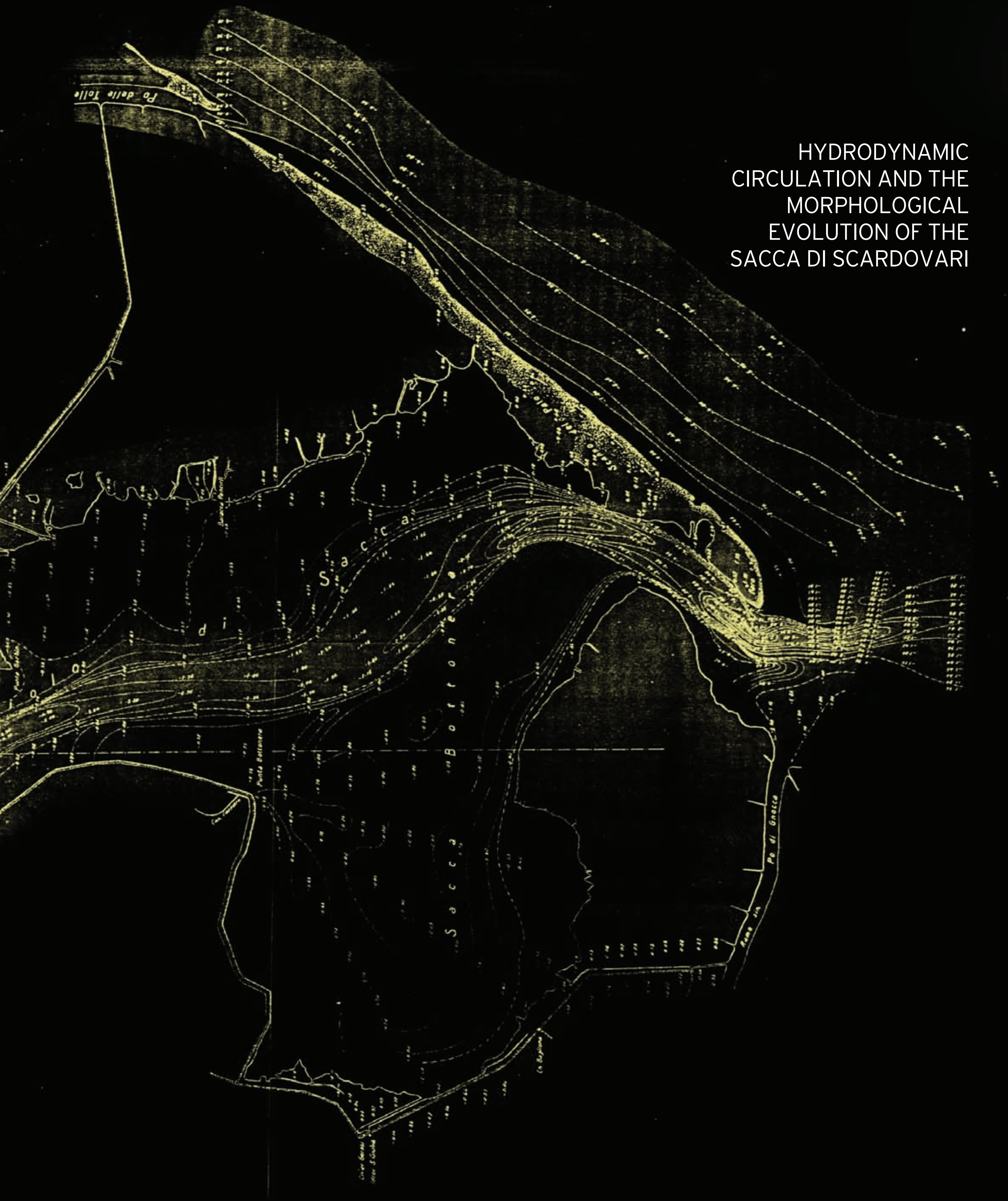
THE PO DELTA LAGOONS

BY THE CONSORZIO DI BONIFICA DELTA DEL PO



HYDRODYNAMIC CIRCULATION AND THE MORPHOLOGICAL EVOLUTION OF THE SACCA DI SCARDOVARI

SEPTEMBER - 2014

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PREFACE

FABRIZIO FERRO
Presidente del Consorzio di Bonifica Delta del Po

About 30 years ago the Consorzio di Bonifica Delta del Po was commissioned by the Regione del Veneto to carry out and process a survey on the hydraulic structure of the valley and coastal areas of the Delta. On the results of this survey, important vivification plans were drawn up involving the Caleri, Vallona, Barbamarco lagoons and the Sacca degli Scardovari, and were financed by and realized within the I.M.P. (Integrated Mediterranean Programmes according to EEC Reg. No. 2088/85). Structural interventions in the Basson lagoon and the Sacca del Canarin were subsequently carried out. As is well known, with Art. 29 of R.L. No. 7/99, the Consorzio was charged with the responsibility of managing the Po Delta lagoons.

The Consorzio's previous publications concentrated on the issues addressed, studies carried out and interventions designed to guarantee lagoon vivification, all the while contributing to the maintenance of an environment that, from a naturalistic point of view, is not only unique, but also has an important role as a source of income for the inhabitants of the territory. In this publication Prof. Luigi D'Alpaos describes the latest studies carried out on the Sacca degli Scardovari, from problems related to hydrodynamic circulation, to the effects of the morphological evolution of the Sacca and the boundary conditions governing lagoon current dynamics, thus proving a highly technical study that takes stock of the situation and highlights elements to be taken into consideration when planning further interventions.

This publication once again underlines how the Consorzio di Bonifica, thanks to collaborations with various entities, universities institutions, has been able to organize an operational structure capable of interacting with the territory in a multidisciplinary and multi-functional way, not only by sharing the hydraulic problem, but by integrating it with a range of issues and interests. The mathematical model designed to simulate the Sacca's hydrodynamic behavior was repeatedly adjusted according to the latest available bathymetric surveys and fine tuned to the various field measurement campaigns. The comparison shows a substantial overlap between the theoretical and actual behavior of the lagoon.

Our objective was achieved by considering not only the Sacca's body of water, but also the different components of the complex hydro-morphological lagoon system that is the bathymetric structure of the mouths, as well as the stretch of sea in front of the lagoon, river flow, wave motion, sediment transport and wind. In order to ensure adequate interventions, it is important to go forth in our commitment to the study of the Po Delta wetlands, a truly unique territory from a natural point of view, as well as source of income for the inhabitants of the territory.

HYDRODYNAMIC CIRCULATION AND THE MORPHOLOGICAL EVOLUTION OF THE SACCA DI SCARDOVARI

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INTRODUCTION

The Sacca di Scardovari is the largest of the Po Delta lagoons, covering an area of almost 30 km^2 between the distributaries of the Po di Tolle to the north, and the Po della Gnocca to the south (Figure 1). Its current configuration is the result of opposing morphological processes that are determined, on one hand, by the constructive effects of the of the two distributaries of the river delta, and on the other, by the distructive action of the sea. Due to the massive extraction of methane water over the whole of the Delta area, having intensified after the end of World War II, soil subsidence phenomena have had no less decisive overlapping effects on these natural processes over the last century.

The consequent rapid morphological changes to the lagoon bottoms and to the configuration of the coastal sandbar barrier separating it from the sea are inevitably accompanied by different hydrodynamic patterns, in part due to interventions carried out by man in the 1990s in an attempt to activate lagoon water exchange with the sea, and to induce improved tidal current circulation.

It was to this end that in 1994, a specific project was drawn up which, if brought to fruition, would allow the volume of tide exchanged by the Sacca and the sea to be increased and would facilitate the exchange of water not only in its internal part, where a lack of water quality was most evident especially in the hot summer months, but in the lagoon in general.

Regarding this project, only a fraction of the planned interventions have been carried out to date which, alongside the opening of a second outlet, effectively completed, would enable the overlapping of periodic circulation induced by the changing tides, a secondary circulation generated by the manouvering of an internal barrier to be kept open during the flow phase and closed during the subdsequent ebb phase. This would result in the possibil-

Figure 1: Delta del Po with the Sacca di Scardovari highlighted.

ity of, for every tidal cycle, inducing a circulation time in the innermost part of the Sacca that would be able to activate the exchange of water in a relatively shorter time that which would occur naturaly.

At the moment the maneuver is obviously not feasible, since less financing has been made available than needed to realize the series of works designed for this purpose. Indeed, the idea seems to have been abandoned, also because the intense erosive processes in the area in recent years, to the detriment of the coastal sandbar barrier that separates the lagoon from the sea, that have become a priority in safeguarding this morphological element without which the Sacca would inevitably be transformed into its own stretch of sea, have used up the limited available financial resources.

The complexity of the Sacca's environmental situation which, due to its size and morphology, has resulted in the exchange of water in the most decentralized part of its basin being more adversely affected, favours the possibilty of the creation of particularly critical conditions for the important productive activities inside the Sacca itself, especially those related to shellfishing. It is in this way that under certain circumstances, clam fishing has been affected, while in other instances only the bodies of water dedicated to the production of mussels were involved.

These are generally controversial episodes that invoke heated discussion, perhaps due the economic operators' difficulty in accepting that man is (thankfully) not always able to control events. The periodic negative events for fishing and production affecting the Sacca are to be seen as possiblie factors not necessarily related to man's responsibility or the adoption of combative measures that are not very, or not at all effective.

On these grounds it is of specific interest to examine certain significant aspects of the Sacca di Scardovari's morphodynamic patterns, and to compare the current conditions with those of the recent past, when anthropic pressure on the lagoon was virtually non-existent and, while subject to a relatively rapid morphological evolution, it was not affected by the works which in later years would somehow try to govern the natural regime of the tidal current within it.

Starting from the years following World War II, a period for which the first general bathymetric survey of the Sacca has been made available (Matticchio, 2009), the purpose of comparative analysis between the different situations is to get a picture of the extent to which, over the following decades, natural phenomena and human intervention have individually and as a whole, impacted on the tidal current regime within the Sacca, making a cognitive contribution based on scientifically and technically accepted survey methods derived from a mathematical-physics procedure that is both controllable and repeatable, and that is supported by field measurements.

With a background of feelings and emotions, no less important to everyday human life in that they intensify passion and contribute to the creation of interest in the problems and one's need to resolve them, some of the remarkable situations which have developed between the 1950s and the present will be examined and discussed with the help of mathematical modeling and the support of experimental observation.

Firstly, we will focus on the hydrodynamic effects produced by the aforementioned anthropogenic subsidence, which has led to a general deepening of the Sacca's bottoms and an appreciable increase in its liquid surfaces.

The analysis will be based on a comparison between the situation in 1950, the period from which the said first available bathymetric survey dates, and that of 1967, a period which saw the Delta area's most intense phase of ground subsidence phenomena as a result of methane deposit exploitation.

According to the 1994 survey, the lagoon's configuration highlights the effects of the second outlet, on the tidal current regime inside the Sacca and on sea-lagoon exchange, shortly after it was opened.

The comparison with the current situation will allow for, however, the opportunity to contemplate the ongoing problems and the possible measures that could be taken to remedy the situation, focussing on positive aspects and not complex interventions that, by their very nature, would involve changes to the environment that would require careful considseration. These are interventions that are often dictated by choices not only of a technical, but also social and political nature, as well as the economic development model one intends to inspire in the government of the Delta territory and of the Sacca di Scardovari in particular. Again, with reference to the Sacca's current situa-

tion, we see the development of some considerations for the classification of complex in and out-flowing tidal current interaction phenomena and the coastal currents induced by the propagation of wind generated wave action, as well as the distribution processes of the fresh water flowing from the Po di Tolle and Po di Gnocca into the saline waters of the sea.

Finally, we will illustrate the processes related to the interaction of currents however induced in the bodies of water in front of the Sacca with sediment on the bottoms and assessing in particular, the problems related to the conservation of the sandbar separating the lagoon from the sea.

SURVEY METHODS

The broadening of knowledge concerning the physics and mathematics governing the propagation of long waves in shallow water, some of which are tides, has for some decades now allowed for a fairly consistent understanding of general and local phenomena that occur in coastal basins. Among the many calculation schemes made available by research in this field, the mathematical models developed by researchers at the University of Padova's Dipartmento IMAGE, are considered technically and scientificaly appropriate, and within the general overview of scientific literature, amoung those which best combine the efficiency and accuracy of the numerical solution to the no less important issues of the physical mathematical modeling of the problem.

These models are based on a finite element solution of the equations of motion developed not only for the numerous surveys conducted in recent years on the Venice Lagoon, but also on the Po Delta lagoons, the testing of which proved to be an important benchmark, thanks to extensive and systematic comparisons between results derived from mathematical simulations and results from specific simultaneously conducted tidal level measurement campaigns, of flow rates through the relevant sections of the simulated systems, and the speeds measured along particularly large internal stretches, thus indicating local and general aspects of the flow field induced by the changing tides, and the spatial distribution of salinity.

Without going into detail regarding the numerical solutions implemented, or the specifics of the mathematical modeling upon which the developed models were based, to which reference is made in the scientific literature (D'Alpaos and Defina, 1992; Defina, 2002; D'Alpaos *et al.*, 2008), it is sufficient to merely to point out certain characteristics of this modeling.

Regarding the hydrodynamic modeling, the first significant point to be highlighted is that it is possible to put together, in a general way in the computation domain, one-dimensional and two-dimensional elements as well as a series of special elements to simulate the presence of any regulation and flow control devices.

The second notable characteristic is that which allows for the description, through the introduction of an original grid model of the large dry-wet transition area of the computation domain, with great operational efficiency without generating the numerical disturbances that other approaches bring to the problem, as noted in the literature.

These phenomena are of some significance to lagoons in which there are large saltmarsh areas that are alternately wet or dried during stronger high tide phases.

With the hydrodynamic modeling, the terms of convective acceleration are treated in a Lagrangian way, while the Reynolds terms are described using the model suggested by Smagorinsky and later refined by Stansby, as a turbulence closure scheme. One should also take any wind and wave generated action into account.

The latter is assessed based on Longuet-Higgins and Stewart's formulation of solving the differential equation that governs the conservation of the wave action in the case of monochrome oscillation and considering both the contributions that tend to add to wave energy (the wind in primis), and those that dissipate it, like bottom resistance, frangibilty and the phenomenon of white-capping.

The direction of wave motion propagation within the computation domain is preliminarily determined by imposing the irrotationality condition per number of waves. In situations where bottom mobility is of importance, the effects related to changes in height over time are analyzed starting from the observation that generally, the times that characterize changes in hydrodynamics and bottoms are very different one from the other. Therefore, from a mathematical modeling point of view, it is possible to treat the two phenomena seperately, whilst maintaining the solution's effectiveness. According to this hypothesis, with each step of the calculation, the motion field hydrodynamics are resolved first, assuming the geometry of the bottom and then sediment transport as invariants, this time considering hydrodynamic sizes as an invariant and determining the altimetric evolution of the bottom, based on the Exner equation:

$$(1-n)\frac{\partial z_b}{\partial t}+\nabla \mathbf{q}_b = D(C)-E$$

As for the two modes of sediment transport, namely bottom and suspensed transport, they are measured separately with specific relations, since the bottom transport is influenced both in intensity and direction by the slope of the bottom, unlike the suspended transport.

The hydrodynamic model coupled with the bottom evolution form can provide information useful in understanding both the outlet stability issues on which sea-lagoon exchanges depend, and erosion and deposit phenomena, especially regarding the waters immediately in front of the sand bars separating the Sacca from the sea.

Due to the fact that in situations characterized by more abundant inflow of fresh water from the Delta distributaries into the sides of the Sacca, the difference in water salinity plays a significant role in the lagoon eviroment's water exchange processes, a 3D multi-layer model was developed in order to get a better overview of such phenomena. In the formulation of such a model however, varying densities are hypothesised for the water column, while retaining the hypothesis of vertical hydrostatic pressure distribution.

From a numerical point of view, the 3D model solution is developed by appropriately adapting the hydrodynamic two-dimensional diagram to the individual layers that make up the water column, assuming that the hypotheses are valid for the so-called "density currents".

Once the elevation of the free surface in the nodes of the computational grid is assessed, one immediately obtains the horizontal speed field and vertical flow exchanged through the interfaces of each element, and therefore the concentration of the transported substances (density of the fluid that varies due to the effects of salinity in particular) using a forward-difference formula (upwind scheme).

All of these briefly described models were used in the Sacca di Scardovari to analyse the consequences of the most important morphological changes that have occurred since 1950, as well as more recent situations that have caused significant anoxic crises and major erosion processes affecting the coast that separates it from the sea.

TIDAL CURRENT

The morpho-dynamic phenomena that characterize the Sacca di Scardovari are basically governed by the tidal currents, even if they are affected in certain circumstances by effects gen-

Figure 2: computational grid used for the two-dimensional model simulations.

erated by the wind and differences in water salinity that modify their behavior.

Refering to tide as the only external force, at least at the outset, and assuming a constant density throughout the flow field are more than acceptable hypotheses providing an overview of the general characteristics of the processes that develop inside the lagoon.

The hypothesis of the bi-dimensionality of motion, the effects of vertical velocity being completely negligible, could also be applied to the analysis of the phenomena by means of extremely accurate mathematical models. Areas that are limited in size are generally exceptions as they, if at all, only marginally affect the general solution, for which the motion characteristics are distinctly three dimensional and cannot be correctly simulated without considering the role of the curvature.

Schematic Diagram of the System and Boundary Conditions

Data used

All of the data used for the implementation of the two-dimensional mathematical model used to study the circulation of tidal currents in the Delta distributaries, its lagoons, and particularly the Sacca di Scardovari in general, were sourced from the Lagoon Geographic Archive recently prepared by the Consorzio di Bonifica Delta del Po. The archive consists of a GIS system made up of the most recent map data, aerial photos and bathymetric surveys of the Delta area.

The map that provided a basis for the construction of the computational grid of the two-dimensional model consisted of the Orthophotomaps of the Veneto Region, which were perfectly integrated with the Regional Technical Map (RTM), and provide a detailed and updated picture of the territory. In this case photographs from TerraItaly NR flight it2000 2006-2007 were used.

The RTM was also a useful support in the construction of the model. Despite the fact that it refers to aerial surveys that are not particularly recent, (the flights were undertaken in 1983 and 1990), the RTM provided vectorial themes necessary for the correct interpretation of Orthophotomaps. The Gauss Boaga West Zone was adopted as a mapping reference system.

Various different available reliefs were used to describe the geometry of the lagoon system and the bathymetry of the seabed in particular. The main reference point is a survey covering the whole basin carried out by the company Bellan on behalf of the Consorzio di Bonifica Delta del Po in March 2008.

The entire Sacca was surveyed using a regular bathymetric grid with a pitch of about 250m, densened with additional intermediate strips and put together with detailed bathymetric surveys of the canals and more significant areas.

The surveys in question were supplemented with a detailed survey of the sea bottoms in front of the outlets and the Scanno del Palo that was conducted by the aforementioned company in January 2009, using a grid with a constant pitch of about 50m. The sum of the reported data was further supplemented with a series of strips obtained in an additional bathymetric survey in January 2008 by Geostat (Padua) aimed at assessing the geometry of the canal which opens into the northern portion of the lagoon from the North Outlet.

Other less recent bathymetric data collected by the Consorzio di Bonifica Delta del Po were used to outline the areas not covered by the surveys listed. In particular, in order to complete the bathymetric survey of the sea in front of the sandbar, sections running perpendicular to the coast extending from the shore to the -15 depth range surveyed in support of a recent hydraulic and morphological study were considered [10], [11].

Lastly a Lidar survey carried out in April 2006 by the Genio Civile di Rovigo involving the sandbar strip and mouth area of the Po di Gnocca was used. This survey, attributable to low tide conditions, provies a detailed representation of the height of the shallow bottom and shoreline areas not described or only partially described in traditional surveys, that make up however, part of the model's computation domain as they are flooded in high tide conditions.

Construction of the Computational Grid

The construction of the two-dimensional model computational grid, based on the cartographic data and bathymetric surveys described in the previous paragraph, that was implemented, was carried out automatically via the software interface of the mathematical models used. This tool enables one to construct a triangulation that rests against the constraints imposed by the morphology of the computation domain, in this way enabling its proper digitalization.

The resulting triangulation is optimized in terms of the shape and size of the triangular meshes. In fact, depending on the hydrodynamic calculation's requirements, the meshes themselves must be smaller in points where the motion field has accentuated gradients (planimetric variations, curves, bumps, etc.) but can be larger where the motion field is more uniform or where less accurate results are required (eg. further away from the shore line).

Figure 2 illustrates the computational grid obtained. It is made up of 25136 nodes and 48654 triangles and therefore allows for an extremely high quality detailled description of the computation domain. The model simulates a total area of about 200 km^2, approximately 29 km^2 of which covers the Sacca di Scardovari itself, while the remaining areas describe the adjacent mouths of the Po di Tolle, Po di Gnocca, Po di Goro, and a wide stretch of sea off the coast.

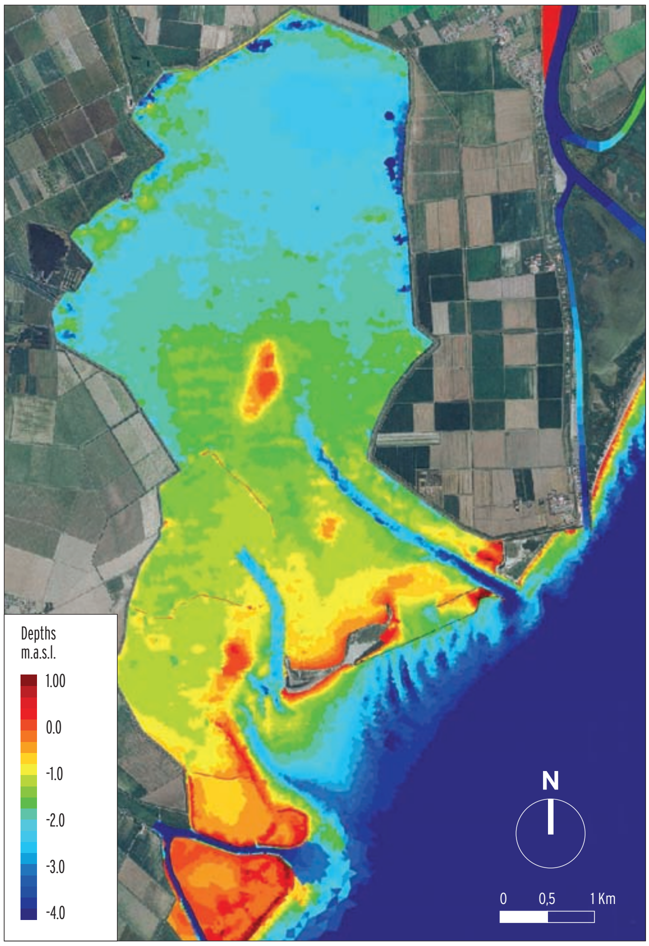
The dimensions of the computational grid meshes are extremely variable. In the Sacca di Scardovari, the focus of the simulations, the mesh sides are on average about 50 to 80m in length, being reduced to about 10m in the sea outlet areas and areas in which the contours' geometry is more complex, for example around the sandbars or along the lagoon edges. The meshes used to describe the stretch of sea in front of the lagoon are much larger. In fact, the bigger triangles have sides that are about 400m in length.

The bathymetric survey of the lagoon according to the prepared schematic modeling is illustrated by a colour scale in Figure 3. In the north (the Sacca di Scardovari itself) the basin is characterized by practically uniform depths, ranging between -2.0m and -2.5 m with trenches and ridges only along the edges.

The central part is a lot shallower, with depths between -1.4 and -1.8 m. The area occupied by the artificial "salt marsh" constructed by the Consorzio di Bonifica Delta del Po as part of their hydrodynamic vivification interventions carried out in the Sacca can be clearly seen, and appears to be partially eroded and somewhat lower compared to its original position, with maximum heights slightly above mean sea level.

In the southern part of the basin (Sacca di Bottonera) the bottoms are generally shallower, the exceptions being the two incisions formed by the canals that from the outlets to the sea penetrate towards the interior, which were part of the vivifcation works carried out in the basin. The canal originating from the North Outlet has bottoms that are deeper than 3m, deepening further in correspondence with the outlet. The South Outlet canal however has a depth in the order of -2.5 m, which drastically reduces

Figure 3: scheme of the Sacca di Scardovari bathymetric survey.



at the outlet, where the canal itself is lost in a series of alternating trenches and ridges.

In the western part of the Sacca di Bottonera one notes the presence of the submerged remains of a cliff that at one time, before the visible signs of subsidence that affected the Sacca, encompassed a large emerged area (the Canestro area). The entire strip extending behind the sandbars has very shallow bottoms in general, often below 1m, and is characterized by the presence of ridges presumably caused by the depositing of suspended material being pushed towards the internal areas by tidal currents.

The bathymetric surveys also documented some significant information regarding the shape of the bottoms on the outside of the Sacca (Figure 3). First of all, moving from north to south, one notes a deep incision due to the presence of the North Outlet, whose canal, exiting between the two piers that shape it, tends to bend decidedly to the south.

A system of bars running almost perpendicular to the coast along the cliff that borders the sandbar is particularly evident. These bars have been developed according to a periodic sequence, with avarage axes of about 150 to 200 m and appreciable height of about 1.5 to 2.0 m.

The bar system testifies to the presence of intense morphodynamic processes associated with sediment transport phenomena caused by the action of the bottoms and currents induced by the coastal wave propagation generated by the wind. This is a morphological configuration caused by the combined action of transport that is parallel to the coast, and that which is perpendicular to the coast, expressed in a coastal erosion process, and the transport of material towards the sea reinforced by rip-currents.

Once more, significant information regarding the bathymetric situation of the bottoms around the South Outlet can be taken from the image in Figure 3. In front of the outlet there is a fairly extensive ridge reducing the depth to less than 1.0m. The tidal canal situated outside the outlet has shifted decidedly towards the SW, close to the sandy strip bordering the lowland area that surrounds the mouth of the Po di Gnocca (Punta del Polesine). The ridge is apparently the result of sand deposits carried by NE-SW wave motion, and seems to extend across the whole outlet, only being interrupted in certain points by trenches along which the shaping action of the tidal currents is presumably of greater intensity.

Boundary Conditions

With reference to the numerous simulations conducted regarding the Sacca's behavior patterns, the boundary conditions used essentially consist of the assignment of tidal level trends to the nodes at the edge of the sea on the computational grid. Specifically, due to the fact that the computation domain also includes the final stretch of the Po di Tolle, it is necessary to assign an input

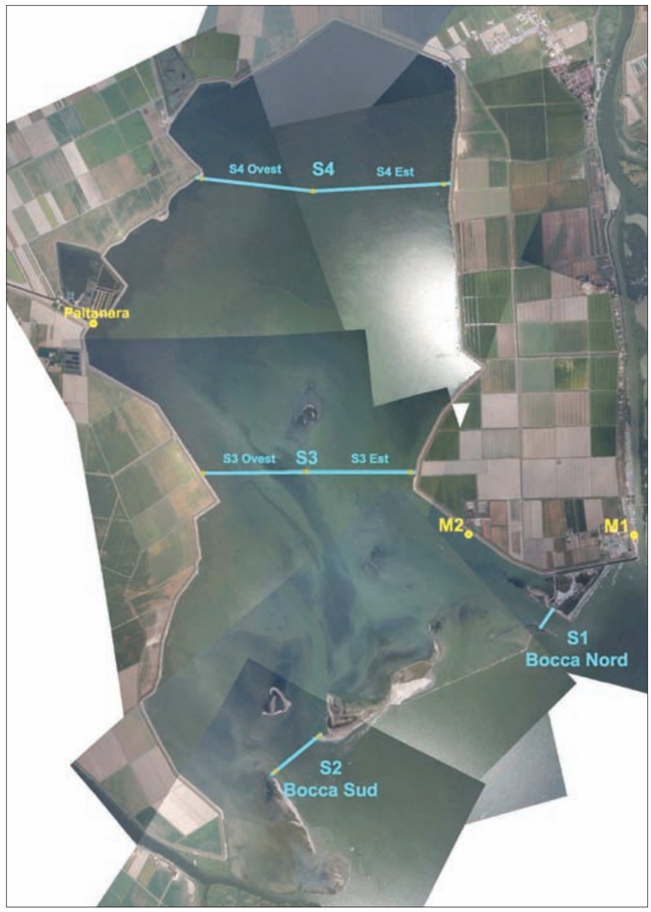


Figure 4: location of tide gauge stations and flow measurement sections of the measurement campaign conducted on 7-8 April 2009.

flow to the section upstream of this Po Delta distributary.

For the first simulations carried out, aimed at comparing the results provided by the model and the situation encountered in the 7-8 April 2009 measurement campaign, in relation to the sea levels, trends measured by specially installed tidal gauges and the nearest gauge of the Porto Caleri ISPRA (ex APAT) network are available. However, as there are no data available for the Po di Tolle flow itself, taking into account its modest influence on the overall current regime, at first an approximate inflow of at minimum of 50 m^3/s was assumed for this distributary.

In a second series of simulations aimed at comparing different situations regarding the geometry of the bottoms, a sinusoidal tide reference of 1m over a 12-hour period, oscillating around the mean sea level mark, was adopted. This tide is practically representative of normal syzygial conditions and is therefore useful, due to its characteristics of regularity and periodicity, as a term of comparison in comparative analysis between different situations.

With regard to the allocation of the roughness coefficients with which resistance to motion is characterized, like the choices made in the context of other studies on the lagoons of the Po Delta [10], [11], it was generally considered appropriate not to differentiate between the value of this parameter and the mesh that makes up the computational grid, since on the one hand, on the basis of the available, data it did not seem possible to identify in the areas considered zones in which there was a justifiable choice of a different bottom roughness, and on the other, as will be seen, the model seemed to be able to reproduce the experimental measurements with sufficient accuracy, even while adopting a single value of the roughness coefficient.

It is ultimately for these reasons that a constant roughness coefficient equal to 35 m1/3 s-1 (expressed in the Strickler formula) was adopted over the whole computation domain.

Comparison between Measurements and Calculation Results

During the 7-8 April 2009 measuring campaign described in detail in the report [12], tide level trends were measured at 3 different stations (M1, M2, Paltanara), as was the flow rate through 4 important sections (the two outlet sections and the 2 internal transects, Figure 4).

The data collected allowed a first calibration of the mathematical model not only in order to compare the calculation results with the experimental observations, but also to get a picture of the Sacca's hydraulic behavior compared to the base units of the propagation phenomenon.

The Puerto Calero ISPRA (formerly APAT) tide gauge network level was assigned as a boundary condition on the nodes of the sea edge, being the only available data along the Delta coast. In fact, under normal meteorological conditions, the shifts of phase and differences in amplitude of the tide between the coasts of Puerto Calero and Scardovari are relatively contained. It is however obvious that the choice made can introduce some uncertainty when comparing the calculation results and experimental measurements.

Despite some limitations, in the hypotheses, the model has proved effective in reproducing all the flow and level data made available by the measurements into more than acceptable approximations. Regarding the levels, the matching of the values calculated with the tidal trends measured by the provisional tide gauges (M1 and M2) and the instrument installed at the Paltanara station is more than acceptable, the model's results accuarately reproducing the phase shift of the signal recorded by the sensors with respect to the sea.

However, there is a difference regarding the amplitude of the tidal oscillations, which in the model's case is slightly higher than that which was measured. These differences are more evident for both tide gauge M1, situated within the dock area at the mouth of the Po di Tolle, in which the calculated oscillation amplitude is excessively high corresponding to the trenches, and for the Paltanara station tide gauge, where the maximum discrepancies correspond to the ridges. As for the M2 tidal gauge, located within the Sacca along the eastern margin, the measured data and calculated values correspond almost perfectly.

Regarding the flow rates, the results obtained from the calculation indicate that the model satisfactorily reproduces their values in all sections considered. Regarding the North Outlet (section S1), the calculated values accurately follow the sequence of values measured in all tide phases. In particular, the model almost perfectly reproduces incoming flow (positive flow sign), indicating a maximum flow rate value of 770 m^3/s around 20h30 on April 7. Only in the outgoing flow (negative flow) phase is there a modest discrepancy with the model, which shows a maximum flow rate value of 405 m^3/s while the measured value is 440 m^3s.

The comparison between the calculation results and measurements at the South Outlet (section 2) is satisfactory. In this case, however, the measurements do not cover all of the tidal stages, and the maximum incoming flow phase, for which the model shows a peak value of 775 m^3/s around 20:30 on April 7, is essentially unexplored. In the outgoing flow phase the model tends to overestimate flow, as can be seen from the maximum calculated value of 345 m^3/s, as opposed to the measured flow rate of 285 m^3/s.

The overall result, taking into account the measurement errors and difficulties inherent to this type of assessment, is more than acceptable. It should be pointed out that the section of measurement, and consequently also that of the model, does not completely intercept all the flow moving through the South Outlet. In fact there are areas with shallow bottoms on the western side of the outlet which have, in the high tide conditions, moderate but not completely negligible rates of flow that, as illustrated in the report on the measurement campaign results [12], were not detectable due to evident operational difficulties.

The comparison between the calculated and measured flow rates at the two internal transects formed by sections S3 and S4 within the Sacca is also very interesting. In the first case (section S3) the values resulting from the calculations and those resulting from the measurements correspond almost perfectly. If we consider section S3 as a whole (red lines), in both cases the maximum incoming flow is approximately 650 m^3/s, while outgoing flow is about 450 m^3/s.

If we consider the two parts into which the section was divided, one can see that the model slightly underestimates the flow rate passing through the eastern section and thus slightly overestimates flow through the western section. However, the calculation measurements highlight a trend in which the exchange of flow along the eastern side is appreciably higher than that in the western part of the Sacca.

This asymmetry seems to be reversed when refering to the two parts into which section S4, situated in the inner part of the Sacca, is divided. In this case the overall maximum flow rates indicated by the measurements are 225 m^3/s in the inflowing phase and 210 m^3/s during outflow, and are only slightly underestimated in the model. Both the measurements indicated by the model and the flow rates passing through the section in its eastern part are smaller those flowing through the western part.

Ultimately, having taken into account the uncertainties of this type of evaluation, linked on one hand to difficulties in developing a model that is able to correctly reproduce the distribution of tidal flow through the lagoon outlets, and on the other, to the difficulties inherent in the experimental measurements, especially in situations such as those in which the sections observed are very large and characterized by alternating depths, the results can be considered more than satisfactory.

One can therefore conclude that the mathematical model developed can be considered adequate for the purposes of the investigation, or to conduct assessments of the hydrodynamic effects that any planned interventions may have on the hydrodynamic circulation of the lagoon.

Evolution of the Sacca's Morphodynamics, 1950 to date

In the second half of the 20th century, The Sacca di Scardovari, like all the Delta lagoons, underwent profound morphological changes due to the superimposing, upon the natural evolutionary processes typical of all coastal basins in areas of recent geological formation, of important subsidence processes resulting from massive underground methane water extraction.

The Available Bathymetric Surveys

In the case of Sacca, the first significant representation of its bottoms dates back to the 1950s, when the Magistrato alle Acque carried out the first extensive bathymetric survey accompanied by, and this is a matter of extreme interest, contemporary hydrographic surveys, in order to assess the extent to which the average changes in sea level could have an impact on the State altimetric network zero benchmark, which at that time coincided with the 1898 mean sea level at Punta della Salute. The analysis carried out on the tide gauge observations regarding this aspect would result in a rise in mean sea level of about 12 cm, fully comparable with that surveyed in the Venice area.

The comparison with the current bathymetric situation highlights significant morphological changes both to the Sacca's inland waterways and the coast that forms its border with the sea. The Sacca is connected to the sea in the south-west via a canal mouth (Canale Curiolo) joining it in a central position and penetrating towards its northern edge.

There are some evident differences that can be seen in the hydrodynamic patterns of the lagoon. Firstly, the bottoms are more differentiated due to the presence of the aforementioned canal, and there are significantly shallower and altogether more complex adjacent water areas than those that can be observed at present, as well as marginal stretches that tend to emerge above the average level of the tide.

The separation between the Sacca di Scardovari bodies of water and those of the Sacca Bottonera, closer to the sea, is also very evident. Finally large stretches of land appear adjacent to the Bottonera corresponding to the where the Bottonera and Scardovari connect, located at altitudes higher than average sea levels, which had therefore been cultivated.

The next available survey of the Sacca carried out by the Ente Delta Padano in 1967 already shows some important changes to the lagoon morphology. There is still, albeit somewhat less evident, the central canal which, starting from the outlet, penetrates towards the northern edges of the Sacca, joining it in the middle. The bottoms of the areas of water adjacent to the canal have grown appreciably and hence so has their total surface area which now merges both the areas situated just behind the coast and the areas to the left of the outlet in the area where the Bottonera and Scardovari connect. These are obvious signs of anthropogenic subsidence which, from a hydrodynamic point of view, have negative repercussions on the Delta, its coastal lagoons and the Sacca di Scardovari in particular.

An appreciable, precise retreat of the shore along the coastaline has begun, again towards the southwest of a wider outlet curving slightly at its edges, and to the northeast, from a smaller outlet which opens very near to the outlet of the Po di Tolle.

Once again towards the northeast, the coastline is rather low and there is the possibility of it being overcome by higher tide levels. The general structure is not positive in that it tends to follow the shoreline with a concave shape that favors, like other conditions, the concentration of wave motion energy and similarily erosion.

The subsequent survey of the Sacca, carried out by the Consorzio di Bonifica Delta del Po, relates to the 1991-1994 period. It confirms the evolutionary trend of the lagoon morphology already evident in previous years. The incision of what had been the Canale Curiolo has now almost completely disappeared, only a trace of which can be seen in the vicinity of the big outlet to the sea to the southwest.

The general deepening process of the seabed, especially in the Sacca di

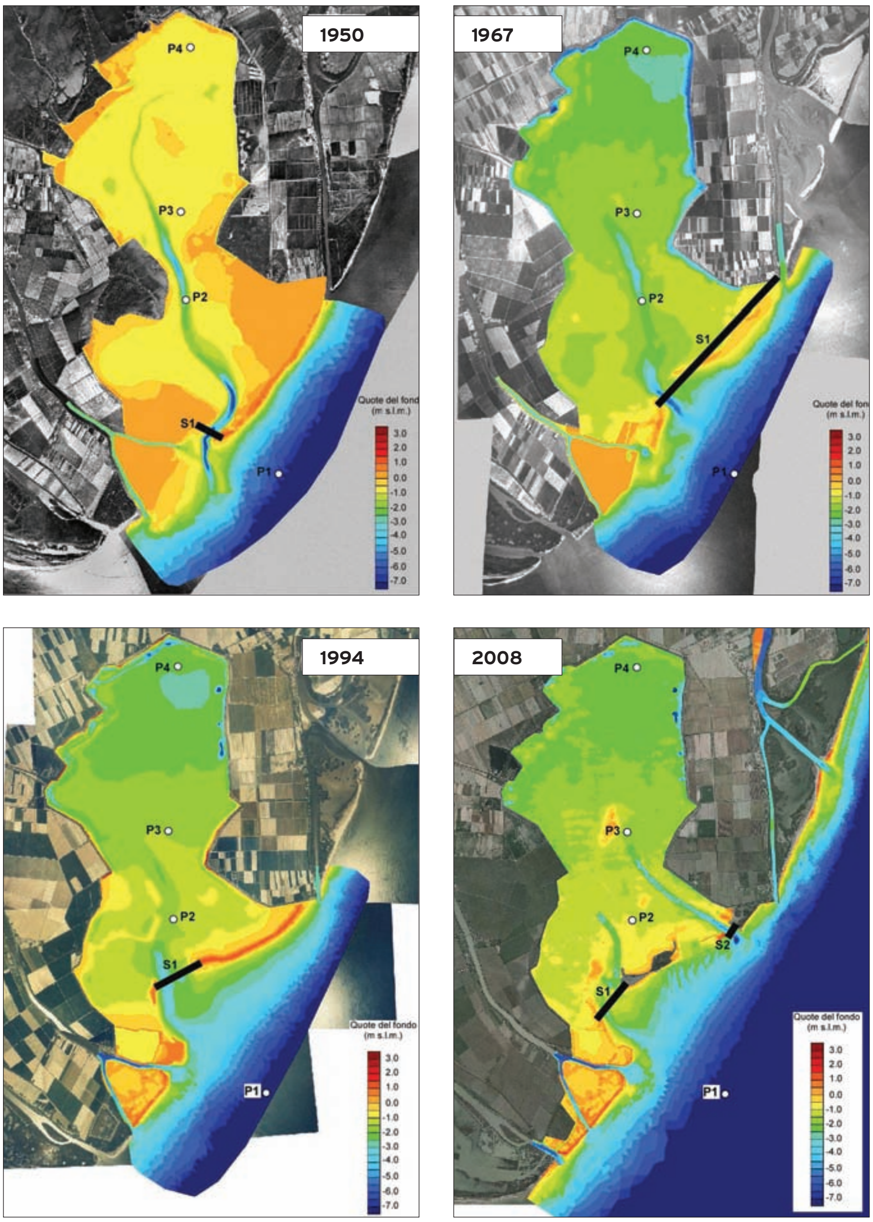


Figure 5: bathymetric maps of schematizations prepared for the analysis of the historical evolution of the Sacca.

