4380	0.0014				14.445	0.353
Tessera period 2	7.2 - 10	18.108	0.019	1.1606	0.0006	2.4371	0.0012	1130	48	12998	0.087	0.004
	3 - 7.2	18.126	0.018	1.1620	0.0006	2.4380	0.0012	9153	385	12998	0.704	0.030
	1.5 - 3	18.140	0.018	1.1628	0.0006	2.4391	0.0012	10857	422	12998	0.835	0.032
	0.95 - 1.5	18.142	0.018	1.1625	0.0006	2.4393	0.0012	25573	1075	12998	1.967	0.083
	0.49 - 0.95	18.128	0.018	1.1616	0.0006	2.4383	0.0012	46621	1817	12998	3.587	0.140
	<0.49	18.093	0.018	1.1598	0.0006	2.4357	0.0012	106418	5066	12998	8.187	0.390
	Total ++			1.1608	0.0007	2.4371	0.0015				15.368	0.425

* ♦ ** # refer to Table 1a.

Tab. 2 – Isotopic composition and concentration of Pb at three sites near Venice.

Aerosols collected at Venice 2001 & 2002										
sampling period	Pb206/204 #		Pb206/207 #		Pb208/207 #		Pb on stage (ng)‡#		Volume (m^3)	Pb Concentration # (ng/m^3)	
		± *		± *		± *		± *			± *
23 Apr -30 Jun 2001	18.26	0.02	1.1686	0.0006	2.443	0.001	727	9	70	10.4	0.1
30 Jun - 14 Aug 2001	18.21	0.02	1.1648	0.0006	2.440	0.001	898	12	89	10.1	0.1
1 Sep - 5 Nov 2001	18.25	0.02	1.1670	0.0006	2.444	0.001	641	8	129	4.96	0.06
29 Nov '01 - 27 Jan '02	18.20	0.02	1.1647	0.0006	2.441	0.001	736	9	112	6.60	0.08
29 Jan - 1 Apr 2002	18.20	0.02	1.1644	0.0006	2.442	0.001	726	9	122	5.97	0.08
Mean++			1.1661	0.0005	2.442	0.001					

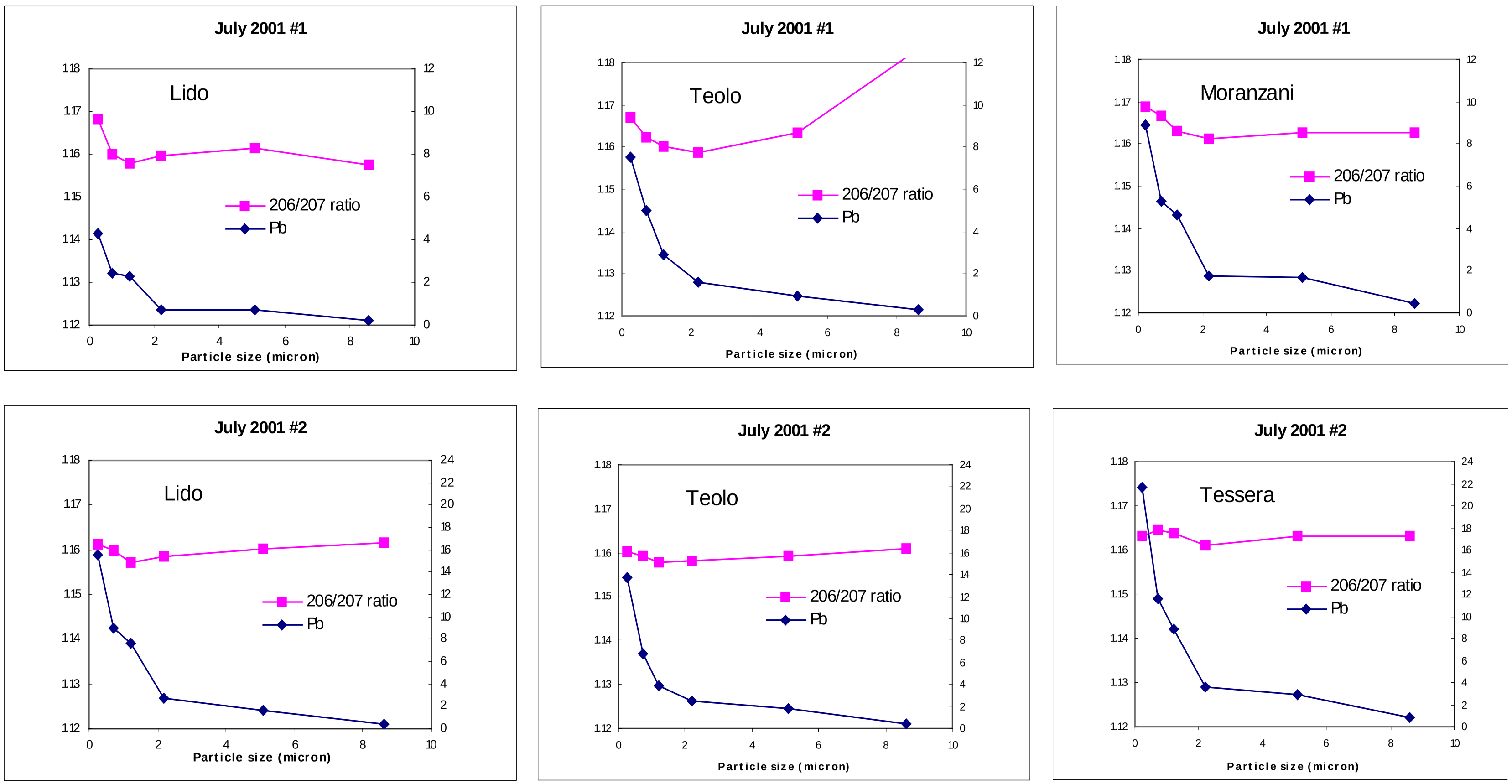

Fig. 2 – Comparison of Pb concentrations (right axe, ng/m^3) and $^{206}Pb/^{207}Pb$ isotopic ratios (left axe) at the locations shown during 16-20 July 2001 (July #1) and 26-30 July 2001 (July #2). The data plotted are from Tab. 1a. Uncertainties are given in the table – they are 0.05% for the isotopic ratios and generally better than 5% for concentrations.

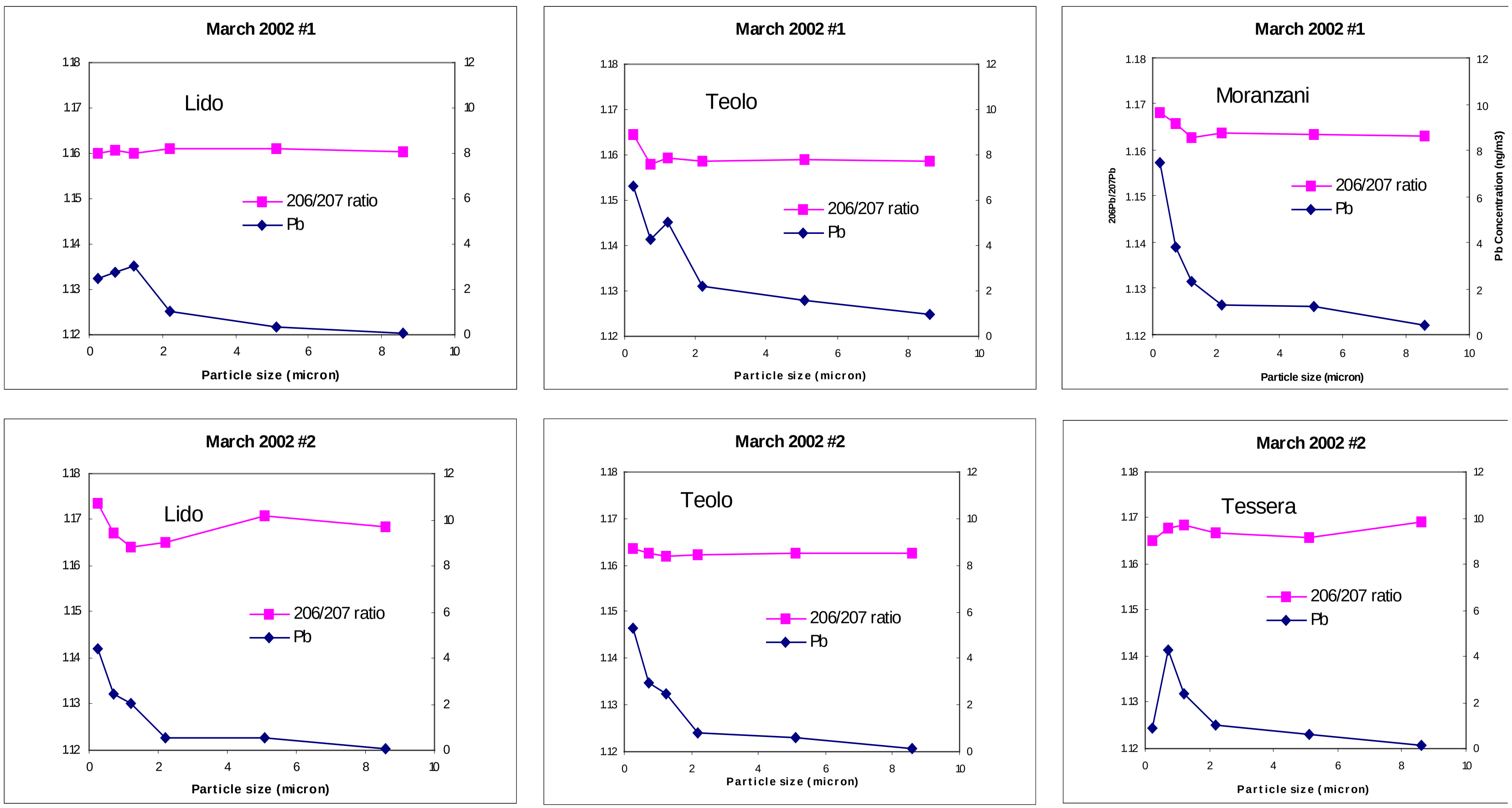

Fig. 3 – Comparison of Pb concentrations (right axe, ng/m^3) and $^{206}Pb/^{207}Pb$ isotopic ratios (left axe) at the locations shown during March 2002. The data plotted are from Tab. 1b. Uncertainties are given in the table – they are 0.05% for the isotopic ratios and generally better than 5% for concentrations.

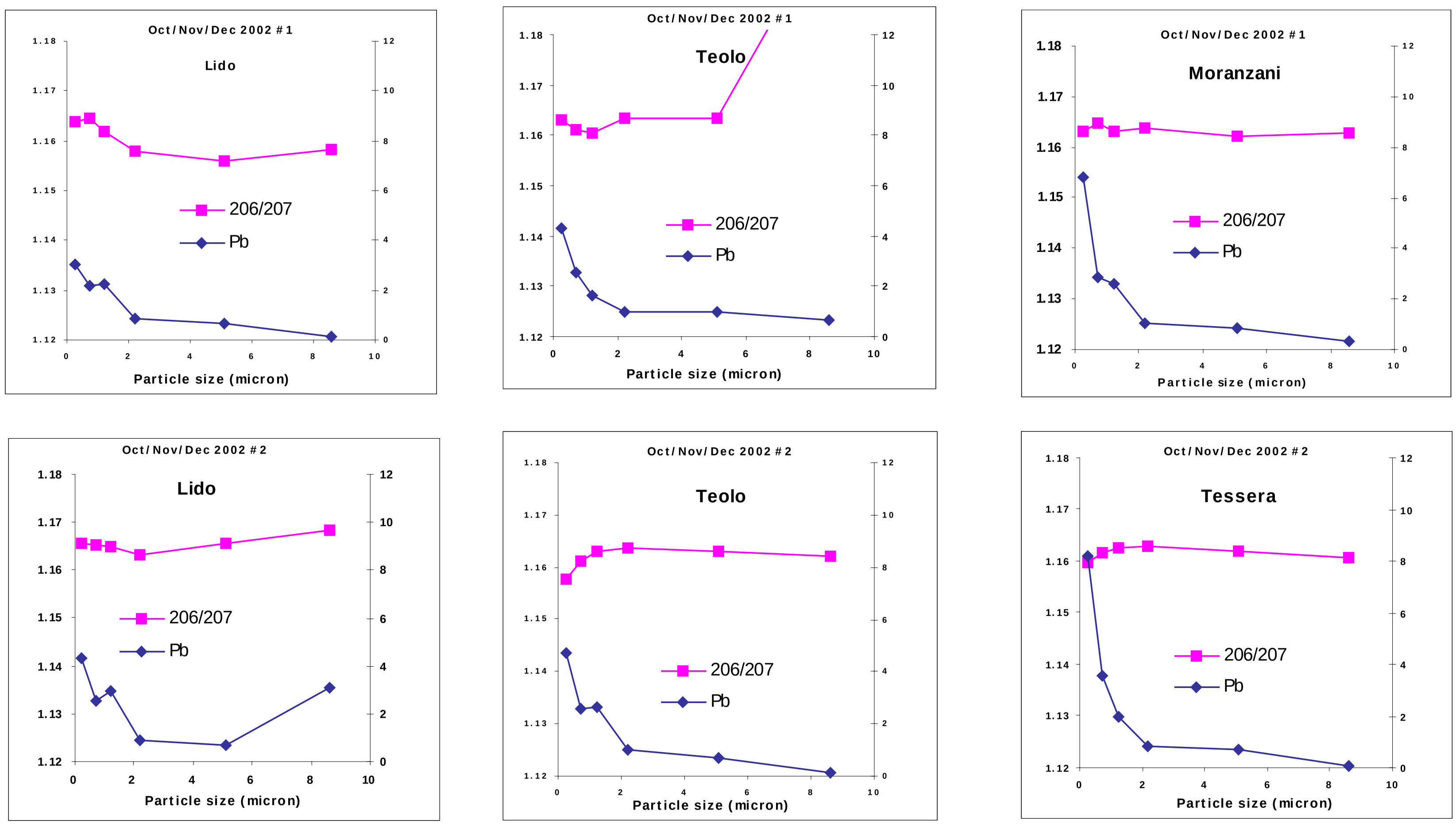

Fig. 4 – Comparison of Pb concentrations (right axe, ng/m^3) and $^{206}Pb/^{207}Pb$ isotopic ratios (left axe) at the locations shown during 8-22 October 2002 (Oct/Nov/Dec #1) and 28 November- 18 December 2002 (Oct/Nov/Dec #2). The data plotted are from Table 1c. Uncertainties are given in the table – they are 0.05% for the isotopic ratios and generally better than 5% for concentrations.

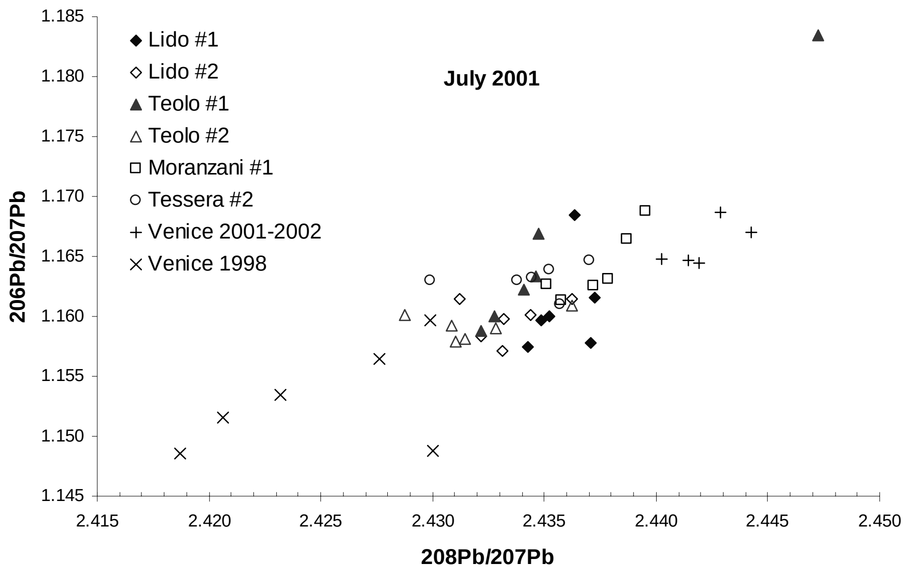

Fig. 5 – Isotopic composition of aerosols in the Venice region. Uncertainties are equal the average size of the symbols. For data Venice 1998 see Bollhofer and Rosman [2002].

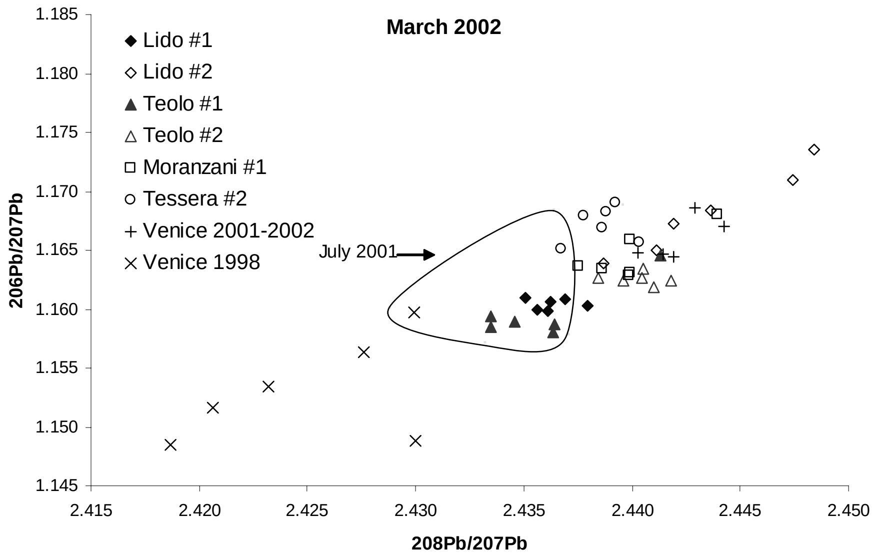

Fig. 6 – Isotopic composition of aerosols from different locations in the Venice region in March 2002. Uncertainties are not shown but equal the average size of the symbols. Samples collected on Venice during 2001-2002 are shown.

3.1 Pb Concentrations.

Reference to Tables 2 a, b and c and Figures 2, 3 and 4 show that the finer particles displayed higher concentrations. While the pattern of concentration with particle size was similar for all sites there was an unusually low concentration at Tessera during the second sampling period in March 2002. However, the general similarity in the patterns suggests that these patterns will not be useful as a means of classifying different sources of pollution.

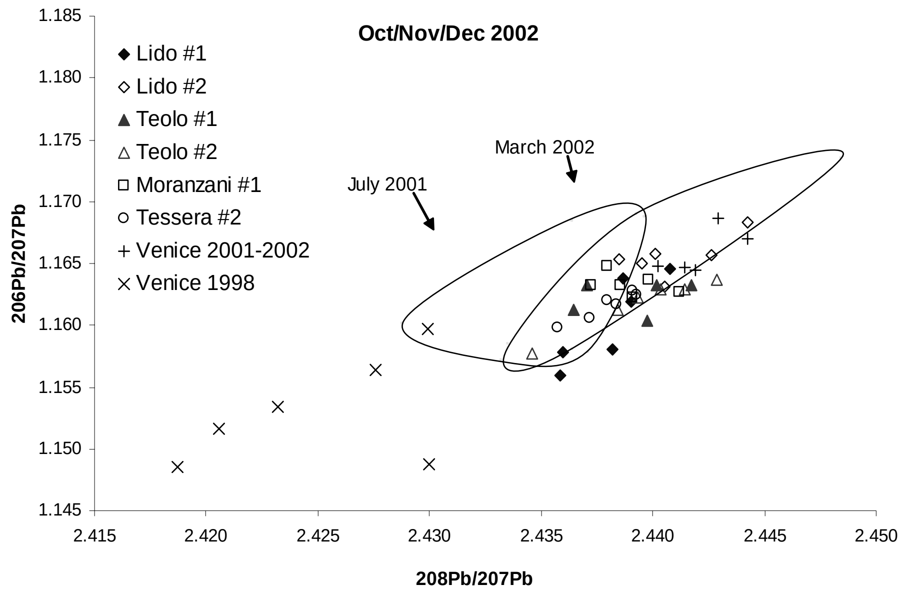

Fig. 7 – Isotopic composition of aerosols from different locations in the Venice region in Oct/Nov/Dec 2002. Not shown is the point (1.20, 2.46) from Teolo #1 Stage 1. Uncertainties are not shown but equal the average size of the symbols. Samples collected on Venice during 2001-2002 are shown.

The concentrations varied enormously from one week to the next. For instance, at Lido and Teolo in July 2001 the concentrations found in the second sampling period were double the first.

Measurements at Venice showed the Pb concentration falling from 10.4 ng/m^3 in April 2001 to 6 ng/m^3 one year later. Concentrations 3 years earlier were more than double these values at about 19 ng/m^3 [Bollhofer and Rosman, 2002] giving strong evidence of a declining Pb concentration in the region.

3.2 Isotopic Ratios.

There appear to be very few studies involving the measurement of Pb isotopes on different size aerosols. This aspect of the study may therefore be of considerable general interest.

Figures 2, 3 and 4 reveal some variations in the pattern of isotopic composition with particle size. The smaller size particles generally show the largest variations in isotopic composition. An exception is the change to the pattern that occurred in Teolo on two occasions, during the first sampling periods in July 2001 and in October 2002, where it was the larger particles that showed a large increase.

The three-isotope plots in Figures 5, 6 and 7 show significantly different isotopic compositions of the Pb at the different sites. In Fig. 6 (March 2002) the effect of particle size on the isotopic composition is relatively small compared with samples collected in July 2001. This increases the possibility of identifying the contributing sources. Further sampling at other times during the year will increase the potential of using the isotopic patterns to identify sources and hence the origin of the aerosols.

The samples collected at Venice during 2001 and 2002 had a similar isotopic composition. Samples collected in the same way in 1998 were significantly less radiogenic. This shift may be due to the reduction in the contribution from petrol Pb allowing the signatures of other sources to become more obvious. This has already been suggested in other studies [eg. Bollhofer and Rosman, 2002].

Conclusions.

This study reports the isotopic composition and concentration of Pb in the air in the Venice region. The aim was to investigate if isotopic signatures could be used to identify the origin of the aerosols.

We have used the powerful technique of isotope dilution coupled with high sensitivity thermal ionisation mass spectrometry to analyse the amount of Pb and its isotopic composition on aerosols with different sizes sampled from four different locations during July 2001, March 2002 and October/November/December 2002. One hundred and thirteen aerosol samples were analysed and numerous other measurements were made to ensure their reliability. Large variations in isotopic composition were detected in these aerosols and changes that might be associated with wind patterns and human activity were observed. A closer examination of these data coupled with published isotopic data on Pb sampled in nearby regions that will give a better understanding of the sources.

However, the interpretation could be significantly improved if samples of the likely candidate source material were to be collected and analysed. Because the source materials and the proportions of these sources are changing over time it is important not to delay in collecting such samples.

Acknowledgements.

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References.

Bellucci L.G., Raccanelli S., Frignani M., and Carraio C., 1999. Polychlorinated biphenyls in sediments of the Venice Lagoon and their toxicity with respect to other organic microcontaminants. *Organohalogen Comp*. 43, 295-298

Bollhofer A. and Rosman K.J.R., 2001. Isotopic source signatures for atmospheric lead: the northern Hemisphere. *Geochim. Cosmochim. Acta.* 65, 1727-1740

Bollhofer A., Chisholm W. and Rosman K.J.R., 1999. Sampling aerosols for lead isotopes on a global scale. *Anal. Chim. Acta.* 390, 227-235

Bollhofer A. and Rosman K.J.R., 2002. The temporal stability in isotopic signatures at selected sites in the Southern and Northern Hemispheres. *Geochim. Cosmochim. Acta.* 66, 1375-1386

Capodaglio G., Gambaro A., Varga A., Barbante C., and Cescon P., 2003. Trace Metals in the Aerosol of the Lagoon of Venice. *J. Phys. IV*, 107, 259-262

Gambaro A., Manodori L., Ferrari S., Toscano G., Varga A., Moret I. and Capodaglio G., 2002. Determination of trace elements and organic pollutants (PCB, PAH) in the Atmospheric aerosol of the Venice Lagoon, in *Scientific Research and Safeguardingof Venice*. ed Campostrini P., Istituto Veneto di Scienze, Lettere ed Arti, 469-475

Miller S.M., Green M.L., Depinto J.V., Hornbuckle K.C., 2001. Results from the Lake Michigan mass balance study: concentrations and fluxes of atmospheric polychlorinated biphenyls and *trans*-nonachlor. *Environ. Sci. Technol.* , 35, 278- 285

Jimenez B., Hernandez L.M., Eljarrat E., Rivera J. and Fossi M.C., 1998. Congener specific analysis of polychlorinated dibenzo-*p*-dioxins and dibenzofurans in crabs and sediments from the Venice and Orbetello Lagoons, Italy. *Environ. Sci. Technol*. 32, 3853

Webster R.K., 1960. Mass Spectrometric Isotope Dilution Analysis, in *Methods in Geochemistry*, eds A.A Smales, & L.D Wager, Intersc. Publ, London, 204 – 205

RESEARCH LINE 3.5
Quantity and quality of exchanges between lagoon and sea

WATER FLUXES IN VENICE LAGOON INLETS AND COASTAL CIRCULATION

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Riassunto.

Dal 2001 vengono misurate le correnti marine nelle bocche di porto della laguna di Venezia, per mezzo di ADCP installati sul loro fondale, unitamente alla corrente superficiale nell'area di mare antistante le bocche di porto, per mezzo di un radar HF. Queste misure hanno consentito di ottenere una dettagliata descrizione dello scambio d'acqua tra la laguna ed il mare aperto, ed i loro tempi di residenza in laguna. Il forzante mareale risulta essere il fattore dominante nello scambio d'acqua, mentre il contributo della variabilità non mareale è meno del 10%. La media annuale dei flussi scambiati è di 100 m^3/sec, in direzione uscente, corrispondente all'immissione di acque dolci in laguna. In questo lavoro viene pure descritta la risposta della laguna al vento locale. Inoltre è stato calcolato il tempo di rinnovo delle acque lagunari usando il metodo *tidal prism* che risultava dell'ordine di un giorno.

Abstract.

Several years of bottom-mounted ADCP measurements in inlets of the Venetian lagoon together with the HF radar surface current measurements in front of the lagoon enabled us to give a rather detailed description of the water exchange pattern between the lagoon and the open sea as well as residence times. Tidal forcing appears the most prominent in driving the lagoon – open sea water exchange, while the contribution of the non-tidal variability is less than 10%. Annual mean water exchange rate shows the net outflow of the order of 100 m^3/sec which corresponds to the freshwater discharge into the lagoon. Detailed description of the lagoon response to the most prominent local wind forcing is presented. Renewal time is calculated using tidal prism method and it resulted of the order of a day.

1. Introduction and data

The aim of this research was to estimate water fluxes through three inlets of the Venice Lagoon from experimental data, and to study their temporal variability on prevalent time scales, from tidal to a yearly one. The variability on scales different than tidal ones, called in the rest of the paper non-tidal variability, was correlated with the possible forcing functions, local or remote. These are more specifically wind, open

Adriatic seiches, freshwater discharge and others. These water exchange rates are basis for estimates of the water renewal times. In addition, the efficiency of the water renewal by the water exchange between the lagoon and the open sea depends also on the coastal current adjacent to inlets that has been studied using a high-frequency (HF) coastal radar.

Current measurements in inlets have been carried out using bottom-mounted Acoustic Doppler Current Profiler (ADCP) installed in each of the inlets. The frequency of these ADCP's was 600 kHz which resulted in one-meter vertical resolution. The position of instruments was chosen after having undertaken series of profilings with the ship-borne ADCP enabling us not only to obtain horizontal and vertical shears but also to calculate water flow rate in different phases of tides [Gačić *et al.*, 2002; Gačić *et al.*, 2005]. The linear regression was calculated between the total water flow rate and the vertically averaged current in different points of the transect. Subsequently the bottom-mounted ADCP was positioned at the point where the linear correlation between the water flow rate and the vertically averaged current was maximal. This way time-series of the water flow rate was reconstructed from ADCP recordings, using the linear relationship between currents and the water flow rates. Sea-level data were also available from tide-gage stations positioned at two stations in the lagoon interior (Chioggia – southern end of the lagoon and Saline – northern part of the lagoon). Wind data were recorded from the oceanographic tower "Acqua Alta" at the height of 15 m above the mean sea level. Rainfall data originated from the meteorological station in the City of Venice at the CNR Institute of Marine Research (ISMAR).

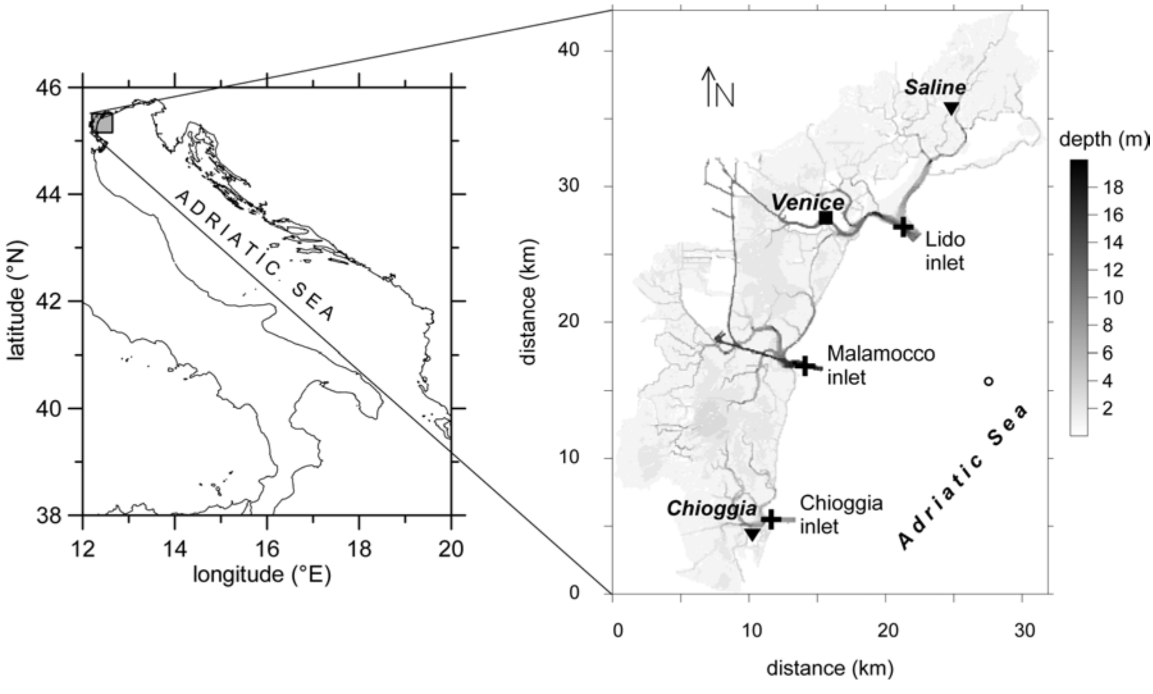


Fig. 1 – The study area. ADCP mooring locations are denoted by crosses, tide gauge stations by triangles, while the position of Acqua Alta Tower is denoted by open circle.

2. Results and discussion.

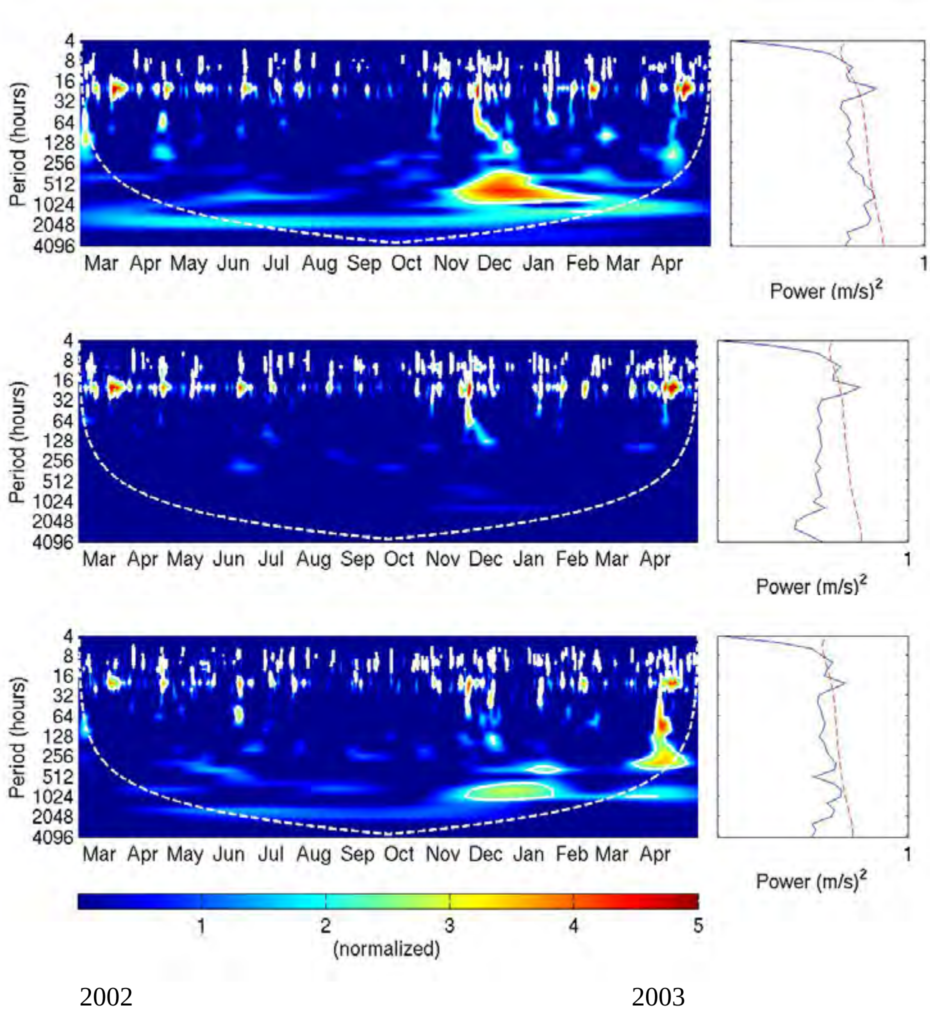
Continuous measurements started mid-June 2001 in Lido and Malamocco inlets, while in Chioggia the ADCP was positioned around mid-February 2002. There, real-time data transmission system has been in function as well (see web site http:\\doga.ogs.trieste.it). Data analysis is carried out for a period when ADCP's in all three inlets were functioning.

Characteristics of tidal oscillations and their relative contributions to the water flow through lagoon inlets were obtained applying the harmonic analysis, while the influence of other forcing functions was studied using both wavelet and power spectra analysis. Moreover, we identified some extreme events of strong winds or high tide and for those situations the relationship between inlet flows, sea-level and its slope was studied in details.

More than 98% of the flow variance is associated with the flow oscillations along the longitudinal inlet axis. Harmonic analysis showed that in average more than 90% of the flow variance is related to the tidal variability considering seven principal diurnal and semidiurnal tidal constituents. Meteorological forcing becomes important only during isolated episodes of the strong winds. Tidal currents are prevalently of a semidiurnal type, and constituents M2 and S2 explain more than 50% of the flow variance. The most important diurnal constituent K1 explains only 10% of the flow variance. Tidal oscillations of sea level are slightly different having M2 and K1 as the two most important constituents. It was shown that the tidal flow between the lagoon and open sea, for currents weaker than 0.5 m/sec, is controlled by the pressure gradient term that balances the local acceleration term. The pressure gradient between the lagoon and the open sea is due to the sea-level differences associated to the time-lag in tidal sea-level oscillations being equal for all major constituents. For currents stronger than 0.5 m/sec the bottom friction becomes important in controlling the tidal flow [Gačić *et al.*, 2004].

Considering the strong current polarization along the inlet longitudinal axes, further analyses was limited to the component along that axis. Positive values were attributed to the outflow. Also, axes of major and minor variance of the wind was determined and it was demonstrated that the major variance axis corresponds rather well with the bora direction, while the minor variance axis is parallel to the sirocco direction.

Non-tidal flow time-series were obtained by subtracting from the hourly data all tidal constituents having signal-to-noise ratio larger than one. Subsequently wavelet analysis was applied that showed that non-tidal variations are mainly due to the Adriatic seiches (diurnal of the period of about 22 hours and semi-diurnal ones of the period of about 11 hours). Seiches are more frequent during autumn and winter period than during the rest of the year (Fig. 2). Chioggia and Lido inlets show also the presence of strong variations at low frequencies (time scales of several tens of days) occurring mainly in November and December. These variations are not so prominent in the Malamocco inlet. Wavelet analysis of the two wind components shows the presence of the variability in the wind field on the same time scale. From the correlation between the wind with a speed over 5 m/sec for various directions and the axial water flow it was shown that the correlation coefficient reaches maximum for the E and NE wind directions in either Lido or Chioggia. The correlation coefficient is negative for Lido and positive for Chioggia suggesting that bora induces an inflow in Lido and an outflow in Chioggia (Fig. 3).



(a)

(b)

(c)

Fig. 2 – The non-tidal wavelet spectra of the flow in Lido (a), Malamocco (b) and Chioggia (c) [Gačić *et al.*, 2004].

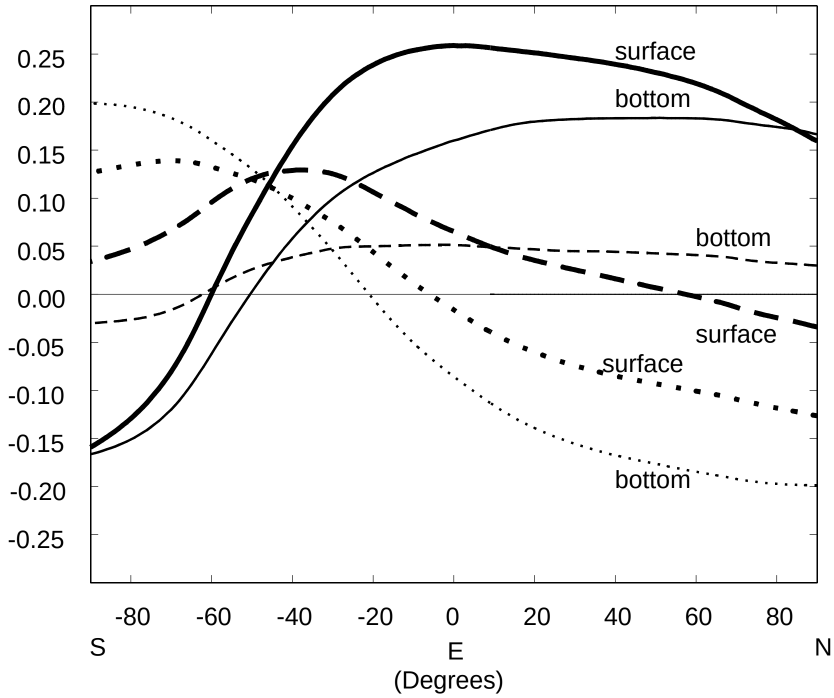


Fig. 3 – Rank correlation function between the wind for various directions (wind speed over 5 m/sec) and the surface and bottom flows at three inlets (Lido – continuous line, Malamocco – dashed line and Chioggia – dotted line) from Gačić *et al.* [2004].

This was explained in terms of the longitudinal sea-level slope due to the bora wind set-up. In that case the interior sea-level at the southern end of the lagoon is higher than the outside sea-level generating an outflow in Chioggia. At the same time at the northern lagoon corner the sea-level inside the lagoon is lower than at the open sea causing an inflow through Lido inlet. In fact from the experimental data, it was shown that the wind blowing from northeast generates higher sea-level at the southern end of the lagoon than at the northern one. Viceversa, the wind blowing from southwest induces sea level higher at the northern part of the lagoon than at the southern one (see Fig. 4).

Water flux rates estimated from the vertically averaged currents show that the total flux rate (sum of all three inlet fluxes) reaches 20.000 m^3/sec. Subsequently, applying the tidal prism method, residence or flushing time was calculated and it is of the order of a day. This suggests that the Venice Lagoon exchanges the water with the open sea very quickly; faster than similar water bodies of the World Ocean [David and Kjerfve, 1998; Kjerfve *et al.*, 1996].

Mean annual fluxes through lagoon inlets are characterized by an inflow in Lido of about 50 m^3/sec, the outflow in Chioggia approximately of the same amount, while Malamocco shows an average annual outflow of about 100 m^3/sec (Fig. 5). Thus, according to our data Venice Lagoon in average discharges annually about 100 m^3/sec into the open sea. This amount corresponds very well with the estimated sum of the riverine inflow in the lagoon of about 40 m^3/sec and the industrial water discharge of about 60 m^3/sec.

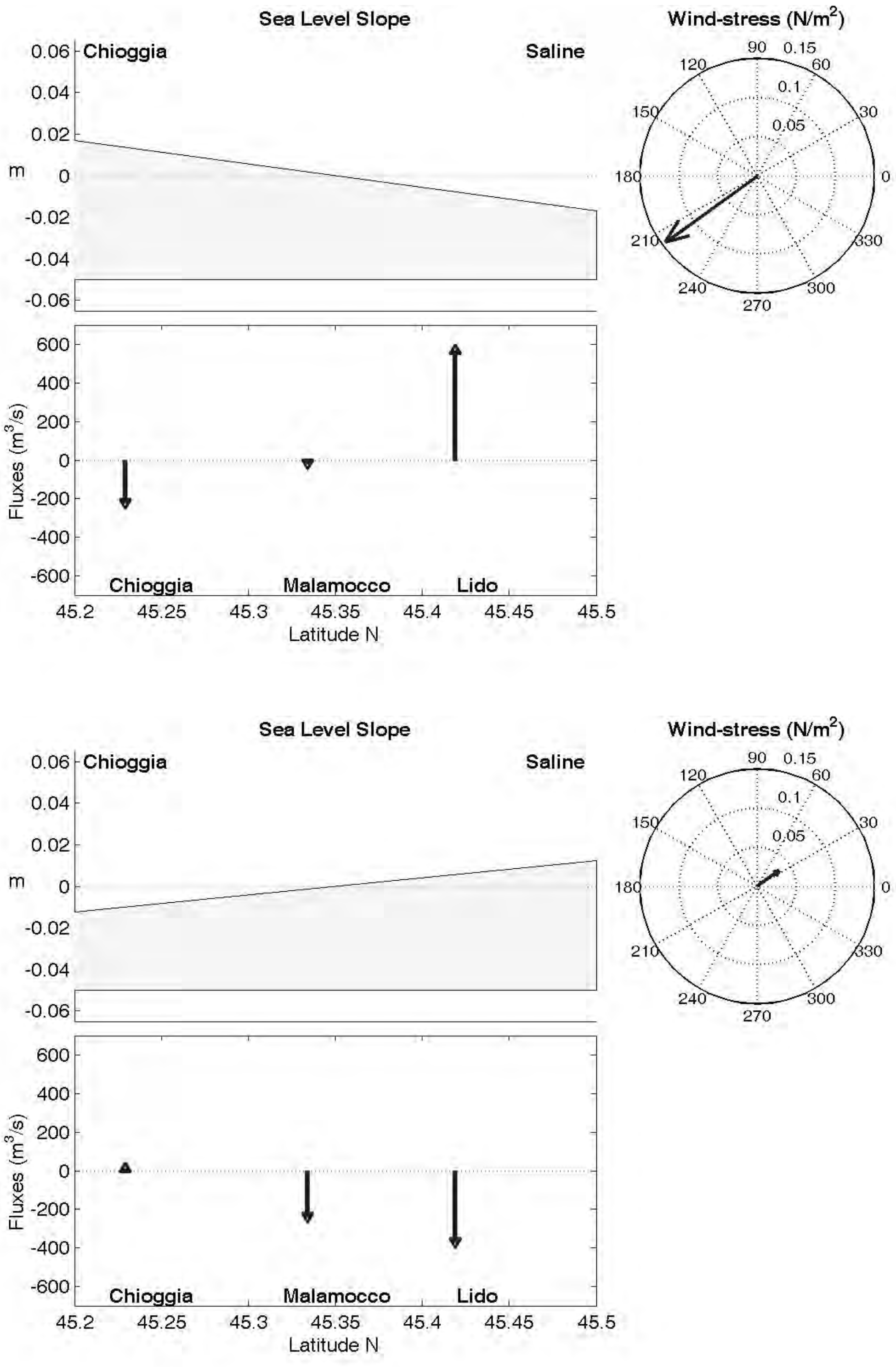


Fig. 4 – Wind and the longitudinal sea-level slope in the lagoon (Saline – northern part of the lagoon, Chioggia – southern part of the lagoon) for 9 December 2002 (upper panel) and 26 November 2002 (lower panel).

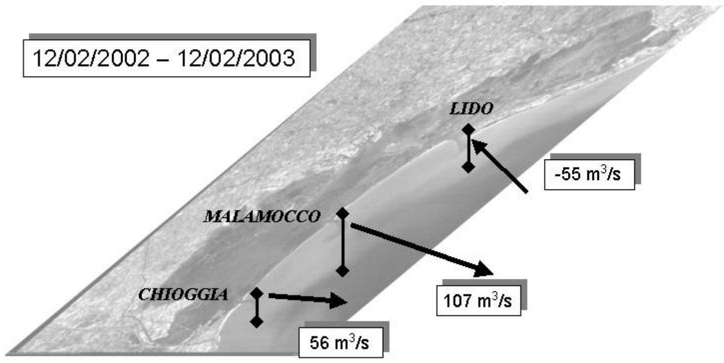


Fig. 5 – Mean annual water flux in three lagoon inlets. Negative values stay for an inflow.

Efficient renewal of the lagoon water by tidal flow depends also on the water flow pattern in the coastal area outside the lagoon. Thus, coastal flow outside the lagoon has been studied in some details. For this purpose we used high frequency (25 MHz) coastal radar (CODAR) with two antennas positioned at islands of Lido and Malamocco. With this antennas' configuration the area adjacent to the Malamocco inlet 15 km wide was covered. The spatial resolution was 750 m and measurements were carried out in the period from 1 November 2001 until 31 October 2002 [Kovačević *et al.*, 2002].

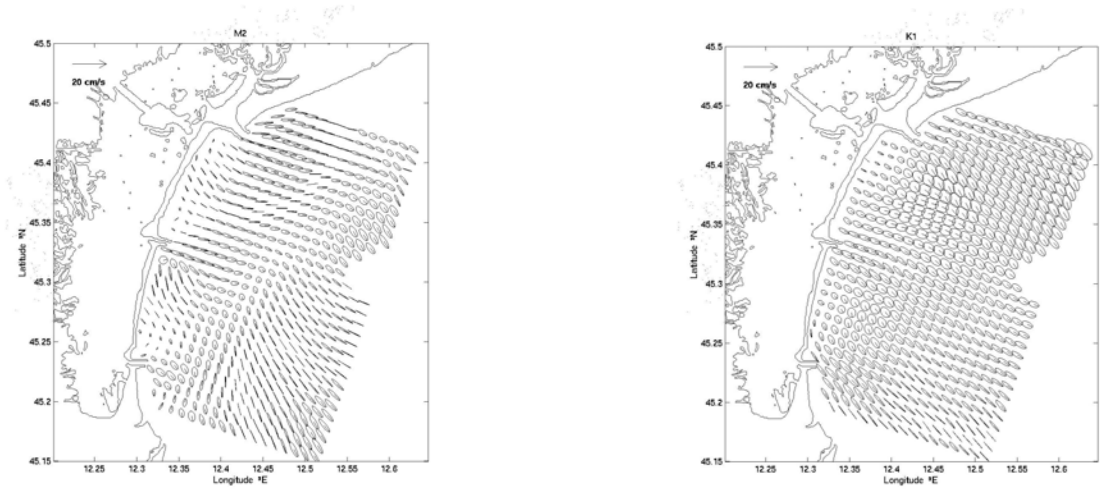


Fig. 6 – Tidal ellipses for the M2 and K1 tidal constituents.

Harmonic analysis was applied at every single experimental point and the results show that the influence of tidal currents in inlets extends in the coastal area 4-5 km adjacent to inlets. This influence is evident from the ellipse orientation and their amplitudes (Fig. 6).

Moreover, in the vicinity of inlets semidiurnal tides prevail as it is the case of inlet currents. Moving toward open sea the diurnal tidal currents become prevalent. Monthly average flow was calculated and it appears that strongest coastal flow occurs in

November and December with the southward current of about 20 cm/sec [Kovačević *et al.*, 2004]. This flow pattern makes part of the Adriatic general circulation. A coastal jet characterizes the flow and in some months it is detached from the coast.

In monthly mean current fields and even more prominent in non-tidal hourly average flow, small-scale eddies were evidenced. These features are present in situations with weak winds or in calm weather conditions [Paduan *et al.*, 2004]. Strong winds homogenize horizontally current field (Fig. 7). During the stratified season in current field inertial oscillations are strongly present with energy increasing with the distance from the coast. Winter season is characterized by the low-frequency response of current field to the wind forcing with inertial oscillations being negligible.

Year-to-year variations of the coastal flow were also evidenced since more than one year of HF radar data are available. It was noticed that the summer mean flow (June – September) in 2002 was characterized by the presence of a stronger jet than that in summer 2003 (Fig. 8). Comparison of the monthly rainfall for these four months between the two years reveals that the summer 2003 was extremely dry and thus probably the presence of the freshwater in the coastal area was much weaker. This then resulted in a much weaker currents (Fig. 9) suggesting that the mean coastal flow is mainly driven by the pressure gradient due to the presence of the freshwater in the coastal area.

Also, fluctuational kinetic energy was much stronger when the mean flow was more prominent probably due to a presence of stronger inertial and other transient motions in the current field.

Conclusions.

In this paper we summarize characteristics of the Venetian lagoon inlets' flow and water exchange features based on long-term bottom-mounted ADCP current measurements as well as on surface current monitoring in front of the lagoon using HF radar. The measurement duration enabled us to determine relative contributions of the flow variations on time scales from diurnal (tides and seiches) up to seasonal and even interannual ones. HF radar measurements with hourly frequency offer a possibility to obtain spatial structure down to sub-mesoscale features associated to both tidal and non-tidal coastal flows. Inlets' water flow tidal variations influences outside current field pattern (tidal ellipse orientation and major axis magnitudes) at a distance of the order of four to five kilometres. Spatial resolution of 750 m by HF radar made it possible to resolve and document the occurrence of sub-mesoscale eddies having typical length scales of about three to four kilometres. Also, seasonal variations of the coastal currents as shown from the monthly mean currents, was discussed. Year-to-year changes of the coastal flow seems to be correlated with the rainfall rate and the presence of the freshwater in the coastal area. Apart from determining the importance of tidal forcing in the lagoon-open sea exchange (more than 90% of flow variance explained by tides), detailed analysis of the non-tidal low-frequency flow was carried out. Generally, coherent and out-of-phase variations of Lido and Chioggia inlets' flow at time scales of the order of weeks to months were explained in terms of the wind forcing generating longitudinal sea-level slope in the lagoon interior. More specifically, bora generates a north-south slope and strengthens the inflow in Lido and outflow in Chioggia, opposite to what is generated by sirocco. Annual mean water exchange shows a net outflow of the order of 100 m^3/sec which equals the freshwater discharge into the lagoon and varies on a year-to year basis in parallel to the rainfall. Residence or flushing time was determined applying tidal prism method and it resulted rather short (of the order of a day) comparing to other similar water bodies.

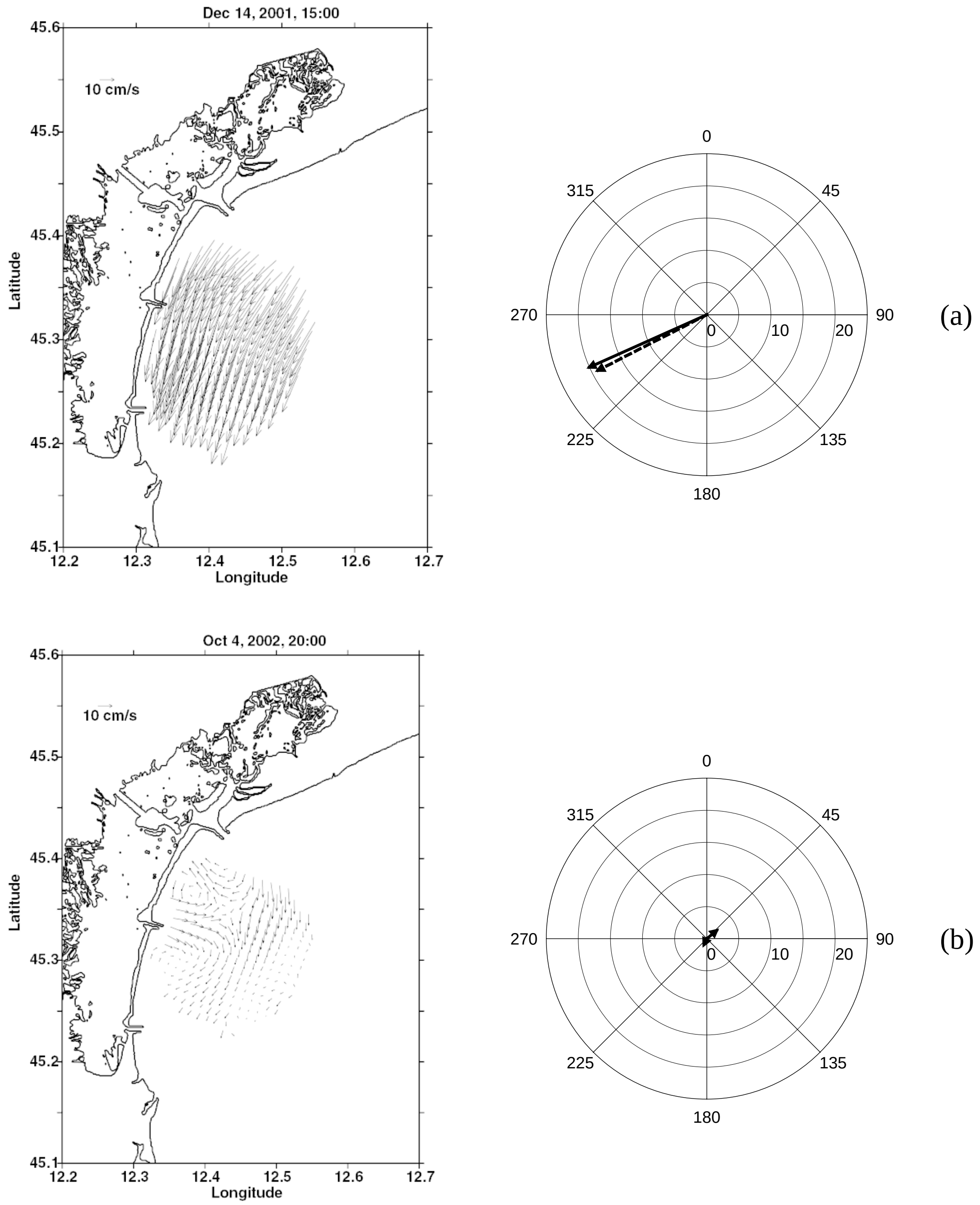


Fig. 7 – Surface non-tidal current field in a situation characterized by a strong wind (a) and in calm weather conditions (b). Average daily and hourly wind vectors are shown at the left portion of the figure. Wind-speed scale is in m/s.

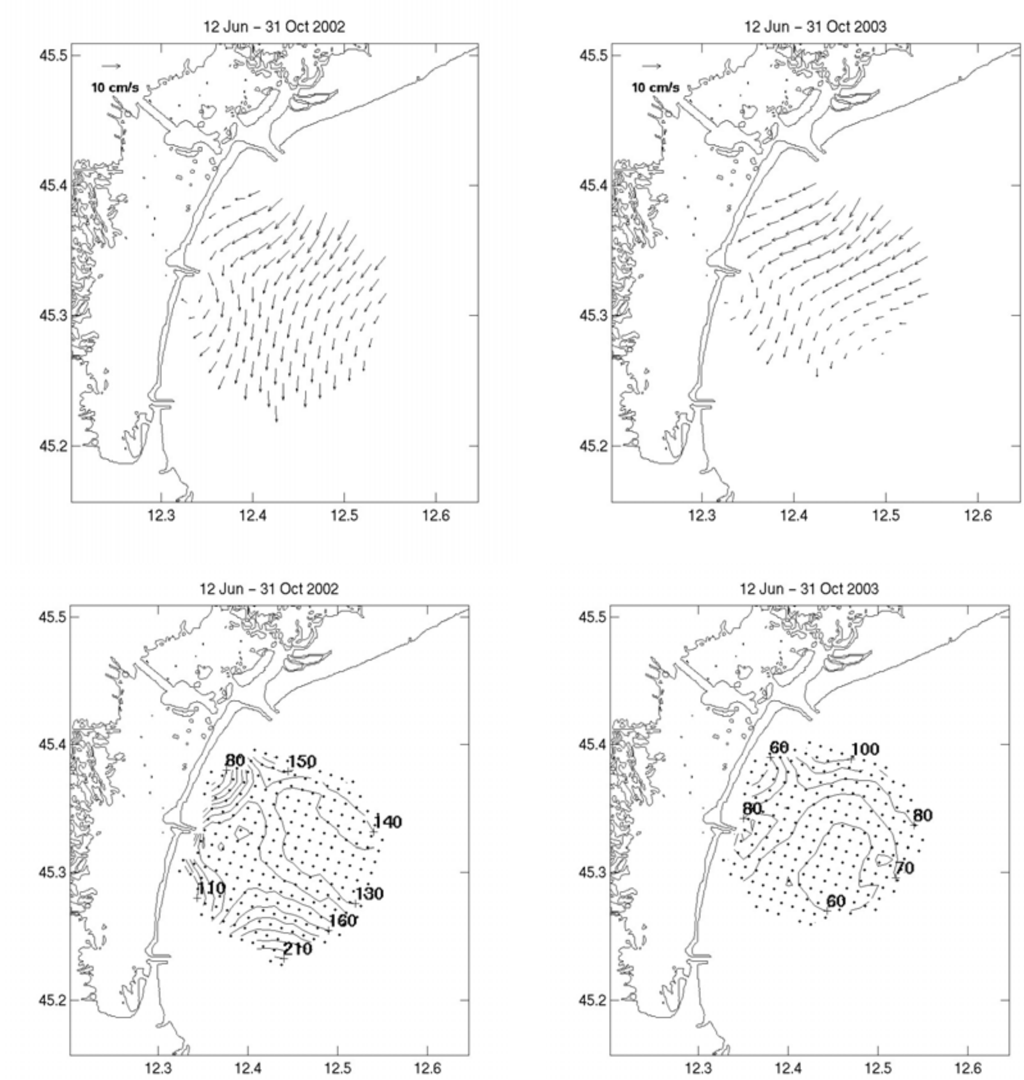


Fig. 8 – Summer (June - October) mean surface flow (upper part of the figure) and kinetic energy (in cm^2/s^2) of the current field (lower part of the figure) for the years 2002 and 2003.

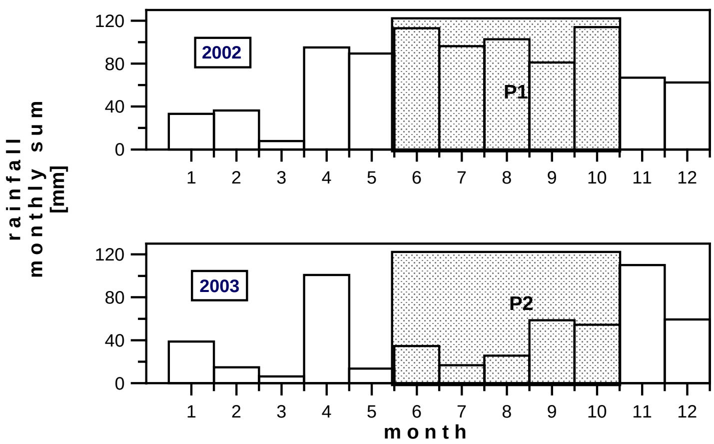


Fig. 9 – Monthly rainfall for the years 2002 and 2003. The period for which mean surface flow is presented, is marked by the square.

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References

David L.T., Kjerfve B., 1998: Tides and currents in a two-inlet coastal lagoon: Laguna di Terminos, Mexico. *Continental Shelf Research*, 18, 1057-1079

Gačić M., V. Kovačević, A. Mazzoldi, J. Paduan, F. Arena, I. Mancero Mosquera, G. Gelsi and G. Arcari, 2002: Measuring Water Exchange between the Venetian Lagoon and the Open Sea. EOS, Transactions, American Geophysical Union, 83, 20, 217-222

Gačić M., I. Mancero Mosquera, V. Kovačević, A. Mazzoldi, V. Cardin, F. Arena and G. Gelsi, 2004: Temporal variations of water flow between the Venetian Lagoon and the open sea. Journal of Marine Systems, 33-48

Gačić M., Kovačević V., I. Mancero Mosquera, A. Mazzoldi, S. Cosoli, 2005: Water fluxes between the Venice Lagoon and the Adriatic Sea. *Flooding and Environmental Problems of Venice and Venice Lagoon: State of Knowledge*, Cambridge University Press, London, in press. Kjerfve, B., Schettini, C.A.F., Knoppers, B., Lessa, G., Ferriera, H.O., 1996: Hydrology and salt balance in a large, hypersaline coastal lagoon: Lagoa de Araruama, Brazil. Estuarine, Coastal and Shelf Science, 42, 701-725

Kjerfve B., Schettini C.A.F., Knoppers B., Lessa G., Ferriera H.O., 1996: Hydrology and salt balance in a large, hypersaline coastal lagoon: Lagoa de Araruama, Brazil. Estuarine, Coastal and Shelf Science, 42, 701-725

Kovačević V., Gačić M, Mancero Mosquera I., Mazzoldi A. and Marinetti S., 2002. Current structure in front of the Lagoon of Venice as derived from the Coastal HF Radar data. In: "*Campostrini P. (ed.), Scientific Research and safeguarding of Venice, CORILA Research Program 2001 results*", Istituto Veneto di Scienze, Lettere ed Arti, Venezia, 477-487

Kovačević V., Gačić, M., I. Mancero Mosquera, A. Mazzoldi and S. Martinetti, 2004: HF radar observations in the Northern Adriatic: Surface current field in front of the Venetian Lagoon. Journal of Marine Systems, 95-122

Paduan J.D., Gačić M., Kovačević V., I. Mancero Mosquera and A. Mazzoldi, 2004: Vorticity patterns offshore of the Venetian lagoon from HF radar observations. Scientific Research and Safeguarding of Venice, Research Programme 2001-2003, Istituto Veneto di Scienze, Lettere ed Arti, Vol. II, 361-372

QUALITY AND QUANTITY OF EXCHANGES BETWEEN THE LAGOON AND SEA: BIOGEOCHEMICAL PARAMETERS

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Riassunto.

Nell'ambito del Primo Programma di Ricerca CORILA 2000-2003 – linea 3.5 "Qualità e Quantità degli Scambi tra Laguna e Mare", l'unità operativa appartenente al WP2 "Misura dei Parametri Biogeochimici", coordinata dall'ISMAR/CNR di Venezia, si è interessata allo studio degli scambi di materiale disciolto e particellato, organico ed inorganico, di plancton, di microinquinanti e di biomarkers molecolari che avvengono tra la laguna di Venezia ed il mare Adriatico. Per considerare la variabilità di tali parametri a diversa scala temporale, sono state condotte campagne sperimentali su ciascuna bocca, con misure e campionamenti ad alta frequenza per più cicli di marea, ripetuti per quattro diverse situazioni stagionali. A completamento, sono stati effettuati campionamenti mensili, per ottenere un quadro più esauriente possibile delle graduali variazioni delle proprietà biogeochimiche alle bocche. I campioni raccolti sono stati analizzati presso i laboratori dell'ISMAR-CNR di Venezia, del Dipartimento di Biologia dell'Università di Padova, dell'ICRAM di Chioggia, del College of Marine Sciences di St. Petersburg, USA. I risultati delle analisi e dei conteggi biologici sono stati accoppiati con i dati di corrente misurati dall'Istituto Nazionale di Oceanografia e Geofisica Sperimentale – OGS di Trieste, ottenendo in tal modo stime stagionali dei flussi e degli scambi tra la laguna di Venezia e la fascia costiera del mare Adriatico. In questo contributo vengono riportati i risultati relativi ad alcuni parametri idrochimici; quelli relativi a plancton, microinquinanti e biomarkers molecolari vengono discussi, su questo volume, in lavori separati. Le concentrazioni dei parametri esaminati hanno evidenziato una variabilità molto ampia e di natura diversa a seconda delle scale temporali considerate: per alcuni di essi (materiale sospeso, pH, ossigeno disciolto e salinità) le variazioni a breve scala temporale (mareale) erano della stessa entità di quelle a scala annuale, mentre altri, principalmente legati alla componente biologica, risultavano maggiormente influenzati dal ciclo stagionale. I flussi alle bocche hanno fornito risultati molto eterogenei, dipendendo dalle concentrazioni e dalle portate istantanee. I bilanci dei nutrienti disciolti mostrano come questi vengano generalmente

esportati dalla laguna verso il mare in tutte le stagioni; in particolare, è stato osservato un accordo tra i trend stagionali dell'azoto e del silicio, ed un comportamento poco omogeneo del fosfato. Al contrario, bloom fitoplanctonici, verificatisi nelle aree lagunari, hanno portato ad un'inversione dei bilanci per azoto e silicio attraverso la bocca del Lido, con un import dalle acque costiere verso la laguna, fenomeno peraltro già descritto negli anni '90. In primavera, il materiale particellato ha mostrato i valori più elevati di export, a causa di un generale aumento del metabolismo lagunare, con conseguente maggior produzione di particellato, sia vivente che detritico. Il materiale sospeso ha evidenziato un'esportazione generalizzata verso il mare, dimostrando come nella laguna di Venezia i fenomeni di erosione prevalgano su quelli di sedimentazione. Unica eccezione era rappresentata da un cospicuo apporto di sospeso dal mare durante un fenomeno di acqua alta, apporto determinato dall'ingressione di acque torbide di deflusso costiero, sospinte in laguna da forti venti di bora.

