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Integrated Management Study of Comacchio Coast (Italy)

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ABSTRACT

The study area covers 21 km of sandy coast between Porto Garibaldi and Porto Corsini (northern Adriatic Sea). The main problem in the area is beach erosion. This is due to the evolution of the delta of the Reno River, and to the effects of past anthropogenic impacts that modified the sediment transport dynamics of the beach. An important factor affecting the morphological evolution of the site is land subsidence. This caused an important modification of the relative elevation of the ground at sea level, increasing the beach erosion. Another phenomenon analysed in the study is the closure of the mouth of the Bellocchio channel, that links the Adriatic Sea with the existing lagoons (Ancone di Bellocchio and Valli di Comacchio). The mouth sanding process influences the water exchange and the hydraulic circulation within the lagoons and creates severe water quality problems. The study takes into account the most important physical and biological variables of the local environment and suggests some management interventions defined and verified with the use of numerical models. The solutions follow the basic principles of Integrated Coastal Zone Management established by the European Community take a wide ranging perspective, build on an understanding of specific conditions in the area of interest, work with natural processes, ensure that decisions taken today do not foreclose options for the future.

ADDITIONALINDEX WORDS: *Adriatic Sea, River Po Delta, Land Subsidence, Sea Level Rise, Numerical Models, Water Circulation*

INTRODUCTION

The study area is located south of the River Po Delta (Figure 1). The northern and southern boundaries of the site are the harbour jetties of Porto Garibaldi and Porto Corsini. Along the beach there are two main river mouths (Reno and Lamone rivers), and a channel mouth (Bellocchio channel) that links the internal lagoons (Vene di Bellocchio and Valli di Comacchio) with the open sea. For a comprehensive sustainability approach, simultaneous attention is requested for all the systems that affect the coastal dynamics. It is necessary to identify the existing relationships among the local economy factors (fisheries, agriculture, industry, tourism, residential claim, bathing and harbours), the conflicts among the environmental and anthropogenic elements, and the natural evolution of the coast.

Public Administration of the area is subdivided among many bodies (Comacchio and Ravenna Municipalities, Ferrara and Ravenna Provincial Authorities, Reno River Authority, Ravenna Harbour Authority, Italian Army, Water Reclamation Consortia, Po Delta Park Authority) that have authority on different aspects of the global environment. This segmentation represents a problem for the correct management of the area. Due to the different local needs and the links existing in the area, a joint approach is required to define a management scheme. The morphological complexity (deltaic areas, lagoon and para-lagoon environments, protected littorals, accreting and eroding beaches, channel occlusion) and the land use diversity require a high interdisciplinary level of study approach.

The study initially focuses on the general geomorphology, meteorological conditions, and waves climates, which subsequently determining the morpho-sedimentary dynamics and the coastal and internal hydrodynamics. After