Scardovari itself, was confirmed. The structure of the coast shows a shoreline that is further back than in the previous survey, and more concave in shape, which is unfavourable if considering the energy and erosion processes triggered along the coast by wave propagation.

Regarding the coast heights, towards the northeast the coast is able to contain normal sea level events and the secondary outlet that previously opened near the Po di Tolle outlet has dissapeared.The last of the available surveys conducted on the Sacca is from 2008, and it confirms the morphological evolution of the coast and the existence of intense damaging erosive processes. Following works carried out as part of the P.I.M. there are now two outlets on the coast, from which, in order to improve water exchange within the lagoon, specially excavated canals branch off into the interior.

These canals only affect the Sacca di Bottonera and run all the way to the strip that separates it from the southernmost part of the Sacca di Scardovari itself. In the Sacca di Bottonera the heights of the bottoms are more articulated as a result of the fact that part of the sediments eroded from the coastaline, and brought into the lagoon areas by the current, were deposited right behind it.

The comparison between the different sythetically illustrated situations is clearly illustrated on the color scale representing the bathymetric surveys, modeling the seabed by means of a triangular mesh grid (Figure 5).

What clearly emerges are the important morphological transformations that the Sacca has undergone over a relatively short period of less than 60 years, and in particular, how there has been a general lowering of the bottoms of, on average, more than 1m in the Sacca di Scardovari itself, and how radical changes have affected the coastline separating it from the sea, initially having an almost convex

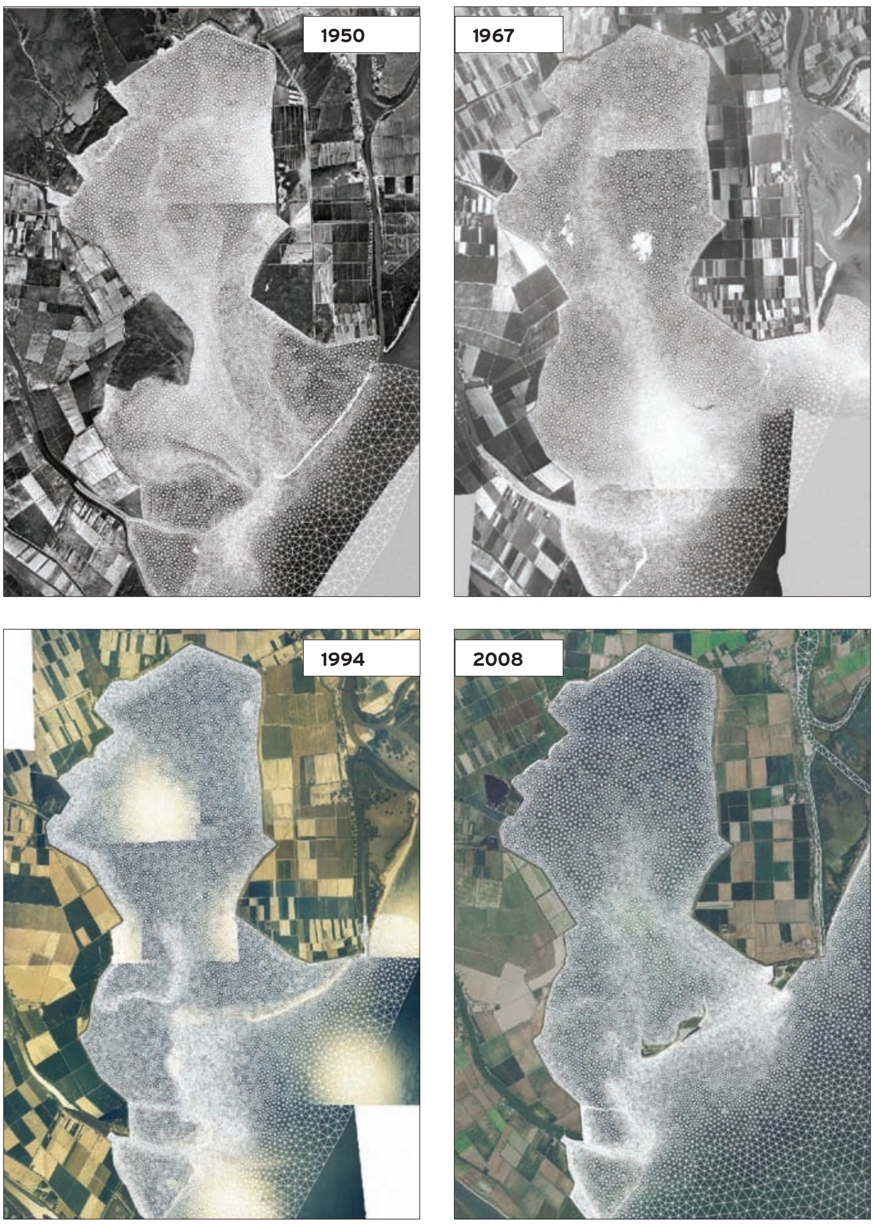


Figure 6: representation of the 4 different computational grids prepared for the analysis of the historical evolution of the Sacca.

planimetric trend towards the sea while more recently becoming decidedly concave.

These changes have led to reflections of some importance regarding the hydrodynamic behavior of the lagoon and the interactions between tidal currents and coastal currents induced by wave motion.

Mathematical Modeling of the Sacca's Hydraulic patterns in the past

The important changes to the morphology of the Sacca'a bottoms at least merit evaluating the fundamental points of the consequent changes in the hydrodynamic patterns of the lagoon from 1950 to the present. With these objectives, the four different configurations of the bag illustrated by the findings of 1950-1967-1991 and 2008 were inplemented and modelled, examining the hydraulic patterns with the predisposed two-dimensional scheme, based on a computational grid comparable, according to its geometric characteristics (number of elements, maximum dimensions, degree of grid densification) for all four situations examined (Figure 6).

Taking into consideration the same sea tide (a 12 hour sinusoid tide oscillating at ±0.5m around the mean value), evaluations and comparisons were made between aboveall, level trends in certain characteristic points, flow exchanged with the sea, instantaneous level gradients with the relative velocity fields and thereafter the method of transportation of certain particle spots that were instantaneously released the Sacca Bottonera and Scardovari itself.

If one examines the rates of flow between the Sacca and the sea, there appear to be quite different patterns for the 4 configurations.

For the first configuration (1950) the maximum rate in flow phase reaches 1000 m^3/s. Lower maximum flow of approximately 800 m^3/s is exchanged during the ebb tide phase, which occurs however, with a longer dip in order to maintain the total outgoing amount. Looking at the levels (Figure 7), there are

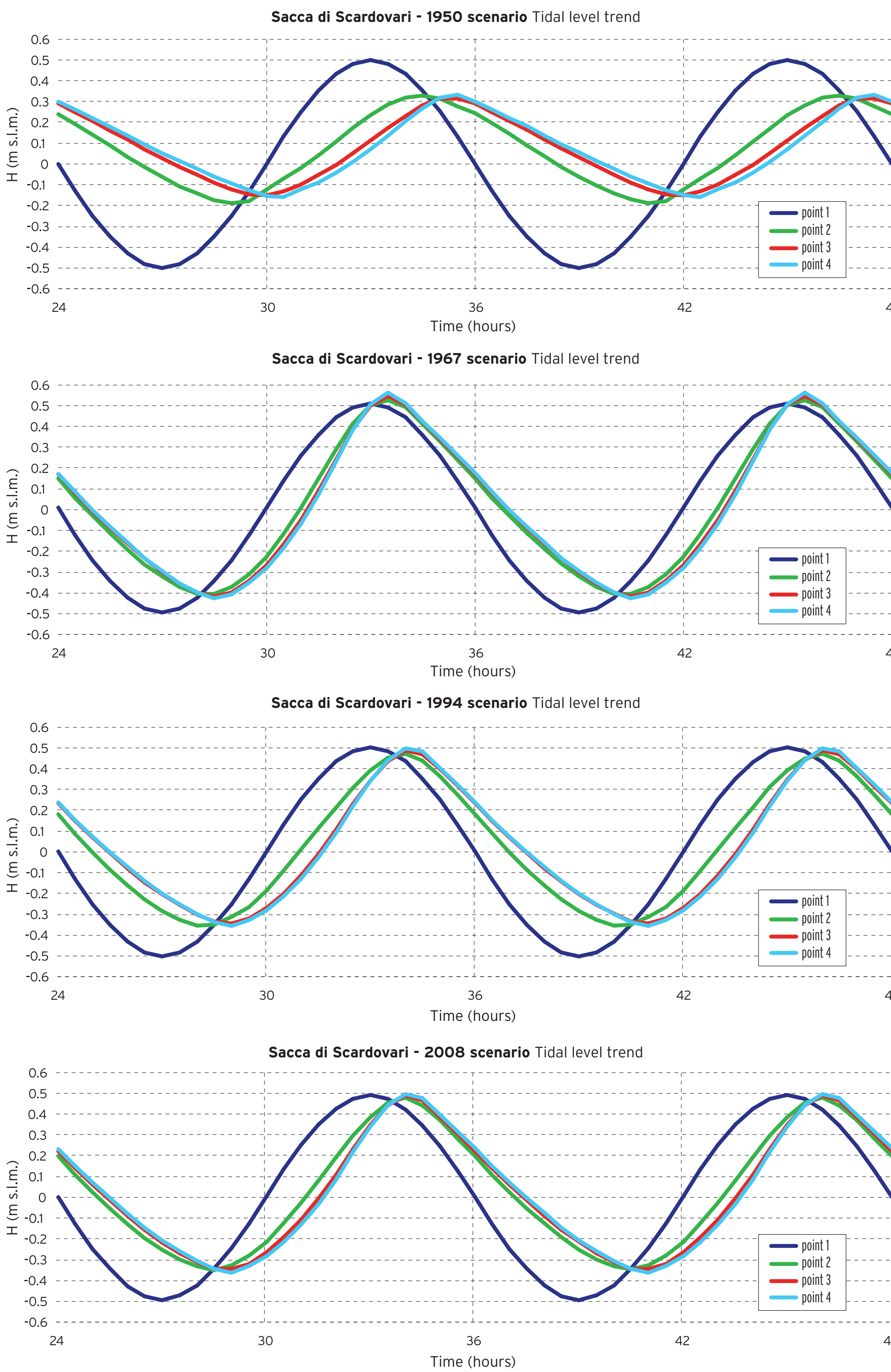


Figure 7: tidal level trends at the points of Figure 5 for the different historical configurations of the Sacca.

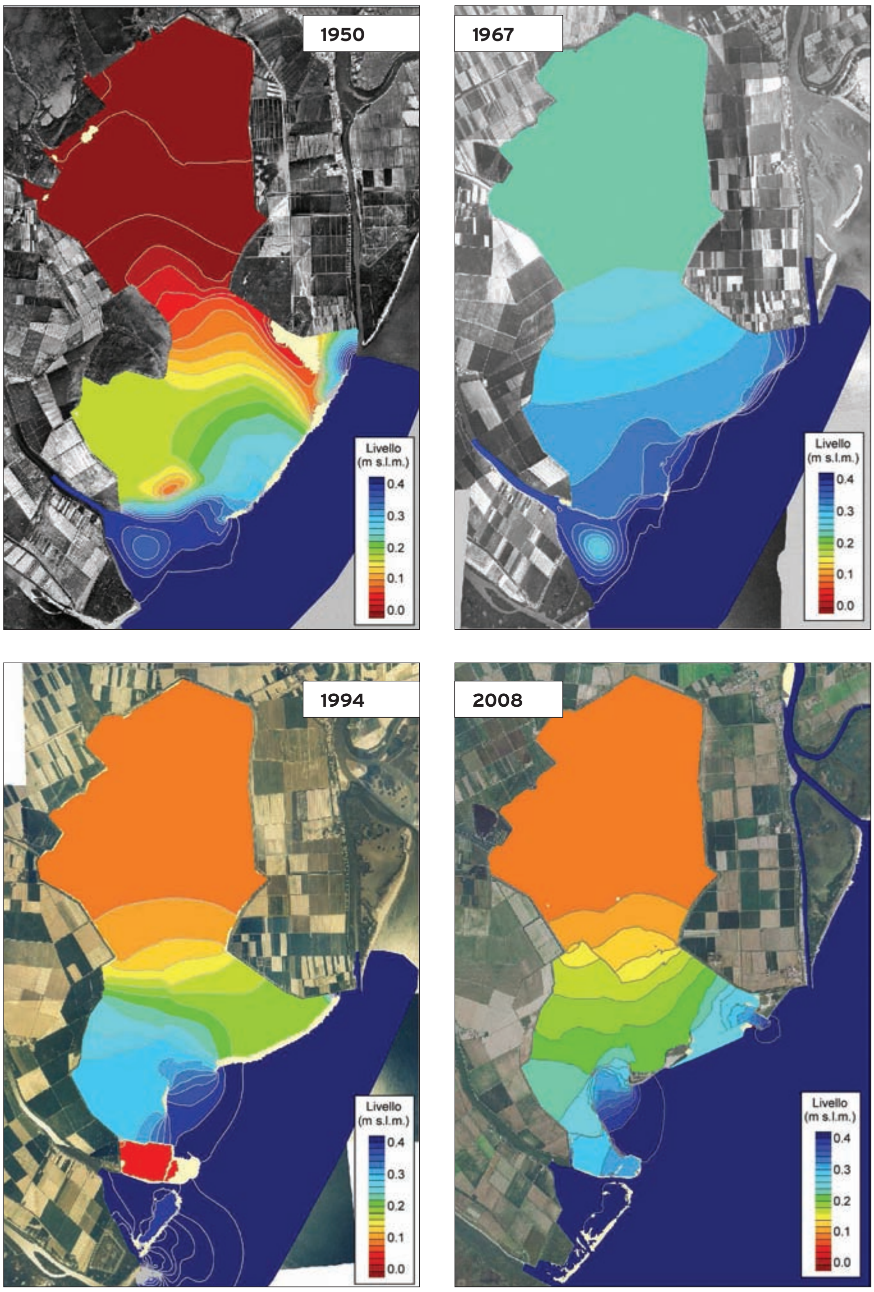


Figure 8: map showing the instantaneous levels in the incoming flow phase (T=32 hours) for the different historical configurations of the Sacca.

significant reductions in the peaks and dips in tide compared to the sea, particularly noticeable in the overflowing of the mouth.

The calculation of the bathymetric configuration in 1967 showed very different tide propagation effects. The tide peaks propagate inward with significantly fewer phase shifts than the previous case, in fact the peaks tend to intesify by a few centimetres to the extent that we move away from the coast and go towards the interior.

The dips, also having less phase shifts, weaken again, but in a less pronounced way than in the 1950 configuration (Figure 7). Everything is determined by the deeper bottoms inside the Sacca resulting from the aforementioned effects of man-made subsidence, but mainly from the lower hydraulic resistance that affect the tide when it flows over the coastal sand bar, having a decidedly larger total mouth area and playing a significant role in terms the inertia of the propagation.

For the considered configuration the volume of water exchanged with the sea increases appreciably, now characterized by maximum rates that in flow phase, reach 2300 m^3/s and 1500 m^3/s during the ebb phase. The Sacca, which in the postwar period saw tide propogation dominated by dissipative phenomena, shows strongly inertial patterns which is also reflected in other aspects of the hydrodynamic regime. Of partucular significance in this regard is the distribution of the instantaneous level gradients (Figure 8) which are very different in the two situations (1950 and 1967), especially in the Sacca di Bottonera.

The different level gradient distribution is accompanied by different instantaneous velocity distribution (Figure 9), which appears to be much less varied in the 1967 configuration compared to that of 1950, when the canal Curiolo principally controlled propagation phenomena. In terms of their hydrodynamic aspect, the patterns of the two Sacca configurations resulting from the 1994 and 2008 surveys are relatively similar, with the latter differing from the first in that it has a second inlet opening to the north which improves current circulation within a complex of planned works that have only in part been realized.

The tide level trends within the Sacca (Figure 7) show an attenuation of the dips with the peaks propogating substantially unchanged compared to the sea and which only appear to be phase-shifted in time. The distribution of instantaneous level gradients in the Sacca di Bottonera (Figure 8) is slightly different, while the velocity fields represent the current state (2008) with more articulated values (Figure 9), thanks to the inner canals dug together with the opening of the northern outlet and then kept active with subsequent dredging operations.

In comparing the different situations, the inactivity of tidal currents in the Sacca di Scardovari itself, hydraulically too far away from the outlets to the sea and morphologically characterized by uniform bottoms, which in turn have an unfavorable affect on the aspects of exchange, is evident.

The analysis of the dispersion of patches of particles released in the same tide phase in the Sacca di Bottonera and the Sacca di Scardovari provides significant findings of this condition. In the latter, for all configurations considered (1950-1967-1994-2008), the dispersion is, if anything, very modest, (Figure 10, 11) and is proof of the water exchange problems that this part of the lagoon has always had. In terms of its water surfaces, if we don't complete the project within the time predisposed by the PIM, the exchange of water will come to depend decisively on dispersion phenomena, particularly those induced by the action of wind, which are modest, and those generated by the different local distribution of the speed of tidal currents which as can be seen, are very modest.

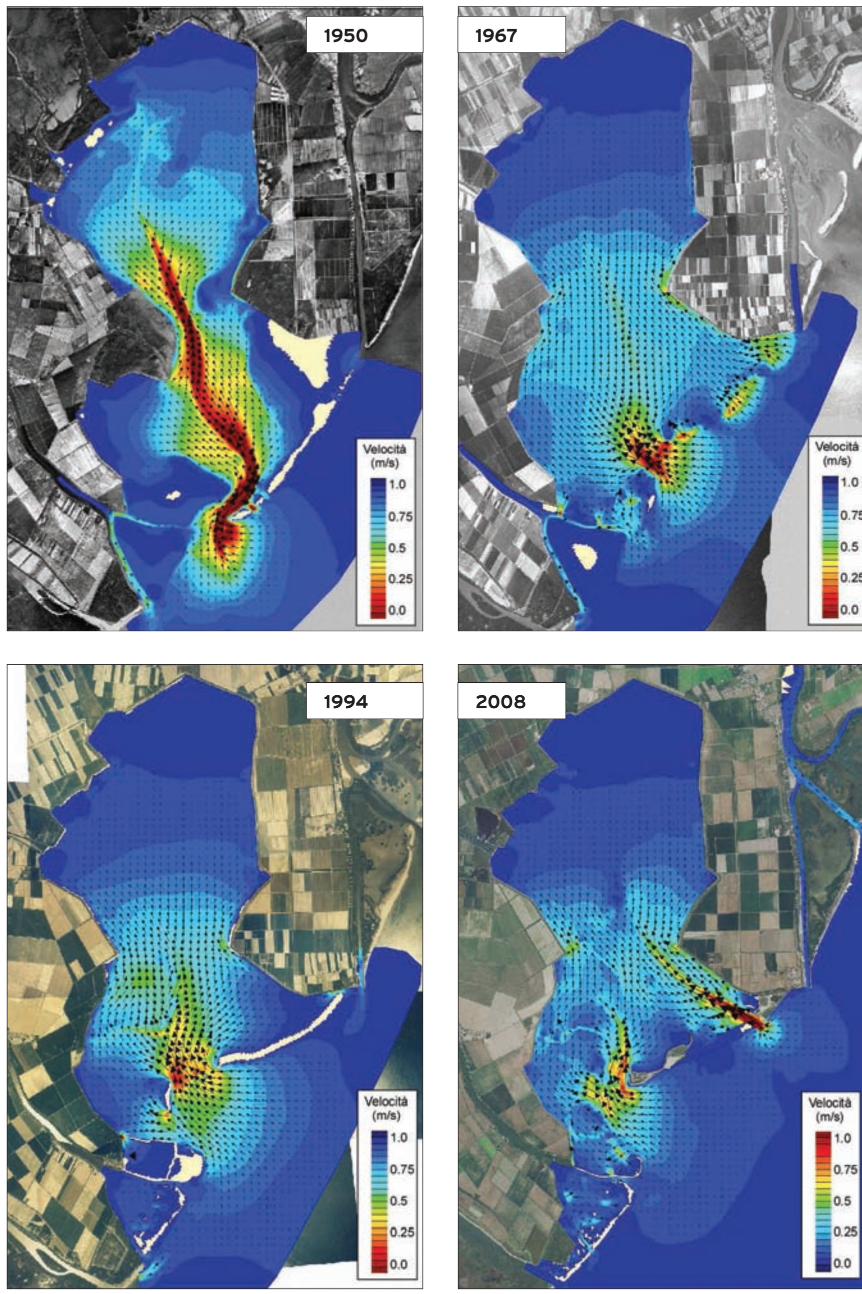


Figure 9: map showing speed in the incoming flow phase (T=32 hours) for the different historical configurations of the Sacca.

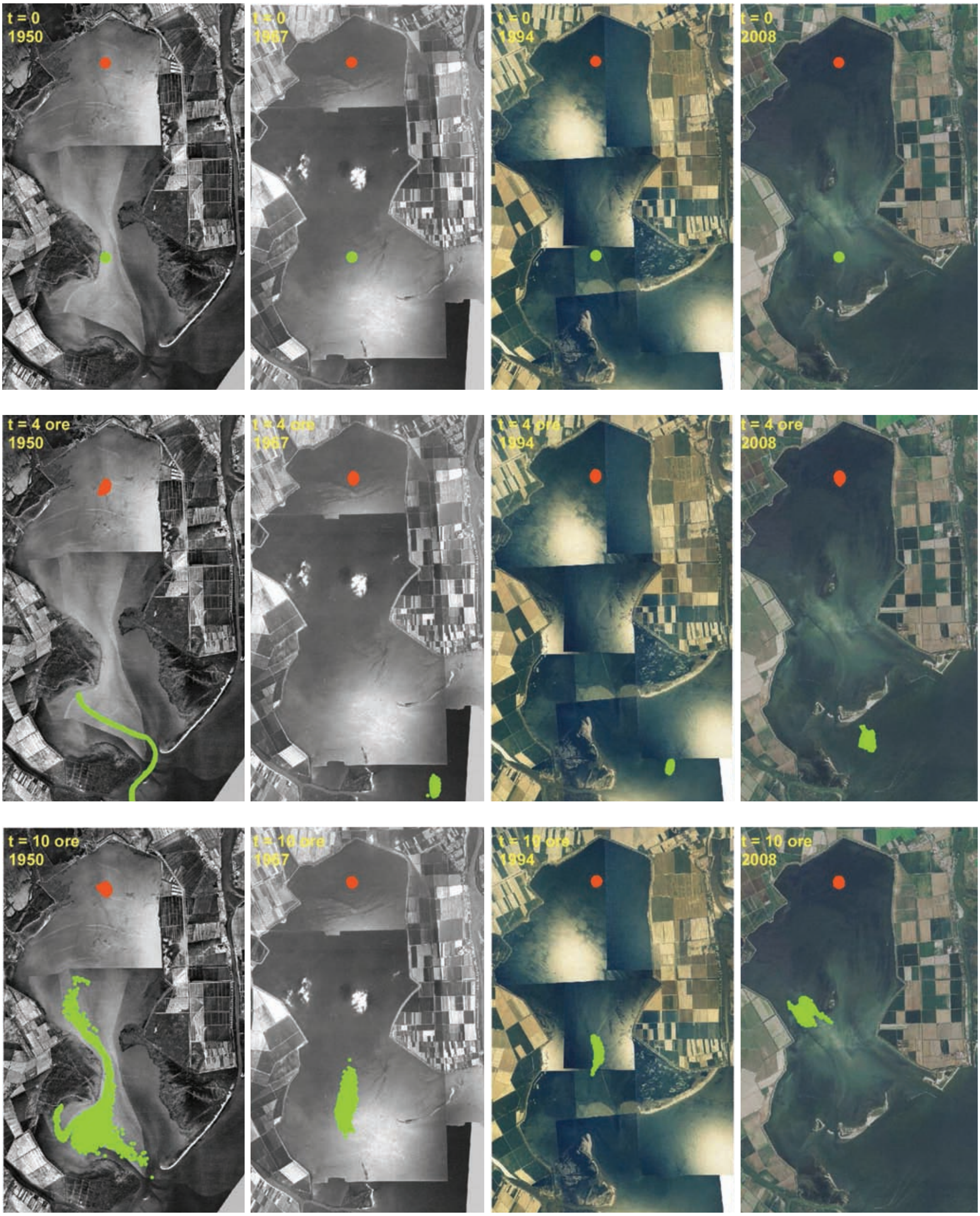


Figure 10: maps representing the dispersion of two "spots" of particles calculated using the Lagrangian-dispersion model for a sinusoidal tide.

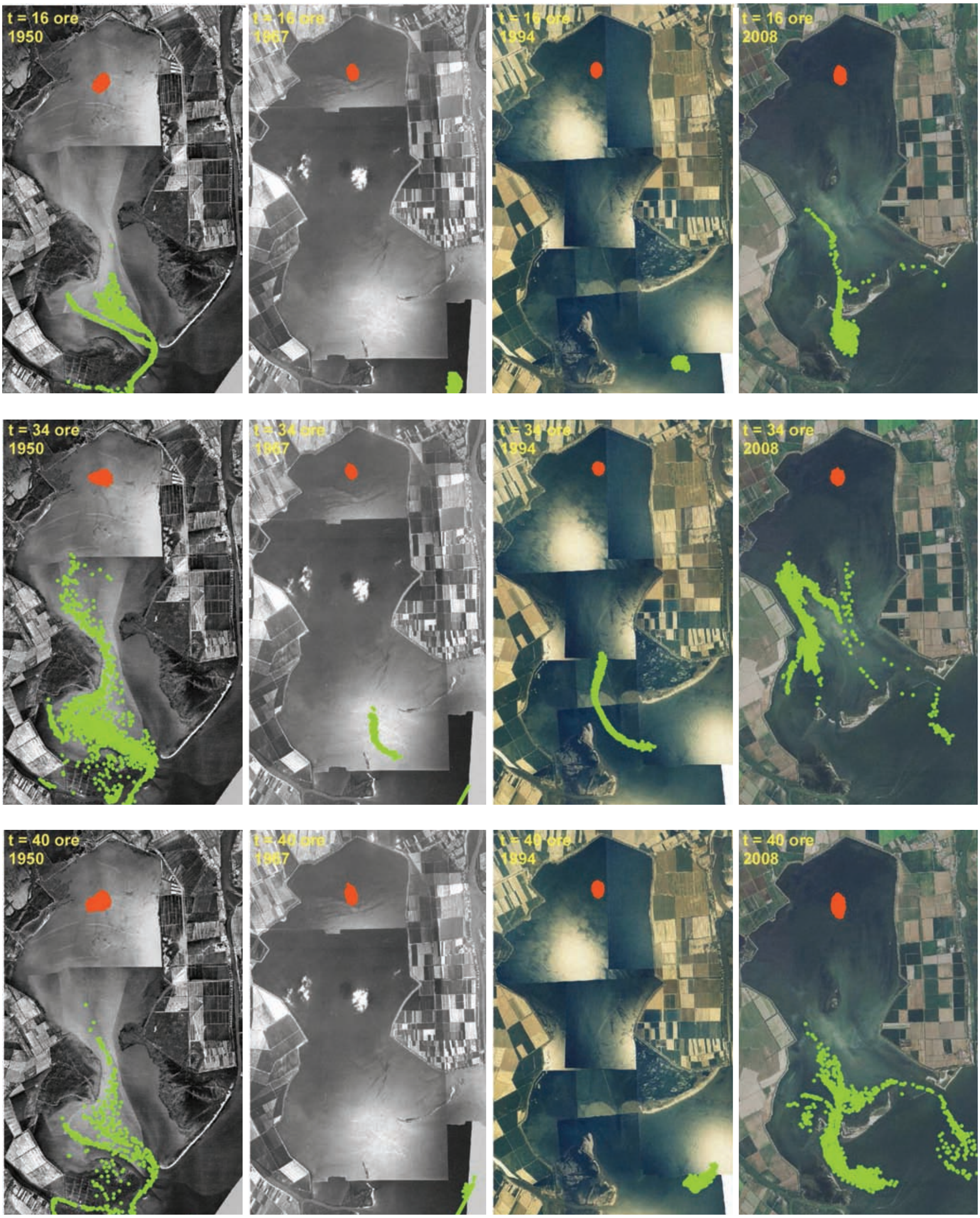


Figure 11: maps representing the dispersion of two "spots" of particles calculated using the Lagrangian-dispersion model for a sinusoidal tide.

The Sacca di Bottonera, where water exchange is directly supported by convective phenomena related to the propagation of tidal currents and is further favored by dispersion phenomena, in turn more significant also due to the fact that the bottoms are more articulated and as shown by the results obtained with the Lagrangian - dispersion model (Figure 10, 11), has favorable conditions.

In terms of these aspects, the opening of the North Outlet and the excavation of the internal canals appear to have been positive measures that were able to accentuate the overall convective dispersion, and hence water exchange.

Analysis of the Current Situation

Once the calibration of the mathematical model had been carried out, simulations were conducted with reference to a hypothetical 12-hour period sinusoidal tide varying between +0.5 and -0.5 m a.s.l. in order to examine the main features of the hydrodynamic circulation in the Scardovari lagoon.

This trend is representative of a spring tide situation, and compared to the current tides, allows for, due to its characteristics of periodicity and regularity, easier comparisons between different scenarios with respect to the current tides.

The simulation was extended to a 48-hour period, the first 24 hours of which were used for redering the system operational so as to lessen the influence of the initial conditions.

The other boundary conditions which, as already mentioned, have a virtually negligible impact on the results of the simulations, but which have to be assigned, were kept unchanged compared to the calculations conducted in the calibration phase. In particular, a hypothetical constant incoming flow of 50 m^3/s was assigned to the sections upstream of the Po di Tolle in order to represent the ordinary conditions of low water regime in that distributary of the Po.

Some of the Results Obtained using the Hydrodynamic Model

Figure 13 shows the results obtained for the tide levels in some selected points within the lagoon (Figure 12) and the flow rates through the two outlets and two transects inside the Sacca.

With reference to the levels, the oscillation of the tide in the lagoon seems somewhat out of phase with the sea, having a slight delay evidently due to the hydraulic resistance that the propagation of the tidal wave encounters when flowing over the outlets. Using the moment in which the tide crosses the portion 0.0m a.s.l. in the growing phase as a reference, this delay might be considered little more than 1 hour at point P1, located near the outlet, and almost 1.5 hours at points P2 and P3 in the inner portion of the Sacca.

With the points inside the lagoon there is an appreciable attenuation of the amplitude of the tide oscillation.

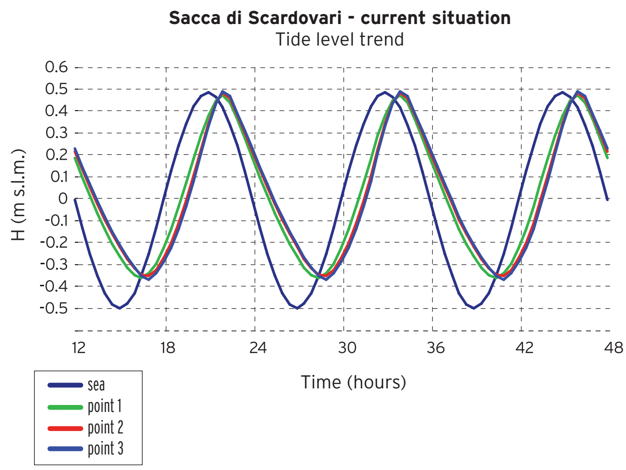
Figure 12: location of points and reference sections for the graphic representation of the simulation results.

Compared to the sea, the excursion is reduced by more than 10% (from 1m to 87 cm). The variation is due mainly to the attenuation of the dips, due to stronger dissipative effects which occur at low tide. The effects on the ridges that are substantially not reduced and indeed tend, in the case of the point P3 located at the edge of the lagoon, to grow slightly, are entirely insignificant.

It is interesting to note that, if variations of the tidal wave between the sea and the interior of the lagoon are extremely pronounced, the differences between the Sacca'a internal points are very small, so much so that they are almost negligible when compared to points P2 and P3.

What follows is that the dissipative effects encountered by the tide in its propagation in the lagoon are, as mentioned before, only relevant when flowing over the outlets. Within the basin however, these effects become practically negligible especially in the northern part of the Sacca where the bottoms are deeper (on average -2.0 to -2.5 m) and more morphologically uniform. Ultimately, in the internal parts, tide propagation is virtually instantaneous and liquid surface oscillation is “almost-static”.

With reference to flow (Figure 13 and Table 1), the calculation results show that for tide such as that under consideration, the maximum flow rates passing through the North outlet are approximately 850 m^3/s in the flow phase and 675 m^3 s in the ebb phase: slightly higher than that passing through the South Outlet. It also appears that the total volume exchanged over half a tidal cycle (6 hours) is about 11.5* 106 m^3 for the North Outlet and about 10.2* 106 m^3 for the South Outlet.



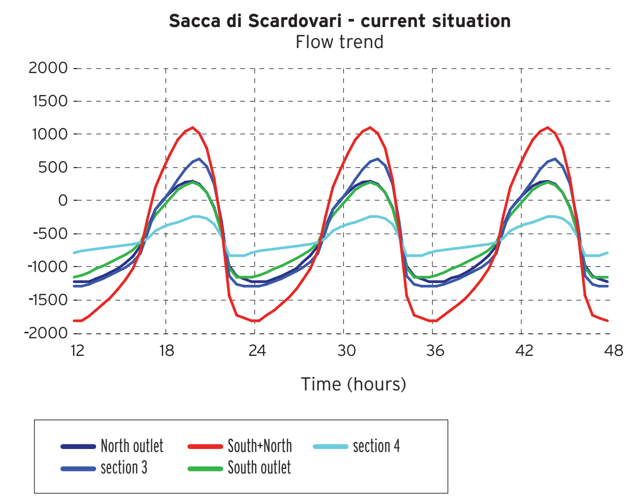


Figure 13: shows the results obtained for the tide levels in some selected points within the lagoon (Figure 12) and the flow rates through the two outlets and two transects inside the Sacca.

	North Mouth	South Mouth	Mouths Total	S3	S4
Qmax in (m^3/s)	839	823	1661	1189	306
Qmax out (m^3/s)	-677	-609	-1266	-744	-284
Volume exchanged (m^3*106)	11.52	10.19	21.70	14.13	3.90

Table 1: maximum flow during ebb and flow phases and total volume exchanged over half a tidal cycle in the sections shown in Figure 12.

In the latter case it must be emphasized that, like the previously mentioned situation, the section of the South Outlet under consideration (Figure 12) does not completely intercept the incoming and outgoing flow from the lagoon, because in high tide conditions the sand bar that borders the outlet to the west is submerged and is crossed by tidal currents in several places. However, the calculation shows that even considering this contribution, the result would not change substantially since the phenomenon of tolerance would mean, in terms of volume exchanged through the South Outlet, an increase of less than 5%.

According to Table 1 the two outlets exchange a total volume of 21.7* 106 m^3 with the sea over half a tidal cycle. Considering that the basin area falling under the outlets amounts to 26.5 km^2 and the excursion of the tide level within the basin is on average slightly more than 85 cm (Figure 13), according to the calculation the volume exchanged would be slightly lower than that which would result from considering a typical "static" pattern with equal peaks and dips everywhere. In fact in this case, the volume exchanged (at times also refered to "tidal prism") would be equal to 22.5* 106 m^3.

For sections S3 and S4, which intercept smaller parts of the inside of the lagoon, the maximum flow rates and volume exchanged are gradually reduced. For the section S3, under which a portion of the lagoon of approximately 16.5 km^2 falls, the volume exchanged is 14.1* 106 m^3, while in section S4, under which an area of 4:35 km^2 falls, the volume traded is 3.9* 106 m^3. In both cases the ratio between surface and volume exchanged is about 0.85 m, which coincides with tide excursion inside the Sacca. The result confirms what was previously mentioned, namely that the patterns of the Sacca as a whole differ little from that which is expected from a "static" model.

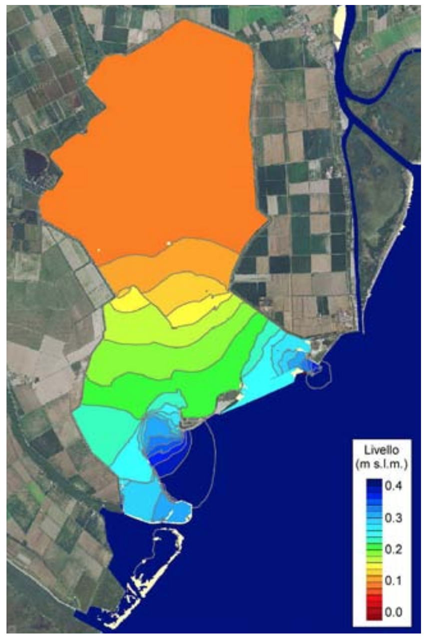


Figure 14: current Situation. Map of tide levels calculated using the two-dimensional model at maximum inflow (T=32 hours).

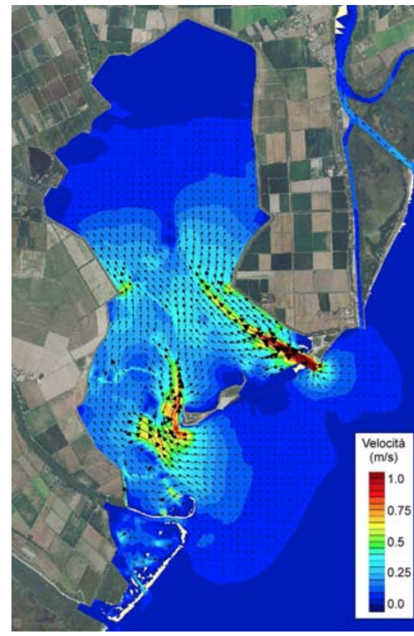


Figure 15: current Situation. Map of the speed of tidal currents calculated using the two-dimensional model at maximum inflow.

The tidal circulation dynamics within the Sacca are significantly described on the maps illustrating the distribution plan of tide levels and current speed.

At maximum inflow (Figure 14), one can see that the gradients of the levels are only significant at the two outlets and in the southern part of the Sacca (Sacca di Bottonera), where almost all the dissipative effects occur. In the northern part of the Sacca (Sacca di Scardovari) however, the free surfaces are practically horizontal. The instantaneous speed field obtained in the maximum incoming flow phase is shown in Figure 15, in which the form and direction of the speed are respectively represented by a colour scale and with vectors (having set the minimum limit of 5 cm/s in the representation of the vectors).

The speed values are only considerable (greater than 0.75 m/s) in the proximity of the two outlets to the sea, even if the speeds remain significant over the whole part of the Sacca

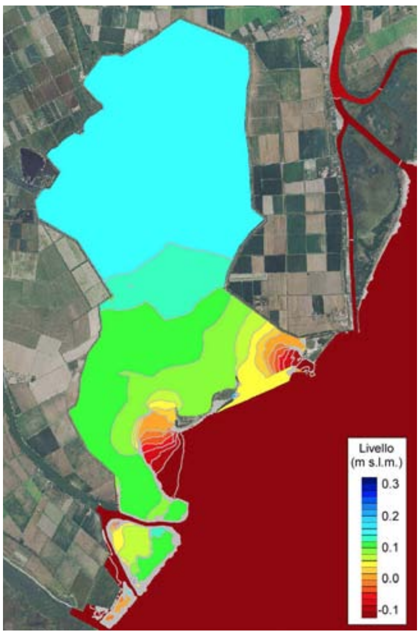


Figure 16: current Situation. Map of tide levels calculated using the two-dimensional model at maximum outflow (T=36.5 hours).