Abstract.

Exchanges and fluxes of dissolved and particulate matter, both organic and inorganic, plankton, micropollutants and anthropogenic biomarkers between the Venice Lagoon and the Adriatic Sea have been studied in the frame of the CORILA 2000-2003 multidisciplinary Research Programme under the co-ordination of ISMAR/CNR (WP 2 "Biogeochemical Parameters"). To give a quantitative picture of their annual variability on different time-scales and to estimate the tide effect on the studied parameters, samplings have been carried out in spring tide, in order to maximise the fluxes. In particular: i) to assess the short-time variability and the exchange rate, intensive seasonal campaigns were carried out with high-frequency measurements and samplings at each inlet (every 3 h), following 8 tidal cycles; ii) to follow the gradual variations between seasons, surveys were performed monthly by simultaneous samplings at the three inlets, in high and low tide. Results related to dissolved and particulate matter are reported in this contribution, while plankton, micropollutants and molecular biomarkers are discussed elsewhere in this volume. The concentrations of the studied parameters were widely variable, according to the temporal scale: statistical analyses showed that some hydrological properties, such as suspended matter, pH, dissolved oxygen and salinity had more pronounced variations at tidal scale (short-term); others, mainly associated to the biological component, were more influenced by seasonality (long-term). To estimate fluxes and exchanges between lagoon and sea, chemical and biological analyses were coupled with current data. Fluxes were very heterogeneous, depending on discharge and on instantaneous concentrations. Nutrient budgets showed a general export from the lagoon towards the sea; both nitrogen and silicate trends were in accordance, while phosphate sometimes behaved differently. During an extreme flooding event at Lido, all dissolved nutrients showed a heavy export from the lagoon. Conversely, in concomitance with phytoplankton blooms in the Lagoon, budget calculations pointed out an import from the sea especially through the Lido inlet, because of the strong biological uptake in the inner areas. Particulate matter related to the biogenic fraction was exported from the lagoon mainly in spring, when the lagoon metabolism increased, while in some situations, when organisms were more abundant in coastal waters, as in summer, the organic particulate fraction was imported from the sea. Total suspended matter was generally exported from the lagoon, highlighting again that

erosion dominated over deposition processes in the Venice lagoon. Nevertheless, during extreme flooding events caused by strong E-N-E winds, contrary to what expected, an import of inorganic seston from the sea, as a contribution by the northern rivers and by the coastal resuspension, was pointed out.

1. Introduction.

Recently several considerations have been done about the modification of the existing fluxes between lagoon and sea that the construction and utilisation of the mobile gates, approved by the Italian Government to defend the city against the "acqua alta", could produce. Until now, all existing data about the lagoon – sea fluxes derive from sporadic measurements at the inlets made by private and public institutions, not framed into a structured experimental design.

Launching the research line 3.5 "Quantity and quality of exchanges between lagoon and sea", the CORILA Research Programme 2000-2003 contributed to filling this gap. In this frame, a detailed multidisciplinary study on fluxes between lagoon and sea of dissolved and particulate matter, both organic and inorganic, plankton, micropollutants and molecular biomarkers, was carried out under the co-ordination of the Institute of Marine Sciences (ISMAR/CNR) of Venice (WP2 "Biogeochemical Parameters").

Some preliminary results on hydrology, seston and plankton appeared in previous works [Bianchi *et al.*, 2002; Bianchi *et al.*, 2004a; 2004b; Bernardi Aubry and Acri, 2004]. In this paper, estimates of variability of the examined parameters at different time scales, as well as seasonal fluxes and budgets between the Venice lagoon and the Adriatic sea, are reported.

2. Materials and methods.

To give an exhaustive picture of the variability and quantities involved at different time-scales and to estimate the effect of tide on the biogeochemical parameters flowing in/out the lagoon of Venice, measurements and samplings were carried out seasonally at the inlets of Lido, Malamocco and Chioggia during spring tides, in order to maximise the tide effects. The following strategy was adopted: i) short-time variability and exchange rate were studied during intensive seasonal campaigns, with high-frequency measurements and samplings (every 3 hours), for a total of 48 hours (8 tidal cycles , 17 samples); ii) monthly variations were assessed by simultaneous samplings at the three inlets, at maximum and minimum tide level, in order to see the gradual modifications of the hydrological and biological properties with time.

The sampling stations were in the centre of each inlet, in correspondence with a bottom-moored acoustic Doppler current profiler (ADCP), which data were generously provided by OGS of Trieste [Gacic *et al.*, this volume] (Fig. 1).

Results are related to the period March 2001 - May 2003. Due to logistic problems, this study started at Lido, then proceeded at Malamocco and Chioggia. The inlets were sampled simultaneously in summer (August 2002).

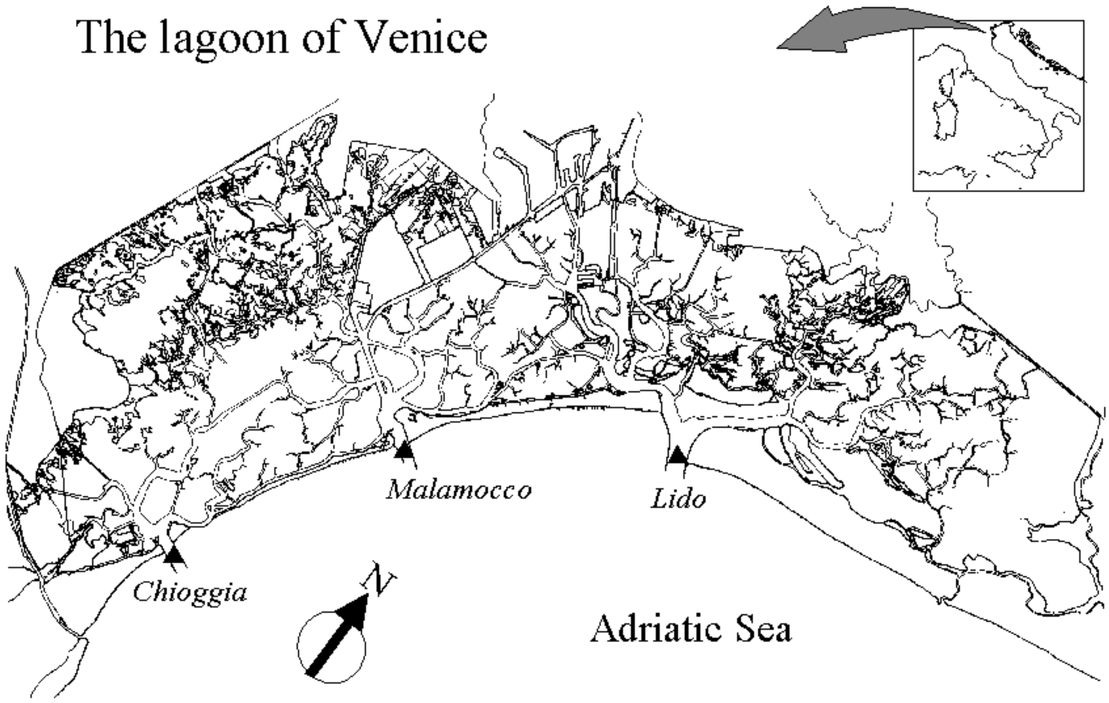

Fig. 1 – The Lagoon of Venice: sampling stations are indicated by triangles.

Measurements and samplings include:

- a total of 32 monthly observations (16 flood + 16 ebb tide) for the Lido inlet, 28 for Malamocco and Chioggia inlets (during the intensive campaigns, monthly surveys were not carried out) (Tab. 1);
- six seasonal intensive campaigns at Lido: winter and spring, as preliminary tests (March 2001, PRO02, and May 2001, PRO03), autumn (November 2001, STG01), winter (February 2002, STG02), spring (May 2002, STG03), summer (August 2002, STG04) (Tab. 2);
- four seasonal intensive campaigns at Malamocco and Chioggia: summer (August 2002, STG04), autumn (November 2002, STG05), winter (January 2003, STG06) and spring (May 2003, STG07) (Tab. 2).

Hydrological measurements on the water column were performed by multiparametric probe casts from surface to bottom, discrete samplings by Niskin bottles deployed at a fixed depth (-5 m), an intermediate level considered as a good integration on the water column after trials carried out in the test periods (PRO02 and PRO03). Samplings took into account the following parameters:

- transparency, with a Secchi disk;
- temperature and salinity, with multiparametric probes (Idronaut 801 and Hydrolab Datasonde4), calibrated against a Guildline Autosal 8400B laboratory salinometer;
- transmittance, as percent of the incident beam, by a Sea Tech 25-cm path length transmissometer, connected to a multiparametric probe;
- dissolved oxygen, according to Winkler's titration method [Strickland and Parsons, 1972];

Tab. 1 – Monthly surveys, coded as Link.

Campaign	*Date*	*Boats*	*Inlets*	*Variables*
LINK01	4-5 Jul 2001	M/B Mysis	Lido, Malamocco, Chioggia	Hydrology, chemistry, particulate, plankton
LINK02	3-4 Aug 2001	M/B Mysis	Lido, Malamocco, Chioggia	Hydrology, chemistry, particulate, plankton
LINK03	17-18 Sep 2001	M/B Mysis	Lido, Malamocco, Chioggia	Hydrology, chemistry, particulate, plankton
LINK04	17 Oct 2001	M/B Mysis	Lido, Malamocco, Chioggia	Hydrology, chemistry, particulate, plankton
LINK05	15 Nov 2001	N/O U. D'Ancona, M/B Mysis	Lido, Malamocco, Chioggia	Hydrology
LINK06	17 Dec 2001	M/B Mysis	Lido, Malamocco, Chioggia	Hydrology, chemistry, particulate, plankton
LINK07	11 Jan 2002	M/B Mysis	Lido, Malamocco, Chioggia	Hydrology, chemistry, particulate, plankton
LINK08	27 Feb 2002	M/B Mysis	Lido, Malamocco	Hydrology (samplings interrupted)
LINK09	28 Mar 2002	M/B Mysis	Lido, Malamocco, Chioggia	Hydrology, chemistry, particulate, plankton
LINK10	23 Apr 2002	M/B Mysis	Lido, Malamocco, Chioggia	Hydrology, chemistry, particulate, plankton
LINK11	11-12 Jun 2002	M/B Mysis	Lido, Malamocco, Chioggia	Hydrology, chemistry, particulate, plankton
LINK12	9-10 July 2002	M/B Mysis	Lido, Malamocco, Chioggia	Hydrology, chemistry, particulate, plankton
LINK13	19-20 Sep 2002	M/B Mysis	Lido, Malamocco, Chioggia	Hydrology, chemistry, particulate, plankton
LINK14	21 Oct 2002	M/B Mysis	Lido, Malamocco, Chioggia	Hydrology, chemistry, particulate, plankton
LINK15	18 Dec 2002	M/B Mysis	Lido, Malamocco, Chioggia	Hydrology, chemistry, particulate, plankton
LINK16	17 Mar 2003	M/B Henetus	Lido, Malamocco, Chioggia	Hydrology, chemistry, particulate, plankton

Tab. 2 – Seasonal intensive campaigns.

Campaign	*inlet*	*season*	*Starting date*	*starting time*	*Stopping date*	*stopping time*
PRO02 – test	Lido	winter	07/03/2001	8:00	09/03/2001	12:00
PRO03 – test	Lido	spring	23/05/2001	12:00	24/05/2001	14:00
STG01	Lido	fall	14/11/2001	10:00	16/11/2001	11:00
STG02	Lido	winter	26/02/2002	10:00	28/02/2002	12:00
STG03	Lido	spring	10/05/2002	22:00	12/05/2002	22:00
STG04	Lido	summer	05/08/2002	20:00	07/08/2002	22:00
STG04	Malamocco	summer	05/08/2002	20:00	07/08/2002	22:00
STG04	Chioggia	summer	05/08/2002	20:00	07/08/2002	22:00
STG05	Malamocco	fall	04/11/2002	16:00	06/11/2002	18:00
STG05	Chioggia	fall	04/11/2002	16:00	06/11/2002	18:00
STG06	Malamocco	winter	30/01/2003	16:00	01/02/2003	18:00
STG06	Chioggia	winter	30/01/2003	16:00	01/02/2003	18:00
STG07	Malamocco	spring	13/05/2003	14:00	15/05/2003	16:00
STG07	Chioggia	Spring	13/05/2003	14:00	15/05/2003	16:00

- dissolved nutrients (ammonia, nitrites and nitrates, orthophosphates and orthosilicates), filtered through Whatman GF/F fiberglass filters (porosity = 0.7 µm) and analysed with a Systea-Alliance auto-analyser, according to the methods generally indicated by Strickland and Parsons [1972] and Hansen and Koroleff [1999];
- chlorophyll *a*, assessed according to Holm-Hansen *et al.* [1965], after filtration through Whatman GF/F filters and measurement of the acetone extract before and after acidification by means of a Perkin Elmer LS5B spectrofluorometer;
- particulate organic carbon (POC) and nitrogen (PTN), determined on Whatman GF/F filters after elimination of inorganic carbon by HCl, with a Perking Elmer 2400 CHN elemental analyser, according to Hedges and Stern [1984];
- samples of dissolved organic carbon (DOC), filtered on board onto Whatman GF/F glassfiber filters (porosity 0.7 µm) and stored at 4°C after addition of a $HgCl_2$ solution. DOC concentration was calculated in a Total Organic Carbon analyzer Shimadzu mod. 5000A, after catalytic oxidisation at high temperature (680°C) and measurement at I.R. light of the CO_2 developed as gaseous phase, following Sugimura and Suzuki [1988].
- total suspended matter (TSM), filtered through pre-weighted Whatman GF/F fiberglass filters and determined by a gravimetric method; organic and inorganic percentage was assessed after incineration at 400°C [Strickland and Parsons, 1972];
- particle size, total number and spectra, determined with a multichannel Coulter Counter particle analyzer Multisizer III; the observed particle size ranged from 2 to 60 µm [Sheldon *et al.*, 1972].

Tidal level and wind speed and direction data were kindly provided by the Municipality of Venice (Centro Previsioni e Segnalazioni Maree).

To compare variability due to the tidal dynamics and to the seasonality, the variation coefficient (CV, expressed as the percentage of the standard deviation on the average) was calculated from the studied variables in each season (seasonal cruises STG), and then a mean value considered (the tidal CV). The annual CV was calculated considering the whole data-set (cruises STG + monthly surveys LINK). The ratio tidal CV / annual CV suggests the dominant time-scale (short or long) of the variations of each parameter [Cadee, 1982]. The more this ratio is close to the unity, the more the short-time variability, due to tide, is of the same level of the seasonal cycle; conversely low ratios show the prevalence of the long-term variability, i.e. the annual cycle.

Fluxes were computed from current measurements by ADCP moored at the inlets. When some gaps in current data occurred, due to technical problems, outputs from a Current Speed Prediction Model, kindly provided by OGS – Trieste, were utilised (Gacic, pers. com.). Discharges were obtained applying the following equations, obtained from several ship-borne ADCP measurements across each inlet (Arena, OGS, pers. com.):

- Lido discharge = 6594.4 · current speed + 123.99
- Malamocco discharge = 6301.6 · current speed + 176.48
- Chioggia discharge = 4969.2 · current speed – 159.61

From these, coupled with the corresponding concentration of the variables of interest, instantaneous fluxes from/into the lagoon of Venice were computed. Conventionally, positive signs indicate outgoing fluxes from the lagoon towards the sea, while incoming fluxes, from the sea into the lagoon, are negative.

Seasonal budgets were calculated by algebraic sum of time-integration of fluxes at each inlet. When all the scheduled samplings were carried out (n = 17) this computation considered 4 flood and 4 ebb tides. The lack of some samplings forced us to reject the corresponding tidal cycle, and to consider only those showing discharges of the same order of magnitude, both into and out of the lagoon. Seasonal exchanges between the lagoon andea were obtained by the sum of each seasonal budget through each inlet, except for autumn, when an important flooding event at Lido occurred (see later).

3. Results.

The results are summarised in the following paragraphs, as main questions launched by the project.

3.1. Typical temporal scales of the biogeochemical variability.

A wide variability of the biogeochemical parameters has been observed in the Lagoon of Venice, as in other transitional environments,. This was due to several factors, such as the different morphology of the inlets, the features of the waters flowing from the drainage basin as well as from the coastal area, the tidal amplitude, the meteorological conditions, the presence and intensity of biological processes, the sampling season and timetable, etc. The crossed analysis of these factors, observed both at short (tide) and at long time-scale (season), could be better understood by looking at the variation coefficient (CV), in particular at the ratio between tidal and annual coefficients (Tab. 3).

Suspended matter showed the highest ratio (0.90), caused by frequent resuspension due to the high current speed (max measured = 1.6 m s^{-1}) or by local turbulence. Other physical and chemical variables were also influenced by the tide, as pH, dissolved oxygen and salinity (ratios respectively from 0.82 to 0.79).

Tab. 3 – Variation coefficients (CV, units = %): tidal CV, calculated from seasonal cruise (STG); annual CV, calculated from seasonal cruises (STG) + monthly surveys (LINK).

	TIDAL CV					**ANNUAL CV**	**RATIO tidal/annual**
	fall	**winter**		**Summer**	**Average**		
Temperature	12.8	6.5	9.6	1.6	**7.6**	**45.7**	**0.17**
Salinity	2.7	2.7	4.6	2.6	**3.1**	**4.0**	**0.79**
PH	3.3	2.5	2.2	1.1	**2.3**	**2.8**	**0.82**
Oxygen %	3.9	2.9	6.5	8.4	**5.4**	**6.7**	**0.82**
DIN	27.4	19.4	64.7	47.3	**39.7**	**63.3**	**0.63**
Silicate	27.9	30.2	53.6	54.6	**41.6**	**53.5**	**0.78**
Phosphate	53.0	44.6	48.0	31.5	**44.3**	**61.7**	**0.72**
DOC	19.9	28.6	28.4	20.5	**24.4**	**63.1**	**0.39**
POC	69.1	39.7	119.8	30.8	**64.8**	**99.6**	**0.65**
PTN	42.5	37.9	109.7	29.0	**54.8**	**98.6**	**0.56**
Chlorophyll	28.9	77.3	53.3	35.8	**48.8**	**126.3**	**0.39**
TSM	87.3	65.0	151.8	102.0	**101.5**	**113.3**	**0.90**
Phytoplankton	52.9	88.8	61.8	49.1	**63.2**	**96.1**	**0.66**
Zooplankton	69.5	58.8	83.1	68.4	**69.9**	**122.5**	**0.57**

On the contrary, temperature showed wider fluctuations on a longer basis (annual), being strongly connected with the seasonal changes (minimum ratio = 0.17).

Low-intermediate ratios highlighted those variables directly associated with the biological components, such as chlorophyll, DOC, POC, TPN and phytoplankton (ratios from 0.39 to 0.66), confirming the influence of long-term cycles on biology.

These results substantially agreed and completed the studies carried out in a restricted area of the northern lagoon (palude della Rosa) in the ‘90s [Bianchi *et al.*, 2000].

3.2. Fluxes of organic and inorganic substances, dissolved and particulate, through the inlets at different time-scales.

Biogeochemical fluxes exhibited a large variability, depending both on the instantaneous concentration of the variables measured and on the discharge. Current and discharge maxima were measured at Malamocco (respectively 1.59 m s^{-1} and 9815 m^3 s^{-1}), with the only exception being winter 2001, when a maximum discharge of 9453 m^3 s^{-1} was measured at Lido. Chioggia had lower values compared with the other inlets (almost 52% of Malamocco and 55% of Lido discharges), because of its narrower average section (around 4785 m^2; Tab. 4; Figs. 2, 3 and 4).

Tab. 4 – Current speed and discharge maximum values, measured during this study. Negative values = incoming flux; positive values = outgoing flux.

	Autumn		**Winter**		**Spring**		**Summer**	
	Current ***m s⁻¹***	**discharge** ***m³ s⁻¹***	**current** ***m s⁻¹***	**discharge**	**current**	**Discharge**	**current** ***m s⁻¹***	**Discharge**
Lido	-1.41	9263	-1.45	-9453	1.31	8786	-1.28	8505
Malamocco	1.51	9668	-1.49	-9183	1.45	9283	-1.59	-9815
Chioggia	1.19	5759	1.07	5165	0.97	4649	0.85	4087

The average seasonal fluxes are reported in Fig. 5. Sometimes the inlets behaved differently due to several factors, i.e. the sampling years (Lido: 2001-2002, Malamocco and Chioggia 2002-2003). The following considerations arise:

1. dissolved nutrients displayed different behaviours, depending on their chemistry, qualitative and quantitative inputs from the drainage basin, presence and intensity of assimilation and/or degradation processes, dominant phytoplankton and phytobenthos associations, etc. In particular:
   a) DIN showed increasing fluxes from autumn to winter (from 824 to 1098 g s^{-1}); then, when the biological processes start, fluxes constantly diminished from spring to summer (from 559 to 194 g s^{-1}), a pattern common to the three inlets; this is a signal that nitrogen is the nutrient commonly taken up by all the autotrophs;
   b) silicate showed fluxes slightly higher than nitrogen, with a decreasing trend from autumn to winter and spring (1158 > 956 > 726 g s^{-1}); these fluxes fit well with the uptake by diatoms and silicoflagellates;
   c) phosphate fluxes were very low, according to their concentration in the water column: they progressively decreased from autumn to winter – spring and summer (respectively 12, 9, 9 and 5 g s^{-1}). This trend can be explained either with high assimilation phenomena occurring in summer and with its chemistry, because of its fast adsorption on different substrata and of its short recycling time [Valiela, 1995];
   d) while these fluxes generally match the concentrations of each nutrient, their seasonal trend sometimes is not common among the inlets;
2. POC and PTN fluxes followed the biological cycle, with a winter minimum (POC = 779 g s^{-1}; PTN = 129 g s^{-1}) and a spring maximum (POC = 1873 g s^{-1}; PTN = 275 g s^{-1}), particularly evident at Malamocco and Chioggia;
3. DOC showed a similar trend: the lagoon-sea fluxes were low in winter (DOC = 6.6 kg s^{-1}) and high in spring (DOC = 9.4 kg s^{-1}). DOC fluxes were one order of magnitude higher than POC, in agreement with their concentration in marine waters, where the dissolved fraction usually dominates on the particulate one (mean ratio = 10 : 1) [Valiela 1995];
4. phytoplankton biomass mean fluxes (as chlorophyll *a*) had low values in autumn (5 g s^{-1}), a winter maximum around 10 g s^{-1}, when a phytoplankton bloom occurred at Lido (with instantaneous fluxes up to 49 g s^{-1}), and slight values in spring and summer (8 – 9 g s^{-1});

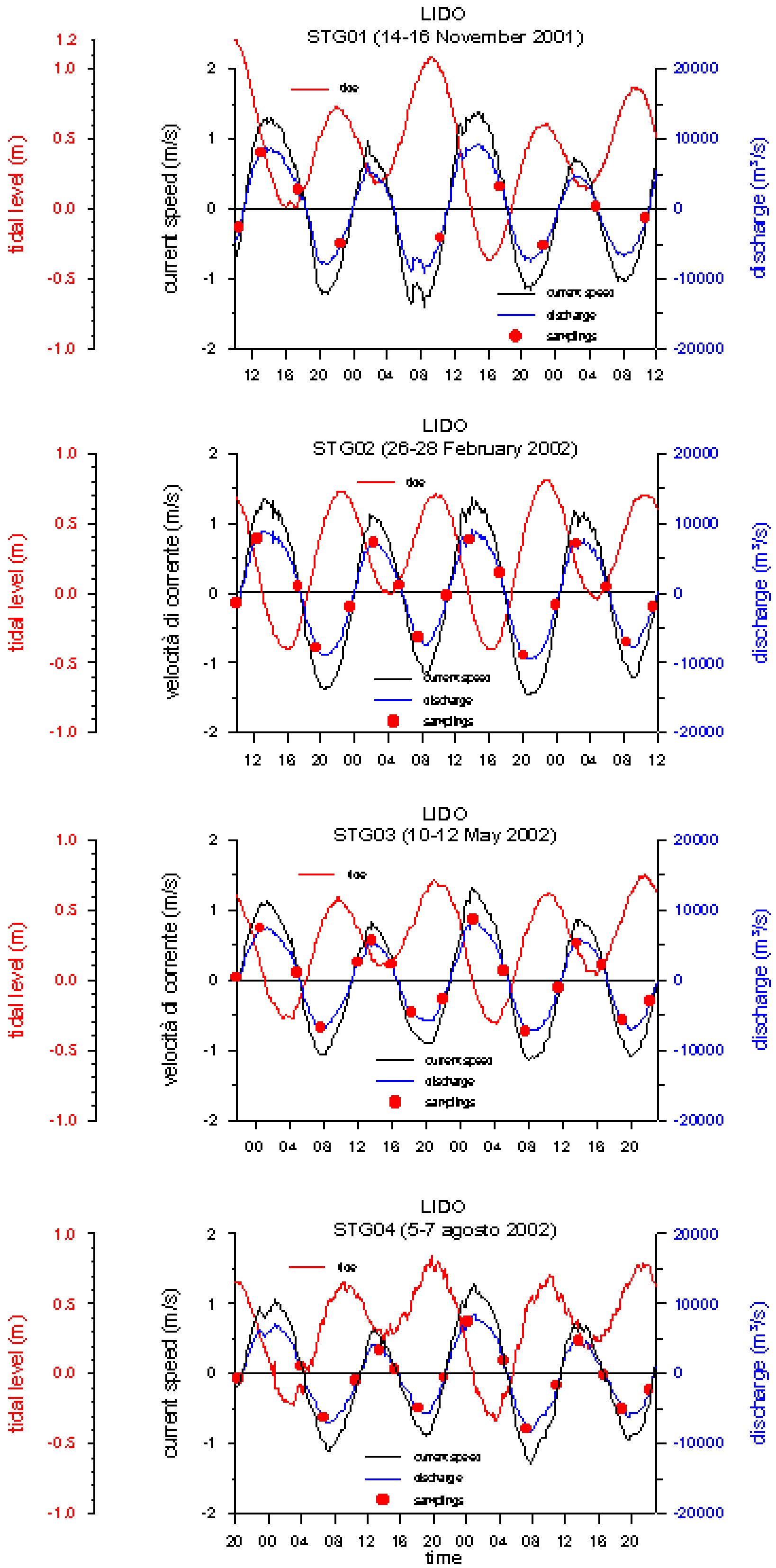

Fig. 2 – Lido inlet: tide, current speed and discharge in the four seasonal cruises. Dots = samplings.

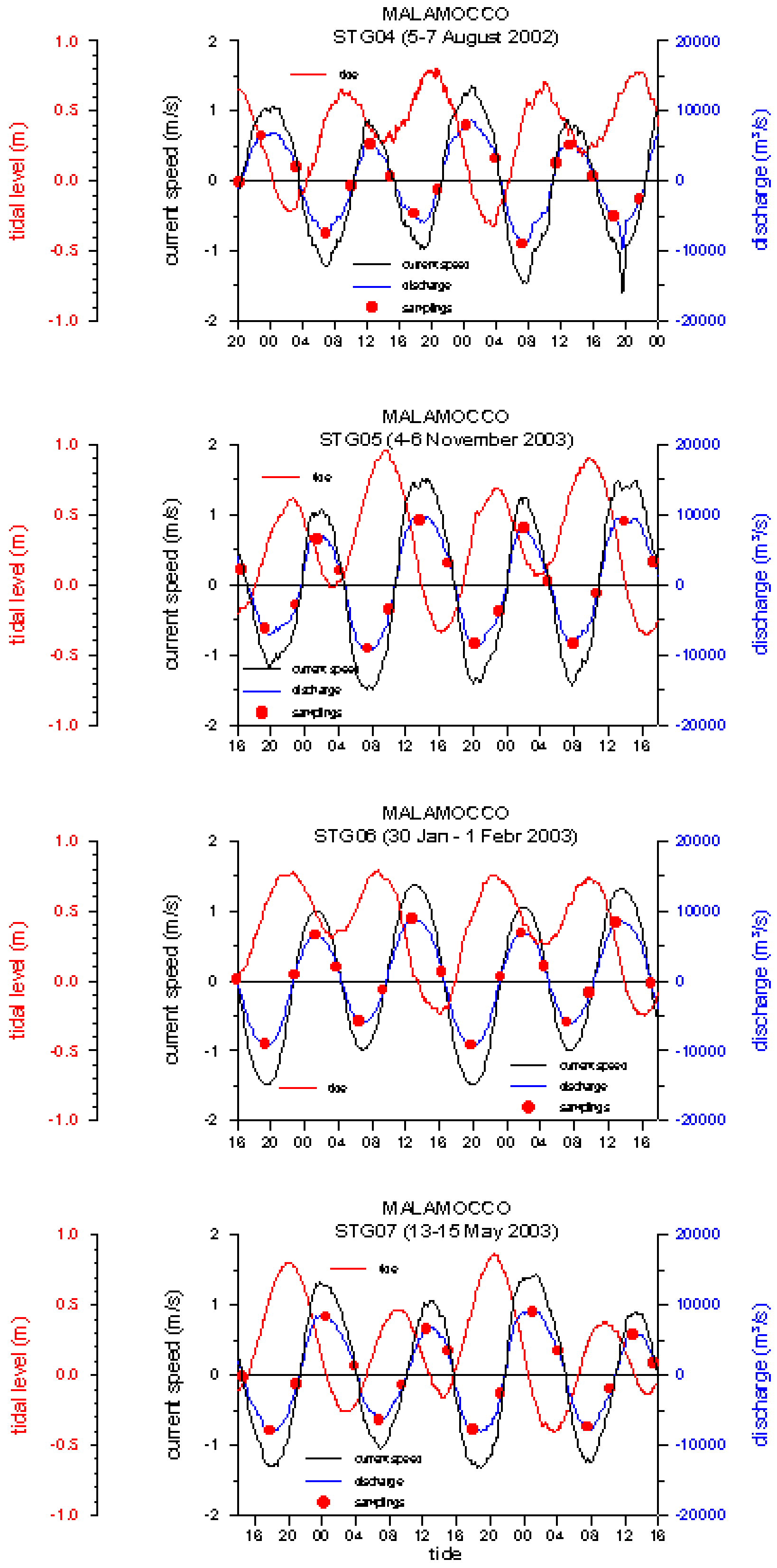

Fig. 3 – Malamocco inlet: tide, current speed and discharge in the four seasonal cruises. Dots = samplings.

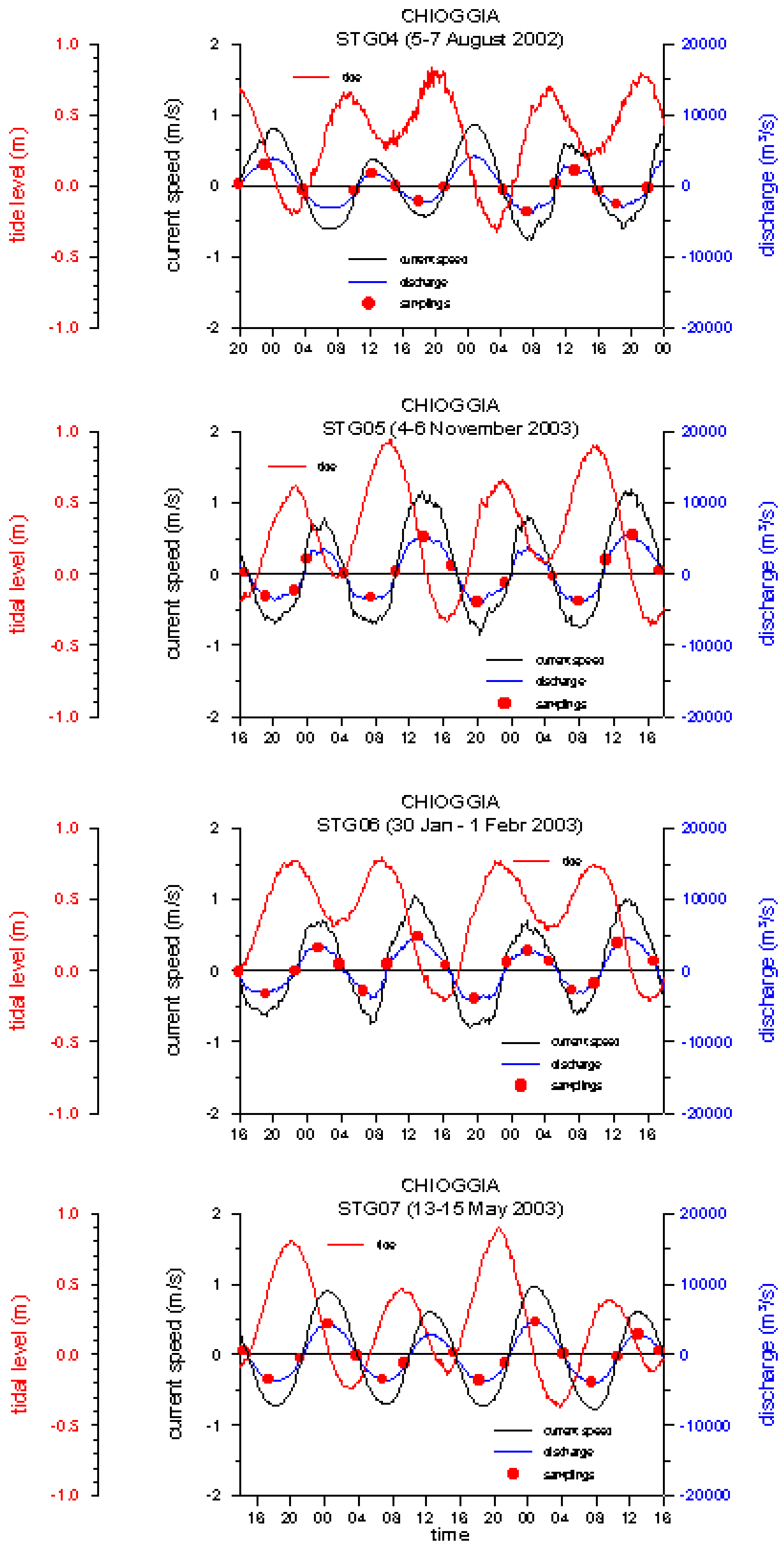

Fig. 4 – Chioggia inlet: tide, current speed and discharge in the four seasonal cruises. Dots = samplings.

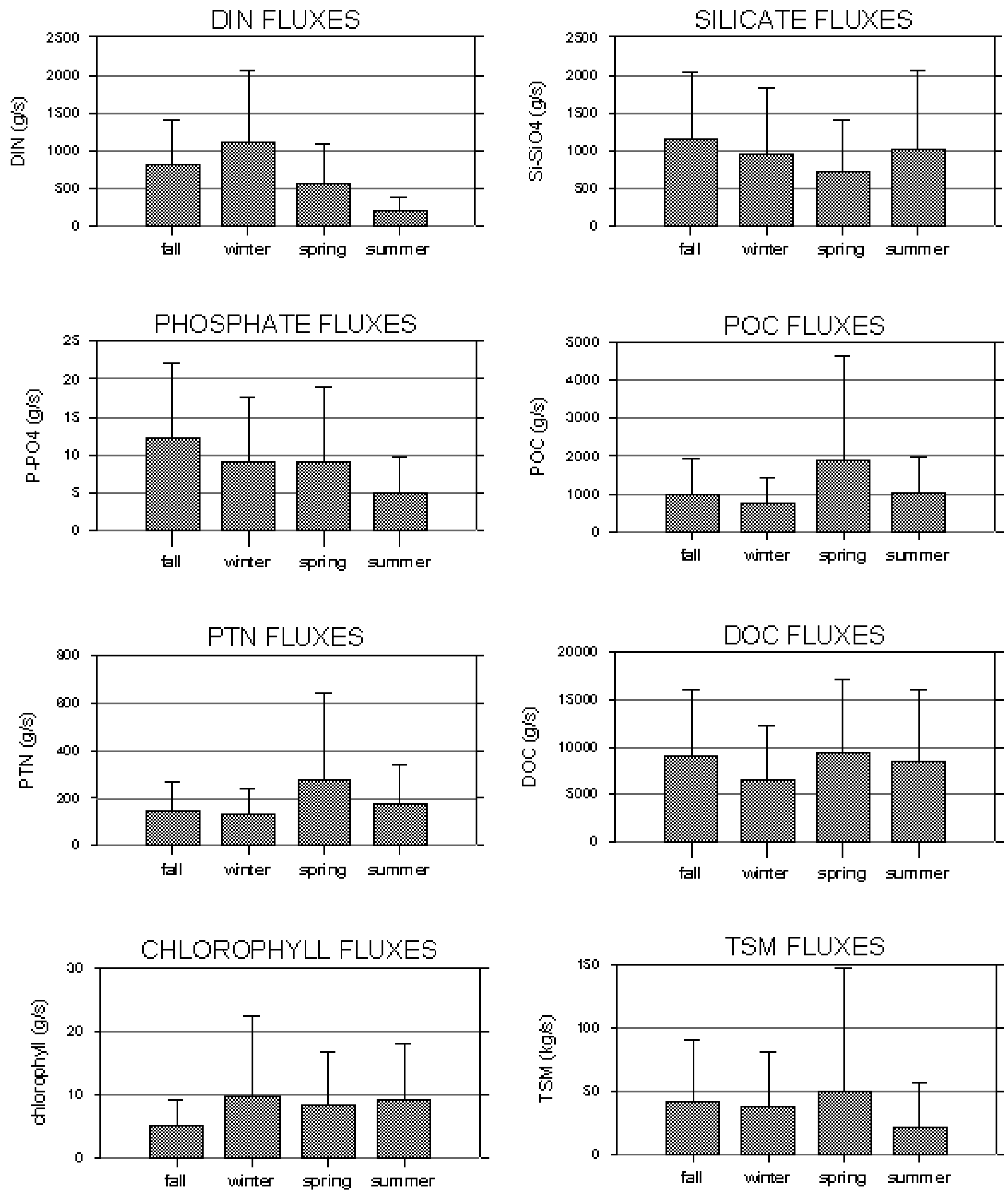

Fig. 5 – Average lagoon – sea fluxes (as absolute values) and standard deviations.

5. TSM mean flux had a maximum in spring (50 kg s^{-1}), a minimum in summer (21 kg s^{-1}), intermediate values in autumn (41 kg s^{-1}) and winter (38 kg s^{-1}). Comparable seasonal trends were shown at Malamocco and Chioggia, with a gradual flux increase from autumn to winter and spring (Malamocco = 43 < 52 < 71 kg s^{-1}; Chioggia = 10 < 26 < 52 kg s^{-1}), and a drop in summer (Malamocco = 18 kg s^{-1}, Chioggia = 11 kg s^{-1}). Conversely, Lido showed a spring TSM minimum (27 kg s^{-1}) and almost similar fluxes in winter and summer (35 ÷ 37 kg s^{-1}). Here, a

peak of 93 kg s^{-1} was calculated during the flooding event of November 2001 (max tidal level = +115 cm), when strong E-N-E winds forced coastal waters, characterised by low salinity and high turbidity, to enter through this inlet [Bianchi *et al.*, 2004a; 2004b].

3.3. Relationships between lagoon – sea exchanges and peculiar environmental conditions, such as anoxia.

Neither hypoxia nor anoxia occurred during our samplings: the lowest relative oxygenation (78%) was measured at Chioggia in August 2002, in correspondence with relatively high organic particulate concentrations (POC > 450 mg dm^{-3}, chlorophyll > 4 µg dm^{-3}, TSM organic fraction > 30%), a signal of the presence of intense respiration processes, but not so heavy to lower the DO to critical levels.

Usually in the lagoon of Venice low dissolved oxygen concentrations can be found in marginal, segregated areas [Bianchi *et al.*, 1987], characterised by scarce tidal dynamics [Marcomini *et al.*, 1993]. In coastal waters, hypoxia can be measured sometimes near the bottom, especially in late autumn – winter, when the thermohaline stratification, maintained by an exceptionally warm autumn and coupled with a high riverine discharge, lasts for a long time [Franco, 1986; Fonda Umani *et al.*, 1992]. Nevertheless, it is common opinion that these processes, when present, are not able to reach the inlets.

3.4. Relationships between lagoon – sea exchanges and peculiar environmental conditions, such as flooding events.

During this study, two exceptional flooding events occurred: i) in March 2001, with a maximum tide level of 107 cm; ii) in November 2001, when the tidal height reached 115 cm. Both episodes were accompanied by local strong E-N-E winds, with speeds exceeding 20 m s^{-1}. Unfortunately, only the Lido inlet was investigated in these periods; so it is not possible to discuss the general lagoon – sea budgets during these special and interesting events.

In concomitance with the flood, low salinities were measured, due to diluted waters driven and accelerated along the coast by winds, mainly derived from the northern rivers (Sile and Piave), and characterised by a high amount of inorganic seston (March 2001: S < 33 PSU, TSM > 27 mg dm^{-3}; November 2001: S = 33.3 PSU, TSM > 40 mg dm^{-3}; Fig. 6).

Fluxes were largely influenced by these episodes. As a matter of fact, budget calculations performed at Lido in November 2001 displayed values of nitrogen, silicate, phosphate and TSM two times higher than those of Malamocco and Chioggia, sampled in different meteorological conditions during November 2002 (Tab. 4).

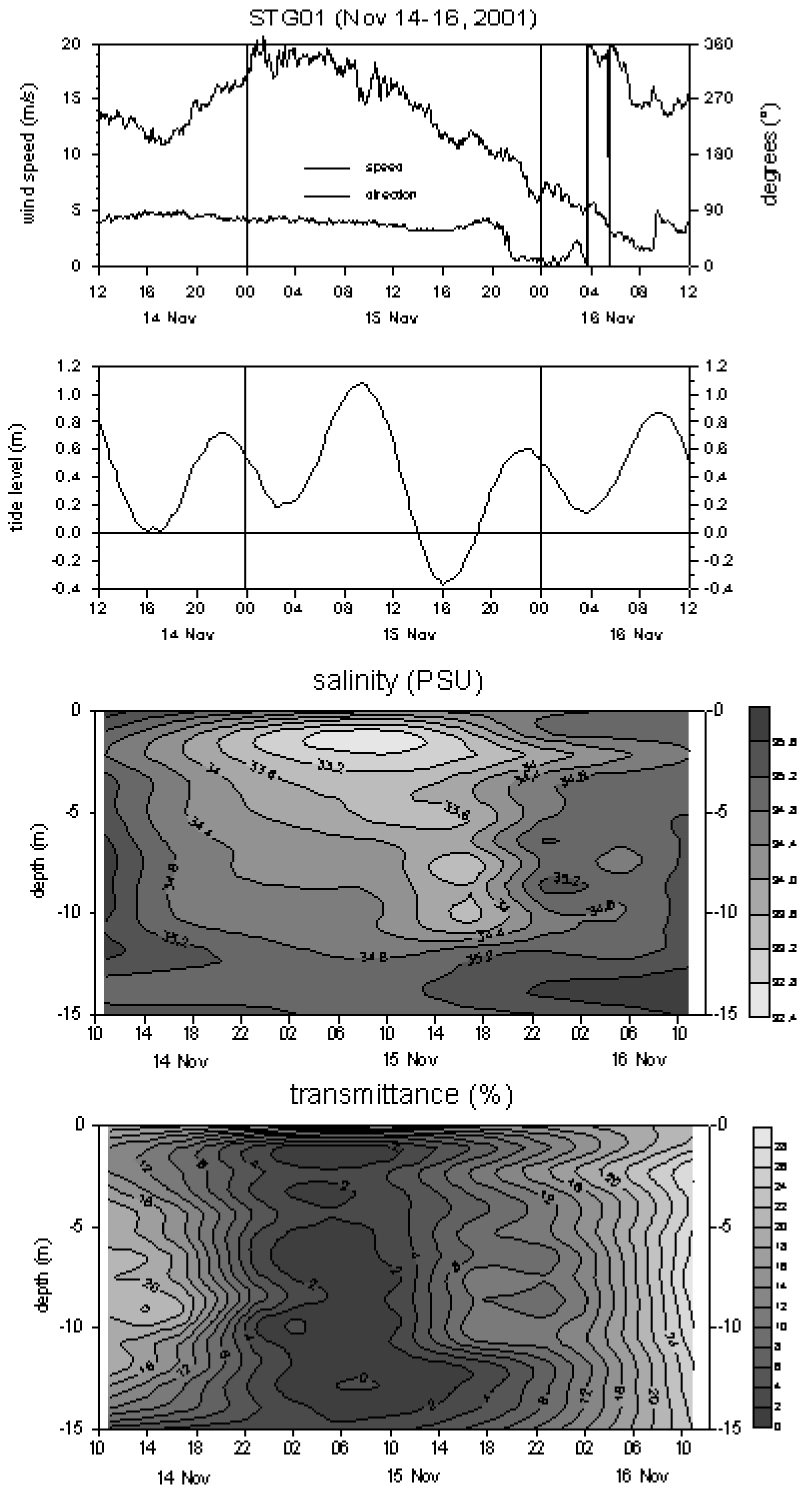

Fig. 6 – Lido, November 2001 (cruise STG01): evidence of a flooding event. From top to bottom: wind speed and direction, tide level, vertical sections of salinity and transmittance by incidence beam in the sampling period (48h).

Tab. 4 – Budgets between lagoon and sea through the three inlets. (1) Flooding event. DIN = dissolved inorganic nitrogen; $Si\text{-}SiO_4$ = orthosilicate; $P\text{-}PO_4$ = orthophosphate; TSM = total suspended matter. Positive values: export from the lagoon; negative values: import from the sea. Units in t d^{-1}.

		DIN	$Si\text{-}SiO_4$	$P\text{-}PO_4$	TSM
Lido	Nov. 2001 (1)	+ 36.2	+ 42.0	+ 1.0	- 2411
Malamocco	Nov. 2002	+ 8.8	+ 14.6	+ 0.4	+ 842
Chioggia	Nov. 2002	+ 7.8	+ 2.7	+ 0.2	+ 275

3.5. Budget computation between lagoon and sea.

Lagoon – sea budgets, calculated seasonally for each inlet by time integration, are shown in Fig. 7. In regards to autumn budgets , because of the flood occurring at Lido in November 2001, data related to this inlet were split into a single bar (light grey), separated from those of Malamocco and Chioggia, sampled in a more stable condition the following year (dark grey); in the other seasons, being the meteorological situations comparable, exchanges between the Lagoon of Venice and sea were calculated from the cumulative contribution of the three inlets (black bars).

The general picture of dissolved nutrients showed an export from the lagoon to the sea, except a very small import of phosphate in summer, almost near the balance. In particular:

- nitrogen and silicate seasonal trends showed a common pattern, with a maximum import in spring (DIN = 29 t d^{-1}; $Si\text{-}SiO_4$ = 45 t d^{-1}) and lower values in autumn (at Malamocco and Chioggia) and winter (17 - 18 t d^{-1}); summer displayed a marked reduction of total nitrogen export (5 t d^{-1});
- phosphate budgets decreased from autumn to spring (571 (Malamocco + Chioggia) in autumn, 454 in winter, 158 kg d^{-1} in spring), with a summer slight inversion (56 kg d^{-1}, import from the sea);
- the flooding event at Lido was responsible of the massive export from this inlet in autumn (DIN = 36 t d^{-1}; $Si\text{-}SiO_4$ = 42 t d^{-1}; $P\text{-}PO_4$ = 1022 kg d^{-1}).

The influence of biological uptake on nutrients was particularly evident: according to the Odum [1971] assertion that lagoons act as "*nutrient traps*", nitrogen, silicate and phosphate highlighted a general export from the Lagoon toward the sea. Nevertheless some unexpected budgetsthrough the Lido inlet occurred: in fact, DIN and silicate pointed out an import in February, when a strong uptake due to the diatom bloom in the inner lagoon took place. In summer, as an effect of another phytoplankton bloom, this time by nanoflagellates, DIN showed again an import from the sea, while silicate, not assimilated by this taxonomic group, was exported towards the sea. This trend partially agrees with the results obtained by Sfriso *et al.* [1994] in the '90s.

In spring, export estimates of particulate matter showed peak for TSM, POC, PTN and chlorophyll *a* (respectively = 7390 t d^{-1}, 78 t d^{-1}, 13 t d^{-1}, 249 kg d^{-1}).

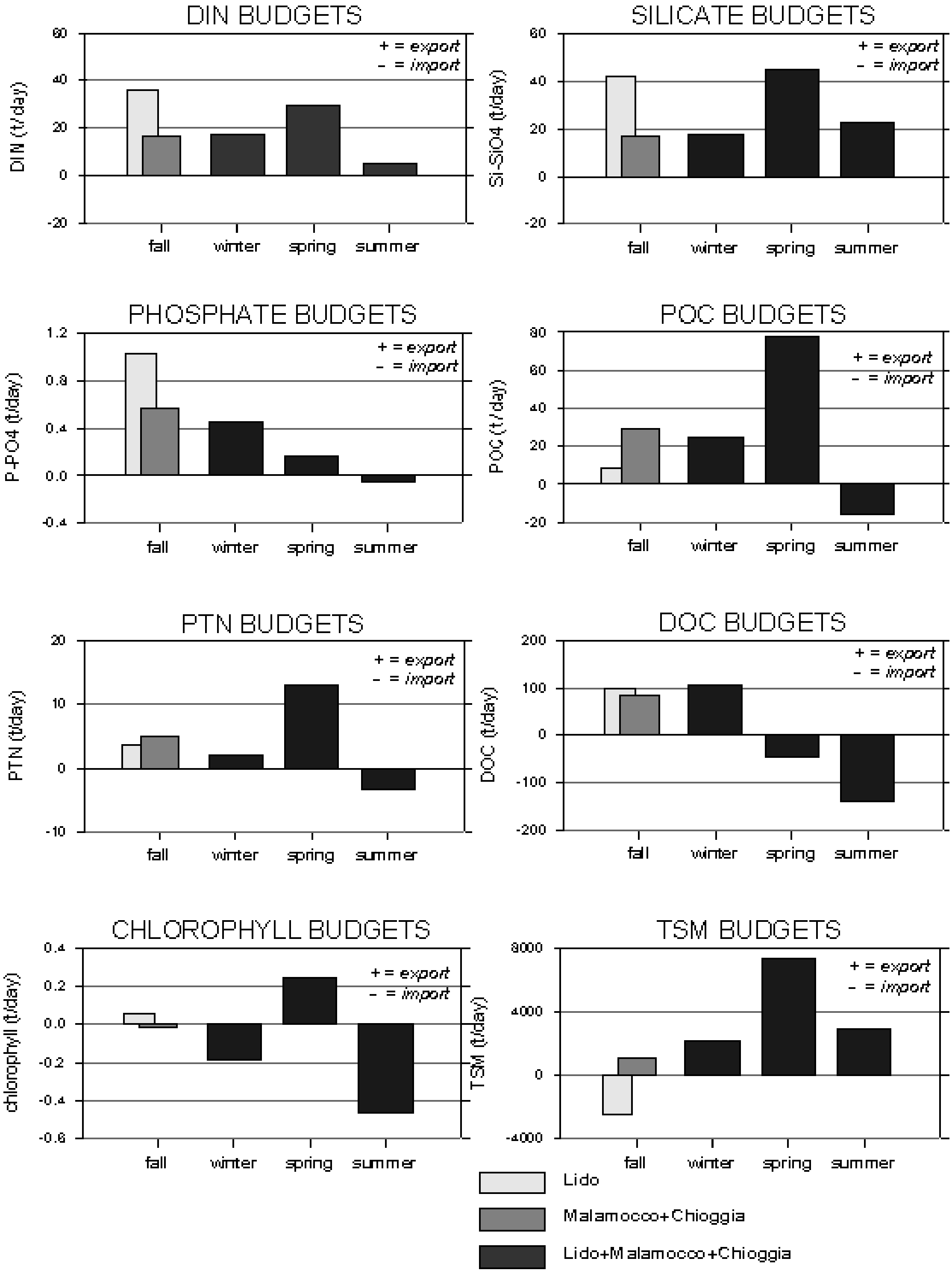

Fig. 7 – Seasonal budgets between lagoon and sea. In fall, Lido is split from Malamocco and Chioggia (see text). Positive and negative bars indicate respectively export from the lagoon and import from the sea.

In this season, detritus reached high values, as shown by high POC/chlorophyll *a* average ratios (221) and inorganic percentages on TSM (73%). Export of biogenic particulate matter decreased in autumn (Malamocco + Chioggia: POC = 29 t d^{-1}, PTN = 5 t d^{-1}) and winter (3 inlets together: POC = 24 t d^{-1}, PTN = 2 t d^{-1}). The dissolved fraction of organic carbon (DOC) followed the trend of the particulate one (POC) in fall and winter, an opposite budget in spring and an inversion in summer, when 137 t d^{-1} were imported into the lagoon. Phytoplankton biomass by chlorophyll *a* exhibited a budget close to the balance in autumn common to the three inlets, an export during spring (249 kg d^{-1}) and imports in winter and summer (respectively = 184 e 466 kg d^{-1}). Since biomass should usually be exported from lagoons, as very productive coastal areas, the reason for this unexpected budget is probably related to the different behaviour of the Lido inlet, accounting for up to 90% of the total budget in winter and 55% in summer.

At Lido, in fact, phytoplankton populations, typical of coastal areas, were observed with higher abundance in flood than in ebb tide. They were mainly represented by the large pelagic diatom *Cerataulina pelagica*, with a mean cell volume of 2530 μm^3, containing high chlorophyll concentrations in its plastids. This phenomenon was observed also at Malamocco in February 2002 (chlorophyll import = 32 kg d^{-1}) and, to a greater extent, at the three inlets in August 2002 (chlorophyll imports: Lido = 257 kg d^{-1}; Malamocco = 110 kg d^{-1}; Chioggia = 99 kg d^{-1}).

TSM budget usually displayed an export from the lagoon to the sea, higher in spring (7390 t d^{-1}), lower in summer (2967 t d^{-1}), winter (2161 t d^{-1}) and autumn (Malamocco + Chioggia = 1118 t d^{-1}). These values confirmed that in the Lagoon of Venice, the erosion generally overcome the sedimentation processes. During the flooding episode at Lido, an opposite budget of TSM was calculated, characterised by an import from turbid coastal waters > 2000 t d^{-1}.

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References.

Bernardi Aubry F. and Acri F., 2004. Phytoplankton seasonality and exchange at the inlets of the Lagoon of Venice (July 2001 – June 2002). *J. Mar. Sys.*, 51, 65-76

Bianchi F., Boldrin A., Cioce F., Rabitti S. and Socal G., 1987. Variazioni stagionali dei nutrienti e del materiale particellato nella laguna di Venezia. Bacino settentrionale. *Ist. veneto Sci. Rappti Studi*, 11, 49-67

Bianchi F., Acri F., Alberighi L., Bastianini M., Boldrin A., Cavalloni B., Cioce F., Comaschi A., Rabitti S., Socal G. and Turchetto M., 2000. Biological variability in the Venice lagoon.

In: *The Venice Lagoon Ecosystem. Inputs and interactions between land and sea. Man and the biosphere series* volume 25. Lasserre P. and Marzollo A. eds. UNESCO and Parthenon Publishing Group. 97-125

Bianchi F., Ravagnan E., Acri F., Bernardi Aubry F., Boldrin A., Camatti E., Campesan G., Cassin D., Comaschi A., Turchetto M., Van Vleet E. and Bressan M., 2002. Variability of hydrochemistry, inorganic and organic matter and plankton between the Venice Lagoon and the Adriatic Sea. Preliminary results (year 2001). In: *Scientific research and safeguarding of Venice. CORILA Research Programme 2001 Results*, *Atti Istituto Veneto SLA*, 513-526

Bianchi F., Ravagnan E., Acri F., Bernardi Aubry F. Boldrin A., Camatti E., Cassin D. and Turchetto M., 2004a. Seasonal fluxes of nutrients and suspended matter between the Venice Lagoon and the Adriatic Sea through the Lido inlet. Years 2001-2002. In: *Scientific research and safeguarding of Venice. Research programme 2001-2003,* vol. I, 2002 results, CORILA ed., 417-425

Bianchi F., Ravagnan E., Acri F., Boldrin A., Cassin D. and Turchetto M., 2004b. Variability and fluxes of hydrology, nutrients and particulate matter between the Venice Lagoon and the Adriatic Sea. Preliminary results (years 2001-2002). *J. Mar. Sys.*, 51, 49-64

Cadee G.C., 1982. Tidal and seasonal variations in particulate and dissolved organic carbon in the Ems-Dollart estuary and the western Wadden Sea, *Netherlands Journal of Sea Research*, 15, 228-249

Fonda Umani S., Franco P., Ghirardelli E. and Malej A., 1992. Outline of oceanography and the plankton of the Adriatic Sea. In: *Marine Eutrophication and Population Dynamics.* Colombo G., Ferrari I., Ceccherelli V.U. and Rossi R. Eds., Olsen & Olsen, Fredensborg, 347-365

Franco P., 1986. Strutture di densità e processi di segregazione in Adriatico settentrionale. *Nova Thalassia*, 8(3), 247-258

Gacic M., Mazzoldi A., Kovacevic V., Cosoli S., Mancero Mosquera I., Arena F., Cardin V., 2005. Water fluxes in Venice lagoon inlets and coastal circulation. *This volume*

Hansen H.P. and Koroleff F., 1999. Determination of nutrients. In: *Methods of seawater analysis.* Grasshoff K., Cremling K. and Erhardt M. Eds., Wiley-VCH Verlag, 159-228

Hedges J.I. and Stern J.H., 1984. Carbon and nitrogen determination of carbonate-containing solids. *Limnol. Oceanogr.* 19, 984-989

Holm-Hansen O., Lorenzen C.J., Holmes R.W. and Strickland J.D.H., 1965. Fluorimetric determination of chlorophyll. *J. Cons. perm. int. Explor. Mer*, 30, 3-15

Marcomini A., Sfriso A. and Zanette M., 1993. Macroalgal blooms, nutrients and trace metal cycles in a coastal lagoon. In: *Macroalgae, eutrophications and trace metal cycling in estuaries and lagoons*, Rijstenbil J.W. and Haritonidis S.H. Eds., EC Report BRIDGE-DG XII, 66-90

Odum E.P, 1971. Fundamentals of Ecology, Saunders Ed., 3rd Edition

Sfriso A., Marcomini A. and Pavoni B., 1994. Annual nutrient exchanges between the central lagoon of Venice and the northern Adriatic Sea. *Sci. Total Environ.*, 156, 77-92

Sheldon R.W., Prakash A. and Sutcliffe W.H., 1972. The size distribution of particles in the ocean. *Limnol. Oceanogr.*, 17, 327-340

Strickland J.D.H. and Parsons T.R., 1972. A pratical handbook of seawater analysis, *Bull. Fish. Res. Bd. Canada*, 167, 311 pp

Sugimura Y. and Suzuki Y., 1988. A high temperature catalytic oxidation method for the determination of non-volatile dissolved organic carbon in seawater by direct injection of a liquid sample. *Marine Chemistry*, 24, 105-131

Valiela I., 1995. Marine Ecological Processes. Springer Verlag Ed., 2nd Edition, pp. 686

PHYTOPLANKTON AND PRIMARY PRODUCTION AT THE INLETS OF THE LAGOON OF VENICE

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Riassunto.

Nell'ambito del Programma di Ricerca CORILA 2000-2003 - Qualità e Quantità degli Scambi tra Laguna e Mare (Linea 3.5), sono stati raccolti, per la prima volta, dati relativi all'abbondanza, alla composizione all'attività fotosintetica della comunità fitoplanctonica.

In questo lavoro vengono sintetizzati i principali risultati ottenuti nell'intero periodo di studio, da luglio 2001 a maggio 2003.

La comunità fitoplanctonica non ha mostrato differenze significative, né qualitative né quantitative, tra le tre bocche di porto. Le abbondanze massime sono state osservate nel periodo estivo, quelle minime in inverno. Nanoflagellati e diatomee hanno caratterizzato i campioni dell'intero periodo di analisi con i maggiori contributi medi all'abbondanza totale (rispettivamente 58% e 38% del totale), Per la maggior parte dell'anno le abbondanze fitoplanctoniche ini marea entrante sono risultate più elevate rispetto a quelle di marea uscente. Soltanto in corrispondenza di fioriture fitoplanctoniche, osservate in laguna nel periodo agosto-ottobre 2001 e in febbraio 2002, le abbondanze sono state maggiori nelle acque di marea uscente. La comunità in fase di marea uscente era costituita da forme neritiche, tipiche delle acque costiere dell'Adriatico Settentrionale; in fase di marea uscente erano prevalenti specie ticopelagiche e specie che hanno dato origine a fioriture nella laguna.

Le curve luce/fotosintesi sono state analizzate alla bocca di poto del Lido in maggio ed agosto 2002 e alla bocca di porto di Malamocco in novembre 2002 e in gennaio 2003. I valori di produzione più elevati sono stati misurati in estate (valore massimo di circa 7 mg C m^{-3} h^{-1}). L'analisi dei parametri delle curve luce/fotosintesi in marea entrante ed uscente ha evidenziato l'importanza delle caratteristiche fisiologiche per differenziare le comunità fitoplanctoniche e definirne le potenzialità produttive.

Abstract.

Data on phytoplankton exchange between the Lagoon of Venice and the Northern Adriatic Sea were gathered, for the first time, in the framework of the Research Programme CORILA 2000-2003 (Linea 3.5).

Throughout the study period (July 2001-May 2003) the phytoplankton community did not differ significantly among the three inlets. Despite the importance of the short time scale variability in the Lagoon of Venice, phytoplankton, abundance and community succession were mainly driven by the seasonal cycle.

The phytoplankton was prevalently most abundant at flood tide, with dominance of neritic species, commonly found in the North Western Adriatic coastal waters; highest abundance at ebb tide were recorded only during bloom in the lagoon.

The analysis of the photosynthesis-light curves at flood and ebb tide emphasizes the importance of the physiological aspects in differentiating the phytoplankton community during the tidal cycle.

1.Introduction.

The phytoplankton community of the Lagoon of Venice has been extensively studied in the last 30 years [Acri *et al.*, 2004], as it regards the taxonomic composition [Socal *et al.*, 1985; 1987; Tolomio *et al.*, 1999; Facca *et al.*, 2002] and the temporal pattern of abundance and biomass [Bianchi *et al.*, 1999; 2000; Socal *et al.*, 1999]. The functional structure of the primary producer community in the lagoon has undergone conspicuous changes since the sixties [Sfriso *et al.*, 1987; Sfriso and Marcomini, 1996; Facca *et al.*, 2002; Curiel *et al.*, 1997]. The decrease of the macrophyte biomass in recent years has given a central position to the phytoplankton, as it regards its contribution to total primary production of the lagoon.

The seasonal phytoplankton variations have been described in the southern [Tolomio and Bullo, 2001], central [Socal *et al.*, 1999; Facca *et al.*, 2002] and northern basins [Voltolina, 1973; Bianchi *et al.*, 1999]. The community appear mainly made up by diatoms and nanoflagellates (mainly Chlorophyceae, Cryptophyceae) and it is characterized by the coexistence of pelagic and benthic forms. Neritic species, adapted to survive to large salinity ranges, and tychopelagic species (often diatoms), i.e. benthic or epiphytic species, re-suspended by means of high hydrodynamics [Socal *et al.*, 1985; Tolomio and Bullo, 2001], clearly dominate the community.