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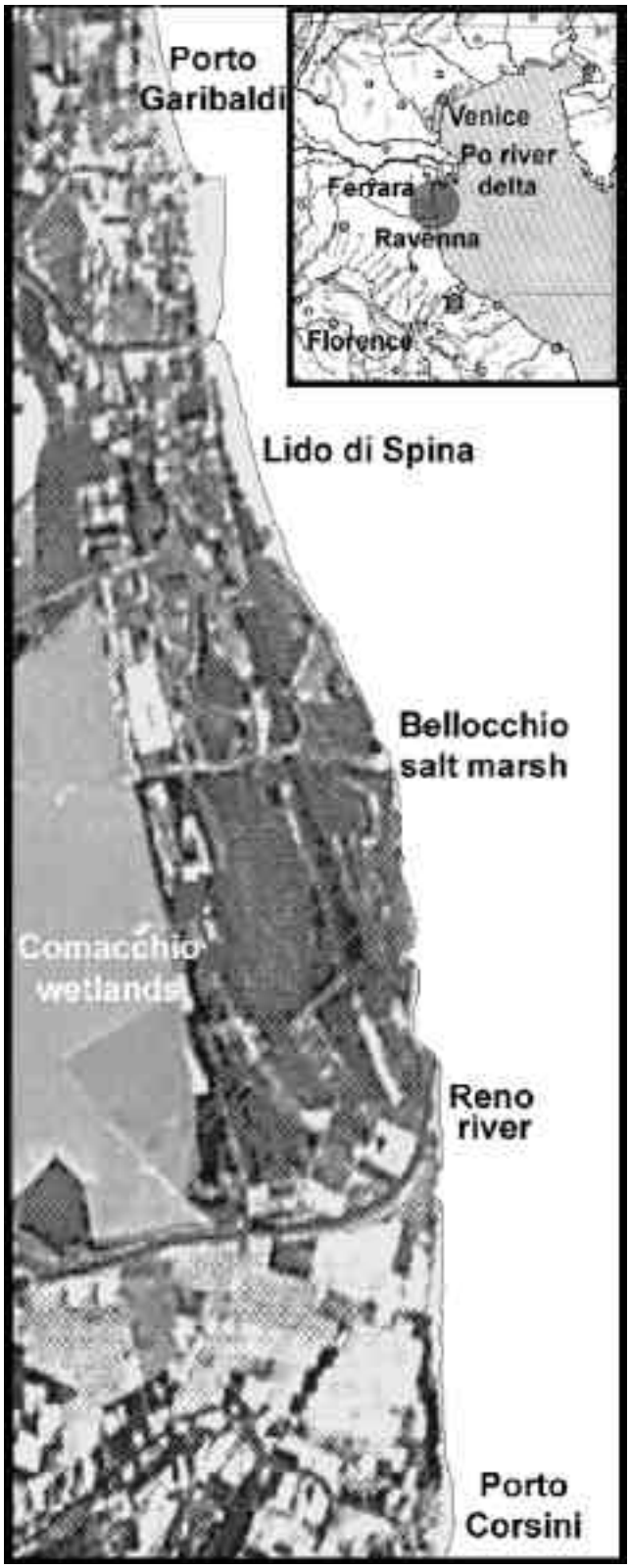


Figure 1. Study area location.

the analysis of the present elevation of the area due to land subsidence occurring since the 1950s, the future DEM (Digital Elevationt Model) is predicted until 2015, taking into account subsidence and sea-level rise effects. Finally, different intervention proposals are evaluated to maintain an efficient water exchange between the lagoons and the open sea.

LITTORAL EVOLUTION

The northern part of the study area is located on the ancient deltaic complex of the Spinetico branch (Eridano) of the River Po, which was active until the VI century A.D., and of the Primaro branch of the River Po, particularly active within the VIII and the XII centuries A.D.. From 1767 to 1795 the Reno River course was attached to the Primaro branch that developed in the XIX century, a north oriented mouth. In the period 1920-1935 the river sediments created a littoral spit, that separated a wide lagoon (Sacca di Bellocchio) from the sea. During this same period the southern beaches were affected by erosion. The progradation of the Reno mouth through the north (BONDESAN *et al.*, 1979) originated as a narrow peninsula among the right riverside and the sea. This peninsula accreted until 1932, but from the 1920s a narrowing was observed.

According to BONDESAN *et al*. (1979) the study area can be divided into three physiographic sub-unities, extending from the southern jetty of Porto Garibaldi and the Reno River mouth, to the Casal Borsetti, and from this latter to the northern jetty of Porto Corsini. From the start of the 1980s the first unit of beach was affected by severe erosion, because of the migration of the Reno River mouth 2km south, causing significant coastal modifications. In the 1978-1983 period, the beach eroded 120m. In 1990 local defences with Tubi Longard and artificial nourishment (40,000m^3 of sand) were used to protect the coastline, but this management was insufficient. The eroded sediment was transported northward accumulating south of the Porto Garibaldi jetty, where an average beach accretion of 50-70m (with peaks of 120m) was detected from 1978 to 1993.

The unit from the Reno River mouth to Casal Borsetti is heavily armoured with beach revetments, which were installed in the 1980s. The unprotected beaches in this area are affected by strong erosion, 80m in the last 15 years (Figure 2).

The third physiographic unit is characterised by a southward littoral drift, which has experienced accretion of about 4 m/year in the last decade (IDROSER, 1996), or relative stability. This is due to the drift of the artificial nourishment which was put in place at the end of the 1980s and also because of other protection works.