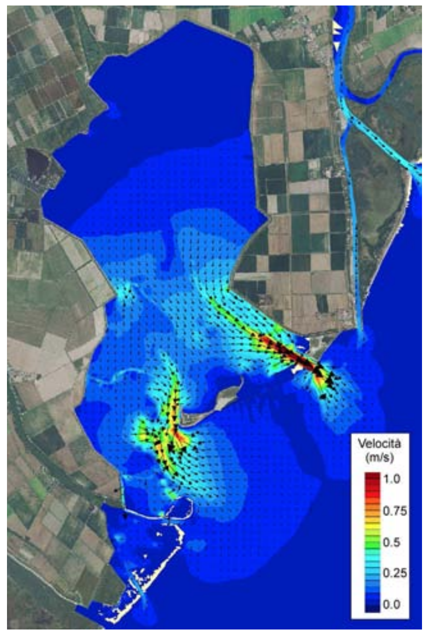


Figure 17: current Situation. Map of the speed of tidal currents calculated using the two-dimensional model at maximum outflow.

around the outlets, especially in the east.

In particular, one notes that along the canal penetrating the lagoon from the South Outlet, speeds remain higher than 0.5 m/s all the way up to Punta Garbin, i.e. the point which marks the separation of the two parts (Bottonera and Scardovari) of the lagoon.

The results obtained also show that a large part of the incoming current from the South Outlet tends to veer towards the east and follow a route in the center of the Sacca di Bottonera. Consequently, current circulation is not very active near the western edge of the Sacca. This situation is determined by the presence of a submerged barrier formed by the remains of the old embankment, which before sinking due to subsidence, bordered the part of the lagoon known as the "Canestro Area".

Evidence of this can be seen in the currentometric measurements, which indicate that the movement of tidal currents is appreciably more intense on the eastern side of the Sacca compared to that of the western side.

Ultimately, in most of the Sacca di Scardovari water surfaces, especially towards the northern margin, tide current intensity is very low, in fact almost negligible.

In Figures 16 and 17 the level and speed fields are represented in the outgoing flow phase. As the tide is considered sinusoidal, the hydrodynamic conditions that occur are, in substance, similar to those obtained for the incoming flow phase, even if their level gradients and maximum speeds are generally lower, as one would expect.

The Lagrangian-Dispersion Model Results

The two-dimensional hydrodynamic model simulations reveal that in a considerable part of the Sacca di Scardovari water surfaces, towards the northern edge, the intensity of tidal currents is very weak and virtually negligible in all tidal stages.

The reduced activity of tidal currents is considered among the leading causes of recurring problems of poor exchange occurring in this part of the basin, which give rise both to anoxic crises especially in the warmer seasons, both with the stagnation of fresh water introduced into the lagoon by the flooding of the Po, and in the presence of particular wind fields.

To highlight more clearly these aspects, a Lagrangian dispersion model simulation was conducted, which permitted the analyzing of flow and distribution of a certain amount of particles initially released within the lagoon and which move around due to the combined effects of "covective transport" induced by the tidal current and a "dispersive" component introduced to take into account, at least in first approximation, the effects of mixing that occur due to the turbulent nature of the flow.

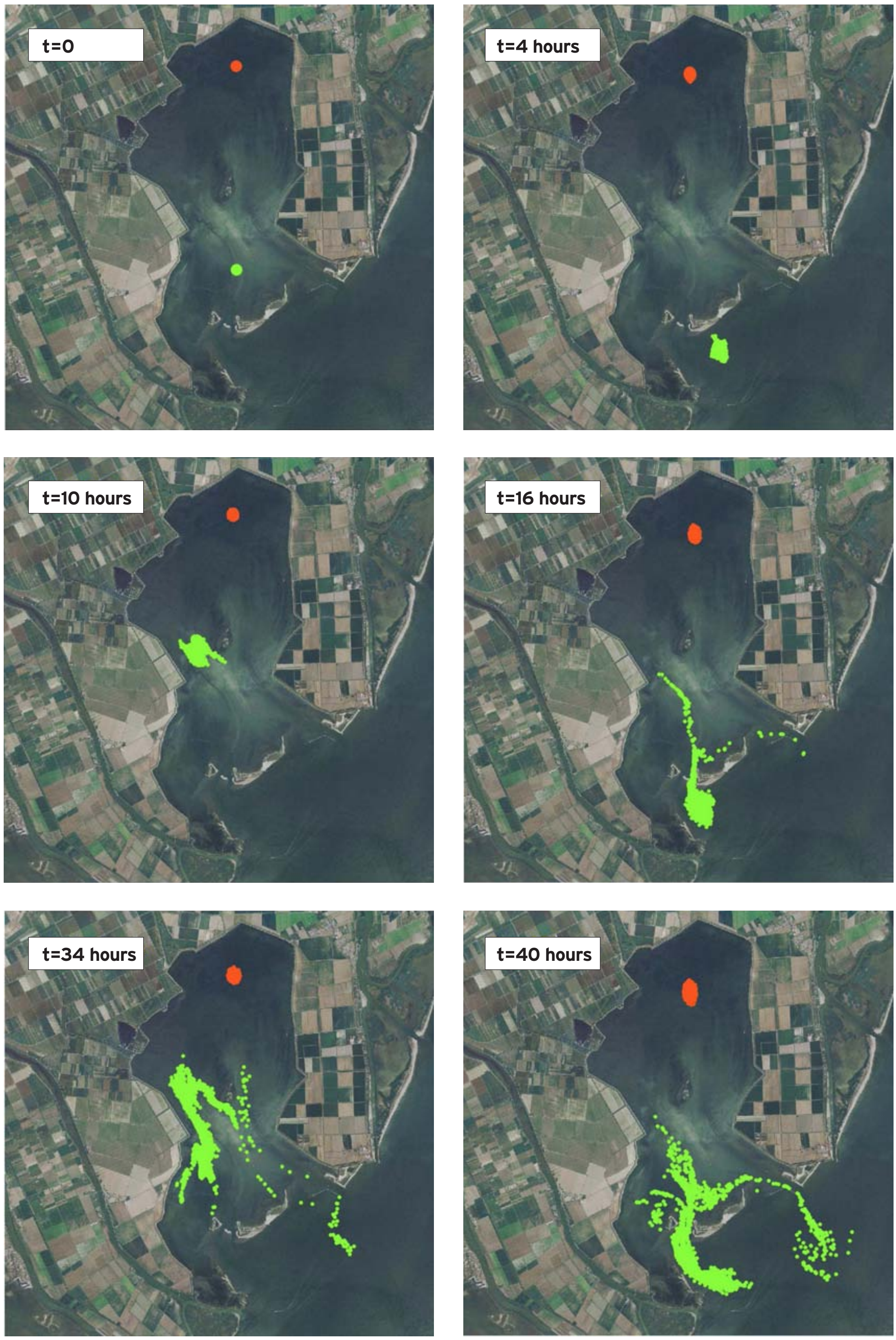


Figure 18: current situation. Simulation of particle transport for a sinusoidal semidiurnal tide oscillating between ±0.5 m a.s.l. using the Lagrangian model.

More specifically, the calculation was performed by releasing 2 "spots" each consisting of 4000 particles, in two different positions of the lagoon water surface belonging respectively to the Sacca di Bottonera and the Sacca di Scardovari itself (the northernmost part of the Sacca).

Figure 18 represents the particles' position in different moments of the simulation, using a 12 hour sinusoidal semidiurnal tide of 1m as an externally applied force. The images show the result of the calculation in and around the instant in which flow is reversed and the particles are at the maximum distance from their initial position.

Although the effectiveness of the representation is limited by the reduced number of instances taken into consideration, from the images one can see how the particles arranged in the vicinity of the outlet (in green) are those subject to more intense dynamics and that tend to move alternately in and out of the outlet itself. The dispersive effects of motion in turn tend to differentiate the trajectories of the particles which are progressively subject to accentuated distancing.

Vice versa, one notices how the particles released in the northern part of the basin (in orange) do not move substantially from their initial position.The result indicates that the convective –dispersive phenomena related to tidal currents and to the turbulence of the flow are very weak in these areas. One can conclude that in this part of the lagoon it might only be the dispersive phenomena induced by the wind that ensures more effective water exchange.

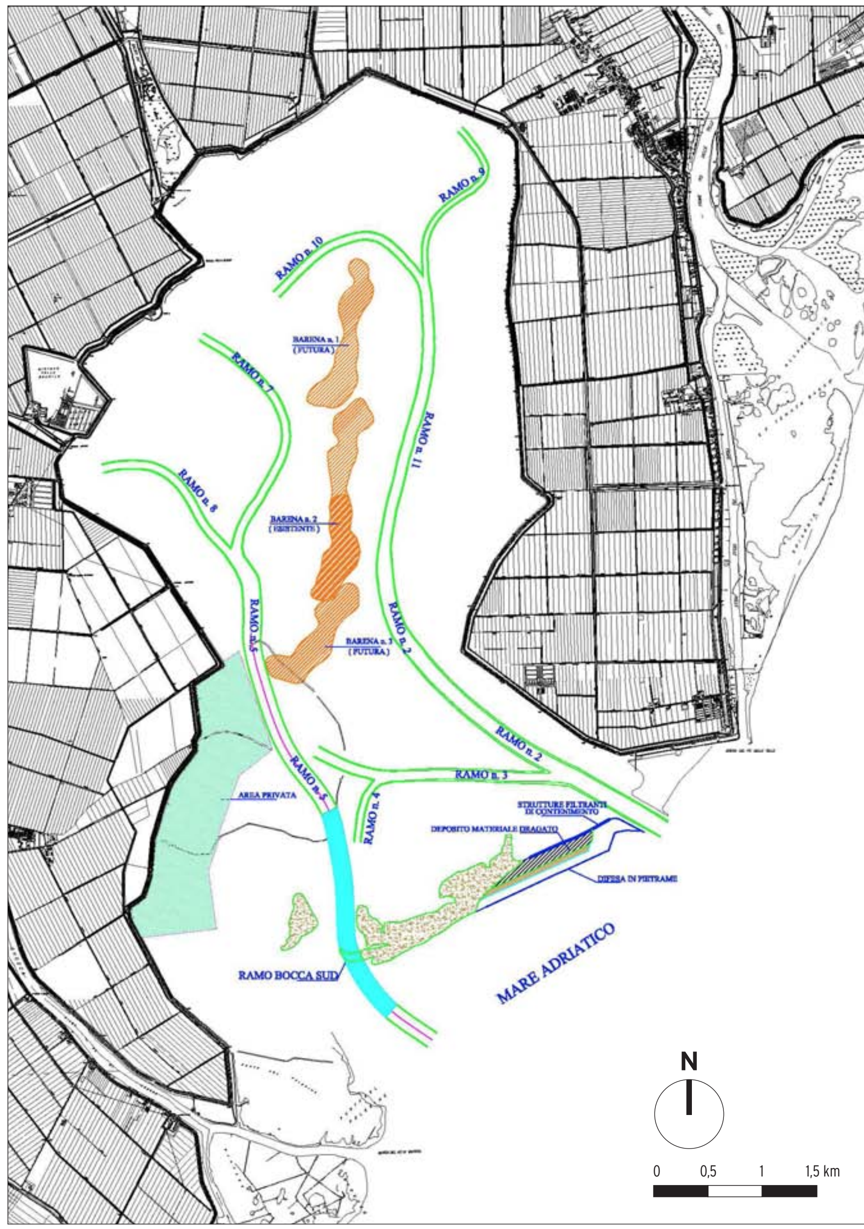


Figure 19: overall plan of the interventions foreseen by the Sacca vivification project.

The Effects of a Further Series of Interventions

The overall plan for the interventions forseen by the P.I.M. projects aimed at arranging and improving the Sacca di Scardovari's hydraulic regime, along with the opening of the North outlet, involved the digging of a canal system, the realization of a line of salt marshes in

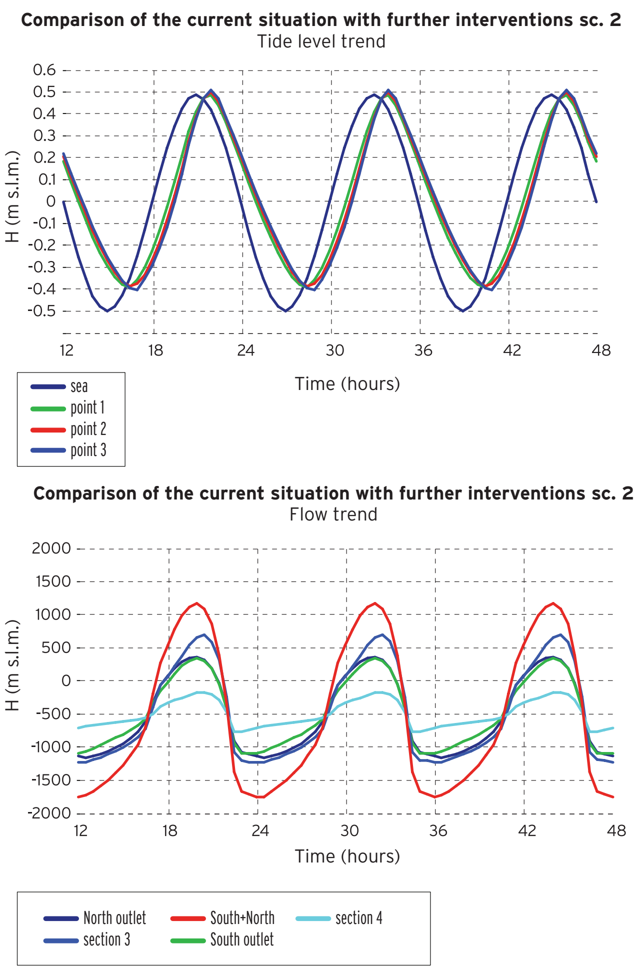


Figure 20: further series of planned interventions - Scenario 2. Tide level and flow trends calculated using the two-dimensional model in the points and sections indicated in Figure 12.

the middle of the lagoon and the construction of a manouverable barricade at the edge of the Sacca di Bottonera capable of completely intercepting tidal current flow moving into the Sacca di Scardovari itself through its western part (Figure 19).

Overall, the suggested measures made concrete the possibility of also actively exchanging the waters of the northern part of the Sacca by manouvering the barricade appropriately, which would fully intercept the tidal currents in the flow phase, thus enabling that area of the lagoon to be fed through canals and the shallow depths of the eastern part of the Sacca, while letting the current naturally evolve in the next ebb phase.

The maneuver, repeated with each tidal cycle, would induce secondary counter-clockwise circulation, allowing the complete exchange of tidal waters in the northern part of the Sacca in a few cycles, and to eliminate the problems that are still evident today and which may have an extremely negative impact on shellfishing activities. Despite the approval of the Progetto Generale di sistemazione della Sacca, only a small part of the planned interventions have been implemented.

There is a strong possibility that over the next few years, not only due to economic reasons, but also because of other considerations (which, unlike those at the time of the initial approval, make disadvantages in production acceptable), only a fraction of the planned measures will be realized. In particular, it is likely that the barricade will not be realized and the possibility of activating water exchange processes in the northernmost part of the Sacca will be renounced definitively, appropriately forcing the circulation of tidal currents.

From this perspective, it seemed worthwhile evaluating the extent to which, and to what benefit, the objectives of this project could be persued, on a smaller scale of course, only carrying out interventions that would not introduce excessive artificiality to the current regime within the Sacca, and that would be limited to considering modest changes to the morphological structure of the lagoon, respecting the "naturalness" of the coastal environment.

Canal excavation, Construction of the Saltmarsh Septum and Excavation of the South Outlet

Of the scenarios that are definetly compatible with the Sacca's "naturalness" is that which foresees the completion the excavation of internal canals according to the original P.I.M. program plan, and the realization of the saltmarsh septum in a south-north position in order to divide the Sacca di Scardovari's water surfaces and induce, as a consequence of the only propragatory phenomena, secondary sea current circulation (Scenario 1). In addition to these measures, one could

		current	Ulterior Interventions sc.1		Ulterior Interventions sc.2		Ulterior Interventions sc.3	
North Mouth	Qmax in (m^3/s)	839	897	6.9%	880	5.0%	880	5.0%
	Qmax out (m^3/s)	-677	-717	5.9%	-706	4.3%	-700	3.5%
	Volume exchanged (m^3*106)	11.52	12.46	8.2%	12.25	6.4%	12.24	6.3%
South Mouth	Qmax in (m3/s)	823	807	-2.0%	852	3.5%	861	4.6%
	Qmax out (m^3/s)	-609	-598	-1.8%	-632	3.7%	-634	4.1%
	Volume exchanged (m^3*106)	10.19	9.93	-2.5%	10.62	4.3%	10.67	4.8%
Mouths Total	Qmax in (m^3/s)	1661	1704	2.5%	1730	4.1%	1738	4.6%
	Qmax out (m^3/s)	-1266	-1286	1.6%	-1314	3.8%	-1312	3.6%
	Volume exchanged (m^3*106)	21.70	22.39	3.2%	22.87	5.4%	22.91	5.6%
section S3	Qmax in (m^3/s)	1189	1148	-3.4%	1166	-2.9%	1166	-2.0%
	Qmax out (m^3/s)	-744	-766	3.0%	-779	4.7%	-782	5.0%
	Volume exchanged (m^3*106)	14.13	14.40	2.0%	14.66	3.8%	14.69	4.0%
section S4	Qmax in (m^3/s)	306	311	1.7%	317	3.7%	317	3.5%
	Qmax out (m^3/s)	-284	-266	-6.3%	-267	-5.9%	-269	-5.3%
	Volume exchanged (m^3*106)	3.90	4.01	2.7%	4.11	5.1%	4.11	5.3%

Tabella 2: comparison of maximum flow during ebb and flow phases and the total volumes exchanged over a tidal half-cycle in the sections shown in Figure 12 for the different scenarios considered.

hypothesise a dredging operation intervention in the South Outlet to bring the current bottoms to at least -2.5 m a.s.l, resulting in more activity than the North Outlet (Scenario 2).

One could possibly add the removal of the obstacle made up of the remains of the delimitation of the already mentioned "Canestro Area" which occupies the western part of the Sacca di Bottonera. In this way one could facilitate the penetration of tidal currents along the western part of the Sacca (Scenario 3).

The calculation results show, for the assumed sinusoidal tide reference, how the complex of foreseen interventions in all cases examined, did not significantly affect tide level trends inside the Sacca (Figure 20 top) and involves limited modifications (of a few percent) to the flow moving through the outlets and that exchanged between the Sacca di Bottonera and the Sacca di Scardovari itself (Figure 20 bottom, Table 2).

The effects of the measures foreseen for the instantaneous tidal level distribution and their gradients in maximum flow and maximum ebb phases (Figure 21 to 23) are more significant.

Compared to the current situation, the level gradients tend to differ more in the Sacca di Scardovari itself. As a result, flow is faster in this part of the lagoon both in inflow (Figure 22) and ebb (Figure 24) phases. The watershed line also tends to shift in an anticlockwise direction, with the lagoon part hydraulically further away from the outlets, which now tend to be fed by water coming mostly from the North Outlet (Figure 22 to 24).

For purposes of water exchange, the results obtained by examining the movement of a spot of particles initially released in two different positions of the Sacca (Figure 25 to 26) with the Lagrangian-dispersive model, are particularly significant and easily interpretable. The comparison with the current situation highlights an appreciable enhancement of the dispersive phenomena for the Sacca di Bottonera.

Even the water surfaces situated in the far northern part of the lagoon are affected by more dispersive effects, yet still far from those that the full implementation of the P.I.M. project in its original formulation would have been able to guarantee. The dredging, even if somewhat modest, scheduled for the South Outlet, together with the excavation of the internal canals (Scenario 2) improves conditions of tidal current flow especially in the Sacca di Bottonera. The result is easy to see and is due to increased flow through the South Outlet (Table 2).

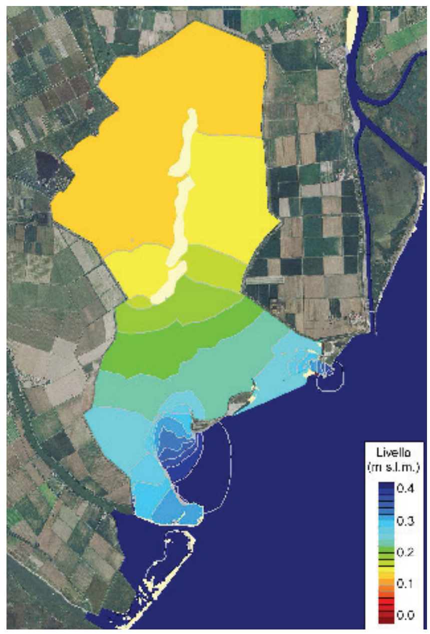


Figure 21: further series of planned interventions - scenario 2. Map of tide levels calculated using the two-dimensional model at maximum inflow (T=32 hours).

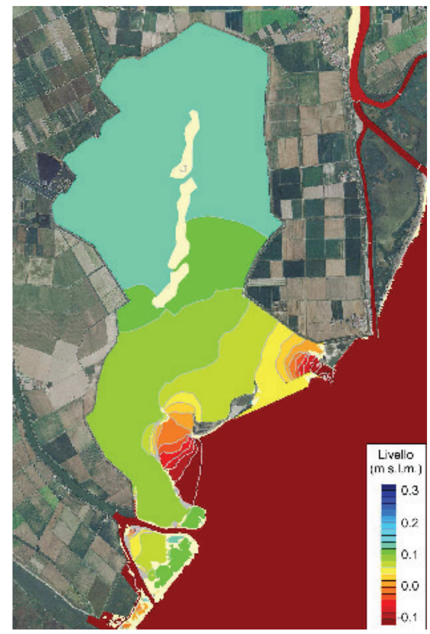


Figure 22: further series of planned interventions - scenario 2. Map of tide levels calculated using the two-dimensional model at maximum inflow (T=36,5 hours).

However, the benefits to the water surfaces of the Sacca di Scardovari itself, for which the water exchange conditions remain problematic due to oft-cited reasons, are still modest.

These conditions generally do not have strong negative impacts on water quality. In some cases however, or for high temperature situations, like those occuring in the summer months or the excessive sweetening of the water, like that which can happen when the Po di Tolle and Po do Gnocca distributary flow rates significantly increase, one cannot exclude problems affecting mussel farming, quite similar to those that have been recorded in recent years.

THE EFFECTS OF VARIATIONS IN EFFICIENCY IN THE MOUTHS OF THE PO DISTRIBUTARIES

In addition to the analysis of tidal current circulation in the Sacca di Scardovari, the two-dimensional finite element model was used to analyze the hydraulic functioning of the terminal section of the Po and the distributaries making up the deltaic system, two of which, the Po di Gnocca and Po di Tolle, open into the sea very nearby the coastline that delimits the lagoon. One of them, the Po di Tolle, was the subject of interventions aimed at facilitating the channeling of flood flow to the sea through the opening of a new distributary (the Busa Sto-

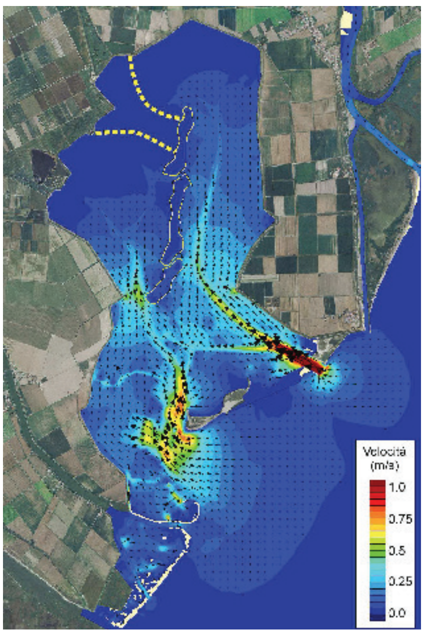


Figure 23: further series of planned interventions - scenario 2. Map of tidal current speed calculated using the two-dimensional model at maximum inflow (T=32 hours). The limits of the area where the water meets is show in yellow.

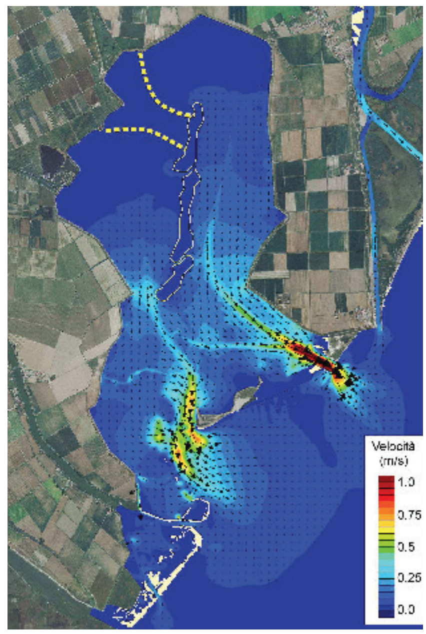


Figure 24: further series of planned interventions - scenario 2. Map of tidal current speed calculated using the two-dimensional model at maximum outflow (T=32 hours). The limits of the area where the water meets is show in yellow.

riona), without considering the alterior consequences of the intervention itself and in particular, those caused by the moving of the deposition point for sediment channelled by the river current to a different position along the coast.

The Two-dimensional Model of the Terminal Stretch of the Po River and its Distributaries

The implementation of the model was based on a schematic aimed at assessing the navigability of the river as part of the Porto Tolle thermal power plant conversion project. The computation domain (Figure 27) includes the terminal stretch of the Po (Po di Venezia and Po di Pila) from the Corbola cove to the sea (about 42 km), as well as the 6 distributaries into which the river is divided in its terminal section (Po di Gnocca, Po di Maistra, Po di Tolle, Busa Dritta, Busa di Tramontana e Busa di Sirocco). Given the purpose of the investigation at the time, the model was used to analyze the functioning of the hydraulic system, mainly in low water conditions.

It can however, also be used to investigate high water situation, to analyze the two-dimensional flow field and the associated bottom and suspended sediment phenomena, as well as, in extreme cases, flooding phenomena. More specifically, the implemented scheme can be generalized to allow multilayer 3D model simulations once the number of layers in which the water column is to be divided and the dimensions of each layer have been decided. Therefore once the model has been fine tuned, it is possible to carry out simulations of the dynamics of the currents in order to investigate, for example, the reoccurence of salt wedge phenomena along the different distributaries of the Po and the possible interaction between freshwater flow from the different delta branches of the river and the saline sea waters that receive it.

The geometry of the sections of the different distributaries of the Delta has been substantially reconstructed using the data made available by the Agenzia Interregionale per il fiume Po di Parma (A.I.PO) and Enel, who, albeit in different periods, have conducted topo-bathymetric surveys along the river.

Herefollows a list of summarized information on the data used for the mathematical modeling, in which the number of available sections and the data source for each delta river distributary can be found:

- Po di Venezia, Po di Pila, Busa Dritta: the sections identified in the 1998-1999 Ministero dei Lavori Pubblici – Magistrato per il Po – Parma study "Upgrading the sections and profiles of the River Po and its embankments" were considered for the main distributary of the Po, which varies its hydronym proceeding downstream. In particular 25 sections were used, from No. 75A in the Po di Venezia at Corbola, to No. 90 at the Busa Dritta outlet the sea;

- Po di Gnocca: for this sub-distrib-

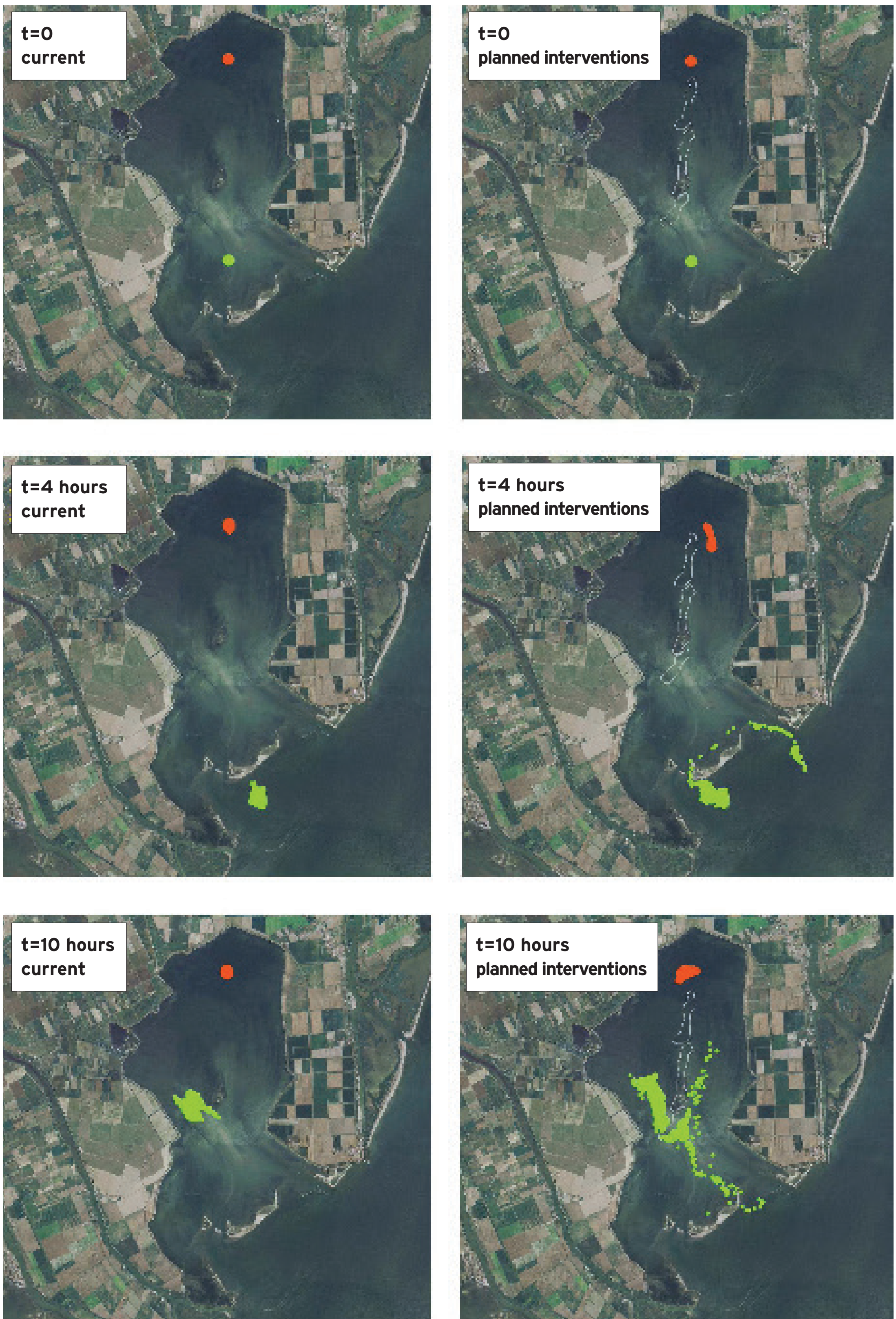


Figure 25: comparison of the current situation with forseen interventions (sc.2). Simulation of particle transport of the semidiurnal sinusoidal tide oscillating between ± 0.5 m a.s.l. using the Lagrangian model.

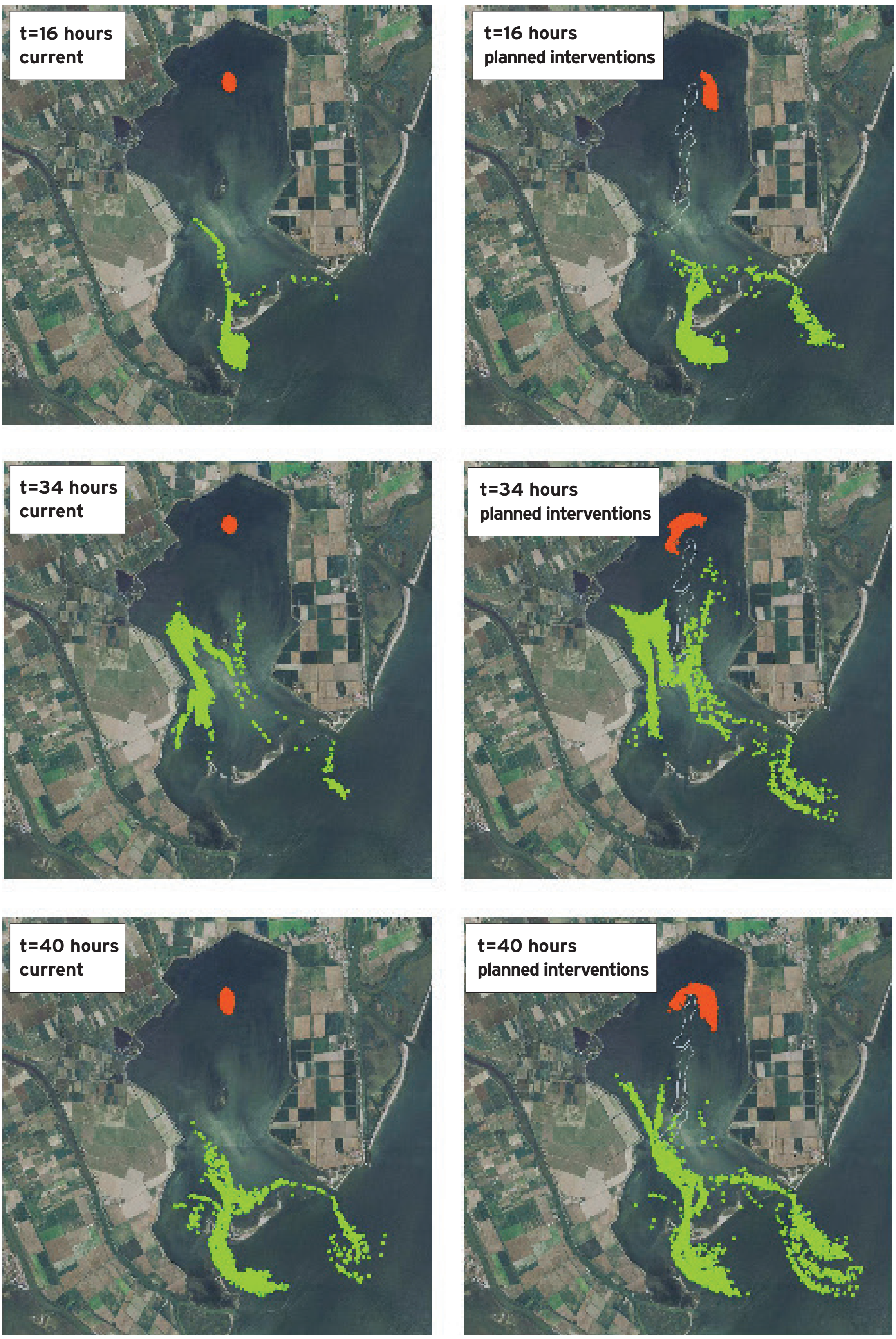
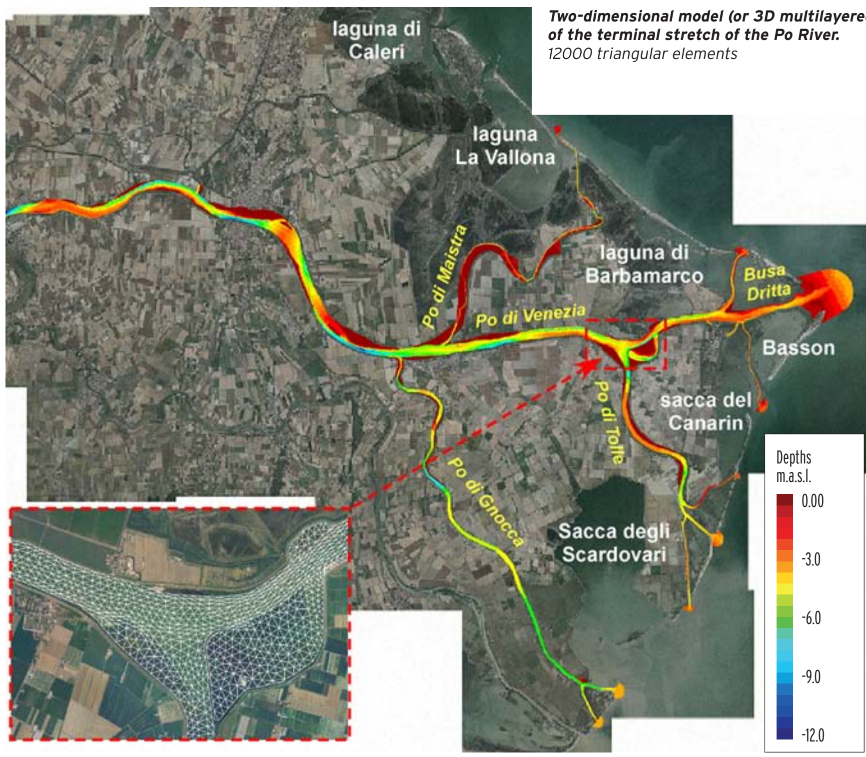


Figure 26: comparison of the current situation with forseen interventions (sc.2). Simulation of particle transport of the semidiurnal sinusoidal tide oscillating between ± 0.5 m a.s.l. using the Lagrangian model.



Two-dimensional model (or 3D multilayered) of the terminal stretch of the Po River.
12000 triangular elements

Figure 27: two-dimensional finite element model of the terminal stretch of the Po and the delta distributaries downstream of the Corbola cove.

utary of the river 40 topographical sections were taken into consideration starting with its branching off to the outlet to the sea as surveyed in 1996 and made available by AIPO;

- Po di Maistra: for this sub-distributary of the river, 25 sections were taken into consideration starting with its branching off to Ca' Venier all the way to the outlet into the sea as surveyed in 1996 and made available by AIPO;

- Po di Tolle and the Busa del Bastimento: for this sub-distributary of the river, 36 sections were taken into consideration starting with its branching off from the Po di Venezia all the way to the successive branching off at Busa del Bastimento as surveyed in 1996 and made available by AIPO. For the terminal stretch of the Po di Tolle, to the outlet to the sea at Porto Barricata, and for the branching off of the Busa del Bastimento, 28 sections and 13 sections surveyed in 1989 by the Magistrato per il Po – Ufficio Operativo di Rovigo as part of the "Systemization Interventions to the Po delle Tolle Mouth in the Bonelli Area" work, were refered to.