Tides are the major factors controlling the distribution of organisms and properties in the lagoons [Smith and Atkinson, 1994; Cervantes Duarte *et al.*, 2001; Kirugara, 2001; Ounissi *et al.*, 2002]. In particular, the lagoon-sea coupling influences the plankton system, its composition, interactions and productivity [Knoppers, 1994]. It is well known [Bianchi *et al.*, 2000; Ravera, 2000] that the water renewal, maintained by the tidal cycle through the three inlets of the Lagoon of Venice, is of crucial importance for the biological communities.

Information about both the quantitative and qualitative aspects of the phytoplankton exchange between the lagoon of Venice and the Adriatic Sea through the three inlets are lacking. This study represents the first attempt to fill this gap. To this purpose, synoptic samplings were performed at the three inlets in the same tidal phase, from July 2001 to May 2003.

The following main questions were addressed: 1) how much phytoplankton is exchanged through the inlets and which is the composition of the community, according to the tidal phase and to the season? 2) Which is the effect of phytoplankton blooms that occur inside the lagoon on the tidal exchange? 3) Which are the effects of the lagoon-sea coupling on the phytoplankton photosynthetic activity?

2. *Material and methods.*

Synoptic samplings were performed at Lido, Malamocco and Chioggia inlets (Fig. 1), from June 2001 to May 2003. The sampling design, the parameters considered and the data elaboration are those reported by Bernardi Aubry and Pugnetti [2004] and by Bianchi *et al.* [this volume]. The measurements of phytoplankton photosynthesis were carried out only at Lido (May and August 2002) and Malamocco (November 2002 and January 2003).

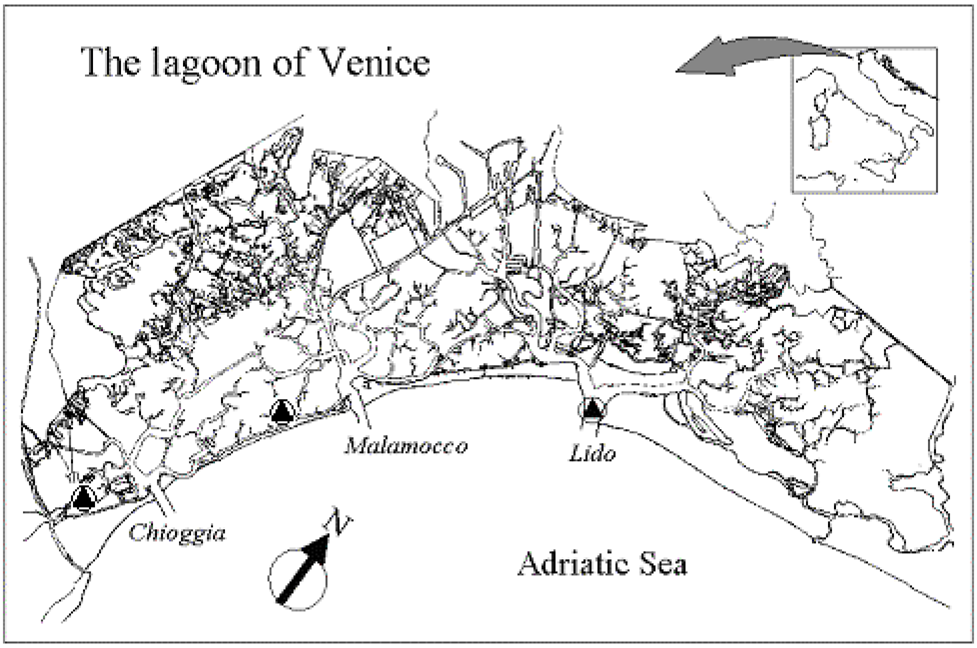

Fig. 1 – Location of the sampling stations.

3. *Synthesis of the main Results.*

The main results are synthesised in the following paragraphs, as answers to the main questions that were addressed by the project. For further details we refer to the papers by Bernardi Aubry and Acri [2004] and by Bernardi Aubry and Pugnetti [2004].

1. HOW MUCH PHYTOPLANKTON IS EXCHANGED THROUGH THE INLETS AND WHICH IS THE COMPOSITION OF THE COMMUNITY, ACCORDING TO THE TIDAL PHASE AND TO THE SEASON?

The phytoplankton showed a seasonal pattern common to the three inlets. Despite the importance of the short-term variability, known for the Lagoon of Venice [Bianchi *et al.*, 2000], the phytoplankton abundance and specie composition was mainly driven by the seasonal cycle. The abundance, the community composition and the alternations of species at flood and ebb tide show, indeed, a marked seasonality. In general, the highest abundances were recorded in summer, the lowest in winter. Species blooming in the lagoon (such as Skeletonema costatum and Nitzschia frustulum), tychopelagic species (Navicula spp, Amphora spp) and nanoflagellates characterized the phytoplankton community at ebb tide. Neritic species (mainly diatoms, e.g.: Cerataulina pelagica, Pseudonitzschia delicatissima complex, Asterionellopsis glacialis), typical of the Adriatic coastal belt, dominate the community at flood tide.

In most cases, the phytoplankton abundance was highest at flood tide (Fig. 2) and neritic species, commonly found in the North-western Adriatic coastal waters, prevailed. The phytoplankton abundances were, on the contrary, highest at ebb tide (Fig. 2) only during the blooms that occurred in the lagoon (August-October 2001, February 2002)

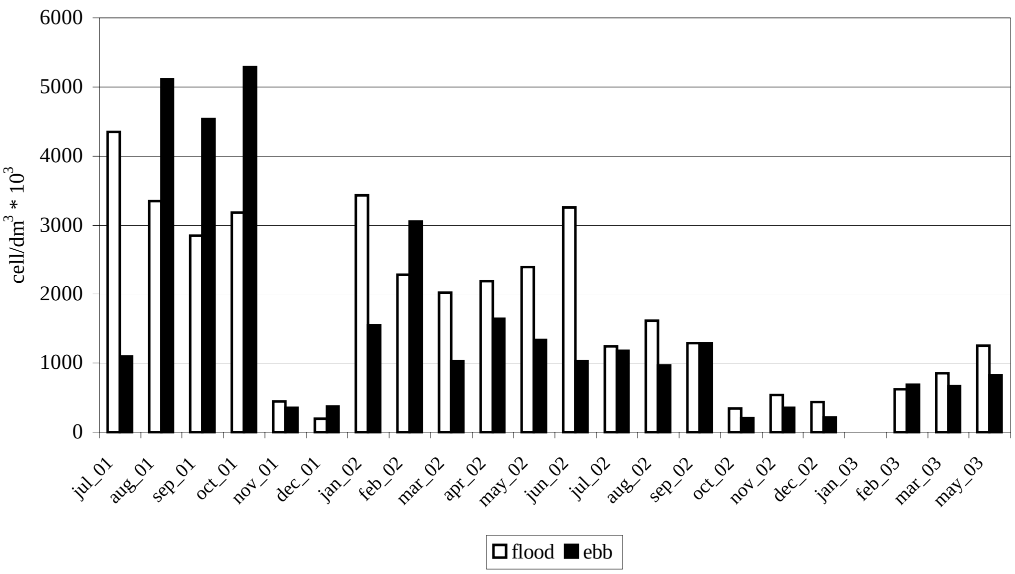

Fig. 2 – Phytoplankton abundances at ebb and flood tide. The data are averages for the three inlets.

2. WHICH IS THE EFFECT OF PHYTOPLANKTON BLOOMS INSIDE THE LAGOON ON THE TIDAL EXCHANGE?

Phytoplankton blooms occurring inside the lagoon can modify the lagoon-sea coupling of the fluxes of some biogeochemical parameters that are directly or indirectly related to the phytoplankton growth. In particular, nutrient concentrations are generally highest at ebb tide, but, when exhausted by phytoplankton blooms, this pattern appears reversed and the highest concentrations are found at flood tide. The nutrient budget, computed for the Lido (Fig. 3) [Bianchi *et al.*, 2004; this volume], indicates an import of DIN (Dissolved Inorganic Nitrogen) and silicate into the lagoon in February 2002, when a strong uptake, of both DIN and silicates, due to a diatom bloom took place in the lagoon. In spring (May 2002), DIN and silicates are exported form the lagoon to the sea, due to the much lower phytoplankton uptake. In summer (August 2002) a new phytoplankton bloom by nanoflagellates caused a deficit of DIN: DIN was imported from the sea, while silicates, not used by nanoflagellates, were exported towards the sea.

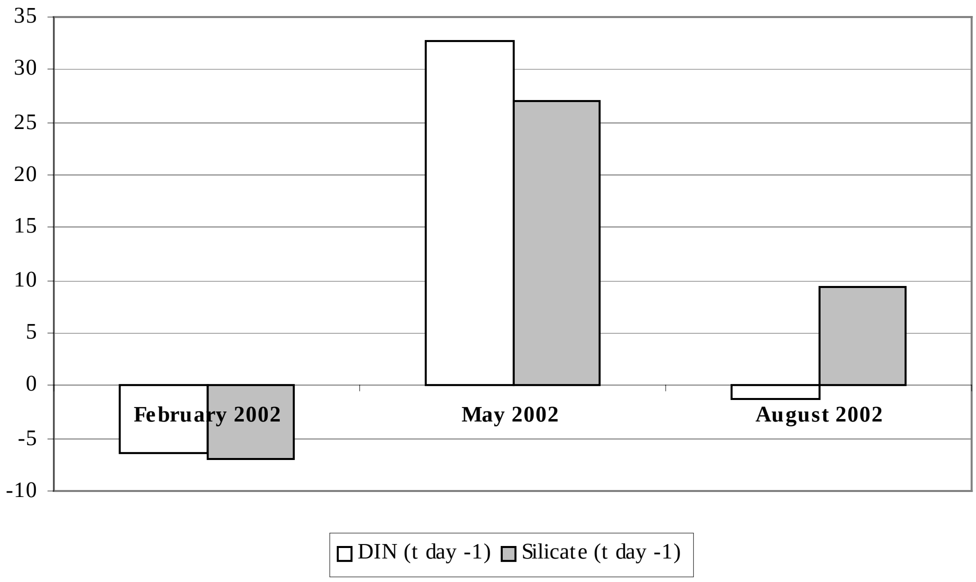

Fig. 3 – Budges of dissolved nutrients (DIN and silicates) calculated through the Lido (Bianchi *et al.*, 2004; this issue).

Moreover, as reported above, the occurrence of bloom inside the lagoon modifies the pattern of plankton exchange: the highest abundances are recorded at ebb tide and the blooming species are exported to the sea (Fig. 2).

3. WHICH ARE THE EFFECTS OF THE SEA/LAGOON EXCHANGE ON THE PHYTOPLANKTON PHOTOSYNTHETIC ACTIVITY?

The few data available in the literature on the phytoplankton production in the Lagoon of Venice indicate that the lowest values are generally recorded in the channels, where, very likely, the photosynthetic activity is hampered by the hydrodynamic [Sorokin *et al.*, 1996; 2002]. Our data (Tab. 1) seems to confirm these observations: both the primary production and the specific production were, in fact, in the lowest range of variation reported for the lagoon. The daily contribution of phytoplankton production to total particulate organic carbon was, however, quite high in summer (49%).

The analysis of the photosynthesis-light curves (Tab. 1) does not indicate a clear and univocal relation between the tidal phase and the phytoplankton photosynthetic efficiency. Moreover, the photosynthetic parameters appeared independent from the qualitative and quantitative characteristics of the phytoplankton community. Information on the physiological aspects appear therefore complimentary to those about phytoplankton structure: community with similar abundance and composition (e.g. May 2002) can show rather different photosynthetic capacity; on the other hand, communities that are clearly different at flood and ebb tide (e.g. August and November 2002) may share similar photosynthetic parameters and contribute to carbon production with a similar efficiency.

Tab. 1 – Primary production experiments: phytoplankton abundance (Ab_p), biomass (C_p), chlorophylla a (Chl a) and composition, parameters of the photosynthesis-irradiance curves (PP_{max}, P_{bmax} and a), and Photosynthetically Active Radiation (PAR).

	May 2002	**May 2002**	**August 2002**	**August 2002**	**November 2002**	**November 2002**	**January 2003**	**January 2003**
	Lido flood	**Lido ebb**	**Lido flood**	**Lido ebb**	**Malamocco flood**	**Malamocco ebb**	**Malamocco flood**	**Malamocco ebb**
Ab_p (cells ml^{-1})	2128	2106	1167	2461	488	82	662	183
C_p (μg dm^{-3})	42	42	39	70	18	7	20	5
Chl *a* (μg dm^{-3})	3.5	2.4	4.6	4.9	0.9	1.2	1.0	0.7
Diatoms (% Ab_p)	22	27	51	23	22	48	13	39
Dinoflagellates (% Ab_p)	5	5	8	10	17	6	11	6
Nanoflagellates (% Ab_p)	68	67	41	66	59	45	71	53
Coccolithophorids (% Ab_p)	3	0	0	2	2	1	4	0
PP_{max} (mg C m^{-3} h^{-1})	1.2	2.2	6.8	5.8	1.1	1.5	0.6	1.2
P_{bmax} (mg C mg Chl a^{-1} h^{-1})	0.4	0.9	1.5	1.1	1.1	1.2	0.6	1.3
α (mg C mg Chl a^{-1} (μE m^{-2} s^{-1})$^{-1}$)	0.0003	0.004	0.0058	0.0062	0.0075	0.0071	0.0072	0.008
PAR(μE m^{-2} s^{-1})	434	722	1965	1900	180	200	70	100

References.

Acri F., Bernardi Aubry F., Bianchi F., Boldrin A., Comaschi A., Rabitti S.and Socal G., 2004. Changes in nutrients and plankton communities in the lagoon of Venice from 1970s until today. *J. Mar. Sys.*, 51, 321-329

Bernardi Aubry F., Acri F., 2004. Phytoplankton seasonality and exchange at the inlets of the Lagoon of Venice (July 2001-June 2002). *J. Mar. Syst.*, 51, 65-76

Bernardi Aubry F., Pugnetti A., 2004. Phytoplankton and primary production at the inlets of the Lagoon of Venice. *Scientific Research and safeguarding of Venice*. Research programme 2001-2003, vol. II, 399-416

Bianchi F., Comaschi A. and Socal G., 1999. Ciclo annuale dei nutrienti, del materiale sospeso e del plancton nella laguna di Venezia. In: *Aspetti Ecologici e Naturalistici dei sistemi Lagunari e Costieri*, Arsenale Editrice, Venezia, 231-240

Bianchi F., Ravagnan E., Acri F., Berbardi Aubry F., Boldrin A., Camatti E., Cassin D. and Turchetto M., 2004. Variability and fluxes of hydrology, nutrients and particulate matter between the Venice lagoon and the Adriatic Sea. Preliminary results (years 2001-2002*). J. Mar. Syst.*, 51, 49-64

Bianchi F., Acri F., Alberighi L., Bastianini M., Boldrin A., Cavalloni B., Cioce F., Comaschi A., Rabitti S., Socal G. and Turchetto M., 2000. Biological variability in the Venice lagoon. In: Lasserre, P. and Marzollo, A. (Eds*) The Venice Lagoon Ecosystem. Inputs and interactions between land and sea.* Man and the biosphere series volume 25. UNESCO and Parthenon Publishing Group. 97-125

Bianchi F., Ravagnan E., Acri F., Antonini F., Boldrin A., Bressan M., Camatti E., Campesan G., Cassin D., Cesca A., Comaschi A., Giani M., Onorini Moneta D., Penzo M., Pugnetti A., Turchetto M., Van Vleet E., 2005. Quality and quantity of exchanges between the lagoon and the sea: biogeochemical parameters. *This volume*

Cervantes Duarte R, Aguirre Bahena F, Reyes Salinas A and Valdez Holguin JE, 2001. Hydrological characterization of a coastal lagoon of Baja California Sur, Mexico. *Oceanides*,16, 94-105

Curiel D., Rismondo F., Scarton F., Marzocchi M., 1997. Flowering of Zostera marina in the lagoon of Venice (North Adriatic, Italy). *Bot. Mar.*, 40, 101-105

Facca C., Sfriso A and Socal, G., 2002. Phytoplankton changes and relationships with microphytobenthos and physico-chemical variables in the central part of the Venice lagoon. *Est. Coas.l Shelf Sic.*, 54, 773-792

Kirugara D, 2001. Temperature and water exchange in a semi-closed lagoon, Bamburi, Kenya. *Coral reef degradation in the Indian Ocean: Status reports and project presentations 2000*, 129-133

Knoppers B. 1994. Aquatic primary production in coastal lagoons. In: Kjerfve B. (ed.) *Coastal lagoon processes*. Elsevier Oceanographic series, 60: 243-286

Ounissi M., Haridi A. and Retima A., 2002. Variability of the zooplankton of the Melah lagoon (Algeria) in relation to tidal advection in winter and spring 1996-1997. *J. Rech. Oceanogr.*, 27, 1-13

Ravera O., 2000. The Lagoon of Venice: the result of both natural factors and human influence. *J. Limnol.*, 59, 19-30

Sfriso A., Marcomini A., 1996. Decline of *Ulva* growth in the lagoon of Venice. *Bioresour. Technol.*, 58, 299-307

Sfriso A., Marcomini A., Pavoni B., 1987. Relationship between macroalgal biomass and nutrient concentrations in a hypertrophic area of the Venice lagoon. *Mar. Environ. Res.*, 22, 297-312

Smith S.V. and Atkinson M. J., 1994. Mass balance of nutrient fluxes in coastal lagoons. In: Kjerfve B. (ed.) *Coastal lagoon processes*. Elsevier Oceanographic series, 60, 243-286

Socal G., Bianchi F. and Alberighi L., 1999. Effect of thermal pollution and nutrient discharges on a spring phytoplankton bloom in the industrial area of the lagoon of Venice. *Vie et milieu*, 49, 19-31

Socal G., Bianchi F., Comaschi A. and Cioce F., 1987. Spatial distribution of plankton communities along a salinity gradient in the Venice lagoon. *Archo Oceanogr. Limnol.*, 21, 19-43

Socal G., Ghetti L., Boldrin A. and Bianchi F., 1985. Ciclo annuale e diversità del fitoplancton nel porto-canale di Malamocco. Laguna di Venezia. *Atti Ist. veneto Sci. Lett. Arti.*, 143, 15-30

Sorokin Yu.I., Sorokin P.Yu., Giovanardi O. and Dalla Venezia L., 1996. Study of the ecosystem of the lagoon of Venice with emphasis on anthropogenic impact. *Mar. Ecol. Prog. Ser.*, 141, 247-261

Sorokin P.Yu., Sorokin Yu.I., Zakuskina O.Yu. and Ravagnan G.P., 2002. On the changing ecology of Venice lagoon. *Hydrobiologia.* 487, 1-18

Tolomio C., Moschin E., Moro I. and Andreoli C., 1999. Phytoplankton de la Lagune de Venise. I. Bassins nord et sud (avril 1988-mars 1889). *Vie et Milieu*, 49, 33-44

Tolomio C. and Bullo L., 2001. Prelievi giornalieri di fitoplancton in una stazione del bacino meridionale della laguna di Venezia; aprile 1993 - marzo 1994. *Boll. Museo Civ. St. nat. Venezia*, 52, 3-23

Voltolina D., 1973., A phytoplankton bloom in the lagoon of Venice. *Archo Oceanogr. Limnol.*, 18, 19-37

QUALITY AND QUANTITY OF EXCHANGES BETWEEN LAGOON AND SEA. ORGANIC AND INORGANIC MICROPOLLUTANTS

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Riassunto.

Allo scopo di calcolare i flussi tra la Laguna di Venezia ed il Mare Adriatico, sono state misurate le concentrazioni di idrocarburi da petrolio, idracarburi clorurati e metalli in traccia alle bocche di porto di Lido e Malamocco. Il contributo delle forme disciolta e particellata alle concentrazioni totali varia sensibilmente a seconda dei contaminanti considerati. I bilanci di flusso calcolati mostrano come i microinquinanti organici siano generalmente in uscita al Lido e, in misura minore a Malamocco, mentre i metalli in traccia sono in uscita a Malamocco nella frazione sospesa. Questi risultati sono da considerare validi solo per i periodi di tempo relativi alle campagne svolte e non paiono adatti a calcolare bilanci di massa a scala più estesa.

Abstract.

Levels of hydrocarbons, chlorinated hydrocarbons and trace metals dissolved in the water and sorbed on SPM have been determined at the inlets of Lido and Malamocco of the Venice Lagoon using time-integrating water samplers with the aim of computing exchange fluxes between the Lagoon and the Adriatic Sea. The contribution of solute and particulate forms to the total concentrations of chemical pollutants varies with the element and the compound considered. Calculated balances of fluxes show that organic contaminants are generally outgoing at Lido and, with minor extent, at Malamocco, while trace metals appear outgoing at Malamocco in the suspended phase. These results are considered valid only for the time periods relative to the campaigns carried out and not extendible to annual mass balances.

1. Introduction.

Exchange of dissolved and particulate micropollutants between the Lagoon and Northern Adriatic Sea plays a critical role in controlling the water quality within the Lagoon. Determining the concentration at lagoon inlets is crucial to calculate input and output fluxes of contaminants and relative balances.

To evaluate the significance of these input/output, an investigation was carried out for a two year period at Lido and Malamocco port entrance using *in situ* samplers following the method previously used in another survey in the Northern part of the lagoon [Fossato *et al.*, 2000]. The following contaminants were measured over individual tidal cycles: petroleum hydrocarbons (aliphatics and polyaromatics), chlorinated hydrocarbons (pesticides and PCBs) and trace metals.

2. Materials and methods.

Samples were collected at Lido Inlet during May and November 2001, and February and May 2002, and at Malamocco Inlet during August and November 2002, and February and May 2003. Trace metals and organic compounds were collected in dissolved and suspended particulate phases (SPM) using a SeaStar B300 or Infiltrex II in situ pumping device over 5-hour periods to integrate the levels of contaminants over individual flood and ebb tidal cycles. Approximately 20-35 liters of seawater were pumped from 5 m depth through filters and columns over two tidal cycles during the periods of maximum tidal currents for each flood or ebb tide. After retrieval columns and filters for trace elements and organic compounds were treated and analyzed following the methods described in Fossato *et al.* [2000].

3. Results and discussion.

The results obtained as concentration values were relatively scattered and clear seasonal trends were not obtained.

Aliphatic hydrocarbons were easily detected both at Lido and at Malamocco, with total aliphatics and UCM generally higher during ebb tide at Lido and the opposite at Malamocco, were not statistically significant using a simple t-test. As expected, concentrations were significantly higher in suspended particulate matter at both inlets.

Within polyaromatic hydrocarbons Fluoranthene and Pyrene revealed higher concentrations both in dissolved and suspended fractions. These two aromatics, considered as good markers of pyrolitic origin, prevailed in ebb tide at Lido while at Malamocco no differences between tides were found. Moreover differences between Lido and Malamocco inlet were not statistically significant.

Chlorinated pesticides concentrations were very low or below the detection limits. Only γHCH was always present as dissolved both at Lido and at Malamocco with higher values during flood tide. PCBs results were below the detection limits in most samples.

Concerning the concentrations of trace elements in water masses flowing through Lido and Malamocco inlet, differences were not observed between ebb and flood tide both in either dissolved or suspended matter. Nevertheless, comparing the behaviour of both inlets, it was noticed that dissolved Zn appeared statistically higher in flood tide at Lido, while suspended Zn, Fe and Cu seemed significantly higher at Malamocco.

Comparing the results at Lido inlet with data obtained with the same sampling and analytical methods in the frame of the project Sistema Lagunare Veneziano [Fossato *et al.*, 2000], basic differences were not found for trace metals and polyaromatic hydrocarbons concentrations while the levels of aliphatic hydrocarbons appear higher in this study in suspended matter. Moreover, chlorinated hydrocarbons results were generally lower in this survey. In a recent paper Bloom *et al.* [2004] reported Hg concentrations in suspended matter in various part of the lagoon, which are comparable to our results.

Using current meter data and applying the correct formulas, reported elsewhere in this volume [Bianchi *et al.*], fluxes were calculated for each contaminant in g/sec for each tidal cycle. Negative fluxes (occurring on flood tides) indicate the transport of material from the Northern Adriatic Sea into the Lagoon of Venice. Positive fluxes (occurring on ebb tides) indicate the transport of material from the Lagoon into the Northern Adriatic. The flux balances were also computed for each campaign. using ebb and flow tide average results.

The resulting balances are shown in the following figures.

Fig. 1, relative to organic compounds, shows some clear evidences:

- aliphatic hydrocarbons and UCM (Unresolved Complex Mixture) generally appear outgoing at Lido, both in dissolved and in suspended phases;
- polyaromatic hydrocarbons are outgoing only at Malamocco in suspended matter;
- total pesticides appear generally ingoing at Lido inlet both in dissolved and in suspended phases.

In Fig. 2a and Fig. 2b flux balances are reported for trace metals, showing the following trends:

- at Malamocco Cd, Ni, Fe, Cu and Hg are outgoing in the suspended matter, while
- at Lido no clear trends are found, at least during the campaigns carried out.

Conclusions.

As a general trend, organic micropollutants appear to leave the lagoon mainly from the Lido port entrance, while trace metals leave the lagoon from Malamocco in the suspended form.

In spite of sampling effort, obtained data and flux calculations are, in our opinion, too sparse to permit a real computing of annual balances and may be only considered valid for the few campaign carried out. A more extensive research program based on monthly survey could probably give a better description of exchange processes of the considered micropollutants between the Sea and the Lagoon.

References.

Bianchi F., Ravagnan E., Acri F., Antonini F., Bernardi Aubry F., Boldrin A., Bressan M., Camatti E., Campesan G, Cassin D., Cesca A., Comaschi A., Giani M., Onorini Moneta D., Penzo M., Pugnetti A., TurchettoM., Van Vleet E., 2005. Quality and quantity of exchanges between the lagoon and sea: biogeochemical parameters. *This volume*

Bloom N.S., Moretto L.M., Scopece P. and Ugo P., 2004. Seasonal cycling of mercury and monomethyl mercury in the Venice Lagoon (Italy). Marine Chemistry, 91, 85-99

Fossato V.U., Campesan G., Craboledda L., Dolci F. and Stocco G., 2000. Organic micropollutants and trace metals in water and suspended particulate matter. In: "*The Venice Lagoon Ecosystem. Inputs and interactions between land and sea*". By P. Lasserre and A. Marzollo, UNESCO and Parthenon Publishing, Carnforth, 81-95

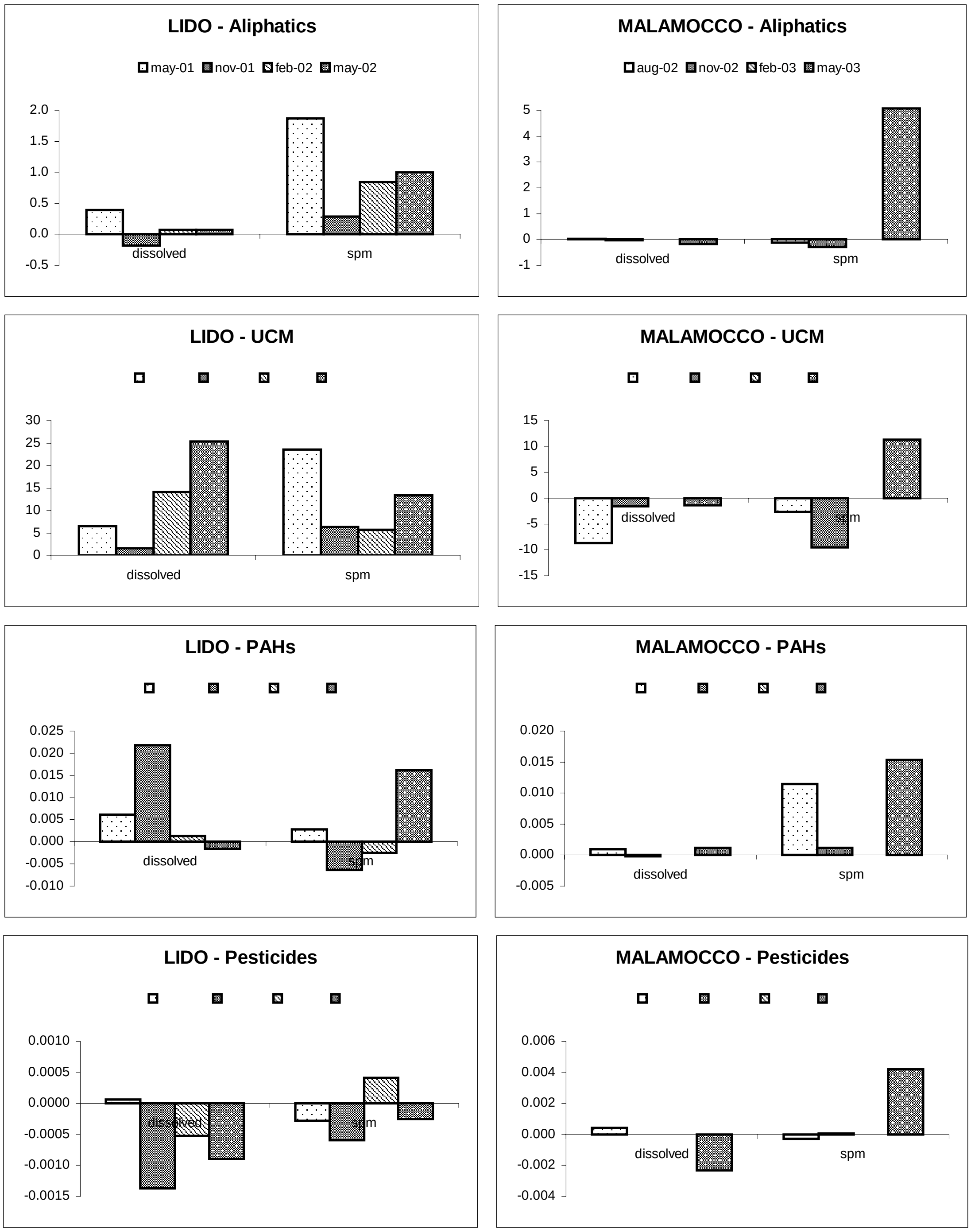

Fig. 1 – Balances of fluxes (g/sec) of organic micropollutant found in the dissolved and particulate phases between the Lagoon of Venice and the Northern Adriatic Sea. Positive values indicate flux out of the Lagoon into the Adriatic. Negative values indicate fluxes into the Lagoon from the Adriatic.

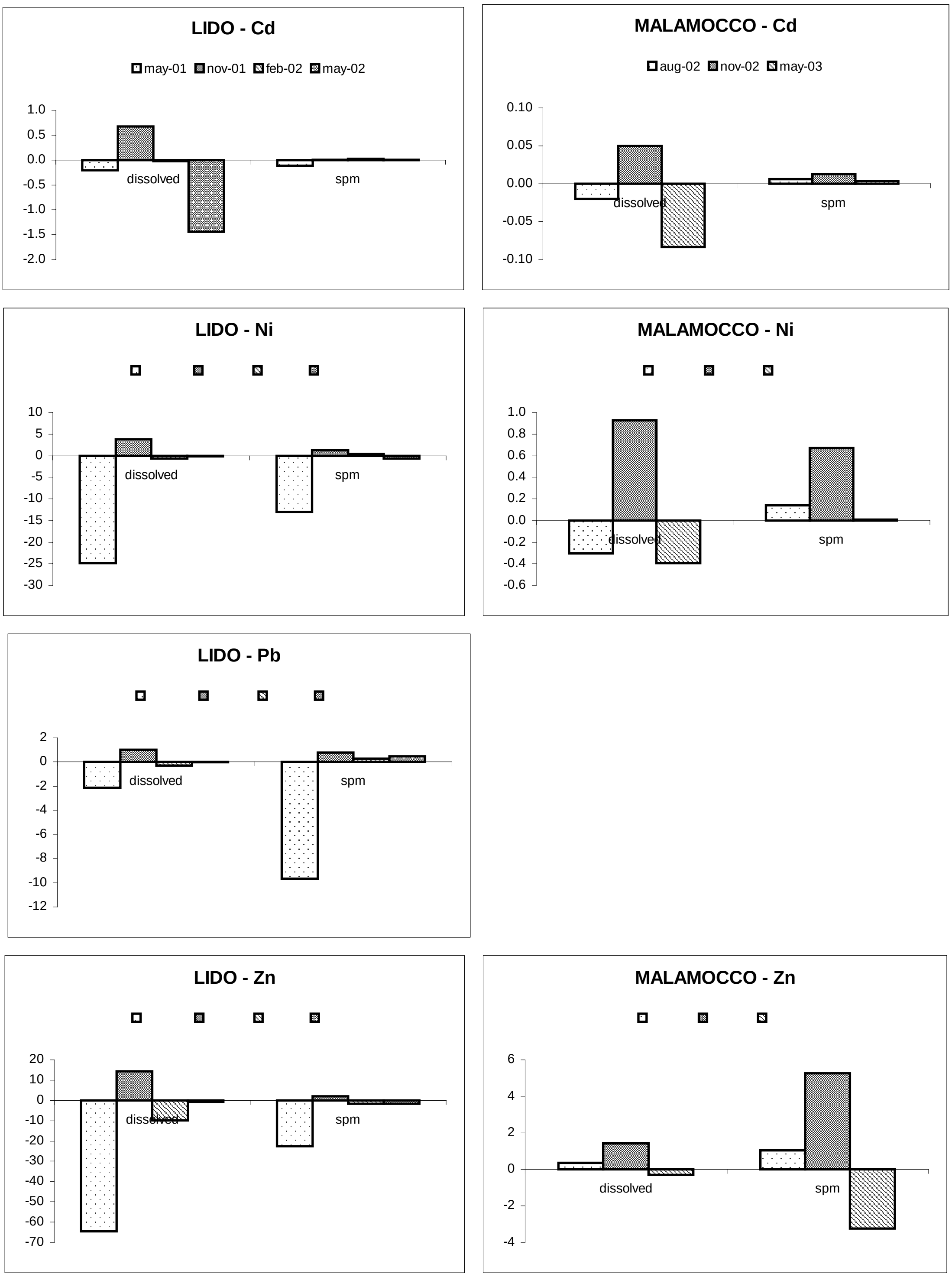

Fig. 2a – Balances of fluxes (g/sec) of trace metals found in the dissolved and particulate phases between the Lagoon of Venice and the Northern Adriatic Sea. Positive values indicate flux out of the Lagoon into the Adriatic. Negative values indicate fluxes into the Lagoon from the Adriatic.

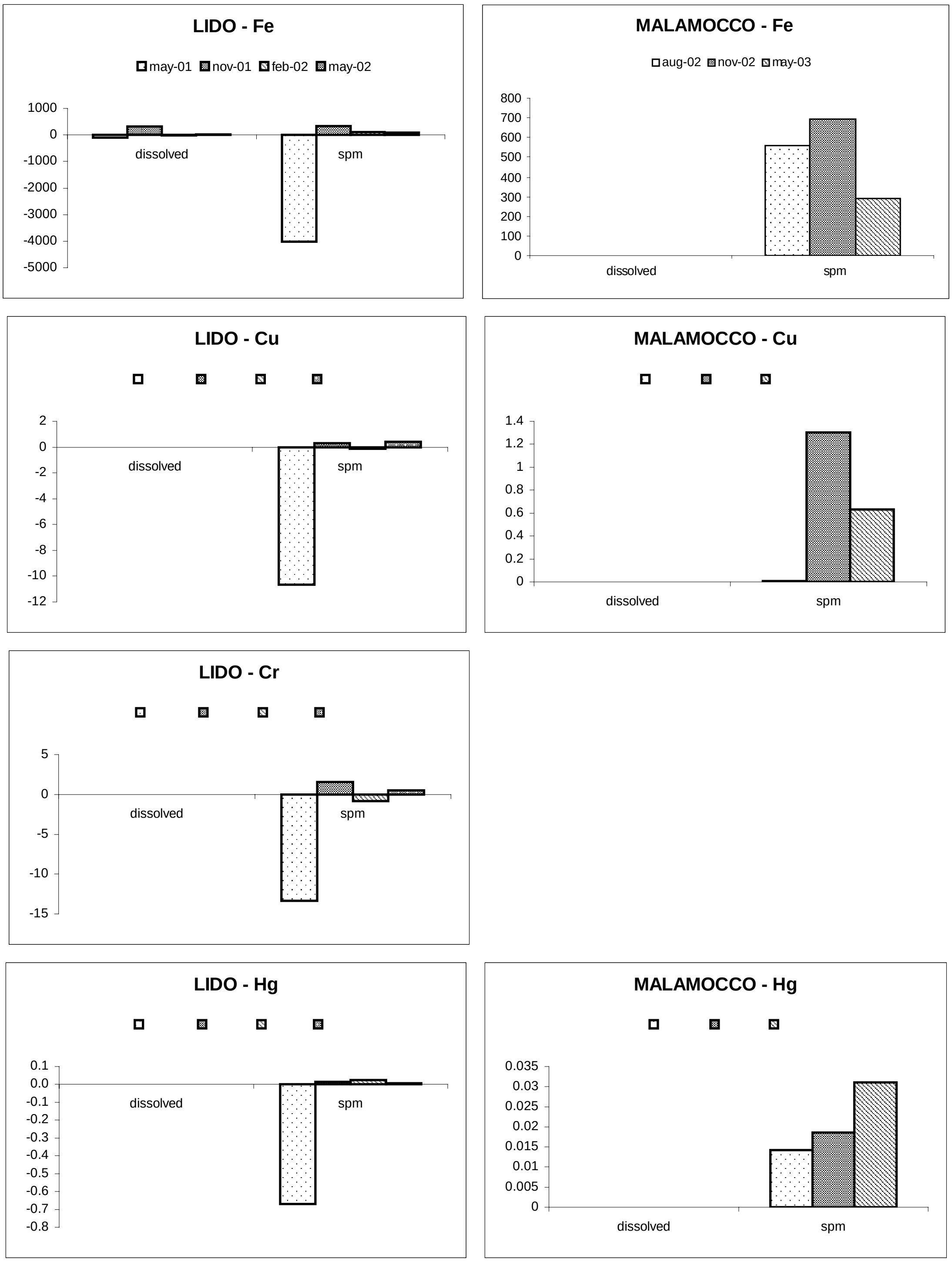

Fig. 2b – Balances of fluxes (g/sec) of trace metals found in the dissolved and particulate phases between the Lagoon of Venice and the Northern Adriatic Sea. Positive values indicate flux out of the Lagoon into the Adriatic. Negative values indicate fluxes into the Lagoon from the Adriatic.

QUALITY AND QUANTITY OF EXCHANGES BETWEEN LAGOON AND SEA. MOLECULAR ORGANIC BIOMARKERS

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Riassunto.

Il presente studio è stato svolto allo scopo di esaminare, dal punto di vista biogeochimico, gli scambi di materia organica disciolta e particellata tra la Laguna di Venezia ed il Nord Adriatico. Il maggior contributo di sostanza organica viene da sorgenti di tipo marino, e, in secondo luogo, da apporti di origine batterica. Il contributo dei biomarkers di origine terrestre appare in quantità minore, mentre quello dovuto a scarichi di tipo urbano è stato trovato in un solo campione. Nessuna differenza significativa si osserva nella distribuzione di biomarkers lipidici tra le due bocche di porto e nemmeno tra gli anni 2001 e 2002. In ogni stagione le maggiori concentrazioni si riscontrano nel particellato rispetto al disciolto, con contributo di tipo marino dominante lungo tutto l'anno. Le maggiori differenze possono essere fondamentalmente attribuite al contributo del fitoplancton. I flussi di lipidi disciolti e particellati sono generalmente maggiori in marea entrante, suggerendo un trasporto netto dal mare verso la Laguna. Alcune variazioni stagionali di questo trend evidenziano un andamento opposto. Gl acidi grassi mostrano i più alti valori di flusso, mentre idrocarburi e steroli appaiono inferiori di uno o due ordini di grandezza.

Abstract.

The present study was undertaken to examine the biogeochemical fluxes of dissolved and particulate organic material between the Lagoon of Venice and the Northern Adriatic Sea. The greatest contribution to the organic matter in all samples came from marine sources, with bacterial sources contributing the second greatest amount. Only minor amounts of terrestrial organic biomarkers were present, and sewage biomarkers were observed in only one sample. No significant differences in lipid biomarker distributions or concentrations were observed between the port entrances of Lido and Malamocco or between samples collected in the years 2001 and 2002. During each season, concentrations were higher in the SPM than in the DOM, with marine inputs dominating throughout the year. Most differences could be attributed to differences in source materials, and primarily to inputs from phytoplankton. Dissolved and particulate lipid fluxes were generally greater on the incoming flood tide than during the ebb tide, suggesting a net transport of dissolved lipids from the Adriatic into the Lagoon. Some seasonal variations from this trend did exist, and resulted in net transport from the Lagoon to the Adriatic. Fatty acids showed the highest fluxes of

material with hydrocarbon and sterol fluxes being one to two orders of magnitude lower than those for fatty acids.

1. Introduction.

Exchange of dissolved and particulate organic material between the Lagoon and Northern Adriatic Sea plays a critical role in controlling water quality within the Lagoon and ecosystem health in the coastal waters of the Northern Adriatic. Determining the different sources of organic matter as well as their quantitative contribution can help establish the role that organic matter plays in maintaining the health of these ecosystems.

Several organic compounds have been established for tracing the contribution of terrestrial, marine and anthropogenic components to the organic carbon found in marine sediments and seawater (including both dissolved and particulate phases). These naturally produced organic molecules have been called “biological marker compounds” or “biomarkers” because they can be unambiguously linked with biological precursor compounds due to the fact that their basic structures are preserved in recognizable form throughout the diagenetic process. Lipid biomarkers can be used to differentiate inputs from terrestrial organisms, marine organisms, bacteria, and sewage sources. To evaluate the significance of these inputs, a systematic investigation of composition and fluxes of lipid biomarkers was carried out in the Lagoon of Venice and the Northern Adriatic Sea. Samples were collected over tidal cycles from two Lagoon inlets on a seasonal basis for a two-year period in order to investigate temporal distribution and fluxes of selected organic compounds diagnostic of source input.

2. Materials and Methods.

The source-specific molecular biomarkers investigated in this study are described in Tab. 1. These compounds represent the major source-specific components normally found in marine, terrestrial, bacterial and sewage inputs. Samples were collected at Lido Inlet during May and November 2001, and February and May 2002, and at Malamocco Inlet during August and November 2002. Dissolved organic matter (DOM) and suspended particulate matter (SPM) were collected using a SeaStar B300 or Infiltrex II *in situ* pumping device over 5-hour periods to integrate the levels of molecular biomarkers over individual flood and ebb tidal cycles. Approximately 30-45 liters of seawater were pumped from mid-depth through filters and columns over two tidal cycles during the periods of maximum tidal currents for each flood or ebb tide. Following retrieval of the SeaStar or Infiltrex samplers, filters and columns were extracted and each of the lipid components described in Tab. 1 were analyzed by gas chromatography and combined gas chromatography as previously reported [Van Vleet, 2004]. Statistical analyses were carried out to investigate variability within the Lagoon from different major source inputs (marine organisms, terrestrial organisms, bacteria, and sewage) and over various time scales (tidal, seasonal, and annual). A “fit model” of log-transformed data using JMP [Sall and Lehman, 1996] was employed to assess differences in the concentration of organic components. Estimated fluxes of these organic materials into and out of the lagoon were determined using current meter and tidal data.

Tab. 1 – Lipid compounds analyzed in the current study to investigate the sources of dissolved and suspended organic matter. Designation refers to the number of carbon atoms, number of double bonds, and position of the double bond where appropriate (example: 16:1w7 Fatty Acid indicates 16 carbon atoms, 1 double bond located in the w7 position, i.e. counting from the opposite end from the carboxyl group of the fatty acid). All carbon chains are normal configuration with no branching unless otherwise noted. PUFA = polyunsaturated fatty acid. HBI - = Highly branched isoprenoid. References are given in footnote at bottom of table.

Compound	**Source**	**Organism**	**Reference**
MARINE SOURCES			
Fatty Acids			
12:0	Marine	Phytoplankton	2, 4
14:0	Marine	Phytoplankton	2, 4
16:0	Marine	Phytoplankton	2, 4
16:1w7	Marine	Phytoplankton	2, 4
16:2	Marine	Phytoplankton	2, 4
16:3	Marine	Phytoplankton	2, 4
18:0	Marine	Phytoplankton	2, 4
18:1w9	Marine	Phytoplankton	2, 4
18:2	Marine	Phytoplankton	2, 4
18:3	Marine	Phytoplankton	2, 4
20:0	Marine	Phytoplankton	2, 4
20:1	Marine	Phytoplankton	2, 4
20:2	Marine	Phytoplankton	2, 4
20:4w6	Marine	Phytoplankton	2
20:5w3	Marine	Phytoplankton	2, 7
22:6w3	Marine	Zooplankton	7
28:0 PUFA	Marine	Dinoflagellates	1
Alcohols			
14:0	Marine	Phytopl/Zoopl	4, 8
16:0	Marine	Phytopl/Zoopl	4, 8
18:0	Marine	Phytopl/Zoopl	4, 8
20:0	Marine	Phytopl/Zoopl	4, 8
Phytol	Marine	Phytoplankton	4, 8
Sterols			
Cholesterol	Marine	Zooplankton	4, 9
Brassiacasterol	Marine	Diatoms	1, 6, 9, 11
Dinosterol	Marine	Dinoflagellates	2, 4, 11
Hydrocarbons			
C15	Marine	Phytopl/Zoopl	4, 11
Pristane	Marine	Zooplankton	4
C17	Marine	Phytopl/Zoopl	4, 11
C19	Marine	Phytopl/Zoopl	4, 11
C25 HBI	Marine	Diatoms	1
C30 HBI	Marine	Diatoms	1

[1][Volkman *et al.*, 1998] [4][Ohkouchi *et al.*, 199]7 [7][Pond *et al.*, 1997] [10][Sherwin *et al.*, 1993]
[2][Mudge *et al.*, 1998] [5][Wakeham *et al.*, 1997a] [8][McCaffrey *et al.*, 1991] [11][Fahl and Stein,1999]
[3][Mudge and Norris, 1997][6][Wakeham *et al.*, 1997b][9][Mudge *et al.*, 1999]

Tab. 1 – Continued.

TERRESTRIAL SOURCES			
Fatty Acids			
24:0	Terrestrial	Plants	2, 4
26:0	Terrestrial	Plants	2, 4
28:0	Terrestrial	Plants	2, 4
30:0	Terrestrial	Plants	2, 4
32:0	Terrestrial	Plants	2, 4
Alcohols			
24:0	Terrestrial	Plants	4, 8
26:0	Terrestrial	Plants	4, 8
28:0	Terrestrial	Plants	4, 8
Sterols			
B-sitosterol	Terrestrial	Plants	9
Stigmasterol	Terrestrial	Plants	3
Hydrocarbons			
C25	Terrestrial	Plants	4, 8, 11
C27	Terrestrial	Plants	4, 8, 11
C29	Terrestrial	Plants	4, 8, 11
C31	Terrestrial	Plants	4, 8, 11
C33	Terrestrial	Plants	4, 8, 11
BACTERIA SOURCES			
Fatty Acids			
C15 iso-branched	Bacteria	Bacteria	2, 5, 6
C15 anteiso-branched	Bacteria	Bacteria	2, 5, 6
C15	Bacteria	Bacteria	2, 5, 6
C16:1w9	Bacteria	Bacteria	2, 5, 6
C17 iso-branched	Bacteria	Bacteria	2, 5, 6
C17 anteiso-branched	Bacteria	Bacteria	2, 5, 6
C17	Bacteria	Bacteria	2, 5, 6
18:1w7	Bacteria	Bacteria	2, 6
C21	Bacteria	Bacteria	2, 5, 6
3-hydroxy fatty acids	Bacteria	Bacteria	2
Sterols			
Stanols (degradation)	Bacteria	Bacteria	8
SEWAGE SOURCES			
Sterols			
Coprostanol	Mammals (humans)	Sewage	9, 10
Epicoprostanol	Mammals (humans)	Sewage	9, 10

3. Results and Discussion.

3.1. Summary of the distribution of organic compounds.

Detailed descriptions of the distribution and concentrations of individual organic compounds were reported in Van Vleet [2004]. Concentrations of total fatty acids, hydrocarbons and sterols in dissolved and particulate organic matter were generally higher in the SPM than in the DOM. Concentrations of fatty acids were always much higher than the concentrations of hydrocarbons or sterols. In most cases, cholesterol was the only sterol observed, commonly originating from a variety of marine zooplankton. Occasionally, minor amounts of brassiacasterol (from diatoms), B-sitosterol (terrestrial plants) and stigmasterol (terrestrial plants) were also observed.

3.2. Summary of the variations in source inputs.

Lipid biomarker concentrations were used to infer source inputs from different biotic origins. Detailed descriptions of the variations in source inputs were reported in Van Vleet [2004]. The greatest contribution to the organic matter in all samples came from marine sources. Bacterial sources contributed the second greatest amount of organic matter. Only minor amounts of terrestrial organic biomarkers were present in either the dissolved or particulate organic fractions, and sewage biomarkers were observed in only one sample during the study. In general, concentrations were higher in the suspended material than in the dissolved material during each season and throughout the flood and ebb tidal cycles.

3.3. Fluxes of organic compounds.

Fluxes of lipid biomarkers were estimated using current meter and tidal data. Fluxes of organic components are reported in units of [g/sec] and also in [tons/day]. Negative fluxes (occurring on flood tides) indicate the transport of material from the Northern Adriatic Sea into the Lagoon of Venice. Positive fluxes (occurring on ebb tides) indicate the transport of material from the Lagoon into the Northern Adriatic. No significant differences were observed in lipid fluxes between Lido and Malamocco inlets.

Fatty acids show the highest fluxes of material on both the incoming and outgoing tides. Hydrocarbon and sterol fluxes were one to two orders of magnitude lower than those for fatty acids (Tab. 2). This was true for both dissolved lipids and particulate lipids. It can be seen from Fig. 1 that for dissolved fatty acids, the fluxes were generally greater on the incoming flood tide than during the ebb tide, suggesting a net transport of dissolved lipids from the Adriatic into the Lagoon. Trends in particulate fatty acid fluxes are not as clear, with the net transport generally being from the Adriatic to the Lagoon, but with some seasonal variations from this trend (Fig. 1). In November, 2001 (fall season) the fluxes of particulate fatty acids were much larger (136 g/sec) on the ebb tide than they were on the flood tide (-47 g/sec), indicating a net transport of particulate fatty acids from the Lagoon to the Adriatic during this period. That trend was not observed the following year (November 2002). The direction and magnitude of the net transport of lipid material can be seen more clearly in Tab. 3. In most cases, the net transport of total dissolved and particulate lipids is negative indicating an overall flux of material from the Northern Adriatic into the Lagoon during most of the year. The strong positive net transport of particulate lipids from the Lagoon to the Adriatic during November 2001 (7.8 tons/day) indicates a large anomaly to the trend observed most of the rest of the year (Tab. 3).

Tab. 2 – Fluxes of dissolved and particulate lipid biomarkers measured during ebb and flood tide. Positive values indicate fluxes from the Lagoon to the Northern Adriatic Sea. Negative values indicate fluxes from the Northern Adriatic into the Lagoon. Values of "0" indicate below detection limits (<0.1 g/sec).

			DOM Avg Flux (g/sec)				SPM Avg Flux (g/sec)			
Month/Year	Season	Tide	Fatty Acids	Hydrocarbons	Sterols	**Total Flux (tons/day)**	Fatty Acids	Hydrocarbons	Sterols	*Total Flux* **(tons/day)**
May-01	Spring	Ebb	46	0	0	**4.0**	68	0	0	**6.0**
May-01	Spring	Flood	-64	0	0	**-5.5**	-84	0	0	**-7.3**
Nov-01	Autumn	Ebb	-	0	-	**0.0**	136	0	0	**11.8**
Nov-01	Autumn	Flood	-45	0	0	**-3.9**	-47	0	0	**-4.1**
Feb-02	Winter	Flood	-	-	-	**-**	-	-	-	**-**
Feb-02	Winter	Flood	-23	0	0	**-2.0**	-65	0	0	**-5.6**
May-02	Spring	Ebb	12	0	0	**1.0**	45	0	0	**3.9**
May-02	Spring	Flood	-21	0	0	**-1.8**	-44	0	0	**-3.8**
Aug-02	Summer	Ebb	9	0	0	**0.8**	55	0	1	**4.8**
Aug-02	Summer	Flood	-29	0	0	**-2.5**	-60	0	-1	**-5.2**
Nov-02	Autumn	Ebb	7	0	0	**0.6**	20	0	0	**1.8**
Nov-02	Autumn	Flood	-5	0	0	**-0.4**	-32	0	0	**-2.7**

Tab. 3 – Net transport of dissolved and particulate lipids between the Lagoon of Venice and the Northern Adriatic Sea. Positive values indicate net transport from the Lagoon to the Northern Adriatic Sea. Negative values indicate net transport from the Northern Adriatic into the Lagoon.

Month/Year	Season	Net Transport Of Total Dissolved Lipids (tons/day)	Net Transport Of Dissolved Marine Lipids (tons/day)	Net Transport Of Dissolved Bacteria Lipids (tons/day)	Net Transport Of Total Particulate Lipids (tons/day)	Net Transport Of Particulate Marine Lipids (tons/day)	Net Transport Of Particulate Bacteria Lipids (tons/day)
May-01	Spring	-1.5	-1.0	-0.6	-1.3	-1.6	0.3
Nov-01	Autumn	-3.9	-	-	7.8	-	-
Feb-02	Winter	-	-	-	-	-	-
May-02	Spring	-0.8	-0.6	-0.2	0.1	0.0	3.5
Aug-02	Summer	-1.7	-1.4	-0.3	-0.4	-3.0	-0.2
Nov-02	Autumn	0.2	0.2	0.0	-0.9	-1.0	0.1

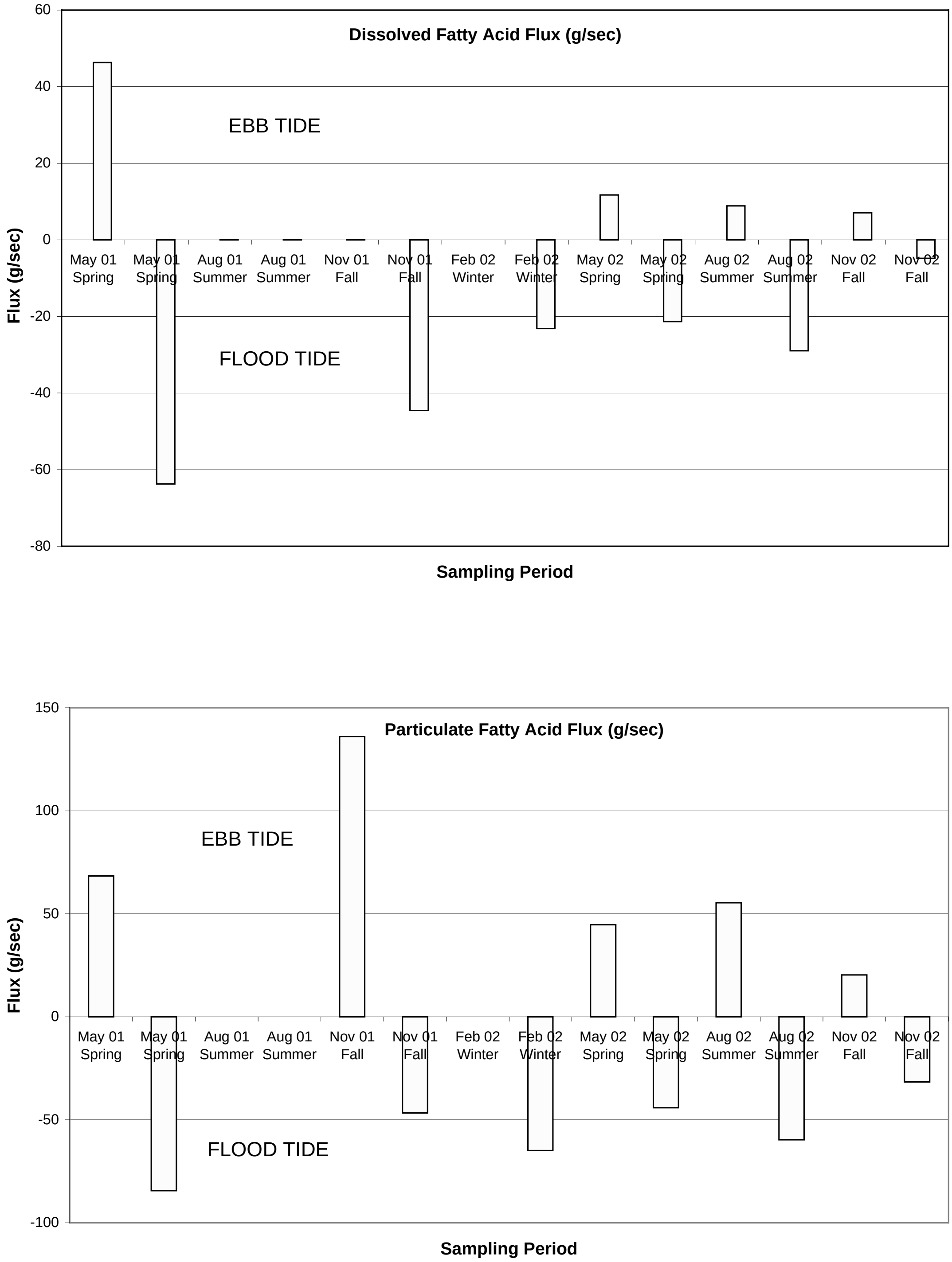


Fig. 1 – Fluxes (g/sec) of total fatty acids found in the dissolved (top) and particulate (bottom) organic matter between the Lagoon of Venice and the Northern Adriatic Sea. Positive values indicate flux out of the Lagoon into the Adriatic. Negative values indicate fluxes into the Lagoon from the Adriatic.

Fluxes of lipid biomarkers between the Lagoon and the Adriatic are dominated by lipid compounds originating from a marine origin (Tab. 4). Although terrestrial and sewage derived inputs appear to be negligible, microbially derived lipids also produce significant input into the total lipid pool (Tab. 4). Nonetheless, marine derived lipids account for an average of 77% of the total. As expected, fluxes of both dissolved and particulate marine lipids are higher on flood tides than on ebb tides (Fig. 2), thus confirming an overall transport of marine derived lipids from the Adriatic into the Lagoon. The same trend is also observed for dissolved bacterially derived lipids (Fig. 3). Lipids arising from bacteria associated with particles, however, show a more complex trend, with higher fluxes being observed on the ebb tides in the spring (May) for both years studied (2001 and 2002) (Fig. 3). The net transport of marine and bacterially derived lipids throughout the year are also shown in Tab. 3. Again it can be seen that during most of the year, negative values dominate, indicating a net transport from the Northern Adriatic Sea into the Lagoon of Venice. Microbial lipids associated with particulate material seem to be an exception to this trend during the spring season.

Conclusions.

The greatest contribution of lipids to the organic matter in the Lagoon of Venice comes from marine sources, with bacterial sources contributing the second greatest amount. Only minor amounts of terrestrial organic biomarkers were present in both fractions, and sewage biomarkers were observed in only one sample.

No significant differences in lipid biomarker distributions or concentrations were observed between the port entrances of Lido and Malamocco or between samples collected in the years 2001 and 2002. Seasonal variability indicated that during each season, concentrations are higher in the SPM than in the DOM, and that marine inputs dominate throughout the year. Most differences could be attributed to differences in source materials, and primarily to inputs from phytoplankton.

Fatty acids show the highest fluxes of material on both the incoming and outgoing tides. Hydrocarbon and sterol fluxes were one to two orders of magnitude lower than those for fatty acids. Fluxes of lipid biomarkers were dominated by compounds originating from a marine origin. Although terrestrial and sewage derived inputs appeared to be negligible, microbially derived lipids also produced significant input into the total lipid pool. Dissolved and particulate lipid fluxes were generally greater on the incoming flood tide than during the ebb tide, suggesting a net transport of dissolved lipids from the Adriatic into the Lagoon. Some seasonal variations from this trend did exist, and resulted in net transport from the Lagoon to the Adriatic.

These data, combined with those of other investigators working on this project, can be used to develop models for predicting coastal exchange processes and forecasting the development of environmental problems. This in turn will lead to improved management practices which are critical in maintaining the ecological health of the Lagoon of Venice and Northern Adriatic Sea.

Tab. 4 – Fluxes of dissolved and particulate lipid biomarkers resulting from different source materials. Positive values indicate fluxes from the Lagoon to the Northern Adriatic Sea. Negative values indicate fluxes from the Northern Adriatic into the Lagoon. Values of “0” indicate below detection limits (<0.1 g/sec).