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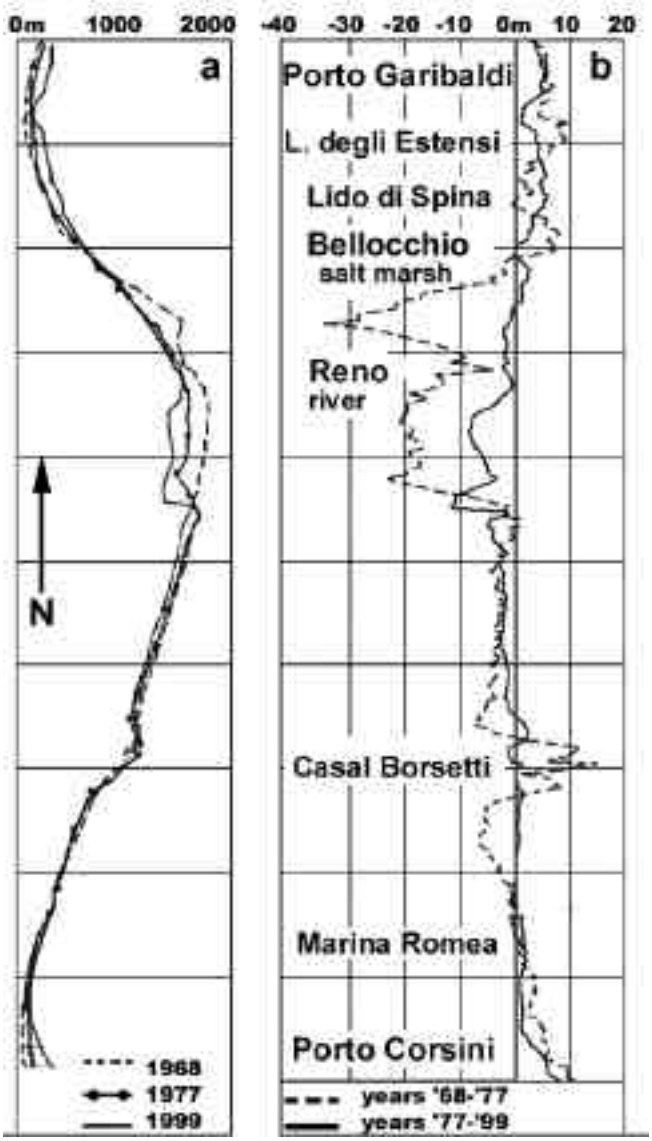


Figure 2. Coast evolution during 1968, 1977, 1999 (a) and calculation of coast line variability (b).

The "Vene di Bellocchio"

A historical map dated 1600 A.D. shows an ancient lagoon connected to both the Po di Primaro and the Valli di Comacchio, which has many links with the open sea. At the end of this same century all sea links appeared to be occluded.

Continous anthropogenic intervention (urban development, construction of different hydraulic works), has transformed the lagoon into a series of small coastal pools and lagoons, with a total surface area of c.140 hectares. The subsequent construction of the Canale Gobbino, built to restore the contact within the Valli di Comacchio and the sea, subdivided this depression into two catchments. The northern catchment has a variable salinity and has been continuously affected by human intervention. The southern catchment is in a better environmental condition. In the last few decades the progressive occlusion of the Canale Gobbino mouth prevented direct exchange of water between the sea and the internal zones.

In the last 30 years, because of coastal erosion, the littoral strip that separates these lagoons from the sea became narrower, and was artificially defended. In the same time the Canale Gobbino mouth closure took place, reducing even more water exchange between the lagoon and the open sea.

SEDIMENT CHARACTERISTICS

The texture characteristics of the sediments within the area have been described in studies made in 1972 (BONDESAN *et al*., 1979), 1993 (IDROSER, 1994, 1996) and in analysis made by SIMEONI *et al.* (2000) in 1999.

From 1968 to 1974 sediments were mainly very fine sands (relative mud content less than 10%), also at the maximum sampling depth, with a good degree of selection in the northern part of the study area, characterized by evident accretion.

The middle unit across the Reno River mouth, characterized by high erosion, had a relative percentage of mud in the superficial samples, greater than in the northern area especially under 5m depth. The distribution of the texture parameters underlines the accumulation area of mud transported by the Reno River mouth and the presence of residual deposits uncovered by the shoal erosion at 2-3m depth.