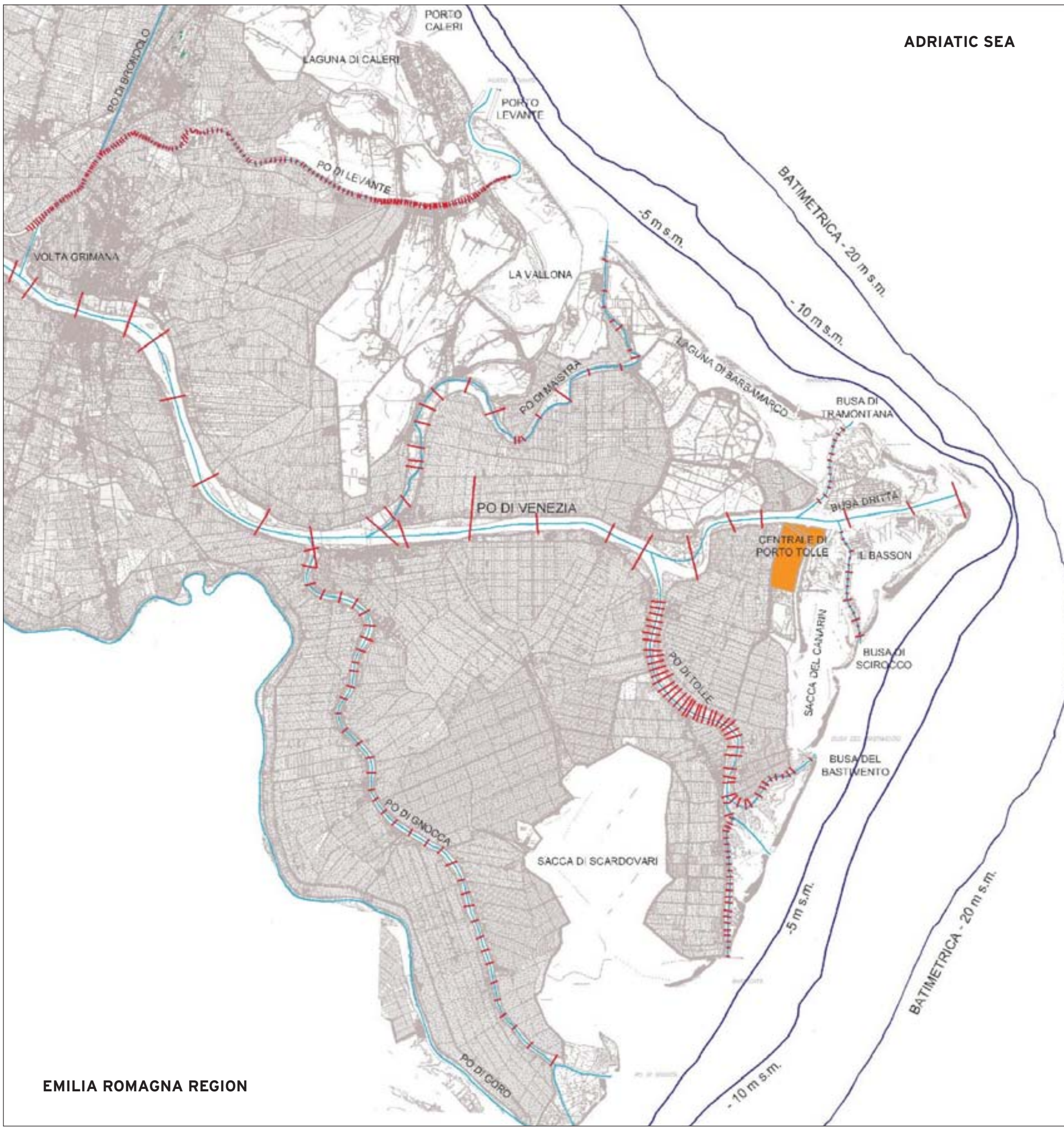
- Busa di Tramontana: for the mathematical model schematic of the last distributary of the river that branches off to the left of the Po near the town of Pila, 12 sections surveyed by Enel in 1972 as part of preliminary studies in the realization of the Porto Tolle power station, were taken into consideration;

- Busa di Sirocco: for this distributary, which develops between the Sacca del Canarin and Basson, to the right of the Busa Dritta, downstream of the Porto Tolle power station, 17 sections, as surveyed by Enel in 1972 as part of preliminary studies in the realization of the aforementioned power station were taken into consideration.

The schematic of the various river distributaries is based not only on the aforementioned geometric elements, but also on aerial photographs in order to verify the planimetric layout of the riverbeds, and the on the 1:5000 scale Regional Technical Map in order to define the coordinates of the holm areas between one section and the next.

The distribution of the available sections (Figure 28) provides acceptable coverage of the computation domain. It must however be noted that the sections, with the exception of those relating to the Po di Venezia -Po di Pila, are derived from extremely dated surveys and could provide a somewhat outdated representation of the geometry of the system. In order to update the schematization of the different distributaries of the river, the most recent surveys avail-

Figure 28: the Po river delta showing the position of the topographical sections of the waterways as surveyed by the competent bodies.



able, consisting of a series of sections carried out on the main branch of the Po and on other branches of Delta in 2005 by AIPO and ARPAV (Figure 29), were refered to.

Examining the locations of these sections reveals, on one hand, that the Po di Venezia -Po di Pila sections are located on the same line as the previous ones (Figure 28), and on the other hand, that there are too few sections in the secondary distributaries (3 sections in the Po di Gnocca, 3 in the Po di Maistra, 4 in the Po di Tolle - Busa Bastimento – Busa Storiona, and none in the Busa di Scirocco and Busa di Tramontana) to provide a satisfactory description of the geometry of the distributaries themselves. It is for this reason that it was not considered appropriate to update the original geometry of the model in some cases, especially since some preliminary checks carried out at the outset showed that the geometry introduced in the scheme can be considered hydraulically equivalent to that which would be obtained using the new data.

The Model of the Terminal Distributaries of the Po, the Lagoons and Coastal Strip

The need to estimate not only the flow transiting through the Po distributaries, and in particular along the Po di

Figure 29: location of the new sections (2005 survey) provided by Arpav.

Tolle and its distributaries, but also the resulting sediment transport in correspondence to the mouths, has necessitated the expansion of the two-dimensional Po distributary model in order to include a wide range of open sea in front of the mouths themselves, in the computation domain.

In this way it is possible to more realistically describe the transport and distribution of suspended sediment material in river currents. At the same time, it is possible to compare the calculation with the analysis of the effects of coastal sediment transport due to the action of currents induced by waves and their interaction with the mouths of the Delta and its lagoons in general.

If we consider the dynamics of sediment transport in terms of the combined effect of river flow and wave motion, the river mouth behaviour patterns often interfere with that of the adjacent lagoon outlets.

For this reason it is appropriate that the model computational grid also includes the lagoons, in order to evaluate any influence of the branches of the delta on flow exchanged through the lagoon outlets due to the effects of the tide. The two-dimensional model allows both of these phenomena, in their complex interaction, to be analyzed, the only limit being computational in cases in which the detail of the grid needs a reduced calculation step due to a very high number of nodes.

A preliminary application of the model according to the above approach, with general rather than local objectives, was conducted as part of a study carried out in 2006 on behalf of the Consorzio di Bonifica Delta del Po. [11] In this survey, which focussed on the regime of coastlines in front of Barbamarco and Canarin lagoons, the two-dimensional model of the Po had already been expanded, including the Sacca del Canarini and Sacca di Scardovari in its domain.

In a further amendment, starting from the shoreline, the computation domain was extended to the open sea, so as to include the entire stretch of coast which could hypothetically be affected by current circulation owing to the tide, and that generated by waves. This stretch is on average about 8 km long, and in some parts extends from the out-

Figure 30: two dimensional model of the terminal distributaries of the Po Delta, its lagoons and the stretch of sea (Matteotti/D'Alpaos - 2006 [11]) with the addition of the Sacca di Scardovari and the stretch of sea facing it.

er edge towards the sea to the bathymetric depth of -25.00 m a.s.l.

Taking the purposes of the survey into account and focusing in particular on the role of the Po di Tolle and of the most recent interventions carried out on it, the Delta distributaries' general pattern was reduced, excluding the branches that are not directly affected in the phenomena investigated from the calculation. The upstream section of the model was therefore set downstream of the Po di Maistra inlet, excluding it from the calculation, as well as the Po di Gnocca.

Ultimately, the model foreseen covers an area of about 343 km^2 and consists of approximately 26600 nodes and 50500 triangular elements. Obviously, it also includes the Sacca di Scardovari and the shoreline in front of it. To this end it was decided to assemble the computational grid developed in the study [11] with that prepared for the analysis of the Sacca's circulation, illustrated here. The resulting computational grid is represented in Figure 30. It covers an area of about 450 km^2, and consists of about of about 46500 nodes and 90000 triangular meshes.

Figure 31 provides a color scale representation of the bathymetry of the computation domain. It is clear how detailed the network is. The dimensions of the sides of the meshes vary from a minimum of about 5m, where the geometry of the system is shown in the highest resolution, to a maximum of about 500m for the larger mesh placed close to the outer edge in the sea.

Apart from the areas along the coasts and at the mouths and lagoon outlets, mesh sizes are generally also very small in all the lagoons. They thus permit very detailed simulations of phenomena that cannot be overlooked in the interaction between the flow field at sea and that in the internal waterways. In particular this refers to transport phenomena (salinity, suspended sediment transport, and the diffusion of conservative and non-conservative substances) and wind induced effects on circulation.

With these computational grid characteristics, given the integration time needed to obtain a stable numerical solution (in the order of 2s), the calculation times required are rather high. In fact in the case of a two-dimensional simulation in which the hydrodynamic problem is coupled with suspended transport, the duration of the simulation on a personal computer of average power is equal to about 1/10 in real time. The prepared model therefore cannot be used for longer two-dimensional simulations (e.g. in the order a month), nor for simulations with the multilayer 3D model unless resorting to adequately powerful calculation tools or using, as is possible, a parallel version of the prepared sequential code.

Alternatively, should very expensive simulations be conducted, it is possible to, with a minimum of intervention, "thin out" the computational grid by increasing the size of the mesh either in a general or limited way, in areas in which it is possible to dispense with the extreme detail of the numerical solution in favor of acceptable calculation times.

Simulation Results

The two-dimensional model of the terminal distributaries of the Po Delta, its lagoons and the sea facing it was used, on one hand, to evaluate the dis-

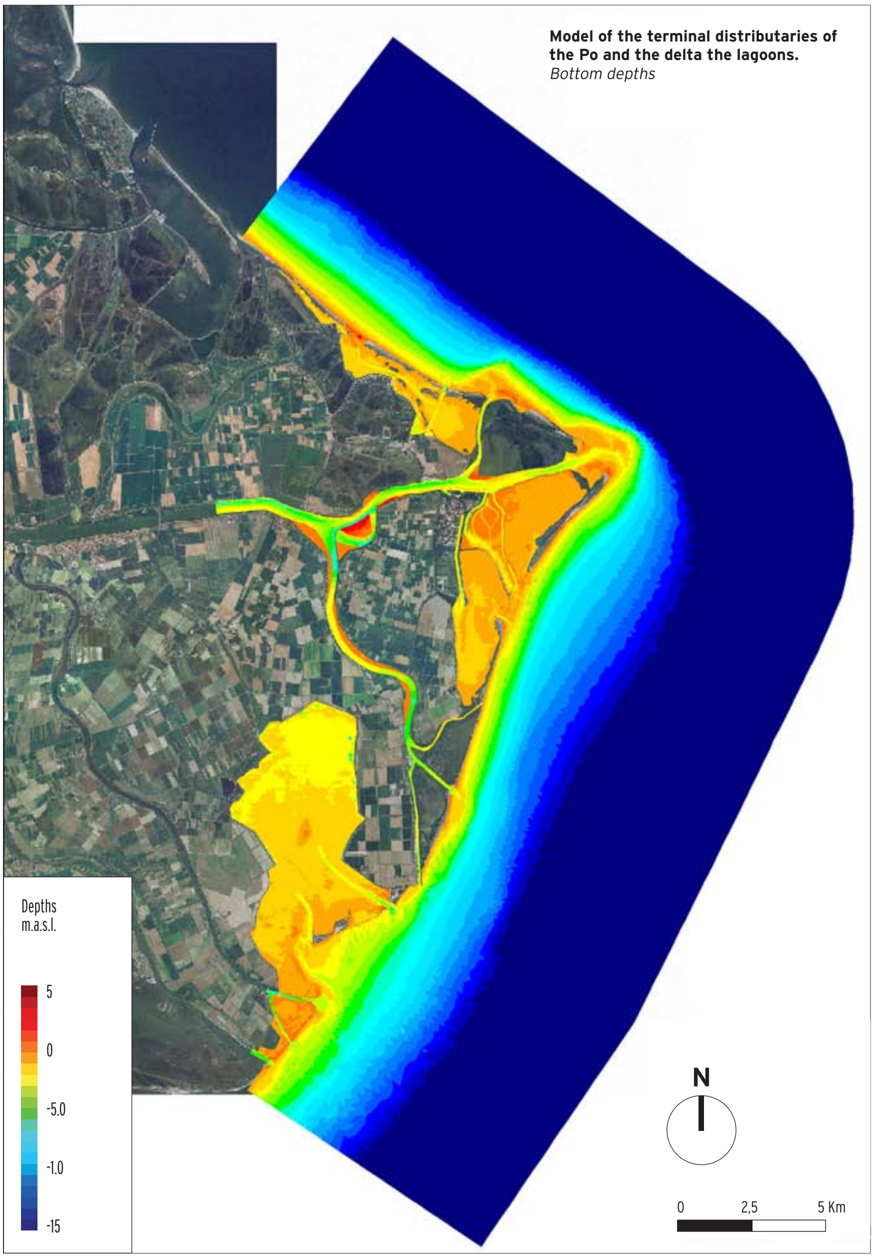


Figure 31: schematic of the bathymetry of the new two-dimensional model of the terminal distributaries of the Po Delta, its lagoons and the sea facing it.

tribution of flood flow between the three distributaries which the Po di Tolle is divided into as it flows into the lowlands known as "Bonelli" before flowing into the sea, and on the other, to evaluate the effects of this distribution on suspended sediment transport and therefore the contribution of river sediment along the adjacent coastline.

In order to get a better idea of the problem, the Consorzio di Bonifica Delta del Po carried out some flow measurements in hydrometric conditions affecting the Po in order to obtain experimental data regarding the aforementioned distribution. The measurements were conducted on 28 November 2007 using an ADCP current meter in conditions in which the Po was characterized by flow rates up to 2000 m^3/s at Pontelagoscuro, as a result of a low water event with a peak flow verified on 26/11 of little more than 2500 m^3/s. This is a relatively low flow rate, which determines conditions influenced by syzygial tide, measurements of which were made several times throughout the day.

Figure 32 shows the location of the 3 measurement sections taken into consideration and included in a table showing the measured flow values. It is apparent that even with substantial flow variation due to tide fluctuations, the fraction of the Po di Tolle flow that runs into the sea through the Busa Storiona (the newly excavated distributary) remains more or less constant, and makes up on average 76% of the total flow coming from upstream.

The temporal variation of the flow crossing the old mouth distributary towards Punta Barricata and the Busa del Bastimento is bigger. On average this flow accounts for 17% and 7% of the total respectively.

It is clear according to the results obtained, that the Busa Storiona distributary, built in the late 1980s by the Magistrato per il Po and recently upgraded, is currently by far the most active distributary of the Po di Tolle, while flow moving through the other two distributaries is heavily penalized. Consequently, even in

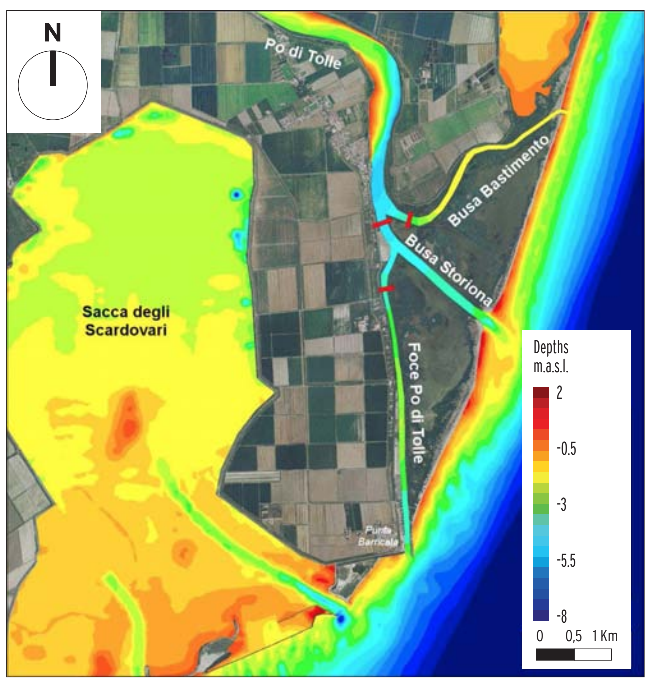


Figure 32: flow rate measurements on the three distributaries into which the Po di Tolle is divided before reaching the mouth as conducted by the Consorzio di Bonifica Delta del Po on 28 November 2007.

Bastimento (m^3/s)	**Po di Tolle monte** (m^3/s)	**Po di Tolle valle** (m^3/s)	**Storiona calc.** (m^3/s)	**Bastimento** %	**Po di Tolle valle** %	**Storiona** %
28.2	352.8	56.1	296.7	7.4	14.7	77.9
33.5	300.1	48.2	251.9	10.1	14.4	75.5
23.5	303.1	51.9	251.3	7.2	15.9	76.9
35.0	323.7	57.2	266.5	9.8	16.0	74.3
24.1	374.5	67.9	306.6	6.1	17.0	76.9
28.0	417.3	71.6	345.7	6.3	16.1	77.6
25.1	457.4	95.6	361.8	5.2	19.8	75.0
24.2	512.7	103.8	408.9	4.5	19.3	76.2
21.0	514.6	108.8	405.8	3.9	20.3	75.8
			Medium value	**6.7**	**17.1**	**76.2**

terms of sediment transport, the Busa Storiona's contribution to the transport of sediment towards the sea should be higher than that of the other two distributaries. It is therefore possible that in recent years there has been a reduction of sediment discharge on the coasts adjacent to the old mouth of the Porto Barricata of the Po di Tolle, hence those of the Sacca di Scardovari. This aspect should be carefully considered, in the light of the intense erosive processes that seem to have occurred at the expense of the coastal strip that physically delimits the Sacca from the sea.

Based on these conditions, in order to examine the current distribution of liquid and sediment transport at the mouth of the Po di Tolle, a simulation was made of the flooding that occurred between 16 November and 25 December 2002, characterized by two peaks in close proximity and a maximum estimated flow rate at Pontelagoscuro of about 7000 m^3/s (Figure 33), which would have a return period of about 5 years [11].

Since the model's computation domain is limited to the terminal part of the Po, downstream of the Po di Maistra inlet (Figure 31) a preliminarily simulation using the model covering entire Delta was conducted in order to assess flow trends upstream of the computational grid.

Figure 33 also shows the comparison between flow trends estimated at Pontelagoscuro and that which was calculated in the above section, of which the peak flow is approximately 4500 m^3/s. The difference with Pontelagoscuro lies in the subtractions of flow due to the upstream delta distributaries not reproduced in the diagram (Po di Goro, Po di Gnocca, Po di Maistra). Tide levels recorded by the tide gauge at Porto Caleri in the simulated period were assigned to the nodes of the open boundary with the sea. Wind recorded at the Porto Tolle station and the movement of the bottoms were also taken into consideration.

The parameter values controlling sediment transport phenomena were determined using relations proposed in technical literature since experimental data needed for their specific identification was not available. Regarding bottom sediment grain size, a representative diameter of d50 of the material equal to 0.1 mm, typical of fine sands, was considered.

It should be noted that the modeling of a moving bed must be primarily aimed at understanding the phenomena in a qualitative sense, allowing for the identification of areas subject to erosion and/or deposition of sediments, while not being free from uncertainty regarding the effective and accurate quantification of changes to bottom depths. A better understanding from a quantitative point of view of the erosion and/or deposition processes classified by the calculation would require tests and experimental controls that are currently unavailable.

Regarding sediment transport, the boundary conditions introduced consist of the assigning of sediment transport exchange to the nodes on the boundary the computation domain.

The assumption translates to the identification of a number of nodes where it is assumed that there is a balance in sediment transport, i.e. there is

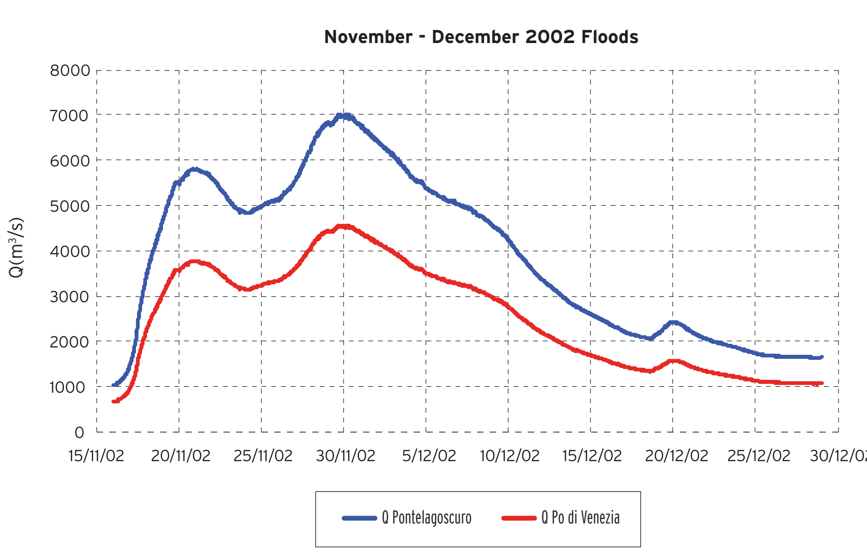
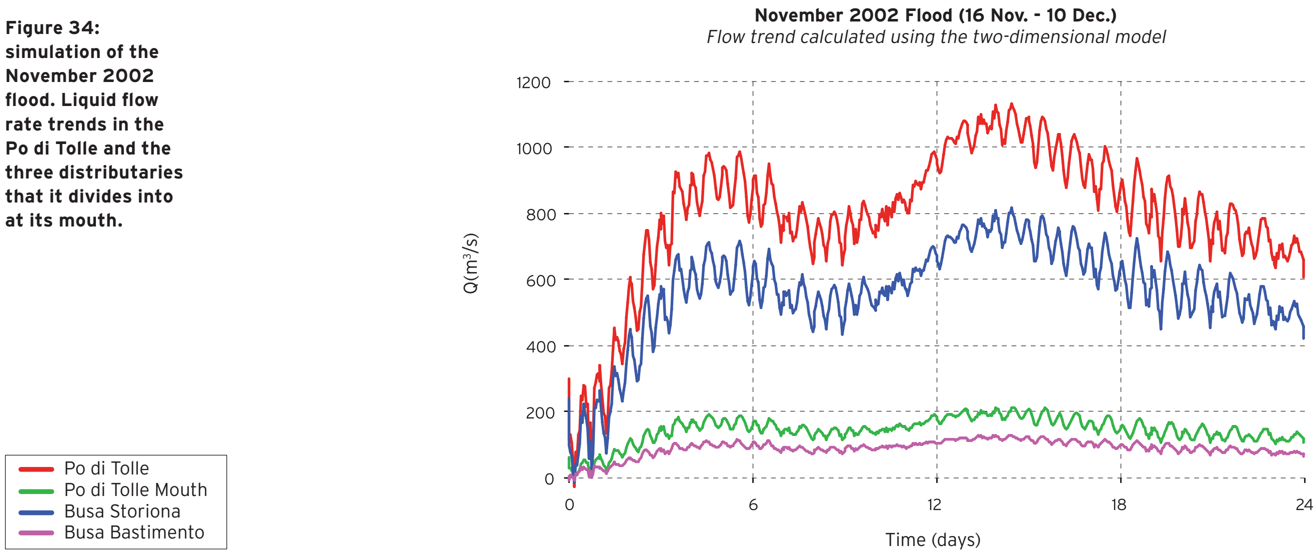


Figure 33: Po flow trends at Pontelagoscuro for the considered flood event.

Figure 34: simulation of the November 2002 flood. Liquid flow rate trends in the Po di Tolle and the three distributaries that it divides into at its mouth.



neither deposition nor erosion. In this specific case these nodes have been identified on the computation domain boundary where liquid flow is released and sea levels are assigned.

The simulation results are shown in Figures 34 and 35. Figure 34 shows the flow rates in the different distributaries of the Po di Tolle. One can see that according to the calculation, the peak maximum flow moving along the Po di Tolle is equal to slightly more than 1000 m^3/s, compared to 4500 m^3/s passing through the Po di Venezia at its peak. One can also see that the flow trend is strongly influenced by the tide.

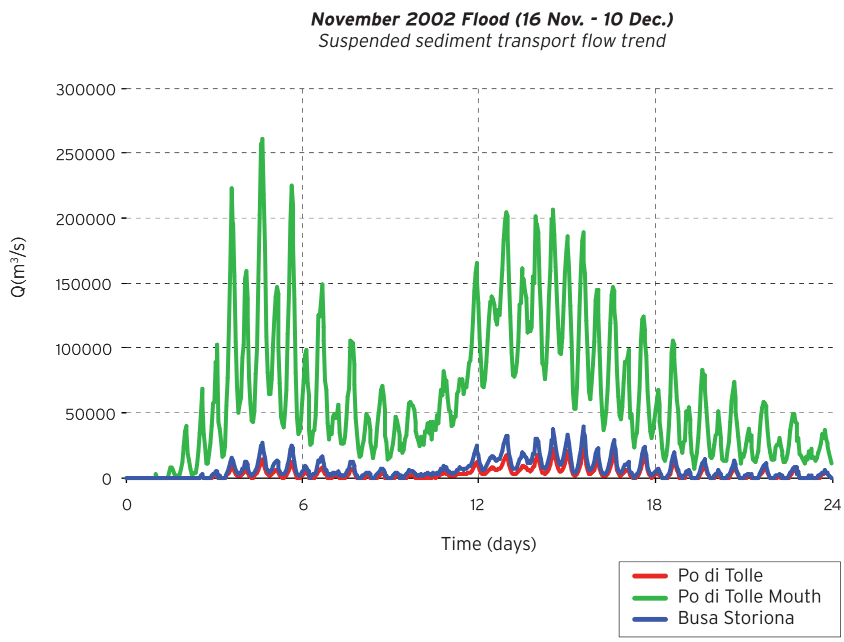
Of the sections of the distributaries into which the Po di Tolle divides towards the mouth, according to estimates, about 750 m^3/s (71%) follow the direction of the Busa Storiona, about 200 m^3/s (19%) flow through the Po di Tolle old mouth and about 100 m^3/s (10 %) the through the Busa Bastimento.

The model largely concurs with the experimental data, satisfactorily reproducing the percentage of distribution of flow between the three distributaries of the Po di Tolle, while confirming that, even in flood situations, the flow moving through the Busa Storiona is far more prevalent than that competing with the other two distributaries and the distributary that leads to the old mouth in particular.

Figure 35 summarizes the results of the simulation in terms of "sediment transport", i.e. flow consisting of suspended material transported by the current. The sections to which the diagram refers appear on the three Po di Tolle distributaries just before it flows into the sea. In the first case (Figure 35 top), the sediment transport is evaluated in the current situation. One can see that the calculated values are distributed in a way that is similar to that of the liquid flow, and that the Busa Strioriona's contribution is clearly prevalent to that of the other two mouths.

However, one can see that, given the non-linearity of the relationship between liquid flow and sediment transport, the differences between the distributaries become notably bigger. The maximum sediment transport values for the Busa Storiona are around 0.2 m^3/s, while for the other two distributaries they are approximately 10 times lower. One can also see that sediment transport evaluated for the Busa del Bastimento is superior to that evaluated for the old mouth of the Po di Tolle. This is due to the shallow bottoms that characterize the first distributary and give rise to more intense current erosion in flood conditions.

The graph in Figure 35 represents the result of a second scenario examined using the model. In fact the complete closure of the mouth of the Busa Storiona was hypothesised, as such forcing the Po di Tolle's entire flow along its two oldest distributaries. It's worth pointing out however, that this situation is not representative of what it could have been before the realization of the Busa Storiona at the end of the 1980s, given that at the time there were openings on the "Bonelli" sandbar through which the Po's flow could move out to sea. It could instead realistically represent the system's pat-



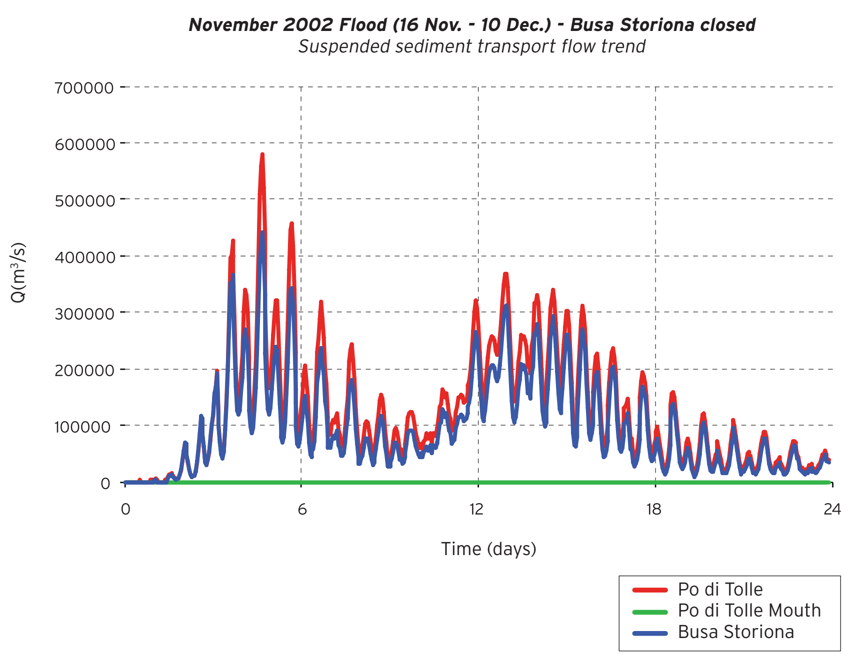


Figure 35: simulation of the November 2002 flood. Current suspended sediment transport flow trend in the Po di Tolle distributaries (top) and with the hypothesis of the closure of the Busa Storiona.

terns before the 1960s when subsidence and the disastrous floods of those years had not yet manifested themselves and the land now occupied by the Bonelli was part of the mainland.

Firstly, the calculation results, in terms of sediment transport, show that sediment discharge has increased substantially. Both on the old distributary of the Po di Tolle and Busa del Bastimento the maximum sediment transport is as much as 0.3 m^3/s and is as a whole, greater than the total of all three branches in the current situation. This is to be compared to the higher speeds which, on average, occur in the beds due to the available liquid sections being smaller in size, therefore resulting in greater intensity of suspended sediment transport.

Secondly, one can see that unlike the previous case, the sediment transport at the old mouth of the Po di Tolle is superior to that of the Busa del Bastimento. This result lends further credibility to the hypothesis that, prior to the opening and expansion of the Busa Storiona, sediment discharge along the Po di Tolle, and therfore towards the coasts of the Sacca di Scardovari, must have been appreciably greater than now.

WAVE ACTION ALONG THE COAST

The waves generated by the wind propagating along the coast trigger erosion and sedimentation processes that are of great importance to the stability of the bottoms, and ultimately the sandbars that separate the lagoon from the sea, in that they ensure their physiographic unity.

These phenomena, whose effects combine with those induced by the currents that involve the many lagoon and river mouths that open to the sea, cause the shore line to be extremely mobile along the front of the Delta. It is not surprising therefore that one witnesses important changes to the morphology coast as a result of more intense storms, with changes over time that are not always positive for the survival of a lagoon.

This is what has been happening to the sandbars that separate the Sacca di Scardovari from the sea for decades, and contrary to the past (see the 1950 lagoon configuration), they now appear to have a planimetric configuration that is concave towards the sea, favoring erosion processes supported by wave motion.

Understanding the phenomena taking place and assessing possible counter measures are important aims since the destruction of the sandbars would inevitably lead to the lagoon transforming into a veritable arm of the sea.

The Mathematical Modeling of the System

Reagrding the propagation of tide waves as well as wave propagation from offshore towards the shoreline, the mathematical modeling of the phenomena under appropriate conditions can help to better understand the processes set in motion and to identify the relative importance of individual causes that contribute to their formation. Despite the evident need to support the model analysis with appropriate experimental observations in order to demonstrate the implemented models' ability to simulate a reality that is clearly very complex, it could be useful, through numerical simulation, in order to get a basic idea of the problems, to analyze the causes of the changes to which shoreline separating the Sacca from the sea is exposed, if only to draw conclusions reagrding the measures to be taken in order to attempt to counter the phenomena taking place.

The Data Used

To establish the characteristics of the wave motion in the sea in front of the Sacca di Scardovari, reference was made to the investigations and information developed in the technical report "Studi idraulico-marittimi nelle lagune deltizie – Sacca di Scardovari" [10], [11].

In the study, the characteristics of the waves at the point in front of the of Sacca di Scardovari (Point S, Figure 36) were obtained through a series of numerical simulations carried out using the SWAN calculation code from data relating to the closest CNR point, for which the characteristics of the wave motion reconstructed using the WAM (Wave model) [10], [11] are available.

Using the correspondence between the data of the CNR point and those reconstructed for Point S, it was possible to give each event at Point S a frequency and thus to reconstruct measurement radar charts for this point as well as for the energy and maximum wave action (Figure37).

By analysing the radar charts and especially the energy radar chart, one can see the presence of two peaks corresponding to Bora (60 ° N) and Sirocco (145 ° N) sea storms. However, with the maximum height ring, it appears that maximum wave heights of about 5m are present both in the Bora and Sirocco sectors.

From the wave motion data relative to Point S, it was possible to reconstruct the flow duration curves for the Bora and Sirocco sectors (Figure 38). It appears that a wave height of 2m is exceeded on average 4 days a year in heavy sea conditions originating in sector 90°- 200 °N (Sirocco), and 10 days per year in sea storm conditions originating in sector 0°-90 ° N (Bora).

Computational Grid and Boundary Conditions

The mathematical model computational grid used for the simulations is in fact the same one that was used for the analysis of the Sacca's hydrodynamic circulation. The only additions were side strips expanding the domain to the north and south in order to set the boundary conditions far enough away from the areas of interest to affect the results of the simulations.

The simulations were conducted under uneven flow conditions. For the hydrodynamic parts the boundary conditions on the side facing the open sea consist of the assigning of the tide level. More specifically, of a semi-diurnal sinusoidal tide oscillating between

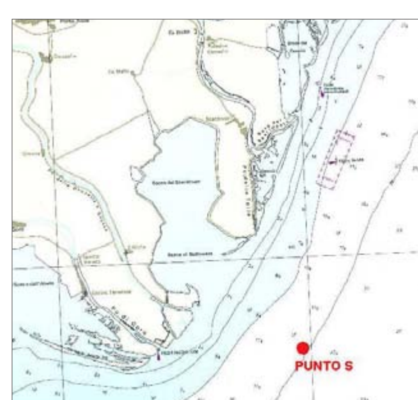


Figure 36: location of Point S.

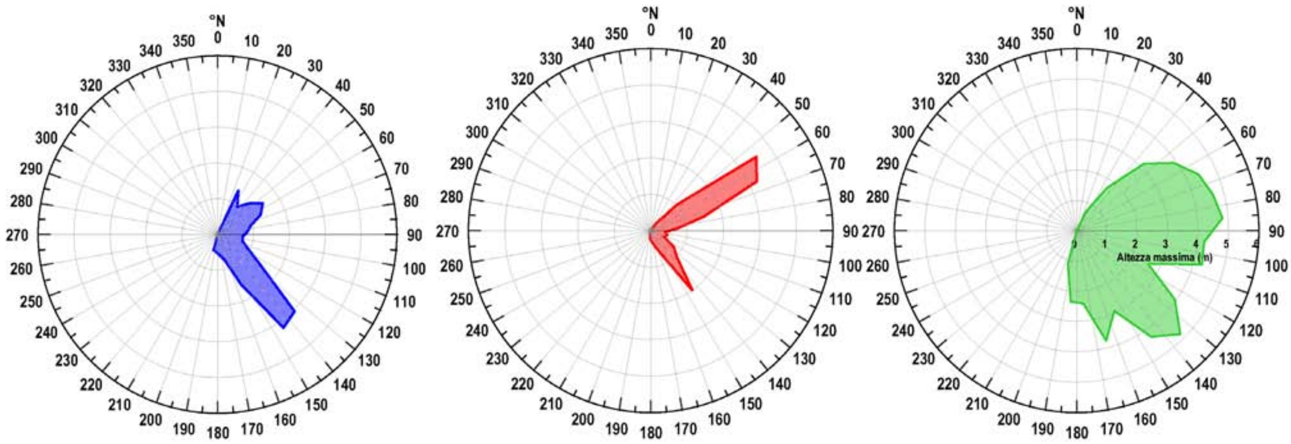


Figure 37: measurement radar chart (in blue), energy radar chart (in red) and maximum heights radar chart (in green) at Point S (from the study [10], [11]).

±0.4m a.s.l.

For wave motion, on the basis of the energy distribution and off shore measurements (Figure 37), two directions were considered (60° N and 145° N) representing the two main areas of origin, as well as their significant heights over a period between 1 day and 30 days. Table 3 shows the characteristics of these waves. The simulations cover a period of 3 days.

On the first and third day the only force was that of the tide, while on the second day the action of the wave motion applied itself as an additional external force. In this way the moving bed simulations allowed for the highlighting of both the effects of sediment transport due to the sea currents only, as well as that linked to the overlapping of the currents induced by the wave action.

Simulation Results

The simulations conducted allow for an interesting analysis related to the propagation of sea storms along the coast, quantifying wave action along the coastline and the intensity of the induced sediment transport, identifying the stretches most affected and those which could possibly be subject to protection to ensure the maintaining of the sandbar that separates the Sacca from the sea.

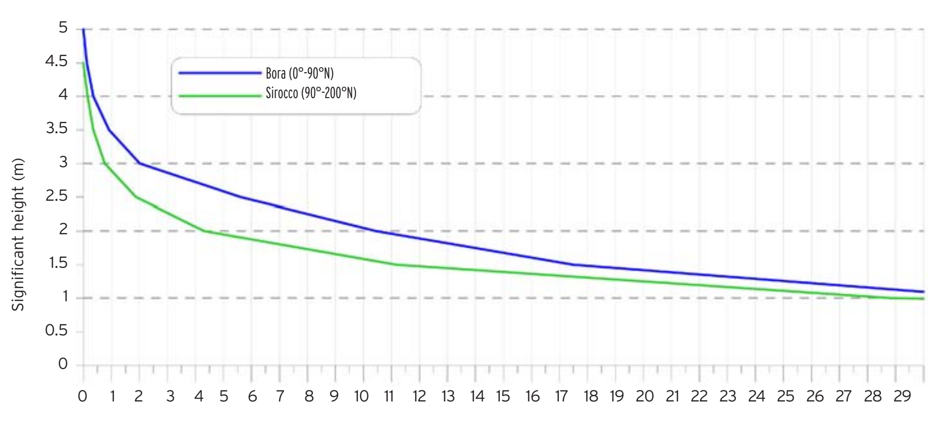


Figure 38: point S duration curves for the Bora and Sirocco sectors (from the study [10], [11]).

Wave Action Propagation

The distribution of wave heights in the strongest Bora storms considered (1 day/ year) in the moments in which the tide is at its highest and lowest is represented contour by the level curve in Figure 39.

According to the wave height calculation, equaling more than 3m off shore, the propagation gradually weakens due to dissipative phenomena (bottom resistance, wave breaking, whitecapping) as it moves towards the shore.

Its interesting to observe how, along the coast north of the mouth of the Po di Tolle (the Bonelli sandbar), the waves are considerably high all the way up to a short distance from shore (the curve relating to the 2m wave is about 500 to 700 m from the coast) only to then weaken rapidly in the area closest to the shore.

On the coast in front of the Sacca di Scardovari, probably due to the shallower bottoms, the wave weakens much more progressively. Consequently, in the bodies of water in front of the sandbar that borders the Sacca (Scanno del Palo), the model shows relatively low wave heights.

The tide outflow involves significant differences in wave height, given that, during high tide the waves propagate at deeper bottoms and are subject to fewer dissipative effects. In front of the Scardovari coast, the two curves relating to the 3m high wave in high and low tide conditions are about 200m from each other. This distance increases slightly for the curves relating to lower wave heights.

Figure 40 shows the wave height trend as calculated by the model considering the wave propagation of the Sirocco for 1 day/year for both high and low tide conditions. According to the calculation, a Sirocco sea storm, with the same probability of occurring as the previously considered Bora sea storm, determines the appreciably smaller wave heights in front of the Scardovari coast.

Even in this case the result of the calculation shows how the different tide conditions considerably influence the position of the level curves representing the wave heights. With the high tide, like other conditions, wave heights along the coast are significantly higher than those at low tide.

It is interesting to compare the results obtained from the calculation relating to the wave height profiles in a series of transects placed at right angles to the Scardovari coast (Figure 41).

For transects No.8 ("Spiaggia delle Conchiglie"), No. 5 (in front of the sandbar) and No. 3 (at the South Mouth) the profiles show the attenuation of the Bora and Sirocco wave heights towards the shore for 1 day/ year, in high and low tide conditions, resulting in the propagation of the wave itself (Figure 42 and Figure 43).

Regarding the Bora wave attack (Figure 42) in high tide conditions (blue lines) along transect No. 8 in front of the Spiaggia delle Conchiglie, the wave height is 2m about 1000m from the coast. In front of the sandbar (transect No. 5) however, the same wave height can be found much further (about 2500m) from the shore. Transect No. 3 which extends inside the South Mouth of the Sacca is completely analogous.