			Avg DOM Flux (g/sec)					Avg SPM Flux (g/sec)				
Month/Year	Season	**Tide**	Marine	Terrestrial	Bacteria	Sewage	**Total Flux (tons/day)**	Marine	Terrestrial	Bacteria	Sewage	**Total Flux (tons/day)**
May-01	Spring	Ebb	42	0	4	0	**4.0**	58	0	11	0	**6.0**
May-01	Spring	Flood	-53	0	-11	0	**-5.5**	-77	0	-8	0	**-7.3**
Nov-01	Autumn	Ebb	-	-	-	-	**-**	-	-	-	-	**-**
Nov-01	Autumn	Flood	-43	0	-1	0	**-3.8**	-44	-2	-3	0	**-4.3**
Feb-02	Winter	Flood	-	-	-	-	**-**	-	-	-	-	**-**
Feb-02	Winter	Flood	-22	0	-1	0	**-2.0**	-60	0	-5	0	**-5.6**
May-02	Spring	Ebb	10	0	2	0	**1.0**	41	0	4	0	**3.9**
May-02	Spring	Flood	-17	0	-4	0	**-1.8**	-41	0	-3	0	**-3.8**
Aug-02	Summer	Ebb	8	0	2	0	**0.8**	51	0	5	0	**4.9**
Aug-02	Summer	Flood	-24	0	-5	0	**-2.5**	-86	-14	-7	0	**-9.2**
Nov-02	Autumn	Ebb	6	0	1	0	**0.6**	19	0	2	0	**1.8**
Nov-02	Autumn	Flood	-4	0	-1	0	**-0.4**	-31	0	-1	0	**-2.7**

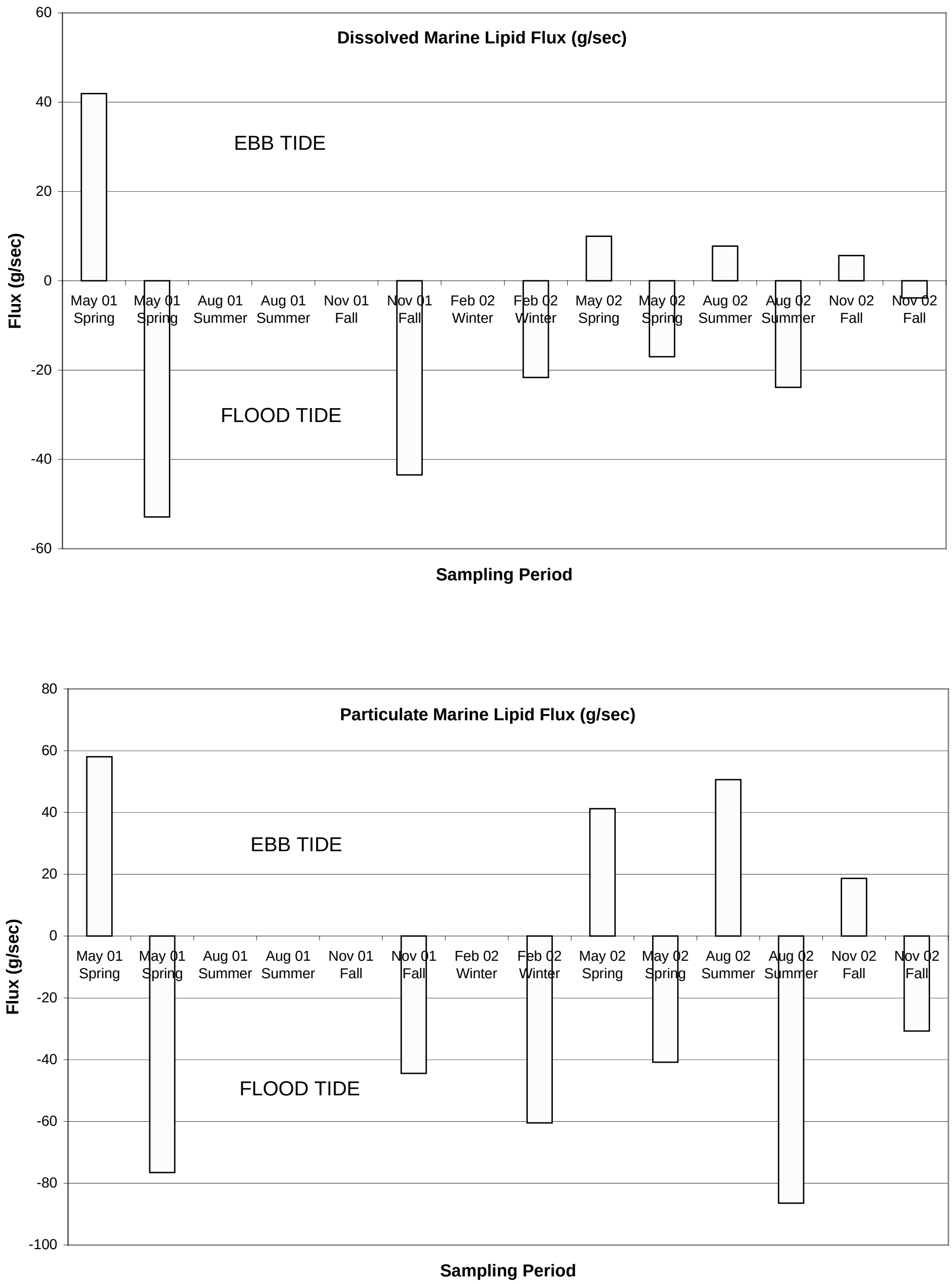
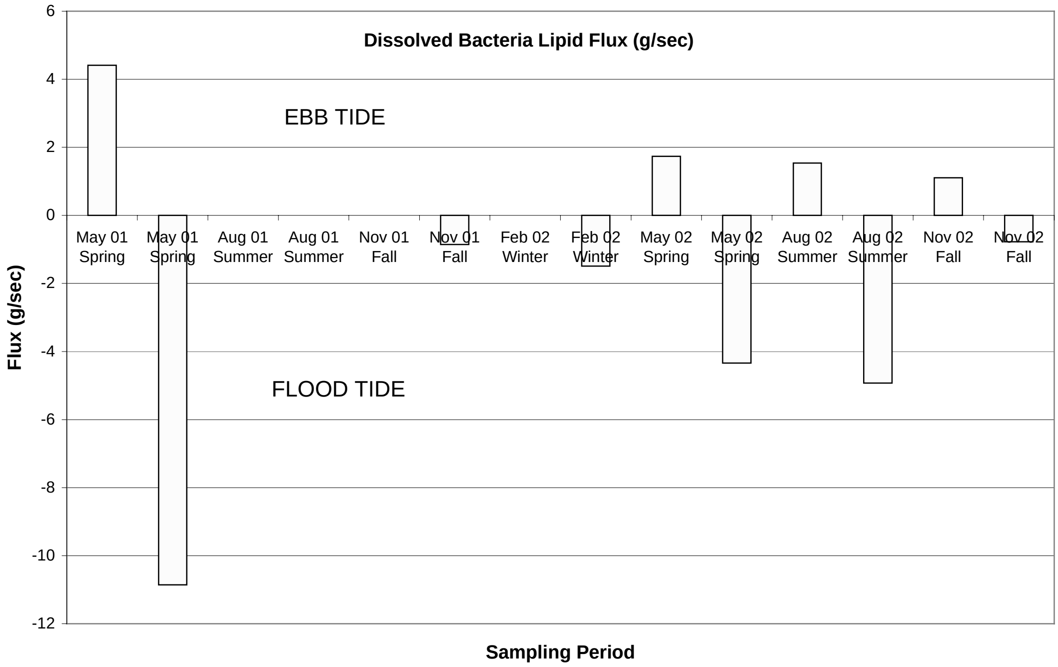


Fig. 2 – Fluxes (g/sec) of lipids of marine origin found in the dissolved (top) and particulate (bottom) organic matter between the Lagoon of Venice and the Northern Adriatic Sea. Positive values indicate flux out of the Lagoon into the Adriatic. Negative values indicate fluxes into the Lagoon from the Adriatic.



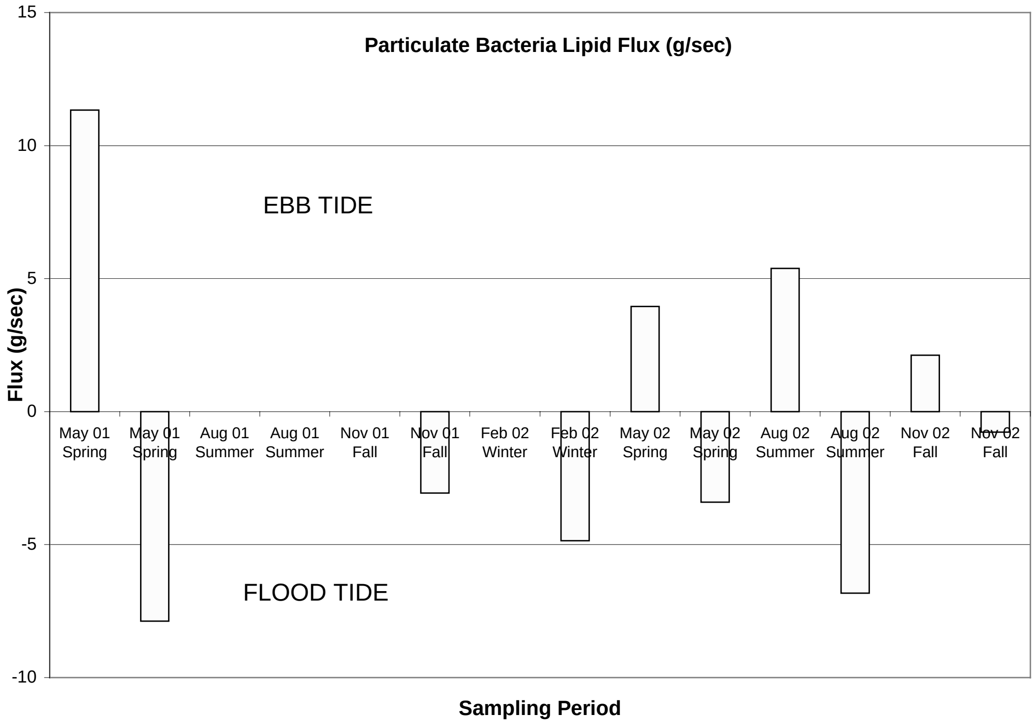


Fig. 3 – Fluxes (g/sec) of lipids of bacterial origin found in the dissolved (top) and particulate (bottom) organic matter between the Lagoon of Venice and the Northern Adriatic Sea. Positive values indicate flux out of the Lagoon into the Adriatic. Negative values indicate fluxes into the Lagoon from the Adriatic.

References.

Fahl K. and R. Stein., 1999. Biomarkers as organic-carbon-source and environmental indicators in the late quaternary Arctic Ocean: Problems and perspectives. Marine Chemistry 63:293-309

McCaffrey M.A., J.W. Farrington and D.J. Repeta., 1991. The organic geochemistry of Peru margin surface sediments: II. Paleoenvironmental implications of hydrocarbon and alcohol profiles. Geochimica et Cosmochimica Acta 55:483-498

Mudge S.M., L.A. Barreira, M.J. Bebianno and J.A. East., 1999. Sterols in the Ria Formosa lagoon, Portugal. Water Research 33:1038-1048

Mudge S.M., L.A. Barreira, J.A. East and M.J. Bebianno., 1998. Fatty acids in the Ria Formosa Lagoon, Portugal. Organic Geochemistry 29:963-977

Mudge S.M. and C.E. Norris., 1997. Lipid biomarkers in the Conwy Estuary (north Wales, UK): a comparison between fatty alcohols and sterols. Marine Chemistry 57:61-84

Ohkouchi N., K. Kawamura and A. Taira., 1997. Fluctuations of terrestrial and marine biomarkers in the western tropical Pacific during the last 23,300 years. Paleoceanography 12:623-630

Pond D.W., J.R. Sargent, D.R. Dixon, M.V. Bell and A.E. Fallick., 1997. Occurrence of 16:2(n-4) and 18:2(n-4) fatty acids in the lipids of the hydrothermal vent shrimps *Rimicaris exoculata* and *Alvinocaris markensis*: Nutritional and trophic implications. Marine Ecology Progress Series 156:167-174

Sall J. and A. Lehman., 1996. JMP Start Statistics: A Guide to Statistical and Data Analysis Using JMP and JMP IN Software. Duxbury Press. Albany

Sherwin M.R., E.S. Van Vleet, V.U. Fossato and F. Dolci., 1993. Coprostanol (5B-cholestan-3B-ol) in lagoonal sediments and mussels of Venice, Italy. Marine Pollution Bulletin 26:501-507

Van Vleet E.S., 2004. Mass Balance Fluxes between the Northern Adriatic and the Lagoon of Venice: Use of Molecular Organic Biomarkers to Investigate Mass Fluxes. Final Report submitted to CORILA. 31p

Volkman J.K., M.P., Mansour, E.L., Sikes, F. Gelin, S.M. Barrett and S.I. Blackburn., 1998. Microalgal biomarkers: A review of recent research. Organic Geochemistry 29:1163-1179

Wakeham S.G., P.J. Hernes, M.L. Peterson, C. Lee and J.I. Hedges., 1997a. Molecular indicators of diagenetic status in marine organic matter. Geochimica et Cosmochimica Acta 61:5363-5369

Wakeham S.G., M.L. Peterson, P.J. Hernes, J.I. Hedges and C. Lee., 1997b. Compositions and transport of lipid biomarkers through the water column and surficial sediments of the equatorial Pacific Ocean. Deep-Sea Research 44:2131-2162

SAND TRANSPORT IN NORTHERN VENICE LAGOON

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Riassunto.

Scopo principale di questo work-package è determinare lo scambio di sedimenti tra laguna e mare, con particolare enfasi sul trasporto di sabbia. La valutazione è stata fatta utilizzando diversi approcci complementari: (1) modellazione numerica usando SHYFED e SEDTRANS05 [Umgiesser *et al.*, in questo volume]; (2) confronto di batimetrie; (3) analisi granulometriche; (4) misure sul campo; (5) accertamenti mineralogici [Bonardi *et al.*, 2002]. L'articolo riassume una valutazione dei risultati ottenuti con due campagne di misura effettuate nel 2003 – 2004 [Amos *et al.*, 2004], specificatamente per i punti (2) e (3) sopraindicati. Le analisi hanno mostrato (a) un trasporto costiero di sabbie, in direzione sud-ovest, verso la spiaggia del Cavallino; (b) un accumulo di sabbia fine in un ampio delta di riflusso, fuori dalla bocca di Lido; (c) una chiara area di accumulo nella bocca di Lido; (d) un debole accumulo nel delta di flusso (Baccan); (e) una netta erosione all'interno del Canale di Treporti, con deposito alla bocca del canale stesso, (fuori da Punta Sabbioni). Questi iniziali risultati supportano le conclusioni fornite dal modello, che evidenzia un chiaro trasporto di sabbia dalla Laguna di Venezia verso il mare, attraverso la bocca di Lido, alimentando la formazione di un complesso delta di riflusso. Sono evidenti anche i buchi di erosione nel punto di incontro di tre canali, ed il forte sviluppo di un delta di riflusso nel Canale di Burano, in prossimità delle bocche dei canali Scanello e S. Antonio. La variazione batimetrica rilevata induce a pensare ad un movimento di materiale nei canali, la cui direzione verso il mare presuppone una sottrazione di sabbia dalla zona nord della laguna.

Il passo successivo sarà la definizione del meccanismo che governa tale sottrazione, in termini di quantità di sabbia annualmente trasportata.

Abstract.

The main purpose of this linea is to determine the exchange of sediment between the lagoon and the sea with emphasis on the transport of sand. This evaluation is being undertaken through several complimentary approaches: (1) numerical modelling using SHYFED and SEDTRANS05 [see Umgiesser *et al.*, this volume]; (2) through a bathymetric comparison; (3) through grain trend analysis; (4) through direct measurements; and (5) through mineralogical assessments [Bonardi *et al.*, 2002]. This paper is an evaluation of results from two field campaigns undertaken in 2003-2004 [Amos *et al.*, 2004]: specifically, items (2) and (3) above. These analyses have shown (1) a southwest longshore transport of sand on the shoreface of Cavallino; (2) an

accumulation of fine sand in a broad ebb-tidal delta off Lido inlet; (3) a net accumulation in the Lido inlet; (4) a subtle accumulation over the flood-tidal delta (Baccan); and (5) net erosion of the inner Treporti Canal system and deposition at Treporti Canal mouth (off P. Sabbioni). These initial results support the conclusions of modelling; that there is a net export of sand from Venice Lagoon through the Lido inlet that is feeding the growth of a complex ebb-tidal delta. Also noted was the scouring of holes at canal triple junctions, and the strong development of ebb-tidal deltas in Burano Canal at the mouths of Scanello and S. Antonio Canals. The overall pattern seen in the changing bathymetry is diagnostic of a movement of material into the canals and seawards suggesting that sand is being lost to the northern lagoon system. The next step is to define the mechanisms governing this loss and the annual volumes of sand in transport.

1. Introduction.

The nomenclature and terminology used in this paper is that defined and described in detail in the Coastal Engineering Manual [1998] Engineering and Design COASTAL GEOLOGY. The general setting of coastal lagoons and their morphological components are discussed in these volumes. Also discussed are the roles of tidal deltas and inlets; a discussion which is particularly relevant to Lido inlet. Also of great relevance are the sections on Cross-shore Sediment Transport Processes and Longshore Sediment Transport. These excellent compilations form the basis of definitions and background reference material for the present study.

The purpose of this paper is to review activities related to the mass transport of sand in northern Venice Lagoon. This work compliments the activities undertaken by Umgiesser et al. on a bottom-up approach (through numerical modelling), those of Mazzoldi, Gačić et al., on long-term ADCP measurements within the inlets and Tosi, Bonardi et al., on high-resolution geophysical exploration. The over-arching objectives of this work are:

(1) to provide top-down evaluations of the transport pathways and mass transport of sand through Lido Inlet, through a morphological analysis of bathymetric data;

(2) to provide in-situ measurements of sand transport at key sites (in Lido inlet) in order to calibrate long-term ADCP measurements in Lido inlet and in particular to attempt to relate backscatter to sand concentration in suspension;

(3) to determine the transport pathways (using grain trend analysis and mineralogical provenance) of sand from source to sink, and the exchanges between morphological elements of our system;

(4) to determine the regime relationship [Bruun, 1978] of the Lido-Treporti-Burano system for existing tidal prisms; and

(5) to define the key mechanisms controlling the mass balance of sand in northern Venice Lagoon.

We anticipate some convergence of results between direct measurements, numerical modelling (bottom-up), grain trend analysis, mineralogical provenance, and morphological analyses (top-down). The sum total of these analyses will provide a robust description of sand transport in the northern lagoon that may form the model for an extension of the work to Malamocco and Chiogga inlets. A full mass balance for Venice Lagoon is only possible once such a series of analyses have been undertaken.

2. Background information.

Venice Lagoon is a tidal-dominated lagoon but with strong wave influences [after Hubbard *et al.*, 1979]. It is also classified as restricted [after Kjerve and Magill, 1989] due to the partial chocking of the lagoon by a well-developed, linked barrier island system made of sand [after Carter, 1988]. The dominant factor governing the long-term evolution of this coastal lagoonal system is the stability and evolution of this barrier island system which is controlled by the availability and supply of sand. The dynamics of barrier island/inlet systems is well reviewed in the Coastal Engineering Manual [1998] and Bruun [1978]. The type of coastal setting and its morphological manifestation is governed by the relative proportions of sand to mud. This is demonstrated clearly in the EMPHASYS Report [2002] *"A Guide to Prediction of Morphological Change within estuarine Systems.* When mud dominates, then fringing tidal flats and wetlands dominate the coastal landscape and barrier islands are largely absent; when sand dominates, then beaches, barriers and lagoons dominate. The fact that Venice is located within a lagoon immediately illustrates the dominating role of sand in the evolution of this coastal setting. The string of barrier islands and beaches fronting Venice Lagoon attest to the supply and longshore transport of sand from fluvial point sources in the NE [Gazzi *et al.*, 1973], as well as artificial replenishment. Indeed much of the shelf off Venice is composed of sand (sculpted into megaripples) indicative of high-energy events in the past high in sand content.

The geomorphological features that comprise Venice Lagoon form part of a system of **elements** that interact and change in time [Townend, 2004]. Using the **systems strategy** defined by Townend [ibid], we wish to understand how the various elements interact through time and the dynamics which control this interaction. From this knowledge-base, robust predictions of evolution may be made using **a top-down strategy**. The results of such an approach may be compared with numerical simulations or measurements of the hydrodynamic processes that drive coastal evolution through a **bottom-up strategy**. At a **macro-scale**, the shoreline may be viewed as the interface between sources within the catchment region that are largely driven by atmospheric variables, and the maritime sinks (and ultimately to the deep-sea). At the **meso-scale**, emphasis is placed on understanding the evolution of coastal morphological features such as dunes, beaches, inlets, and channels. (It is this scale which is the focus of this study). The **micro-scale** is also important: Within the context of Venice Lagoon, studies such as F-ECTS [Bergamasco *et al.*, 2003] were largely at this scale with emphasis on animal-sediment relationships, plant effects, human activities, and degree of exposure. Much of this work is reported within the Special Issue on Venice Lagoon [Gačić and Solidoro, 2004] and in the papers of Schiozzi and Brambati [2000], Coracci *et al.* [2004] and Umgiesser *et al.* [2004].

As a starting point, it is vital to clarify the concept of a **coastal cell**. That is, the region within which elements of our system are linked by a common sediment transport pathway (from source to sink). We know that the majority of sediment within our system is derived from the rivers feeding the coastline [Carbognin and Cecconi, 1997].

The coastal cell of Venice Lagoon is thus defined by the catchment of the major rivers that once drained into it: the Tagliamento, Piave, Sile, Brenta, Adige etc. The sands can be traced from source to sink through mineralogical analyses [Gazzi *et al.*, 1973; Weltje, 1995]. These analyses clearly demonstrate that most is held in the coastal shoreface of Venice and moves in a SW direction along the shoreline. It is the longshore transport of sand over the last 5000 years that has been key to the development and evolution of Venice Lagoon [Bondesan and Meneghel, 2004].

The most important morphological (coarse grained) elements of our system are: **beach-shoreface**; **ebb-tidal delta; flood-tidal delta**; **channel-inlet**; **tidal channels**; and **tidal flats**. Sand is cycled between and through these elements as they move from source to sink. The divergence or convergence of the transport vectors along the transport pathways determines net growth or loss within a given element. It follows that the sum total change of all elements defines the evolutionary trend of the lagoon as a whole (the mass balance). Our first task is thus to examine the morphological changes which manifest this mass balance of sand.

The mass balance of fine-grained sediment has been documented by Carbognin and Cecconi [1997] to be outwards at 1 x 10^6 m^3/yr. However, the inorganic sediment budget of Venice Lagoon comprises two parts: fines (moving largely in suspension) and sand/gravel (moving largely as bedload/saltation). The mass balance of the coarse-grained elements influences profoundly the stability and evolution of the fine-grained elements: **salt marshes**; **mudflats**, **mud banks**; and **canals.** Without the protection afforded by the sandy barrier islands, Venice Lagoon would not exist nor would the sheltering effects of the lagoon, which allows deposition of fines and mudflat creation, be possible. Without the stabilizing influence of a sandy substrate (which characterises most estuarine tidal settings [Evans, 1965; Perillo, 1995], a mudflat would not be able to accumulate. This is because the sand provides a stable foundation (above the influences of stronger, eroding tidal flows) for mudflat growth and affords shelter from locally-generated waves. The submerged beaches of Burano Canal are examples of this sheltering effect [Amos *et al.*, 2002]. This trend is common to most estuaries with the exception of those dominated by fluid mud. It is thus key to the long-term evolution of the tidal flats of Venice Lagoon. Following the notation of Dal Monte and Di Silvio [2002], we consider Lido inlet to be a first order (rank) channel, Treporti and S. Nicolò to be second order channels, Burano, S. Felice to be third order channels, and Scanello, S. Antonio Crevan and Gaggian channels to be fourth order channels. One objective is to examine the link between channel order and morphological evolution.

3. Results.

A total of 300 line km of bathymetry, sidescan sonar, and 3-D sonar data were collected during this study. As well, 258 bottom sand samples were collected within the transport cell of Venice Lagoon (rivers, beaches, inlets, and canals). The details of these surveys are reported in Amos *et al.* [2004]. The results of the bathymetric survey are presented within four distinct sub-environments of northern Venice Lagoon: Lido inlet and ebb-tidal delta; inner Lido inlet and flood-tidal delta; Treporti Canal; and Burano Canal and tributaries. The interpreted bathymetry has been compared to the bathymetry of 1990 supplied by Umgiesser (CNR) to define regions of erosion and deposition. As well, first order estimates of annual fluxes have been calculated from the volumetric estimates and inferences made on the transport directions of sand.

The results of bathymetry and sidescan backscatter intensity, determined during our survey, are shown in Figures 1(A) and 1(B) respectively. The region covered is from the Lido inlet through Treporti Canal and to the head of Burano Canal (a primary canal system). We included the major (secondary canals) tributaries to this system (Scanello, S. Antonio, S. Felice, and Cravan Canals). The data is tidally corrected, calibrated against direct measurements, and considered spatially accurate to ± 5 m. All features evident in the 1990 data set are evident in our data. However, it is immediately clear that we have not covered the distal parts of the ebb-tidal delta. The backscatter shows trends consistent with the bathymetry and with the bottom samples: low backscatter in the mud belt off Cavallino; intermediate backscatter on the ebb-tidal delta, the sandy Treporti Canal, and the submerged beaches of lower Burano Canal; and high backscatter on Cavallino beaches, the flood-tidal delta and the submerged beaches of S. Felice Canal. In general terms, the region of Venice Lagoon extending east of a line running through S. Erasmus Island and through inner Scanello Canal is sand dominated; west of that line the bed is predominantly muddy.

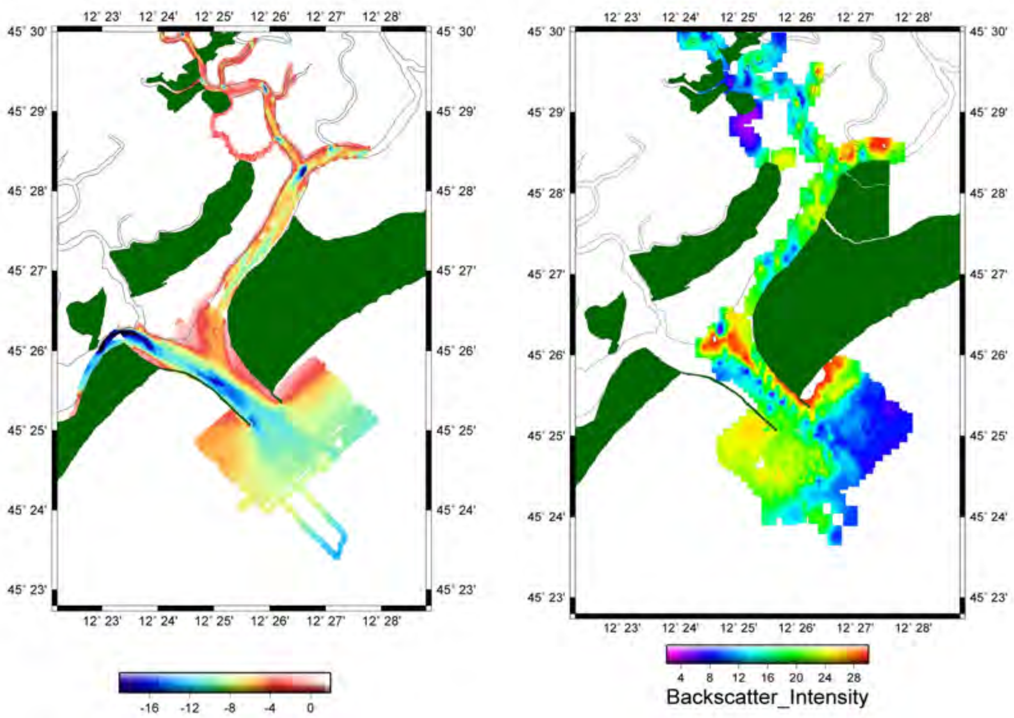

Fig. 1(A) – Bathymetry of the Lido Inlet and Northern Venice Lagoon surveyed in 2004. (B) – Backscatter intensity (dimensionless) of the study region taken from sidescan sonar. All depths are in metres.

3.1. Outer Lido, the ebb delta, and Cavallino beaches.

A survey of the bathymetry of the outer Lido region (a first order canal) was undertaken in May, 2004. The survey lines are shown in Fig. 2(A). The bathymetric plot shows clearly scouring within the mouth of Lido and the existence of a classical asymmetric ebb-tidal delta reflecting a longshore transport to the south [after Oertel, 1982]. The entrance may be classified as “restricted” in the terminology of Kjerve and Magill [1989] and is tide dominated [after Hubbard *et al.*, 1979]. Clearly seen in the figure is the main throat of the channel a marginal flood channel to the northeast, and an asymmetric terminal lobe oriented to the SW. The inlet has the character of being “stable” based on Fitzgerald [1988], and the presence of swash bars formed by landward migration behind the southernmost breakwater. A middle ground is evident several km off the entrance and sub-aqueous levees are evident off each breakwater. The two elements of flow through an idealised inlet are evident: the jet, which is the cause of scouring in the entrance and mouth, and the expanding lobe, which is the cause of the depositional apron (terminal lobe) off the Lido inlet. Swash platforms are evident beyond the levees either side of the two main breakwaters [after Carter, 1988].

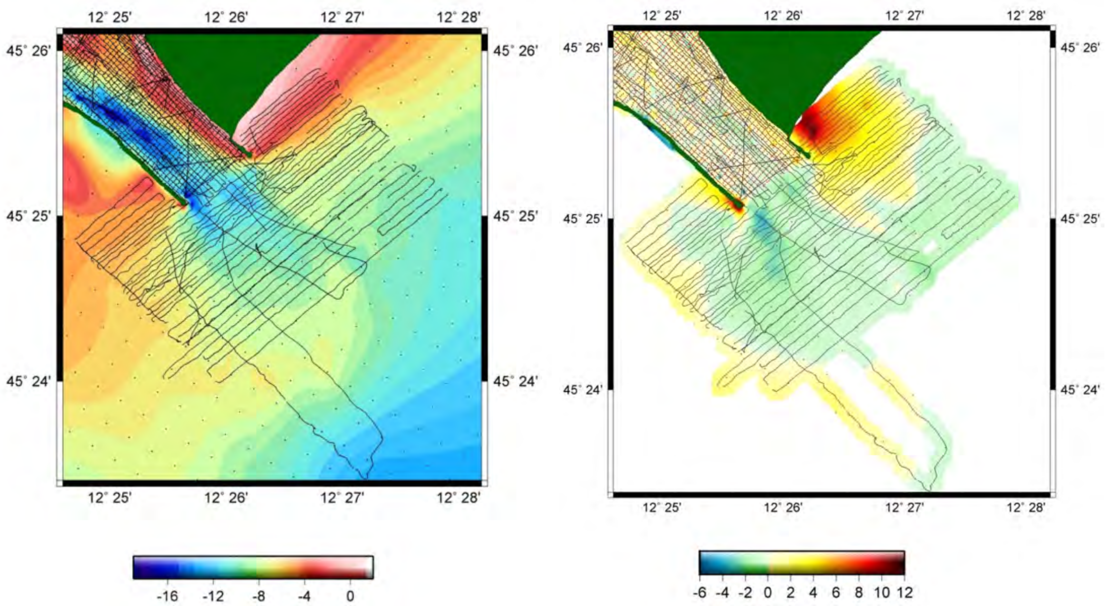

Fig. 2(A) – A bathymetric plot of Lido inlet and ebb-tidal delta based on collected 2004. The survey lines were collected as part of this study and were used to show changes in bed level 2(B). All depths are in metres.

Our survey covers the majority of the lateral parts of the delta but does not extend to the delta front. However, it covers the swash platforms and jet regions of the throat of the inlet. A comparison of bathymetry between 1990 and 2004 is shown in Fig. 2(B). The region of greatest sand accumulation (8 m) is adjacent to the northern breakwater on Cavallino beach where infill of the construction canal has occurred. Infill has extended to the seaward limit of the breakwater where evidence exists of a newly formed lateral lobe. Accumulation (up to 10 m) of fine sand has taken place adjacent to the southern breakwater in the lee of the ebb-tidal jet. 1-2 m of deposition has occurred along the northern margin of the Lido inlet. To a lesser extent, infill of the entrance has taken place throughout at an approximate rate of 0.1 m/yr. The southern distal part of the ebb delta shows up to 3 m accretion. This region is composed almost entirely of fine sand (Fig. 3) and shows internal, form-concordant stratification indicative of growth

(Tosi, pers. comm., 2004). The region has been mapped by Albani *et al.* [1998] as part of the inner littoral-lagoonal foraminiferal biotope, and hence linked to a source within Venice Lagoon. It is thus unlikely that sediment bypassing of Lido inlet (from northwest to southeast) is taking place. The source of the sand is thus from within Venice Lagoon. Umgiesser *et al.* [this volume] shows that SHYFED and SEDTRANS05 model of flow for 1987 conditions yields an export of fine sand to the Adriatic through Lido inlet. Our results agree with this interpretation. It remains to see if the model can predict the depocentre of sand on the southern delta lobe. The source of the sand is somewhat enigmatic: the map of Bondesan *et al.* [2004] shows that the margins of Treporti Canal are composed of fine sand, as is much of southern Burano Canal. As shall be seen, erosion of these canals is the most likely source.

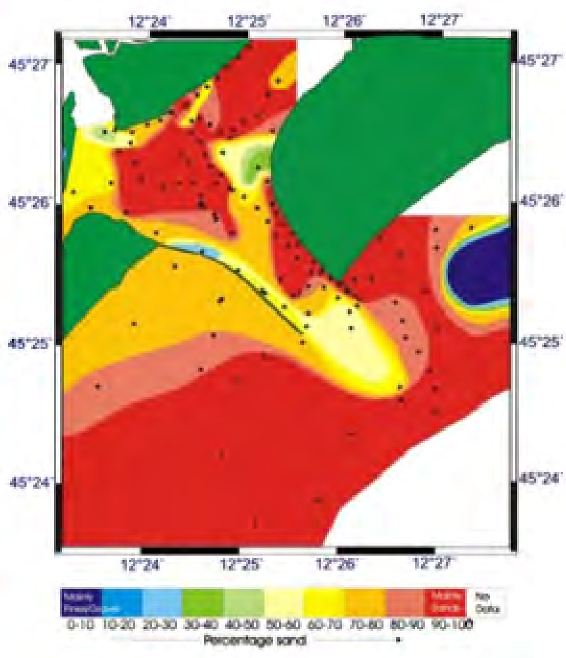

Fig. 3 – Bottom samples collected during 2004 as part of this study. The contours denote percentage sand.

Scour appears to be occurring off the southern breakwater (up to 6 m) and to a lesser extent off the central Lido inlet. The region of maximum scour corresponds to the main ebb-tidal channel. Dredging of the shipping channel is also evident on the delta top.

The majority of the region is underlain by well-sorted sand. The exceptions are the ebb-tidal channel in Lido inlet and the ebb jet over the inner delta ramp which are composed of shelly gravel lag. Sand in this region is thus moved largely in suspension and does not settle to the bed in the long term. A region of mud is also evident on the inner shelf north of the tidal delta. This mud belt (dark blue region in Fig. 3) has been noted earlier by several authors [Gazzi *et al.*, 1973; Albani *et al.*, 1983] and is probably the result of river plume sedimentation through "oceanic flooding" events as described by Wheatcroft and Borgeld [2001] from the Piave and Tagliamento rivers.

3.2. Inner Lido and the flood delta.

This survey covered much of the inner Lido inlet, and as far landwards as S. Nicolò in the west. Lines were surveyed as far landwards S (over Baccan) as water depth would allow (1 m), and the lower portions of Treporti Canal were also included. The survey lines and interpreted bathymetry are shown in Fig. 1(A). The region is dominated by a flood-tidal delta (Baccan) that has formed at the confluence of S. Nicolò, Treporti and the Lido inlet. It is welded into the island of S. Erasmus in a manner typical of many lagoonal systems reported in the literature. The flood ramp of the delta is a site of maximum net accumulation (2 m). Much of the inner survey region is also depositional. High accumulation was evident on the shore-attached ebb spit, near P. Sabbioni. The northern flank of Lido inlet navigation channel is also strongly depositional (2 m of sand) as is the ebb channel. The backscatter intensity from the seabed indicates that the sand is contiguous with the sandy beaches of Cavallino (Fig. 1(B)) and hence suggests spill-over around the northern breakwater is remitting with a net inflow of sand into the lagoon. However, the flood channel appears to have increased in depth perhaps in response to the lateral deposition of sand. The patchy nature of bed level changes is suggestive of dredging activities of the inlet that complicates interpretation of natural trends. The trends we found agree largely with those published by Magistrato alle Acque [1993], with the exception of the absence of erosion in the ebb tidal channel within Lido inlet.

The flood-tidal delta is composed of pure sand, whereas the channels have a high shelly gravel content. The ebb dominant tidal channel is largely scoured clean of sand. Hence accumulated material must be a coarse shelly lag.

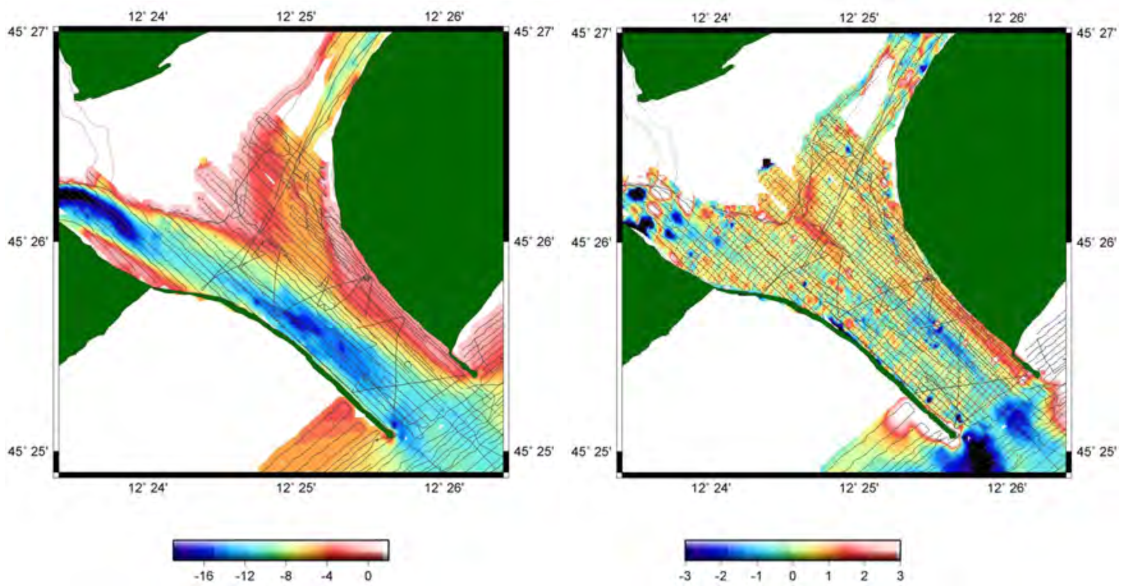

Fig. 4(A) – Survey lines undertaken during 2003 and 2004 of inner Lido inlet and flood-tidal delta, and the interpreted bathymetry; 4(B) – Comparison of bathymetry between 1990 and this survey. All depths are reported in metres.

3.3. Treporti Canal.

The main features seen in the Treporti Canal (a second order canal) is the deep central channel (8 m) and the scour (20 m) at the triple junction of Treporti-Burano-S. Felice Canals (Fig. 5(A)). The scour hole has been studied in detail by Reed [2001] and active erosion was evident during this survey. The mechanism given for the scour was instabilities at the front between converging water masses at the triple junction of second and third order canals. Deepening of the scour the has taken place by about 3 m showing that the mechanism of erosion continues today. Accretion around the scour has formed a berm that is typical of scouring in general. Scour holes are also evident at fourth and third order canals (such as Crevan and Gaggian). These are asymmetric in form, and have berms associated with them at the margins of the regions of scour.

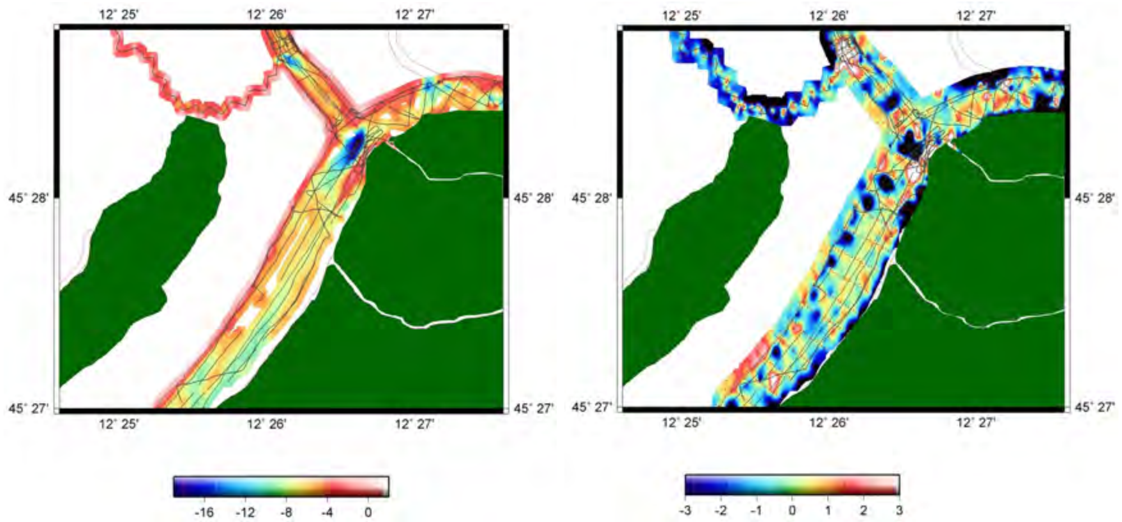

Fig. 5(A) – Survey lines undertaken during 2003 and 2004 of Treporti Canal and outer S. Felice Canal, and the interpreted bathymetry; 5(B) – Comparison of bathymetry between 1990 and this survey. All depths are reported in metres.

The backscatter in Treporti is intermediate in intensity and diagnostic of a sandy substrate. The highest intensities are found off a tributary of Cavallino and is associated with a depositional prodelta developing on the margin of the main canal. High vaues of backscatter are evident along the banks of Southern Palude della Centrega and are associated with well developed submerged beaches in this region which have been documented and monitored in previous studies.

The irregular patchwork of net accretion and erosion is likely due to the orientation of survey lines in the two surveys being compared, which are at right angles. There appears to be a general trend of erosion along the Cavallino margin and deposition along the S. Erasmus margin. S. Felice canal shows infill whereas south Burano canal appears subject to erosion. These trends are also highly patchy in nature and may reflect simply the survey structure.

3.4. Burano Canal.

Burano canal (a third order canal) was surveyed along its entire length. Also included were the fourth order canals of Cravan, Scanello, S. Antonio, Mazzorbo. The canal system is shallower than Treporti and lacks clearly defined ebb and flood tidal pathways. He dominant features of this region are the scour holes at the mouths of the fourth order canals. Burano is slightly flood dominant yet the scour holes are all oriented seawards (Fig. 6(A)). There appears to be scouring at the margins of the canal and infill at the central deeper axis. The greatest accumulation has taken place as berms around the scour holes. The most profound example is off Cravan (Fig. 6(B)), where more than 3 m of accumulation has taken place in the form of a nascent ebb-tidal delta. Other examples of berm development are clear off Scanello and S. Antonio. The inference of this is that these canals are exporting large amounts of material into Burano Canal during the ebb-tide phase. This export was measured in an ADCP survey of the region reported in Amos *et al.* [2002].

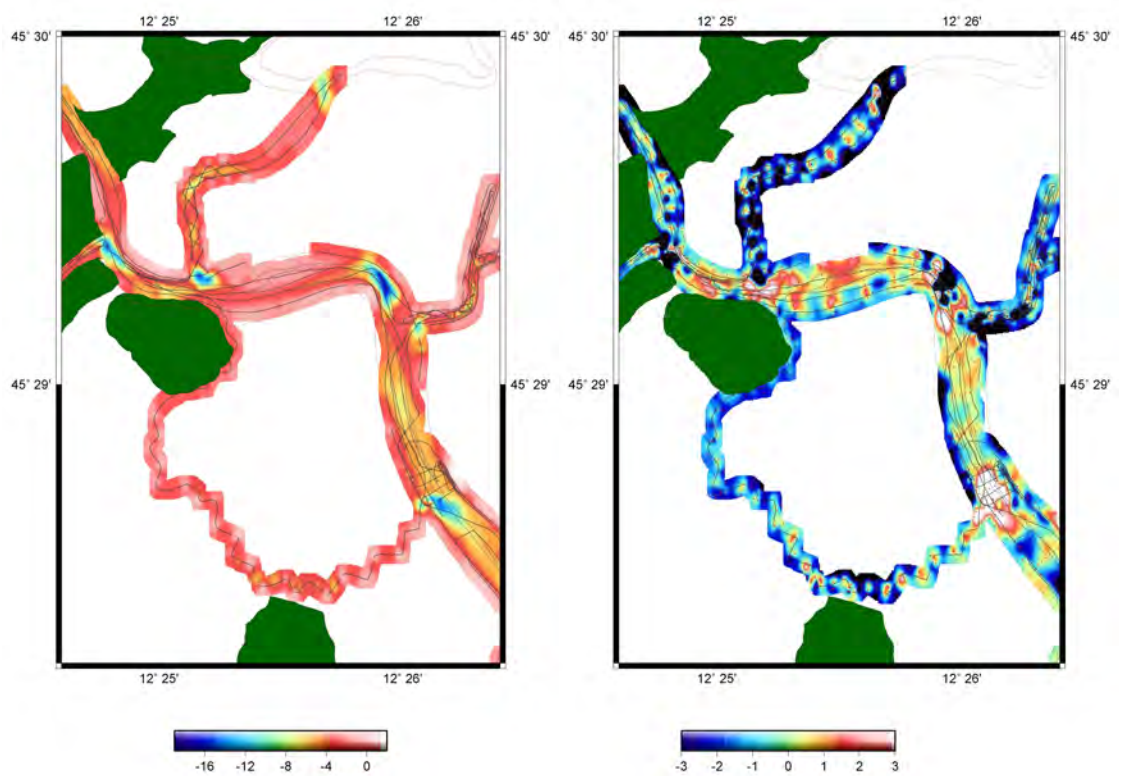

Fig. 6(A) – Survey lines undertaken during 2003 and 2004 in N, Burano Canal and tributaries, and the interpreted bathymetry; 6(B) – Comparison of bathymetry between 1990 and this survey. All depths are in metres.

The seabed backscatter in Burano Canal decreases in intensity from south to north. The lowest values appear around Burano and Mazzorbo Islands and within the S. Antonio Canal. Curious high intensity reflectors were observed in Scanello Canal in the region indicated as possessing Roman archaeological artefacts. High values were also detected adjacent to S. Erasmus Island in Cravan Canal. We presume that sand erosion and transport is taking place with movement towards Burano Canal.

4. Discussion of results.

The results presented in this paper are the first phase of a three phase survey of the net movement of sand in the Lido inlet and associated canal system. It largely comprises an interpretation of results of a bathymetric and sidescan survey undertaken in 2004. The morphological features seen in previous bathymetry are still evident in our data though they have changes in position and elevation with time. The changes in bathymetry have been used to postulate the nest sand transport pathways in the survey region. These are shown schematically in Fig. 7. The ebb-tidal delta off Lido inlet is the largest morphological element in the survey region. It represents the distal part of a transport pathway of fine sand, which appears to originate within the lower Burano and Treporti canals. It is thus indicative of net export from the lagoon governed by ebb tidal flows. Unfortunately, we cannot quantify the exported volume as our survey did not extend over the entire region of the delta.

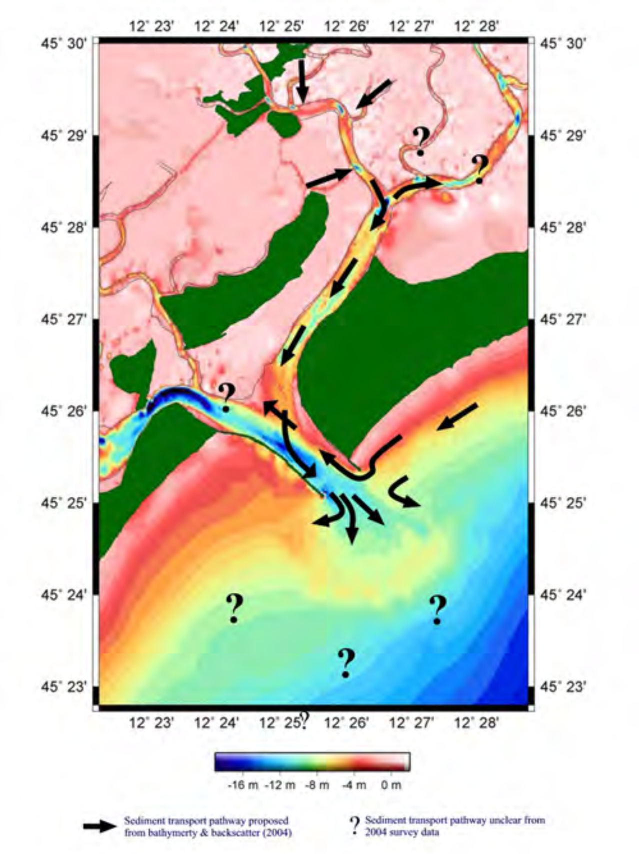

Fig.7 – The combined bathymetry (1990 and 2004) of the survey region with the inferred sand transport pathways superimposed.

The next most important element in the sand transport system is the shoreface of Cavallino, which appears contiguous (through a slight import of sand) with the northern flank of Lido inlet. Here accumulation has also taken place probably by bypassing the northern breakwater and import on the flooding tide. The seabed backscatter is high along this sand transport pathway and extends to the flood tidal delta of Baccan. This appears to be the distal depo-centre of this transport pathway. If this is the case, then there are two distinct transport pathways move in opposite directions in Lido inlet and cross over at the mouth of Treporti Canal.

The asymmetry in the morphological features of Burano suggest an ebb dominance in sand transport with the majority sweeping outwards through Treporti. However, net deposition in the flood-dominated S. Felice canal suggests import of sand in this region. The canals feeding Burano appear to all provide sediment as each displays a depositional berm beyond the region of scouring. Thus all are ebb-dominant: Scanello and S. Felice providing sediment from the north; Cravan providing sediment from the south.

The sidescan sonar imagery has been used to map morphological features of the seabed that are not distinguished in the bathymetric analysis. Four sidescan sonograms are presented in Fig. 8. Fig. 8a shows the seabed (in Burano Canal) extending away from the boat from left to right. In the middle distance are two briccole (channel markers) with asymmetric scour diagnostic of net transport direction. In fig. 8b (Burano Canal) we see three briccole with the acoustic shadows behind cutting through a submerged beach (high reflectivity) adjacent to the main channel and a seawall in the distance.

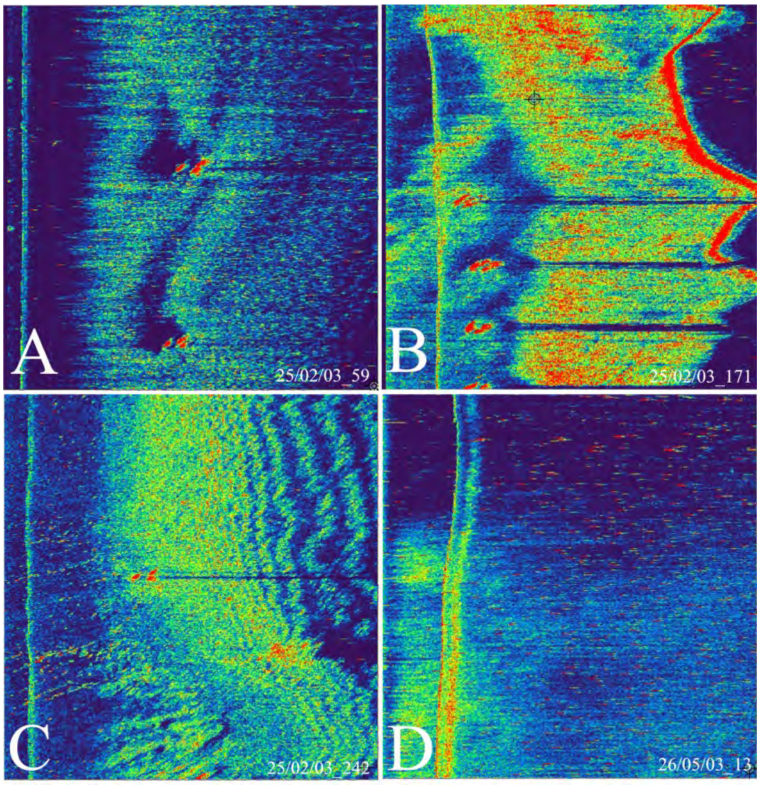

Fig. 8 – Four examples of sidescan sonograms collected during this survey.

Fig. 8c shows the results of dredging in Burano Canal, and Fig. 8d shows the main navigation channel approaching Lido inlet: the transition from fine to coarse sand is evident with sand evident in suspension. A synthesis of the data is in progress.

Conclusions and future work.

This paper describes the first step in a series of analyses on the mass transport of sand in the Lido inlet and vicinity. Bathymetric and sidescan sonar lines were surveyed from the ebb-tidal delta off Lido to landwards of Torcello: that is the main canal system comprising Lido-Treporti-Burano. A comparison of these data with data collected during 1990 and was compared with results presented by Magistrato alle Acque [1993] and the trends were very similar. These trends show:

(1) a strong deposition on the ebb tidal delta south of Lido inlet. The source of the fine sand is thought to be Venice Lagoon, and more specifically Treporti Canal;
(2) scouring of the flood tidal channel in Lido inlet and scour of the ebb-tidal ramp was prevelant and perhaps signifies an increase in the magnitude of the ebbing tides;
(3) a flood-tidal delta is found inside Lido inlet, and has attached itself to S. Erasmus island. The delta is prograding steadily seawards pushing the main shipping channels towards the east;
(4) Treporti Canal is rather patchy in response, but shows erosion of the margins and accumulation in the main channel. The scour hole at the triple junction of treporti-Burano-S. Felice has deepened in time, and a berm has developed around it which has extended into S. Felice Canal;
(5) Burano is also irregular in evolution. Scour holes at the confluences of fourth order tributaries are apparent. These are asymmetric to the ebb; accretionary berms are situated beyond the scour holes and are diagnostic of a source of sediment from these tributaties;
(6) The seabed backscatter shows that the sand from Cavallino shoreface is contiguous with the northern flank of Lido inlet and the flood tidal delta. This represents one distinct sand transport pathway. Intermediate values of backscatter (fine sand) link lower Burano Canal, Treporti Canal, Lido inlet and the ebb-tidal delta as a distinct sand transport pathway;
(7) A conclusive sand budget analysis cannot be made until we have completed the bathymetric survey to include the distal portions of the ebb-tidal delta. Accretion of 3 m in 14 years points to a steady accretion of about 0.2 m/year over a wide region. This suggests that there is a net loss of sand from Venice Lagoon through lido inlet;
(8) Future work will involve: (i) completion of the bathymetric survey; (ii) analysis of bottom samples for granulometric and mineralogical trends to compare with those inferred from the bathymetric results; (iii) direct measurements of sand transport in the flood and ebb dominant parts of the Lido inlet; and (iv) numerical simulation of sand transport for the region surveyed under a variety of conditions that typify Venice Lagoon in an attempt to reproduce the transport pathways, and as important the sites of sand accumulation. In particular, we will

be attempting to simulate the growth of the ebb-tidal delta. The geophysical data collected in Linea 3.16 will be of particular value in this part of the study.

Acknowledgements.

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References.

Albani A.D., Favero V.M. and Serandrei Barbero R., 1983. Apparati intertidali della laguna di venezia. *Ministero dei Lavori Pubblici, Magistrato alle Acque, Venezia:* 17p

Albani A.D., Favero V.M. and Serandrei Barbero R., 1998. Distribution of sediment and benthic forminifera in the Gulf of Venice, Italy. Estuarine, Coastal and Shelf Science 46: 251-265.G.

Amos C.L., Helsby R. and Friend P.L., 2004. Final report – CORILA 3.2 – Idrodinamica e morfologia della laguna di Venezia (VELMA). *Final Report to CORILA*, Venice: 23p

Amos C.L., Umgiesser G., Reed P., Munford G. and Lea J., 2002. The residual tidal circulation and organics in northern Venice Lagoon, Italy. *In Scientific Research and Safeguarding of Venice. Research programme 2001-2003, Volume II*: 189-202

Bergamasco A., DeNat L., Flind, M.R, and Amos C.L., 2003. Interactions and feed-backs amongst phytobenthos, hydrodynamics, nutrient cycling and sediment transport in estuarine ecosystems. Coastal and Nearshore Oceanography 23(17): 1715-1741

Bonardi M., Tosi L. and Rizzetto F., 2002. Mineralogical Characterization of the Venice Lagoon top sediments. *In Scientific Research and Safeguarding of Venice. Research programme 2001-2003, Volume II*: 145-155

Bondesan A. and Meneghel M., 2004. Geomorphologia della Provincia di Venezia, *Publ. Estrada, Padova*: 516p

Bondesan A. *et al.*, 2004. The Geomorphological Map of the Province of Venice. *La Cartografia, Publ. Provincia di Venezia,* 15p

Bruun P., 1978. Stability of Tidal Inlets, Theory and Engineering. *Elsevier Scientific Publishing Company,* 506p

Coracci E., Umgiesser G., Scalvo M. and Amos C.L., 2004. Modeling sand transport in the Venice Lagoon inlets. *In Scientific Research and Safeguarding of Venice. Research programme 2001-2003, Volume II*: 157-173

Carbognin L. and Cecconi G., 1997. The Lagoon of Venice – environmental problems, remedial measures. *Meeting of Environmental Sedimentology, IAS,* 71p

Carter R.W.G., 1988. Coastal Environments. An Introduction to the Physical, ecological and Cultural Systems of Coastlines. *Publ. Academic Press, London*

Coastal Engineering Manual., 1998. Engineering Design. COASTAL GEOLOGY. *Publ. Dept. of the Army, Washington, Manual No*. 1110-2-1810

Dal Monte L. and Di Silvio G., 2002. Long-term sediment concentration and morphological characteristics of a tidal lagoon. *In Scientific Research and Safeguarding of Venice. Research programme 2001-2003, Volume II*: 129-144

EMPHASYS Consortium., 2000. A Guide to Prediction of Morphological Change within Estuarine Systems. *MAFF Project FD1401 Publication*: 53p + Appendixes

Evans G., 1965. Intertidal flat deposits and their environment of deposition in the Wash. *Quaternary Journal of Geological Society of London* 121: 209-245

Fitzgerald D.M., 1988. Shoreline erosional-depositional processes associated with tidal inlets. *Hydrodynamics and Sediment Dynamics of Tidal Inlets. Publ. Springer-Verlag* 189-225

Gačić M. and Solidoro C., 2004. Lagoon of Venice. Circulation, Water Exchange and Ecosystem Functioning. *Journal of Marine Systems Special Issue* 51, 359p

Gazzi P., Zuffa G.G., Gandolf G. and Paganelli L., 1973. Provenienza e dispersione litoranea delle sabbie delle spiagge adriatiche fra le foci dell'Isonzo e del Fogilia: inquadramento regionale. *Memorie della Societa Geologica Italiana* 12: 1-37

Hubbard D.K., Oertel G. and Nummedal D., 1979. The role of waves and tidal currents in the development of tidal-inlet sedimentary structures and sand body geometry: examples from North Carolina and Georgia. *Journal of Sedimentary Petrology* 49: 1073-1092

Kjerve. B. and Magill K.E., 1989. Geographic and hydrodynamic characteristics of shallow coastal lagoons. *Mar Geol* 88:187-199

Magistrato alle Acque, 1993. Evoluzione morfologica della Laguna di Venezia. Confronto batrimetrico tra la batimetria del 1992 e del 1970. Convenzione 7322, Sezione 20, Stralcio 2

Oertel G.F., 1982. Inlets, marine-lagoonal and marine fluvial. *The Encyclopedia of Beaches and Coastal Environments.* M.L. Schwartz (ed) *Publ. Hutchinson, Ross*: 489p

Perillo G.M.E., 1995. Geomorphology and Sedimentology of Estuaries. *Publ. Elsevier, Amsterdam*, 471p

Reed P**.,** 2001. An ADCP survey of a tidal front in the northern Venice Lagoon. *Unpublished M.Sc. Thesis*. University of Southampton

Schiozzi L. and Brambati A., 2000. Evoluzione paleoambientale tardoquaternaria dell'Isola di S. Erasmo (Laguna di Venezia). *Studi Trentini di Scienza Naturali – Acta Geologica* 77: 139-154

Townend I., 2004. Coastal and Estuary Behaviour Systems. *ABPmer Special Publication, Southampton*: 15p

Umgiesser G., Sclavo M., Carniel S. and Bergamasco A., 2004. Exploring the bottom stress variability in the Venice Lagoon*. Journal of Marine Systems* 51: 161-178

Umgiesser G., Ferrarin C., De Pascalis F. and Amos C., 2005. Modeling sand transport in a canal system, northern Venice Lagoon. *This volume*

Weltje G.J., 1995. Unravelling mixed provenance of coastal sands: The Po Delta and adjacent beaches of the Northern Adriatic Sea as a test case. In: Oti, M.A. and Postma, G. (eds), *Geology of Deltas, Balkema, Rotterdam*. P181-202

Wheatcroft R.A. and Borgeld J.C., 2001. Oceanic flood deposits on the northern California shelf: large-scale distribution and small-scale physical properties. *Continental Shelf Research* 20: 2163-2190

MODELING THE TIDE INDUCED WATER EXCHANGES BETWEEN THE VENICE LAGOON AND THE ADRIATIC SEA

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Riassunto.

In questo lavoro un modello idrodinamico bidimensionale basato sul metodo degli elementi finiti è stato applicato per analizzare gli scambi d'acqua che avvengono attraverso le tre bocche di porto della Laguna di Venezia.

Il modello risolve le equazioni Shallow Water su un dominio spaziale che descrive l'intero mare Adriatico e la Laguna di Venezia mediante una griglia agli elementi finiti con risoluzione spaziale variabile.

Il modello è stato calibrato attraverso il confronto con i dati sperimentali di livello mareale provenienti da 20 stazioni di misura disposte internamente alla laguna di Venezia e lungo le coste del mare Adriatico.

Il modello calibrato è stato quindi utilizzato per simulare la propagazione della marea astronomica all'interno del dominio di indagine.

Quindi i flussi d'acqua attraverso le tre bocche di porto sono stati analizzati e i risultati confrontati con misurazioni effettuate mediante sonda elettroacustica ADCP posizionata all'interno delle bocche di porto.

Abstract.

A 2D hydrodynamic model of the Venice Lagoon and the Adriatic Sea has been developed. The model is based on the finite element method. It solves the shallow water equations on a spatial domain constituted by a staggered finite element grid. The grid represents the Adriatic Sea and the Venice Lagoon with different spatial resolutions varying from 30 m for the smallest channels of the lagoon to 30 km for the inner areas of the central Adriatic Sea.

Empirical measurements collected by more than twenty tide gauges displaced inside the Venice Lagoon and the Adriatic Sea have been used in the different calibration process. After the calibration, the tidal wave propagation in the North Adriatic and in the Venice Lagoon is well reproduced by the model.

The water exchanges through the three inlets of the Venice Lagoon has been analysed. To validate the model results, empirical data measured by ADCP probes installed inside the inlets of Lido and Malamocco have been considered.

1. Introduction.

The lagoon of Venice is a complex and unique environment both for the ecological aspects and for the beauty of its landscape. In the last decades due to the increased frequency of the flooding events and to the deterioration of the water quality, more research has been focused to control and preserve the hydrologic and bio-geo-chemical characteristics of the lagoon.

The city of Venice is an island situated approximately in the center of the lagoon with other important islands in the southern or in the northern part (Fig. 1) The lagoon is connected to the Adriatic Sea through inlets which guarantee the water exchange with the open sea. The southern and the central inlet (Chioggia and Malamocco, respectively) are about 500 meters wide whereas the northernmost inlet (Lido) is nearly 1000 m wide. The maximum depth is around 8 m for Chioggia and 14 meters for Malamocco and Lido.

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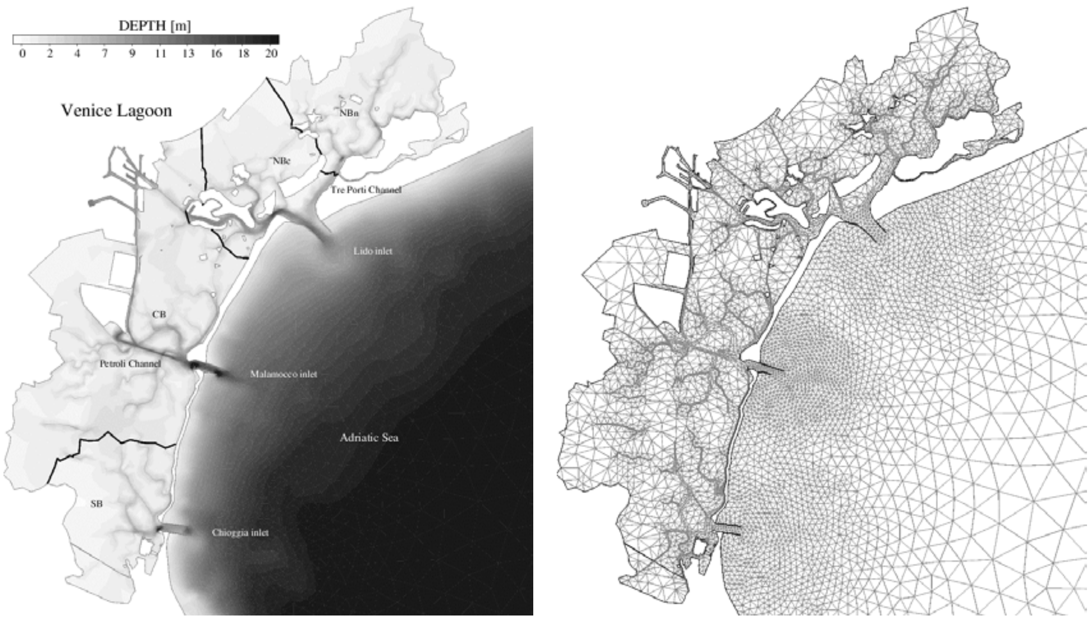

Fig. 1 – Bathymetry (left panel) and finite element grid (right panel) of the Venice Lagoon and Gulf of Venice, a subset of the numerical domain of the model.

The inlets have undergone major changes in the second part of the 19th and the first part of the 20th century. Due to silting up of the entrances only small boats could pass in this period. Therefore jetties have been constructed that reach 2-3 km into the

Adriatic Sea and that gave the inlets the shape and morphology that can nowadays be observed.

It might be surprising that, even with the importance that the inlets have to the Venice lagoon, no major studies have been carried out that try to measure or describe the exchange and its mechanisms through the inlets. Two modeling studies deal with this subject. The first one is a tentative by [Umgiesser, 2000] to understand the residual currents due to the most prominent wind regimes found in the northern Adriatic. It uses a finite element model [Umgiesser and Bergamasco, 1993; 1995] that is able to capture most of the bathymetric details inside the lagoon. This study modeled also the residual currents of a complete year [1987]. The other study [Bergamasco *et al.*, 1998] applied the POM model]Blumberg and Mellor, 1987; Mellor, 1991] to the lagoon and parts of the Adriatic Sea and used the resulting hydrodynamic current field to run a simple eutrophication model consisting in phytoplankton and macronutrients, forced also by water temperature and light intensity.

Both approaches suffered from main deficiencies. Both models could not be validated with data because flux measurements were not available at the inlets. Moreover, the second study applied the POM model with a 1200 m grid size that is to coarse to resolve the important hydrodynamic features of the Venice lagoon. On the other side, the first study used a calibrated model for the water levels inside the lagoon with good resolution of the channel system (due to its finite element method), but failed to describe well the interface dynamics, since the model domain ended exactly at the inlets.