In the last physiographic unit erosion progressively decreases towards the harbor jetties of Porto Corsini. This behavior can be explained by the sediment transport from the Lamone River mouth (about 55,000 m^3/year) which drifted southward by the littoral currents.

From 1984 to 1993 IDROSER (1996) demonstrated that, despite the reduction of sediment extraction from the river beds and the river quarries, the decrease of the subsidence trend and the relative increase of the sediment transport from the river mouth, the erosion trend of the beach was not significantly modified. Some modifications have been observed in the morpho-bathymetric aspect of the seabed and in the sediment distribution. The texture data from 1993 depict a relative reduction of the mud percentage.

The southward movement of the Reno River mouth from 1981 to 1993 has determined the movement of the depositional area of fine material transported by the river. The influence of the river sediment transport, and of the effect of the jetties, is evident from the reduction of the average sediment dimension moving from Reno mouth to Porto Corsini.

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The investigations made in 1993 (IDROSER, 1996) have confirmed that the mud percentage is relatively smaller on the seabed in front of Porto Garibaldi and Lido di Spina in comparison to the northern coast. This confirms the hypothesis that the south limit of the influence of the fine material transported by the River Po is placed in correspondence of the Porto Garibaldi jetties.

Finally, a small reduction of the average dimension of the material close to the beach line, during approximately 20 years, has been identified. This has been ascribed to the effects of the new defense works. At greater depths this trend was inverted, with the presence of coarser sediment than that sampled in 1972. This behavior has been attributed to the increase of sand transport from the river mouths (15% of the total from the Reno River and 79% from the Lamone River), due to the reduction of quarry extraction along the river courses.

The comparison between the morpho-bathymetric investigations made in 1999 with the 1972 and 1993 findings (Figure 2) demonstrates that the sampled sediments presently have greater mud percentages both at the smaller and greater depths, with maximum modification within –2m and –4m depth (SIMEONI *et al.,* 2000). The influence of sand transport from the river is evident only close to the mouths, , while the muddy load is brought far in offshore areas.Areas where mud has been deposited indicates that the fine sediments from the Reno River have been distributed off-shore, with a principle northward direction and a secondary southward direction, meanwhile the Lamone fine sediments are dispersed off-shore and southward.

The planar distribution of the average diameter, made with the 1999 samples, depicts the divergence of the coarse sediment paths along the beach. From the Reno River mouth (divergence point) the sand moves north towards Porto Garibaldi and south towards Porto Corsini , where the sediments are captured by the jetties. Meanwhile the fine River Po sediments stop north of Porto Garibaldi.

This is due to an increase of sediment transport from the Reno River, particularly because of the reduction of sand extraction during the early 1990s. This increase causes an estimated volume of 190,000 m^3/year of sand from the Reno mouth for sediment transport which is suitable for beach nourishment (IDROSER, 1996). This volume is equivalent to that estimated in the 1970. Despite this retrieval of the transport rate, the delta apparatus reveals erosion over the 30 years, which probably will continue in the following years. Some attenuation of the erosion can be predicted taking into account the increase of the sediment transport from the Reno River (250,000 m^3/year at the 2015, following the IDROSER forecast, 1996) and the reduction of land settlement due to the regulation of the anthropogenic causes.

The reduction of the mud percentage (with increase of the average diameter and better distribution of the sediments) that occurred between 1993 and 1999 south of the Reno River mouth, appears quite complex. The decrease can not be linked to the increase of the bed sediment transport of the Lamone River (from 55,000 m^3/year in 1990 to 90,000 m^3/year in 2000) or to the contribution of the artificial nourishment of sand dispersed along the coast (about 90,000 m^3). The texture distribution underlines that the defense works break off the sedimentary unity of the area, because they stop the sediment drift from the Reno mouth to Porto Corsini.

The southern unit can therefore be subdivided into three cells (Reno mouth-Casal Borsetti, Casal Borsetti-Lamone mouth, Lamone mouth-Porto Corsini), which helps explain the texture distribution observed on site. The northern cell is characterized by the major erosion trend and by a southward littoral drift, as showed by the Casal Borsetti beach accretion. The high increases of the coarser sediments (>0.250mm) are around –2 m and -4 m depth, where there are very fine (0.125-0.0062mm) and fine (0.250-0.125mm) sand fractions, while off-shore the modifications are minor. On the basis of these observations it can be concluded that this area is fed by the Reno mouth transport with the finer fractions; the southward drift, in effect, is not as strong as the northern drift and only the finer sediments can move in this direction. It is also possible that the mud transport from the Reno mouth which is dispersed southward, is deposited prevalently in front of Casal Borsetti.