One can see that in the cases of transects 3 and 5 the shallow bottoms induce a progressive lowering of the height of the wave, while with transect

	H (m)	T (s)	Dir. (°N)
Bora (1 day/ year)	3.46	7.05	60
Bora (30 day/ year)	1.09	4.06	60
Scirocco (1 day/ year)	2.89	7.53	145
Scirocco (30 day/ year)	0.99	5.61	145

Table 3: characteristics of waves used in the simulations.

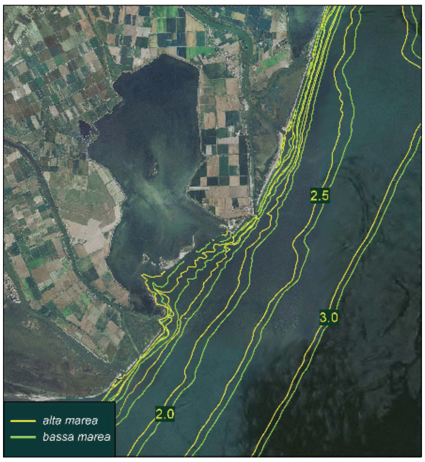


Figure 39: map of the wave heights in Bora sea storm conditions with offshore waves for 1 day/year in conditions of high and low tide (Hs = 3.46m, T = 7.05 s; Dir = 60 °). The diagram uses a 0.5 m step for the wave heights.

Figure 40: map of the offshore wave heights in Sirocco sea storm conditions for 1 day/year in high and low tide conditions (Hs = 2.89m, T = 7.53 s; Dir = 145°). The diagram uses a 0.5 m step for the wave heights.

Figure 41: location of the transects off the Scardovari coast.

No. 8 the deeper bottoms favor the propagation of higher waves up to a short distance from coast. As already mentioned, the results also allow the quantification of the effect of the tides on wave propagation. While offshore the effect is small, the changing tide conditions along the coast result in differences in wave height of as much as 30 to 40 cm. These effects are obviously more evident in transects 3 and 5 because of their shallower bottoms. The same profiles calculated with the model for the Sirocco wave attack for 1day/year is illustrated in Figure 43.

Due of the deeper bottoms of the sea, the wave attack along transect No. 8 propagates toward the shore with significantly higher wave heights than the other two transects. One notes also that the dissipative effects along transect No. 3 (South Mouth) are much more pronounced than the previous case, since the transect in question is in a more protected stretch of sea than the Sirocco.

Figure 44 shows the wave heights for Bora wave attack comparing the results obtained for sea storms for 1 day/year and 30 days/year in the moment in which the tide level is equal to the mean sea level. The height of the wave, and therefore the energy, is substantially different in the two cases.

These differences, being macroscopic along the coast along which the mouths of the Po di Tolle (Bonelli lagoon) open, and along the Spiaggia delle Conchiglie, are markedly reduced in front of the sandbar that currently delimits the Sacca di Scardovari. The calculation results confirm that the intensity of the wave in front of the Sacca's sandbar does not reach levels much higher than those of the more frequent sea storms.

This is a dissipative effect which is clearly only limited to one stretch of sea directly in front of the sandbar. In fact the area in front of the point at the mouth of the Po di Gnocca (Punta del Polesine), for sea storms 1 day/year, is exposed to wave action that maintains its elevated height right up to the shore.

Regarding the two Sirocco waves, the heights resulting from the calculation are shown in Figure 45. In this

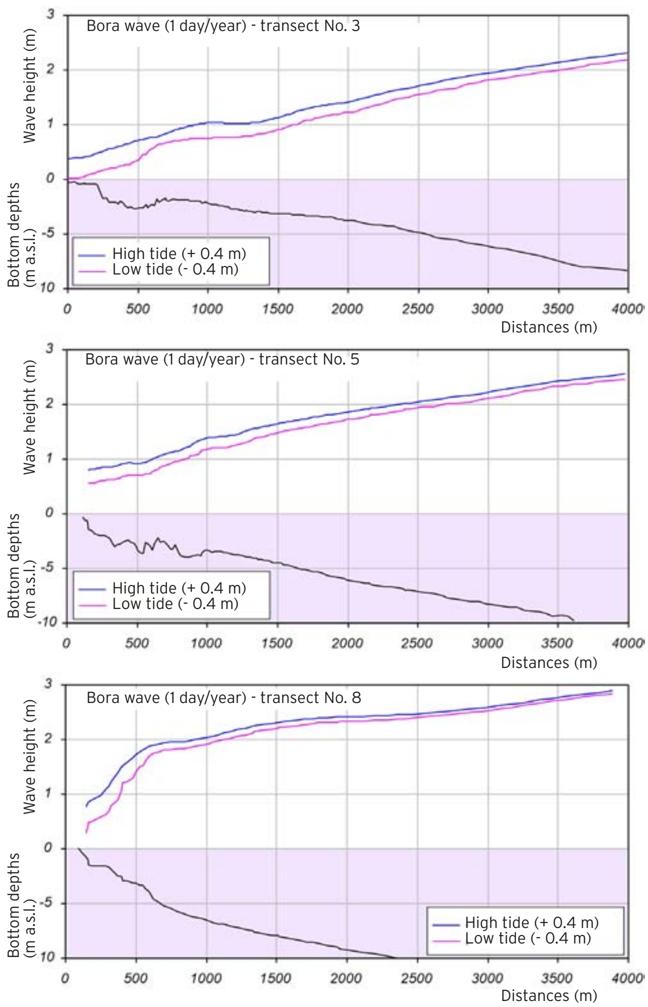


Figure 42: transects positioned orthogonally to the coast (tr3/ spiaggia conchiglie, tr5/ sandbar and tr8/ south mouth) for Bora wave with a frequency of 1 day/ year in high and low tide conditions.

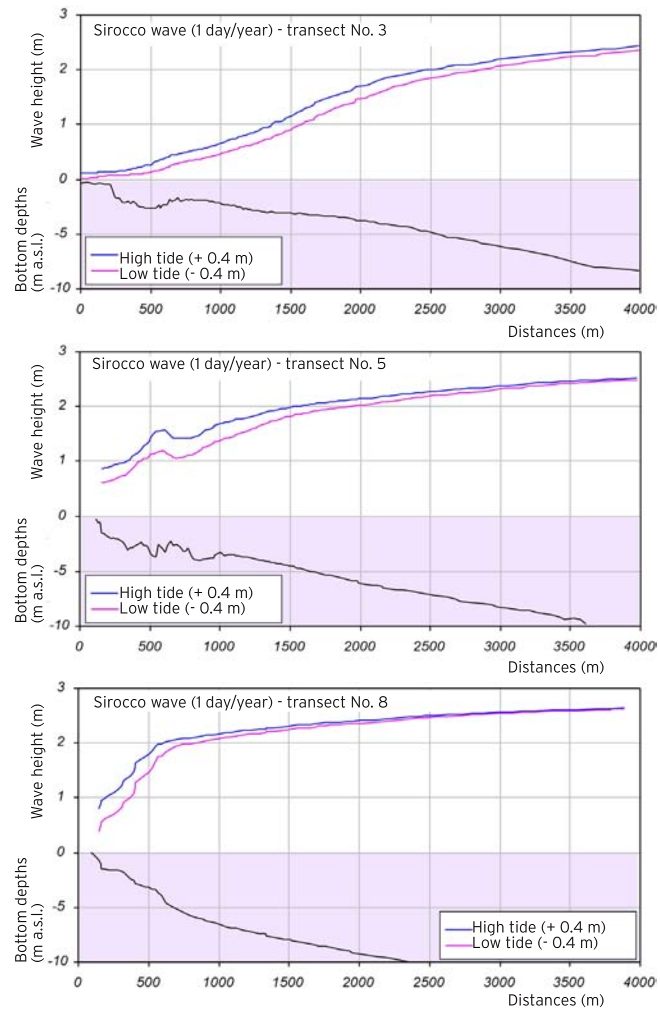


Figure 43: transects positioned orthogonally to the coast (tr3/ spiaggia conchiglie, tr5/ sandbar and tr8/ south mouth) for Scirroco wave with a frequency of 1 day/ year in high and low tide conditions.

case the result for the 30 days/year sea storm is not particularly significant, because the wave height is already very modest off shore (0.99 m, see Table 3).

For this reason only the level curve of 0.5 m. is represented on the map under these sea conditions. Once again, with the 30 days/year sea storm one can see in the end that the wave heights in the stretch of sea in front of the Sacca the tend to be higher than those in Bora sea storm conditions. The result should be seen in relation to the different directions from which the wave attack arrives and therefore to the associated refraction effects. In essence, the Sirocco wave affects the Scardovari coast more directly and consequently its propagation towards

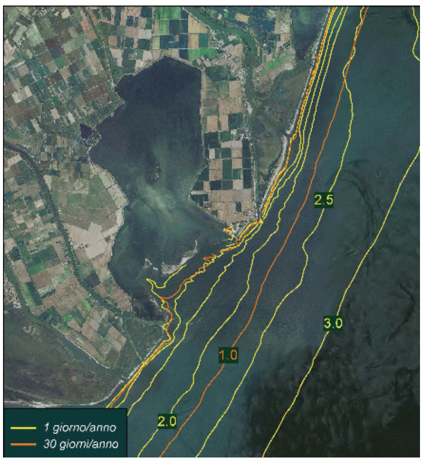


Figure 44: map of the wave heights in Bora sea storm conditions with an offshore wave for 1 day/year and 30 days/year in mean sea level conditions.

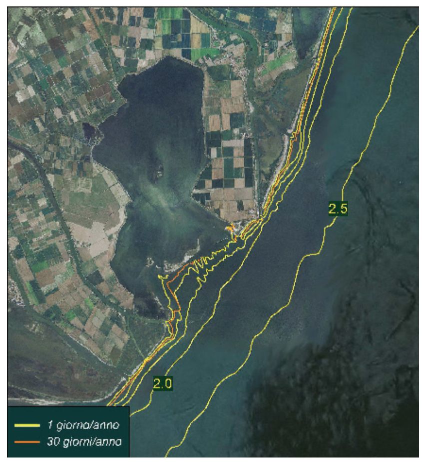


Figure 45: map of the wave heights in Sirocco sea storm conditions with an offshore wave for 1 day/year and 30 days/year in mean sea level conditions.

the shore is weaker.

Figures 46 and 47 show the profiles of the wave heights for the cases examined. These diagrams further support the above considerations.

Effects of Wave Action on Coastal Sediment Transport

With reference to coastal sediment transport induced by wave action, numerical simulations also provide results regarding suspended sediment transport caused by wave motion and its induced currents.

The maps in Figure 48 and Figure 49 use a colour scale to represent the distribution of the concentration of suspended sediment transport in Bora sea storm conditions for 1 day/year, distinguishing high tide (level equal to +0.4 m a.s l.) and low tide conditions (level equal to -0.4 m a.s.l.). From the moment in which suspended sediment concentration is directly correlated to sediment resuspension action due to currents and waves, it can be considered an effective indicator of the areas where the erosive action of the sea is most intense.

In the same figures, the direction of the sediment transport is represented by unit length vectors in order to identify the paths followed by suspended sediments. The results obtained have allowed for the following interesting observations to be made.

Firstly one notes that the Bora sea storms induce coastal transport along the coast directly from NE to SW. The intensity of sediment transport is very high along the whole coast north of the Po di Tolle, in front of the Bonelli lagoon. The point in which concentration is highest, which potentially corresponds to that in which highest erosive effects develop, is located close to the western side of the Po di Tolle mouth. High suspended sediment concentration values are also found in front of the Spiaggia delle Conchiglie and along the coast south of the Po di Gnocca mouth.Concentrations of suspended sediment in the stretch of sea directly in front the Scanno di Palo or the coast that separates the Sacca from the sea are much lower.

Here the concentrations are generally very small (less than 100 mg/l), and become higher only in some stretches of coastline limited to the stretch immediately behind the shoreline.

Comparing the maps in Figure 48 and Figure 49, it is evident that the effects of the different tide conditions on coastal sediment transport are not negligible. One can see that, in high tide conditions (+0.4 m above sea level), sediment transport intensity along the coast is appreciably higher than that calculated in low tide conditions (-0.4 m).

The maps in Figure 50 and Figure 51 show similar representations of the results for the 1 day/year sea storms, coming however from the Sirocco sector. In this case coastal transport direction is the opposite of the previous case: in fact, sediment transport is from SW to NE. Comparing the maps with those relating to the Bora sea storm, one can see that quantitatively, in this second case, the intensity of sediment transport is generally lower.

Qualitatively however, the distribution of the areas in which suspended sediment concentration is at a maximum does not change substantially, indicating that the most vulnerable areas from

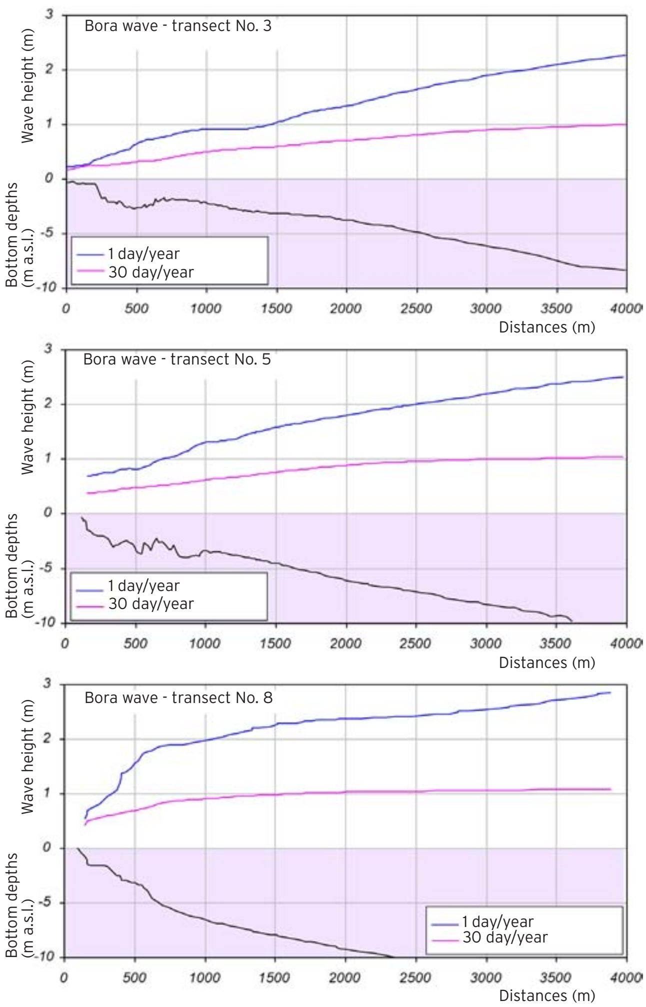


Figure 46: transects positioned orthogonally to the coast (tr3/ spiaggia conchiglie, tr5/ sandbar and tr8/ south mouth) for the Bora wave with a frequency of 1 day/ year for levels equal to the mean sea level.

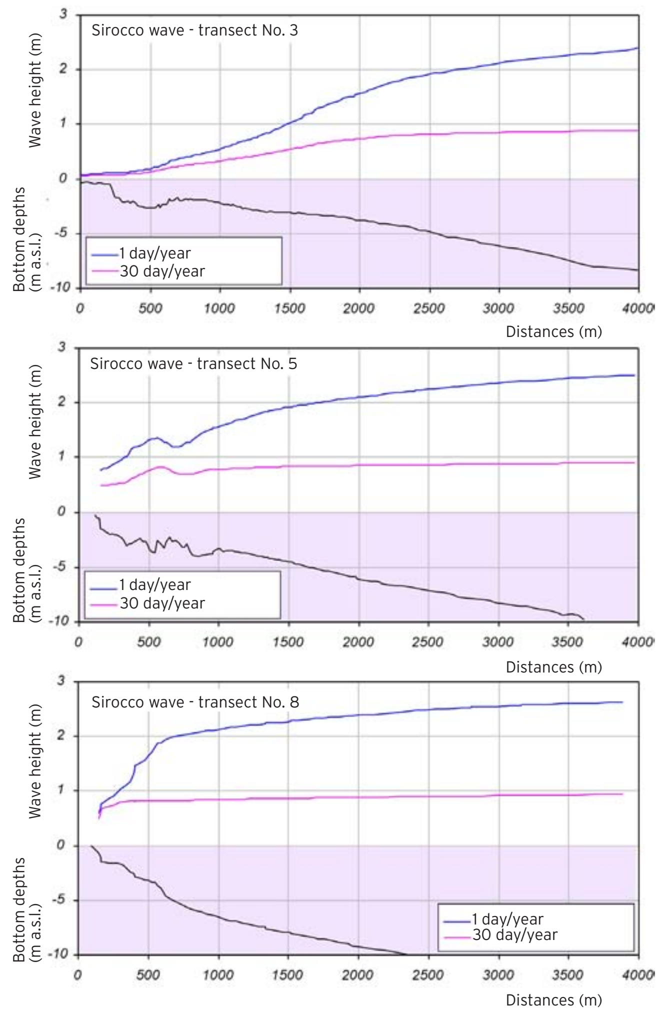


Figure 47: transects positioned orthogonally to the coast (tr3/ spiaggia conchiglie, tr5/ sandbar and tr8/ south mouth) for the Sirocco wave with a frequency of 1 day/ year and 30/year for levels equal to the mean sea level.

an erosion point of view in fact remain the same. In any case, it should be noted that, by virtue of the difference in transport direction, the stretch of coastline on the north side of the mouth of the Po di Tolle is less affected, while, though not by much, the intensity of transport in the area of the mouth of the Po di Gnocca and bodies of water in front of the Scanno del Palo that delimits the Sacca increases.

Finally, once again with the Sirocco, the model simulation shows that at low tide sediment transport along the coast tends to be significantly less intense, as already reported for the Bora winds.

Limited to the shoreline in front of the Sacca, the maps in Figure 52 illustrate in greater detail the results shown in the

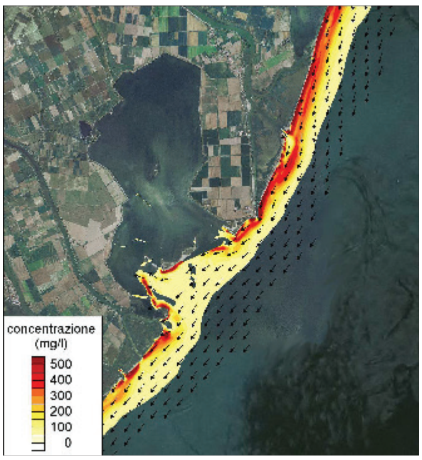


Figure 48: distribution of the concentration of transported suspended sediment for the 1 day/year Bora sea storm at high tide. The vectors indicate the direction of sediment transport.

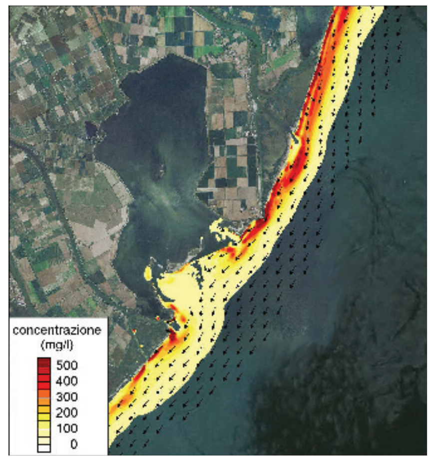


Figure 49: distribution of the concentration of suspended sediment transported during the 1 day/year Bora sea storm at low tide. The vectors indicate the direction of sediment transport.

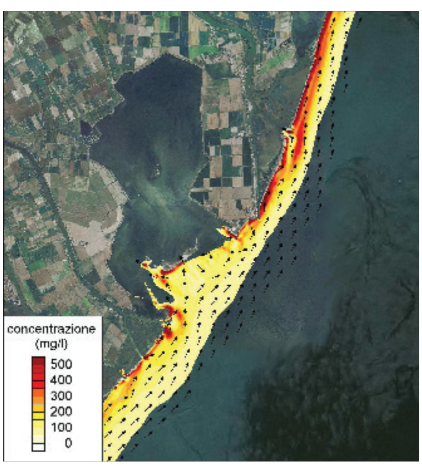


Figure 50: distribution of the concentration of suspended sediment transported during the1 day/year Sirocco sea storm at high tide. The vectors indicate the direction of sediment transport.

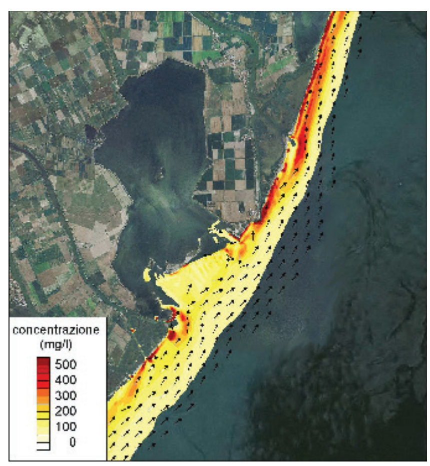


Figure 51: distribution of the concentration of suspended sediment transported during the 1 day/year Bora sea strom at low tide. The vectors indicate the direction of sediment transport.

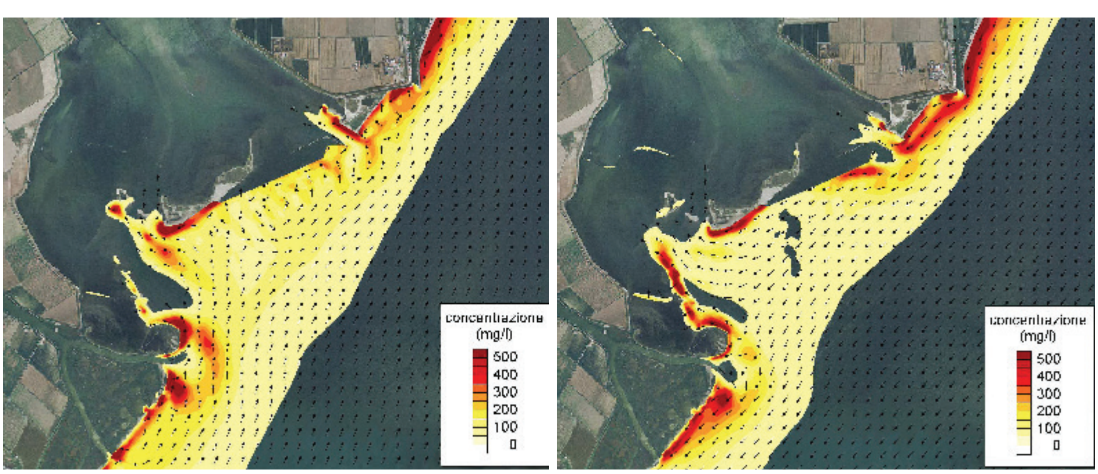


Figure 52: details of the suspended sediment concentration maps of the 1 day/year Bora and Sirocco sea storm at high tide. The vectors indicate the direction of sediment transport.

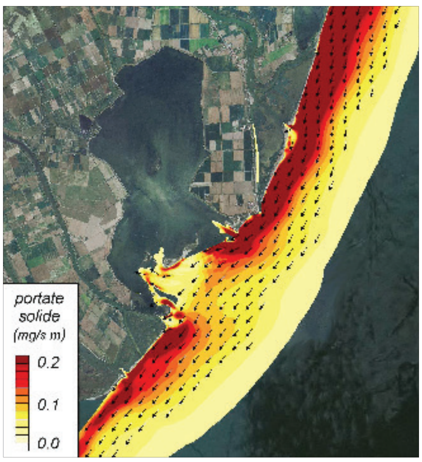


Figure 53: suspended sediment transport distribution for the 1 day/year Bora sea storm at high tide. The vectors indicate the direction of transport.

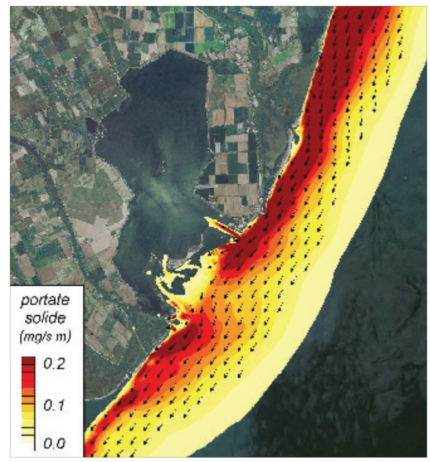


Figure 54: suspended sediment transport distribution for the 1 day/year Bora sea storm at high tide. The vectors indicate the direction of transport.

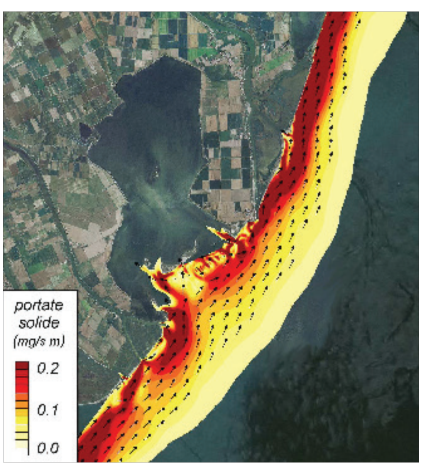


Figure 55: suspended sediment transport distribution for the1 day/year Sirocco sea storm at high tide. The vectors indicate the transport direction.

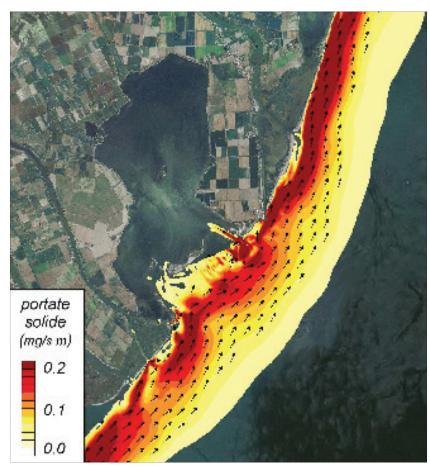


Figure 56: suspended sediment transport distribution for the 1 day/year Sirocco sea storm at high tide. The vectors indicate the transport direction.

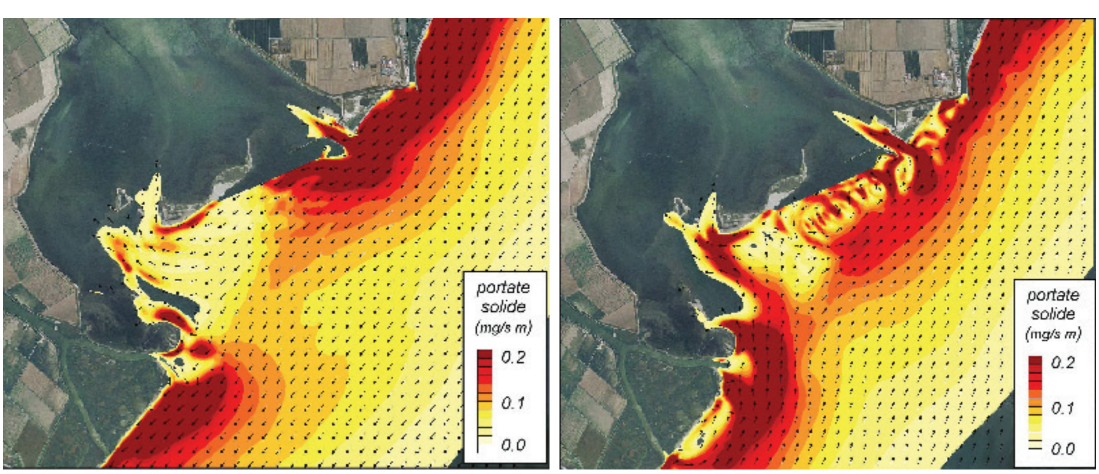


Figure 57: details of the suspended sediment transport maps for the 1 day/year Bora and Sirocco sea storms at high tide. The vectors indicate the transport direction.

above images for the 1 day/year Bora and Sirocco sea storms. It is possible to draw further impetus for analysis from these maps. One can see that with both the Bora and Sirocco sea storms, both mouths of the Sacca are affected by suspended sediment flow towards the internal parts.

In the case of the Bora sea storm (Figure 52 left), with regard to the North Mouth, one can see in particular how the transported suspended sediment is particularly intense in front of the Spiaggia delle Conchiglie and follows a path that tends largely to lead into the Sacca through the mouth.

Once again with the Bora sea storm, there is also a clear tendancy of suspended sediment entering the lagoon around the South Mouth. The model clearly shows however that the areas most affected are at the southern end of the Scanno del Pole, starting from the edge of the defensive dyke realized in recent years by the Consorzio, to the sandy strip that delimits South Mouth on its southern side.

The conditions change in the presence of the Sirocco wave (Figure 52 right), especially for the latter portion of coast which, due to the different orientation of the wave attack, hardly seems to be affected.

The transport directions are also significantly different. In front of the defensive dyke that protects the Palo di Scanno the current distribution is not in fact oriented in a consistent way, but tends to follow a swirling movement.

Similar conditions occur around the North Mouth and in front of the Spiaggia delle Conchiglie where, compared to the case of the storm of Bora, the intensity of transport is significantly reduced.

Figures 53 and 57 summarize the results obtained for suspended sediment flow which is substantially determined by the product of the sediment concentration for the liquid flow, giving indications on the active stretch of coastal transport.

With the Bora storm storms (Figures 53-54), this active stretch extends for about 3.5 km (up to a bathymetric depth of approximately -15) in front of the mouth of the Busa Storiona and expands up to more than 5 km in front of the South Mouth.

The stretch affected by relevant sediment transport (indicated by the orange to red color-gradient) however, is much smaller (about 1.6 km in front of the Busa Storiona with depths of up to -8 and -9 m a.s.l.). It is interesting to note that sediment transport is rather modest (and practically negligible at low tide) in front of the Scanno di Scardovari and in the South Mouth area.

The result of the Sirocco sea storm (Figure 55 to 56) is different in terms of sediment transport. For these conditions, the active stretch of coastal transport is slightly narrower than the previous case. The phenomenon is related to the lower intensity of the waves off shore. With the Sirocco sea storm, sediment transport passing through the bodies of water in front of the Sacca's sandbar is also significantly higher, even if the direction of transport, as previously pointed out, is not well defined, but rather indicates the onset of swirling movement phenomena.

Finally, Figure 57 represents the fields of sediment transport around the Sacca di Scardovari for the Bora and Sirocco sea storms at high tide in more detail. One can see the aspects that have already been underlined more clearly. In particular, the Bora wave (Figure 57 top) has the maximum sediment transport, developing adjacent to the coast in the Po di Tolle mouth, North Mouth and Po di Gnocca mouth areas, transiting far off shore of the South Mouth, and only minimally affecting the bodies of water in front of this mouth and the western portion of the Scanno del Palo.

This situation changes in the case of Sirocco wave (Figure 57 bottom) for which as already pointed out, the directions of transport are not well defined and seem to indicate the onset of local recirculation phenomena.

For the 1 day/year Bora and Sirocco sea storms, the temporal trend for the sediment transport that passes through some transects (Figure 41) are shown in Figure 58. There is only significant sediment transport in the central 24 hours of the simulation in which there is wave action.

According to the calculation the total Bora sea storm solid transport is greater than that of the Sirocco, varying on average between 0.15 e 0.20 m^3/s and 0.1 e 0.15 m^3/s respectively.

In general, sediment transport does not differ much between one transect and another. Sediment transport that makes up the central transects (transects 3 to 7) for which there are also fluctuations in value are slightly lower. The phenomenon seems to be linked to sea level fluctuations and is more evident because these transects, having shallower bottoms, are more affected by hydrometric altitude variations induced by the tide.

For the trend of sediment transport passing through the two lagoon outlets, in the initial and final stages of the simulation of the Bora sea storm (Figure 59 top) when the only force is the oscillation of the tide, there is a certain behavioral asymmetry between the two mouths.

In essence, incoming sediment transport flows through the South Mouth while outgoing sediment transport passes through the North Mouth. In the phase affected by wave action (24 to 48 hours) the incoming sediment transport grows considerably (by approximately 2.5 times its amount) while outgoing sediment transport changes only slightly.

Similar results are obtained for the Sirocco sea storm (Figure 5.24 below), for which the maximum incoming sediment transport is significantly higher than that measured for the Bora.

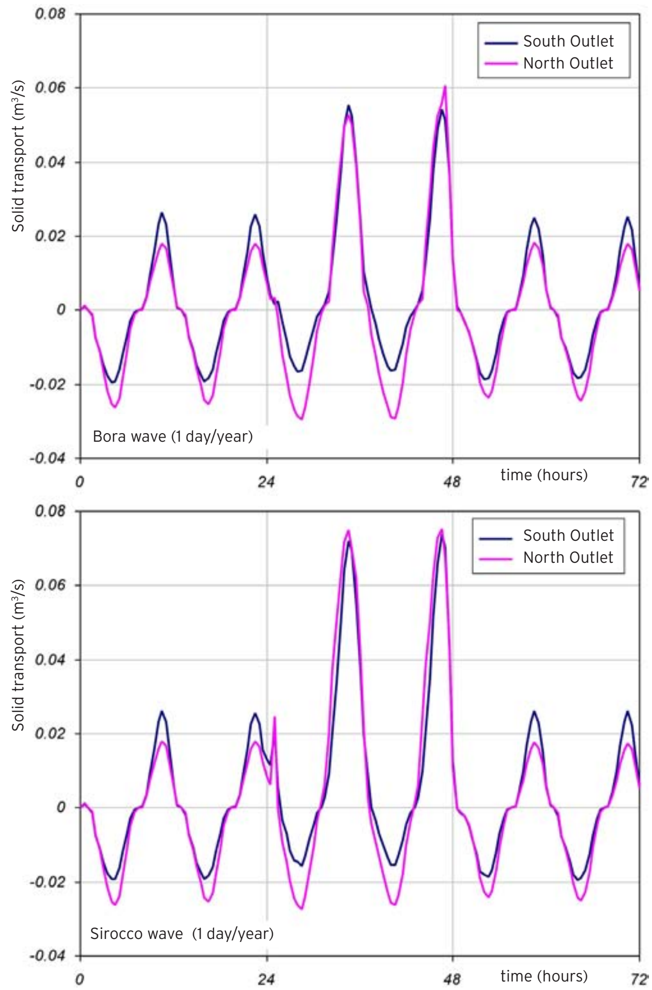


Figure 59: sediment transport trends exchanged through the two mouths of the Sacca di Scardovari (positive transport if incoming) due to the effects of the 1 day/year Bora and Sirocco sea storms.

CURRENT CIRCULATION IN CONDITIONS OF STRATIFICATION

Since the computational onus needed for the application of the 3D model multilayer is far greater than that of the two-dimensional model, the three-dimensional schematization of the Sacca is based on a somewhat different computational grid which allows the Sacca's bottoms to be represented in a similar, but less detailed way to that of the two-dimensional model (Figure 60). Regarding the number of layers, after some preliminary attempts, the water column is described subdividing it into 10 layers on the vertical axis. The model having been prepared for the consideration of layers of variable thickness, the 10 layers were defined as having thicknesses varying between between 25 to 50 cm for the surface layers and about 1m for the deeper layers.

In this way, even in areas where the hydraulic heads are modest, the calculation is conducted taking a number of layers into consideration, enough to de-

Figure 60: the Computational grid of the multilayer 3D model and diagram of the subdivision of the water column into 10 layers.

scribe any density gradients along the vertical axis in fine detail.

Boundary Conditions

The boundary conditions for the simulations with the 3D model are made up, for the open boundary nodes, of water level trends and incoming or outgoing flow over time for each layer, as well as the density distribution for each layer. The conditions relating to the various sizes of the Delta distributaries described in the implemented scheme are also specified.

The defining of such a large number of parameters, far greater than with the two-dimensional model, generally poses some difficulties both in the phase of gathering the necessary data and with reference to the allocation of these data in a form that is appropriate to the model.

For example, regarding salinity, the assigning of boundary conditions requires knowing the horizontal and vertical salinity distribution in the sea, as well as its time variation. These data are not generally available, or only available in rough form, having been obtained from large scale models of the Adriatic Sea, and are therefore inaccurate in relation to the local problems of the Delta lagoons.

All the more so in the case of Sacca di Scardovari where salinity distribution in the sea evolves according to particularly complex dynamics due to the interaction of the average circulation in the Adriatic, the effects of local circulation induced by wind and wave action and river transport channeled to the sea by the distributaries of the Po di Tolle, Po di Gnocca and Po di Goro.

In this regard it can be reasonably assumed that the seasonal effects and those of the average circulation in the Adriatic are minor compared to those relating to the flooding of the river and the local marine weather phenomena.The effects produced by flow discharged into the Sacca by the Paltanara and Bonello (Figure 61) pump stations which drain significantly large basins, may be of some significance for the purposes of the analyzes relating to the dynamics of the contact between fresh and salt water as well as related current density.

Although the maximum flow discharged from the pump stations which amounts to some m^3/s is not comparable with the flow that the Sacca exchanges with the sea, incoming flow of fresh water from the pump stations for prolonged periods, however, can take on an important role for the bodies of water around the point of entry, especially in the case of the Bonello pump station which is located in a part of the basin in which tidal current circulation is particularly weak.

The problems associated with the intrusion and spread of fresh river

Figure 61: map showing the locations of the salinity and wind measuring stations and pump stations.

water within the Sacca is of particular importance mainly in relation to the impact that it has on fishing and shell fishing activities. It was for this reason that, a few years ago, the Consorzio di Bonifica Delta del Po together with ARPAV, set up a monitoring system consisting of a series of buoys in order to continuously measure the main physico-chemical parameters of the Delta lagoon water.

There are currently two of these buoys (Figure 61) in the Sacca di Scardovari, the first near the North Mouth (Scardo sea) and the second near the internal edge of the lagoon (Scardo int.).

The tide

The tide levels are one of the main forces in the system consisting of the Sacca di Scardovari and the stretch of sea off the sandbars and the mouths of the Po di Goro and the Po Di Gnocca distributaries. Tide oscillation amplitude has an important influence on sea-lagoon exchange processes, and in particular, on the temporal and spatial distribution of salinity along the coast and within the lagoon itself. It is for this reason that for the simulations conducted, instead of considering a periodic reference tide of consistent size as is usual in these cases, reference was made to a typical astronomical tide specific to this part of the Adriatic coast, over a period of one lunar month (28 days). The tide trend used is illustrated in Figure 62. The oscillation period is approximately 12 hours, while the amplitudes for the greater of the two daily phases vary between slightly more than 1.0m in syzygial periods and about 50 cm in quadrature periods.

The wind

The wind data available are those measured at the Pradon, Porto Tolle station, located in the southern part of the Po Delta and managed by ARPAV - Centro Meteorologico di Teolo, which is equipped with a 10m high anemometer. The average wind speed recorded during the period (1998 -2001) is around 2 m/s with peaks of around 10 m/s for winds coming from the East sector (Levante) and the Northeast (Bora).

Figure 62: the Astronomical tide used in the simulations.

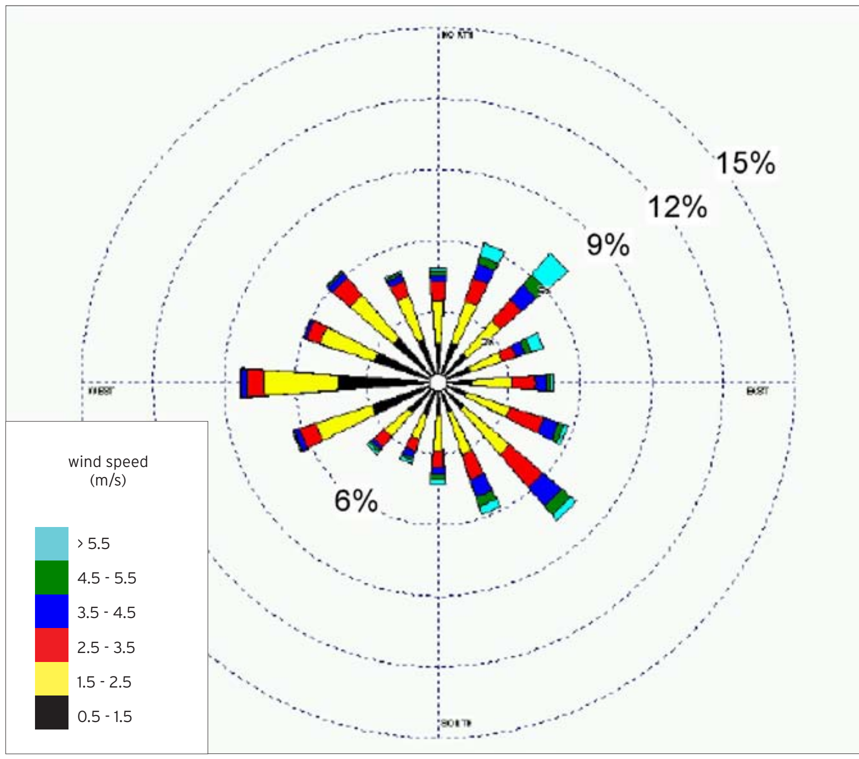


Figure 63 shows the wind ring obtained from the processing of the data covering the considered period. One notes how the most frequent winds (prevailing winds) are those from the NE sector (Bora), SE (Sirocco) and W (Ponente). The first two, coming from the sea, are far more intense winds (prevailing winds).