In the year 2000 an interdisciplinary project has been started by the Consortium for Coordination of Research Activities Concerning the Venice Lagoon System (CORILA) that aims to investigate the exchange mechanisms between the lagoon and the Adriatic Sea, both by measurements of fluxes and biochemical parameters at the inlets, and by the application of models that can be validated through these field campaigns. During this project bottom mounted Acoustic Doppler Current Profilers (ADCP) have been installed at the three inlets and the data has been analysed (Gacic *et al.*, 2002). This is the first time that good current and flux measurements are available for the Venice lagoon inlets.

This article is concerned with the modeling aspects of this project. The model used is a 2D hydrodynamic finite element model, the same as in Umgiesser [2000]. However, the model domain now comprises not only the Venice Lagoon, but also the whole Adriatic Sea, in order to move the open boundary as far away as possible from the area of interest. In this study the model is calibrated with harmonic constants of tidal data available at stations around the Adriatic Sea and just o side the Venice Lagoon. The fluxes computed at the inlets are then validated with the astronomical contribution of the measured ones.

2. Methods.

In this section the equations and the construction of the model and the numerical grid are described. After that a summary about the available data (sea surface elevation and ADCP data) is given. Finally we described the general simulation set-up and the model calibration process followed to reproduce the tides in the Adriatic Sea.

2.1. The hydrodynamic model.

For this application a finite element hydrodynamic model developed at ISMAR-CNR (Istituto di Scienze Marine) has been used [Umgiesser and Bergamasco, 1993; 1995]. This model has already been applied successfully in its 2D version to the Venice lagoon [Umgiesser, 2000; Melaku Canu *et al.*, 2001; Umgiesser *et al.*, 2004] and in its 3D version to the Adriatic Sea [Umgiesser and Bergamasco, 1998].

The finite element method is especially well suited for the application to the Venice Lagoon with its narrow channels that run between large flat shallow areas. It gives the possibility to faithfully follow these channels, reducing the grid resolution in other areas that are less important for the propagation of the tidal wave. It also gives the possibility to increase the resolution close to the inlets and move the open boundary further away, reducing numerical disturbances close to the zone that is under investigation.

The model is here applied in its 2D version. The focus of this paper is an investigation of the water exchanges between the lagoon and the Adriatic Sea. In the lagoon, due to its shallow character and the relatively high tides (50 cm during spring tide) stratification can develop only far from the inlets where the tidal energy is lowest. Inside the inlets, the water velocities are high (over 1 m/s) [Gacic *et al.*, 2002], and therefore the velocity shear creates enough turbulence to mix the water. It must be noted that the exchanges between the lagoon and the sea are mostly driven by the tide and the wind action, and are therefore essentially barotropic in nature. The baroclinic contribution is in this case a minor one.

The model uses finite elements for horizontal spatial integration and a semi-implicit algorithm for integration in time. It resolves the vertically integrated shallow water equations in their formulations with levels and transports The terms treated implicitly are the water level gradient and the Coriolis force in the momentum equation and the divergence term in the continuity equation. The friction term is treated fully implicitly for stability reasons due to the very shallow nature of the lagoon. All other terms are treated explicitly. The model is unconditionally stable what concerns the fast gravity waves, the bottom friction and the Coriolis acceleration [Umgiesser and Bergamasco, 1995].

The equations read:

$$\frac{\partial U}{\partial t} - fV + gH\frac{\partial \varsigma}{\partial x} + RU + F_x = 0 \tag{1}$$

$$\frac{\partial V}{\partial t} + fU + gH\frac{\partial \varsigma}{\partial y} + RV + F_y = 0 \tag{2}$$

$$\frac{\partial \varsigma}{\partial t} + \frac{\partial U}{\partial t} + \frac{\partial V}{\partial t} = 0 \tag{3}$$

where ζ is the water level, U and V the vertically-integrated velocities (barotropic transports) in x and y direction,

$$U = \int_{-h}^{\varsigma} v \partial z \qquad V = \int_{-h}^{\varsigma} u \partial z \tag{4}$$

g is the gravitational acceleration, H = h + ζ the total water depth, h the undisturbed water depth, t the time, f the Coriolis parameter and R the friction term. The terms X and Y contain all other terms like the wind stress, the nonlinear advective terms and those that are treated explicitly in the time discretization.

The friction term has been expressed with a standard bulk formula:

$$R = \frac{c_b}{H}\sqrt{u^2 + v^2} \tag{5}$$

with c_b the value of the bottom friction coefficient. This term can be assumed either as constant with the standard value for oceanographic applications of 2.5×10^{-3} or dependent on the depth through the Strickler formula:

$$c_b = \frac{g}{c^2} \qquad c = k_s H^{1/6} \tag{6}$$

with C the Chezy coefficient and Ks the Strickler coefficient.

At the open boundaries of the domain the water levels are prescribed while at the closed boundaries the normal velocity is set to zero and the tangential velocity is a free parameter. This correspond to a full slip condition.

The model allows also for flooding and drying of the shallow water flats. This is especially important for the Venice lagoon, since about 15% of the area is partially wet and dry during a spring tidal cycle. The flooding and drying mechanism has been implemented in a mass consistent way, and spurious oscillations that are generated by are damped out fast.

2.2. The numerical grid.

In the studies mentioned before the numerical grid consisted of either the lagoon of Venice alone [Umgiesser, 2000; Melaku Canu *et al.*, 2001; Umgiesser *et al.*, 2004] or the Adriatic grid alone [Umgiesser and Bergamasco, 1998]. The bathymetric information for the lagoon has been collected from the regional charts that have been compiled in 1970 with some interpolations in the 1990s. For the bathymetry of the Adriatic Sea the global data base of the National Ocean and Atmospheric Administration (NOAA, link to www.ngdc.noaa.gov/mgg/bathymetry/relief.html) has been used with the resolution of the gridded data of 1/12 of a degree.

These two available grids have been merged together in order to construct a unified grid of the Adriatic Sea and the Venice lagoon. The areas close to the inlets have been re-gridded, in order to guarantee a smooth transition of the two grids. The resulting grid consists of 10948 nodes and 20013 triangular elements (Fig. 1 and Fig. 2).

For the bathymetry of the inlets and the areas around it new data collected by the Consorzio Venezia Nuova (CVN) in the 1992 during the project VENICE and provided by CORILA has been used. These data consist of depth values on a regular grid with a resolution of 50 m inside the inlets and of 300 m just outside the inlets in the Adriatic Sea. The data has been interpolated together with the old data in a transition zone in order to not create sharp gradients with the older grids.

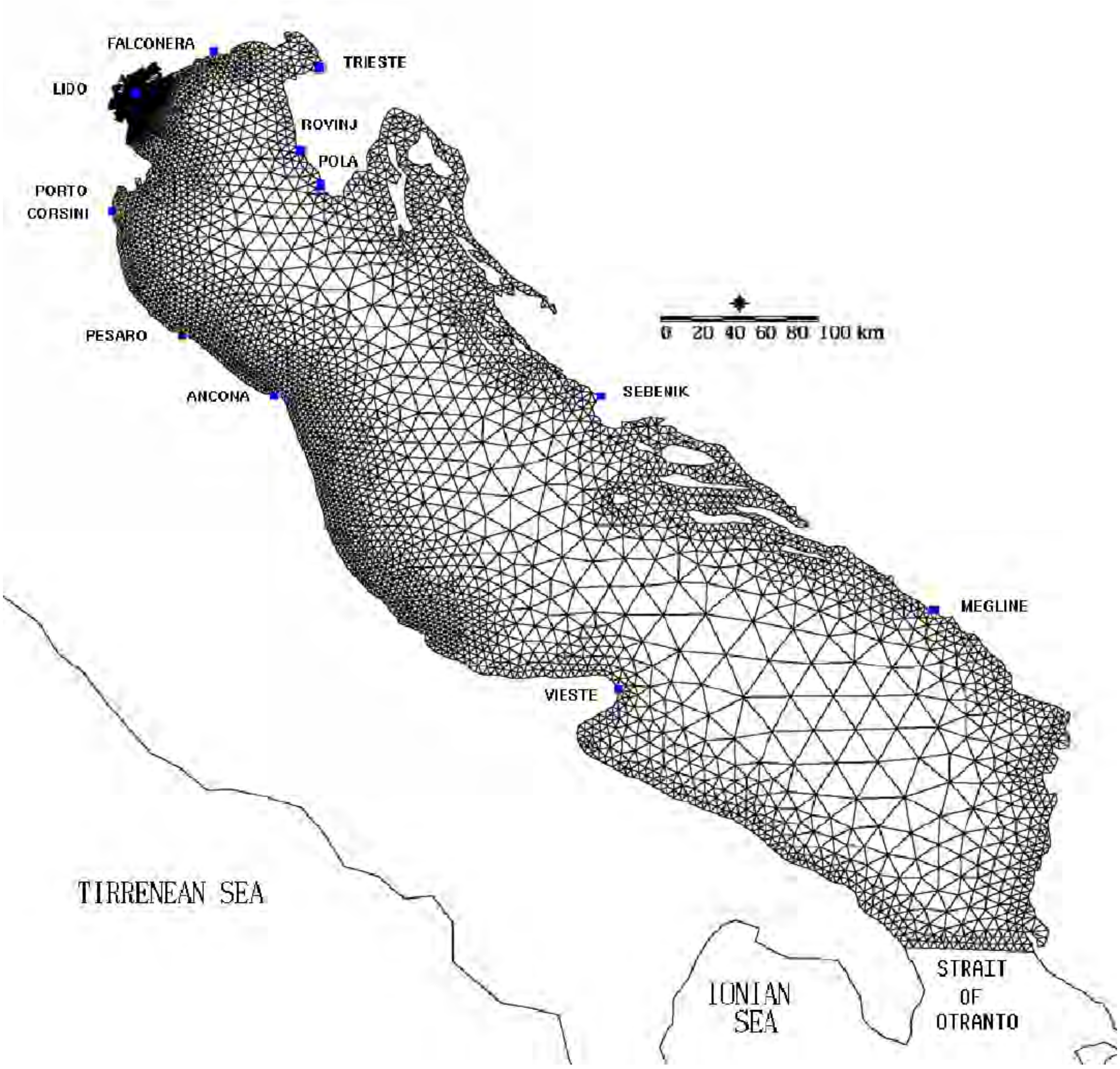

Fig. 2 – The numerical domain of the Adriatic Sea and the location of the tide gauges considered during the calibration process.

The open boundary has been chosen as a straight line across the strait of Otranto (Fig. 2). This seems a logical choice for the Adriatic Sea, because on one side the boundary is far away from the investigated area of the inlets and on the other side the strait of Otranto is the narrowest part of the whole Adriatic Sea. This parametrization was suggested by the results obtained in a previous work by Malacic *et al.* [2000]. In that case the open boundary was chosen between Pesaro and Kamenjak in the Northern part of the basin close to the Venice Gulf. From the model calibration the worst results were obtained just for the stations located in the western part of the basin close to the Venice Lagoon (Venezia-Lido, Malamocco and Porto Corsini), which is the studied area of the present work. Therefore the location of the open boundary conditions far away from the investigated area was considered. Moreover the adopted parametrization is the same followed by Cushmain-Roisin and Naimie [2002] even if, in that case, the model, based also on the finite element method, was used in the 3D version with a horizontal resolution varying from 16 to 2 km. Since the description of the vertical stratification of the water column is not the aim of the present work, the use of a two-dimensional model is considered as suitable [Malacic *et al.*, 2000].

2.3. The available data.

In this work two different sets of measured data have been considered both to calibrate the model and to corroborate the simulation results. The first dataset concerns the amplitude and the phase of the main tides that dominate the sea surface elevation (SSE) of the Adriatic Sea. The second one contains the discharge data through the three lagoon inlets measured by ADCP probes.

23.1. Water level data.

The Adriatic sea is a basin characterized by moderate tides. The highest amplitudes are found in the Northern sub-basin (extending from the line connecting Pesaro to Kamenjak to the northern coast) where the amplitude of the M2 frequency reaches 0.266 m.

Tidal observations in the Northern sub-basin have been collected from the middle of the 18th century. For some stations the length of the water level records is more than 100 years (Trieste, Venezia-Lido, Rovinj). The most important tidal constituents are M2, S2, K1, N2, K2, O1 and P1 [Polli, 1960]. For these tidal constituents amplitude and phase values have been derived from the tide gauge measurements in stations along both the western and eastern coast [Polli, 1960; 1961; Mosetti, 1987].

In Tab. 1 the harmonic constants of the most energetic semidiurnal and diurnal tides (M2, S2 and K1) are reported for the stations chosen as calibration points for the tidal simulations of the Adriatic sea (Fig. 2).

For what concerns the tides in the Venice lagoon, measured data of amplification and delay of the main diurnal and semidiurnal constituents with respect to the Diga Sud Lido tide gauge are reported for many stations inside the lagoon by Goldmann *et al.* [1975]. This dataset has been considered for the calibration of the model to reproduce the tidal propagation in the Venice lagoon [Umgiesser *et al.*, 2004].

2.3.2. The flow rate ADCP data.

The ADCP data at the inlets were collected in the framework of the CORILA project that started in January 2001. The program includes 2 years of simultaneous current measurements in all three lagoon inlets. The aim of these measurements is to study the time-dependent variability of the inlet currents as well as of water exchange rates.

The current data have been collected using bottom-mounted ADCP installed in each inlet. Current speed and direction along the water column are recorded every 10 minutes with a vertical resolution of 1 meter in selected locations inside the inlets.

Tab. 1 – Comparison between model results (m) and observations (o) of the amplitude H and phase g of the most energetic tidal constituents (M2, S2 and K1) at the eleven tidal stations in the Adriatic Sea.

Site	Constituent	H_m [cm]	H_o [cm]	H_m - H_o [cm]	(H_m - H_o)/H_o [%]	g_m [deg]	g_o [deg]	g_m - g_o [deg]
Lido	M2	23,4	23,4	0	0	295	291	3
	S2	14	14	0	0	303	298	5
	K1	17,6	17,6	0	0	84	77	7
Falconera	M2	23,1	24	-0,9	-6	289	289	0
	S2	13,9	14	-0,1	-1	290	297	-7
	K1	18,3	18,3	0	0	82	79	3
Trieste	M2	28,2	26,6	1,6	7	289	276	13
	S2	17,3	16	1,3	9	292	284	8
	K1	19,3	18,6	0,7	4	83	70	13
Porto Corsini	M2	14,3	15,6	-1,3	-5	305	303	2
	S2	8,2	9,2	-1	-6	307	310	-3
	K1	16,5	15,9	0,6	-3	89	81	8
Rovinj	M2	16,9	19,3	-2,4	-12	273	270	3
	S2	10	11,2	-1,2	-11	273	277	-4
	K1	16,9	16,1	0,8	-5	76	71	5
Pula	M2	12,9	15,1	-2,2	-14	261	265	-4
	S2	7,5	8,7	-1,2	-13	259	273	-14
	K1	15,9	15,5	0,4	2	82	69	13
Pesaro	M2	9,7	12,8	-3,1	-24	316	311	5
	S2	5,4	6,8	-1,4	-20	318	313	5
	K1	15,3	15,4	-0,1	-1	92	84	8
Ancona	M2	3,7	6,6	-2,9	-43	9	332	37
	S2	2,1	3,5	-1,4	-40	27	347	40
	K1	12,7	13,2	-0,5	-4	104	88	16
Sebenik	M2	11,3	6,3	5	80	121	135	-14
	S2	7,5	4,4	3,1	70	120	132	-12
	K1	8,99	9,3	-0,4	-3	69	57	12
Vieste	M2	11,2	9,4	1,8	20	104	105	-1
	S2	6,9	6	0,9	15	105	115	-10
	K1	4	5,1	-1,1	21	99	91	8
Megline	M2	11,3	9,1	2,23	24	100	99	1
	S2	6,8	5,9	0,9	16	99	103	-4
	K1	4,3	5	-0,7	-14	67	52	15

During a preliminary phase, measurement campaigns have been carried out to estimate the relationship between the vertically-averaged water velocity collected by the fixed ADCP and the inlet flow rate. About 100 ship-borne ADCP surveys were conducted to estimate the water inflow and outflow through each inlet both during spring and neap tide. Comparing the discharge results with the average vertically velocity collected by the bottom mounted ADCP for the same period, the parameters of a linear correlation function has been calculated [Arena and Arcari, 2001]. Therefore, the flow rate is available every 10 minutes applying the calculated linear regression formula to the vertically integrated measured current values [Gacic *et al.*, 2002].

On June 17, 2001 the continuous current record started inside Lido and Malamocco inlet. At Chioggia the measurements started only one year later, on May 8, 2002.

2.3.3. ADCP data processing and usage.

From the harmonic analysis of the ADCP discharge time series collected at the Malamocco inlet during the period between June 17, 2001 and July 29, 2001 it was found that the signal is mainly due to the principal tidal components less than a residual of about 4% of total amplitude due to meteorological forcing (wind and pressure). This result is expected, since the ADCP data refers to the summer season. In fact, during this period, intense meteorological events generally do not occur and the wind variation is characterized mainly by a sea breeze diurnal cycle which contribution to the total flow is extremely difficult to separate from the tidal one [Gacic *et al.*, 2002].

A different situation is the winter period, in particular those months characterized by the acqua alta (high tide) events. An example is given by the November 2001 discharge time series (Fig. 3). This data set, being collected during a period of exceptional high tides, contains a strong signal caused by wind and pressure forcing. Therefore the average contribution of the residual components, during the whole month, is very high with a top value of residual flow measured in the Malamocco inlet of about 5300 m^3/s (the astronomical contribution to the flow rate can reach up to 10000 m^3/s inside this inlet).

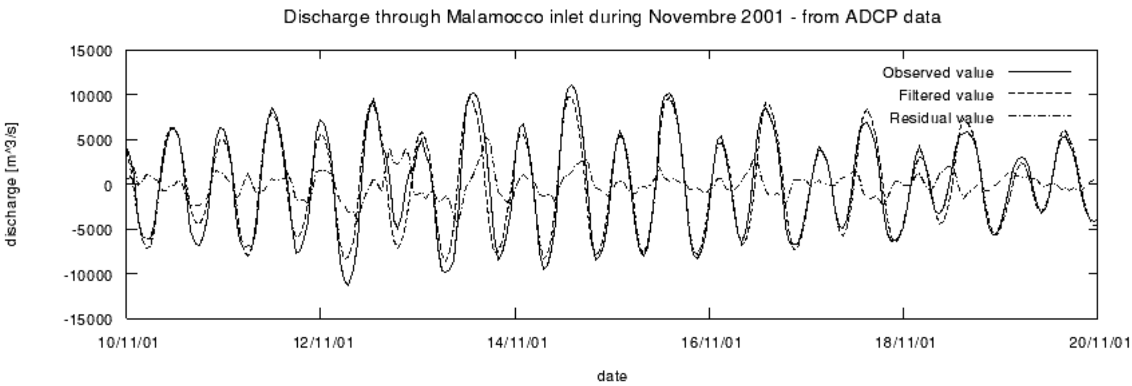

Fig. 3 – Discharge time-series through the Malamocco inlet, derived from ADCP data, for a 10 days period during November 2001. Observed, tidal signal and residual values.

Even if the meteorological contribution can affect strongly the dynamics of the water exchanges, it has not been considered in this work. In fact, the residual water level in the Adriatic sea and the related residual flow through the lagoon inlets are generated by the intense meteorological phenomena that occur in this area. To reproduce their effect on the water circulation, hydrodynamic models are forced with wind and pressure data that covers the whole Adriatic Sea. These data are the result of atmospheric numerical models (i.e., ECMWF global meteorological model) and generally strongly underestimate the real meteorological status [Cavaleri and Bertotti, 1996], especially in the Venice Gulf, where the meteorological phenomena are more intense at the synoptic scale. This can be considered the main cause of error for the storm surge models used to forecast the exceptional high tide in the Venice Lagoon that carries a strong contribution to the residual water circulation.

A storm surge finite element model has been set up and made operative at the Venice Municipality [Canestrelli *et al.*, 2003] with the aim of forecasting the water level elevation generated by the meteorological action (the residual water level). The results obtained by forcing the model with the ECMWF meteorological data set (wind direction and intensity and pressure values every 6 hours over the whole Mediterranean sea with a spatial resolution of half a degree) are in good agreement with other forecast models of the area, but are still not good enough for a reliable water level forecast and for a computation of the exchange rate through the inlets in extreme meteorological situations.

Therefore in this work only the contribution of the tide to the flow rate through the inlets has been considered. The model has been set up and calibrated to simulate the tidal wave propagation in the Adriatic Sea and in the Venice lagoon. To validate the model results, only the tidal signal of the measured discharge data has been considered.

Harmonic analysis is therefore applied to the ADCP data collected at Lido and Malamocco inlet during the period between September 1st, 2001 and December 31st, 2001. The contribution of the seven major tidal components to the total flow rate -M2, S2, K2, N2, O1, P1, K1- was obtained and the parameters related to these constituents are presented in Tab. 4.

2.4. The general simulation set-up.

All simulations presented in this work have been carried out using a time step of 300 seconds. This time step could be achieved due to the unconditionally stable time integration scheme of the finite element model.

As forcing the SSE is prescribed at the open boundary of Otranto. In this work tidal constituents M2, S2, K1, N2, K2, O1 and P1 are imposed. During the calibration, the empirical amplitudes and phases of the single tidal constituents at Otranto were modified. No variations of these values across the open boundary line was considered.

A spin up time of 30 days has been used for the model runs. This value has been found by numerical simulations carried out to test the sensitivity of the model to different forcing conditions. A simulation has been run for two months with only the M2 tide as forcing at the open boundary. From the water level results, the spin up time is calculated. It is the time over which the difference between consecutive water level maxima is less than 1% with respect to the tidal excursion. This time is enough to damp out basically all the noise that has been introduced through the initial conditions.

No meteorological forcings, such as wind pressure and heat fluxes are considered. The baroclinic contribution of the fresh water input released inside the basin by the main Italian rivers is also not taken into account. All of these processes are neglected because the focus of this work is to reproduce the barotropic tidal contribution to the Lagoon-Sea water exchange only.

As mentioned in section 2.1, the bottom boundary condition enforces quadratic friction based on barotropic (depth-averaged) velocity according to the classical quadratic drag law. In this application two formulations for the bottom friction coefficient C_b have been considered. For the deeper areas of the domain (Adriatic Sea) the coefficient it is imposed to be constant with value of $2.5x10^3$. However, in the shallow parts (Venice Lagoon) it has been set up as dependent on the depth through the Strickler formula. In particular, inside the lagoon, different areas have been distinguished, such as channels, tidal flats, inlets etc., and different values of C_b have been computed in these areas by varying the Strikler coefficient in the Chezy formula (6) [Umgiesser *et al.*, 2004].

2.5. Model calibration.

The model has been calibrated to reproduce the harmonic constants in the Adriatic Sea and, more specifically, in the gulf of Venice. The first step in this model calibration is to seek a match between the model results and the sea level data measured by the 11 stations chosen along the coast-line of the Adriatic Sea (Fig. 2).

Starting from the harmonic constants (amplitude and phase) of the main semidiurnal constituent (M2) given for the Otranto station by Polli [1960], we prescribed pre-calculated SSE values as open boundary condition in the model. A first set of calibration runs is then carried out. The duration of these simulations is 120 hours after the spin-up time. The calculated SSE values for all the 11 stations are then compared to the observations and the differences with the real data are minimized by varying the tidal constants at Otranto.

Once an accordance between the model results and observations at Diga Sud Lido station has been found, the other semidiurnal and diurnal main constituents have been considered separately, and further calibration runs have been carried out.

Finally, a complete SSE with all the 7 main tidal frequencies has been prescribed at the open boundary of Otranto and the harmonic constants have been varied until the gaps with the real data at Diga Sud Lido station were close to zero. These calibration runs have been extended to 8760 hours (1 year), a time that is sufficient to separate the K2 and S2 frequencies in the harmonic analysis [Foreman, 1996]. The coupling of all the main tidal constituents is necessary because of the non linear e ect of the bottom friction that links the components between both in terms of retarding e ects and amplification.

We assume that the calibrated harmonic constants at Otranto are representative for the SSE along the whole open boundary line of the strait of Otranto. This is because we do not have any exact information about the tides on the Eastern side of the strait and the variation of the SSE along the boundary is unknown. This shortcoming could in principal overcome by using larger models, that include the Ionian Sea and are able to reproduce the SSE along the strait of Otranto [Cushmain-Roisin and Naimie, 2002]. Otherwise in the previous work of Malacic *et al.* [2000] the harmonic constant of the main tidal components were known both on the western and eastern side of the boundary line in the northern Adriatic. These informations allowed the use of parametric polinomial functions to reproduce the SSE along the boundary line. In this case the calibration process was based on the varying of the SSE polynomial function parameters. Due to these shortcomings we expect the results for the Southern Adriatic to be less satisfactory, which could be combined also by the results.

The second step in the model calibration is to reproduce the propagation of the tide inside the Venice lagoon. This step can be tackled separately from in the Adriatic Sea, since tidal level in the lagoon does not really influenced the one in the open sea. For the explanation of the method we refer to Umgiesser *et al.* [2004] and to Solidoro *et al.* [2004].

3. Results.

In this section the model results are presented. In the first part, the model calibration results are compared with the available harmonic data. In the second part, the fluxes through the lagoon inlets are computed and compared with the ADCP data.

3.1. Tidal simulations.

In this simulation the propagation of the main tides in the Adriatic sea is reproduced. The calibrated model is forced with SSE values at the open boundary of Otranto and then the results are compared with the real data from stations along the Adriatic sea and inside the Venice lagoon.

In Tab. 2 the set of harmonic constants obtained from the model calibration and the discrepancies with the initial values given by Polli [1960], are shown. For what concerns the amplitude of the main frequencies (M2, S2 and K1), the tides imposed as forcing at the open boundary of Otranto overestimates the empirical data by values always lower than 24%. Moreover an average difference of about 20 degrees is detected for what concerns the phase. From these harmonic constants the SSE values to be imposed as open boundary conditions at Otranto have been constructed.

Tab. 2 – Open boundary condition. Comparison between the amplitude H and phase g of the main tidal constituents of the SSE imposed as forcing along the open boundary of Otranto (m) and the observed values (o) at this stations.

Constituent	H_m **[cm]**	H_o **[cm]**	$H_m - H_o$ **[cm]**	g_m **[deg]**	g_o **[deg]**	$g_m - g_o$ **[deg]**
M2	8.1	6.5	1.6	103	110	-7
S2	4.4	4	0.4	104	116	-12
N2	1.4	1.2	0.2	103	104	-1
K2	1.4	1.7	-0.3	80	118	-38
K1	2.6	2.5	0.1	42	83	-41
O1	1.2	0.7	0.5	51	58	-7
P1	1	0.8	0.2	33	72	-39

In Tab. 1 the amplitudes and the phase lags of the main semidiurnal and diurnal tides (M2, S2 and K1) are compared to the observations along the coast of the Adriatic sea (for locations see Fig. 2).

As we could expect the calibrated model reproduces the SSE at Diga Sud Lido station with high accuracy. In Tab. 3 the harmonic constants of the whole set of tides are reported for this station. For what concerns the elevations, no discrepancies with real data can be noted.

The phase differences of the most energetic constituents (M2, S2 and K1) are always less then 7 degrees. The highest phase lag of 10 degrees has been found for the N2 frequency, which contribution to the total tide is the weakest of all the constituents considered. What concerns the rest of the domain, we can assume that the area of interest, far away from the open boundary, is the Northern Adriatic Sea which is limited in the South by the line connecting Pesaro to Pula. The stations located in this area are Falconera, Porto Corsini, Trieste, Rovinj, Pesaro and Pula.

Tab. 3 – Comparison between model results (m) and observations (o) of the amplitude H and phase g of the whole set of tide at Diga Sud Lido stations.

Constituent	H_m **[cm]**	H_o **[cm]**	g_m **[deg]**	g_o **[deg]**
M2	23,4	23,4	295	291
S2	14	14	303	298
N2	3,9	3,9	298	288
K2	4,2	4,2	289	294
K1	17,6	17,6	84	77
O1	5,4	5,4	64	64
P1	6	6	72	72

The results obtained for the stations close to the Venice Gulf, Falconera and Porto Corsini are in good agreement with the empirical data. The SSE o shore the Venice lagoon is in fact reproduced with an error always lower than 6% for the amplitude of the main tides and with a phase difference not higher than 8 degrees. These results are in accordance with the main task of this work which is the reproduction of the fluxes through the three lagoon inlets.

A first look at the other stations inside the Northern sub-basin, (Trieste, Rovinj, Pesaro and Pula) reveals that the phase discrepancies are always lower than 14 degrees. For what concerns the amplitudes, the worst results are obtained for Pesaro with an underestimation of the M2 and S2 tides of about 24% and 20% respectively. For the same station and frequencies, Cushmain- Roisin and Naimie [2002] underestimates the real data by 16% and 12%. The last three stations (Trieste, Rovinj and Pula) present differences in the amplitude with respect to the real data always lower than 15%. In particular in all the cases the results show an underestimation of the semidiurnal components and an overestimation of the diurnal ones. An exception is given by the Trieste station which values overestimate the real data both at the semidiurnal and diurnal frequencies. In particular slightly better results than in Cushmain-Roisin and Naimie [2002] have been found for this station especially for the amplitude of the most energetic tides (an underestimation of 8% both for M2 and K1 in Cushmain-Roisin and Naimie [2002] against 7% and 4% respectively in this work). As we can see in Fig. 4 the differences of the semidiurnal amplitudes (M2 and S2) present a similar trend which tends to zero approaching to the Diga Sud Lido station. Better results can be found in the diurnal frequency band where the amplitude for the stations of the Northern sub-basin is reproduced by the model with an error always lower than 10%.

The southern part of the domain, that comprises the Central and the Southern Adriatic sea, is strongly affected by the imposed boundary condition and in this work is not taken into account. Nevertheless a brief digression can be done about the results obtained for the stations of Ancona and Sebenik. Even if not located closed to the open boundary, the results for these stations show strong discrepancies with respect to the real data, especially for what concerns the semidiurnal tides. This can be partially explained by the vicinity to the semidiurnal amphidromic point [Polli, 1961]. In fact the tidal excursion in this area is very weak especially at the semidiurnal frequencies and this gives rise to higher relative errors both for the water level computation and for the harmonic analysis.

What concerns the model results about the propagation of the tide inside the Venice lagoon we always refer to Umgiesser *et al.* [2004] for a more accurate description.

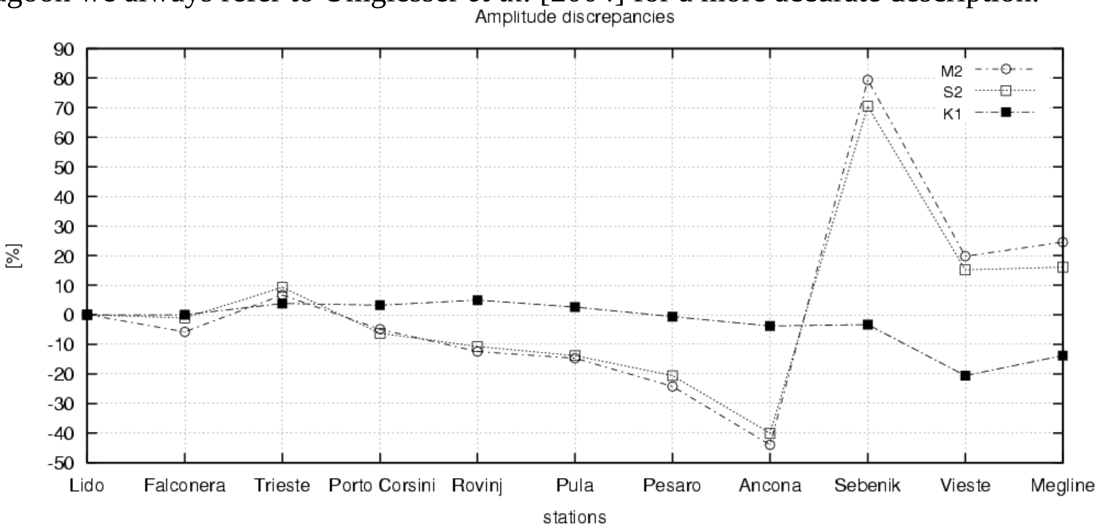

Fig. 4 – Relative difference between model and observed values of the amplitude of M2, S2 and k1 tidal constituents at the eleven stations in the Adriatic Sea.

3.2. Flux data validation.

Once the model has been calibrated with the water levels, it has been used to estimate the water exchange through the three inlets when only the tide drives the circulation between the two basins. A tidal simulation of 152 days long has been carried out. The open boundary condition was derived by the calibration process as explained above (see section 2.5). The SSE values are imposed at the open boundary of Otranto to reproduce the expected tides in the Adriatic sea in the period between September and December 2001. Computed fluxes have been compared with ADCP data measured inside the Lido and Malamocco inlet. In the following the results of the comparison are given.

The duration of the simulation and the period investigated is the same that is covered by the ADCP data. The harmonic analysis is applied both to the measured flux data and to the Malamocco and Lido inlet discharge time series obtained by the model. In Tab. 4 the amplitudes and the phases of the most energetic frequencies (M2 and K1) are given and compared with ones derived from the real data. As we can see in all cases the model overestimates the real data. At Lido inlet the differences in the phase are about 7% for the M2 and 6% for K1. The results for Malamocco inlet are lightly worse at the diurnal frequency K1 (9%) while quite similar to the previous case at the semidiurnal frequency M2 (7%). What concerns the phases, the model results show a general delay with respect to the real data. At Lido, the M2 frequency shows a time delay of about 16 minutes while, for the diurnal frequency K1, the time delay is about 11 minutes. At Malamocco the discrepancies are more marked than at the Lido particularly for the diurnal component which shows a delay of about 40 minutes, whereas the M2 component shows a delay of about 30 minutes.

Tab. 4 – Water discharge of the Lido and Malamocco inlet. Comparison between empirical data (o) (derived from ADCP measurements) and model results (m) of the amplitude H and phase g of the most energetic diurnal and semidiurnal frequencies (M2, and K1).

Inlet	Constituent	H_m [cm]	H_o [cm]	H_m - H_o [cm]	(H_m - H_o)/H_o [%]	g_m [deg]	g_o [deg]	g_m - g_o [deg]
Lido	**M2**	5209	4813	396	7	219	227	-8
	K1	2508	2347	161	6	272	275	-3
Malamocco	**M2**	4830	4509	321	6	251	266	-15
	K1	2180	1973	207	9	288	301	-13

At the most energetic frequencies, M2 and K1, the model reproduces the variability of the water exchange through the two inlets with an accuracy of what concerns the amplitude values better than 90% and with a phase error always lower than 15 degrees.

To investigate the contribution to the sea-lagoon water exchange of the complete tide, the computed discharge time series has been compared with the real data. In Fig. 5 the empirical and the modeled fluxes due to the tide trough Lido and Malamocco inlet are plotted. The time series shows only the month of November 2001, a sub-sample of the whole data set used for the analysis.

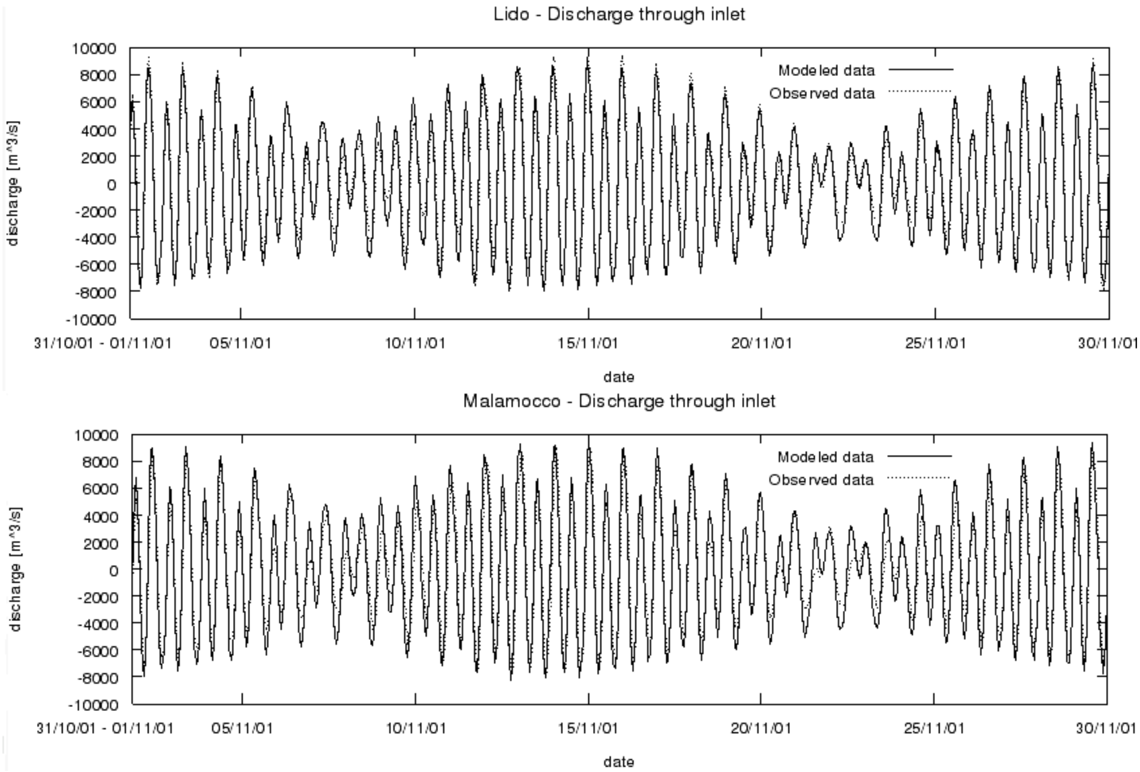

Fig. 5 – This plot shows the time-series of the fluxes through the Lido and Malamocco inlet derived from ADCP data and obtained by the model simulation for the period of November 2001.

Both for Lido and Malamocco, the correlation index with the real data is high: 0.98 and 0.94 respectively. The computed values present a delay with respect to the empirical ones in both cases. At Lido a time lag of about 20 minutes has been estimated. At Malamocco, the derived time lag is a little larger (about 30 minutes). As we expected by the previous results, the worst case has been found for Malamocco. Moreover, for Lido, the combined effect of the whole set of tides has increased the phase-displacement initially detected for the M2 and K1 constituents only, from 10 minutes to 20 minutes.

The intensity of the discharge rates is generally overestimated by the model both for Malamocco and Lido inlet. If the time series is adjusted with respect to the phase lag, the model results show an overestimation of 13% at Malamocco and 8% at Lido.

To explain the differences with the empirical data we can distinguish two different groups: one related to the measured data and one related to the numerical model.

The empirical discharge data, as explained in section 2.3, have been obtained from the vertically averaged water velocity value measured by ADCP probe for a fixed location inside each inlet. From the velocity value the discharge rate through each inlet has been extrapolated. The described method is suitable especially to measure tidal only flow. When the discharge rate is affected by high residual flow generated by intense meteorological events, such as during the period that we consider, the measurements are subjected to an adjoin uncertainty which is not known.

Further source of error for the empirical data, is related to the harmonic analysis. In fact, due to the high residual signal that affects the discharge rate data, the amplitude and the phase values obtained for each main tidal constituents from the harmonic analysis, are subjected to high relative errors.

What concerns the model, a source of error can be related to the reproduction of the SSE outside and inside the inlets. The discharge rate through the inlet is dependent on the SSE gradient along the inlet channel and therefore the accuracy of the SSE inside and outside the Lagoon strongly affects the model results. This error can not be easily assessed but the high sensitivity of the accuracy of the computed discharge values with respect to the SSE values can be realistically be assumed.

Finally, the use of recent bathymetric data to reproduce the morphology of the Venice Lagoon and the inlets could reduce the error of the model what concerns the reproduction of the SSE inside the lagoon basin and consequently of the discharge rate through the inlets.

Conclusions.

Before this study, no major studies have been carried out that try to measure or model the exchange and its mechanisms through the Venice Lagoon inlets. The object of the present work is to reproduce by numerical modeling the water exchange dynamic through the three lagoon inlets. Before this study, no major studies have been carried out that try to measure or model the exchange and its mechanisms through the Venice Lagoon inlets. The object of the present work is to reproduce by numerical modeling the water exchange dynamic through the three lagoon inlets.

With this aim we implemented a 2D hydrodynamic model of the Adriatic Sea and the Venice Lagoon based on the finite element method. The spatial resolution of the model varies from 50 meters inside the Venice Lagoon inlets to 20 km in the middle of the Adriatic Sea, with a transition zone between the open sea and the lagoon characterised by a 300 meters resolution. The open boundary has been chosen as a straight line across the strait of Otranto.

In this application the model was used in the barotropic mode to reproduce the discharge rate through the lagoon inlets driven by the action of the tide only. Along the open boundary line the tidal SSE is imposed. No other forcings such as wind and pressure have been considered, only the tide drives the water circulation inside the two basins.

The model has been calibrated to reproduce the tidal propagation in the Adriatic Sea and in the Venice Lagoon. The parameter to be varied during this process was the SSE along the open boundary line of Otranto and the bottom friction coefficient inside the Venice Lagoon basin. For the validation the model results have been compared to empirical data of harmonic constants collected in 24 stations located along both the west and the east coast of the Adriatic Sea and inside the Venice Lagoon. In this article only the results referred to the tidal propagation in the Adriatic Sea are reported. The tidal dynamic inside the Venice Lagoon and the results of the related calibration process is treated Umgiesser *et al.* [2004].

What concerns the tide, the model reproduces the set of harmonic constants for the Diga Sud Lido station, with an error always less than 1% for what concerns the amplitude and with a maximum phase lag of 7 degrees for the most energetic tidal constituents (M2, S2 and K1). The results obtained for the other stations close to the Venice Gulf, are also in good agreement with the empirical data. The SSE o shore the Venice lagoon is in fact reproduced with an error always lower than 6% for the amplitude of the main tides and with a phase difference not higher than 8 degrees. These results are in accordance with the task of this work which is the reproduction of the tidal flow through the three lagoon inlets.

Finally the water fluxes through the inlets have been computed by the model when only tide is forcing the basin. The results have been compared with empirical data of water discharge derived from ADCP measurements collected inside each inlet. The model reproduces the fluxes through the inlets with an average overestimation of about 10% with a time delay of about 25 minutes.

The success of these simulations on the reproduction both of the SSE inside and outside the Venice Lagoon and of the tidal flow through the lagoon inlets indicates that the finite element model is performing adequately on the barotropic mode. Therefore this model can be realistically considered as a fundamental support for studies that aim to investigate the nutrients, salinity or pollutants budgets of the lagoon and their exchange with the open sea. In the future it is desirable to integrate also the meteorological component in the forcings in order to describe the residual flow through the inlets adequately.

References.

Arena F., Arcari G., 2001. Rapporto tecnico sulle misure correntometriche alle Bocche di Porto di Venezia. *Technical Note* 191, 65 72

Bergamasco A., Carniel S., Pastres R., Pecenik G., 1998. A Unified Approach to the Modelling of the Venice Lagoon-Adriatic Sea Ecosystem. *Estuarine, Coastal and Shelf Science* 46, 483 492

Blumberg A. F., Mellor G. L., 1987. A description of a three dimensional coastal ocean circulation model. *Coastal and Estuarine Sciences* AGU (4), 1 16

Canestrelli P., Cucco A., Umgiesser G., Zampato L., 2003. An operational forecasting system for the sea level in venice based on a finite element hydrodynamic model. *Technical Note* of the Venice Municipality

Cavaleri L., Bertotti L., 1996. In search of the correct wind fields in a minor basin. *Monthly Weather Review* 125, 1964 1975

Cushmain-Roisin B., Naimie C. E., 2002. A 3D finite element model of the Adriatic tides. *Journal of Marine System* 37, 279 297

Foreman M. G. G., 1996. Manual for tidal heights analysis and prediction. *Pacific Marine Science Report* 77 (10)

Gacic M., Kovacevic V., Mazzoldi A., Paduan J., Arena F., Mosquera I. M., Gelsi G., Arcari G., 2002. Measuring Water Exchange between the Venetian Lagoon and the Open Sea. *EOS*, Transactions, AGU 83 (20), 217,221 222

Goldmann A., Rabagliati R., Sguazzero P., 1975. Characteristics of the tidal wave in the Lagoon of Venice. *Technical Report* 47, IBM, Venice Scientific Center

Malacic V., Viezzoli D., Cushmain-Roisin B., 2000. Tidal dynamics in the northern Adriatic Sea. *Journal of Geophysical Research* 105 (C11), 26,256 26,280

Melaku Canu D., Umgiesser G., Solidoro C., 2001. Short term simulations under winter conditions in the lagoon of Venice: a contribution to the environmental impact assessment of a temporary closure of the inlets. *Ecological Modelling* 138 (1 3), 215 230

Mellor G.L., 1991. User s Guide for a Three Dimensional, Primitive Equation, Numerical Ocean Model. *Progress in Atmosphere and Ocean Science Princeton University,* Princeton, 35

Mosetti F., 1987. Distribuzione delle maree nei mari Italiani. *Boll. Oceanol. Teor. Appl.* 5, 65 72

Polli S., 1960. La propagazione delle maree nell'Alto Adriatico. Publications of the Istituto Sperimentale Talassografico, Trieste 370

Polli S., 1961. La propagazione della marea nel Golfo di Venezia. Publications of the Istituto Sperimentale Talassografico, Trieste 385

Solidoro C., Canu D.M., Cucco A., Umgiesser G., 2004. A partition of the Venice Lagoon based on physical properties and analysis of the general circulation. *Journal of Marine Systems* 51 (1-4), 147 160

Umgiesser G., 2000. Modeling residual currents in the Venice Lagoon. In: *Yanagi, T. (Ed.), Interactions between Estuaries, Coastal Seas and Shelf Seas*. Terra Scientific Publishing Company (TERRAPUB), Tokyo, pp. 107 124

Umgiesser G., Bergamasco A., 1993. A staggered grid finite element model of the Venice Lagoon. K. Morgan, E. Ofiate, J. Periaux and O.C. Zienkiewicz. Pineridge Press, pp. 659 668

Umgiesser G., Bergamasco A., 1995. Outline of a primitive equations finite element model. *Rapporto e Studi*, Istituto Veneto of Scienze, Letter ed Arti XII, 291 320

Umgiesser G., Bergamasco A., 1998. The spreading of the Po plume and the Italian coastal current. In: *Dronkers, Sche ers (Eds.), Physics of Estuaries and Coastal Seas*. Balkema, Rotterdam, pp. 267 275

Umgiesser G., Canu D.M., Cucco A., Solidoro C., 2004. A finite element model for the Venice Lagoon. Development, set up, calibration and validation. *Journal of Marine Systems* 51 (1-4), 123 145

RESEARCH LINE 3.6
Biodiversity in the Venice Lagoon

COMPOSITION AND DISTRIBUTION OF FISH ASSEMBLAGES IN THE SHALLOW WATERS OF THE VENICE LAGOON

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Riassunto.

Nel presente lavoro, sono riportati in sintesi alcuni dei risultati più significativi dei tre anni di ricerca della linea 3.6 del progetto CORILA, incentrata sull'analisi delle comunità ittiche dei bassi fondali della laguna di Venezia. In particolare, la composizione qualitativa della comunità lagunare, in termini di ripartizione delle specie fra i diversi gruppi funzionali (*guilds*), è stata confrontata con quanto ottenuto in precedenti studi relativamente alle comunità ittiche caratterizzanti altre zone estuariali e lagunari europee. La composizione della comunità ittica è stata ottenuta integrando i dati provenienti da tutti i campionamenti svolti durante i tre anni del progetto che, essendo stati condotti con due diversi e complementari attrezzi da pesca (rete da circuizione e rete da posta), si sono rivelati capaci di dare un'informazione piuttosto completa e rappresentativa della struttura della comunità ittica di bassofondale. Inoltre, l'abbondanza degli individui nei diversi gruppi funzionali è stata utilizzata per redigere mappe di distribuzione relative all'intera laguna e alle tre diverse stagioni di campionamento. Tali mappe permettono di visualizzare in modo rapido e sintetico le variazioni spazio-temporali delle abbondanze dei diversi gruppi ecologici. I risultati suggeriscono che nel suo complesso la comunità ittica della laguna di Venezia non si discosta significativamente, in termini di composizione funzionale, dalla tipica comunità ittica degli ambienti estuariali europei atlantici, fortemente dominata dal gruppo dei residenti estuarini, che presentano specifici adattamenti agli ambienti di transizione. La distribuzione dei residenti estuarini in laguna di Venezia evidenzia l'ubiquità e la variabilità stagionale di questa guild funzionale. Al contrario, differenze spaziali di interesse si rilevano per i gruppi di specie marine migratrici, ed in particolare per i migratori giovanili, che sembrano concentrarsi maggiormente nel bacino Nord e nelle aree interne caratterizzate da elevata torbidità, fondali fangosi e apporti di acqua dolce. Queste mappe spaziali possono quindi permettere di individuare le principali "aree di nusery" della laguna, dimostrandosi quindi uno strumento utile ai fini della corretta gestione del patrimonio ittiologico.

Abstract.

In this paper, the main results of three years of CORILA project on the lagoon fish diversity are summarised. In particular, the composition of the shallow water fish assemblages, in terms of allocation of fish species to the different functional groups (ecological guilds), has been compared with that found in previous studies on the "typical European" estuarine fish assemblage. The data obtained from the sampling carried out with two complementary fishing gear (fyke nets and beach seine), conducted during the last three years in different seasons, were combined to get a representative and complete picture of the entire lagoon shallow water fish assemblage. Further, the abundances of individuals allocated to the different ecological groups were used to elaborate spatial maps of the entire lagoon for each season. These maps allow to track the spatial-temporal variation of the abundance distribution of each functional group. Results suggest that the Venice Lagoon fish assemblage closely resembles the typical fish assemblage of European estuarine environments, being dominated by the group of estuarine residents. This group is homogeneously distributed in the lagoon, with strong seasonal fluctuations. By contrast, marine migrant fish are more localized in particular areas, and this is specifically true for marine migrant juveniles. These are more concentrated in the Northern lagoon sub-basin and appear to be associated to some particular habitats, like the internal salt marshes, characterized by high turbidity, muddy bottoms and freshwater inputs. Hence these maps may allow to localize the nursery areas in the lagoon, and could be a useful tool for the correct management of the ichthyological resources of the Venice Lagoon.

1. Introduction.

Fish assemblages of estuaries and coastal lagoons have been extensively studied worldwide, in tropical, sub-tropical and temperate areas [McHugh, 1967; Haedrich, 1983; Wallace *et al.*, 1984; Potter *et al.*, 1990; Blaber, 1997; 2000; Whitfield, 1999; Elliott and Hemingway, 2002; Nordlie, 2003]. However, as highlighted by Phil *et al.* [2002], few data from the Mediterranean are available. The present work, as part of a wider project on the Venice Lagoon biodiversity (CORILA 2000-2003), aids the knowledge on fish assemblages in this Mediterranean area by studying the Venice Lagoon shallow water fish assemblages. They were investigated during 2001 and 2002, by using two different gear types, the fyke nets and a small beach seine [Mainardi *et al.*, 2002; 2004]. This study allowed to characterize the lagoon fish assemblages in relation to the different shallow water areas and habitats where they were found. The present paper, in particular, summarizes and discusses the conclusive findings of this three-year CORILA project. The overall structure of the lagoon shallow water fish community is presented and discussed in the light of the findings of other authors in other similar areas elsewhere. The functional guilds approach, in particular, has been used. The use of functional groups provides more information on the functioning of fish communities compared with the traditional taxonomic classification. Further this approach, by reducing highly connected and complex ecosystems to an ecologically meaningful level of complexity [Garrison and Link, 2000], should be particularly useful in heterogeneous environments, such as the Venice Lagoon. Moreover, the distribution of the functional groups composing the lagoon fish assemblages is summarized and visualized by means of maps, in order to provide useful tools for the management of this complex environment.

2. Materials and Methods.

Fish sampling was carried out from March 2001 to November 2002 in the shallow waters of the Venice Lagoon, by using two different gear, a small beach seine net and fyke nets. Beach seine sampling was conducted in 68 stations distributed over 5 shallow subtidal habitats in the lagoon, whereas fyke nets samples were taken in 4 areas located in the three lagoon sub-basins. The detailed descriptions of sampling methodologies and designs are reported in Mainardi *et al.* [2002; 2004]. The fish abundance in each sampling station was measured as fish density (number of individuals 100 m^{-2}) for the seine net sampling and as catch per unit effort (CPUE, with single trap as unit effort) for the fyke nets sampling. The lists of species caught with the two sampling gear were integrated in order to obtain a single, complete list of the fish fauna found in the lagoon shallow water habitats.

Fish species were allocated to a number of functional groups, according to Mathieson *et al.* [2000] and Mainardi *et al.* [2002; 2004]: estuarine residents (ER), marine adventitious visitors (MA), diadromus (catadromous/anadromous) migrants (CA), marine seasonal migrants (MS), marine juvenile migrants (‘nursery species’) (MJ) or freshwater adventitious visitors (FW). The lagoon fish assemblage composition, in terms of these functional guilds, was compared with the “typical European estuarine fish assemblage” defined by Elliott and Dewailly [1995].

Data from seine net catches were employed to obtain distribution maps of the functional groups of the fish assemblages. The abundances of resident species (ER), of nursery species (MJ) and of the other marine transient species (MS+MA) were spatially interpolated using the ordinary kriging method after the analysis of the spatial correlations, and the fish densities of the functional groups are visualized in thematic maps for each season (Spring, Summer and Autumn).

3. Results.

3.1. Composition of shallow water lagoon fish assemblage.

The shallow water lagoon fish assemblage consisted on the whole of 62 species, belonging to 29 families (Tab. 1). 39 species (63% of the total number) were sampled with both gear types, whereas the others were caught with either fyke nets (10 species) or beach seine (13 species) (Tab. 1). Both the gear types provided representative samples of the resident component of the lagoon fish community, in terms of number of species, as species caught exclusively with either the fyke nets or the beach seine were mostly marine species (Tab. 1). The sand smelt, *Atherina boyeri* Risso, 1810, was predominant in the fyke nets catches, accounting for almost 82% of the total CPUE (Tab. 1, Fig. 1a). *Zosterisessor ophiocephalus* (Pallas, 1814) and *Solea vulgaris* (Linnaeus, 1758) (4% each), *Gobius niger* Linnaeus, 1758 (3.4%) and *Engraulis encrasicolus* (Linnaeus, 1758) (2.2%) followed, whereas the remaining 43 species caught with the fyke nets accounted for less than 1.5% each of the total CPUE (Tab. 1, Fig. 1a). Most of fishes caught with this gear type were adults. The beach seine catches, in turn, appeared to be more diverse: *Pomatoschistus marmoratus* (Risso, 1810) (accounting for 27% of the total abundance), *Atherina boyeri* (17%), *Knipowitschia* *panizzae* (Verga, 1841) (11.5%), *Syngnathus abaster* Risso, 1827 (10%), *Syngnathus typhle* Linnaeus, 1758 (7.5%), *Liza saliens* (Risso, 1810) (5%), *Pomatoschistus minutus* (Pallas, 1770) and *Zosterisessor ophiocephalus* (4% each), *Engraulis encrasicolus*, *Aphanius fasciatus* (Valenciennes, 1821) and *Pomatoschistus canestrinii* (Ninni, 1883) (about 2% each) were the most abundant species, whereas the remaining 41 species caught with the beach seine accounted for less than 1.5% each of the total fish abundance (Tab. 1, Fig. 1b). About half the fishes caught with this gear type were juveniles.

Tab. 1 – List of the fish species sampled in the shallows of the Venice Lagoon. Species are divided by family and functional group (FG), and relative fish abundances in the catches of fyke nets (CPUE%) and beach seine (Abb%) are reported.

Species Code	Species	Family	FG	CPUE%	Abb%
Aan	*Anguilla anguilla*	Anguillidae	CA	0.08	
Abo	*Atherina boyeri*	Atherinidae	ER	81.59	17.30
Bbe	*Belone belone*	Belonidae	MS	0.09	0.09
Pga	*Parablennius gattorugine*	Blennidae	MA	0.005	
Psa	*Parablennius sanguinolentus*	Blennidae	MA		0.08
Pte	*Parablennius tentacularis*	Blennidae	MA		0.01
Spa	*Salaria pavo*	Blennidae	ER	0.36	0.53
Ala	*Arnoglossus laterna*	Bothidae	MA		0.005
Cri	*Callionymus risso*	Callionymidae	MA	0.003	0.05
Ttr	*Trachurus trachurus*	Carangidae	MA	0.05	
Alfa	*Alosa fallax*	Clupeidae	CA	0.002	
Spi	*Sardina pilchardus*	Clupeidae	MS	0.001	0.002
Ssp	*Sprattus sprattus*	Clupeidae	MS	0.16	0.02
Cco	*Conger conger*	Congridae	MA	0.004	
Cca	*Carassius carassius*	Cyprinidae	FW		0.02
Apfa	*Aphanius fasciatus*	Cyprinodontidae	ER	1.16	2.26
Een	*Engraulis encrasicolus*	Engraulidae	MS	2.21	2.27
Mme	*Merlangius merlangus*	Gadidae	MJ	0.001	0.002
Gco	*Gobius cobitis*	Gobiidae	MA	0.04	0.13
Gni	*Gobius niger*	Gobiidae	ER	3.38	0.44
Gpa	*Gobius paganellus*	Gobiidae	ER	0.04	
Kpa	*Knipowitschia panizzae*	Gobiidae	ER	0.05	11.47
Pca	*Pomatoschistus canestrinii*	Gobiidae	ER	0.01	2.13
Pma	*Pomatoschistus marmoratus*	Gobiidae	ER	0.21	27.45
Pmi	*Pomatoschistus minutus*	Gobiidae	MJ	0.13	4.43
	Zosterisessor ophiocephalus	Gobiidae	ER	3.97	4.17
Sro	*Symphodus roissali*	Labridae	MA	0.01	0.02
Symp1	*Symphodus sp.1*	Labridae	MA		0.005
Symp2	*Symphodus sp. 2*	Labridae	MA		0.03
Dla	*Dicentrarchus labrax*	Moronidae	ER	0.16	0.005
Cla	*Chelon labrosus*	Mugilidae	MS	0.004	0.01

Tab. 1 – Continue.

Species Code	Species	Family	FG	CPUE%	Abb%
Lau	*Liza aurata*	Mugilidae	MS	0.20	0.23
Lra	*Liza ramada*	Mugilidae	MJ	0.32	1.43
Lsa	*Liza saliens*	Mugilidae	ER	0.21	5.43
Mce	*Mugil cephalus*	Mugilidae	MJ		0.002
Mba	*Mullus barbatus*	Mullidae	MJ	0.02	0.13
Pfl	*Platichthys flesus*	Pleuronectidae	ER	1.11	0.49
Gho	*Gambusia holbrooki*	Poeciliidae	ER	0.001	0.02
Str	*Salmo trutta*	Salmonidae	FW	0.001	
Sum	*Sciaena umbra*	Sciaenidae	MA		0.02
Uci	*Umbrina cirrosa*	Sciaenidae	MJ	0.001	
Ssc	*Scomber scombrus*	Scombridae	MA	0.001	
Srh	*Scophthalmus rhombus*	Scophthalmidae	MJ		0.002
Sim	*Solea impar*	Soleidae	MJ		0.005
Svu	*Solea vulgaris*	Soleidae	MJ	3.97	0.48
Bbo	*Boops boops*	Sparidae	MA	0.01	0.04
Dan	*Diplodus annularis*	Sparidae	MS	0.09	0.03
Dpu	*Diplodus puntazzo*	Sparidae	MA		0.01
Dsa	*Diplodus sargus*	Sparidae	MA	0.01	0.005
Dvu	*Diplodus vulgaris*	Sparidae	MA	0.01	
Lmo	*Lithognathus mormyrus*	Sparidae	MS	0.001	0.01
Sau	*Sparus aurata*	Sparidae	MJ	0.02	0.005
Hgu	*Hippocampus guttulatus*	Syngnathidae	MA	0.08	0.02
Hhi	*Hippocampus hippocampus*	Syngnathidae	MA	0.01	0.005
Nop	*Nerophis ophidion*	Syngnathidae	ER		1.07
Sab	*Syngnathus abaster*	Syngnathidae	ER	0.13	9.87
Sac	*Syngnathus acus*	Syngnathidae	MA	0.01	0.02
Sta	*Syngnathus taenionotus*	Syngnathidae	ER	0.004	0.14
Ste	*Syngnathus tenuirostris*	Syngnathidae	MA	0.02	0.02
Sty	*Syngnathus typhle*	Syngnathidae	ER	0.10	7.52
Evi	*Echiichthys vipera*	Trachinidae	MA		0.01
Tlu	*Trigla lucerna*	Triglidae	MJ	0.004	0.04

The functional guilds composition was similar between the catches of fyke nets and beach seine: estuarine residents (ER) dominated the fish assemblages, accounting for about 90% of the total abundance, followed by marine migrant juveniles (MJ, 6.5% in beach seine catches, 4.5% in fyke nets catches) and marine seasonal migrants (MS, about 3% in both catches) (Fig. 2b). In terms of number of species, ER and MA were the most abundant groups, accounting for about 30% of the total number of species each (Fig. 2a). The marine migrants, MS and MJ, followed, with a relative number of species between 15% and 19%, respectively, whereas freshwater (FW) and diadromous (CA) species were less represented in the catches, with CA group never sampled with the beach seine (Fig. 2a).

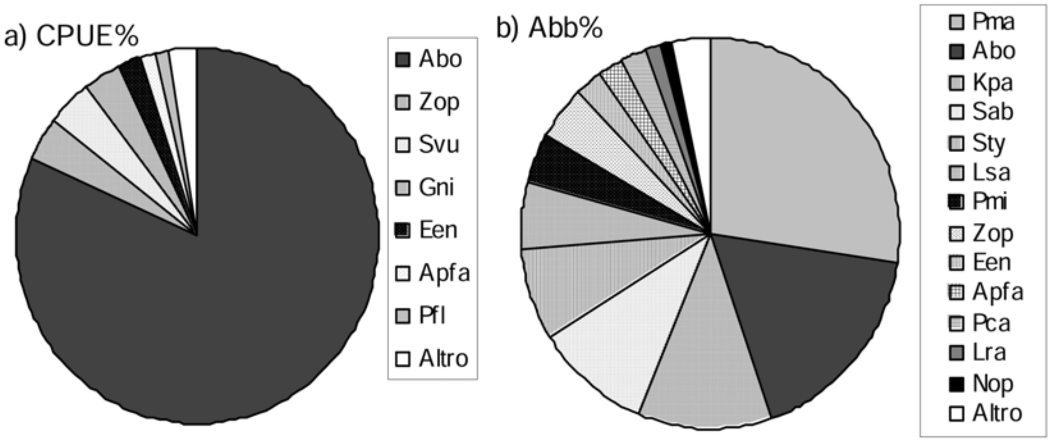

Fig. 1 – Species composition, in terms of fish abundance, of the catches obtained by a) fyke nets (CPUE%) and b) beach seine net (Abb%) in the shallows of the Venice Lagoon. Species codes are those reported in Tab. 1.

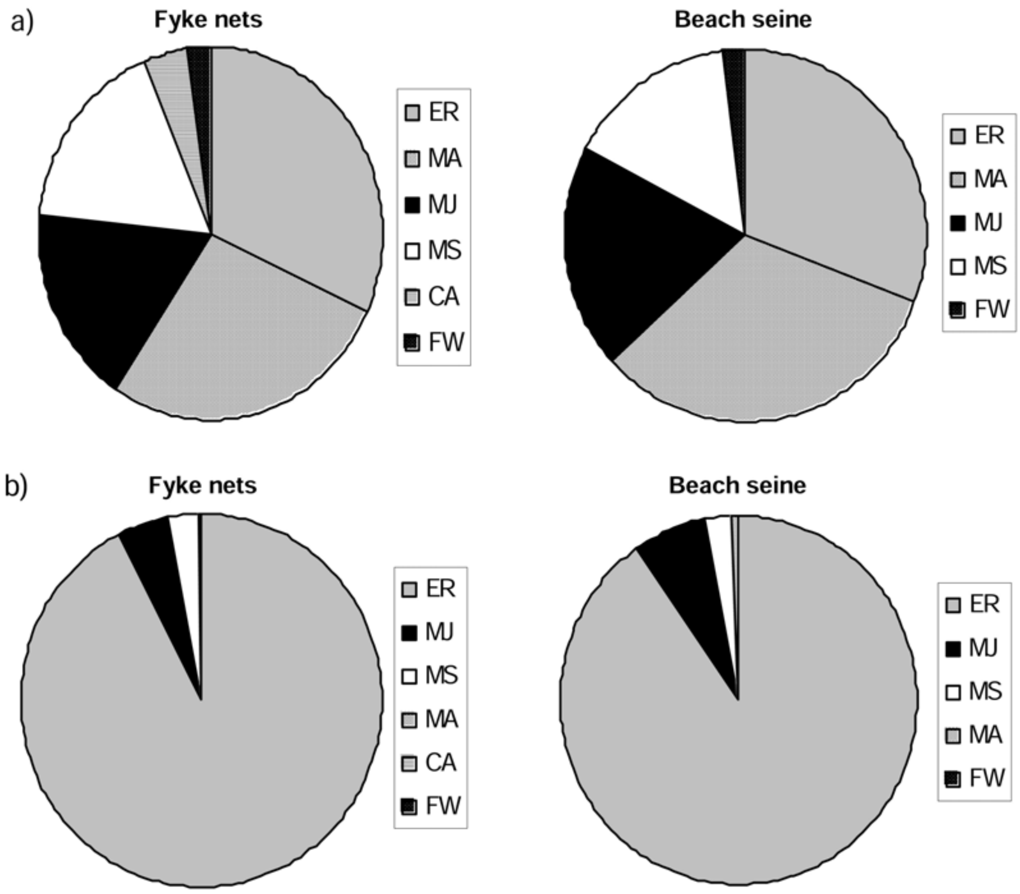

Fig. 2 – Functional guilds composition, in terms of a) number of species and b) fish abundance, of the catches obtained by fyke nets and beach seine in the shallows of the Venice Lagoon.