FUTURE RELATIVE SEA-LEVEL CHANGE

The analysis of the elevation of the area is one of the core items of the study, to evaluate the inundation risk in both the short and medium term.The problem has to be analyzed with regards to both subsidence and sea level rise. The first cause has been approached analyzing the elevation changes defined on the basis of the topographical surveys (Figure 3a) made in the area at different times (1984, 1987, 1993 and 1999) , collected by ARPA (Regional Environmental Agency). A Digital Terrain Model with 50x50m cells has been defined (Figure 3b) using the topographic data available from the most recent cartographic bases (1986/1987). To obtain the elevation scenarios following the year of the survey (1987) the periods 1984-1987, 1987-1999 and 1999-2020 have been considered. The map of the ground vertical movements has been obtained, interpolating the subsidence trend data available from the comparison among the elevations measured in the points surveyed in the topographical campaigns.

Major lowering in the past has been detected close to the gas withdrawal well of Dosso degli Angeli, in the middle of the area, this decreases moving northward and southward. To estimate elevation in the future, the altitude of the Digital

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Terrain Model has been projected along e time using the subsidence trends defined in the isokinetic maps. The first step has been the reconstruction of the actual elevation, applying the subsidence trend computed for the period 1987-1999. A second step was to forecast the altitude in 2020.

In this second period two different hypotheses have been applied. In the first hypothesis the actual subsidence trend has been considered; in the second one some reductions in the subsidence trend of the points close to the area of Dosso degli Angeli have been applied because the gas withdrawal has been completed.

In the forecast period 1999-2020, the coastal zones north of the Reno River, already in a critical altitude position at the beginning of the analysis period, experiences a generalized lowering, taking into account the same distributed subsidence trend of the previous period (1987-1999). A coastal area of some kilometers could go under the medium sea level.

In 2020 the area south of the river may present many zones with elevation between 0 and –0.5m, divided from the sea by a coastal strip with a high mean sea level.

No substantial difference has been observed in the scenario that considers the decreasing of the local effect in Dosso degli Angeli site. The second basic item is represented by the sea level rise. The data considered uses an average increase of 11cm in sea level from 1986 to 2020. The sea level rise has been added to the subsidence trend in the elevation scenarios from 1986 to 2020. The effect of the sea level rise is negligible compared to that of land subsidence in the analysis of the relative ground-level position. In the last subsidence analysis at 2020 (Figure 3b) the zone with an elevation between –0.5 and –1m has been considered with attention, because it presents the highest inundation risk. This zone is located close to the Reno mouth, in the Bellocchio area, while the situation in the southern area is less critical.

ANALYSIS OF POSSIBLE INTERVENTION

The analysis of different intervention scenarios has been based on a numerical modeling approach. In particular, a single line morphological evolution model (LITPACK, Danish Hydraulic Institute, 1993) has been used to represent the evolution of the sandy beach starting from the actual state, with and without the intervention proposed. A 2D vertical integrated hydrodynamic model (MIKE 21, Module HD, DHI, 1993) has been applied to analyze the internal water circulation in the wet areas and the water exchange within the open sea.