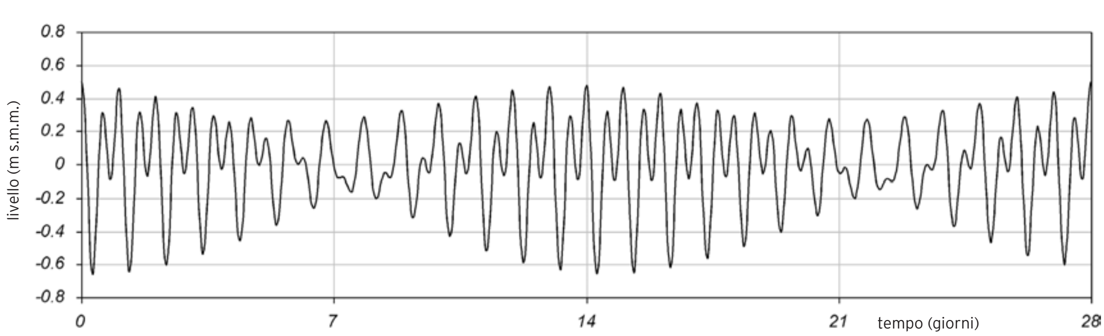
The graphs in Figure 64 represent the wind rings for two samples of recorded data for the summer and the winter respectively. They show very different distribution from the overall distribution, in which western sector winds prevail with the strongest winds coming from the Bora sector during the winter months, and prevailing winds from the Sirocco sector (but in this case with the strongest winds oriented to the Bora) during the summer months.

It is also important to examine Enel's Polesine Camerini anemometer station records [10], [11] in addition to the Pradon-Porto Tolle data. With reference to the data in question, the compass rose at emission plume centerline height (250 m in height) and the ground level 10 m in height) are available.

Below is a statistical elaboration of the data represented by the ring, of the ground wind speed according to the direction from which it originates. For each direction the frequency of the wind which is classed in different intensities is represented by sections differing in thickness, as is clear from the graph.

The elaboration, shown in Figure 64, is based on the recordings carried out between 1 January, 1993 – 31 March, 2005. It is clear that the wind

Figure 63: wind ring: Pradon Station, Porto Tolle for the period 1998-2001 (source: ARPAV).



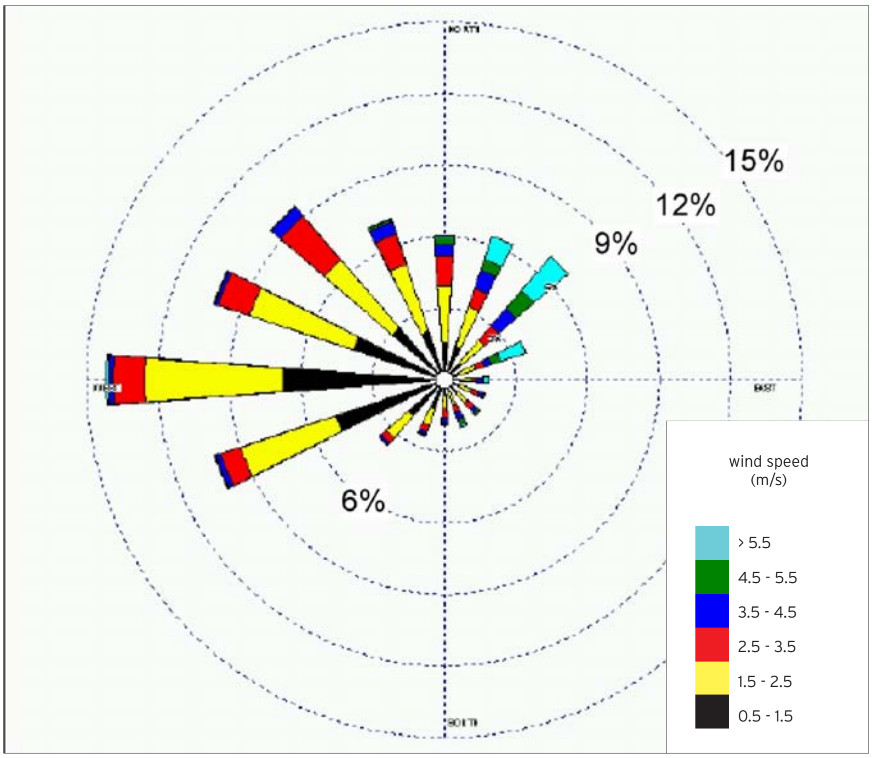
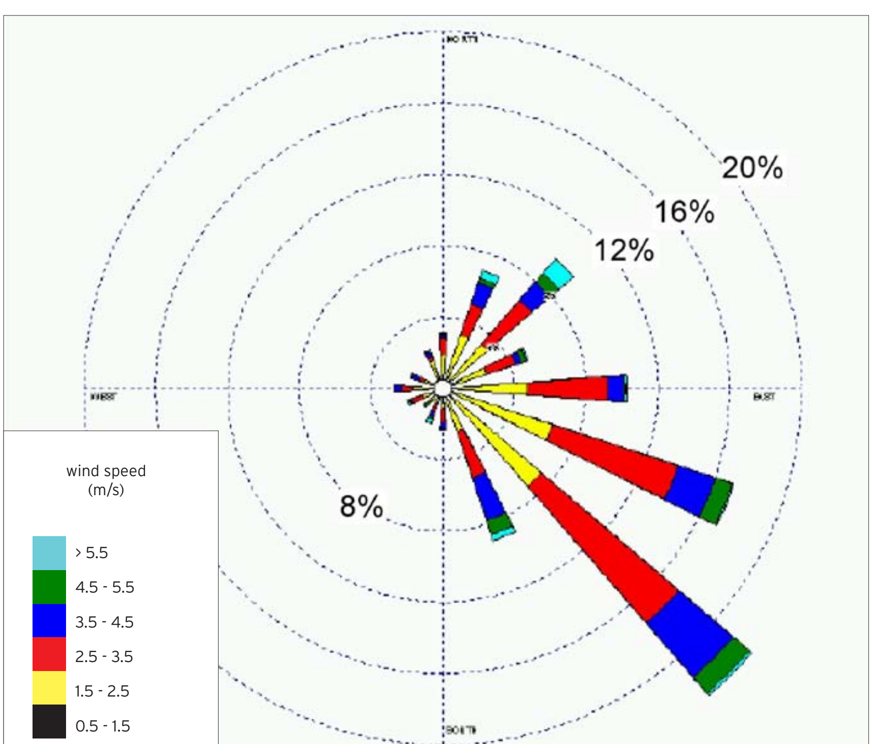


Figure 64: wind ring: Pradon Station, Porto Tolle for the winter and the summer period (between 14h00 and 16h00) from 1998 to 2001 (source: ARPAV).



speed recorded is once again less than 12 m/s and that the events characterized by greater intensity come from the Bora (45 °N), the Levante (90 °N) and Sirocco (115 °N) sectors. These data also confirm that it is the Bora and Sirocco winds that are more frequent in the area. Of the two it is once again the Bora that is on average more intense. Along the edges of the Sacca there are two pump stations from which water is discharged into the lagoon (the Bonelli and Paltanara stations).

Figure 65 shows the two stations' average flow for the year 2008. The average annual flow discharged is approximately 0.68 m^3/s, with the June maximum values slightly exceeding 1.76 m^3/s. It is of course a very modest amount of fresh water compared to the flow that, due to the oscillations of just one tide, the lagoon exchanges with the sea (about 500 m^3/s in the section that divides the Sacca di Bottonera from the Sacca di Scardovari).

It is for this reason that this incoming flow does not have a significant effect on the average salinity of the Sacca's waters. The stations' discharge therefore, can be considered at most as a contribution of some importance only in relation to the salinity of the water around where the water is discharged from the stations and during periods prolonged operation.

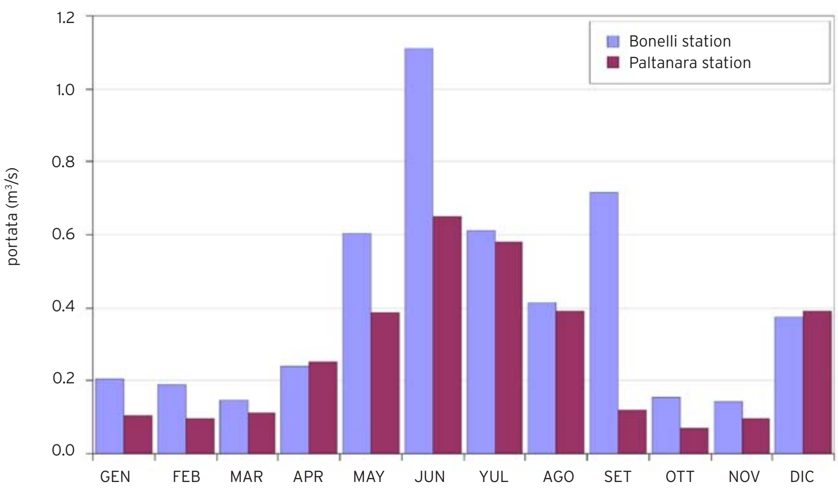


Figure 65: average monthly flow discharged into the Sacca di Scardovari from the Paltanara and Bonelli stations (based on 2008 data).

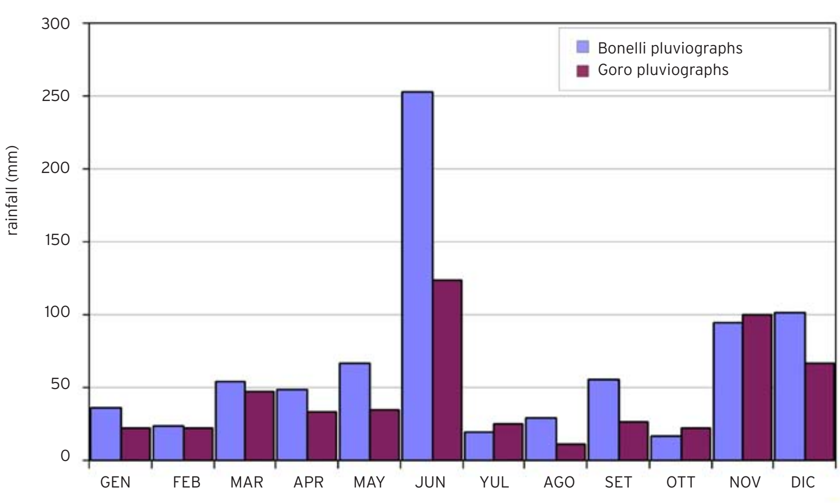


Figure 66: temporal rainfall trend measured in 2008 at the Bonelli and Goro pluviographs.

Rainfall

The effects of direct rainfall on the Sacca surface area are not relevant to the problems examined. Based on the rainfall data available at the Bonelli and Goro pluviographs (Figure 66), the direct meteor contribution to the Sacca as a whole is quantitatively similar in size to that of the pump stations, but being distributed over the entire water surface, have less significant effects. Taking into consideration a lagoon surface area of about 29 km^2, the average monthly inflow of 67 mm recorded at the Bonelli pluviograph (the Goro pluviograph recorded a monthly average inflow of 44 mm in 2008) corresponds to a constant flow of 0.7 m^3/s with a peak of 2.8 m^3/s in the month of June.

For the inner portion of the lagoon (the Sacca di Scardovari itself), characterized by an area of approximately 16.5 km^2, the values of average annual flow and peak flow for the month of June go down to 0.4 m^3/s and 1.6 m^3/s respectively. It is of course a very modest amount of fresh water, as previously stated, comparable to that discharged into the lagoon basin by the Paltanara and Bonelli stations.

Salinity

Salinity is relatively low along the entire delta coast compared to the typical characterstics in the Adriatic because of fresh water flow from the Po and the Adige. Figure 6.9 shows by way of example, a salinity map calculated with a circulation model of the Adriatic (AdriaRoms model available from ARPA Emilia Romagna, http://www.arpa.emr.it/sim/?mare&idlivello=72.

It shows how a "plume" of water with

a low salt content spans a wide stretch in front of the delta coast. The dimensions and salinity values of this "plume" are highly variable throughout the year in relation to the flow regime conveyed by the two aforementioned rivers and to the coastal circulation system, which takes on particularly complex characteristics, especially in the sea in front of the Sacca di Scardovari and Sacca di Goro in conjunction with intense marine weather and meteorological events [17].

In addition to these indications, there is also a series of salinity measurements within the lagoon that relate to the sea in front of the lagoon. As mentioned, the Consorzio di Bonifica Delta del Po, in collaboration with Arpav, manages two buoys that continuously measure salinity, temperature, pH and dissolved oxygen. An example of the temporal salinity trend recorded for the years 2007 and 2008 is shown in Figure 68.

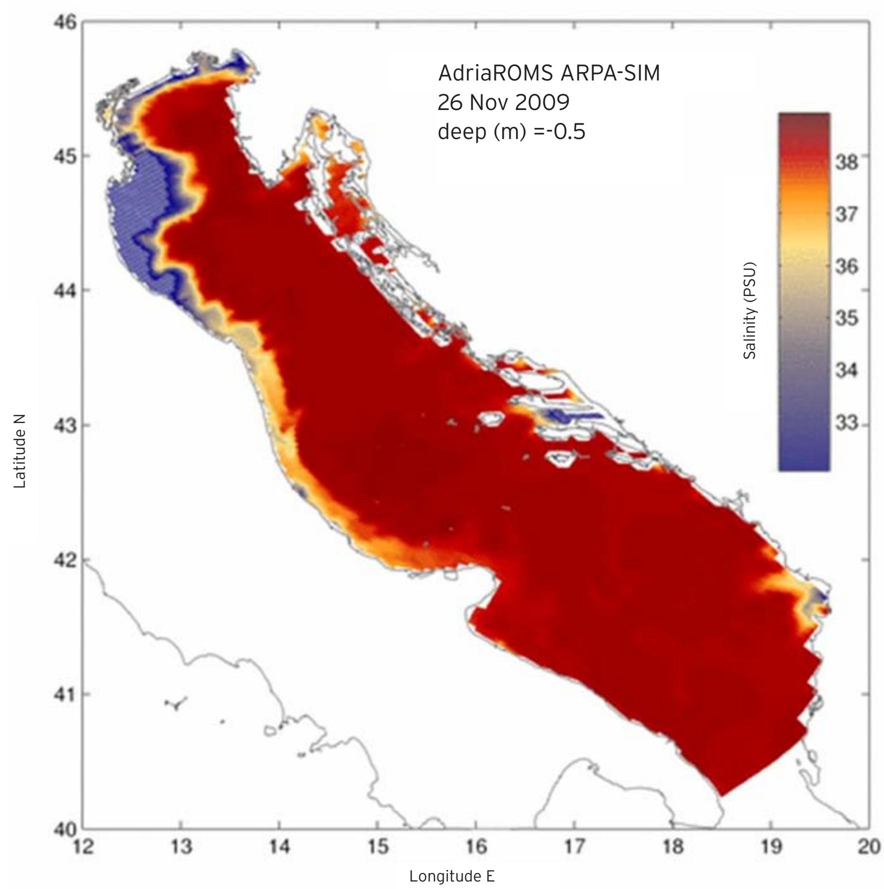


Figure 67: example of a map of average salinity at a depth of 0.5m from the surface, calculated with the AdriaRoms circulation model of the Adriatic (ARPA Emilia Romagna).

The trends observed show, on one hand, the strong seasonal variations which the salinity is subject to both in the inner and outer portions of the lagoon. These are variations that are to be considered in relation to the already highlighted seasonal variations in salinity along the coast of the Po delta. At the same time more frequent fluctuations in salt content are observed as being substantially determined by tide action, the amplitude of which however, varies according to its distance from the mouths: amplitudes in the order of 10 ppt are recorded at the station next to the North Mouth, while significantly lower amplitudes in the order of 1 to 2 ppt are recorded at the internal bouy.

Further quantitative data, characterized by a short temporal extension but with a significantly wide spatial distribution is obtained from the results of two measurement campaigns carried out by the Consorzio in support of the opening of the North mouth in 1996 and 1997.

The two measurement campaigns, carried out before and immediately after the opening of the North Mouth, made it possible to detect some important lagoon hydrodynamic aspects using special multiparametric probes able to acquire high-resolution vertical profiles for temperature, salinity, dissolved oxygen and chlorophyll, by means of a series of current flow measures and mareographs.

These investigations have for the

first time allowed us to obtain a salinity distribution map of the Sacca highlighting the considerable spatial and temporal variations that may occur in the basin even in ordinary weather and sea conditions, and the extent of both horizontal and vertical stratification.

The maps in Figure 69 and 70 provide a summary of the results obtained. Aboveall, they show the large differences in salinity distribution in the Sacca not only between one measurement campaign and another, but also over a few hours in a single campaign, depending on the different tidal conditions and the evolution of salinity distribution in the stretch of sea in front of the coast. Secondly, they provide significant information on the stratification of the water column.

Ultimately, the results confirm greater intensity of the sea-lagoon exchange in the area closest to the mouth which manifests itself in strong variations in salinity over one tidal cycle. Strong stratification conditions can be found in this area, which intensify during flow phases and are less pronounced during ebb phases due to the vertical mixing that occurs within the lagoon basin.

In the lagoon's internal area however, its salinity is subject to small tide scale variations and there is no obvious stratification phenomena. The eastern side has slightly more salinity than the west side which is characterised by lower salinity levels due to fresh water inflow from the pump stations and the differences in salinity recorded in the stretch of sea in front of the North and South Mouths.

Analysis of the Current Situation

Prior to the analysis of the hydrodynamic patterns of the Scardovari lagoon through the 3D multilayer model, a series of preliminary tests to assess the consistency with the results provided by the two-dimensional model were conducted. Perhaps the most compelling example is the temporal comparison of the changing flow rates through the Sacca'a two mouths for a sinusoidal reference tide (Figure 71).

Using the 3D multilayer model, one can identify the main behavioral features of the Sacca di Scardovari when the system is forced by different natured events, which in the Po, could be considered flood or low water events in the presence the Bora and Sirocco winds. After the initial conditions were identified, they were defined in a preliminary simulation over 28 days, in order to fine tune the system by applying the tide in Figure 62 to the open boundary and assuming a constant salinity of 35‰.

Constant flows of 200 m^3/s (Po di Tolle), 170 m^3/s (Po di Gnocca) and 110 m^3/s (Po di Goro) were assigned to the

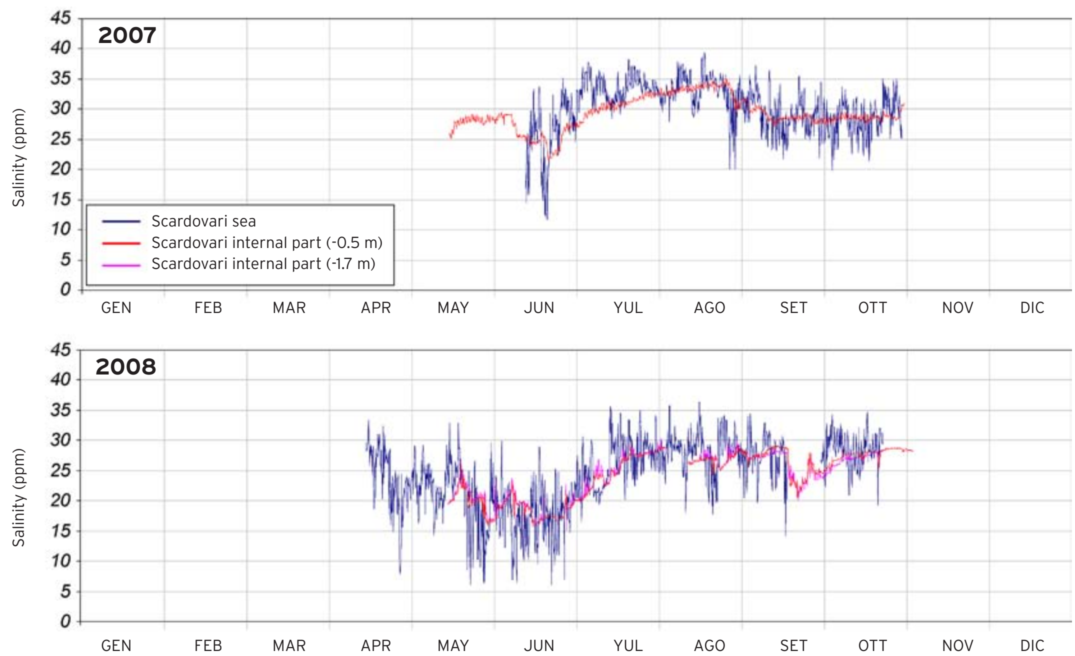


Figure 68: Temporal salinity trend measured in 2007 (top) and 2008 (bottom) at the two fixed stations, the locations of which are shown in Figure 61.

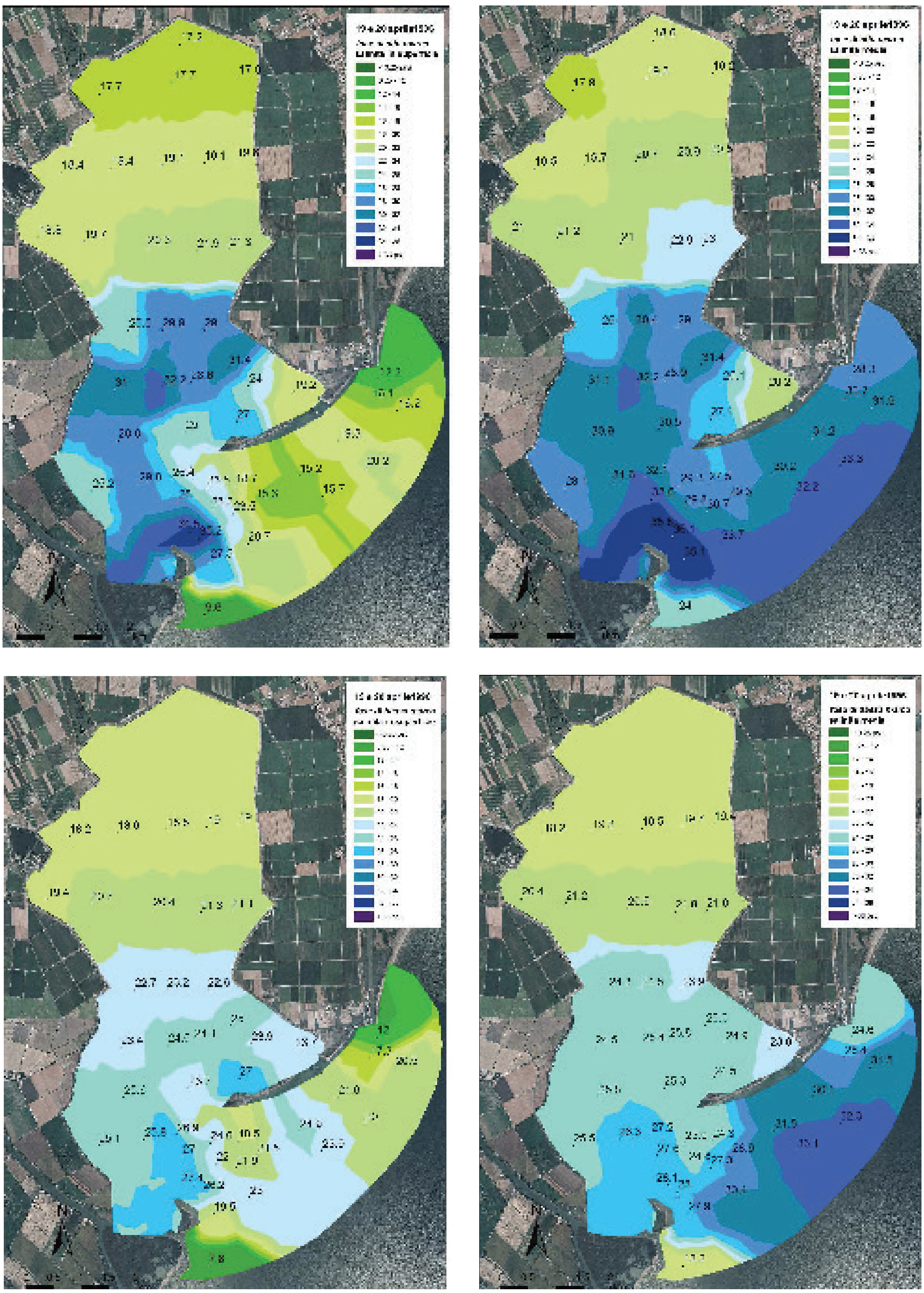
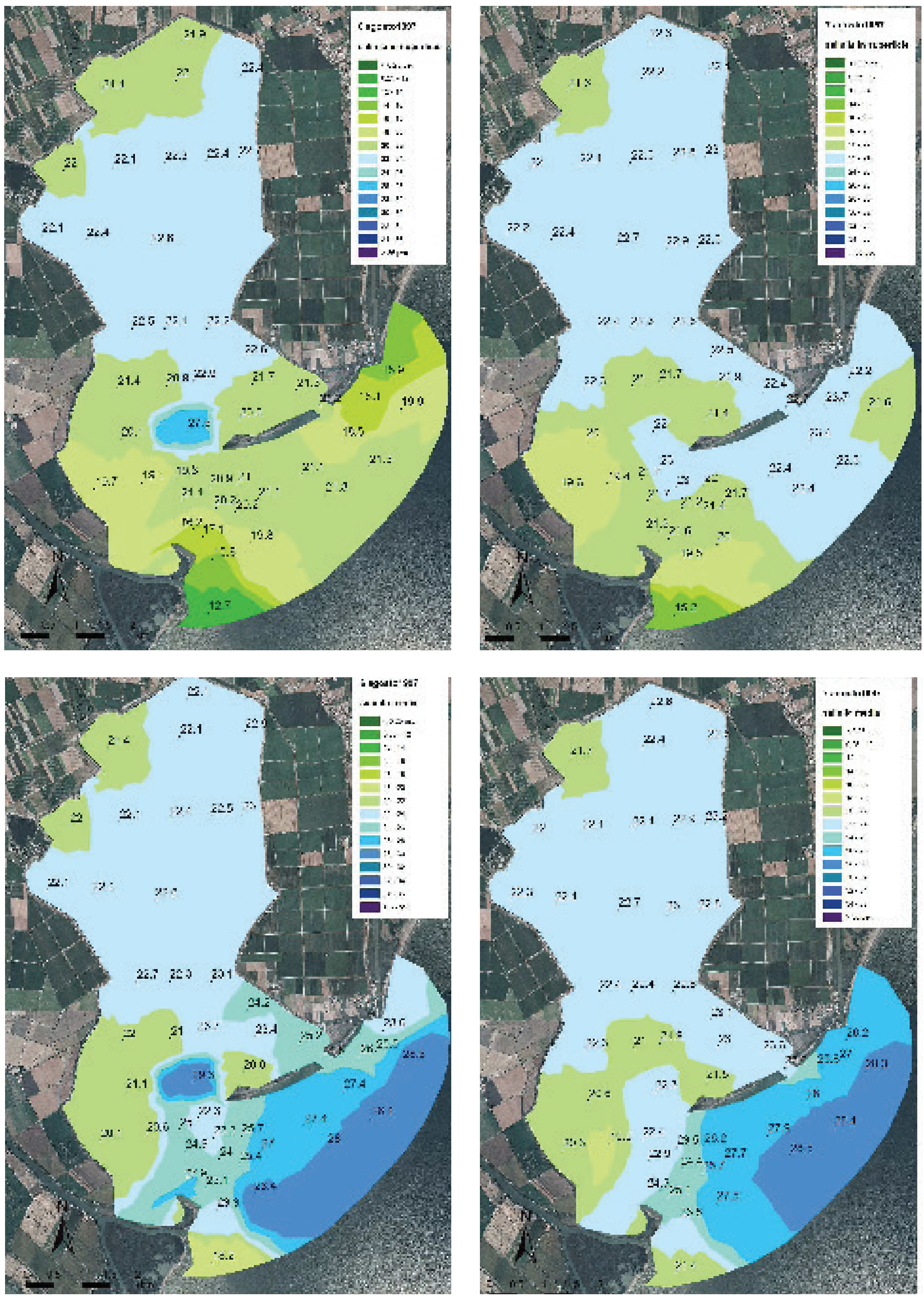


Figure 69: chemical and physical parameter measurement campaign in the Sacca di Scardovari conducted on 27 April 1996 before the opening of the North Mouth. Maps of the average surface (between 0 and 0.5 m from the surface) salinity detected in the phases of high and low tide over the entire water column.

Figure 70: chemical and physical parameter measurement campaign in the Sacca di Scardovari conducted on 6-7 August 1997 before the opening of the North Mouth. Maps of the average surface (between 0 and 0.5 m from the surface) salinity detected for a one day timeframe over the entire water column.



entrances of the Po distributaries involved. This represents average flow conditions of the Po regime [11] occuring when flow at Pontelagoscuro is about 1000 m^3/s which, according to available records, is exceeded in 50% of cases [11].

Flow corresponding to the annual average values of 0.27 m^3/s and 0.41 m^3/s were attributed to the Paltanara and Bonelli pump stations respectively. Looking at the results in four different points in the lagoon, at different depths and along two distinct longitudinals in certain characteristic instances of the calculation (Figure 72), it is possible to briefly comment on the patterns of the lagoon in relation to salinity distribution. Among those considered, for the innermost point and the three different depths, the salinity fluctuations over time are barely perceptible (Figure 73).

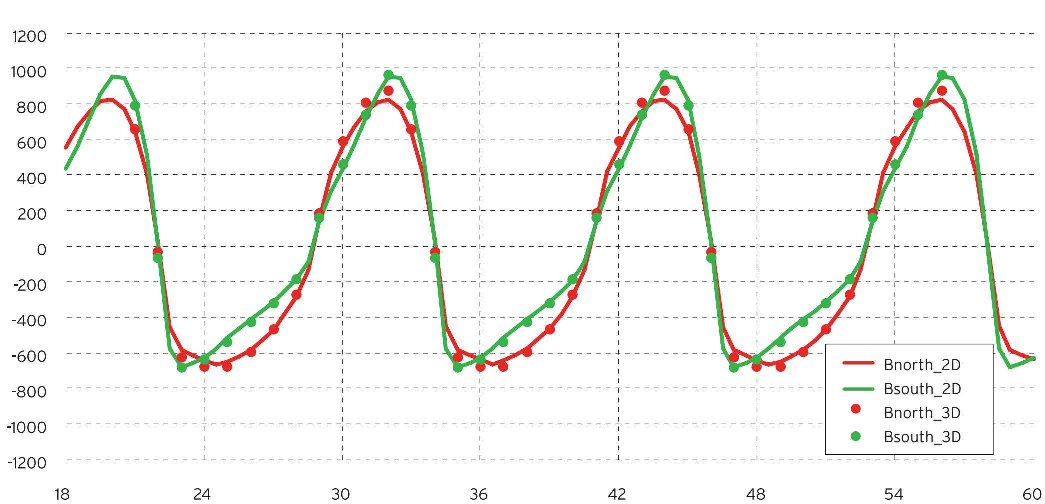
A greater variation in salinity is found for the center point with oscillations of about 2 to 3 ppt in amplitude. Furthermore there is fairly constant salinity distribution along the vertical axis for both points, meaning that the liquid column is substantially mixed. For the two points corresponding to the lagoon mouths there is, however, a relatively high variation in salinity during the tidal cycle with amplitudes that oscillate between 5 ‰ and 10 ‰ at the surface. The liquid column also shows substantial stratification phenomena, with salinity significantly lower at the surface, especially during flow phases .

It should be noted that due to the effect of stratification, the amplitude of the variations of the saline content of the layer located immediately below the surface layer (50 cm on average below the free surface) is significantly lower than the salinity oscillation amplitudes of both that layer and the deeper layers.Stratification characteristics are more obvious when examining salinity distribution along the two longitudinal profiles considered in two different instances of the tidal cycle (Figure 74 and 75).

Reagarding the North Mouth profile in particular (Figure 74), at the end of the flow phase, large scale stratification extending for a few hundred meters within the lagoon from the sea area in front of the mouth itself can be seen. During the final phase of ebb flow however, the stratification is less pronounced and is only limited to a part of the sea. The innermost part of the lagoon shows very different patterns with its salinity showing modest changes and being considerably uniform in the vertical direction over an entire tidal cycle. Similar conditions are found in the profile of the South Mouth (Figure 75).

Along this profile however, surface salinity is lower than that of the previously considered profile, and the stratification, which is significantly more pronounced, stretches along the inside of the lagoon almost as far as the Paltanara pump station discharge. Also in this case stratification is extremely evident in the flow phase, while in the ebb phase the lagoon is characterized by substantially uniform salinity distribution. Overall, the salinity within the lagoon is slightly lower along the South Mouth profile compared to the

Figure 71: comparison between the flow rates at the mouths calculated using the 2D and 3D multilayer models for a sinusoidal tide of 0.5m.



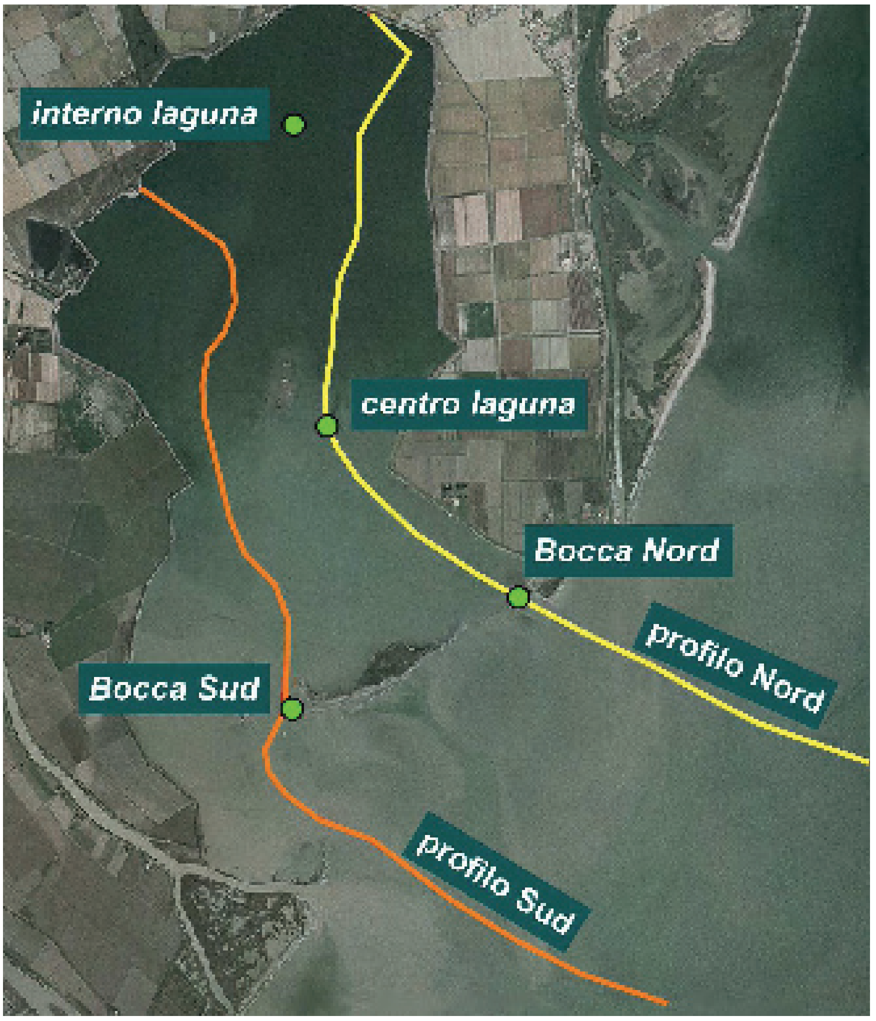


Figure 72: the location of the four points inside the lagoon where temporal salinity trends were recorded and the location of the two longitudinal profiles of the lagoon mouths.

values of that of the North Mouth.

Figure 76 illustrates the quantitative evaluation of this particular pattern in the vicinity of the lagoon mouths, or of the presence of a marked stratification during the phases of flow, and the substantially uniform distribution of salinity along the vertical axis during the flow phases.

The first two graphs illustrate the temporal salinity trends at the two mouths relative to the surface and below the surface layers, while the third graph shows the difference between surface salinity and that which lies below the surface, making a distinction between the ebb and flow phases.

One can clearly see a big difference in salinity, and therefore stratification, which characterizes the flow phases with values that go up to 15 ‰ during syzigial periods. During ebb phases however, apart from the short peaks near the reversal of the tide, the differences in salinity between the surface layer and the underlying layer are only 2-3‰.

The various results obtained confirm that the part of the lagoon closest to the mouths is very active and is characterized by intense sea-lagoon exchange. During the flow stages, the current is significantly more layered, with fresh water that tends to penetrate the surface near the lagoon basin especially through the South Mouth.

Once inside the lagoon, this water is subject to both vertical and lateral dispersion phenomena, as a result triggering active mixing processes that render the salt content

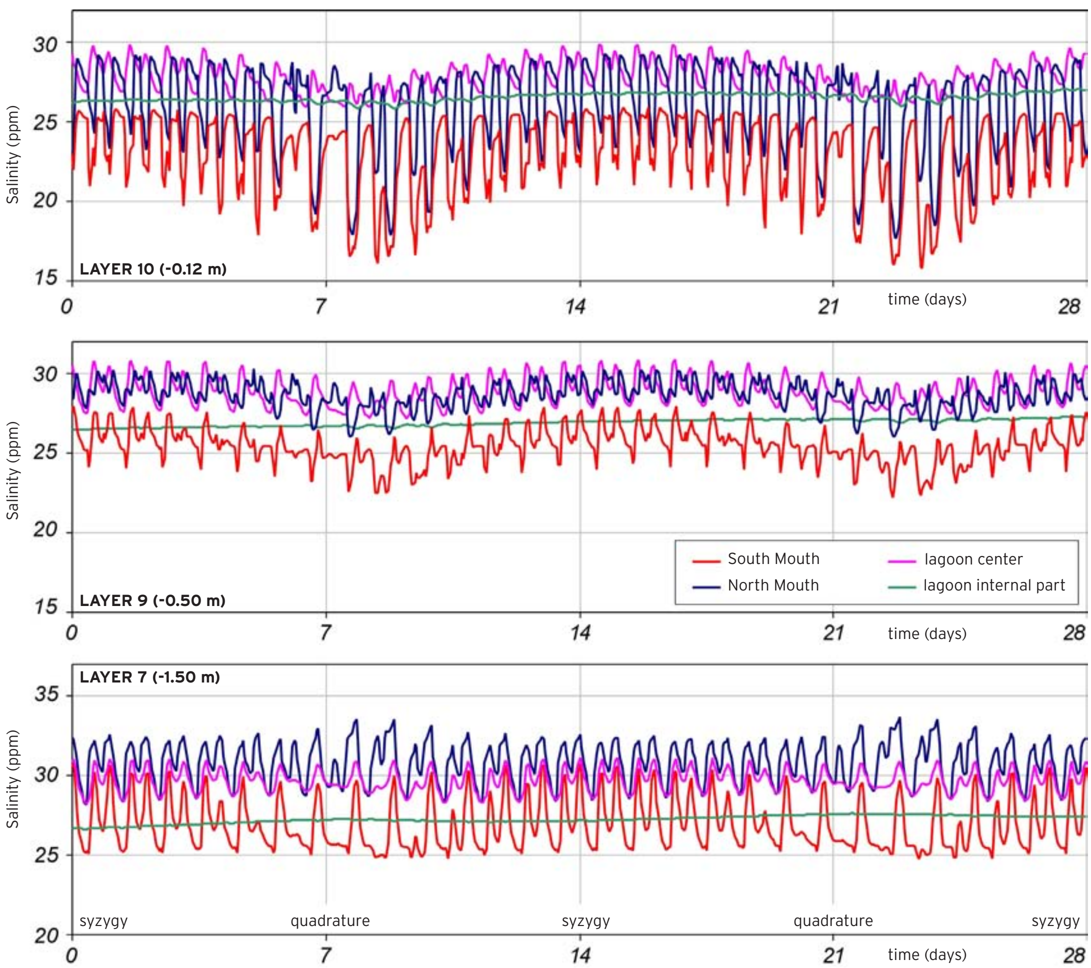


Figure 73: salinity trends at four points inside the lagoon (see Fig 72) in relation to the layers: 10 (first 25 cm), 9 (50 cm from the surface), and layer 7 (1.5 m from the surface).

of the water substantially uniform. In the ebb phases, the internal waters, having been mixed once again, do not show characteristics of stratification exiting through the lagoon mouths.