Due to this similarity in the functional guilds composition of the fish catches between the two sampling methods, the integration of the two species list, as in Tab. 1, may be considered representative of the overall lagoon shallow water fish assemblage. Hence the functional structure of the lagoon fish community may be compared with that of the European estuarine fish assemblages, defined by Elliott and Dewailly [1995] (Tab. 2). Despite they resulted basically similar, a higher abundance of marine adventitious species (MA) and a lower one of diadromous species (CA) was highlighted in the Venice Lagoon with respect to the "typical" European estuary.

Tab. 2 – Comparison of the functional guilds composition of the fish assemblages between the Venice lagoon (shallow waters) and the typical European estuary defined by Elliott and Dewailly [1995].

	Venice Lagoon	typical European estuary		
		average	min	max
ER	27.4	24	14	33
MA	35.5	25	5	48
MJ	17.7	24	14	37
MS	12.9	10	8	14
CA	3.2	12	4	23
FW	3.2	5	0	31

3.2. Spatial distribution of fish assemblages in the lagoon shallow waters.

Estuarine resident species showed low abundances by Spring (1.6 to 7.7 individuals 100 m^{-2}), and were almost homogeneously distributed in the lagoon, with only some internal areas showing higher abundance values (7.7-31.8 individuals 100 m^{-2}) and the highest values (up to 92.2 individuals 100 m^{-2}) found in the Northern sub-basin (Fig. 3). During Summer, estuarine residents showed an average higher density and a high spatial variability, with aggregation spots (more than 200 individuals 100 m^{-2}) located both near the sea inlets and in the salt marsh areas of the inner part of the lagoon (Fig. 3). During Autumn abundances of this functional group were lower than in Summer, with high values both across the central-southern part of the lagoon and in the Northern sub-basin (Fig. 3).

Nursery species (MJ) showed low abundances in most of the lagoon shallow waters by Spring, except for the salt marsh area close to the Dese River mouth, in the Northern sub-basin, where a very high fish density (from 127.6 to 136.7 individuals 100 m^{-2}) was found (Fig. 4). By Summer, marine juvenile migrants showed again a regular low density distribution (from 0 to 15.6 individuals 100 m^{-2}) in the lagoon, and a strong aggregation of individuals (with abundances up to 15 times higher than in the rest of the lagoon) in the internal areas of the Central sub-basin (Fig. 4). The abundances of this functional guild were low also in Autumn, with only some areas north of Venice showing abundance values above the overall average (Fig. 4).

The other marine transient species (MS+MA) were almost absent in the Venice Lagoon by Spring, with the exception of some areas both in the inner part of the lagoon (salt marsh areas in the Central and Southern sub-basins) and closer to the Chioggia and Lido inlets, where only few individuals were found (with a maximum of 2.1 individuals 100 m^{-2}) (Fig. 5). During Summer these groups of migrant species showed low abundances (from 0 to 13.1 individuals 100 m^{-2}), which were homogeneously distributed in the lagoon shallow areas, although two spots of higher density (up to 5 times higher than the average value) could be identified in the northern part of the lagoon, one in the internal mud flat area close to the Tessera airport, and the other near the Lido sea inlet (Fig. 5). By Autumn, the marine transient species group showed a pattern of spatial distribution similar to that observed by Spring, with null or extremely low abundance in the whole lagoon and only some areas characterized by relative higher fish densities (Fig. 5).

4. Discussion.

Shallow waters are the most common condition in the Venice Lagoon. Hence the overall picture of the shallow waters fish assemblages drawn by the present study may be considered as a good representation of the lagoon fish fauna, although it is not exhaustive due to the lack of samples from channels and deeper areas. Moreover, the use of two sampling gear types having different selectivity (fyke nets and beach seine net) and the integration of the data resulting from the two samplings further support the validity of the results here discussed.

On the whole, 62 fish species were found in the lagoon shallow waters, belonging to 29 families. Atherinidae and Gobiidae are the most abundant families, as confirmed by studies on estuarine and lagoon fish assemblages carried out elsewhere in temperate and semi-tropical areas [Potter *et al.*, 1990; Elliott and Dewailly, 1995; Costa *et al.*, 2002]. The two used gear types, fyke nets and beach seine, proved to be complementary in the sampling of the lagoon fish assemblage, in terms of both fish abundance and species composition, as already highlighted by Mainardi *et al.* [2004]. Hence these studies further aids our knowledge of the effectiveness of different gear types in describing the community structure.

The use of functional guilds approach in studying the lagoon fish assemblage allows a more straightforward comparison with that reported for European estuarine areas by Elliott and Dewailly [1995]. Root [1967] defined a guild as a group of species that exploit the same class of environmental resources in a similar way. Hence a guild gives information on the function and bio-ecological needs of the species, irrespective of their taxonomic identity, thus highlighting in a better way the availability and the occupation of the ecological niches in estuarine areas [Elliott and Dewailly, 1995]. In terms of ecological guilds, the lagoon fish assemblage composition is qualitatively quite similar to that indicated by Elliott and Dewailly [1995] as the "typical European estuarine fish assemblage", being dominated by marine adventitious visitors (MA) and estuarine resident species (ER). These are the ecological guilds contributing most to the fish fauna in estuarine systems [Pihl *et al.*, 2002], and are followed by marine migrant species (MJ and MS). In turn, freshwater adventitious (FW) and diadromous species (CA) are less represented than the other ecological guilds, in the Venice Lagoon as well as in the European estuaries [Elliott and Dewailly, 1995].

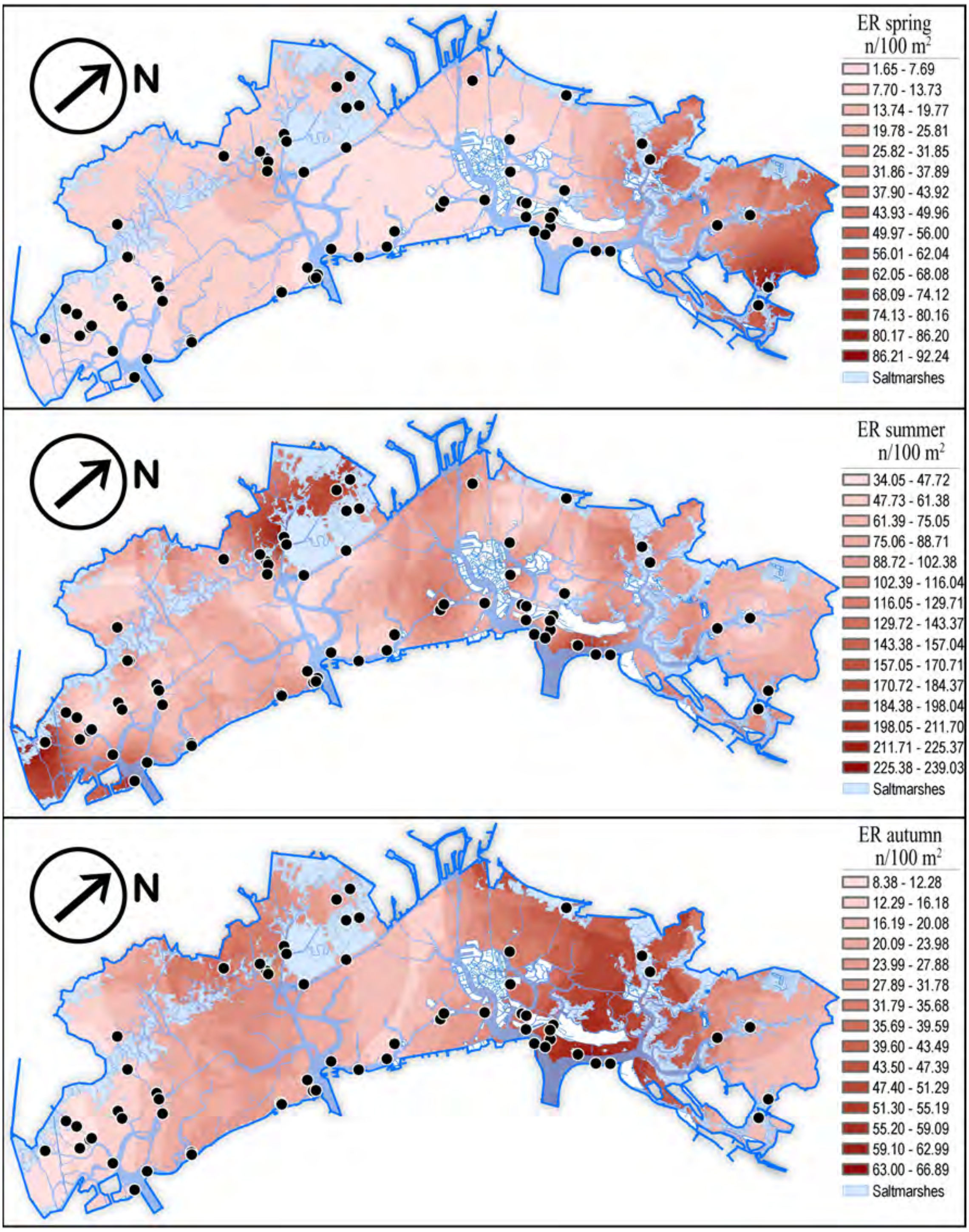

Fig. 3 – Spatial distribution of the abundance (number of individuals/100 m^2) of estuarine resident species (ER) in the Venice Lagoon shallow waters by Spring, Summer and Autumn. Sampling stations are represented by black dots.

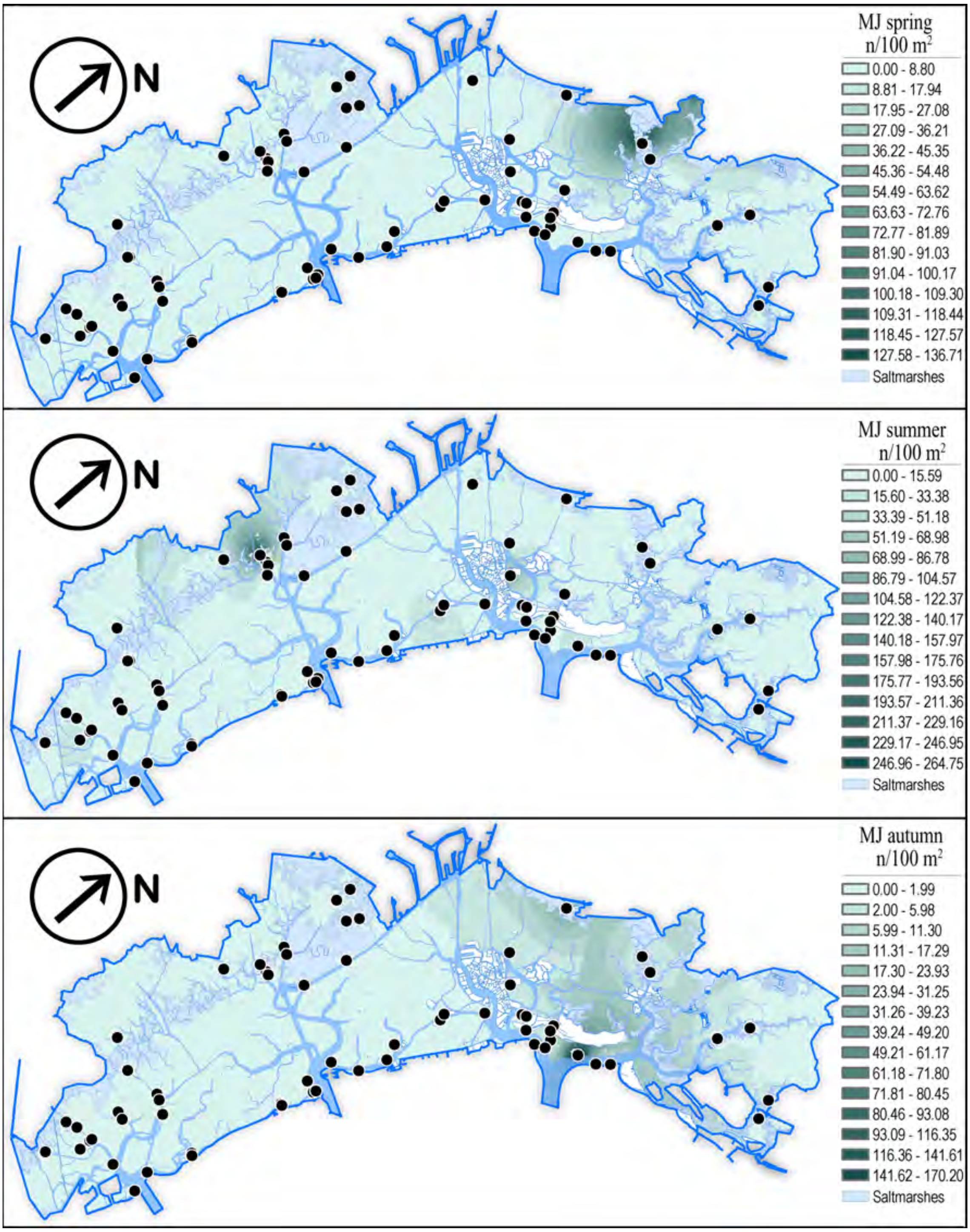

Fig. 4 – Spatial distribution of the abundance (number of individuals/100 m^2) of marine juvenile migrant (nursery) species (MJ) in the Venice Lagoon shallow waters by Spring, Summer and Autumn. Sampling stations are represented by black dots.

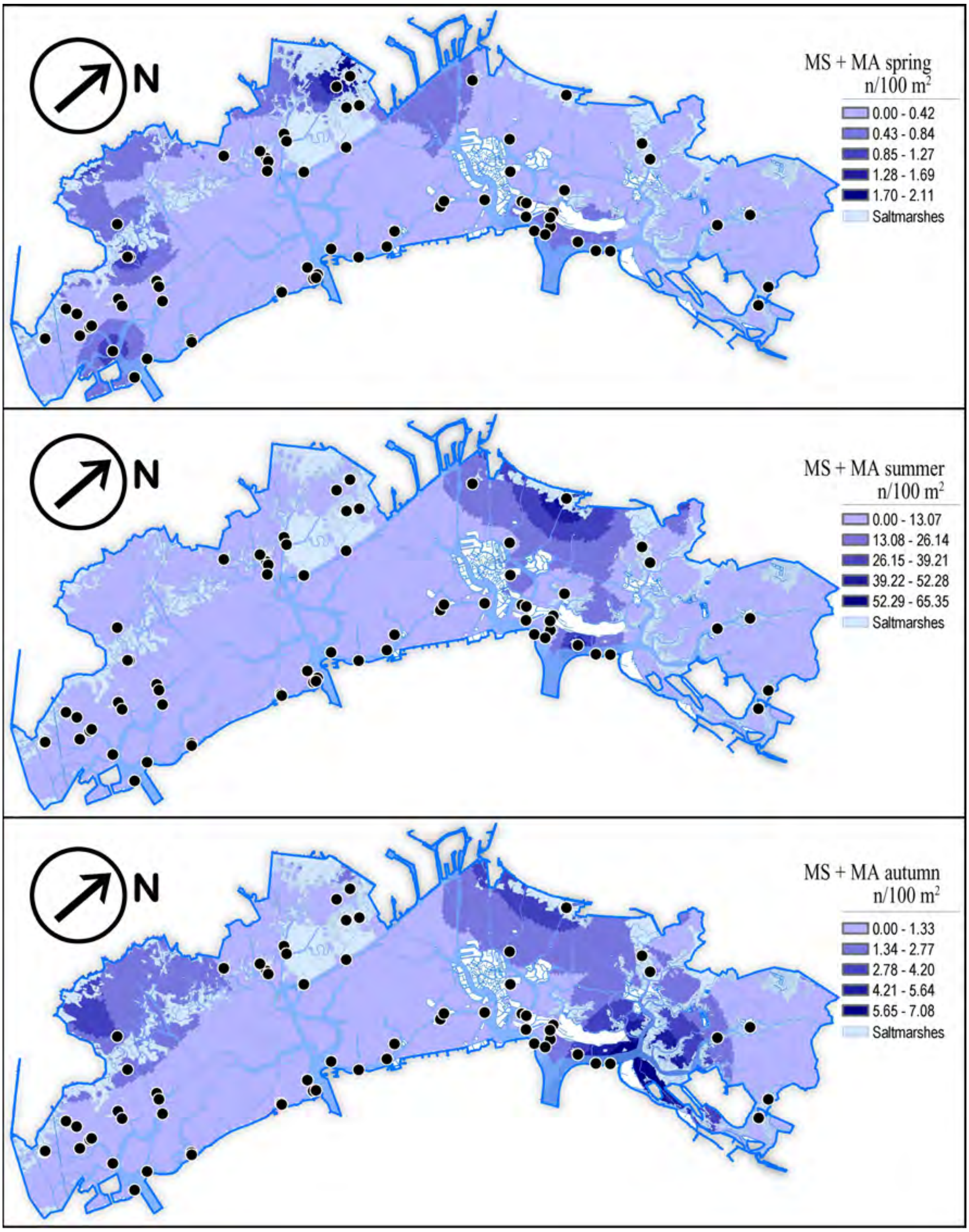

Fig. 5 – Spatial distribution of the abundance (number of individuals/100 m^2) of marine transient species (MS+MA) in the Venice Lagoon shallow waters by Spring, Summer and Autumn. Sampling stations are represented by black dots.

This similarity between the Venice Lagoon fish assemblage and those of the other European estuarine areas described by Elliott and Dewailly [1995] might be unexpected, due to the difference between all these environments. Elliott and Dewailly [1995], in fact, considered 17 estuarine areas having different characteristics, from the Portuguese coastal lagoons to the Northern Sea deep fjords; in addition, all the estuarine environments considered by these authors are localized on the Atlantic seaboard of Europe and are influenced by wider tidal ranges (from 2.2 to 7 m) [Mathieson *et al.*, 2000] than the Venice Lagoon (1 m at most) [Umgiesser *et al.*, 2004] and the Mediterranean in general. Hence the similarity found between so different environments suggests a common use of estuarine environments by fish fauna, irrespective of the taxonomic identity of the species [Elliott and Dewailly, 1995]. This is probably caused by the marked temporal and spatial variability of the estuarine areas in general, which leads to common adaptations and specializations of fish species living in these transitional waters and to a wide variety of niches available for fish fauna [Knox, 1986; Wootton, 1990; Pihl *et al.*, 2002].

The distribution of functional guilds in the lagoon area is a good indicator of the use of this environment by fish fauna. Hence the maps presented in this paper may be a useful tool for a correct management of this complex ecosystem. The observed marked seasonal fluctuations in guilds abundances highlight the importance of the lagoon environment for fish fauna during Summer, although shallow lagoon areas appears to be important also during Spring and Autumn for marine species using this environment as a nursery ground in particular. These seasonal patterns reflect the seasonality of both recruitment of estuarine residents and colonization of lagoon environment by marine migrant species [McErlean *et al.*, 1973; Allen and Horn, 1975; Hoff and Ibara, 1977; Knox, 1986; Potter *et al.*, 1986; Loneragan and Potter, 1990]. Estuarine residents, accounting for the larger amount of fish fauna in the lagoon (about 90%), are widely distributed all over the lagoon shallow habitats, showing a high spatial variability in their distributions across seasons. This guild, in fact, is made up of species having various habitat requirements, for example pipefish and grass goby, *Z. ophiocephalus*, which distribute preferably in seagrasses [Malavasi *et al.*, 2002; Riccato *et al.*, 2003], and *K. panizzae* and *P. canestrinii*, which are usually found on bare muddy bottoms, in relatively internal habitats [Maccagnani *et al.*, 1985; Franco, 2004; Franco *et al.*, 2005]. In contrast, the more localized spatial distribution of marine species using the lagoon as a nursery ground (MJ) suggests a particular nursery function of the Northern lagoon sub-basin. According to Dando [1984], Quignard *et al.* [1984], and Loneragan and Potter [1990], the settlement of larvae of marine species entering from the sea may be promoted by lower hydrodynamic conditions, such as those present in the Northern sub-basin with respect to the Central and Southern ones (as indirectly indicated by Ministero delle Infrastrutture e dei Trasporti [1999] and Amos *et al.* [2002]). In addition, the higher nutrient and chlorophyll *a* concentrations in the waters of the Northern sub-basin with respect to the others [Solidoro *et al.*, 2004] may favour the survival and growth of larval and juvenile stages in this area. The seasonal distribution of marine juvenile migrant species also shows that they distribute preferably in the internal habitats of the lagoon, such as mud flats and salt marsh areas, particularly in the vicinity of freshwater inlets, for example at the Dese River mouth or close to the Tessera airport, confirming our preliminary observations [Mainardi *et al.*, 2004]. The brackish turbid shallow waters in marsh sites are described as nursery habitats for juvenile fish by many authors [Shenker and Dean, 1979; Weinstein, 1979; Ayvazian *et al.*, 1992; Mathieson *et al.*, 2000], as in these waters protection from visual predators and the availability of food material for fishes are provided [Blaber and Blaber, 1980]. This leads also to a role as feeding grounds of these habitats in the lagoon, as confirmed by the spatial distribution of marine transient species (MS+MA). In turn, the concentration of marine species (MJ, MA and MS) in the area close to the Lido sea inlet (Northern lagoon) is likely to be caused by either the occasional entrance of marine visitors from the sea, or the use of this area as a pathway of migration from sea to the internal lagoon nursery and feeding grounds, and *vice versa*, by the seasonal migrant fish (MJ and MS).

References.

Allen G.A. and Horn M.H., 1975. Abundance, diversity and seasonality of fishes in Colorado Lagoon, Alamitos Bays, California. *Estuarine and Coastal Marine Science*, 3, 371-380

Amos C.L., Umgiesser G., Bonardi M. and Cappucci S., 2002. Sedimentation mechanism in Northern Venice Lagoon, in: *"Scientific research and safeguarding of Venice, CORILA Research Program 2001 results"*, by P. Campostrini (Editor), Istituto Veneto di Scienze, Lettere ed Arti, CORILA, Venezia, pp. 315-332

Ayvazian S.G., Deegan L.A. and Finn J.T., 1992. Comparison of habitat use by estuarine fish assemblages in the Acadian and Virginian Zoogeographic Provinces. *Estuaries*, 15, 368-383

Blaber S.J.M., 1997. *Fish and Fisheries of Tropical Estuaries (Fish and Fisheries Series 22)*, Chapman & Hall, London, 367 pp

Blaber S.J.M., 2000. *Tropical Estuarine Fishes: Ecology, Exploitation and Conservation*, Blackwell Science, Malden, MA, 372 pp

Blaber S.J.M. and Blaber T.G., 1980. Factors affecting the distribution of juvenile estuarine and inshore fish. *Journal of Fish Biology*, 17, 143-162

Costa M.J., Cabral H.N., Drake P., Economou A.N., Fernandez-Delgado L., Gordo L., Marchand J. and Thiel R., 2002. Recruitment and production of commercial species in estuaries, in: *"Fishes in Estuaries"*, by M. Elliott and K.L. Hemingway (Editors), Blackwell Science Ltd., Oxford, UK, pp. 54-123

Dando P.R., 1984. Reproduction in estuarine fish, in: *"Fish Reproduction: strategies and tactics"*, by G.W. Potts and R.J. Wootton (Editors), Academic Press, Harcourt Brace, Jovanovich Publishers, London, pp. 155-170

Elliott M. and Dewailly F., 1995. The structure and components of European estuarine fish assemblages. *The Netherlands Journal of Aquatic Ecology*, 29, 397-417

Elliott M. and Hemingway K.L., 2002. *Fishes in Estuaries*, Blackwell Science Ltd., Oxford, UK, 636 pp

Franco A., 2004. *La comunità ittica della laguna di Venezia: struttura e dinamiche spazio-temporali*, PhD thesis, Department of Environmental Sciences, University Ca' Foscari of Venezia, 107 pp

Franco A., Fiorin R., Franzoi P. and Torricelli P., 2005. Threatened fishes of the world: *Pomatoschistus canestrinii* Ninni, 1883 (Gobiidae). *Environmental Biology of Fishes*, 72, 32

Garrison L.P. and Link J.S., 2000. Dietary guild structure of the fish community in the Northeast United States continental shelf ecosystem. *Marine Ecology Progress Series*, 202, 231-240

Haedrich R.L., 1983. Estuarine fishes, in: *"Ecosystems of the World, 26, Estuaries and Enclosed Seas"*, by B.H. Ketchum (Editor), Elsevier Scientific Publishing Co., Amsterdam, pp. 183-207

Hoff J.G. and Ibara R.M., 1977. Factors affecting the seasonal abundance, composition and diversity of fishes in a Southeastern New England estuary. *Estuarine and Coastal Marine Science*, 5, 665-678

Knox G.A., 1986. *Estuarine ecosystems: a systems approach. Vol. 1*, CRC Press Inc., Boca Raton, Florida, 289 pp

Loneragan R.J. and Potter I.C., 1990. Factors influencing community structure and distribution of different life-cycle categories of fishes in shallow waters of a large Australian estuary. *Marine Biology*, 106, 25-37

Maccagnani R., Carrieri A., Franzoi P. and Rossi R., 1985. Osservazioni sulla struttura di popolazione ed il ruolo trofico di tre specie di gobidi (*Knipowitschia panizzae*, *Pomatoschistus marmoratus*, *Pomatoschistus canestrinii*) in un ambiente del delta del Po, *Nova Thalassia*, 7, 373-378

Mainardi D., Fiorin R., Franco A., Franzoi P., Giovanardi O., Granzotto A., Libertini A., Malavasi S., Pranovi F., Riccato F. and Torricelli P., 2002. Fish diversity in the Venice Lagoon: preliminary report, in: *"Scientific research and safeguarding of Venice, CORILA Research Program 2001 results"*, by P. Campostrini (Editor), Istituto Veneto di Scienze, Lettere ed Arti, CORILA, Venezia, pp. 583-594

Mainardi D., Fiorin R., Franco A., Franzoi P., Granzotto A., Malavasi S., Pranovi F., Riccato F., Zucchetta M. and Torricelli P., 2004. Seasonal distribution of fish fauna in the Venice Lagoon shallow waters: preliminary results, in: *"Scientific research and safeguarding of Venice, CORILA Research Programme 2001-2003, Volume II, 2002 results"*, by P. Campostrini (Editor), Istituto Veneto di Scienze, Lettere ed Arti, CORILA, Venezia, pp. 437-447

Malavasi S., Coppola J., Pranovi F., Granzotto A., Franco A. and Torricelli P., 2002. Habitat riproduttivo di *Zosterisessor ophiocephalus* Pall. (Pisces, Gobiidae) in laguna di Venezia e osservazioni sulle caratteristiche dei riproduttori. *Lavori della Società Veneta di Scienze Naturali*, 27, 47-56

Mathieson S., Cattrijsse A., Costa M.J., Drake P., Elliott M., Gardner J. and Marchand J., 2000. Fish assemblages of European tidal marshes: a comparison based on species, families and functional guilds. *Marine Ecology Progress Series*, 204, 225-242

McErlean A.J., O'Connor S.G., Mihursky J.A. and Gibson C.I., 1973. Abundance, diversity and seasonal patterns of estuarine fish populations. *Estuarine and Coastal Marine Science*, 1, 19-36

McHugh J.L., 1967. Estuarine nekton, in: *"Estuaries"*, by G.H. Lauff (Editor), Amer. Assoc. Adv. Sci. Spec., Publ. No. 83, Washington, DC, pp. 581-619

Ministero delle Infrastrutture e dei Trasporti - Magistrato alle Acque – tramite il suo concessionario Consorzio Venezia Nuova, 1999. *Mappatura dell'inquinamento dei fondali lagunari, studi ed indagini. Relazione finale*, OP 128, cap. 2, 4.1, 4.3

Nordlie F.G., 2003. Fish communities of estuarine salt marshes of eastern North America, and comparisons with temperate estuaries of other continents. *Reviews in Fish Biology and Fisheries*, 13, 281-325

Pihl L., Cattrijsse A., Codling I., Mathieson D.S., McLusky D.S. and Roberts C., 2002. Habitat use by fishes in estuaries and other brackish areas, in: *"Fishes in Estuaries"*, by M. Elliott and K.L. Hemingway (Editors), Blackwell Science Ltd., Oxford, UK, pp. 10-53

Potter I.C., Claridge P.N. and Warwick R.M., 1986. Consistency of seasonal changes in an estuarine fish assemblage. *Marine Ecology Progress Series*, 32, 217-228

Potter I.C., Beckley L.E., Whitfield A.K. and Lenanton R.C.J., 1990. Comparisons between the roles played by estuaries in the life cycles of fishes in temperate western Australian and southern Africa. *Environmental Biology of Fishes*, 28, 143-178

Quignard J.P., Man Wai R. and Vianet R., 1984. Le poissons de l'Etang de Mauguio (Herault, France). Inventaire, structure du peuplement, croissance et polymorphisme de tailles. *Vie Milieu*, 34, 173-183

Riccato F., Fiorin R., Franco A., Franzoi P., Libertini A., Pranovi F. and Torricelli P., 2003. Population structure and reproduction of three pipefish species (Teleostei, Syngnathidae) in a sea grass meadow of the Venice lagoon. *Biologia Marina Mediterranea*, 10, 138-145

Root R.B., 1967. The niche exploitation pattern of the blue-gray gnatcatcher. *Ecological Monographs*, 37, 317-350

Shenker J.M. and Dean J.M., 1979. The utilisation of an intertidal salt marsh creek by larval and juvenile fishes: abundance, diversity and temporal variation. *Estuaries*, 2, 154-163

Solidoro C., Cossarini G. and Pastres R., 2002. Numerical analysis of the nutrient fluxes through the Venice Lagoon inlets, in: *"Scientific research and safeguarding of Venice, CORILA Research Program 2001 results"*, by P. Campostrini (Editor), Istituto Veneto di Scienze, Lettere ed Arti, CORILA, Venezia, pp. 545-555

Umgiesser G., Melaku Canu D., Cucco A. and Solidoro C., 2004. A finite element model for the Venice Lagoon. Development, set up, calibration and validation. *Journal of Marine Systems*, 51, 123-145

Wallace J.H., Kok H.M., Beckley L.E., Bennett B., Blaber S.J.M. and Whitfield A.K., 1984. South African estuaries and their importance to fishes. *South African Journal of Science*, 80, 203-207

Weinstein M.P., 1979. Shallow marsh habitats as primary nurseries for fishes and shellfish, Cape Fear River, North Carolina. *Fishery Bulletin*, 77, 339-357

Whitfield A.K., 1999. Ichthyofaunal assemblages in estuaries: a South African case study. *Reviews in Fish Biology and Fisheries*, 9, 151-186

Wootton R.J., 1990. *Ecology of Teleost Fishes*, Chapman & Hall, London, UK, 404 pp

GENETIC DIVERSITY IN THE GRASS GOBY Zosterisessor ophiocephalus FROM THREE LAGOONS OF NORTHERN ADRIATIC SEA

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Riassunto.

Le indagini sono state rivolte allo studio della diversità genetica di *Zosterisessor ophiocephalus* (Perciformes, Gobiidae) di tre lagune dell'Alto Adriatico fra il 2001 e il 2004. In particolare, cinque sono state le aree di raccolta di campioni di popolazione nella laguna di Venezia: Ca' Zane, Lido, Lago dei Teneri, Chioggia, Ponte della Libertà; una a Marano(2003); una a Goro (2004). La variabilità genetica è stata studiate su 17 loci enzimatici e 13 loci microsatelliti. I risultati indicano una bassa variabilità dei loci enzimatici e una elevata variabilità dei loci microsatelliti. Nonostante l'elevata variabilità i loci microsatelliti non danno differenze significative nel confronto fra popolazioni, che vengono invece rilevate a livello allozimico con differenziazione del campione di Goro.

Abstract.

The researches have been focused on the genetic diversity. The spatial and temporal patterns of genetic diversity at the population level in *Zosterisessor ophiocephalus* (Perciformes, Gobiidae) were investigated by molecular markers, allozymes and microsatellites. Samples have been collected during four years (2001-2004) from 5 areas of the Venice Lagoon representative of different conditions (Ca' Zane, Lido, Lago dei Teneri, Chioggia, Ponte della Libertà), from Marano Lagoon in July 2003, from Goro Lagoon in July 2004. The analysis revealed lack of variability at 17 enzymatic loci and high level of polymorphism at 8 microsatellite loci. Despite the high level of variability at microsatellite loci no significant differentiation was found between the samples from the three lagoons with these marker, whereas allozymes indicate the differentiation of Goro sample.

1. Introduction.

Biodiversity includes the different living organisms and their functions in a given habitat. The recognised study level are three, namely a) the molecular level, b) the species level, c) the community level. By definition the study of the biodiversity is the study of complex systems and requires an adequate interdisciplinary approach. This hold is specially true if the goal is to obtain robust and applicative results in a delicate ecosystem such the Venice Lagoon, largely affected by anthropogenic stress.

In the framework of investigations (Scientific research and safeguarding of *Venice* - CORILA Program 2000-2003) focused on biodiversity in the Lagoon of Venice and on the ecological role of fish community, attention has been devoted to the genetic structure, gene expression, biochemical and physiological markers on the grass goby *Zosterisessor ophiocephalus* (Pallas, 1811).

Z. ophiocephalus is an important component of the fish community, being widely distributed and present in all seasons [Mainardi *et al.*, 2002]. Due to its benthic life style and potential exposure to xenobiotics, the species has been recently proposed as a bioindicator. Moreover the species presents alternative male reproductive tactics and is therefore a good model for the study of the evolution of mating systems and sexual selection.

This paper reports the results obtained by the study of biodiversity at the genetic level on several population samples of *Z. ophiocephalus* from the Lagoon of Venice, compared with those from other two lagoons of Northern Adriatic Sea (Marano and Goro).

The genetic diversity is the central issue in the biological evolutionary processes. This level of biodiversity is critical in order for a species to adapt to changing conditions and to continue to evolve in the most advantageous direction for that species. Pollution and environmental stress can modify the genetic composition and population dimension. Stochastic processes in small population can produce the reduced fitness and favour population decline/extinction phenomena. Therefore, the study of genetic effects at population level of human impact on the species should be required to evaluate the impact of pollution and the environmental quality. Moreover, the genetics diversity dynamics allows to estimate the effective population size, the degree of subdivision of population in relation to habitat fragmentation, the dispersal ability and the migration rates. Genetic polymorphisms are useful to discriminate the species also in case of sibling species or in absence of diagnostic characters.

The spatial and temporal patterns of genetic biodiversity on the grass goby *Zosterisessor ophiocephalus*, were studied by the application of molecular techniques. The genetic markers used were allozymes and microsatellite loci. Allozyme electrophoresis allows to identify different alleles by their rate of migration through a gel in an electric field [Féral, 2002]. Microsatellite loci are characterised by short motifs of one to some base pair repeated a variable number of times [Litt and Luty, 1989] and strong mutation rate; it is generally assumed that the variation of these markers is essentially selectively neutral because they represent usually noncoding DNA regions.

2. Materials and Methods.

A total of 607 grass goby comprising 19 different samples (17 from Venice Lagoon, one from Marano lagoon, and one from Goro lagoon) were collected in 2001, 2002, 2003 and 2004 at different seasons (Tab. 1). The specimens from the lagoon of Venice were caught from five sampling locations: Ca' Zane, Ponte della Libertà, Lago dei Teneri, Lido, Chioggia. Franco *et al*. [2002] described the general ecological characteristics of the sampling site and the fish sampling techniques. The level of pollution and ecological risk class of every station area is described by Critto and Marcomini [2001].

The sample from the Marano and Goro lagoons was collected from professional fishermen. All the specimens were sexed by observing the dimorphic urogenital papilla [Miller, 1984] and were measured for total length (TL±0.1 cm).

Tab. 1 – Sampling details for all *Zosterisessor ophiocephalus* samples indicating, location, geographic situation, class ecological risk, number of individuals (N), and sampling period.

Station **Sampled area**	**Location**	**Geographic location**	‡	**N**	**Sampling period**
1 Ca' Zane	Venice Northern Basin	45° 31' 27'' N 12° 28' 47'' E	3-4.	9 16 34	Nov 2001 Apr 2002 May 2002
2 Ponte della Libertà	Venice Central Basin	45° 27' 31'' N 12° 16' 44'' E	6-7	71 17	Mar 2002 Sep 2002
3 Lago dei Teneri	Venice Central Basin	45°24'07'' N 12°13'11''E	6-7	27 20 27 23	Oct 2001 Nov 2001 Mar 2002 Apr 2002
4 Lido	Venice Central Basin	45°24'26'' N 12°19'59''E	3-4	18 30 30 20	Oct 2001 Nov 2001 Apr 2002 May 2002
5 Chioggia	Venice Southern Basin	45° 13' 40'' N 12° 14' 37'' E	2-3	44 12 14 22 24 5 29 17	Nov.2001 Mar 2002 Apr 2002 May 2002 May 2003 Jun 2003 Apr 2004 Jun 2004
6 Sant'Andrea Island	Marano Sant'Andrea Basin	45° 42' 913 N 13° 11' 424 E	ND*	50	Jun 2003
Goro	Goro	44° 51' 06 N 12° 17' 65'' E	ND*	48	Jun 2004

[‡ TEL benchmark as reported by Critto and Marcomini, (2001); * No data]

2.1. Allozyme electrophoresis.

Two electrophoresis techniques were used: native, carried out on cellulose acetate by SartophorSystem-Sartorius, and isoelectrofocusing, carried out on acrilamyde gels with a mixture of carrier ampholytes (Pharmalyte) by PhastSystem-Amersham-Pharmacia. The best experimental conditions were reported in Bisol [2002]. The enzyme systems analyzed are reported in Tab. 2. Nomenclature for protein-coding loci followed the recommendations of Shaklee *et al*. [1990]. The allele designations were assigned sequentially with *a* for the allele closest to the anode (native electrophoresis) or with the lowest pI (isoelectrofocusing).

Tab. 2 – Enzyme investigated in *Z. ophiocephalus* from three Northern Adriatic Sea lagoons.

Enzyme	**E.C. no.**	**Locus**	**Tissue**
Adenilate kinase	2.7.4.3	AK*	Muscle
Fumarate hydratase	3.2.1.2	FH*	Muscle, Liver
Glucose-6-phosphate isomerase	5.3.1.9	GPI-A*	All tissue
		GPI-B*	All tissue
Glyceraldehyde-3-phosphate dehydrogenase	1.2.1.12	GAPDH*	All tissue
Isocitrate dehydrogenase ($NADP^+$)	1.1.1.42	IDPH-1*	Liver
		IDHP-2*	Liver, muscle, eye
L-Lactate dehydrogenase	1.1.1.27	LDH-A*	All tissue
		LDH-B*	All tissue
		LDH-C*	Eye
Malate dehydrogenase	1.1.1.37	sMDH-1*	All tissue
		sMDH-2*	All tissue
		mMDH*	All tissue
Malic enzyme ($NADP^+$)	1.1.1.40	sMEP*	All tissue
Phosphoglucomutase	5.4.2.2	PGM-A*	Muscle, liver, eye
		PGM-B*	Muscle, liver
Phosphogluconate dehydrogenase (PGDH: EC)	1.1.1.44	PGDH*	All tissue
Superoxide dismutase	1.15.1.1	SOD*	Liver

2.2. Microsatellites.

Microsatellites are tandemly repeated motifs of 2-6 bases present in both coding and non coding regions of all prokariotic and eukariotic genomes.

Two enriched partial genomic libraries were constructed from DNA of a single specimen using FIASCO protocol (Fast Isolation by AFLP of Sequences Containing repeats) [Zane *et al.*, 2002] and thirteen microsatellite loci were tested for population analysis.

Genetic analysis employing microsatellites involves PCR amplification of DNA using oligonucleotide primers complementary to a flanking region of a given microsatellite locus, size fractionation of the amplified product on a polyacrylamide gel and detection of DNA fragments on the gel. The details for Z. ophiocephalus are reported on Gallini *et al.* [2005]. The genotypes for the microsatellite loci were classified by Genographer 1.6.0 software [Benham, 2001] and Genotyper 3.7 (Applied Biosystem).

2.3. Data analysis.

The genetic data were analysed by Genepop 3.1 [Raymond and Rousset, 1995] and Arlequin 2.0 [Schneider *et al.*, 2000] softwares. Classical variables such as proportion of polymorphic loci in each sample and level of heterozygosity were calculated. Allelic richness, a measure of the number of alleles independent of sample size (allowing to compare this quantity between samples of different sizes) was estimated per locus, within sample, and overall samples. The above statistics were tested among sexes, sites or temporal samples as well as in combined samples. Hardy-Weinberg expectations (HW) were tested per locus and per sample, by log-likelihood G statistics applied to contingency tables obtained from the randomised data sets. Exact test of population differentiation [Raymond and Rousset, 1995] and AMOVA test [Excoffier *et al.*, 1992] were also calculated and used for among samples comparisons.

3. Results.

3.1. Allozymes.

The survey of 12 enzyme systems produced 18 consistently scorable loci, in a total of 493 analysed individuals. In 12 of the 18 loci studied only one allele was found in all the samples. At the loci *GPI-B**, *LDH-B**, *PGM-A**, and *PGM-B** two alleles were scored six times in samples from the Venice lagoon. Two allele were scored also at the loci sMEP* and IDHP-2* in the sample from Goro. Polymorphism was detected at GPI-2, PGM-1 and PGM-2, sMEP* and IDHP-2* *loci* according to the larger polymorphism criterion (the frequency of the most common allele is greater than 0.99) and Hardy-Weinberg equilibrium was respected. Consequently, the level of allozymic polymorphism resulted very low (Tab. 3).

Tab. 3 – Summary of allozymic polymorphism level on the *Z. ophiocephalus* from three lagoon of Northern Adriatic Sea. (N°= Number of individuals; A= average number of allele per locus; Hobs= average of observed heterozygosity; Hexp average of expected heterozygosity).

Sample	N°	A	Hobs	Hexp
Venice 2001+2002	435	1,24	0,000	0,001
Marano 2003	48	1	0,000	0,000
Goro 2004	10	1,12	0,017	0,017

Similar values are lower than the ones (H=0.05-0.06) found in average in marine teleosts [Smith and Fujio, 1982; Kirpichnikov, 1992; Ward *et al*., 1992]. They also differ from the findings of previous studies of this species, carried out on very few specimens collected from the Marano and Venice Lagoon. These differences concern sMEP* in the Venice lagoon [McKay and Miller, 1991] and IDHP-2* in the Marano lagoon [Miller *et al.*, 1994].

In fact, these loci were formerly found to be more heterozygous, and the frequency of the most common alleles were 0.80 and 0.75 respectively. As far as it is possible to compare results obtained with different techniques at different times, these data indicates that the average enzymatic polymorphism level in *Z. ophiocephalus* is reduced in the Venice and Marano, while the polymorphism level of Goro sample is in line with previous finding. It is possible that the great part of the genetic variation has been eliminated during the last ten years at least for two loci. In this case, the present day lack of heterozygosity could represent an example of rapid evolutionary change in response to environmental pressure. This could be in agreement with the hypothesis of adaptive mechanism in the grass goby from Venice and Marano based on a high phenotypic plasticity due to genetic homogeneity.

Nevertheless, considering allozyme only, the experimental evidences in support of selection phenomena are not as strong to exclude that the level of genetic variability could reflect genetic drift phenomena: low genetic variation is an expected result of repeated bottlenecks associated with the colonization of suitable habitats.

No significant heterogeneity of allelic and genotypic distribution was observed between males and females, and within or between the samples in all the comparisons between the samples from Venice and Marano: pairwise and overall, grouped for site or season of collection. This indicates that the grass goby population from Venice and marano lagoon is an unique panmittic unit from statistic point of view. On the contrary, the exact test of population differentiation indicated a significant (p= 0.03) allozymic differentiation between Goro population and those from the other two lagoons.

3.2. Microsatellites.

To further investigate the problem, a second series of investigations has been carried out by specie-specific microsatellites. Microsatellites are DNA level markers that, so far, represent the most polymorphic molecular tool available for population analysis. A total of 240 individuals have been analyzed with 13 microsatellites. Eight loci proved to be polymorphic, revealing from 3 to 32 alleles. All *loci* resulted to be both in Hardy-Weinberg and in *linkage equilibrium*.

The average values of polymorphism are reported in the Tab. 4. In contrast with findings from allozyme analysis, it can be noticed that the population samples from the three lagoons show a very similar level of heterozigosity, ranging from 0.365 to 0.368. No evidence for a lower variability in Venice and Marano populations than in the Goro one, is found using these markers.

Tab. 4 – Summary of microsatellite polymorphism level on the *Z. ophiocephalus* from three lagoon of Northern Adriatic Sea. (N°= Number of individuals; A= average number of allele per locus; Hobs= average of observed heterozygosity; Hexp average of expected heterozygosity).

Sample	**N°**	**A**	**Hobs**	**Hexp**
Venice 2002	65	8.07	0,365	0,366
Marano 2003	48	6.00	0,366	0,369
Goro 2004	48	6.69	0,368	0,368

Despite this high level of variability no significant differentiation was found between the samples from the three lagoons. The exact test of population differentiation did not allowed to reject the hypothesis of panmissia for the three populations, that resulted genetically homogeneous.

Conclusions.

In this study we report the genetic analysis of specimens from three lagoons of the Northern Adriatic Sea: the Goro lagoon, the Venice lagoon and the Marano lagoon. Investigations were performed at the protein and at the DNA level.

Analysis at the protein level revealed an extremely low level of genetic variation at gene-enzyme systems in the Venice and Marano samples, that is among the lowest reported for a vertebrate species. The analysis of individuals from the Goro lagoon showed the existence of a higher level of polymorphism and indicated the presence of a genetic differentiation between sites. While the polymorphism level of Goro sample is in line with previous finding, the low variability of Venice and Marano samples is unexpected and could be originated in the last few years.

Microsatellite markers revealed a high level of genetic variation. No significative differences and a similar level of heterozygosity between the samples from the three lagoons was observed, allowing to rule out the hypothesis that the low genetic variability observed with allozymes is the result of genetic bottlenecks.

These results suggest that:

1) The allozymic variability on *Z. ophiocephalus* is lowest in samples heavy affected by anthropic stress like Marano and Venice Lagoon.
2) Both enzymatic and microsatellite loci indicate the grass goby populations are not genetically structured or subdivided inside Venice Lagoon.
3) The levels of allozymic polymorphism in *Z. ophiocephalus* from the Venice Lagoon could be resulting by natural selection phenomena probably dependent on alteration and reduction of the elective habitats.

References.

Benham J.J., 2001. *Genographer* (1.6.0). Montana State University, Bozeman, Montana

Bisol P.M., 2002. Ecogenetic biodiversity in *Zosterisessor ophiocephalus* from the lagoon of Venice: gene-enzyme polymorphisms, in *Scientific research and safeguarding of Venice. CORILA Research Program 2001 results,* by P.P. Campostrini, Ist. Veneto di Scienze Lettere ed Arti, Venezia. (S. Servolo, Venezia, 4-5 aprile 2002). pp. 601-608

Critto A., Marcomini A., 2001. Rischio ecologico e inquinamento chimico lagunare. pp 162 Milano: Libreria Editrice Cafoscarina Pscrl

Excoffier L., Smouse P.E. and Quattro J.M., 1992. Analysis of Molecular Variance inferred from metric distances among DNA haplotypes: application to human mitochondrial DNA restriction data. *Genetics,* 131**,** 479-491

Féral J.P., 2002. How useful are the genetic markers in attempts to understand and manage marine biodiversity. *J. Exp. Mar. Biol. Ecol.*, 268, 121-145

Franco A., Malavasi S., Pranovi F., Franzoi and Torricelli P., 2002. Preliminary data on gonadal development and fecundity in the grass goby, *Zosterisessor ophiocephalus* (Pallas, 1811) from the Venice lagoon (northern Italy). *Acta Adriatica,* 43 (2), 43-48

Gallini A., Zane L. and Bisol P.M., 2005. Isolation and characterization of microsatellites in *Zosterisessor ophiocephalus* (Perciformes, Gobiidae). *Molecular Ecology,* 5, 24-26

Kirpichnikov V.S., 1992. Adaptive nature of intrapopulational biochemical polymorphism in fish. *Journal of Fish Biology* , 40, 1–16

Litt M., Luty J.A., 1989. A hypervariable microsatellite revealed by in vitro amplification of a dinucleotide repeat within cardiac muscle actin gene. *Am. J. Hum. Genet*., 44, 397-401

Mainardi D., Fiorin R., Franco A., Franzoi P., Giovanardi O., Granzotto A., Libertini A., Malavasi S., Pranovi F., Riccato F. and Torricelli P., 2002. Fish diversity in the Venice lagoon: preliminary report. In: *Scientific research and safeguarding of Venice. CORILA Research Program 2001 results,* by P.P. Campostrini, P.P, Ist. Veneto di Scienze Lettere ed Arti, Venezia. (S. Servolo, Venezia, 4-5 aprile 2002). pp 583-594

McKay S.I., Miller P.J., 1991. Isozyme criteria in the testing of phyletic relationships between species of *Gobius* and related easterns Atlantic-Mediterranean genera (Teleostei: Gobiidae). *Journal of Fish Biology* , 39, 291-299

Miller P.J., 1984. The tokology of Gobioid fishes, in *Fish Reproduction: Strategies and Tactics,* by Potts, G.W. & Wootton, R.J., Academic Press London, pp 119-153

Miller P.J., Serventi M., Soregaroli D., Torricelli P. and Gandolfi G., 1994. Isozyme genetics and the phylogeny of Italian freshwater gobies (Teleostei: Gobioidei). *Journal of Fish Biology* ,44, 439-451

Raymond M., Rousset F., 1995. GENEPOP (version 1.2): population genetics software for exact tests and ecumenicism. *Journal of Heredity*, 86, 248-249

Schneider S., Roessli D. and Excoffier L., 2000. Arlequin. A software for population Genetics Data Analysis. http://anthro.unige.ch/arlequin

Shaklee J.B., Allendorf F.W., Morizot D.C. and Whitt G.S, 1990. Gene nomenclature for protein-coding loci in fish. *Transactions of the American Fisheries Society* 119, 2–15

Smith P.J. and Fujio Y., 1982. Genetic variation in marine teleosts: high variability in habitat specialists and low variability in habitat generalists. Mar. Biol. 69, 7–20

Ward R.D., Skibinsky D. O.F. and Woodwark M., 1992. Protein heterozigosity, protein structure, and taxonomic differentiation. *Evolutionary Biology* 26, 73-157

Zane L., Bargelloni L. and Patarnello T., 2002. Strategies for microsatellite isolation: a review. *Molecular Ecology*, 11, 1-16

MACROFOULING ECOLOGICAL SUCCESSION ON HARD SUBSTRATA IN THE LAGOON OF VENICE: EFFECTS OF COPPER-CONTAINING ANTIFOULING PAINTS

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Riassunto.

Abbiamo studiato la successione ecologica del macrofouling di substrato duro su pannelli di legno e di acciaio, immersi per un anno in tre stazioni della laguna meridionale diverse per caratteristiche batimetriche e idrodinamiche. L'evoluzione delle comunità del macrofouling su pannelli rivestiti di vernici antivegetative contenenti composti del rame come principio attivo è stata confrontata con quella osservata su pannelli di controllo e trattati con vernici a base di TBT. Per descrivere gli effetti sulla comunità ci siamo avvalsi di diversi descrittori della biodiversità che hanno permesso di evidenziare gli effetti destrutturanti delle vernici antivegetative, capaci di selezionare specie resistenti.

Abstract.

We studied the ecological succession of macrofouling on hard substrata on wooden and steel panels immersed for one year in three stations, different for bathymetric and hydrodynamic characteristics, of the southern lagoon. The development of macrofouling biocoenoses on panels coated with copper-containing antifouling paints was compared with what observed on both control and TBT-treated panels. In order to describe the effects on biocoenoses, we used various biodiversity indexes which enabled us to highlight the disturbing activity of the antifouling paints, that results in the selection of resistant species.

1. Introduction.

Substrata permanently immersed in the marine environment are colonized by fouling organisms more or less rapidly depending on a set of chemical, physical and biological factors. In the successions of the biocoenoses which settle on hard bottoms, it is possible to recognize: 1) a *temporal sequence,* due to the duration of the immersion of the substratum, 2) a *seasonal sequence*, and 3) a *biotic succession* [Redfield and Delvy, 1952]. In the lagoon of Venice, the studies about the macrofouling biocoenoses on hard substrata reporting an ecological succession are very scanty [Relini *et al.*, 1972].

The organisms naturally settling on the hard substrata of the intertidal zone in the lagoon of Venice follows a determinate ecological succession, subdivisible in various phases beginning from the formation of the primary biofilm, in which bacteria and the diatoms represent the pioneer organisms, favouring the further settlement of secondary organisms. The vegetable population can appear at any time of the ecological succession although it never reaches an appreciable abundance. Initially, inside the animal biocoenosis the settlement of serpulids occurs, which are organisms with rapid population increase although it never forms a remarkable biomass. Then the cirriped population follows in the settlement succession: it represents one of the most common animal group in the lagoon owing to its capacity of colonizing various substrata by adaptation to the various environmental conditions. Moreover, a high number of bryozoans and ascidians colonize the substratum, occupying large surfaces with a remarkable vertical development. At the same time, porifers often appear. Finally, bivalves settle only with the genera *Mytilus* and *Ostrea*, the individuals of which are never abundant, although they can reach a remarkable size.

A lot of antifouling paints are largely employed in the world since many years on crafts and permanently submerged structures in order to preserve them and reduce the economic cost. However, the severe damages on the aquatic coastal ecosystems due to leaching of the biocidal substances contained in these paints are well-known since 1980s [Champ and Seligman, 1996]. After the total ban of the organotin compounds - the main used compound was TBT - by IMO-MEPC (1998) and subsequently by EC (ordinance No. 782/2003, 14 April 2003), the paint industry developed new substitutive formulations, containing a principal biocide and a series of booster substances in order to increase the antifouling efficaciousness. Among them, in the Northern Adriatic Sea, the copper-containing paints are numerous in commerce. Copper oxidule (Cu_2O) and copper thiocyanate (CuSCN) are the main copper (I) compounds used as biocides, always associated to boosters, which, as Voulvoulis *et al.* [1999] remarked, have the potential to cause environmental damages. Therefore, we evaluated the disturbing effects on the macrofouling biocoenoses on hard substrata comparing the new generation of copper (I)-containing paints with a TBT containing paint.

This is the first study of the effects of antifouling paints in the lagoon of Venice, that has been carried out by analysing monthly series of wooden and steel panels immersed in three stations of the Southern Lagoon from February 2002 to February 2003. The sampling stations were chosen near the Chioggia harbour with different bathymetric and hydrodynamic characteristics:

- Station 1: mussel rearing fallen into disuse, placed along the Perognola channel;
- Station 2: wooden manufacture boundering a zone of low depth, placed in the face of Isola dei Cantieri;
- Station 3: floating pier along the Sottomarina channel.

In these stations, we installed a system of artificial substrata. Each system was formed of nine units, and each unit was formed of a nylon rope, a brick for basement and two panels (20 x 15 x 2.5 cm), i.e., an upper wooden panel and a lower steel panel (Fig. 1).

Though fluctuating, the immersed panels showed always a light-exposed side (“front surface”) and a shading side (“back surface”). The upper panels were immersed for about 50 cm on the basis of the tide variations in order to avoid their possible emersion. Of the nine units, eight had panels coated with antifouling paints, and one represented the control unit painted with an enamel paint containing silicone alkylic resins, generally used on the craft waterline (Sikkens Super Gloss). The choice of the paints was carried out on the basis of their widespread utilization in the lagoon of Venice (Tab. 1).

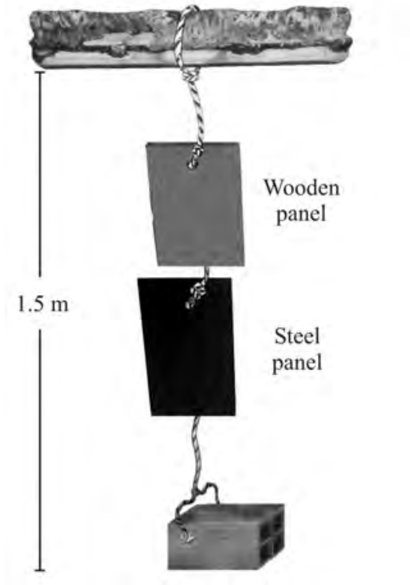

Fig. 1 – Scheme of the unit of the panel systems immersed in the three stations.

Tab. 1 – Antifouling paints used to coat the panels of the units immersed in the sampling stations.

	PAINT	*BIOCIDES*	*MATRIX*	*USE*
A	Sigmaplane Antifouling HB	TBT methacrylate, CuO	Self-polishing with methacrylate copolymers	Fishing boats and freighters with length >25 m (hulls in steel, tarred wood coated by epoxy resin)
B	Sikkens Vinyl Antifouling 2000	Cu_2O (41%)	Hard matrix with vinyl resin and colophony	Sailing boats, yachts (hulls in steel, wood, polyester; not aluminium)
C	Sikkens Selfpolishing Antifouling 2000	CuSCN (20%), Diclofluanid (9%)	Self-polishing with n. sp. polymers and colophony	Sailing boats, yachts (hulls in wood, steel, aluminium, polyester)
D	Baseggio Sirena	Cu_2O, Irgarol 1051, Clorothalonil	Self-polishing with modified vinyl resin and colophony	Fishing boats (hulls in wood, steel, plastic reinforced by incorporated fibreglass)

Our observations produced a list of the species seen on both the treated panels and the control ones for the entire sampling period. For the analysis of the changes in both ecological succession and biodiversity in comparison with controls, we used parameters on the basis of which we grouped our data in specific tables.

- The *species richness* was represented through linear graphics which report the temporal trend of the species number present on the panels of the three sampling stations.
- The *biocoenosis structure* was quantified by pie charts, in which each taxon is expressed as percentage in respect of the total taxa forming the biocoenosis on each panel.

- The <u>*covering-abundance index*</u> was obtained with the Benninghoff's scale (Tab. 2) which supplies a quantity analysis of the settlement capacity of the various species on areas calculated on the digital images through the Casti-Imaging and MicroImage softwares.

Tab. 2 – Benninghoff's covering-abundance indexes.

Index	**Description**
r	Rare individuals and covering only a very little portion of the sampling area
1	Numerous individuals, covering less than1/20 of the sampling area or abundantly scattered but with a high covering value
2	With some number of individual covering a range of 1/20 and 1/4 of the sampling area, or with numerous individuals but covering less than 1/20 of the area
3	Covering a range of 1/4 and 1/2 of the sampling area
4	Covering a range of 1/2 and 3/4 of the sampling area
5	Covering more than 3/4 of the sampling area

- The <u>*similarity index*</u> measures the likeness between two floristic and/or faunal lists with the number of the shared species in comparison with the total species reported in the two samplings. Among the numerous algorithms, we have chosen the Sørensen's index with the formula $P_s = 2c/(a+b)$, where a is the number of species present on the control panel; b is the number of species present on the panel coated with an antifouling paint (A, B, C or D); c is the number of species shared by the control unit and the treated one. Such index was represented through graphs which describe the temporal trend in the three sampling stations.

2. Observations on the control panels.

The ecological succession obtained by the analysis of the control panels is similar to that reported in previous works [Relini *et al.*, 1972; Candela and Torelli, 1983; Cornello and Manzoni, 1998; Cornello and Occhipinti Ambrogi, 2001]: the pioneer organisms, appearing in April, are branching bryozoans, tunicates, serpulids and macroalgae, associated in various manners on the panels of the sampling stations. The dominant populations, which appeared in the summer months, are represented by serpulids, branching and encrusting bryozoans, tunicates and, occasionally, cirripeds. In the climax, which appeared in December, porifers (*Hymeniacidion sanguinea*, *Halichondria bowerbanki*), bivalves (*Mytilus galloprovincialis*) and macroalgae (*Ulva lactuca*, *Ceramium ciliatum*, *Polysiphonia sertularioides*) occur and tunicates persist with both solitary (*Styela plicata*, *Ciona intestinalis*) and colonial (*Botryllus schlosseri* and *Botrylloides leachi*) species (Fig. 2). Among the grazer organisms, amphipods were observed above all with vicarious species in the various months and, with a less important amount, also isopods, decapods, wandering polychaetes, gastropods and echinoderms. The maximum peak of the species richness was reached in August or September on both wooden and steel panels. In the station 3, the fouled surface was always wider than those in the other sampling stations. This is probably due to the characteristics of this station placed near the built-up area where seawater has a limited hydrodynamics. Comparing the wooden panels with the steel ones, there is not a clear distinction as regards the structure and the dynamics of the biocoenosis in all the sampling stations, but the settlement areas of the various organisms appear to be increased on the steel panels. No difference between the front and the back side of each panel occurs, therefore excluding a direct effect of the sunlight.

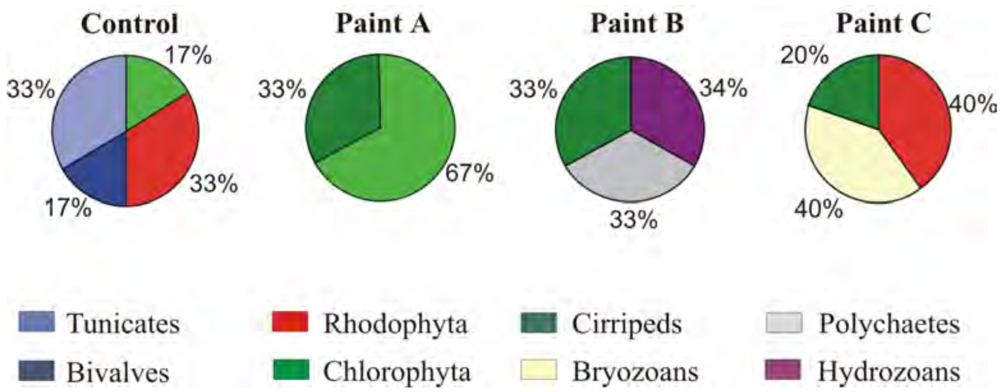

Fig. 2 – Structure of climax biocenosis on wooden panels coated with different paints.

3. Observations on the panels treated with antifouling paints.

Generally, fouling appeared in subsequent moments on the panels treated with antifouling paints in comparison with control panels and was preceded by the bacterial film. However, the surface extension of such settlement on the treated panels resulted less than that of the control panels and often with a spot distribution.

3.1. Paint A.

In all stations and on both wooden and steel panels, a delay in the appearance of the bacterial film was observed, so the panels lacked any kind of fouling until May (or July too). The pioneer organisms were chlorophytae, cirripeds and, only in one occasion, porifers. No ecological succession was recognizable, but only the appearance of organisms resistant to the biocidal action, as chlorophytae (*Enteromorpha* sp.) and barnacles, which, however did not ever cover large areas of the substratum (Fig. 2). Generally, the number of the species present in the various months is scarce. The steel panel of the station 3 represents an exception since its species richness (bryozoans, tunicates, serpulids, cirripeds and macroalgae) resulted greater than that of the other two stations during all the sampling period. In the stations 1 and 2, the similarity index vanishes, whereas, in the station 3, the index has a discontinuous trend.