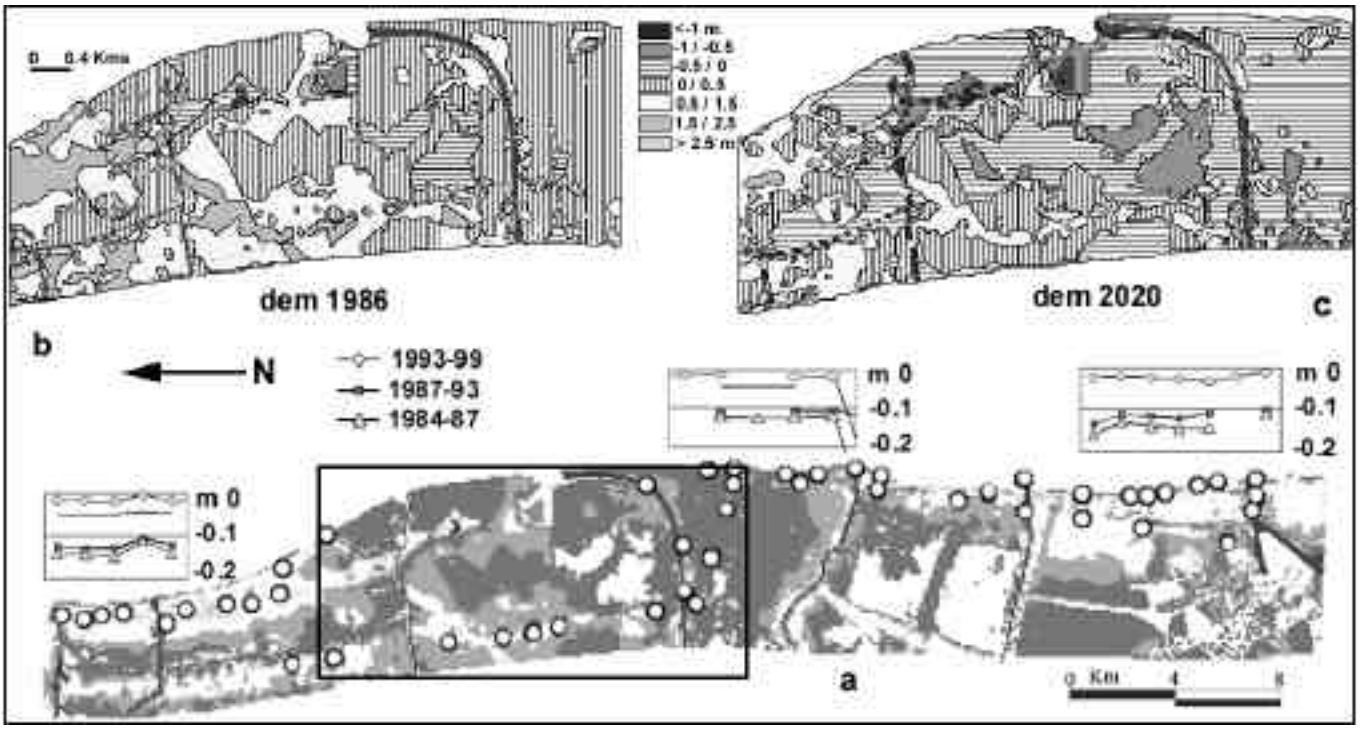


Figure 3. Positions and elevation changes of bench mark in the study area from 1984 to 1999 (a), and elevation changes of the land. Two digital elevation models shown the situation in 1984 (b) and a hypothetical projection of year 2020 (c), considering the actual subsidence and sea level rise.

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The major forcing factor of the morphological model is represented by the local wave climate. The wave climate has been reconstructed starting from the off-shore wave data monitored in a platform of the Italian company for gas exploitation (Agip), placed in front of the study area in the period 1970-1992, and transferred close to the shoreline with a spectral wind-wave model (MIKE 21, Module NSW, DHI, 1993). The single event wave data, including the calm conditions, have been distributed with a seasonal criterion throughout the year, in order to obtain a realistic event.

With the modules Litdrift and Litline of LITPACK the morphological model of the beach line has been set up, using on-site data surveyed during the study (bathymetric profiles and sediment data). Litline integrates the Litdrift results along the coastline and applys the sediment continuity equation, calculating the evolution of the beach line. The model has been calibrated comparing the results of a hindcast simulation model, with the evolution of a defined beach line looking at surveys from 1968, 1977 and 1999. Litdrift calculates the sediment transport capacity along a beach profile given the bathymetry, the sediment characteristics and the wave conditions. The bed roughness and the closure depth for the cross transport have been used as calibration factors to optimize the model set up.