In the inner part of the lagoon the saline content, on a tidal scale, remains substantially constant both for the fact that this part of the Sacca is fed by waters that have already been mixed moving from areas closest to the mouths, and because the flow affecting the northern area is significantly lower than that of the southern part of the lagoon basin. Under normal conditions, the western part of the Sacca is characterized by slightly lower saline content than the eastern part.

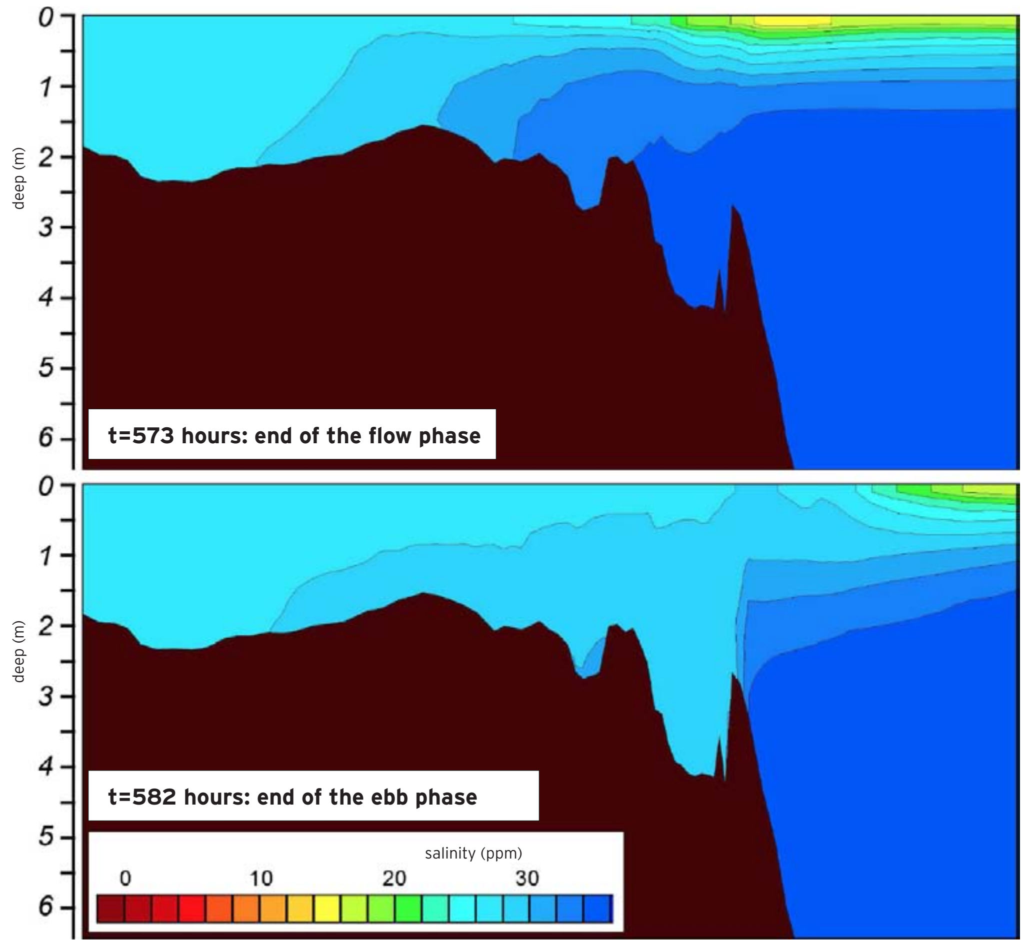
This circumstance is justified on one hand, by the mouth of the eastern distributary of the Po di Gnocca's close proximity to the South Mouth, and on the other, by the presence of flow discharge originating from the Paltanara and Bonelli pump stations located along the western edge of the lagoon.

These considerations, in relation to the hydrodynamic patterns of the lagoon in average climatic and hydrological conditions, are briefly illustrated on the maps in Figure 77 which show the minimum and maximum saline distribution for the surface layer and underlying layer (layer 7).

Po Flood Effects

Starting from the aforementioned average system conditions, the consequences of the flooding of the Po were simulated, putting together the upstream sections of the Po di Tolle, Po di Gnocca and Po di Goro distribu-

Figure 74: salinity distribution along the North Mouth profile (see Figure 72) at the end of the flow and ebb phases.



taries with the synthetic flood hydrographs equal to 1000 m³/s, 850 m³/s and 550 m³/s (Figure 78) respectively, which roughly correspond to values of about five times the average flow.

These flood hydrographs were introduced into the system in two different instances during the simulated period: the first at t=0, when the lagoon basin was affected by a sygzigial tide (Figure 62), and the second at more or less t=21 days, when the system had recovered from the first event and the lagoon basin was affected by a quadrature tide (Figure 62). Figure 79 shows the temporal salinity trends calculated at four points in the lagoon (Figure 72) at three different depths: at the surface, slightly below the surface (on average 50 cm below the free surface) and at a depth of about 1.5m near the bottom. In the inner part of the lagoon, the flood event results in a slight reduction in salinity, with maximum variations in the surface layer not exceeding 2 ‰.

In contrast, in the vicinity of the lagoon mouths and in particular that of the South, there is a large reduction in salinity again in the surface layer, with peaks of about 20 ‰ and a significant parallel increase of the amplitude of the salinity oscillations associated with the same tide. Changes in salinity are influenced by the characteristics of the tide. During quadrature phases, fresh water penetrates the lagoon more easily, resulting in a greater reduction in salinity compared to an identical flood event in syzygial tide conditions.

Figure 80 shows, in map form, saline content spatial distribution during the second simulated flood event at the end of the ebb and flow phases. The maps refer to salt concentrations calculated for the surface layer and

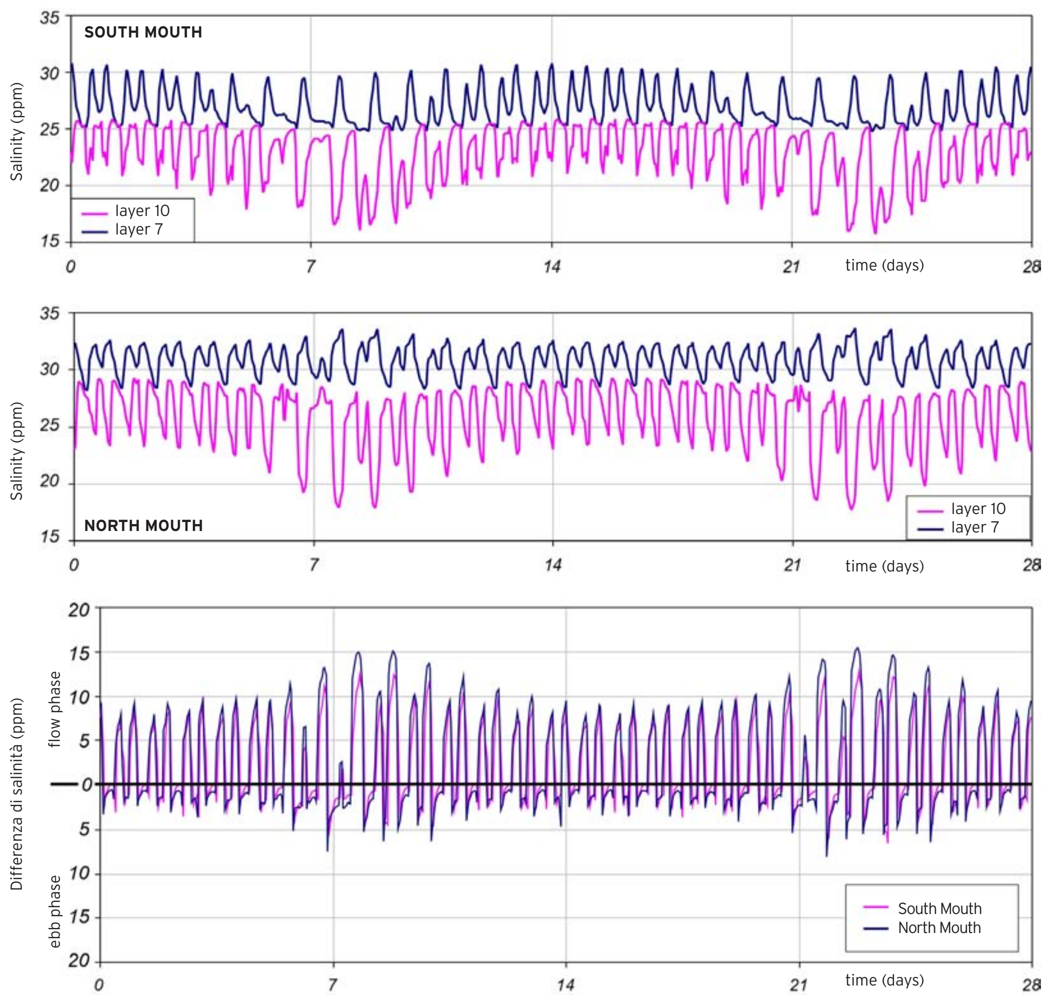


Figure 75: salinity distribution along the South Mouth profile (see Figure 72) at the end of the flow and ebb phases.

an intermediate depth layer (of about 1.5 m). This confirms that in the inner part of the lagoon salinity variations in flood conditions are relatively modest in the Po. Furthermore the salinity is vertically distributed in a fairly uniform manner.

On the contrary, in the southern part of the lagoon and especially near the South Mouth, there are large temporal variations in salinity and a marked stratification which is more pronounced at the end of flow phase. The modest variations in salinity found in the innermost part of the lagoon are determined by the fact that the flood event simulated is relatively short (2 days), meaning that the reduced salinity conditions in the sea in front of the mouths do not have time to propagate deep into the lagoon. The above considerations, as will be seen, are confirmed in the results of the lagoon basin patterns in prolonged low water conditions in the Po.

Effects of Prolonged Low Water Conditions in the Po

As always, the effects of prolonged low water in the Po were simulated based on the average conditions in the system. In particular, low flow rates of 20 m^3/s, 17 m^3/s and 11 m^3/s were given, corresponding to the upstream sections of the three distributaries of the Po di Tolle, Po di Goro and Po di Gnocca respectively, amounting to roughly one-tenth of the average flow of the distributaries themselves.

Figure 81 shows the temporal salinity trends calculated in the same four points within the lagoon already indicated for three different depths: at the surface, at an intermediate depth of about 50 cm below the surface and at a depth of approximately 1.5 m near the bottom. In general there is an evident increase in salinity over the entire lagoon.

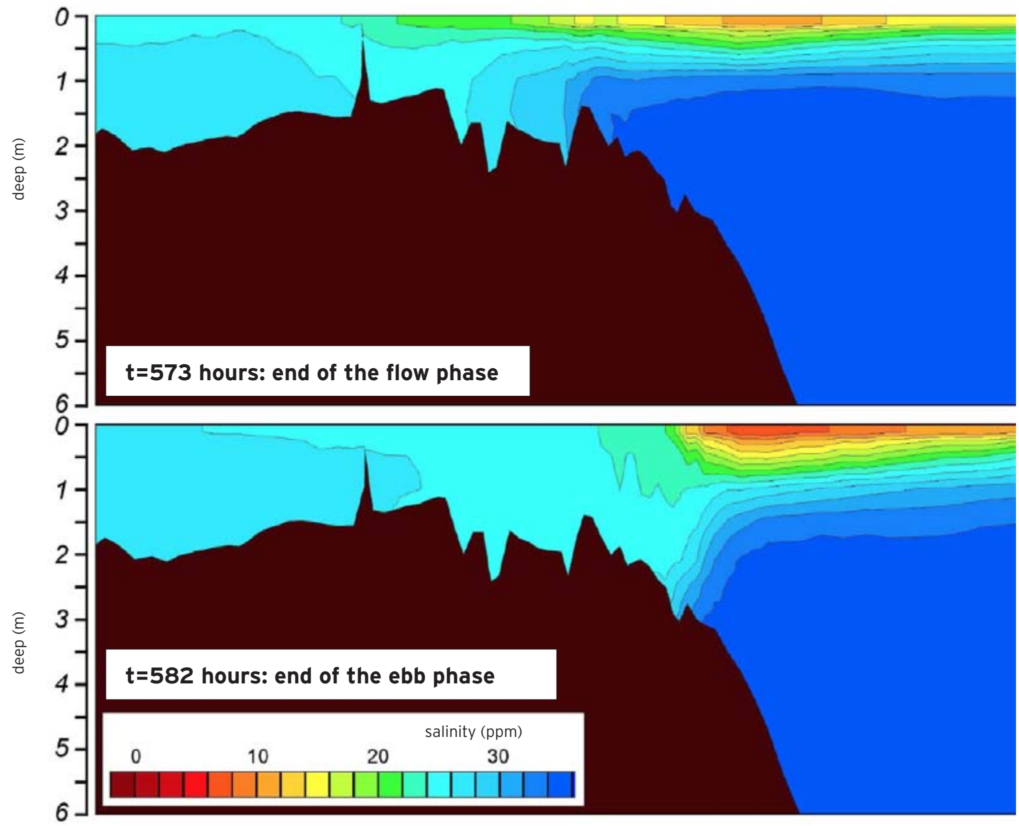


Figure 76: temporal salinity trends of the surface layer (layer 10) and for the underlying layer (layer 7) corresponding to the two mouths, and the temporal trend of the difference between them distinguished according to ebb and flow phases.

This increase is relatively rapid (a few days) for the two points located near the mouths, while in the inner part of the lagoon the variation of salinity is much slower and continues for the duration of the simulation (about one month). The changes in salinity are distributed fairly uniformly both planimetrically and vertically, throughout the liquid column. They are relatively small, about 2 ‰.

Effects of the Bora and Levante winds

Once again, based on average conditions, the effects of wind on mixing processes within the lagoon and, above all, on the exchange between the lagoon and the sea, were simulated. In these simulations, a NE wind (45 °N) characterized by a constant velocity of 12 m/s blowing continuously for 24 hours, and the Levante wind (90 ° N) with a speed of 8 m/s over a 24 hour period were considered.

Both the Bora and Levante were placed in a syzygial period to highlight the effect of the amplitude of the tide oscillations on the phenomenon.

Figure 81 shows the temporal salinity trends calculated in the same four points within the lagoon already indicated for three different depths: at the surface, at an intermediate depth of about 50 cm below the surface and at a depth of approximately 1.5 m near the bottom.

The analysis of the results obtained shows a significant reduction in salinity within the lagoon during both the Bora and Levante events. The Levante is generally more effective in pushing the fresh waters within the lagoon producing reductions in salinity of up to 20 ‰ during the event. Obviously the surface layers are mostly affected by the effects of wind.

Deeper, near the bottom, different patterns of freshwater flow for the two mouths are evident. The effects of the Levante at the North Mouth are modest, and those of the Bora even less.

Near the South Mouth, however, there is a significant reduction in salinity when the Levante blows. During quadrature tides there is a decrease

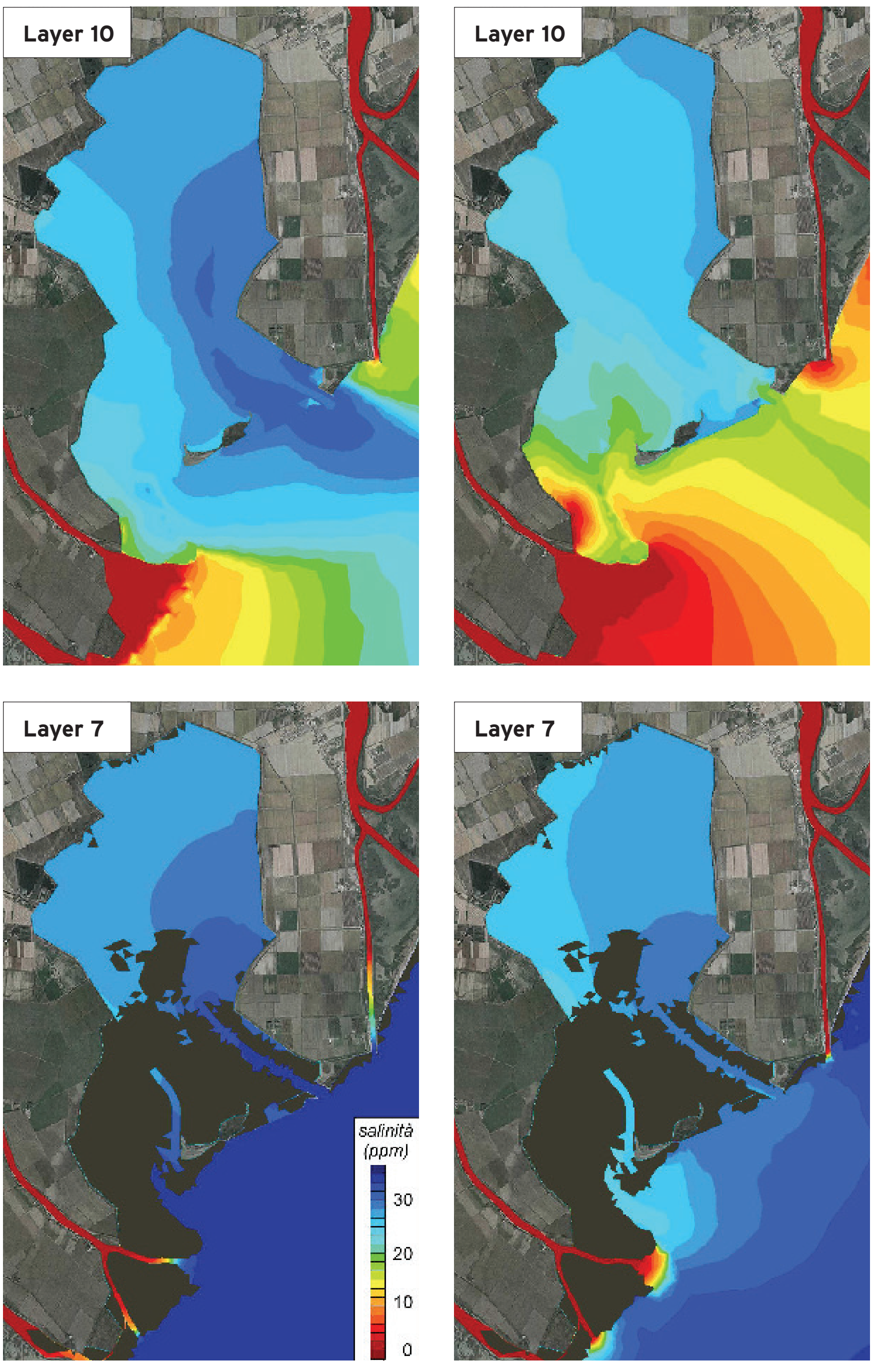


Figure 77: spatial distribution of the maximum (left) and minimum (right) saline content values for the surface (layer 10) and underlying (layer 7) layers.

in salinity of almost 10 ‰. However, the reduction of salinity in the presence the Bora is negligible.

In the centre of the lagoon only the surface layer is affected to an appreciable extent by the wind, with even more significant reductions accompanying the Levante. The intensity of the phenomenon is similar during syzygial and quadrature periods.

For the innermost portion of the lagoon, in the end the simulations conducted indicate modest salinity variations of about 2 ‰ both at the surface and deeper down. These changes assume values independently of both the wind (Bora or Levante) and the tide conditions of (syzygial or quadrature).

The spatial distribution of salinity inside the Sacca at the end of the ebb and flow phases, relative to the surface layer and a deeper layer near the bottom is illustrated in Figure 82 and 83 for the Bora and Levante respectively.

In short, the results already discussed regarding salinity temporal trends in certain points within the lagoon are confirmed. In addition, during a Bora event (Figure 82), surface waters are pushed towards the Southwest due to the characteristic wind origin direction.

In particular, the North Mouth is mainly fed by fresh water from the Po di Tolle eastern distributary, while more saline water enters through the South Mouth, the flow being discharged from the Po di Gnocca distributary and driven along the coast towards the southwest.

This can also be seen in Figure 81 in relation to the top layer.

In Levante wind conditions (Figure 83), which blow almost at right angles to the coast, fresh water present in the stretch of sea in front of the sandbar is pushed towards the mouths and then into the lagoon, significantly reducing the upper layers' salinity. The results obtained indicate how the innermost portion of the lagoon is negligibly affected by these forces, the variations in salinity which occur under Bora or Levante conditions both at the surface and especially deeper down, being modest.

For a more significant quantitative evaluation of the effects of the wind in the inner part of the lagoon, i.e. in the part which is most affected by often insufficient water exchange, the results of simulations in wind conditions were compared with those relating to conditions in which there was no wind. In particular, surface layer temporal salinity trends, being most sensitive to the wind, were compared, considering four interior points of the northern part of the lagoon (see Figure 84).

The comparison results are shown in Figure 85. It is evident that variations in salinity produced by the wind in this part of the lagoon are very small.

The exception being perhaps in Bora conditions and a quadrature tide where the variations in salinity are more consistent, even if they are shorter. In these simulations, the wind is rather intense (the Levante having a speed of 8 m/s and the Bora 12 m/s) and is consequently less likely to occur frequently. It was for this reason that the verification of the hydrodynamic behavior of the lagoon was carried out in wind conditions that occur more frequently with speeds considerably lower than those taken into consideration.

In such conditions the wind has considerably less effect and is difficult to pinpoint. Some conclusions can however be drawn from the results of

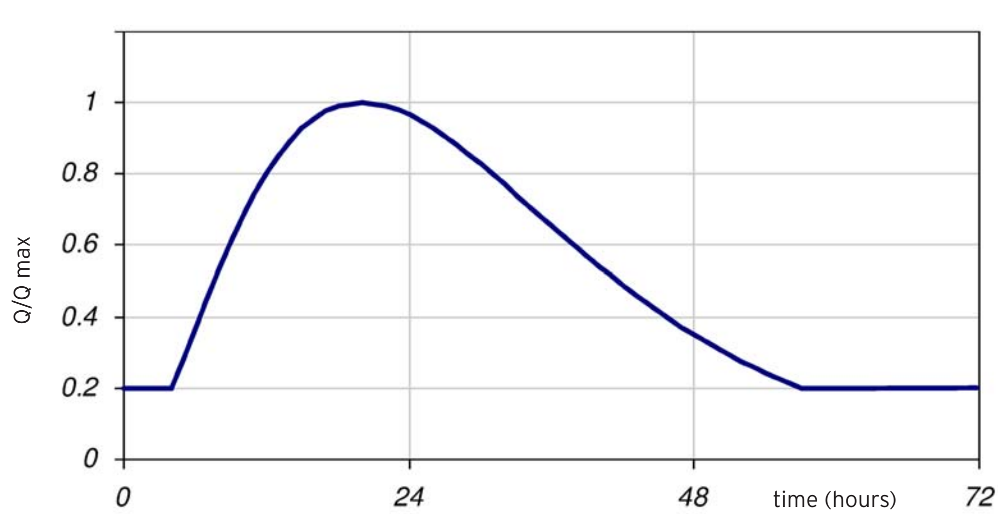


Figure 78: synthetic flood hydrograph in dimensionless form.

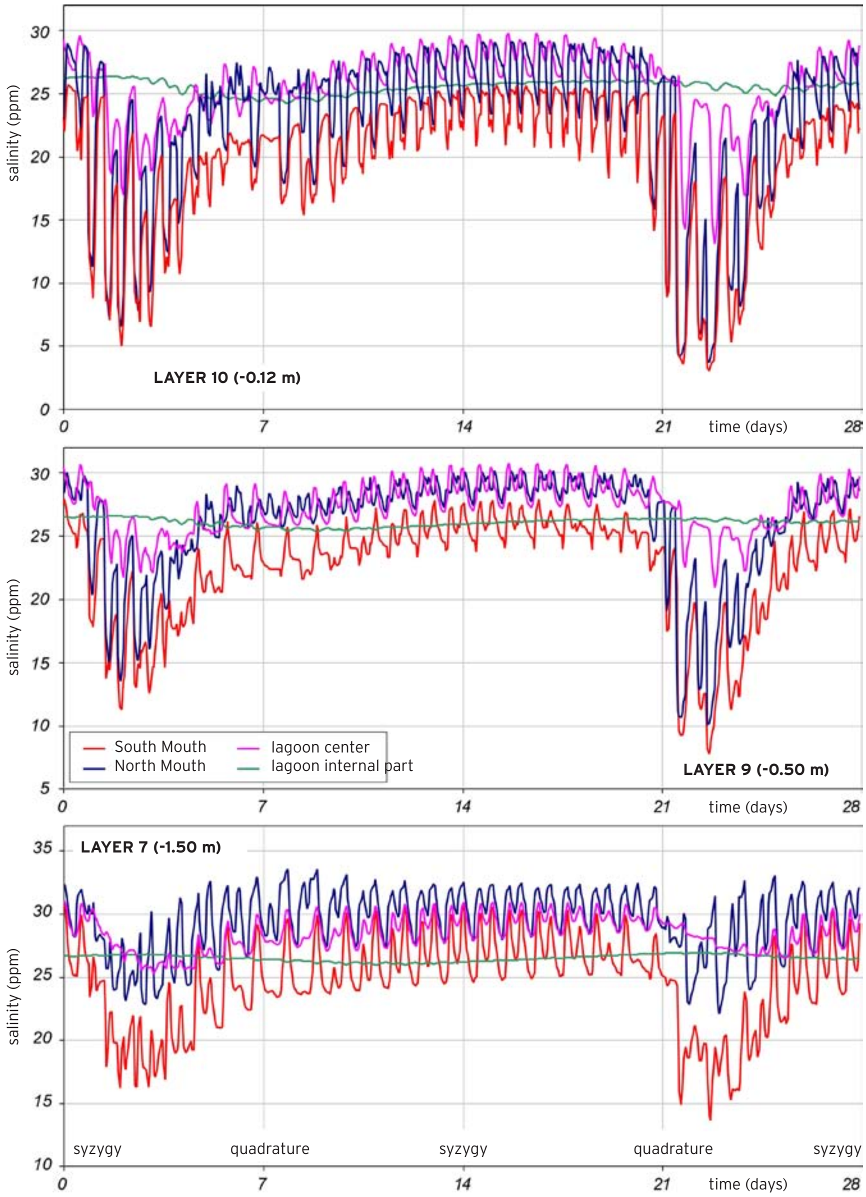


Figure 79: salinity trends at four points inside the lagoon (see Figure 72) relating to layers: 10 (first 25 cm), 9 (50 cm from the surface, and layer 7 (1.5 m from the surface) during two Po flood events.

simulations analyzing the dispersion processes of a group of particles examined with the use of a Lagrangian-dispersive model.

Considering a 1m sinusoidal tide over a period of 12 hours, the calculation was performed by releasing 2 "spots" consisting of 4000 particles each, in the same positions used for the estimates described previously when referring to the use of two-dimensional model.

Figure 86 shows the comparison between the results obtained using the hydrodynamic solution provided by the two-dimensional model (see Figure 18) and those from the multi-layer 3D model. From a qualitative point of view, the two different models' results are congruent. There is more dispersion however, when referring to the hydrodynamics calculated with the 3D model. One should bear in mind in this regard that the 3D model uses a computational grid that is less refined and this could result in some sort of numerical dispersion in the physical process.

Figure 87 summarizes the results of the same calculation (only relative to the use of the 3D model) in instance t=96 hours. Initially located in the inner part of the lagoon, the spot undergoes modest dispersion, remaining significantly compact. It is interesting to note that the dispersive processes are essentially characterized by the same intensity both in the surface layer and at greater depth (layer located near the bottom - red).

One also notes, as already shown in the two-dimensional model results, that the spot's initial position remains

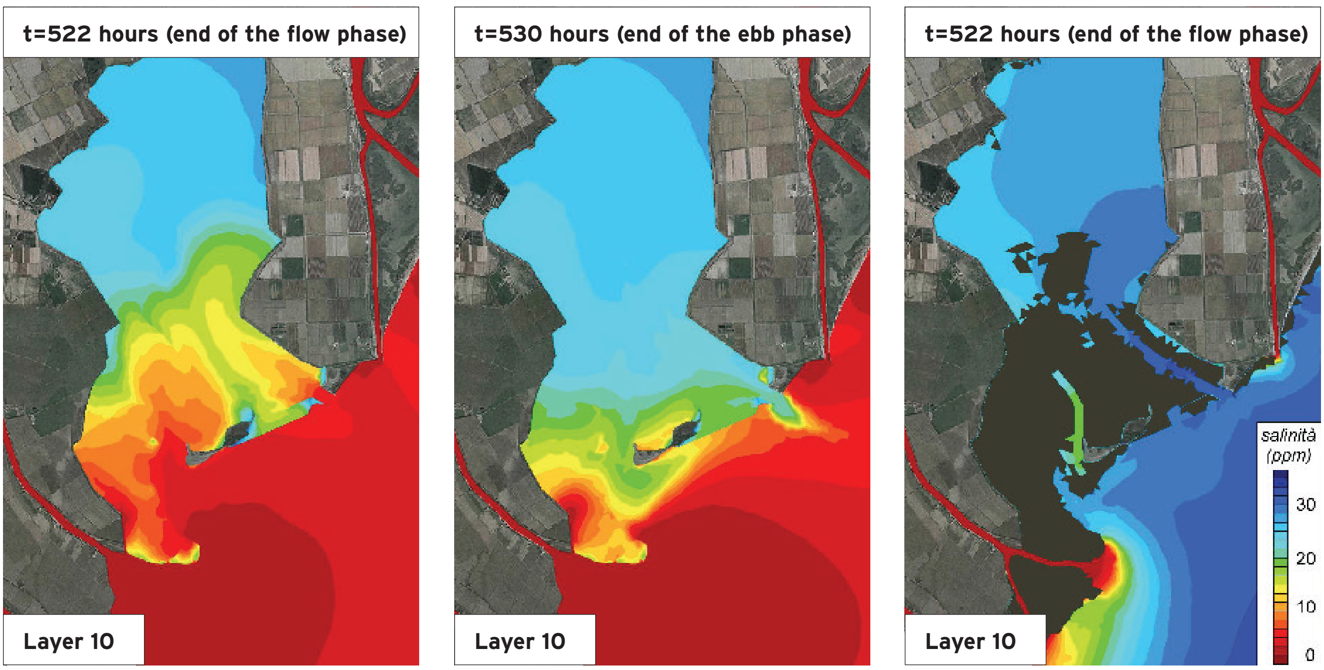


Figure 80: spatial distribution of salinity at the end of the flow (left) and ebb (right) phases of the surface (layer 10) and underlying (layer 7) layers during a flood event.

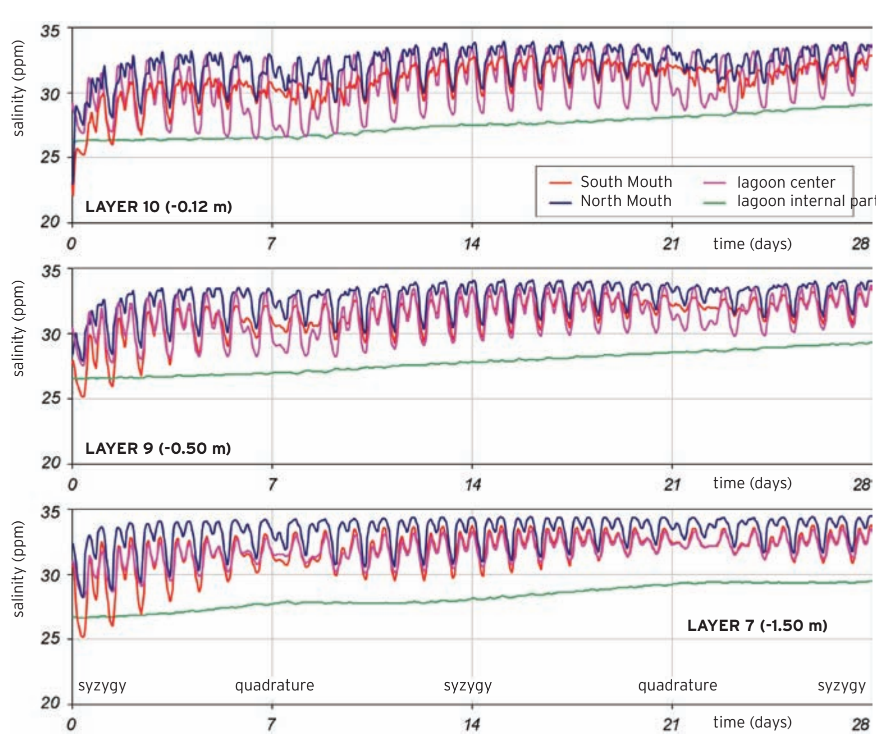


Figure 81: salinity trends at four points inside the lagoon (see Figure 72) relative to the layers: 10 (first 25 cm), 9 (50 cm from the surface), and layer 7 (1.5 m from the surface) during prolonged low water in the Po.

substantially unchanged, indicating the absence of substantial residual inter-tidal currents.

In contrast, one notes different patterns for the surface layer (green particles) and the deeper layer (blue) relative to the dispersion of the spot initially located in the southern part of the lagoon in the same figure. While the particles that occupy the deeper layer, due to slower speeds, undergo reduced dispersion and tend to move slowly to the South Mouth, the dispersion undergone by the particles in the surface layer is notable.

The influence of a weak Bora wind on mixing processes was analyzed. From the force conditions used in the previous simulation, a Bora wind blowing uniformly in a N direction, at 45° at a speed of 4m/s for 12 hours every day was imposed.

Figures 88 and 89 show the results of the calculation taking surface layer and a deeper layer near the bottom in to account at the t = 40 h and t = 96 hour instances.

In the southern part of the lagoon, the Bora wind pushes both surface layer and deeper layer particles towards South Mouth. In particular, it should be noted that in the presence of wind, the spot remains significantly more compact compared to when there is no wind (Figures 86 and 87).

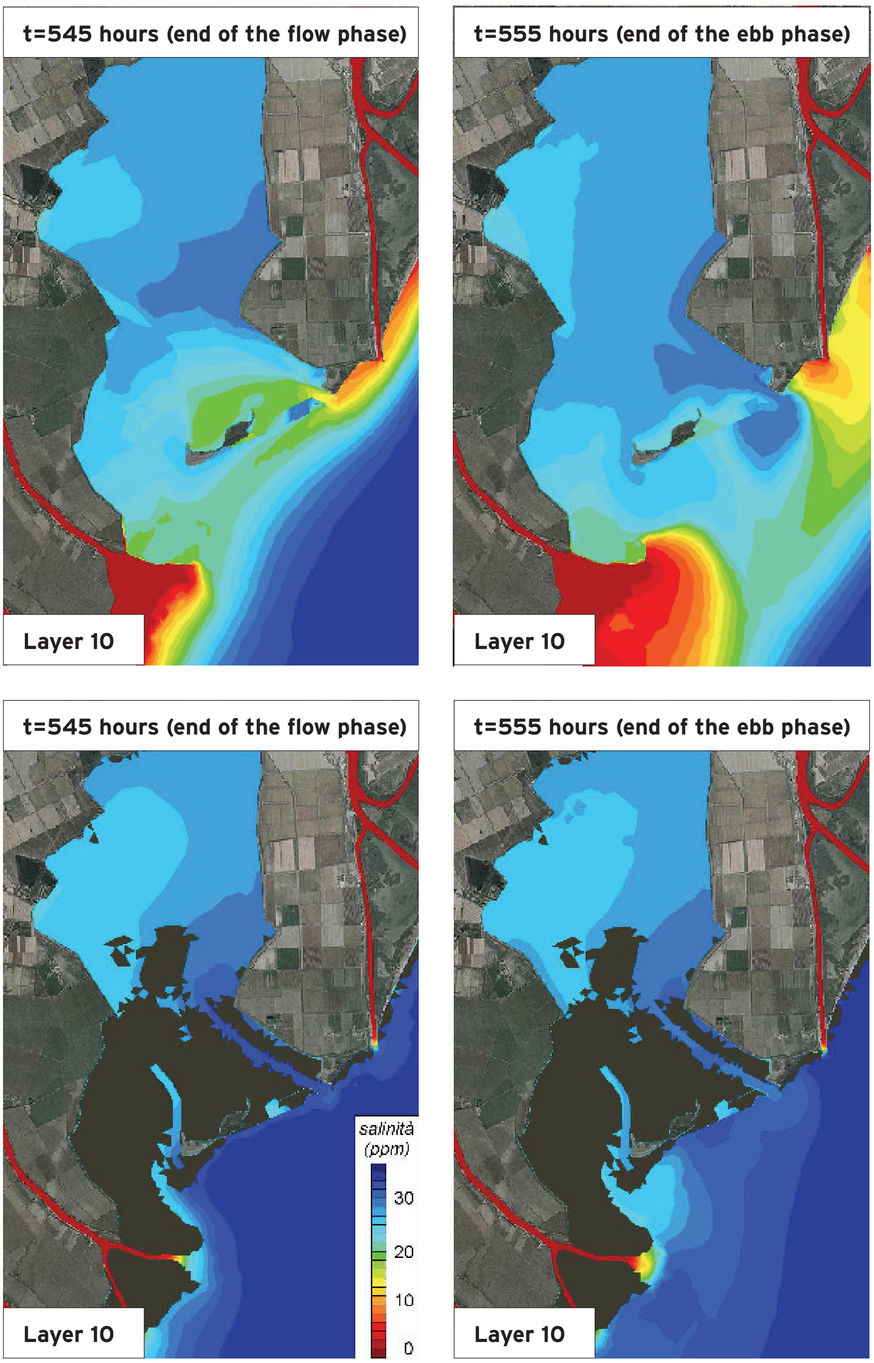
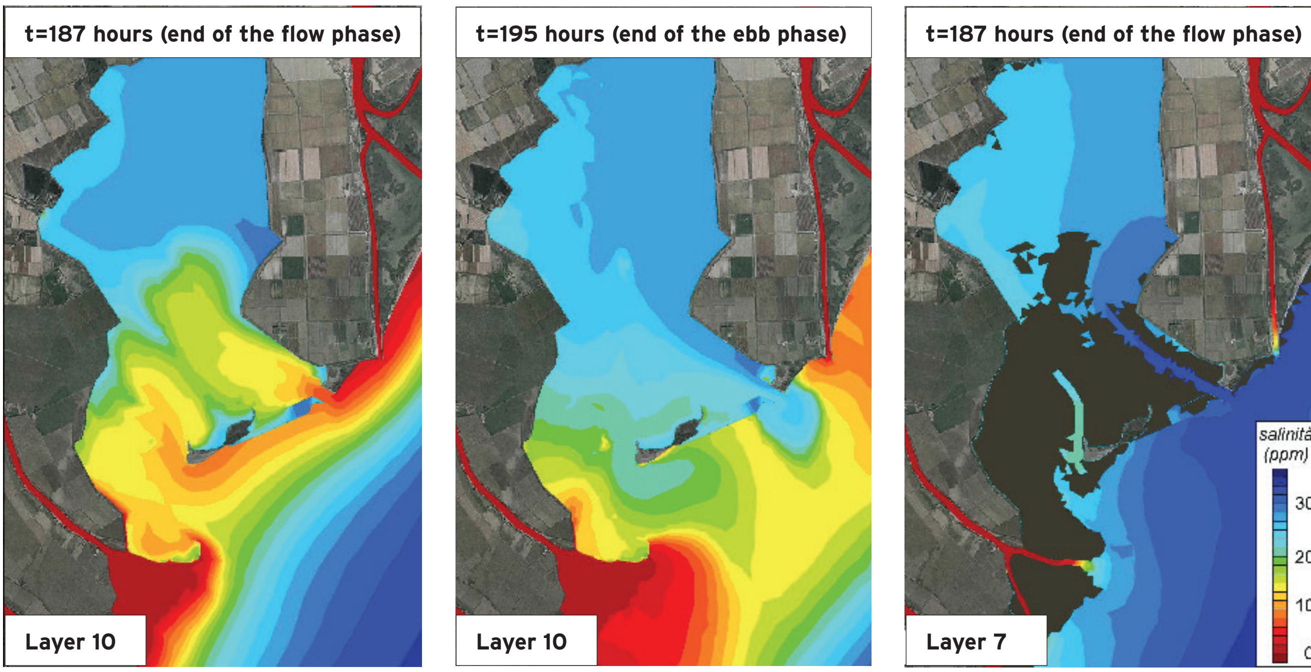
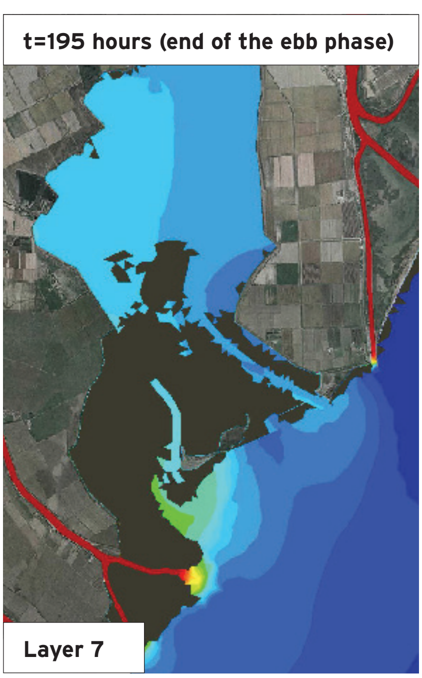


Figure 82: spatial distribution of salinity at the end of the flow phase (left), and ebb phase (right) for the surface layers (layer 10) and deep layers (layer 7) during Bora wind conditions.