3.2. Paint B and C.

The stable covering with fouling organisms of all the panels occurred from July. Previously, only a not lasting settlement of organisms appeared, represented by porifers and serpulids alternated with a fouling of bacterial film. As regards these paints, the ecological successions resulted different or with a less complex structure in comparison with those on the control panels. Moreover, organisms like hydrozoans (*Tubularia crocea*) and cirripeds were exclusive of the treated panels, suggesting the selection of tolerant species. After the formation of the bacterial film, the subsequent settlement of pioneer species was represented by serpulids, macroalgae and, more occasionally, cirripeds and bryozoans. As regards the paint B, some species which settled at the beginning of the succession often disappeared in the following month: probably, the efficaciousness of the biocide substance, which is higher in the first months of the panel immersion, progressively decreased. During summer, tunicates and bryozoans or hydrozoans and cirripeds appeared. Even the climax is reached with different organisms, bivalves and tunicates or hydrozoans and cirripeds (Fig. 2). It is important to consider that the successions present on the panels of the station 3 coated with both the paints are very similar to that of the control panels, although the extension of the covering surface varies. The similarity indexes for the panels coated with the paints B and C vanish at the beginning of the ecological succession and then increase reaching a plateau in summer - always less than 1 - suggesting a progressive loss of the biocidal efficaciousness.

3.3. Paint D.

The paint D showed a similar action of the B one in the first months of immersion. However, the succession was discontinuous also in the following months. Generally, the settlement of the macrofouling appeared to be much more limited on the wooden panels in comparison with that on the steel ones in all the sampling stations. The fouling by various pioneer species, represented by bryozoans, chlorophytae and cirripeds was always very limited. The presence of such species never exceeded one month, so often the bacterial film appeared again to replace the organisms previously settled and not survived. The similarity index is always close to zero and the settlement seems to be random and never stabilized.

Conclusions.

The comparison of the effects on the various biodiversity indexes allow us to establish an order of biocidal efficaciousness of the antifouling paints examined as follows:

$$B < C < D \leq A$$

It appears that the paint with minor biocidal effect is B, which has a hard matrix and does not contains any booster, confirming the importance of the type of matrix (hard or self-polishing) and the presence of biocidal boosters which enlarge the toxic effect of the copper-containing paints.

Moreover, in consideration that the wide use of these antifoulings is accompanied by a continuous leaching of their active substances in the environment, our data evidence the dangerousness of these xenobiotics towards the coastal marine biocoenoses, in particular to delicate ecosystems like the lagoon of Venice, and suggest the necessity of a greater control and monitoring before the introduction in commerce of new formulations of biocides alternative to TBT as antifouling agents.

References.

Candela A. and Torelli A.R., 1983. Note sulla colonizzazione di pannelli artificiali posti nell'intermareale all'isola di S. Erasmo (Laguna di Venezia). *Atti del Museo Civico di Storia Naturale di Trieste*, 35, 225-234

Champ M. and Seligman P.F., 1996. An introduction to organotin compounds and their use in antifouling coatings, in "*Organotin Environmental Fate and Effects*", by Chapman & Hall Eds, London, 1-25

Cornello M. and Manzoni A., 1998. Caratterizzazione stagionale degli insediamenti di organismi macrobentonici su substrati sperimentali nel bacino centrale della laguna di Venezia. *Bollettino del Museo Civico di Storia Naturale di Venezia*, 49, 135-144

Cornello M., and Occhipinti Ambrogi A., 2001. Struttura e dinamica dei popolamenti macrofouling in relazione al periodo di insediamento nel bacino centrale della laguna di Venezia. *Bollettino del Museo Civico di Storia Naturale di Venezia*, 52, 113-128

Redfield L.W. and Delvy E.S., 1952. "*Temporal sequences and biotic succession. Marine fouling and its prevention*". Wood Hole Oceanografic Institute Ed., Wood Hole, 42-47

Relini G., Francescon A. and Barbaro A., 1972. Osservazioni sistematico-ecologiche sulla distribuzione dei Cirripedi toracici nella Laguna Veneta. *Atti dell'Istituto Veneto di Scienze Lettere e Arti*, 130 (Cl. Sci. Mat. Nat.), 449-459

Voulvoulis N., Scrimshaw D. and Lester J.N., 1999. Alternative antifouling biocides. *Applied Organometallic Chemistry*, 13, 135-143

UNDERSTANDING THE FUNCTIONAL RESPONSES OF M. galloprovincialis AND Z. ophiocephalus BY GENE IDENTIFICATION AND GENE EXPRESSION PROFILING

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Riassunto.

Il consolidamento di metodi della genomica funzionale nell'uomo sta aprendo rapidamente nuove vie alla comprensione della risposta degli organismi ai cambiamenti ambientali. Le variazioni di espressione di geni e proteine in cellule e tessuti specifici possono infatti fornire profili diagnostici e nuovi marcatori per descrivere funzioni fondamentali e risposte indotte di un dato organismo.

Mytilus galloprovincialis e *Zosterisessor ophiocephalus* sono specie autoctone della laguna di Venezia utilizzate nell'accertamento del rischio ecologico dovuto all'inquinamento e alla antropizzazione dell'ecosistema lagunare (progetto ICSEL, MAV/CVN). Nonostante mitilo e gò siano da tempo oggetto di studi specifici, le conoscenze sui loro geni sono frammentarie o quasi inesistenti.

Nell'ambito del programma di ricerca CORILA 2000-2003 la preparazione di librerie 3'terminali di mitilo e di gò ha reso possibile definire una collezione di 5664 e 1920 EST rispettivamente rappresentative di 1731 and 967 trascritti genici.

L'intera collezione di EST di mitilo ed altre sequenze di controllo sono state utilizzate nella definizione di un cDNA *microarray* la cui potenzialità d'uso è in corso di valutazione. I primi risultati si riferiscono a mitili trattati in laboratorio con miscele di contaminanti e mitili prelevati da diverse zone dell'ambiente lagunare. I profili di espressione tessuto-specifici relativi a tali mitili indicano la capacità della piattaforma genica (MytArray 1.0) di distinguere effetti indotti da contaminanti diversi e lo stato funzionale di mitili della zona industriale rispetto ad aree lagunari di riferimento. Queste valutazioni trovano continuità nel programma Co.Ri.La 2004-2007 (3.11, WP2.3).

Abstract.

The increasing validation of technologies from functional genomics in humans is rapidly establishing new approaches for studying the organism's response to the environment. In fact, global changes of gene and protein expression in selected cells and

tissues can provide diagnostic profiles and new biomarkers for tracing essential functioning and induced responses in reference species.

In the lagoon of Venice, *Mytilus galloprovincialis* and *Zosterisessor ophiocephalus* are indigenous species currently used in the multidisciplinary assessment of ecological risk possibly caused by pollution and other human-related activities (ICSEL project, MAV/CVN). Despite the published literature, only fragmentary or very scarce information is available on the gene sequences of these organisms.

In the frame of the Co.Ri.La research programme 2000-2003 the preparation of species-specific 3'end-cDNA libraries yielded a collection of 5664 and 1920 sequenced 3'ESTs, representing 1731 and 967 independent transcript tags for mussels and grass goby, respectively.

The whole collection of transcript-specific mussel 3'ESTs and a number of unrelated controls have been used to define a cDNA microarray which potential application in now under evaluation. The first hybridization data refer to mussels treated with contaminant mixtures or collected from selected sites of the Venice lagoon area. The resulting transcription profiles show the capacity of MytArray 1.0 to discriminate the early effect of different contaminant mixtures and the functional status of mussels living near the industrial district or in reference lagoon areas. Work is in progress within the Co.Ri.La Research Programme 2004-2007 (3.11, WP2.3).

1. Introduction.

The application of technologies from functional genomics to the ecological research provides a great opportunity for understanding the organism's response to environmental variation.

Admitted the availability of sequence data, the currently applied microarray technology can makes comprehensive concurrent analysis of thousands of genes real for any organism. The global analysis of the response of genes to a toxic insult, i.e. the 'toxicogenomics' approach, opposes to the historical method of examining a few select genes and provides a more complete picture of toxicologically significant events. In fact, the use of genomic microarrays has allowed the discrimination between different classes of toxicants and showed that cells respond to toxicant stress by modulating genes related to cell growth, DNA repair and other protective functions [Newton *et al.*, 2004]. Consequently, genes and proteins acting in response to different stressors could be globally used as early warning of exposure and effects in the environment and as an indicator of the overall health of organisms in the environment [Waters and Fostel, 2004; Cunningham and Lehman McKeeman, 2005].

Actually, the proposed term 'ecotoxicogenomics' aims to describe the integration of genomics (transcriptomics, proteomics and metabolomics) into ecotoxicology [Snape *et al.*, 2004]. Depending upon the severity and duration of the contaminant exposure, genomic measures may be short-term toxicological responses leading to impacts on survival and reproduction, or the 'genotoxic disease syndrome' [Kurelec, 1993].

However, reference species currently used in the environmental biomonitoring of pollution, and other stress factors, represent non-canonical models of study and basic knowledge on their genomes and genes is lacking.

2. Materials and Methods.

2.1. 3'cDNA libraries from multiple tissues of mussel and grass goby.

A few juvenile grass gobies (*Z. ophiocephalus*) as well as adult mussels (*M. galloprovincialis*) were collected from a relatively clean reference area of the Venice lagoon. Following dissection, selected tissues (*goby*: liver, gills, spleen, intestine wall, eye, brain, muscle; *mussel*: digestive gland, gills, muscles, mantle and gonads) were used for the purification of messenger RNA and for the preparation of a 3'end-specific cDNA libraries as described elsewhere (Venier *et al.*, 2003).

The cDNA libraries were plated on solid medium and recombinant colonies randomly selected and arrayed for independent growth in 384-well microplates. The cDNA inserts were amplified with universal primers and reliable amplification products greater than 0.5 kb on gel electrophoresis were subjected to automatic single-pass DNA sequencing (ABI3700 96 capillary sequencer, Applied Biosystems). The resulting sequences were electronically processed for quality, vector and repeats and finally clustered using specific software programmes.

Following further manual inspection, reliable virtual consensuses and singletons referring to each EST cluster were converted in FASTA format and searched in Gene bank (BLAST similarity searches) in order to define the putative identity of each independent transcript.

2.2. The mussel cDNA microarray and related hybridization experiments.

Selected mussel ESTs were re-purified and, together with unrelated controls, printed on derivatized glass slides (Micromax SuperChip I, PerkinElmer, GenpakArray21, Genetix) and UV-cross-linked (UV Stratalinker1800, Stratagene), thus defining a platform of 1745 elements.

Following suitable protocols, RNA samples from mussels treated in laboratory with selected contaminants or collected from different sites of the Venice lagoon were tested by competitive hybridization (sample and reference RNAs) on the mussel cDNA microarray. Microarray scanning was performed by GSI Lumonics LITE dual confocal laser scanner and ScanArray Microarray Analysis System (PerkinElmer). Raw scanner images were analyzed with QuantArray Analysis Software (GSI Lumonics). Data normalization for the total replicated spots was performed with MIDAS (TIGR Microarray Data Analysis System) using Lowess (Logfit) transformation [Saed *et al.*, 2003]. Then, replicated values of each spot were averaged and differentially expressed genes identified by Significance Analysis of Microarray (SAM) software [Tusher *et al.*, 2001]. Principal component analysis, cluster analysis, k-means and profile similarity searching were performed with R software [Gentleman *et al.*, 2004].

3. Results and conclusions.

The above Tab. 1 refers the increasing availability of sequence data for the Mediterranean mussel and for the grass goby in comparison to some other species.

Tab. 1 – Nucleotide and protein sequences publicly available in 2002 and 2005 for selected species.

	H. sapiens	*D. rerio*	*O. mikiss*	*S. salar*	*T. rubripes*	***M. galloprovincialis***	***Z. ophiocephalus***
A	46	48	60	60	44	28	46
B	3.5	1.7-2.3	1.9-2.9	3.0-3.3	0.40	1.41-1.92	1.43
N	9078924	807425	229611	108849	91450	**4504**	**21**
P	253723	20739	1659	782	1141	**207**	**2**
A, diploid chromosome complement. **B**, cellular DNA (aploid C value in pg). Nucleotide (**N**) and protein (**P**) records at NCBI at March **2005**							
N						**170**	**3**
P						**129**	**2**
Nucleotide (**N**) and protein (**P**) records at NCBI at March **2002**							

Despite the presence of some thousand sequences, mussel nucleotide entries mainly include ESTs submitted in these last years (correspondently, microsatellites are the main records for the grass goby).

Not taking into account the mussel ESTs, less than 100 gene-related sequences are reported, evidently representing a very small fraction of the total mussel gene number (1.42-1.92 pg of double stranded DNA should account for 1.39-1.88x10^9 bp according to the conversion proposed by R. Gregory, www.genomesize.com).

An ***E**xpressed **S**equence **T**ag* is a tiny portion of an entire gene that can be used to help identify unknown genes and to map their positions within a genome (NCBI)

We produced 3'ESTs from normal mussels and gobies following specifically established methods. One combined sample of messenger RNA derived from multiple tissues was used to prepare a 3'cDNA library, that is a collection of transcript tags physically maintained in suitable plasmid vector and bacterial host cells (each transcript tag being the stable retrotranscribed copy of a transient messenger RNA, a sequence fragment located in the 3' terminal transcript region).

Cloning and systematic sequencing of the cDNA fragments from the grass goby yielded 768 3'-specific ESTs. A total of 612 ESTs, rigorously selected for quality, were clustered and 432 independent sequences subjected to BLAST similarity search against the non-redundant nucleotide and aminoacid sequences available from other species.

Such experimental approach allowed the production of a more extended collection in *Mytilus galloprovincialis*. Of the 5664 sequenced and processed ESTs, 3913 were clustered and 1731 independent sequences were subjected to BLAST similarity searches.

About 40 and 50% searched EST did not find any significant similarity with the existing sequence records (all species) and likely represent novel genes transcribed in the tissues of gobies and mussels, respectively.

Based on the annotated ESTs, genes playing a role in protein synthesis, tissue structure and defense were putatively identified in the grass goby. The multiplicity of mussel gene expression has been described and, interestingly, includes catchin, twitchin and byssal adhesive proteins [Venier *et al.*, 2003].

The whole collection of independent mussel EST have been used to build a cDNA microarray of 1745 elements printed twice on the same slide (also, each probe in duplicated positions).

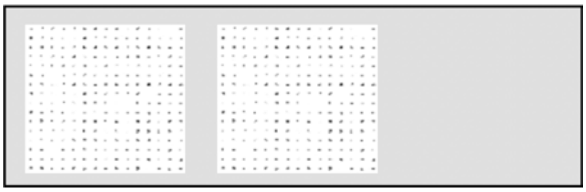

Fig. 1 – Representation of the mussel microarray (MytArray 1.0) printed twice on a derivatized glass slide.

This platform is optimal for performing parallel hybridization reactions with reciprocal labeling (Cy3, Cy5) of the test and reference RNA samples (competitive targets). This strategy yields four replicates for each probe anchored on the slide.

Experimental groups of mussels were treated in laboratory with mixtures of selected contaminants (metals or organic compounds) in order to ascertain the performance of the mussel microarray (MytArray 1.0). The first results obtained with RNA samples purified from selected tissues of the treated mussels indicate that digestive gland and gills (i.e. transcript profiles based on MytArray 1.0) correctly discriminate the two treatment mixtures.

Also, transcript profiles referred to the digestive gland of mussels from the inner Venice lagoon (industrial area) and from one lagoon inlet (Lido) have indicated substantial functional differences, likely related to variation of contaminant levels and other factors from the industrial area to off-shore. Further study will consolidate and extend these preliminary results.

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References.

Cunningham M.L., Lehman McKeeman L., 2005. Applying toxicogenomics in mechanistic and predictive toxicology *Toxicol. Sci.* 83(2): 205-206

Gentleman R.C., Carey V.J., Bates D.M., Bolstad B., Dettling M., Dudoit S., Ellis B., Gautier L., Ge Y., Gentry J., Hornik K., Hothorn T., Huber W., Iacus S., Irizarry R., Leisch F., Li C., Maechler M., Rossini A.J., Sawitzki G., Smith C., Smyth G., Tierney L., Yang J.Y., Zhang J., 2004. Bioconductor: open software development for computational biology and bioinformatics. *Genome Biol.* 5, R80

Kurelec B., 1993 The genotoxic disease syndrome. *Mar. Environ. Res.*, 35(4): 341-348

Newton R.K., Aardema M., Aubrecht J., 2004. The utility of DNA microarrays for characterizing genotoxicity. *Environ. Health Perspect.* 112(4): 420-422

Saeed A.I., Sharov V., White J., Li J., Liang W., Bhagabati N., Braisted J., Klapa M., Currier T., Thiagarajan M., Sturn A., Snuffin M., Rezantsev A., Popov D., Ryltsov A., Kostukovich E., Borisovsky I., Liu Z., Vinsavich A., Trush V., Quackenbush J., 2003.

TM4: a free, open-source system for microarray data management and analysis. *Biotechniques*, 34(2):374-8

Snape J.R., Maund S.J., Pickford D.B., Hutchinson T.H., 2004. Ecotoxicogenomics: the challenge of integrating genomics into aquatic and terrestrial ecotoxicology. *Aquat. Toxicol.*, 67(2): 143-154

Tusher V.G., Tibshirani R., Chu G., 2001. Significance analysis of microarrays applied to the ionizing radiation response. *Proc. Natl. Acad. Sci.* U.S.A. 98(9), 5116-21

Venier P., Pallavicini A., De Nardi B., Lanfranchi G., 2003. Towards a catalogue of genes transcribed in multiple tissues of *Mytilus galloprovincialis. Gene*, 314C, 29-40

Waters M.D., Fostel M., 2004. Toxicogenomics and systems toxicology: Aims and prospects. *Nature Rev. Genetics*, 5(12): 936-948

THE DESE ESTUARY (LAGOON OF VENICE, ITALY): A CASE OF STUDY FOR BIODIVERSITY AT THE COMMUNITY LEVEL

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Riassunto.

Viene analizzata la distribuzione delle comunità di molluschi e policheti lungo l'estuario del Dese in primavera, estate ed autunno. Le comunità bentoniche seguono un modello di distribuzione influenzato dal gradiente di salinità e instaurato attraverso diversi raggruppamenti di specie. Questo modello, evidente in primavera, è modificato dall'estate all'autunno a causa dell'esplosione di *Streblospio shrubsolii*. Le possibili spiegazioni sono da attribuire non solo al ruolo giocato dalla temperatura e dalle condizioni trofiche come fattori determinanti l'incremento delle popolazioni di *S. shrubsolii* ma anche alla competizione dovuta a differenti gradi di opportunismo delle specie dominanti.

Abstract.

Distribution of mollusc and polychaete communities in the Dese estuary were analysed in spring, summer and autumn. The benthic communities follow a distribution pattern which is affected by salinity gradient and established through different assemblages of species. This pattern, evident in spring, is modified from summer to autumn because of the explosion of *Streblospio shrubsolii*. Possible explanations include not only the role played by temperature and trophic conditions as factors determining the increase of *S. shrubsolii* populations but also competition due to different degrees of opportunism of dominant species.

1. Introduction.

Studies concerning biodiversity at community level underpin the basic knowledge of different fields of environmental research: nature conservation, long-term studies and ecosystem health. Giangrande [2003] underlines the need of taxonomic studies at species level as the first step towards any discussion on biodiversity and basis for the conservation and sustainability of natural systems. Furthermore, basic studies of biodiversity proved indispensable because they provide a data set for future comparison.

Benthic communities are widely used in the environmental control programmes because they consist of organisms characterized by restriction or lack of mobility, relatively long biological cycles, close relationship with the bottom, ability to integrate effects of pollutants in time; afterwards the knowledge of community structure and functioning could provide more complete information on environmental conditions than the sole analysis of abiotic parameters.

As for the lagoon of Venice, works reconstructing an outline of macrobenthic community distributions, as they would have been prior to human interventions, date back to the 30's [Vatova 1940; 1949], 40's and 60's [Giordani Soika and Perin, 1974; Maggiore, 2002]. These concern the whole lagoon and provide a basic understanding of benthos distribution.

Complete benthic community studies on the three basins of the Venice lagoon, concern foraminiferal fauna in the Chioggia basin [Serandrei Barbero *et al.*, 1999], in the Malamocco basin [Donnici *et al.*, 1997] and in the Lido basin [Serandrei Barbero *et al.*, 1989] and invertebrate fauna in the Lido and Malamocco basins [Comune di Venezia - Assessorato all'Ecologia, 1991; Aleffi *et al.*, 1995a; Maggiore and Taroni, 2002].

In the lagoon of Venice special benthic community studies were aimed at verifying the influence of certain factors on the community structure such as eutrophication [Aleffi *et al.*, 1995b; Ceretti *et al.*, 1985; Tagliapietra *et al.*, 1998; 2000], sediment quality assessment [Volpi Ghirardini *et al.*, 1999], bottom morphology and water dynamic modifications [Aleffi *et al.*, 1995a; Pranovi *et al.*, 1998b], introduction of allochthonous species [Casale *et al.*, 2001], impact of bivalve fishing gears [Pranovi *et al.*, 1998a; Pranovi and Giovanardi, 1994; 2000], influence of phanerogames to improve biodiversity [Pranovi *et al.*, 2000; Sfriso *et al.*, 2001].

Most of these works were carried out in restricted areas in the three basins that make up the lagoon of Venice: Chioggia [Casellato 1996; Casellato *et al.*, 1995; 1997; Pranovi and Giovanardi 2000; Pranovi *et al.*, 1998b], Malamocco [Pranovi and Giovanardi 1994; Pranovi *et al.*, 1998a; Sfriso *et al.*, 2001] and Lido basins [Aleffi *et al.*,1995b; Tagliapietra *et al.*, 1998; 2000; Volpi Ghirardini *et al.*, 1999]. Only for some of them temporal variability of benthic community structure were also analysed [Casellato *et al.*, 1995; 1996; 1997; Ceretti *et al.*, 1985; Tagliapietra *et al.*, 1998; 2000; Pranovi *et al.*, 1998a; 2000; Sfriso *et al.*, 2001].

In this context a study on biodiversity along the Dese estuary was established; the goal was to give an outline of spatial and temporal distribution of taxonomic biodiversity of soft macrobenthos along the Dese estuary as a background of an area of the Venice Lagoon little known from this point of view and to verify if there was a biological zonation pattern based on ecological role of species. In this work the molluscs and polychaetes component was analysed.

2. Materials and methods.

2.1. Area description.

The Dese estuary (Fig. 1) is a distinctive habitat in the lagoon of Venice; it is characterized not only by wide tidal amplitudes, but also by the Dese river flow; it is the main tributary into the lagoon [Zuliani *et al.*, 2001] and an important source of urban and agriculture pollution [Collavini *et al.*, 2001]. The estuary (about 14 Km) is located inside the northern Venice lagoon basin and it extends from the Dese outflow in the lagoon to the Lido inlet, forming a narrow, meandering channel (Canale di Burano) between the salt marshes and mud flats.

The whole area is characterized by marked variations of physical and chemical factors, which determine its real estuarine conditions. In Fig. 2 some features of the Dese estuary (data supplied by Ministero delle Infrastrutture e dei Trasporti-Magistrato alle Acque on behalf of Consorzio Venezia Nuova, 2002) are given. A decreasing gradient of salinity is established from the Lido inlet to ‘Palude di Cona’ with more marked fluctuations in the inner area in winter and spring. Temperature values are very low in January (from 0,7 to 5,4 C°) and they show the maximum in late summer. Chlorophyll a, total nitrogen and phosphorous show a general increasing gradient from Lido inlet to “Palude di Cona” and a great variability with the highest values in late spring and early summer for the first, and in autumn for the latter two. The lowest values are recorded in early spring and late summer for Chlorophyll a and in summer for total nitrogen and phosphorous. Trend of dissolved oxygen shows a decrease from winter to late summer, never going down to 6 ppm, and a following increase up to the end of the year. Grain size distribution (Fig. 3) shows a decreasing gradient from the Lido inlet to “Palude di Cona”.

The investigated area consists of nine stations located in the mud flats (Fig. 1).

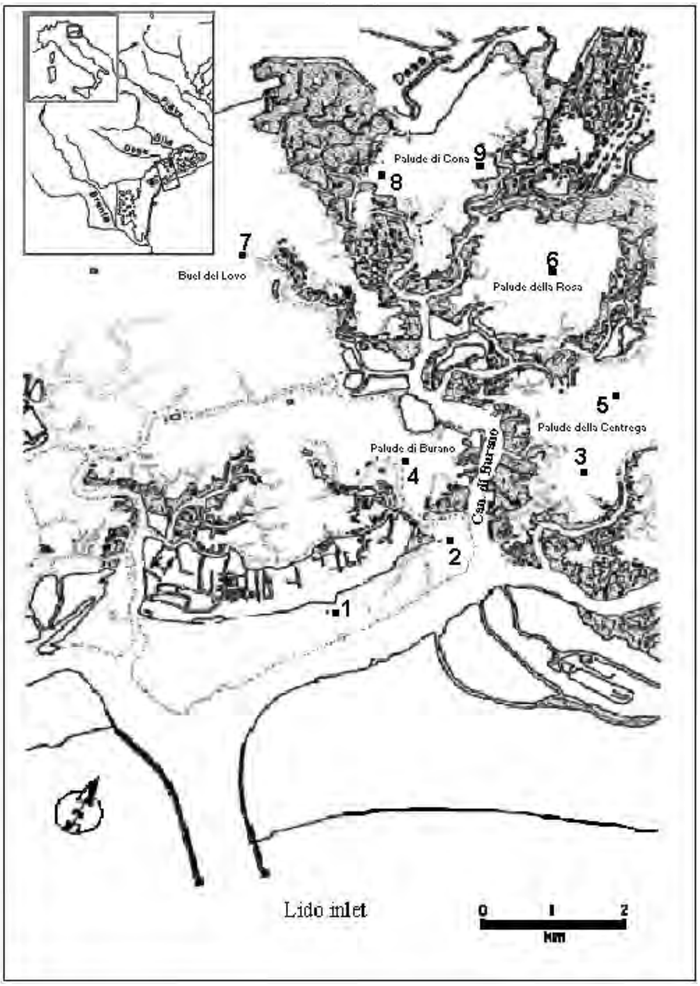

Fig. 1 – Map of Dese estuary showing the position of the sampling stations.

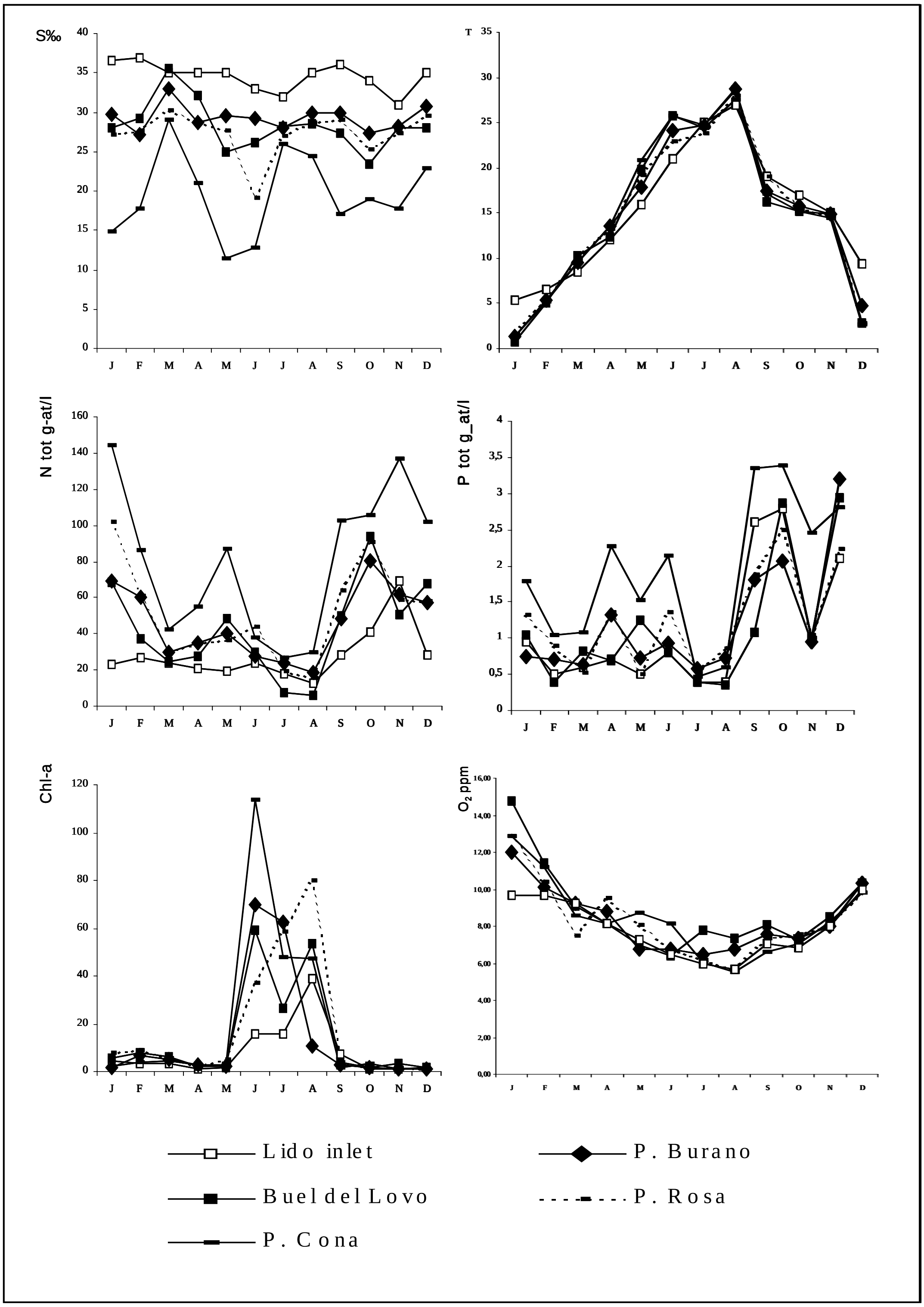

Fig. 2 – Monthly trend of salinity, temperature, total nitrogen, total phosphorous, chlorophyll a and oxygen in the water column in five sampling areas. Data were supplied by Ministero delle Infrastrutture e dei Trasporti-Magistrato alle Acque on behalf of Consorzio Venezia Nuova [2002].

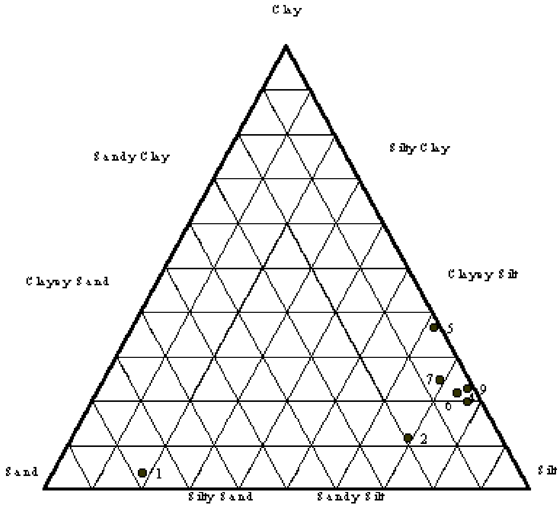

Fig. 3 – Shepard's triangular diagram. Data were supplied by Ministero delle Infrastrutture e dei Trasporti-Magistrato alle Acque on behalf of Consorzio Venezia Nuova [1999].

2.2 Data collection.

Quantitative samples were taken in the mud flat at an average depth of 0.5 m; at each station geographical position was recorded by GPS. Samplings were carried out during May, August and October 2002 and three bottom samples were collected with an Ekman box corer (0.06 m^2). Material was washed through a 1.0 mm mesh screen. Organisms retained were fixed in 4% buffered formalin. The individuals were sorted and molluscs and polychaetes were identified to the lowest possible taxon and enumerated.

2.3 Data analysis.

Data were analyzed through Correspondence Analysis [Benzecri, 1973] and Cluster Analysis (metodo k c-means) [Hartigan, 1975] to identify station groups characterized by the same assemblages of species. To determine more important species in each cluster, percentage mean abundance was calculated for each species.

3. Results.

Tab. 1 shows the list of Molluscs and Polychaetes species and genera collected along the Dese estuary; 51 species and 4 genera are listed according to their distribution along the estuary; two main groups of species can be recognized: one restricted to the outer stations (1, 2, 3) and one distributed in almost total study area.

In Spring 669 molluscs/m^2 and 12038 polychaetes/m^2 were found, in summer 1434 molluscs/m^2 and 54966 polychaetes/m^2, in autumn 2912 molluscs/m^2 and 98340 polychaetes/m^2.

Fig. 4 a, b and c is the graphic output of the Correspondence Analysis performed, respectively, on the spring, summer and the autumn data; it seems, in spring and summer cases, that station-points and species-points arrange themselves in a parabolic outline; in autumn all stations, except st.1 and 3, are grouped close to the axes origin**.**

Tab. 1 – Species collected along the Dese estuary. Species are listed according to their distribution along the estuary. P= Molluscs; M= Polychaetes; s=spring, su=summer, a=autumn. The acronyms of species, quoted in Figure 4, are listed in the second column, species marked by X are rare species taken off the Correspondence Analysis.

			1			2			3			4			5			6			7			8			9		
			s	su	a	s	su	a	s	su	a	s	su	a	s	su	a	s	su	a	s	su	a	s	su	a	s	su	a
P	Pe	Pigospio elegans Claparède, 1863			+																								
P	X	Glycera tridactyla Schmarda, 1861	+																										
P	Nr	Nassarius reticulatus (Linnaeus, 1758)	+																										
P	X	Perinereis cultrifera (Grube, 1840)			+																								
M	Sm	Solen marginatus Pulteney, 1799					+	+																					
M	Ap	Abra prismatica (Montagu, 1808)					+	+																					
M	Chg	Chamelea gallina (Linnaeus, 1758)					+	+																					
M	Pha	Paphia aurea (Gmelin, 1791)					+	+																					
P	Prc	Prionospio caspersi Laubier, 1962					+	+																					
P	Pind	Polycirrus ind.					+	+																					
P	X	Cirratulus cirratus (O.F.Müller, 1776)					+																						
P	Pm	Prionospio multibranchiata Berkeley, 1926						+																					
P	Marf	Marphysa fallax Marion & Bobretzky, 1875						+																					
M	X	Gastrana fragilis (Linnaeus, 1758)						+																					
M	Nn	Nucula nucleus (Linnaeus, 1758)						+																					
P	Clyc	Clymenura clypeata (Saint Joseph, 1894)								+	+																		
P	X	Euclymene oerstedi (Claparède, 1863)								+																			
P	Ct	Cirriformia tentaculata (Montagu, 1808)							+																				
P	X	Phyllodoce madeirensis (Langerhans, 1880)							+																				
P	Psa	Pseudopolydora antennata (Claparède, 1870)	+				+																						
P	X	Glycera rouxii Audouin & Milne Edwards, 1833		+				+																					
P	Stsc	Sternaspis scutata (Renier, 1807)	+						+		+																		
P	Nc	Neanthes caudata (Delle Chiaje, 1828)	+			+	+	+		+																			
P	Pf	Pseudoleiocapitella fauveli Harmelin, 1964	+			+	+	+	+	+																			
P	Nl	Notomastus latericeus M. Sars, 1851	+			+	+	+	+	+	+				+														
P	Am	Aphelochaeta multibranchiis (Grube, 1863)	+				+	+	+	+	+					+													
P	Sd	Spio decoratus Bobretzky, 1870	+				+			+						+													
P	X	Micronephtys sphaerocirrata (Wesenberg Lund, 1949)					+				+																		
P	Do	Desdemona ornata Banse, 1957						+							+	+													
P	Mars	Marphysa sanguinea (Montagu, 1815)					+											+											
P	Cs	Cossura soyeri Laubier, 1962						+	+	+	+				+	+	+												
P	Mm	Microspio mecznikovianus (Claparède, 1869)					+	+		+			+			+													
P	Pmac	Phyllodoce maculata (Linneaus, 1767)						+		+	+				+		+	+											
P	Hf	Heteromastus filiformis (Claparède, 1864)	+				+		+	+	+				+	+	+			+			+						
P	Mc	Mediomastus capensis Day, 1961	+					+		+													+						
P	X	Laevicardium crassum (Gmelin, 1791)						+												+			+						
M	Tt	Tellina tenuis Da Costa, 1788					+	+												+			+						
M	Aind	Abra ind.						+		+				+					+	+		+						+	+
P	Nh	Nephtys hombergi Savigny, 1818				+	+				+	+		+	+	+	+	+	+	+	+	+	+						
M	Hn	Hemilepton nitidum (Turton, 1822)				+	+	+		+	+				+			+		+								+	+
P	Polc	Polydora ciliata (Johnston, 1838)					+						+		+					+		+	+				+	+	+
P	Mp	Mysta picta (Quatrefages, 1865)						+												+		+	+						+
M	X	Tapes decussatus (Linnaeus, 1758)							+												+	+					+		
M	As	Abra segmentum (Recluz, 1843)												+	+				+	+	+		+		+			+	+
M	At	Abra tenuis (Montagu, 1803)												+						+		+	+		+			+	+
M	Hind	Haminoea ind.											+		+			+											
P	Nu	Nematonereis unicornis Schmarda, 1861																		+			+						
M	X	Abra alba (W.Wood, 1801)																		+									
P	X	Spiophanes ind.																				+							
P	X	Neanthes succinea (Frey & Leuchart, 1847)																										+	
P	Hd	Hediste diversicolor (O.F.Müller, 1776)							+			+		+		+		+	+	+	+	+	+	+	+	+	+	+	+
P	Ccap	Capitella capitata (Fabricius, 1780)	+		+	+	+	+					+	+	+					+			+						+
P	Pl	Paradoneis lyra (Southern, 1914)	+			+	+	+	+	+	+			+	+	+		+	+				+						+
M	Cg	Cerastoderma glaucum (Poiret,1789)			+	+	+	+			+				+	+	+		+		+	+	+					+	+
P	Strshr	Streblospio shrubsolii (Buchanan, 1890)	+	+	+	+	+	+	+	+	+		+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+

Cluster Analysis identified four clusters of stations in each season; species, with percentage mean abundance higher than 1% in each cluster, were listed in Tab. 2.

Tab. 2 – Mean abundance (%) of the species of each cluster in spring (a), summer (b), autumn (c).

a

CLUSTER 1 ■ St 2, 6, 7, 8, 9	%	CLUSTER 2 ♦ St 4, 5, 6	%	CLUSTER 3 ▲ St 3	%	CLUSTER 4 ● St 1	%
H. diversicolor	46.6	N. hombergi	22.8	N. latericeus	73.4	N. latericeus	28.4
S. shrubsolii	32.5	H. filiformis	19.4	P. lyra	7.9	S. shrubsolii	16.2
Nereididae ind.	7.2	H. nitidum	12.7	S. scutata	5	M. capensis	14.8
Polichaetes ind.	5.1	S. shrubsolii	11.9	S. shrubsolii	3.6	Capitellidae ind.	8.1
P. lyra	2.5	H. diversicolor	8.5	A. multibranchiis	3.6	C. capitata	8.1
P. fauveli	2.3	Haminea ind.	7.6	H. diversicolor	2.9	H. filiformis	5.4
A. segmentum	1.1	D. ornata	5.9	H. filiformis	1.4	N. reticulatus	5.4
		P. maculata	2.5			A. multibranchiis	4
		P. lyra	1.7			P. antennata	2.7
		C. soyeri	1.7			P. lyra	2.7
		M. sanguinea	1.7			P. fauveli	1.4
						N. caudata	1.4
						S. scutata	1.4

b

CLUSTER 1 ■ St 1, 5, 6, 7, 8,9	%	CLUSTER 2 ♦ St 4	%	CLUSTER 3 ▲ St 3	%	CLUSTER 4 ● St 2	%
S. shrubsolii	85.8	C. capitata	55.2	A. multibranchiis	37.9	M. mecznikovianus	44.7
H. diversicolor	11.4	S. shrubsolii	27.5	C. clypeata	21.8	S. shrubsolii	12.2
		Haminea ind.	6.8	S. shrubsolii	12.1	C. capitata	5.7
		P. ciliata	3,5	C. soyeri	10	H. nitidum	4.6
		Capitellidae ind.	3.5	P. lyra	8.6	N. latericeus	4.3
		H. diversicolor	3.5	N. latericeus	5.3	C. glaucum	4
				H. filiformis	1.1	Polycirrus ind.	3.7
						S. decoratus	2.8
						P. fauveli	2.6
						N. caudata	2.6
						P. caspersi	1.7
						P. antennata	1.4
						P. lyra	1.4
						T. tenuis	1.4
						Capitellidae ind.	1.1

c

CLUSTER 1 ■ St. 4, 5, 6, 7, 8, 9	%	CLUSTER 2 ♦ St 2	%	CLUSTER 3 ▲ St 3	%	CLUSTER 4 ● St 1	%
S. shrubsolii	93	S. shrubsolii	62.1	S. shrubsolii	49.7	C. capitata	71
H. diversicolor	3	P. fauveli	14	P. lyra	32.8	S. shrubsolii	25.4
		N. latericeus	5	N. latericeus	3.2	P. elegans	3.6
		Polycirrus ind.	2.7	C. soyeri	2.7		
		T. tenuis	2.3	A. multibranchiis	2.3		
		M. mecznikoviani	1.3	P. maculata	1.8		
		C. soyeri	1.3	H. nitidum	1.8		
		P. multibranchiata	1.2	Cirratulidae	1.4		
		N. caudata	1	C. clypeata	1.4		

3.1. Spring.

A succession of four communities, defined by species with high percentage mean abundance, is shown from Dese river mouth to the Lido inlet (from the positive to the negative pole) (Fig. 4a):

- the first one (■), characteristic of inner stations (st.7, 8, 9) and st. 2, is made up of brackish species as *Hediste diversicolor* and *Streblospio shrubsolii*; st. 2 community seems to be a typical community of more confined areas, even if it is under inlet influence;
- the second cluster (♦) groups the intermediated stations 4, 5 and 6; species belonging to it, are marine species able to penetrate up to the estuaries as *Nepthys hombergi* and *Heteromastus filiformis* [Wolff, 1973; Rasmussen, 1973]; 20.4% is represented by brackish water species (*S. shrubsolii* and *H. diversicolor*) (Tab.2a);
- the third (▲) and fourth one (●) correspond, respectively, to st. 3 and 1; the two communities are characterised by the presence of marine species as *Notomastus latericeus*, *Paradoneis lyra*, *Sternaspis scutata*, *Aphelochaeta multibranchiis*, the dominance of *N. latericeus* and the decreasing importance of brackish water species (Tab.2a), but station 1 community is different for the presence of *Mediomastus capensis*, *Nassarius reticulatus*, *Neanthes caudata* and the opportunistic species;
- *Pseudopolydora antennata*, *Capitella capitata* and *Pseudoleiocapitella fauveli* [Borja *et al.*, 2000].

3.2. Summer.

In summer (Fig. 4b), the Correspondence Analysis shows a distinct succession of four communities along axis 1; in table 2b species with the percentage mean abundance higher than 1% in each cluster are quoted:

- the first cluster (■) includes inner stations 7, 8 and 9, intermediated stations 5 and 6, and outer station 1; species linked to it are brackish water species firstly *S. shrubsolii*, secondly *H. diversicolor*.
- the second cluster (♦) correspond to st 4; dominant species are the first-order opportunistic species *C. capitata* [Grassle and Grassle, 1974; Pearson and Rosemberg, 1978] and *S. shrubsolii*;
- the third (▲) and fourth one (●) correspond, respectively, to st. 3 and 2; the two communities are characterised by the presence of marine species, with a different specific composition *A. multibranchiis*, *Clymenura clypeata*, *Cossura soyeri*, *P. lyra* and *N. latericeus* being most important species in the first, *Microspio*, *mecznikovianus*, *C. capitata*, *H. nitidum* in the second; between dominant species *S. shrubsolii* can be included.

3.3. Autumn.

Fig. 4c shows results of Correspondence Analysis in autumn; the concentration of *C. capitata* and *Pygospio elegans* only in station 1, makes it very far away from all the others flattening them on axis 2. Focusing the attention on the latter**,** the graphic shows most of the stations grouped close to the axes origin; this seems to suggest the presence of one sole community strongly dominated by *S. shrubsolii* (Tab. 2c).

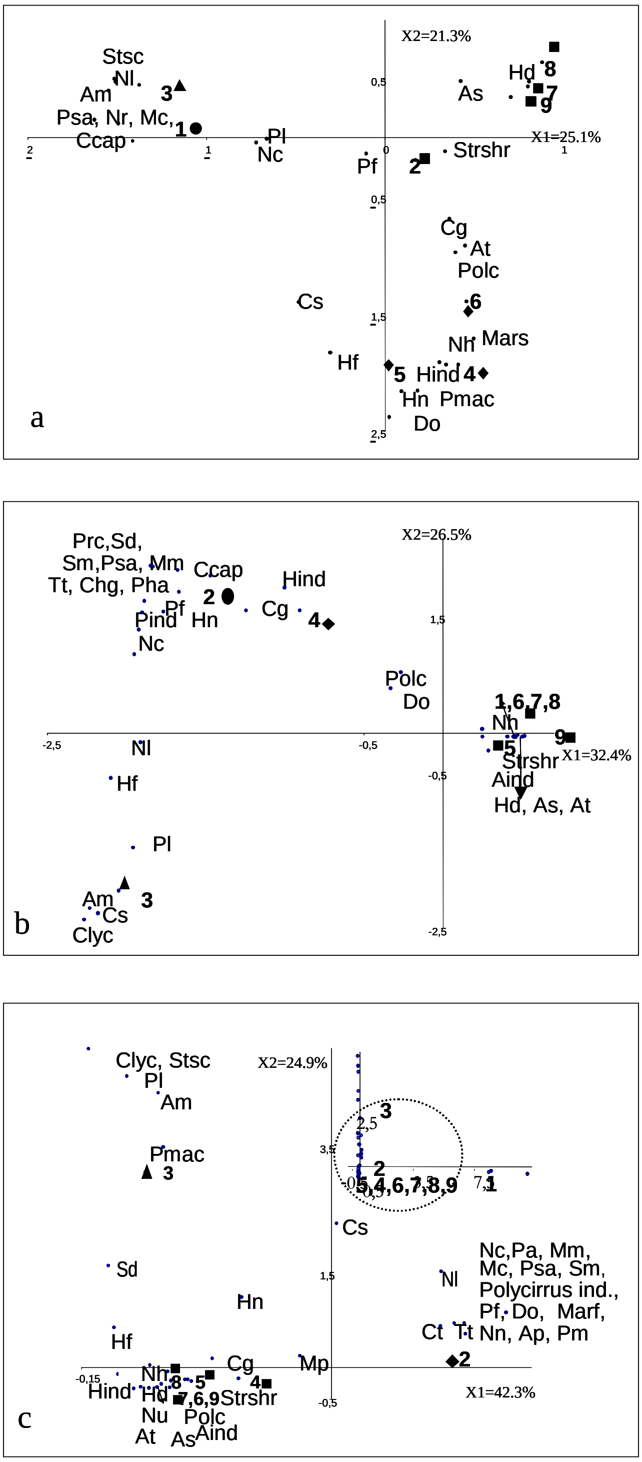

Fig. 4 – Correspondence Analysis in spring (a), summer (b) and autumn (c): ■Cluster 1, ♦ Cluster 2, ▲ Cluster 3, ●Cluster 4.

Cluster Analysis evidenced four cluster(s):

- the first (■), including intermediated and inner stations, is strongly dominated by *S. shrubsolii* (93%);

- the second (♦) (station 2) is made up of *S. shrubsolii* (62.1%) and marine species as *Pseudoleiocapitella fauveli* and *N. latericeus*;
- the third (▲) (station 3) is mainly characterized by *S. shrubsolii* (49.7%) and *P. lyra* (32.8%);
- the fourth (station 1) is mainly characterized by *C. capitata* (71%) and *S. shrubsolii* (25.4%).

4. Discussion and conclusion.

4.1. The scenario in spring.

Stations and species seem to arrange themselves in a parabolic outline (Guttman effect) implying that axis 2 was a quadratic function of axis 1 [Benzecri, 1973]; this occurs when the system is controlled by one dimensional phenomenon. A succession of animal populations, whose distribution is established by the distance from the sea, is shown along axis 1. Fig. 5 a is the result of Cluster Analysis plotted on the Dese estuary map, it gives a clearer picture of zoobenthos distribution. Zoobenthos shows a zonation pattern that seems to follow the salinity gradient; with marine species near the Lido inlet, more eurialyne species in the central area and estuarine species in the marginal area.

The anomalous location of station 2 need a thorough analysis.

4.2. The scenario in summer.

Stations and species seem to arrange themselves in a parabolic outline in summer too; the zoobenthos distribution pattern of spring is modified; indeed the inner community (cluster 1) of spring partly invades the space of intermediated community (cluster 2) (Fig. 5b). This change is attributed to the spreading of *S. shrubsolii* which becomes the dominant species in intermediate and inner areas, in cluster 2 co-dominant with *C. capitata* (Tab. 2b).

The whole estuary deals with physico-chemical parameters changes: temperature and O_2 concentrations, homogeneous in whole estuary, show, respectively, the maximum and the minimum value of the year, O_2 never going below hypoxic conditions; Chl a shows between the highest values of the year and a general decreasing gradient from the inlet to the inner area; salinity change greatly only in the inner area.

In summer, general conditions of the estuary can be expressed, therefore, in terms of increase of trophic status.

Trophic status and the autoecology of some species can explain changes in benthic community structure.

S. shrubsolii is known as an opportunistic species with life span of one year; his reproductive activity is concentrated within short period of the year in cool temperate areas, while it is extended throughout the year in warm temperate areas with two maxima in late spring and autumn [Lardicci *et al.*, 1997]; it is typical of organically enriched sediments [Pearson and Rosemberg, 1978; Sardà and Martin, 1993] and the food availability is the main factor for the explosion of the populations of this species [Sardà and Martin, 1993; Rossi and Lardicci, 2002]. A study carried out by Llanso [1993] in lower Rappahannock river (Chesapeake Bay) shows, for the congeneric species *S. benedicti*, peaks related to increasing water temperature and organic enrichment from plankton decay. *C. capitata* is a marine species known as a first-order opportunistic species able to firstly colonize areas where gross organic enrichment caused elimination or reduction of fauna [Pearson and Rosemberg, 1978].

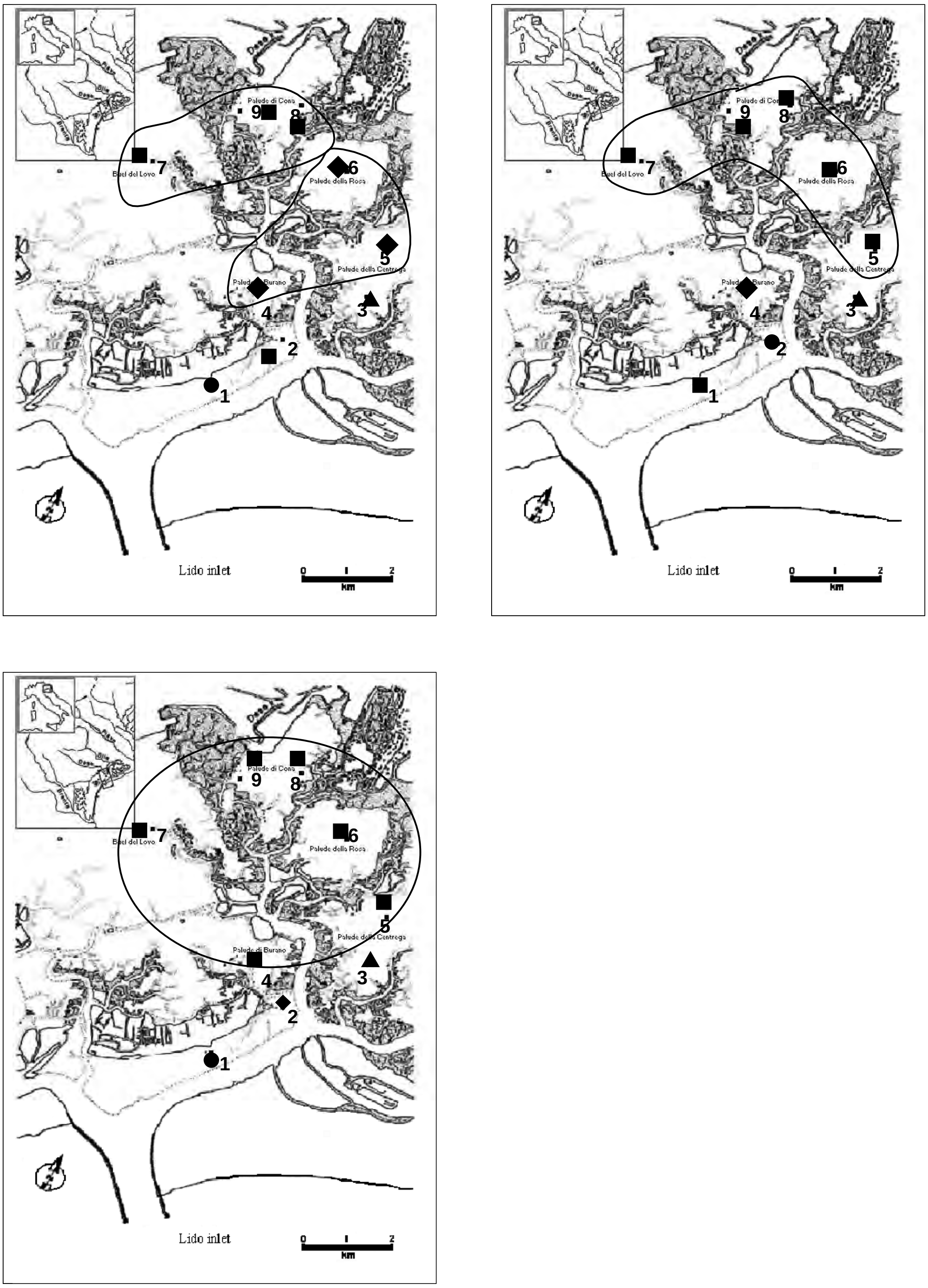

Fig. 5 – Cluster Analysis plotted on the Dese estuary map: spring (a), summer (b) and autumn (c): ■Cluster 1, ♦ Cluster 2, ▲ Cluster 3, ●Cluster 4.

The anomalous location of station 1 need a thorough analysis.

4.3. The scenario in autumn.

Most of the stations and species point tend to get close to each other around the axes origin, situation occurring when only one community is present; indeed the inner community (cluster 1) of spring completely invades the space of intermediated community (cluster 2) (Fig. 5c) getting to affect outer stations (Tab. 2c) because of the explosion of *S. shrubsolii*.

In autumn temperature and O_2 concentrations decrease to the spring values, Chl a falls down, but nutrients show the highest values of the year.

4.4. The outer stations.

They are stations which communities show great temporal variations in specific composition and dominance (Tab 2 a, b and c). Most of the species in the outer stations are considered opportunists, even if their degree of opportunism is not known except for *C. capitata* [Grassle and Grassle, 1974]. Different life strategies could influence the equilibrium between species determining seasonal changes in their density.

In conclusion benthic communities follow a distribution pattern affected by salinity gradient, and established through different assemblages of species. This pattern, evident in spring, is partly modified from summer to autumn. Indeed, *S. shrubsolii* spreads from the inner community of spring to the intermediate community in summer, reaching and affecting outer community in autumn. Possible explanations include not only the role played by temperature and trophic conditions as factors determining the increase of *S. shrubsolii* populations, but also competition due to different degrees of opportunism of dominant species.

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References.

Aleffi F., Chiozzotto E., Grim F., Ore, G:, Scattolin M., 1995a. Ricerche sui popolamenti bentonici animali della laguna di Venezia. *S.it.E. Atti* 16, 35-37

Aleffi F., Ceschia C, Curiel D., Grim F., Ore, G:, Rismondo A.., 1995b. Ricerche sui popolamenti bentonici della zona di Campalto (Laguna di Venezia). *S.it.E. Atti* 16, 39-41

Benzecri J.P., 1973. L' analyse des données. V.2. Dunod Paris, 619 pp

Borja A., Franco J., Perez V., 2000. A marine biotic index to establish the ecological quality of soft-bottom benthos within European estuarine and coastal environments. *Marine Pollution Bulletin* Vol. 40, No. 12, 1100-1114

Casale M., Giovanardi O., Grimm F., Orel G., Pessa G., 2001. Distribuzione ed abbondanza delle principali specie di Molluschi Bivalvi nella laguna di Venezia nell'estate 1999, con particolare riguardo per *Tapes philippinarum* (Adams & Reeve, 1850). *Biologia Marina Mediterranea* 8(1): 413-423

Casellato S., Caneva F., Santagiuliana B., 1995. Composizione e distribuzione dei popolamenti macrobentonici nella Laguna di Chioggia. *S.it.E. Atti* 16, 57-60

Casellato S., 1996. Oligochaetes in the southern basin of the Venetian Lagoon: Community composition, species abundance and biomass. *Hydrobiologia*, 334(1-3): 103-114

Casellato S., Conti G., Petris A., 1997. Distribuzione dei crostacei nel bacino meridionale della Laguna di Venezia. *Biologia Marina Mediterranea* 4(1): 359-363

Ceretti G., Ferrarrese U., Scattolin M., 1985. I Chironomidi della laguna di Venezia. Risultati delle ricerche 83-84 e proposte di lotta. Arsenale editrice.59pp

Collavini F., Zonta R., Bettiol C., Fagarazzi O.E., Zaggia L., 2001. Drain project workshop; Venezia, Giugno 2001: 53-60

Comune di Venezia - Assessorato all'Ecologia, 1991. Le alghe della laguna di Venezia. Arsenale editrice

Donnici S., Serandrei Barbero R. and Taroni G., 1997. Living benthic foraminifera in the lagoon of Venice (Italy): population dynamics and its significance. *Micropaleontology* 43(4): 440-454

Giangrande A., 2003. Biodiversity, conservation, and the 'Taxonomic impediment'. Aquatic Conservation: Marine and Freshwwater Ecosystems 13: 451-459

Giordani Soika A., Perin G., 1974. L'inquinamento della laguna di Venezia: studio delle modificazioni chimiche e del popolamento sottobasale dei sedimenti lagunari negli ultimi vent'anni. *Bollettino del Museo Civico di Storia Naturale, Venezia*. 26: 25-68

Grassle J.F., Grassle J.P., 1974. Opportunistic life histories and genetic systems in marin benthic Polychaetes. *J. mar. Res., 32 (2)*: 253-283

Hartigan J., 1975. Clustering algorithms. Wiley & Sons, New York: 351 pp

Lardicci C., Checcherelli G., Rossi F., 1997. *Streblospio shrubsolii* (Polychaeta: Spionidae): temporal fluctuation in size and reproductive activity. *Cah. Biol. Mar.* 38: 207-214

Llanso R.J., 1993. Effects of Hypoxia on estuarine benthos: the lower Rappahannock river (Chesapeake Bay), a case study. Estuarine Coastal and Shelf Science 35: 491-515

Maggiore F.,2002. Benthic community distribution in the lagoon of Venice in the years 1948 and 1968. *Bollettino del Museo Civico di Storia Naturale, Venezia* 53: 69-91

Maggiore F., Taroni G., 2002. Biodiversity studies at macrobenthic community level in the Lido Basin (Lagoon of Venice): a review. In: Scientific Research and Safeguarding of Venice, Istituto. Veneto Scienze Lettere ed Arti – CORILA Publ. Proc. Annual General Meeting of CORILA, Venezia: 649-660

Ministero delle Infrastrutture e dei Trasporti-Magistrato alle Acque on behalf of Consorzio Venezia Nuova. 1999. Mappatura dell' inquinamento dei fondali lagunari

Ministero delle Infrastrutture e dei Trasporti-Magistrato alle Acque on behalf of Consorzio Venezia Nuova 2002. Monitoraggio Ecosistema Lagunare. Campagne di misura della qualità dell'acqua dalla XVII alla XIX del 2002

Pearson T.H., Rosenberg R., 1978. Macrobenthic succession in relation to organic enrichment and pollution of the marine environment. *Oceanography and Marine Biology. An Annual Revue* 16: 229-311

Pranovi F., Curiel D., Rismondo A., Marzocchi M., Scattolin M., 2000. Variations of the macrobenthic community in a seagrass transplanted area of the Lagoon of Venice. *Scientia Marina* 64(3): 303-310

Pranovi F., Giovanardi O., 1994. The impact of hydraulic dredging for short-necked clams, Tapes spp., on an infaunal community in the lagoon of *Venice Scientia Marina* 58(4): 345-353

Pranovi F., Giovanardi O., 2000. Caratterizzazione della comunità macrobentonica in un'area del bacino sud della laguna di Venezia. *Bollettino del Museo Civico di Storia Naturale, Venezia*: 50: 213-222

Pranovi F., Giovanardi O., Franceschini G., 1998a. Recolonization dynamics in areas disturbed by bottom fishing gears. *Hydrobiologia* 375/376: 125-135

Pranovi F., Lombardo I., Giovanardi O., 1998b. Dinamica dei popolamenti bentonici nella Valle di Brenta (Laguna di Venezia). *Biologia Marina Mediterranea* 5(1): 581-582

Rasmussen E., 1973. Systematycs and ecology of the Isefjord marine fauna (Denmark). *Ophelia*, 11: 1-507

Rossi F., Lardicci C., 2002. Role of the nutritive value of sediment in regulating population dynamics of the deposit-feeding polychaete *Streblospio shrubsolii*. *Marine Biology* 140: 1129-1138

Sardà R., Martin D., 1993. Population of *Streblospio* (Polychaeta: Spionidae) in temperate zones: demography and production. *Journal of Marine Biological Association of U.K.* 73: 769-784

Serandrei Barbero R., Albani A.D., Favero V., 1989. Distribuzione dei foraminiferi recenti nella laguna a Nord di Venezia. *Boll. Soc. Geol. It.* 108: 279-288

Serandrei Barbero R., Carbognin L., Taroni G., Cova E., 1999. Distribution of recent benthic foraminifera in the southern basin of the Venice lagoon (Italy): Statistical evaluation of taxa significance. *Micropaleontology*. 45(1):99-111

Sfriso A., Birkemeyer T., Ghett, P.F., 2001. Benthic macrofauna changes in areas of Venice lagoon populated by seagrasses or seaweeds. *Marine Environmental Research* 52:323-349

Tagliapietra D., Pavan M., Wagner C., 1998. Macrobenthic community changes related to eutrophication in *Palude della Rosa* (Venetian Lagoon). *Estuarine Coastal and Shelf Science* 47: 217-226

Tagliapietra D; Pavan M; Wagner C., 2000. Benthic patterns in a salt marsh basin: a snapshot of Palude della Rosa (Venetian L *Wetlands Ecology and Managem*ent 8(4,): 287-292

Vatova A., 1940. Le zoocenosi della laguna veneta. *Thalassia* 3(10): 1-28 9 tav. f.t

Vatova A., 1949. Caratteri di alcune facies bentoniche della laguna veneta. *Nova Thalassia.*1(4): 1-15

Volpi Ghirardini A., Birkemeyer T., Arizzi Novelli A., Delaney E., Pavoni B., Ghetti P.F., 1999. An integrated approach to sediment quality assessment: the Venetian lagoon as a case study. *Aquatic Ecosystem Health and Management* 2: 435-447

Wolff W.J., 1973. The estuary as a habitat. An analysys of data on the soft-bottom macrofauna of the estuarine area of the river Rhine, Meuse, and Scheldt. *Zoologische Verhandelingen* 126: 1-242

Zuliani A., Zonta R., Zaggia L., Fagarazzi O., 2001. Drain project workshop. Venice, Giugno 2001: 31- 36

RESEARCH LINE 3.7
Forecasting and management models

LONG TERM NET EXCHANGE OF SANDS THROUGH VENICE INLETS

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Riassunto.

Viene formulato un modello analitico semplificato in grado di fornire una stima dello scambio netto di sabbie che si verifica alle bocche della laguna di Venezia durante la sequenza di eventi mareali registrati negli anni dal 1994 al 1998.

I risultati suggeriscono che le bocche in questione si trovano in una condizione lontana da quella d'equilibrio statico ove questa venga definita dal criterio per cui la massima velocità indotta dalle correnti di marea uguaglia il valore corrispondente alla tensione critica per il trasporto di sedimenti.

Inoltre, è stato possibile quantificare un limite superiore per la perdita di sabbie fini dalle bocche della laguna supponendo la portata solida unicamente determinata dalla capacità di trasporto locale. I risultati indicano che la perdita annua di sabbia dalla laguna è di un ordine di grandezza inferiore alla perdita totale di sedimenti usualmente dichiarata e che tale perdita si realizza principalmente in corrispondenza d'eventi estremi.