The sediment input in the model considers both the sediment transport from the Reno River mouth (200,000 m3/year), and an apparent sediment loss due to the combined effect of subsidence and sea level rise (14,300 m3/year/m). The hydrodynamic model has been set up using the bathymetric data of the Canale Bellocchio and of the lagoons detected during on site surveys. The forcing factor of the model is represented by different types of tides characteristic of the area. The model considers the actual state and the intervention scenarios, looking at different strategies to modify the bathymetry in order to increase the internal water circulation and the water exchange with the open sea. During analysis not only have efficiency and cost been considered in the solutions, but also the tuning with the local environmental state, minimizing the amount of impact and not prohibiting future dynamics of the area. Four intervention strategies have been proposed and verified, two for beach stabilization and two for the internal waters.

Coast Intervention

The typical engineering solution to defend a mouth from progressive sediment accumulation, consists of two jetties to either totally or partially block the littoral drift. This solution has negative effects on the adjacent beaches. As It causes an abnormal accretion upstream in the direction of the dominant littoral currents, and severe erosion downstream, causing undesired morphological effects along the coastline. To manage and limit these effects a jetty extended to the –3m depth has been implemented as the solution, which does not stop completely the sediment transport from south to north.

Despite this mitigated solution, the drift that overpasses the protected mouth is not sufficient to avoid severe erosion of the beach in the northern area, so the installation of a dewatering system in that area has been considered. The dewatering system is a drainage system placed under the beach line that increases the water absorption capacity of the beach, reducing the cross-shore sediment transport with minor effects on the longitudinal drift (VESTERBY, 1996). Looking at the previous application experiences, an accretion rate of 50 m^3/year can be obtained with this kind of protection, and which is characterized as having a very low environmental impact. By coupling the two intervention strategies (jetties and dewatering) it is possible to mitigate the negative effects of mouth protection: the jetties reduce inlet closure and the dewatering stabilizes the northern beach.

Because sediment is not totally blocked by the jetties, the mouth will sometimes be closed, with an accumulation rate of about 3,600 m^3/year. A sediment by-pass strategy will be sufficient to ensure the efficiency of the mouth, considering the general morphologic equilibrium.

Intervention in the "Valli di Bellocchio"

The forcing factor that creates the internal water circulation in the lagoons (Figure 4) is the tide which is often limited because of inlet closure. After the mouth opens a first intervention strategy consists of deepening the Bellocchio channel; the bed is presently at –1.5m. By increasing the depth at –4m it may be possible to obtain an increase of discharge and of the volume exchanged through the channel mouth with the open sea.

The transformation of the lagoons in "piallasse" have been considered and tested with numerical modeling to increase the water exchange, enhance the internal circulation (avoiding water quality problems) and stabilize the channel mouth. The "piallasse" (the original etymology means "take" and "leave" of the tide), traditionally applied by the Venetian hydraulic engineers from the XVII century, consisted of a particular management of the lagoon bed, with the creation of a dendritic network of submerged channels (Figure 5), to increase the capacity of the tide to penetrate in the lagoons. Both the volume exchanged in a tide cycle and the peak of discharge at the mouth are increased consistently. The discharge at the mouth can be increased by 50% in respect to the solution with only the excavation of the channel. This increase of discharge helps the sediment transport capacity of the mouth current, and will therefore improve the "self cleaning" capacity of the channel against sedimentation. The penetration of the tide avoids water circulation problems in the internal zones of the lagoons (Figure 6).

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CONCLUSIONS

On the basis of the critical and analytical comparison among the different intervention scenarios verified with the numerical models, the solution of the four intervention strategies described, seems very appropriate to stabilize the actual beach line (also if any beach accretion is generated). It is speculated that these measures will prohibit erosion north and south of the Bellocchio mouth, maintaining the actual morphological and environmental state. This proposal guarantees adequate protection for the mouth from sedimentation and enhanced water circulation within the internal area.

The experience gained in similar studies and the analysis of the simulation results give the opportunity to define the modification of the actual efficiency because of the subsidence and the sea level rise expected in the next 20 years. If the increase of the water depths in the lagoons (due to the sea level rise and subsidence), can facilitate the exchange of large water volumes between the lagoons and the open sea, then the decrease of the water movement velocities will be a factor that facilitates the deposition of suspended sediment and therefore the occlusion phenomena. The lowering of the terrain will determine a widening of the wet areas, including zones that actually are not occupied by the waters. The water circulation in these zones is not guided by existing tide channels, so the transversal flux directions can facilitate the sedimentation of material in the existing channels, creating deposition problems.