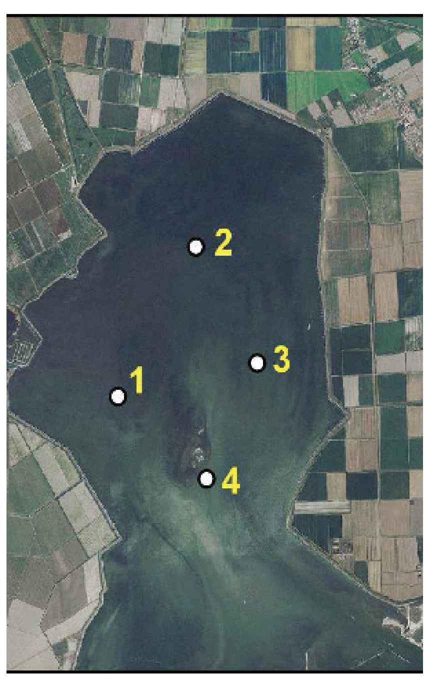
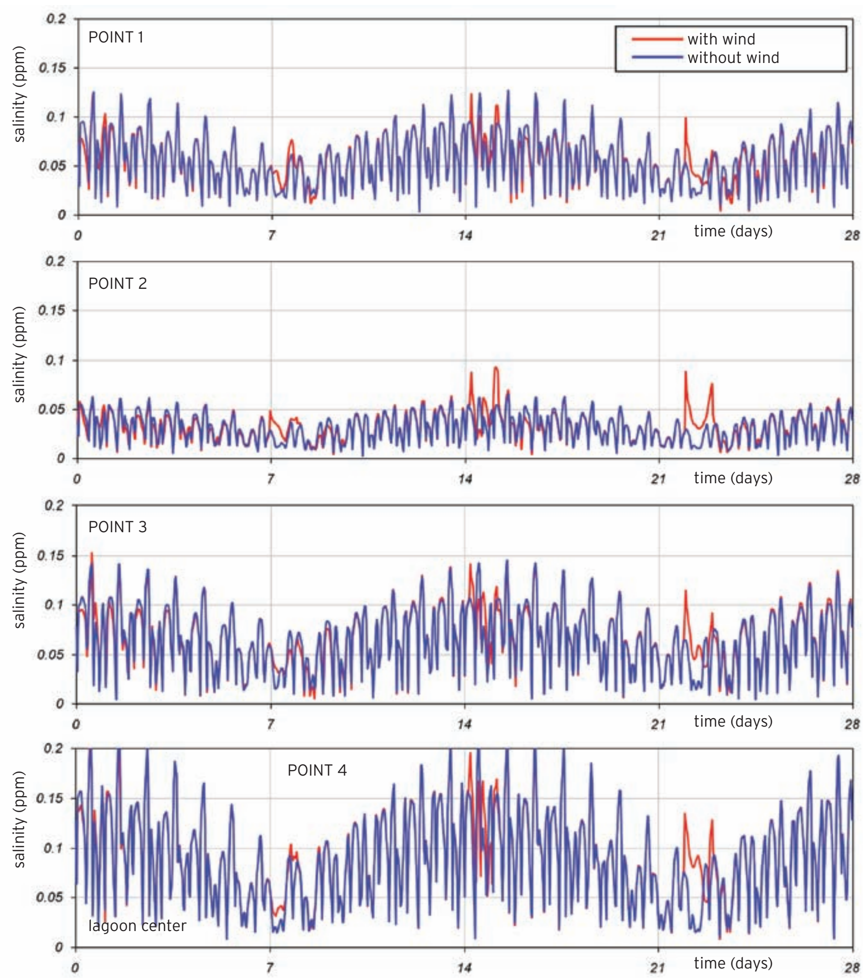


Figure 83: spatial distribution of salinity at the end of the flow phase (left), and ebb phase (right) for the surface layers (layer 10) and deep layers (layer 7) during Levante wind conditions.

Figure 84: location of the four points in the northern part of the lagoon in which the effects of the wind were evaluated.

Figure 85: temporal salinity trends in four places in the northern part of the lagoon (see 84): comparison between the situations with and without wind.



In the northern part of the lagoon, the dispersive process is significantly more pronounced. In particular there is the triggering of a transverse movement on a vertical plane that is fairly parallel to the coast. The surface water (orange spot) is pushed to the west by the wind, while in the deeper layer the spot (in red), caught in the returning current, moves eastward. These are decidedly modest mixing processes in any case.

We wanted to analyze the influence of a more intense Bora wind. To this end, the previous simulations were repeated having increased the wind speed from 4 m/s to 10 m/s, which is only slightly less intense than the simulations outlined above.

From a qualitative point of view, the behaviour of the spots of particles corresponds to that described above (Figures 88 and 89), characterized by a migration to the South Mouth of the particles released in the southern part of the lagoon, a westward migration in the surface layer, and an eastward movement in the underlying layer, of the particles released in the northern part.

The distances moved however, are considerably higher. In particular, it is evident that within 40 hours, the particles released in the southern part that correspond to the surface layer (in green) passing through the South Mouth, move out of the computation domain and for this reason cannot be seen in the images shown.

The particles belonging to the underlying layer (in blue) are heavily dispersed and contrary to the previous case, tend to move out of the lagoon through the North Mouth.

Like the previous case, the particles released in the northernmost part, are dragged in the opposite, roughly east-west direction. The result confirms the triggering of a transverse circulation in a vertical plane following this same direction. The flow intensity is still significantly high and, after 96 hours (Figure 91), the particles are pushed against the lagoon edges and become denser.

From the results, the critical role that the dispersive phenomena induced by the wind play in the northern most part of the lagoon (Sacca di Scardovari itself) is evident. Above all it is these phenomena that determine water exchange, which takes much longer than it does in the Sacca di Bottonera where tidal currents build up speed and have gradients of some significance favoring processes that

Figure 86: current Situation. Lagrangian model particle transport simulation for the semidiurnal sinusoidal tide oscillating between ± 0.5 m a.s.l.: comparison of 20 (top) and 30 (bottom: particles in green and orange for layer 10 and in red and blue for the layer 7).

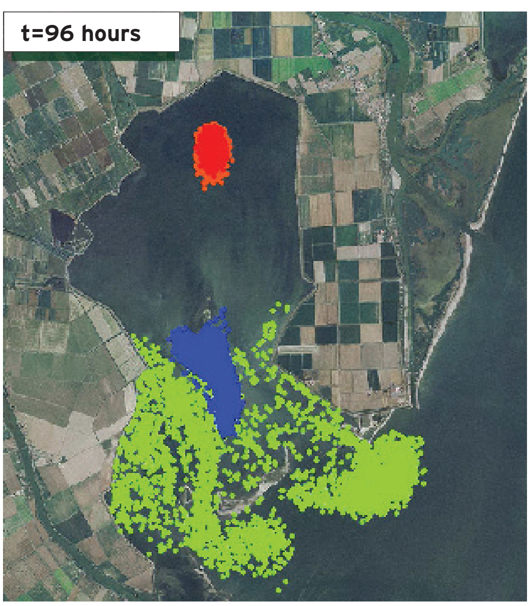


Figure 87: current Situation. Lagrangian model particle transport simulation for the semidiurnal sinusoidal tide oscillating between ± 0.5 m a.s.l.: (particles in green and orange for layer 10 and in red and blue for the layer 7).

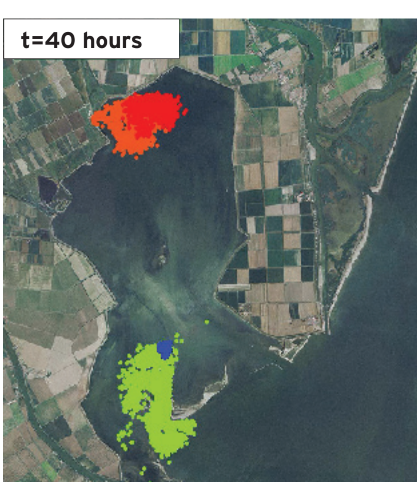


Figure 88: current Situation. Lagrangian model particle transport simulation for the semidiurnal sinusoidal tide oscillating between ± 0.5 m a.s.l and a Bora wind blowing at a speed of 4m/s for 12 hours every 24 hours: (particles in green and orange for layer 10 and in red and blue for the layer 7).

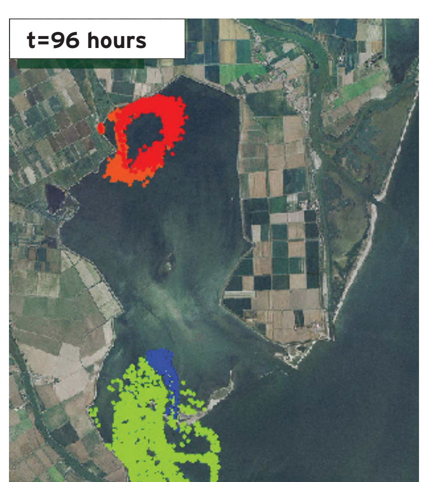


Figure 89: current Situation. Lagrangian model particle transport simulation for the semidiurnal sinusoidal tide oscillating between ± 0.5 m a.s.l and a Bora wind blowing at a speed of 4m/s for 12 hours every 24 hours: (particles in green and orange for layer 10 and in red and blue for the layer 7).

all together allow the residing water to be exchanged more quickly.

Effects of a Further Series of Interventions forseen in the Sacca

Further restorative interventions forseen in the Sacca di Scardovari consist of extending the stretch of sandbars that makes up the longitudinal partition of the Sacca and the dredging of inland canals which extend to the northern part of the Sacca. However, the construction of the building protected by movable barriers which was included in the original formulation of the design which would permit the induction of a "forced" circulation across the entire lagoon, is not foreseen.

In the new situation, the temporal salinity trend in four points in the Sacca, positioned at the outlets inside the Sacca (see Figure 72), is illustrated in Figures 92 and 93 with reference to the superficial layer of the water column and the underlying layer near the bottom. According to the calculation, in normal conditions both in the two points corresponding to the lagoon outlets as well as the interior points, variations in salinity are minimal, almost negligible for practical purposes.

The modeling results indicate that the complex of forseen interventions does not produce appreciable changes to the salinity trend within the lagoon, even taking into consideration that the Po distributaries adjacent to the Sacca have higher flow rates than the ordinary ones. (Figures 94 and 95).

SOME FINAL CONSIDERATIONS

The investigations carried out with the aid of certain mathematical models on the hydraulic behavior of the Sacca di Scardovari highlight the existence of problems of a different order in reference to the tidal current system and water exchange in the hydraulically more removed areas of the lagoon compared to those at the outlets, both in reference to interaction between currents induced by wave motion along the coast and flow moving across the lagoon and river mouths which open in this particular area of the Po Delta. The most significant results obtained have lead to the following conclusions:

Failure to complete the interventions forseen in the PIM project aimed at restoring the Sacca has resulted in unresolved water exchange problems in the northern part (of the Sacca di Scardovari itself). So far, the opening of the North Mouth and the digging of internal canals has not been enough to appreciably activate neither the direct action of tidal currents nor that of the secondary circulation induced by the non-linearity of the propagatory phenomenon.

Water exchange in this part of the Sacca is therefore entrusted to its dispersive phenomena, especially to those induced by the wind. These phenomena guarantee very slow water renewal processes however, and are unable to quickly resolve negative situations that may arise due to an abnormal decline in water quality caused by excessive increases in temperature, the rapid growth of algal blooms, or the significant reduc-

Figure 90: current Situation. Lagrangian model particle transport simulation for the semidiurnal sinusoidal tide oscillating between ± 0.5 m a.s.l and a Bora wind blowing at a speed of 10m/s for 12 hours every 24 hours: (particles in green and orange for layer 10 and in red and blue for the layer 7).

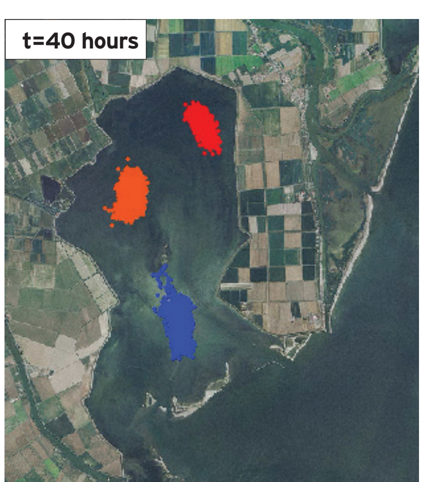
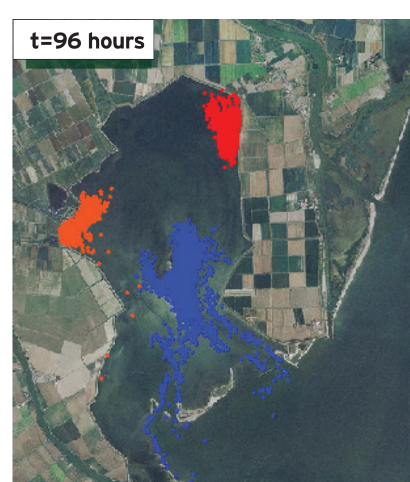


Figure 91: current Situation. Lagrangian model particle transport simulation for the semidiurnal sinusoidal tide oscillating between ± 0.5 m a.s.l and a Bora wind blowing at a speed of 10m/s for 12 hours every 24 hours: (particles in green and orange for layer 10 and in red and blue for the layer 7).



tion in water salinity that, as seen in the surveys, can be determined by the introduction of fresh water flow to the sea through the outlets of the mouths of the Po di Tolle and Po di Gnocca adjacent to the Sacca.

The results of the mathematical modeling, conducted with a 3D pattern, regarding the dispersion of fresh water inside the Sacca that is introduced, especially through its outlets, confirm the important difference of the Sacca di Bottonera's hydrodynamic patterns, being closer to the sea than the Sacca di Scardovari. In the latter, the fresh water, that penetrates it due to the joint action of tidal currents and wind, tends to disperse in a vertical direction and the water column shows substantially uniform vertical salinity distribution as well as having much lower values than those found in the adjacent Sacca di Bottonera.

There is therefore a differentiation in the patterns of the two parts of the lagoon (Sacca Bottonera and Sacca di Scardovari) that involves stratification phenomena, also in a horizontal direction, between the most affected part of the Sacca and that which is closest to the outlets, where one can see rapidly evolving variations in salinity in both vertical and horizontal directions. These significantly different patterns in the two parts of the Sacca in relation to salinity distribution is an index that confirms, in turn, the different very active and favorable tidal current regimes that have been established in the Sacca di Bottonera which are of little significance in the Sacca di Scardovari itself.

In the above scenario, the completion of the interventions forseen in the PIM general plan, with the construction

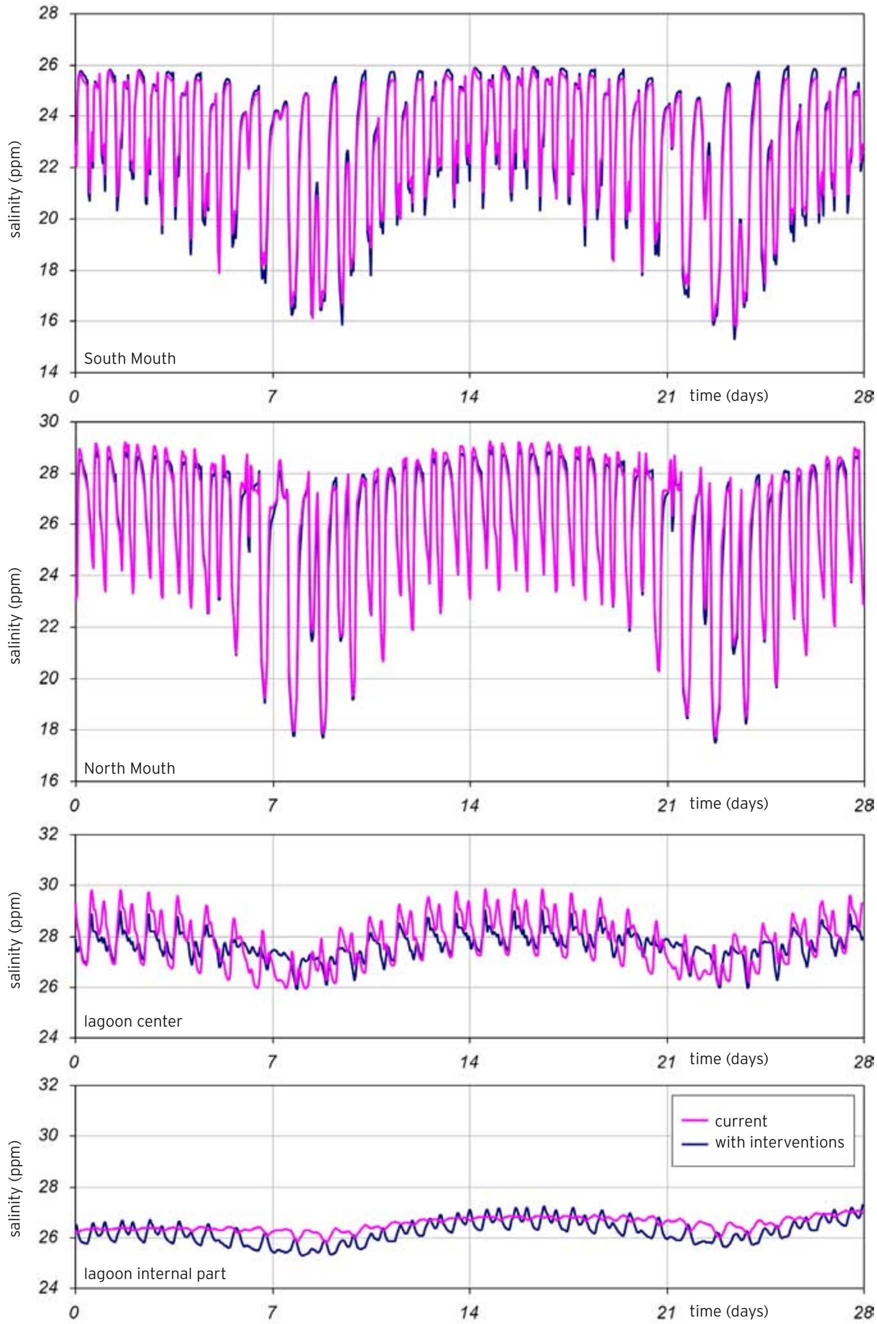


Figura 92: temporal salinity trend at four points inside the lagoon (see Figure 72): a comparison between the current situation and that foreseen in a further series of planned interventions with reference to the surface layer (layer 10), under ordinary conditions.

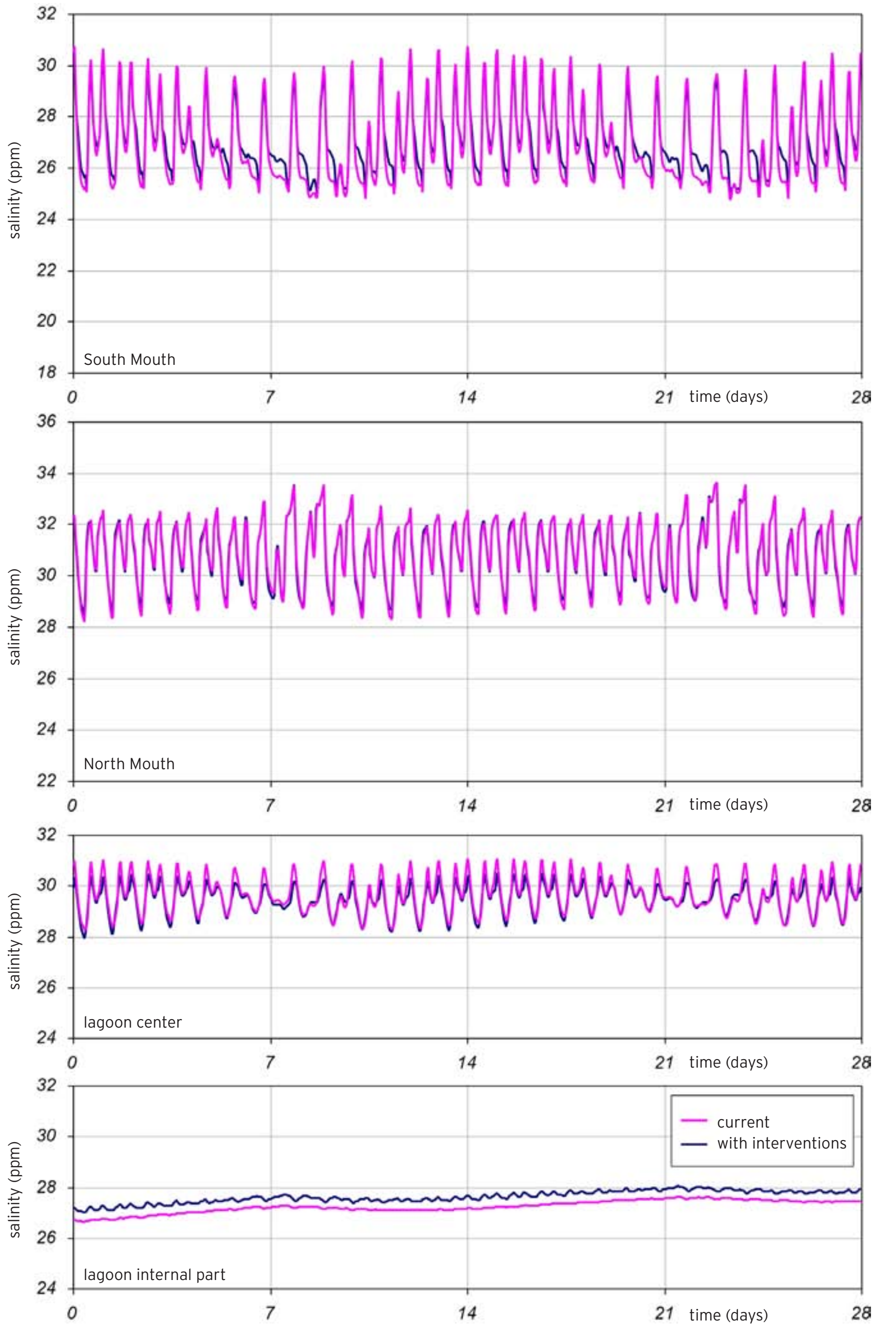


Figura 93: temporal salinity trend at four points inside the lagoon (see Figure 72): a comparison between the current situation and that foreseen in a further series of planned interventions with reference to the underlying layer (layer 7), under ordinary conditions.

of the central stretch of salt marshes in order to divide the Sacca's northern bodies of water, and the digging of a network of deep canals, is of only modest benefit in hydrodynamic terms.

If the forseen barrier, which would permit the overlaying of intense secondary circulation and natural tidal currents through appropriate maneuvers during the ebb and flow of the tide, is not realized, the exchange of water in the northernmost part of the Sacca will not bring about any significant improvement compared to its current condition. Consequently, the use of the Sacca di Scardovari bodies of water for shellfishing will possibly be exposed to the risks of, on one hand, abnormal temperature increases, and on the other, the intrusion of an excess of fresh water from the sea in sustained and persistent Po flood conditions.

For some time now the sandbars that separate the Sacca di Scardovari from the sea and permit the lagoon habitat to be distinguished from the sea have clearly been exposed to somewhat intense erosive phenomena. There are a variety of causes, primarily attributable to the effects of subsidence caused by the extraction of methane water which began in the1930s and which in particular, intensified after World War II. The retraction and change in curvature of the shore line which can be seen when comparing different avaialble surveys can, in all probability, be traced back to subsidence.

However, no positive effects can be derived from other interventions, such as those carried out as of the 1980s on the Po Tolle distributary, with the opening of the Busa Storiona which has significantly reduced flow liquid, and hence the solid flow which at one time was carried to the mouth of Porto Barricata adjacent to the Scardovari. Experimental measurements and evaluations of the distributaries and the lagoons confirm these flow rate changes and their potentially negative effect on erosive processes, to the detriment of the Scardovari coast. The results obtained with moving bed mathematical models, that are able to describe the effects of the superimposition of coastal currents induced by waves on the currents affecting the lagoon and river mouths facing the sea directly in front of the Sacca, allow for the analyzing of the salient aspects of the sediment transport near the coast that borders the lagoon.

From this analysis, it is apparent how the more intense and generalized sediment resuspension and transport phenomena mainly affect the coastalines adjacent to the Sacca. Apart from the odd local effect there is less intense activity in the areas facing the coast between the North Mouth and the South Mouth which are affected by lower waves due to their shallower bottoms.

These areas seem to be hidden compared to coastal current sediment transport. They are therefore not very involved as opposed to the complex processes that govern the remobilization and redistribution of sediment brought to the sea via the river mouths and that therefore show limited redeposition. The Sacca coast is, in any case, still affected by significant local phenomena involving sediment movement, as can be seen by the changes in the morphology of the bottoms in front of it and the coastaline quotas of the last decade. It is likely that these phenomena have been accentuated by the accidental opening

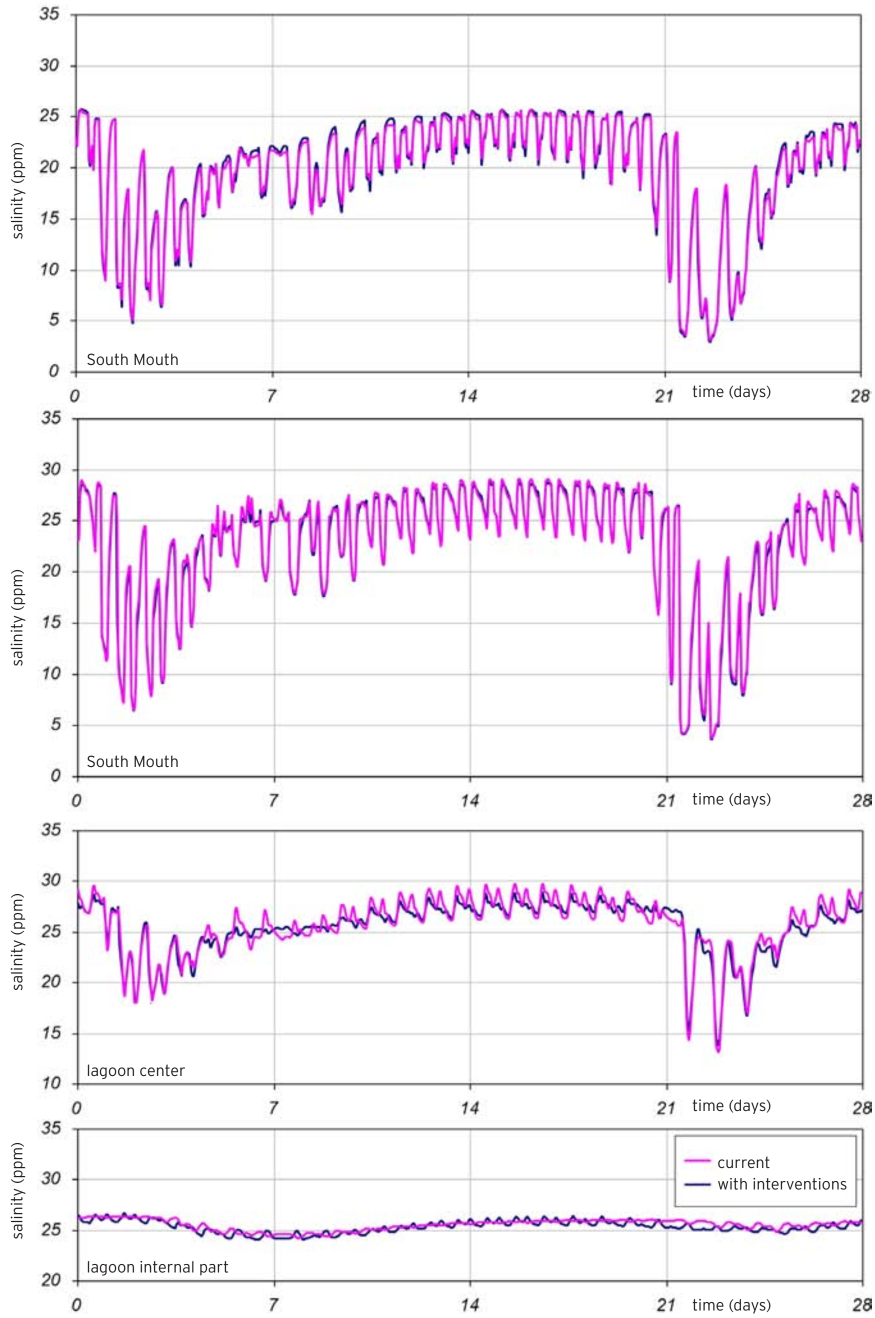


Figure 94: temporal salinity trend at four points inside the lagoon (see Figure 72): a comparison between the current situation and that foreseen in a further series of planned interventions with reference to the surface layer (layer 10), under Po River flood conditions.

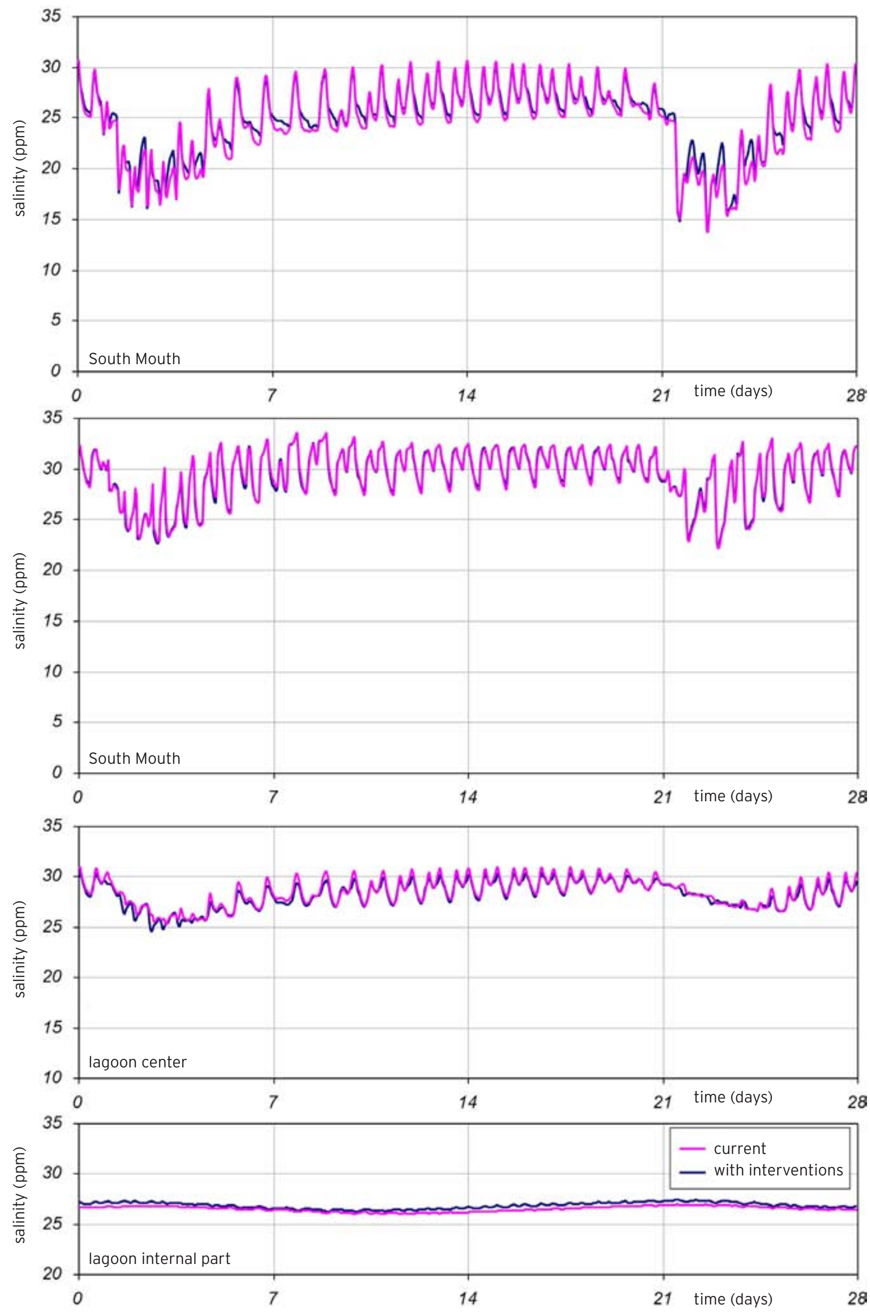


Figure 95: temporal salinity trend at four points inside the lagoon (see Figure 72): a comparison between the current situation and that foreseen in a further series of planned interventions with reference to the underlying layer (layer 7), under Po River flood conditions.

of a connection between the lagoon and the sea near the North Mouth, which could not be recuperated quickly. The fact is that local sediment movement affecting the area directly in front of the coast, with the introduction of material inside the lagoon by wave action and tidal currents, should be hindered, above all ensuring continuity to the streatch of coastal sandbars, making it insurmountable from the North Mouth to the South Mouth.

Secondly, one should, as far as possible, hinder the southward movement of sediment along the whole coast as well as between the mouths in order to, on one hand, stabilze the coastal defense embankment which is in the processds of being completed, and on the other to reduce the sinking tendency of the South Mouth. In the light of the analyzes performed and the results obtained, it is important to protect the foot of the cliff, that currently defends much of the coastline, from erosion. In fact this is crucial to the hydrodynamic circulation of the Sacca, and in particular to its internal part, the Sacca di Bottonera.

From an engineering point of view, the objective can be pursued both by realizing structures of a traditional type, like small spur breakwaters arranged orthogonally to the existing stone defense embankment, as well as innovative environmental structures carefully tested in advance by observing their performance in the field. In this sense, it would be of benefit to put to the test some of the innovative solutions that various parties have proposed, yet whose operational effectiveness remains uncertain having provided positive results in some cases and uncertain results in others.

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THE PO DELTA LAGOONS

By the Consorzio di Bonifica Delta del Po
September 2014

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Production of the edition and project series:
Consorzio di Bonifica Delta del Po (Taglio di Po)

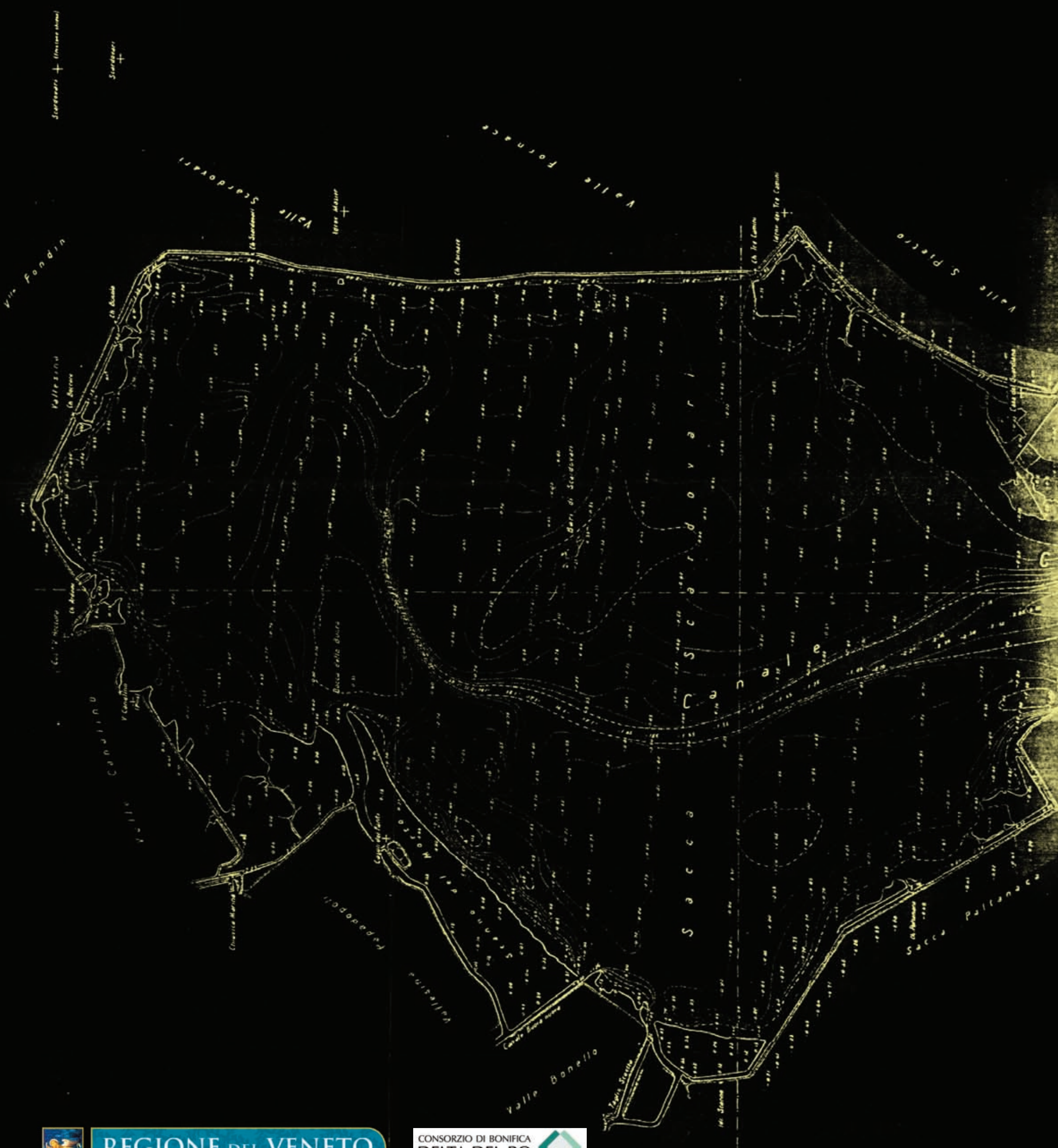
Editing:
Giancarlo Mantovani, Maria Saccon, Michela Casagrande

Graphic design and layout:
Dasler comunicazione (Vittorio Veneto)

Project coordination:
Tepco S.r.l. (Vittorio Veneto)

Translations:
Stephen Trollip (The Language Centre, Vittorio Veneto)

Contributi grafici:
Bruno Matticchio (IPROS S.r.l., Padova)



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