Tali risultati appaiono di rilievo nei confronti della valutazione dei provvedimenti necessari ad arrestare il degrado morfologico della laguna di Venezia.

Abstract.

In the present work, we formulate a simple model of the inlet hydrodynamics which allows us to estimate the net exchange of sand associated with the sequence of tidal events recorded for several years. Firstly, it turns out that the present configuration of each of the inlets is far from the static-equilibrium limit, defined as the condition such that the maximum speed is equal to the critical speed for sediment motion. Secondly, we obtain an estimate of an upper bound for the loss of sediments experienced by each inlet through the years assuming that the amount of sediments carried by both flood and ebb currents is determined by their transport capacity. Results suggest that the yearly loss of sand experienced by Venice Lagoon is an order of magnitude smaller than usually claimed. Finally, the interpretation of the above results in the light of the recent morphodynamic evolution of Venice lagoon is discussed.

1. Introduction.

Venice lagoon has undergone through the centuries significant morphological changes which have progressively led to a tendency of the lagoon to lose its original characters to acquire those typical of a bay.

The two main facts which have played a significant role have been, the diversion of rivers discharging into the lagoon and the construction of long jetties bounding the inlets. Once the above actions were completed, virtually all the fluvial supply of sediments was removed from the lagoon. Furthermore, after the construction of the jetties, the inlets were moved a few hundred meters away from the coast reducing the amount of sediment resuspended by wave breaking in the surf zone able to reach the inlets during the flood phase.

Along with the above processes, various further man induced actions, undertaken to enhance the industrial development of the city, together with natural phenomena, namely *sea level rise* and *subsidence*, have led to a pronounced process of sinking of the city (roughly *23 cm* in the last century). The major hydrodynamic manifestation of the latter process is an increased frequency of high waters, which nowadays threatens the survival of Venice city. From a morphodynamic point of view, the progressive loss of salt marshes, deepening of shoals and canal siltation, are evidences of the morphological evolution undergone by the lagoon. For these reasons, along with the major problem of defending Venice from flooding due to high water, the next issue in the agenda is to attempt counteracting the morphodynamic degradation of the lagoon. The latter goal is fairly difficult to achieve, and calls for a deeper understanding of the exact nature of the mechanisms controlling the long term sediment loss in Venice lagoon.

In this paper we investigate one such mechanism, namely the exchange of sand through the tidal inlets. We focus on inlets since their geometry is often claimed to be a major factor controlling the exchange of sediments. The argument is motivated by the fact that the construction of jetties, besides the reduction of the sediment supply from the sea, has had the further consequence to enhance the degree of ebb-flood asymmetry experienced by the flow field in the near inlet region. Furthermore, we confine our attention on the exchange of sand as this is the type of sediment present on the bottom of the near inlet regions (the grain size typically falling in the range 0.1 – 0.3 *mm*). These sediments can be entrained in suspension and transported as bed load. The role of the finer sediments, unable to settle during the tidal cycle and driven to the sea by ebb currents, will be analyzed below and will help to reconcile our results with the estimates of sediment loss currently available.

The procedure employed in the rest of the paper is as follows. In the next section we formulate our mathematical model. Chapter 3 is devoted to a discussion of inlet equilibrium. In chapter 4 we propose an estimate of the exchange of sand occurred through each of Venice inlets in the period 1994- 1998 for which records of the tidal oscillations of free surface elevation in the Adriatic sea close to Venice inlets are available. Finally chapter 5 concludes the paper with some discussion.

2. Formulation of the mathematical model.

In order to obtain an estimate of the long term exchange of sand between the lagoon and the sea, an appropriate model must be simple enough to be able to reproduce the process for periods of years or decades with a non prohibitive numerical effort, and sufficiently sophisticated to capture the main features of the phenomenon. We attempt at formulating such a model taking advantage of the following assumption:

- *one – dimensional tide propagation in the channel;*

- *horizontal free surface in the basin;*
- *sediment transport in equilibrium with local hydrodynamics.*

The first two assumptions are approximations justified by the observation that the length of the lagoon and the length of the inlet channel are both small compared with the tidal wavelength.

The implication of the third, apparently severe, assumption is that we are looking at the most unfavorable situation for the exchange of sand through the inlet: in fact, we are essentially assuming that, during the ebb phase, all the sand transported as bed load or suspended load is lost to the sea, on the contrary we are not accounting for the effect of flood currents possibly overloaded in the far field by resuspension due to breaking waves during storm events. In other words, we may reasonably expect that the output of the analysis provides an *upper bound for the loss of sand* from the lagoon.

Let us then model each of the three Venice inlets as a straight rectangular channel with length L, constant width B and mean flow depth D_0 relative to a flat and fixed bottom. The channel connects the portion of the lagoon drained by the inlet, i.e. a basin with surface area S, with the open sea (Fig. 1). Typical values of the relevant physical quantities useful to appreciate the approximations discussed below are reported in Tab. 1.

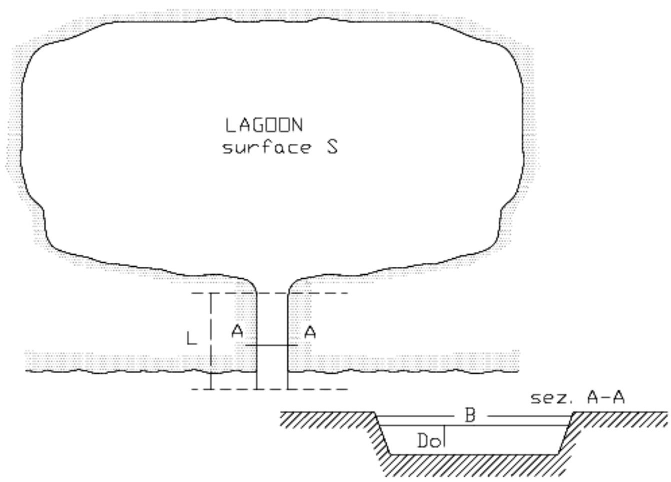

Fig. 1 – Sketch of the model of the system sea - channel - lagoon considered in the paper and notations.

Tab. 1 – Geometrical parameters characteristic of Venice inlets.

INLET	*L[m]*	*S[m^2]*	*D_0[m]*	*B[m]*	*L_e[m]*
Lido	4500	1.55 10^8	8.9	900	6000
Malamocco	3000	1.30 10^8	14.4	500	5000
Chioggia	2000	0.82 10^8	8.5	570	4000

The variables of the problem can be scaled as follows:

$$x' = \frac{x}{L_e}, \quad t' = \omega t, \quad h' = \frac{h}{a_0}, \quad D' = \frac{D}{D_0}, \quad U' = \frac{U}{U_0}, \quad C' = \frac{C}{C_0}, \qquad \text{(1a-f)}$$

where t denotes time, x is the landward oriented longitudinal axis with the origin at the inlet – sea boundary, D is the local flow depth, h is the water surface elevation relative to the still water level, U is the instantaneous velocity averaged over the cross section, and C is the flow conductance.

Furthermore, ω is the angular frequency of the tidal wave, a_0 a characteristic tidal amplitude, Le an equivalent length of the inlets (typically greater than L) which accounts for energy losses at the end sections, finally C_0 and U_0 are a characteristic scale for the flow conductance and the average channel velocity respectively. Using Strickler's relationship to estimate C and C_0, we can write:

$$C_0 = \frac{K_s}{\sqrt{g}} D_0^{1/6}, \quad C' = D'^{1/6}. \tag{2}$$

Furthermore, we may express the dimensionless local flow depth D' in the form:

$$D' = 1 + \frac{a_0}{D_0} h'(x,t) = 1 + \varepsilon h'(x,t) \tag{3}$$

where ε is the relative amplitude of free surface oscillations, which at the Venice inlets attains typically small values ($\varepsilon \cong 0.05 << 1$).

The basic one-dimensional partial differential equations describing the unsteady water flow in a rectangular channel with a fixed bed are the classical de Saint Venant equations of mass and momentum conservations, which in a dimensionless form read respectively:

$$\frac{\partial U'}{\partial x'} = -(\varepsilon\sigma)\frac{\partial h'}{\partial t'} - \varepsilon \frac{\partial h'}{\partial x'} \tag{4}$$

$$\delta_1 \frac{\partial U'}{\partial t'} + \frac{F_0^2}{\varepsilon} U' \frac{\partial U'}{\partial x'} + \frac{\partial h'}{\partial x'} + \delta_2 \frac{U'|U'|}{C'^2 \, D'} = 0, \tag{5}$$

where, having denoted gravity with g,

$$\sigma = \frac{\omega L_e}{U_0}, \quad \delta_1 = \frac{U_0 L_e \omega}{g a_0}, \quad \delta_2 = \varepsilon \delta_1^2 \frac{g}{L_e C_0^2 \omega^2}, \quad F_0^2 = \frac{U_0^2}{g D_0}. \tag{6}$$

In eqn (4) the quantity $\frac{\partial h'}{\partial x'}$ is small as the drop of free surface elevation through the inlet channel is typically only a small fraction of the amplitude a_0 of the tidal oscillation, furthermore, though the quantity $\frac{\partial h'}{\partial t'}$ is an order one quantity, the parameter σ ranges typically about 0.3; hence, at the leading order of approximation, the spatial derivative of the channel velocity U' is indeed 'small', and we can set $U'=U'(t)$.

The eqns (4) and (5) are to be solved with appropriate boundary conditions. At the channel inlet ($x' = 0$) we simply assume that the free surface oscillation is determined by the tidal forcing:

$$h'|_{x=0} = h'_1 = f(t') \tag{7}$$

At the inner boundary ($x' = 1$) we impose a continuity condition whereby the flow discharge through the end cross section of the channel gives rise in a 'quasi – static' fashion to variations of the mean free surface elevation h_2 in the basin:

$$UD|_{x=L} = \alpha \frac{S}{B}\frac{dh_2}{dt} \quad \Rightarrow \quad U'D'|_{x'=1} = \alpha \frac{S\omega a_0}{BD_0U_0}\frac{dh'_2}{dt'} \tag{8a,b}$$

where α is a time-dependent coefficient which accounts for the 'quasi – uniform' (rather than uniform) behavior of the free surface oscillations in the basin.

The value of α has been estimated by means of an analytical model and turns out to differ from one by a fairly small amount of the order of few per cents; hence in the following we will simply set α equal to one.

Using eqn. (8b) with $D'=1$ we can estimate U_0 and write:

$$U_0 = \alpha \frac{Sa_0\omega}{BD_0} \Rightarrow U' = \frac{dh'_2}{dt'}[1+\mathrm{O}(\varepsilon)] \tag{9a,b}$$

As far as the momentum equation (5) is concerned, since the quantity $\frac{\partial U'}{\partial x'}$ is small as discussed above, the Froude number F_0^2 ranges about 10^{-2} while the parameters δ_1 and δ_2 range about 10^{-1}, the convective term in (5) can be neglected. Using the eqn. (8) and noting that the quantity $\frac{\partial h'}{\partial x'}$ is only a function of time, we can integrate (3) to obtain:

$$h'_1 - h'_2 = \delta_1 \frac{d^2 h'_2}{dt'^2} + \delta_2 \frac{dh'_2}{dt'}\left|\frac{dh'_2}{dt'}\right| \tag{10}$$

The eqn. (10) is solved for the unknown function $h'_2(t)$ with the forcing imposed by the boundary condition (7), finally eqn. (9b) gives the velocity at the inlet.

Once the inlet hydrodynamics is determined, we can proceed to evaluate the exchange of sand through the inlets. In the approach employed herein we assume that the sediment supply equals the transport capacity during both the flood and the ebb phases. Furthermore we deliberately ignore the role of very fine sediments unable to settle during the tidal cycle, which may be transported as wash load and lost to the sea by the ebb currents. This material is made available by wind driven resuspension in salt marshes and/or bank collapse during storm events. Its role is quite important in the assessment of the sediment balance for Venice lagoon and will be discussed in the last section of the present paper.

The total sediment load is evaluated at each instant of time throughout the tidal cycle using Engelund and Hansen's [1967] predictor, which is known to perform fairly well when applied to tidal currents of Venice Lagoon.

Integrating in time the total load we are finally able to estimate the temporal evolution of the volume of sand exchanged through each inlet.

Below we perform two exercises: in the former we assume a simple harmonic forcing for the function $f(t')$ and investigate the general characteristics of the inlet hydrodynamics; in the latter we force the system with the actual tidal oscillations recorded through the years in the Adriatic sea close to Venice inlets in order to determine the sequence of hydrodynamic events which have determined the exchange of sediments through the inlets.

3. Inlet hydrodynamics and inlet equilibrium.

The approach described in the previous section (eqns 9b, 10) suggests that the solution for *U'* is a function of the dimensionless parameters δ_1 and δ_2 as well as of the harmonic content of the tidal forcing through the boundary condition (7). Hence, the maximum value attained by the (dimensional) speed U_{max} in a tidal inlet for a prescribed tidal forcing can be written in the general form:

$$U_{\max} = \phi(\delta_1, \delta_2)\frac{S\omega a_0}{BD_0} \tag{11}$$

where the function ϕ is obtained solving numerically the eqn. (10) for h'_2 with the forcing condition (7), and then differentiating the solution with respect to time (eqn 9b). Following this procedure and using the data reported in table 1, we have derived the latter function which is plotted in Fig. 2, for a pure M2 tidal oscillation with amplitude a_0=0.5 *m*. This choice is motivated by the fact that the latter value is typical of tidal events in the Adriatic Sea close to Venice inlets, as confirmed by Fig. 3a, which shows that the most frequent tidal amplitudes observed in the years 1994-1997 have ranged about 0.45 *m*. Furthermore, as regards Malamocco inlet, the temporal evolution of the average cross sectional speed obtained from the model described herein, fits very well (Fig. 3c) with the velocity measurement recorded during an event occurred in 1968, characterized by sea level oscillations which are well interpreted by a pure M2 with amplitude $a_0 = 0.5$m.

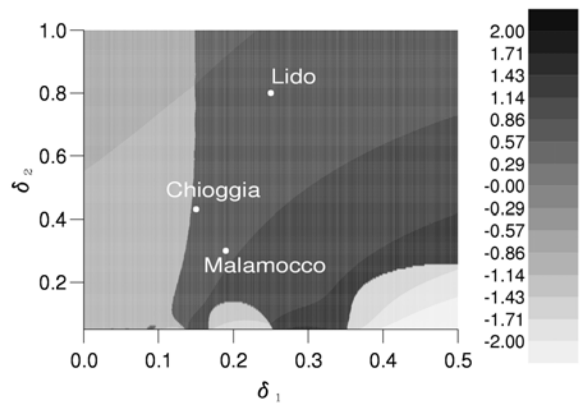

Fig. 2 – The function ϕ is plotted as a function of the dimensionless parameters δ_1 and δ_2 for a pure M2 forcing tide with amplitude a_0 =0.5m. Also plotted are the conditions corresponding to each of Venice inlets. Negative values (lighter colors) mean that the maximum of the velocity in cycle is reached during ebb phase (ebb dominated flow).

The dimensional relationship (11) between the maximum speed in a tidal cycle and the inlet depth for values of the remaining parameters appropriate to each of Venice inlets is plotted in Fig. 4.

A glance at Fig. 4 allows some general observations of relevance for the issue of inlet equilibrium.

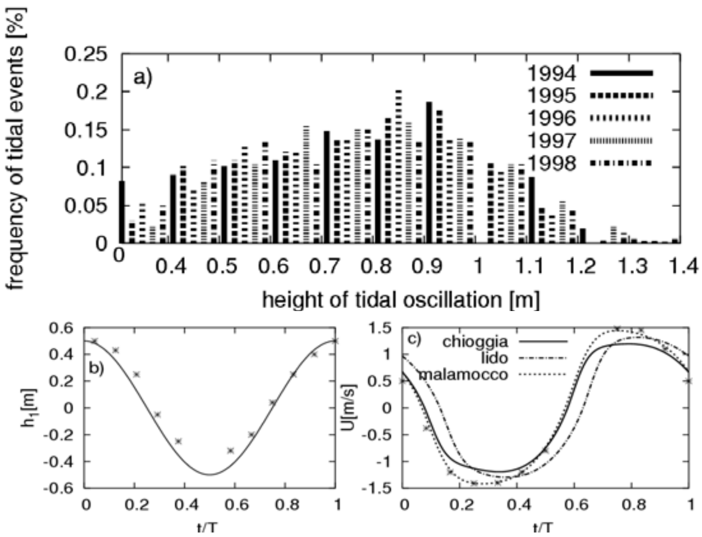

Fig. 3 – a)The frequency of the tidal events in the Adriatic sea near Venice inlets is plotted versus the height of the tidal oscillation, defined as the difference between the maximum and minimum free surface elevation in a tidal cycle.(b)The temporal evolution of the average cross sectional speed at each of Venice Inlets under a pure M2 forcing tide with amplitude a_0 =0.5m (c). For Malamocco inlet a comparison with measurement recorded in September 1968 is also reported [data from ‘Le correnti di marea nella Laguna di Venezia”, Padova 1979].

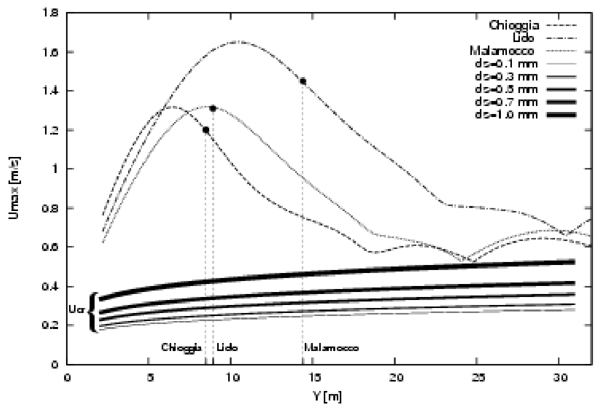

Fig. 4 – The maximum speed at each of Venice inlets is plotted versus the inlet depth for a pure M2 forcing tide with amplitude a_0 =0.5m. Also plotted is the critical speed for sediment motion for sizes in the range 0,1-1 mm.

Firstly, for the value of the tidal amplitude chosen to construct Fig.4, it appears that the maximum value of U_{max} is associated with a value of the inlet depth D_c smaller than the present value experienced by that inlet. This is an important observation. In fact, as pointed out by Marchi [1990], while the branch of the curve corresponding to values of $D>D_c$ describe *stable conditions*, the branch corresponding to $D<D_c$ describe *unstable conditions* (a reduction of the flow depth is there associated with a reduction of the flow speed, hence with a decreased sediment transport capacity which encourages deposition and a further reduction of the inlet depth).

Secondly, if we examine the *static equilibrium limit*, defined by the inability of tidal currents to transport (either in suspension or as bedload) the sediments available in the bed, the threshold equilibrium conditions are obtained by stipulating that the maximum current speed must not exceed the critical speed for sediment motion defined by Shields criterion. The latter conditions are plotted in Fig. 4 for a realistic range of sediment sizes, suggesting that the present configuration of each of the Venice inlets is quite far from static equilibrium.

To complete our understanding of the inlet hydrodynamics, let us touch the issue of flood and ebb dominance of the flow field. Fig. 3c shows the temporal dependence of the average cross-sectional speed at each inlet under a pure M_2 tidal forcing: it appears that, under an M_2 forcing, flow at all the inlets is weakly flood dominated. Results are confirmed by Fig.2, which suggests that the character of the flow turns out to depend on the values attained by the relevant dimensionless parameters. The flood-ebb dominant character of the flow, plays an important role in the process of sand transport through the inlet, but, as discussed in the next section, it turns out to be strongly dependent on the harmonic content of the tidal forcing, a feature which typically varies throughout the year.

4. An estimate of an upper bound for the yearly volume of sand lost from Venice lagoon.

The second exercise we performed was to assume for the forcing function *f* (eqn 7) the sequence of tidal oscillations recorded in the last few years by the CNR gauge station located in the sea region adjacent to Venice lagoon, and to evaluate the sediment discharge following the approach discussed in sect. 2.

The temporal evolution of the net volume of sand exchanged through each inlet in 1994 is plotted in Fig. 5a, the one occurred in 1995-1998, though not reported, has a very similar behavior. In particular, in 1994 and 1995 the loss of sediment is almost equally distributed through the three inlets, while in 1996 1997 and 1998 the loss of sand was slightly greater at Lido. Fig. 5b reports a comparison between the yearly loss of sediments of Venice lagoon in the years from 1994 to 1998.

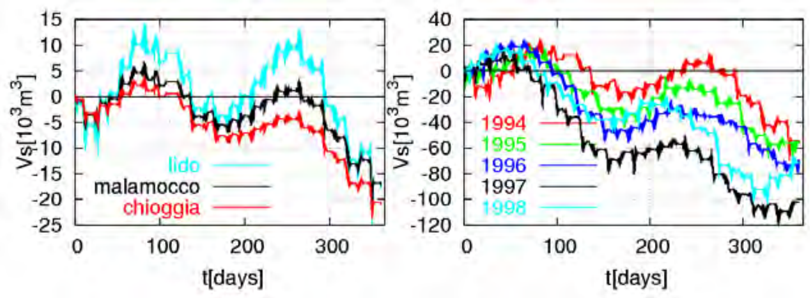

Fig. 5 – (a) Temporal evolution of the net volume of sand exchanged through each of Venice inlets in 1994,. (b) Comparison between the temporal evolution of the net volume of sand exchanged through all Venice inlets in the years from 1994 to 1998.

Note that the latter values have roughly the same order of magnitude ranging around 80000 m^3 and display a maximum in 1997, an year characterized by the maximum number of extreme events (Fig. 3a).

The relevant result is, however, that the yearly loss of sand is more than an order of magnitude smaller than the overall loss of sediments usually claimed. This suggests that the major contribution to the yearly sediment loss from Venice lagoon is not associated with an exchange of the sand available in the bed close to the inlets, amenable to transport either as bedload or as suspended load, but rather with the very fine material resuspended by wind in the shoals which may be fine enough to be transported by tidal currents as wash load.

A second observation clearly emerges from Fig. 5: the net volume of sand exchanged at the inlets displays a *repetitive seasonal dependence*, being invariably positive (entering the lagoon) only in winter and summer.

In order to clarify the mechanism underlying the above behavior we have correlated the net exchange of sediments with the characteristics of the tide. In Fig. 6 the net volume of sand exchanged through Chioggia inlet in each of the tidal cycles examined is plotted versus the maximum tidal amplitude experienced during that cycle. Data are also grouped according to the phase φ of the diurnal components of the tide relative to the semi-diurnal one.

Results suggest that the intensity of the net exchange of sand increases with the amplitude of the tidal oscillation. Moreover, in the absence of further components of the tide, a fairly clear correlation emerges between the sign of the net sand flux and the phase difference φ :if $0< \varphi < \pi$ ($\pi < \varphi < 2\pi$) the net volume of sediment exchanged through the inlets is positive (negative), and its modulus reaches a maximum when φ ranges about $\pi/2$ ($3\pi/2$). The presence of further harmonics in the forcing spectrum makes the picture less straightforward and justifies the few exceptions emerging in the correlation presented in Fig. 6.

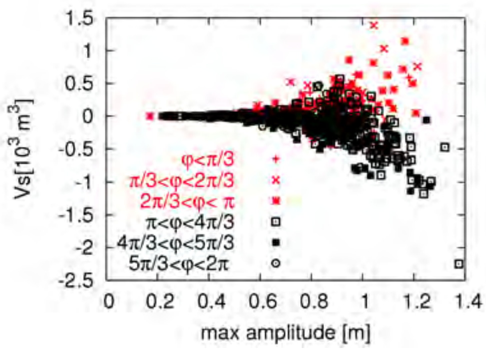

Fig. 6 – The net volume of sand exchanged in a tidal cycle is plotted versus the maximum amplitude experienced in that cycle. Data are grouped according with the phase difference between the diurnal and semi-diurnal components of the forcing tide.

Conclusions.

The present work allows us to reach some preliminary conclusions. Firstly, if we restrict our attention to the fine sands available in the near inlet region, an upper bound for the net yearly loss from Venice lagoon ranges about $10^5 m^3$. Such an estimate can be refined by including the excess supply of sediment driven to the inlet by the nearly irrotational flood currents overloaded in the far field by storm events. We are presently making some progress in this direction. However, the present estimates allow us to infer that modifying the inlet shape such to reduce the degree of ebb- flood asymmetry may increase the supply of fine sands to the lagoon region close to the inlet but will not be able to invert the present tendency of the lagoon to morphodynamic degradation.

A second preliminary conclusion arising from the present computations is that, if the lagoon actually loses an amount of sediments much larger than predicted herein, this may only occur provided the ebb currents are overloaded above transport capacity by the very fine sediments resuspended by the wind in the inner lagoon and unable to settle within the channel network.

In fact, particles sizes ranging about *20-30* μm are characterized by settling speeds smaller than *1 mm/s*. Hence, they need many hours to deposit and may well reach the inlet to be lost into the sea by the ebb currents.

Furthermore, the water volume yearly exchanged by the lagoon with the sea is readily estimated to range around 10^{11} m^3/year, hence volumetric concentrations of very fine sediments of the order of 10^{-5} are sufficient to drive a yearly loss of such sediments of the order of 10^6 m^3.

These arguments will have to be supported by detailed measurements of sediment concentration at the inlets and further theoretical investigations able to couple the availability of very fine sediments in the inner lagoon with the action of wind on shoals and salt marshes. Developments are in progress.

References.

Engelund, F. and Hansen, E.,1967. *A monograph on Sediment Transport in Alluvial Streams*, Danish Tech. Press, Copenhagen

Marchi, E., 1990. Sulla stabilità delle bocche lagunari a marea, *Rend. Fis. Acc. Lincei*, 9, pp. 137-150

Ministero dei Lavori Pubblici, 1979. Le correnti di marea nella Laguna di Venezia. Cura dell'Istituto d'Idraulica dell'Università di Padova, Padova

ON THE MIGRATION OF TIDAL BARS

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Riassunto.

Si propone un modello mediato sulla profondità per la formazione di barre libere nei canali mareali. Obiettivo del lavoro è l'individuazione del meccanismo che controlla la migrazione di tali forme di fondo. Il trasporto in sospensione viene modellato attraverso la formulazione di Bolla Pittaluga e Seminara [2003] per moti lentamente variabili. L'approccio bidimensionale si rivela appropriato, fornendo curve di stabilità marginale congruenti con quelle derivate da modelli tridimensionali [Seminara e Tubino, 2001]. In accordo con quanto emerge dall'analisi dei suddetti autori, in presenza di un'onda di marea simmetrica le barre alternate si rivelano forme di fondo mediamente stazionarie, ossia caratterizzate da migrazione netta nulla nell'arco di un ciclo di marea. Il modello qui proposto evidenzia come la presenza di oscillazioni di ampiezza finita o di frequenze ultra-armoniche nel moto base induca una migrazione netta delle forme di fondo. La direzione del processo di migrazione è controllata dalla fase delle armoniche superiori rispetto alla fondamentale.

Abstract.

We derive a depth-averaged model for the formation of free bars in tidal channels. The main aim of the analysis is to investigate the mechanism whereby tidal bars do exhibit a net migration over a tidal cycle. Suspended sediment flux is modeled by means of the analytical relationship derived by Bolla Pittaluga and Seminara [2002] for slowly varying flows. The results of the model proposed herein show a fairly satisfactory agreement with those of the three-dimensional model of Seminara and Tubino [2001]. Symmetrical tidal waves give rise to bed forms characterized by no net migration over a tidal cycle. The role of overtides and finite amplitude depth oscillations is investigated, showing that a flood or ebb asymmetry of the basic flow gives rise to a net migration of bars. The direction of the migration process is found to depend on the phase lags between the overtides and the dominant harmonic.

1. Introduction.

The bed topography of tidal channels is characterized by the presence of a wide variety of bedforms at scales falling in the range of a few centimetres to some kilometres. Tidal bars are sediment waves with wavelengths scaling with channel width, arising from a mechanism of instability of the interface between the erodible bed and the fluid phase [Seminara and Tubino, 2001]. Darlymple and Rhodes [1995] classified estuarine bars into 'repetitive barforms' (alternate, point and braid bars), 'elongate tidal bars' (typically observed at locations where there is strong, rectilinear, tidal flow, i.e. at the outer part of macrotidal estuaries but also at the mouth of estuaries with smaller tidal ranges), ‘delta-like bodies’ (located at points of flow expansion, typically at the end of channels).

Our attention is focused on the former class of estuarine bars, in particular on the formation of alternate free bars in straight channels. The problem of formation and evolution of such features has been widely investigated in the fluvial context [Colombini *et al.*, 1987; Schielen *et al.*, 1993; Repetto *et al.*, 1999; Federici and Seminara, 2003] being considered as a key factor controlling several important fluvial processes, like river meandering and braiding. Recently, Seminara and Tubino [2001] tackled the problem of formation of tidal bars by means of a fully three-dimensional model showing that, unlike river bars, tidal free bars are steady features: in the absence of a mean residual current, they migrate alternatively forward and backward in a symmetric fashion, displaying a vanishing net migration in a tidal cycle.

In order to evaluate the role of overtides and finite amplitude depth oscillations on the net migration of bars, we derive a two-dimensional model for bar formation. The three-dimensional nature of suspended load is accounted for by means of the approach proposed by Bolla Pittaluga and Seminara [2003], suitable to slowly varying contexts.

The present analysis is shown to capture the main mechanism responsible for the formation of bars in tidal channels, encouraging the use of depth averaged models to investigate more complex problems, like the non linear development of tidal bars.

Results show that a flood or ebb asymmetry of the basic flow, induced either by the phase lags between the overtides and the dominant harmonic or by finite amplitude effects of tidal oscillations, gives rise to a net migration of bars which falls in the range of a few meters per day.

The theoretical model is formulated in the next chapter. In chapter 3 we summarize the linear stability analysis of the basic tidal solution with respect to perturbations of the bar type. Results concerning the migration of bars are reported in chapter 4 which is followd by some concluding remarks.

2. Problem formulation.

We consider an infinitely long straight channel with rectangular cross-section of constant width *2B*, connected at one end with a tidal sea. We assume the channel banks to be non-erodible while the bed is cohesionless with uniform grain size, the diameter d_s^* being suspended by tidal currents throughout most of the tidal cycle. Bar length being typically of the order of a few channel widths, we describe the problem of their formation by means of the shallow water equations coupled with the bottom evolution equation. The governing system then reads:

$$\begin{gathered}
UU_{,x} + VU_{,y} + H_{,x} + \beta \frac{\tau_x}{D} = 0 \\
UV_{,x} + VV_{,y} + H_{,y} + \beta \frac{\tau_y}{D} = 0 \\
(UD)_{,x} + (VD)_{,y} = 0 \\
\left(F_0^{\,2} H - D\right)_{,t} + Q_0\left(Q^b_{x,x} + Q^b_{y,y}\right) + \frac{1}{(1-p)\sigma_0}\left(Q^s_{x,x} + Q^s_{y,y}\right) = 0
\end{gathered} \qquad \text{(1a-d)}$$

In Eqs. (1a) – (1d) x and y denote the longitudinal and lateral cartesian coordinates respectively, with x aligned with the channel axis; t is time; U and V are longitudinal and lateral components of the depth averaged velocity; H and D represent free surface elevation and flow depth respectively, while τ_x and τ_y are the longitudinal and lateral components of the bottom stress; $\boldsymbol{Q}^b$ and $\boldsymbol{Q}^s$ are the depth averaged bed load flux and suspended flux respectively, their longitudinal and lateral components being denoted by the subscripts x and y respectively.

Note that the relevant dimensional quantities (denoted by a superscript star) have been made dimensionless employing the following scales:

$$\left(U^*,V^*\right)=U_0^{\,*}\left(U,V\right)$$

$$\left(H^*,D^*\right)=D_0^{\,*}\left(F_0^{\,2}H,D\right)$$

$$\boldsymbol{\tau}^*=\rho U_0^{\,*2}\boldsymbol{\tau} \tag{2 a-g}$$

$$\left(x^*,y^*\right)=B\left(x,y\right),\qquad t=\omega\, t^*$$

$$\mathbf{Q}^b=\mathbf{Q}^{*b}/\sqrt{\left(s-1\right)gd_s^{\,*3}},\quad \mathbf{Q}^s=\mathbf{Q}^{*s}/\left(U_0^{\,*}D_0^{\,*}\right)$$

where ω is the tidal wave angular frequency, U_0^* the tidal peak velocity in the channel reach under investigation, D_0^* the mean water depth, F_0^2 the square of Froude number $F_0^2 = (U_0^{*2}/gD_0^*)$, s is the relative density and g is gravity. In the dimensionless problem (1a) – (1d) two fundamental parameters arise, namely the aspect ratio β and the ratio between the hydrodynamic and morphodynamic time scales Q_0 which read:

$$\beta=B/D_0^{\,*}$$

$$Q_0=\frac{\sqrt{\left(s-1\right)gd_s^{\,*3}}}{\left(1-p\right)\omega D_0^{\,*}B} \tag{3 a, b}$$

where p is porosity of the granular medium. Note that in Eqs. (1a) - (1c) we have neglected terms involving the temporal derivatives of U, V, D since they are multiplied by the small parameter σ_0, defined in the form:

$$\sigma_0=\omega B/U_0^{\,*} \tag{4}$$

which represents the ratio between the time required for the flow to travel along a reach of length B and the tidal period. With typical values of the channel width B of the order of a few tens of meters and U_0^* about $1\ m\ s^{-1}$, the value of σ_0 for a semidiurnal tide ($\omega = 1.4\ 10^{-4}\ m\ s^{-1}$) is found to fall in the range 10^{-3}-10^{-2} , thus suggesting that we can safely neglect the local inertia effects.

The governing equations (1a) - (1d) must be associated with closure relationships for bottom stress and sediment flux. The former can be written in the form:

$$\left(\tau_x,\tau_y\right)=\rho\, C_f\left(U,V\right)\sqrt{U^2+V^2} \tag{5}$$

where the friction coefficient C_f follows the classical logarithmic form for plane bed:

$$C_f = \left[6 + 2.5\ln\left(\frac{D}{2.5 d_s}\right)\right]^{-2} \tag{6}$$

Here d_s is the relative roughness d_s^*/D_0^*, having assumed the value $2.5\ d_s^*$ for the absolute roughness.

The boundary conditions to be associated with the differential system (1a) – (1d) impose vanishing fluid and sediment fluxes trough the side walls, hence:

$$V = Q_y^{b,s} = 0 \qquad (y = \pm 1) \tag{7}$$

To account for the effect of lateral bed slope on particle trajectories, we write the bed load flux in the form [Seminara, 1998]:

$$\mathbf{Q}^b = \Phi\left[\frac{\boldsymbol{\tau}}{|\boldsymbol{\tau}|} - \frac{r}{\beta\,\vartheta^{0.5}}\left(F_0^2 H - D\right)_{,y}\mathbf{j}\right] \tag{8}$$

where r is an empirical parameter varying over the range of *0.5-0.6* (*0.56*) [according to Talmon *et al.*, 1995], $\boldsymbol{j}$ is the unit vector in the y direction and ϑ is the Shields parameter which depends on the friction velocity u_* according to the relationship:

$$\vartheta = \frac{u_*^2}{(s-1)gd_s^*} = U_0^{*2}\,\frac{C_f\sqrt{U^2+V^2}}{(s-1)gd_s^*} \tag{9}$$

Bed load intensity, indicated by Φ in eq. (8), is evaluated by means of the classical Meyer-Peter and Müller [1948] formula:

$$\Phi = 8(\vartheta - 0.047)^{3/2} \tag{10}$$

We evaluate the vector $\boldsymbol{Q}^s$ following the formulation of Bolla Pittaluga and Seminara [2003] who developed a depth-averaged model for the transport of suspended sediment in slowly varying flows, based on a rational perturbation method. It's worth noting that their approach does retain in a formally correct fashion all the relevant information arising from the three-dimensional nature of the convection-diffusion equation. The perturbation approach relies on the assumption that advective and unsteady effects are smaller than gravitational settling and turbulent diffusion. This assumption, written in a mathematical form, reads:

$$\frac{U_0^*}{W_s^*}\frac{D_0^*}{L_0^*} << 1 \tag{11}$$

where W_s^* is the particle fall velocity and L_0^* is a longitudinal scale for spatial variations of the flow field, in our case the bar wavelength. Note that the assumption (11) is satisfied for large enough values of the bar wavelength. In order to avoid an uncomfortable dependence of the small parameter on a variable quantity, namely the bar wavenumber, we define:

$$\delta = \frac{U_0^*}{W_s^*}\frac{1}{\beta} \tag{12}$$

having chosen as a relevant spatial scale the typical scale of classical bar theories, i.e. the channel width. We formally assume that δ is a small parameter, recalling that this assumption is justified for small enough values of bar wavenumber $\lambda\left(=2\pi B/L_0^*\right)$.

We then write the suspended sediment flux by means of the analytical relationship derived by Bolla Pittaluga and Seminara [2003]:

$$\left(Q_x^s, Q_y^s\right) = D(U,V)\psi \tag{13}$$

where ψ is expressed as follows:

$$\begin{gathered}\psi = \int_{\zeta_R}^{1} C\,F(\zeta)\,d\zeta = \int_{\zeta_R}^{1}\left[C_0 + \delta\,C_1 + O\,(\delta^2)\right]F(\zeta)\,d\zeta = \\ \psi_0 + \delta\psi_1 + O(\delta^2)\end{gathered} \tag{14}$$

In (14) C is the concentration of suspended sediment, ζ is a vertical coordinate defined such that the cross section is mapped into a rectangle, $F(\zeta)$ is the logarithmic distribution of the longitudinal velocity, while ζ_R is the dimensionless reference height where the concentration takes its equilibrium value C_e, calculated by means of Van Rijn's [1984] relationship.

Finally ψ_0 and ψ_1 are functions of the perturbations of the flow field.

3. The formation of tidal bars.

At the bar scale the unperturbed flow at the leading order consists of a non stationary uniform flow. We now investigate the stability of the basic flow with respect to perturbations U_1, V_1, H_1, D_1 of infinitesimal amplitude ξ. Since we employ the formulation of Bolla Pittaluga and Seminara [2003] for the concentration field, it is appropriate to expand the perturbed flow configuration in the form:

$$(U,V,H,D) = (U_0(t),0,H_0(t),D_0(t)) + \xi\left[(U_{10},V_{10},H_{10},D_{10}) + \delta(U_{11},V_{11},H_{11},D_{11})\right] \tag{15}$$

Furthermore:

$$\begin{gathered}\psi_0 = \psi_{00} + \xi\left[\psi_{010} + \delta\psi_{011}\right] \\ \psi_1 = 0 + \xi\psi_{110} + O(\xi\delta)\end{gathered} \tag{16 a, b}$$

We then perform a normal mode analysis of the perturbations and write:

$$(U_{1k},V_{1k},H_{1k},D_{1k}) = (u_{1k}(t)S_m, v_{1k}(t)C_m, h_{1k}(t)S_m, d_{1k}(t)S_m)E + c.c., \quad (k=\ 0,1) \tag{17}$$

where m denotes the transverse Fourier mode, *c.c.* denotes the complex conjugate and S_m, C_m, E read:

$$\begin{gathered}S_m = \cos m\frac{\pi}{2}y, \quad C_m = \sin m\frac{\pi}{2}y, \qquad \text{(m even)} \\ S_m = \sin m\frac{\pi}{2}y, \quad C_m = \cos m\frac{\pi}{2}y, \qquad \text{(m odd)} \\ E = \exp(i\lambda x)\end{gathered} \tag{18 a-e}$$

The lateral structure of free bars is identified by m = 1. On substituting from (15)-(18) into the governing system (1) and performing the linearization, we find the following differential problem at leading and first order:

$\boxed{O\left(\xi\delta^0\right)}$

$$L\begin{pmatrix} u_{10} \\ v_{10} \\ h_{10} \\ d_{10} \end{pmatrix} = 0, \tag{19}$$

$\boxed{O\left(\xi\delta\right)}$

$$L\begin{pmatrix} u_{11} \\ v_{11} \\ h_{11} \\ d_{11} \end{pmatrix} = f_{10}, \tag{20}$$

where L is a differential operator depending on the basic flow and f_{10} is the forcing term dependent on the solution at the previous order.

Marginal stability conditions, i.e. the values of the parameters β and λ for which perturbations do not experience a net growth or decay within a tidal cycle T, are then determined by setting:

$$\ln\left| d_1(T) \right| = 0 \tag{21}$$

where $| d_1 |$ is the modulus of the complex variable.

$$d_1 = d_{10} + \delta\, d_{11} \; . \tag{22}$$

In Fig. 1 we report the marginal stability curve at the leading order of approximation and the one corrected to order $O(\xi\delta)$. Note that the higher order corrections play an increasing role as bars shorten. In fact as the bar wavenumber λ increases, the concentration field diverges from the equilibrium solution. The $O(\xi\delta)$ marginal curve is consistent with the corresponding one obtained by Seminara and Tubino [2001] by means of a fully three-dimensional approach.

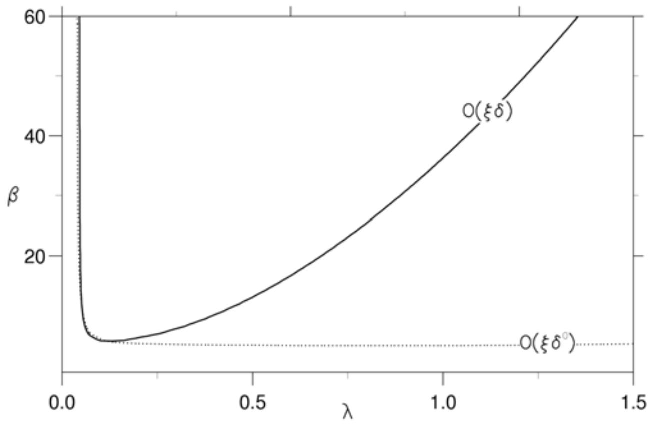

Fig. 1 – Marginal stability curves for tidal free bars at the leading order of approximation $O(\xi\delta^0)$ and at the first order $O(\xi\delta)$. Values of the relevant parameters are: R_p = 4, d_s = 2 10^{-5}, ϑ_0 = 0.75.

Fig. 2 shows the effect of the Shields stress, and therefore of suspended load, on the marginal conditions. In agreement with Seminara and Tubino's findings, the present model predicts a destabilizing role of suspended load at low wavenumbers, displayed by the decrease of the marginal value of β associated with increasing Shields stress; high wavenumbers show an opposite picture, with an increasing stabilizing contribution associated with increasing suspended load. Hence, we can safely conclude that the two dimensional model proposed here is appropriate to investigations of tidal bar formation.

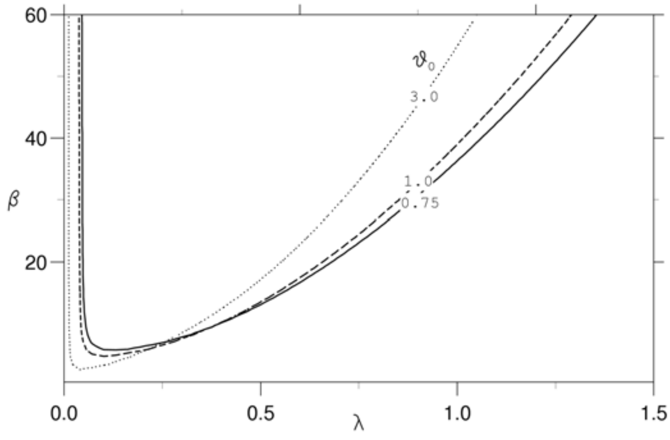

Fig. 2 – Marginal stability curves for different values of the peak Shields stress ϑ_0 *(R_p = 4, d_s = 2 10[-5]).*

4. The effect of overtides and finite amplitude depth oscillations on bar migration.

The main purpose of this work is to evaluate the role of overtides and finite amplitude tidal waves on the migration of free bars. Hence we define the net migration over one period as:

$$\Delta x = -\frac{\vartheta_{d_1}}{\lambda} \, , \tag{23}$$

ϑ_{d_1} being the argument of d_1. In agreement with the analysis of Seminara and Tubino [2001], a basic flow consisting of a purely semidiurnal tide with constant depth, gives rise to bed forms characterized by no net migration over a tidal cycle.

4.1 $O(\xi\delta^0)$.

In order to give a simple physical interpretation of bars migration, we follow the lead of Seminara and Tubino [1989] and write:

$$\begin{aligned}\left(u_{10}, v_{10}, h_{10}, d_{10}, q^b_{x10}, q^b_{y10}, q^s_{x10}, q^s_{y10}\right) = \\ \left(|u_{10}|, |v_{10}|, |h_{10}|, |d_{10}|, |q^b_{x10}|, |q^b_{y10}|, |q^s_{x10}|, |q^s_{y10}|\right) \\ \exp\left[-i\left(\delta_1, \delta_2, \delta_3, \delta_4, \delta_5, \delta_6, \delta_7, \delta_8\right)\right]\end{aligned} \tag{24}$$

where $\delta_i\ (i=1,8)$ denotes the phase lag of the corresponding quantity relative to bottom elevation $(F_0^2 h_{10} - d_{10})$. For example the longitudinal velocity perturbation U_{10} can be expressed in the form:

$$U_{10} = |u_{10}| \exp\{i[\lambda(x-ct) - \delta_1]\} \exp(\Omega t) \sin(\pi/2y) + c.c. \tag{25}$$

On substituting from (24) and (25) into the sediment continuity equation, it turns out that the instantaneous bar speed c can readily be written as a sum of four distinct contributions:

$$c = P_1 + P_2 + P_3 + P_4\ , \tag{26}$$

with

$$P_1 = Q_0 \frac{|q^b_{x10}|}{|\eta_{10}|} \cos\delta_5,\ \ P_2 = Q_0 \frac{\pi}{2\lambda} \frac{|q^b_{y10}|}{|\eta_{10}|} \sin\delta_6,$$

$$P_3 = \frac{1}{(1-p)\sigma_0} \frac{|q^s_{x10}|}{|\eta_{10}|} \cos\delta_7, \tag{27}$$

$$P_4 = \frac{1}{(1-p)\sigma_0} \frac{\pi}{2\lambda} \frac{|q^s_{y10}|}{|\eta_{10}|} \sin\delta_8$$

Hence the tidal bars migration is related to the amplitudes and phase lags of bed load and suspended load fluxes.

We proceed now to investigate the case of sea oscillations consisting of a combination of a lunar semidiurnal tide M_2, a solar-lunar diurnal tide K_1 and an overtide M_4, a situation that is typically encountered in Venice Lagoon.

$$U_0(t) = \cos t + \varepsilon_{M4} \cos[2(t-\varphi_{M4})] + \varepsilon_{K1} \cos\left[\frac{1}{2}(t-\varphi_{K1})\right], \tag{28}$$

In Fig. 3 it is shown that a flood or ebb asymmetry, namely the fact that the flood (/ebb) peak velocity is higher than its ebb (/flood) value, affects the amplitude of perturbations, giving rise to an asymmetric forward-backward movement of bed forms throughout the tidal cycle. Hence, under these conditions, tidal bars do exhibit a net migration. Note that no net contribution to bar migration arises from the phase lags of bottom profile with respect to the fluxes of bed load and suspended load perturbations, since they show a symmetrical pattern throughout the tidal cycle.

Fig. 4 shows the role of each quantity affecting bar migration. The tidal wave investigated herein gives rise to a dimensionless net migration $\Delta x \approx 0.2$. The dimensional value is obtained multiplying by the length scale B, hence, recalling the values of the relevant parameters, we find:

$$\Delta\mathbf{x}^* = B\,\Delta\mathbf{x} \cong 2\,m\ , \tag{29}$$

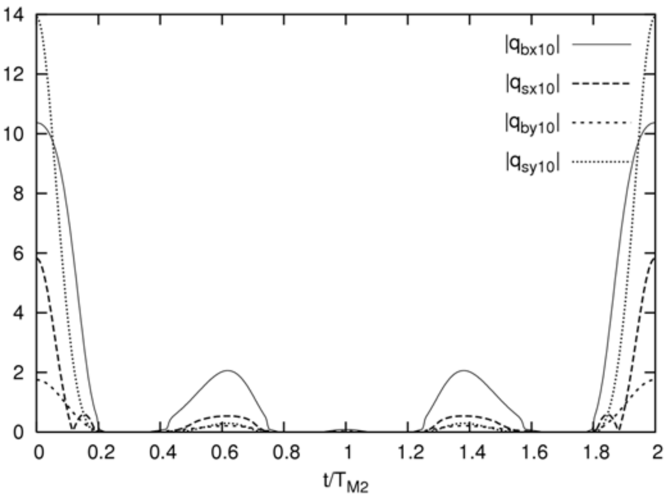

Fig. 3 – The amplitudes of bed load and suspended load fluxes perturbations are plotted as functions of time. In order to compare the magnitude of bed load and suspended load the latter has been multiplied by $\frac{\sqrt{(s-1)gd_s^{*3}}}{U_0^* D_0^*}$. ($\lambda$ = 0.55, β = 10, R_p = 4, ϑ_0 = 0.75, d_s =10^{-4}, ε_{M4} = 0.2, ε_{K1} = 0.6, φ_{M4} = φ_{K1} = 0).

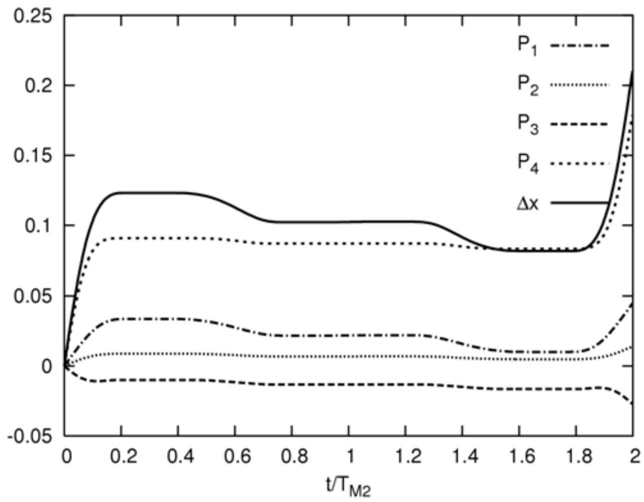

Fig. 4 – The terms P_1, P_2, P_3, and P_4 are plotted as functions of time. Values of the relevant parameters are the same as in Figure 3.

In order to evaluate the role of finite amplitude tidal waves, an oscillating contribution has been added to the dominant constant depth term. We then examine the combined effect of overtides and depth oscillations expressed in the form:

$$D_0(t) = 1 + \varepsilon_D \cos(t - \varphi_D). \qquad (30)$$

Fig. 5 shows that bar migration is further increased by finite amplitude oscillations.

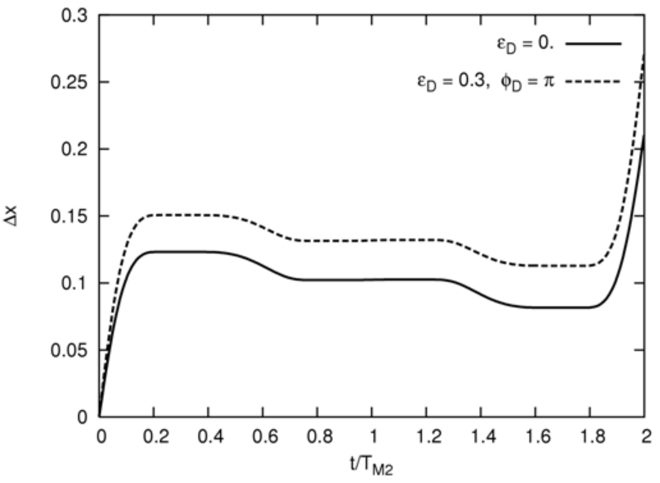

Fig. 5 – The dimensionless migration is plotted as a function of time for both the cases of constant and oscillating depth. Values of the relevant parameters are the same as in Fig. 3.

4.2 $O(\xi\delta)$.

We now proceed to evaluate bar migration at the following order of approximation and investigate the role of suspended load. For a given value of the β parameter, we find decreasing bar wavenumbers λ_{max} characterized by the maximum growth rate as the peak Shields stress increases. As one may expect, bar migration increases significantly as the peak Shields stress, and therefore suspended load, increases.

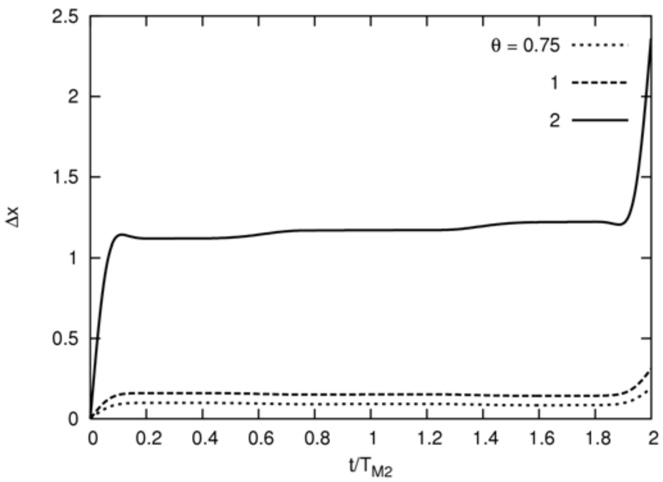

Fig. 6 – The migration of bars characterized by wavenumber λ_{max} is plotted as a function of time for different values of the peak Shields stress. ($\beta = 10$, $R_p = 4$, $\vartheta_0 = 0.75$, $d_s = 10^{-4}$, $\varepsilon_{M4} = 0.2$, $\varepsilon_{K1} = 0.6$, $\varepsilon_D = 0$, $\varphi_{M4} = \varphi_{K1} = \varphi_D = 0$).

Conclusions.

Finally, let us briefly summarize our achievements. Firstly we have shown that the problem of bar formation can be formulated in the context of a depth averaged model employing Bolla Pittaluga and Seminara [2003] analytical relationship for suspended sediment flux: the marginal stability curves predicted by our analysis are consistent with the ones derived by the three-dimensional model of Seminara and Tubino [2001]. The choice of a 2-D model has allowed us to investigate with a relatively small computational effort the role of overtides and finite amplitude depth oscillation on bar migration. We have shown that a flood or ebb asymmetry gives rise to a net migration of bars which can be positive or negative according to the phase lags between the overtides and the dominant harmonic. Under the examined conditions bar migration turns out to be of the order of meters per day.

References.

Bolla Pittaluga M. and Seminara G., 2003. Depth-integrated modeling of suspended sediment transport. *Water Resour. Res.*, 39 (5), 1137

Colombini M., Seminara G. and Tubino M., 1987. Finite-Amplitude Alternate Bars. *J. Fluid Mech.*, 181, 213-232

Federici B. and Seminara G., 2003. On the convective nature of bar instability. *J. Fluid. Mech.*, 487, 125-145

Darlymple R.W. and Rhodes R.M., 1995. Estuarine dunes and bars. In *Geomorphology and Sedimentology of Estuaries*, Development in Sedimentology, 53, 359-422

Meyer Peter E. and Müller R., 1948. Formulas of bedload transport. *III Conf. Of Internat. Ass. Of Hydraul. Res., Stockholm, Sweden*

Repetto R., Tubino M. and Zolezzi G., 1999. Free bars in rivers *J. Hydr. Res.*, 37(6): 759-775

Schielen R., Doelman A. and de Swart H.E., 1993. On the nonlinear dynamics free bars in straight channels. *J. of Fluid Mech.*, 252, 325-356

Seminara G., 1998. Stability and morphodynamics. XIII Congresso Nazionale AIMETA, Siena, 29 sett. - 3 ott. 1997, *Meccanica*, 33, 59-99

Seminara G. and Tubino M., 2001. Sand bars in tidal channels. Part 1. Free Bars. *J. Fluid Mech.*, 440, 49-74

Seminara G. and Tubino M. ,1989. Alternate bars and meandering: free, forced a mixed interactions. River Meandering, edited by S.Ikeda and G.Parker, *Water Res. Monogr.*, 12, AGU, Washington, D.C., 267-320

Talmon A.M., Struiksma N. and Van Mierlo M.C.L.M., 1995. Laboratory measurements of the sediment transport on transverse alluvial-bed slopes. *J. Hydraul. Res.*, 33, 519-534

Van Rijn L.C., 1984. Sediment Transport, Part II: Suspended Load Transport, *J. Hydraul. Engng. ASCE*, 110, 1613-1641

AREA 4
DATA MANAGEMENT AND DISTRIBUTION

RESEARCH LINE 4.1
Distributed information system

MANAGING SCIENTIFIC KNOWLEDGE ON THE VENICE LAGOON

PIERPAOLO CAMPOSTRINI, CATERINA DABALÀ, STEFANIA DE ZORZI, ENRICO RINALDI

CORILA

Riassunto.

La raccolta, gestione e messa a disposizione dei dati e delle informazioni rese disponibili dalle ricerche condotte dal CORILA è tra gli obiettivi istituzionali del CORILA stesso.

A questo scopo sono state avviate, nel corso del Primo Programma di Ricerca, una serie di attività che hanno consentito di realizzare un'infrastruttura per la conservazione e l'archiviazione dei dati e delle ricerche prodotte.

Il progetto "Rivela", iniziato nel 2001, ha riguardato diversi aspetti organizzativi legati sia alla parte più infrastrutturale (reti, personal computer, sistemi di pubblicazione delle informazioni) ma anche di tipo organizzativo (gestione di flussi e procedure, nonché organizzazione della conoscenza).

L'idea progettuale è stata realizzata utilizzando un approccio multi obiettivo, nel quale sono stati tenuti in considerazione sia obiettivi di breve termine, che di più lungo respiro.

Abstract.

One of CORILAs' main institutional goals is to gather, manage and disseminate data and information relating to CORILA managed research projects.

In reference to this objective, an infrastructure, for conserving and storing data and research results, was developed during the First Research Program.

The "Rivela" Project, initiated in 2001, addressed several aspects regarding the infrastructure (network, personal computer, information publishing systems) as well as the organisation (process and procedure management, knowledge management).

The project was conducted on the basis of short and long term objectives.

1. Information management.

The First Research Program was divided into three principal theme areas: Architecture, Economics and Environment; as well as a research area dedicated to gathering and managing data and information generated in the three areas.

The information, data and results produced in these research areas are quite heterogeneous. The list below provides a sampling of the information types considered:

- field data,
- archive research data,
- software classification,

- mathematical model,
- statistical analysis,
- environmental model.

Each of these information categories may be stored in different file formats and data types, all of which are available on the retail market.

The data and information may be structured or randomly presented, saved in a single worksheet or managed in a database.

The information gathered may be an image file, a graphic format, an article in text format or a visual presentation.

In some cases it is possible to assist researchers in using tools similar to those already available, in other situations the work presented is the result of years of research and the information is managed with tools developed by third parties.

The information must as well be made available to a diverse user community. The researchers engaged in CORILA Research Line projects come from different universities, different scientific fields, different cultural backgrounds and have had different exposure to computer based tools.

In the first work plan, the project mission was to concentrate all the information in a single, unique database that would contain one data model.

The variability of data and information types gathered made it necessary to analyse the methods and tools most frequently used by researchers in different scientific fields.

The nature of the information and the method by which the “data model” describes the reality may not always be represented in a single data model which serves to develop the data base structure.

Attention was thus focused primarily on methods for gathering information and data and the respective characteristics, rather than on the single data structure.

During the project importance was placed on collecting information made available by researchers as well as providing options to view information transversally, using different explosion levels and aggregation criteria.

The plan to disseminate only data, and not all of the correlated information, seemed limited. The intent was not to develop “metadata” models or to refer to “ontology” concepts, that is to describe the significance of every single data element.

As the project continued it became clear that numeric data, considered so important by the scientific community, is of partial importance if not enriched with a more complete view, such as the history of the project from which the data was collected, the collection and analysis methods as well as eventual errors encountered.

The final work plan was thus focused on making available information in an integrated manner, starting from single data or from general information that characterizes the data.

The development of a Portal (referred to as “**Rivela Portal**”) designed to make available data and research findings seemed the logical solution.

2. Multidisciplinary Context.

In general the 21st century has been considered the Information Century, with emphasis placed on the exchange of information through advanced communication systems.

As stated by Professor Ernesto Damiani: “modern education encourages specialization. The general knowledge historian or physicist has been replaced by individuals with specific knowledge (ex.: Renaissance Historian or Astrophysicist). However, intellectual progress stems from “lateral” interconnection between disciplines more so than through “vertical” research. In conclusion:

Knowledge = organised information”[1]

Research projects within CORILA have undoubtedly the task of promoting knowledge dissemination. The organisation of data and information produced in the first triennium of research makes it possible to gather knowledge on the three theme areas.

The possibility that researchers from different disciplines can meet and confront each other provides the basis for “lateral” interconnection and thus makes the multidisciplinary hypothesis realistic.

As well, the interaction between different scientific cultures (architects and engineers, biologists and chemists,…) permits the diffusion of data analysis techniques, or the application of solutions from a single discipline to other sectors or fields of study.

Due to the advantages that “organised information” offers to the scientific community, the “Rivela Portal” has become of primary importance.

3. Bilingual Communication.

The proposed article, as the entire publication, is presented in English. English is considered the common language for the international scientific community; thus, an important element in defining scientific articles.

Initially web communication was conducted exclusively in Italian, both in reference to data as well as all relative metadata or auxiliary information.

The need to guarantee a continual interaction with the international scientific community served as the basis for developing initially, the database and subsequently, the Portal in both Italian and English. Both access modes are updated in a synchronous manner.

This design change has required a significant reorganisation effort for the front end structures of the Portal as well as the entire CORILA web site, a part of which is already available in English.

Once the project has been completed, both language versions will be updated simultaneously. Material made available in Italian will be updated in real time in English, thus serving a user group consisting of local, national and international members.

4. Confidential Data Management.

A most important aspect of the project is the information dissemination policy. CORILA has the task of collecting information and data produced through CORILA

[1] [http://ra.crema.unimi.it/ontology/introduzioneontologie_file/v3_document.htm].

financed research projects. The information may vary from raw data, elaborations, articles or any other form of information made available through the project.

The information and data made available by the Research Lines may be characterized by different dissemination methods and timing schemes, or the information may simply not be released for public use.

In order to assure that privacy requests are respected a system has been developed that assigns to every information element an allowed viewing level.

At the moment the researcher prepares the data transmission package a desired viewing level must be selected from the access policies proposed.

5. Connectivity with remote archives.

The open system architecture and development approach of the Rivela Portal make it possible to connect different data sources: remote databases or single files as well as web applications.

The technical system design is based on a multi-platform concept. The available operating systems are *windows, unix, macintosh,* the database management software are *oracle, sql server, access, my sql* and the publishing software are *ILS, apachi, tomcat, webobject*.

The “open code” structure provides the basis for connecting existing archives and databases already implemented.

Several development activities are currently in progress to connect various databases within our system as well as external data sources. Several parts of this system have been recently tested. The relative details are provided in Charter 2, section on system architecture.

Conclusion.

In conclusion, we have listed below the primary goals forming the basis of this project.

Goal 1: create a simple and easy to use interface which provides connectivity with all information archived, managed or simply accessible through CORILA, the information is not necessarily stored in a database;

Goal 2: record knowledge produced by studies on the Venice Lagoon, through CORILA Researchers or other professionals, in order to provide the scientific community with general information, raw data or organised data thus supporting the development of new knowledge;

Goal 3: make available to our user community common services and data already collected;

Goal 4: provide different access levels on the basis of function, area of interest or information type requested;

Goal 5: provide a bilingual site, opening the portal to a vast scientific community.

By accessing our web site you may already consult the information released to date. As this is an on going project additional information will continue to be released in the future. We are working diligently to provide valid support to the scientific community and we welcome any feedback which may improve the quality of this service.

Bibliography.

Fox W.M., Connor L., Copplestone D., Johnson M.S. and Lee R.T., 2001. The organochlorine contamination history of the Mersey estuary (UK) revealed by analysis of sediment cores from salt marshes. *Marine Environmental Research*, 51, 213-227

Beinat E., 1997, Case study: expert based value function models for cleaning up a polluted site, in "*Value Functions for Environmental Management*", by Beinat Euro, Kluwer Academic Publishers, Netherland

Ugo P., 2002. *Personal Comunication*

Pastres R., Solidoro C., 1999. Trattamento ed analisi dei dati anche mediante un modello di qualità dell'acqua (ex art. 55 del Capitolato Speciale) - Rapporto finale. In "*Interventi per l'arresto del degrado connesso alla proliferazione delle macroalghe in laguna di Venezia 1997-1998*". Consorzio Interuniversitario "I.N.C.A." - Consorzio "Venezia Nuova" - Istituto Nazionale di Oceanografia e Geofisica Sperimentale, Venezia

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