Because of the general complexity of the area, also the indicated solutions, already optimized looking at the environmental aspects, can not be maintained efficiently without a serious and continuous effort to monitor and manage the intervention measures. Also referring to the principles of ICZM, a good management plan can avoid the necessity of great intervention, ensuring the efficiency of the proposed strategy and mitigating the environmental impact. In this particular case the management based on detailed monitoring, will have to be focused on the necessary sediment by-pass activity from the southern to the northern beach of the Bellocchio mouth, on the efficiency control of the beach drainage system, and on the control and periodic excavation of the tide channels in the lagoons.

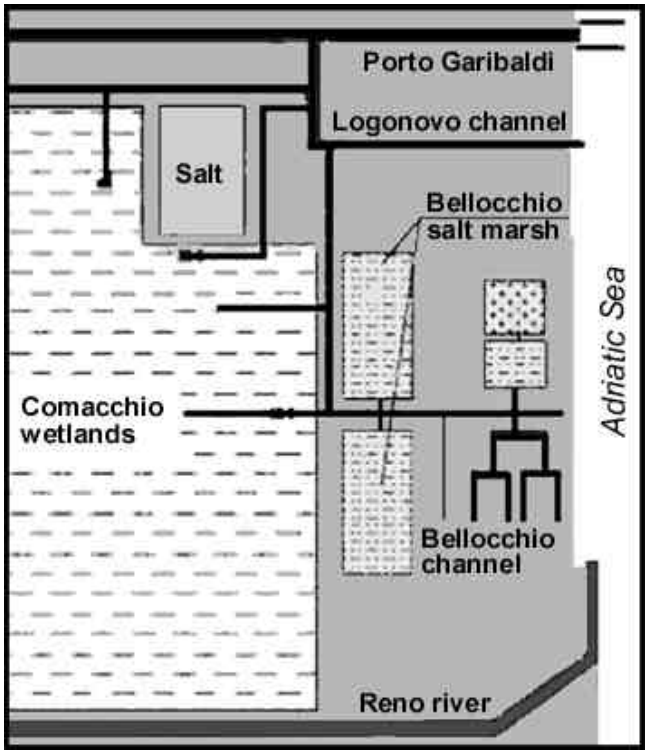


Figure 4. Hydraulic circulation scheme of Comacchio wetlands and Bellocchio salt marshes.

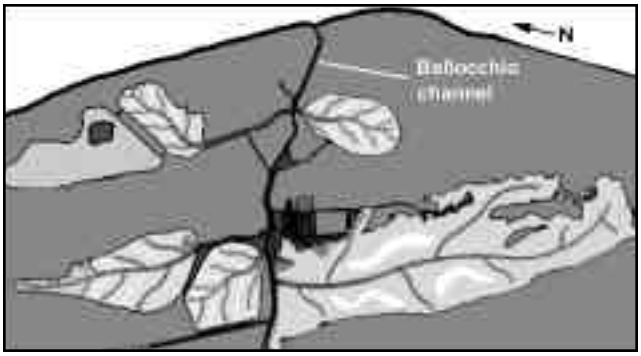


Figure 5. Dendritic construction scheme of channel beds in the transformation of Bellocchio salt marshes in Piallasse.

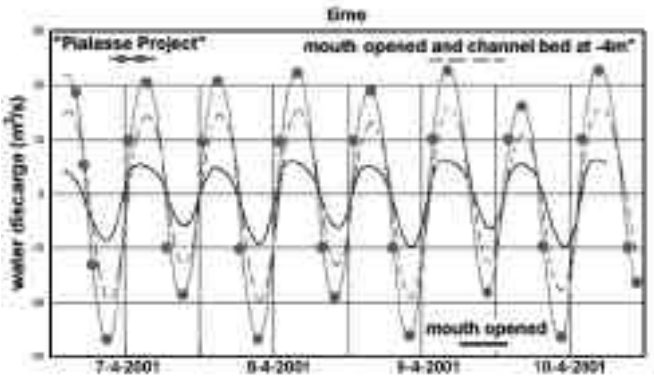


Figure 6. Water discarge variations of Bellocchio channel under three different scenarios: channel mouth opened only, channel mouth opened and bed excavation to –4 meters and transformation of Bellocchio salt marshes in "Piallasse".

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