THE EROSION OF THE OMBRONE RIVER DELTA (ITALY)

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ABSTRACT

A gross estimate of the volume of the sediments forming the Ombrone River delta in 1883 yields a value of approximately 2 billion m$^3$, having accumulated at a mean rate of 1 million m$^3$/year.

During the second half of the XIX century, river diversions performed to reclaim marshy areas primed a beach erosion that started at the river mouth and progressively expanded to lateral beaches. This process was studied through a reconstruction of the coastline evolution carried out by comparing different maps (1883, 1929 and 1954), air-photos (1954, 1973, 1979 and 1984), and bathymetric surveys (1883, 1977 and 1987). A topographic survey of the shoreline was also performed in 1990 for this purpose.

Estimates of the present sedimentary input give values one order of magnitude lower than those which characterized the accretional phase. The comparison of 1977 and 1987 bathymetric surveys indicates a mean sedimentary loss of 830,000 m$^3$/year. This scenario is in agreement with the estimated mean sedimentary input of the Ombrone River for the last two thousand years.

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Since land reclamation was completed during the mid-Twentieth century, the ongoing erosion (10 m/yr at the river mouth) may be attributed to river-bed quarrying, reduction in farmed areas and slope stabilization works. Relative sea-level rise (approximately 1 mm/yr of eustatic nature, and at least 3 mm/yr due to local land subsidence) is responsible for about 17% of the present deficit.

Figure 1 - Aerial photograph of the Ombrone River delta showing old beach-ridges cut by the erosion (courtesy L. Innocenti).

INTRODUCTION

The Ombrone River delta has formed during the last two thousand years due mainly to the increased soil erosion consequent to the land clearance that accompanied the demographic evolution of Central Italy (Innocenti & Pranzini, 1993). Although some erosional phases occurred also in historical times, as a consequence of the population decrease due to political instability, pestilence, etc., the one presently affecting the delta is really impressive (fig. 1), reaching 10 meters per year.

Since the area lacks coastal defences, its evolution fits well with a model of cuspatate delta erosion proposed by the Author in 1989. This model provides a gradual shifting off the delta apex of two balance points separating the
shore stretches in erosion from those in accretion. Therefore, each shore stretch suddenly passes from an accretional to an erosional status, without seeing an equilibrium stage. Without a careful monitoring of the shoreline evolution, this can generate an emergency reaction in those whose economy is based on the beach resort. In the case, the presence of a Regional Park advises against the construction of any coastal defence and makes the forecast of the future scenarios necessary, in order to plan a correct recreational use of the beach.

**MATERIALS AND METHODS**

A large amount of documents is available to trace the history of the Ombrone River delta beaches during the last one hundred years, even if they are not homogeneous as far as both the surveying methods and their reliability are concerned.

For the present study, the following documents were used:
- 1883: topographic map at the scale 1:50,000 of the Istituto Geografico Militare, enlarged to the scale of 1:25,000 by the Institute itself;
- 1929 and 1954: topographic maps at the scale 1:25,000 of the Istituto Geografico Militare;
- 1990: direct topographic survey of the shoreline.

The delta evolution for the periods 1883-1929 and 1929-1954 was obtained through the superposition of the three maps. That for the periods 1954-1973, 1973-1979, 1979-1984/85 and 1984/85-1990 by reporting the shoreline on the Carta Tecnica Regionale at the scale 1:5,000. The shoreline surveyed in 1990 was drawn on the same map. Areal variations of the berm were measured by a planimeter Planix 5000 across the 15 kilometers of the delta, which was divided for this purpose in 16 sectors.

As concerns the submerged delta evolution, the following documents are available:
- 1883 and 1977: bathymetric soundings of the Istituto Idrografico della Marina;
- 1987: bathymetric sounding performed by Idrocart, Genoa.

Comparison of these data was carried out along selected profiles where a good overlap was present.

Part of these data had already been used to study the evolution of the delta (Bartoloni & Pranzini, 1985; Pranzini, 1989; Innocenti, 1990), but the full set of documents now available and the greater reliability of the comparison here performed at the scale 1:5,000 - together with the availability of data on the river sedimentary input during the last 150 years and on the loss determined by land regradations (Milano, 1986; Paris, 1991) allow a deeper analysis of the processes controlling this evolution.

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THE DELTA AND THE RIVER INPUT IN THE MID NINETEENTH CENTURY

Eighteenth century maps (fig. 2) show the delta as a very prominent form, with the river mouth about one kilometer offshore its present position. But we must wait until the second half of the last century to have reliable documents to reconstruct the shoreline evolution. A French Navy map dated 1847 is considered reliable enough to be compared with cadastral maps of 1830 and with Istituto Geografico Militare maps of 1883. A quantitative analysis was carried out only on more recent documents - starting from 1883 maps - but a simple map overlay shows that in the period here considered the fast progradation phase of the XVII-XIX century (Innocenti & Franzini, 1993) was near to an end, and that the first signs of beach erosion were present at the delta apex.

The volume of the delta, in its emerged and submerged parts, was computed on the basis of the bathymetric map surveyed in 1883 by the Istituto Idrografico della Marina Italiana: 2 billion m$^3$ of sediments were carried by the River during the last 2,000 years to form the delta. Since part of the sediments carried by the river - namely the fines - move away from the area and settle on the continental shelf, the figure here obtained is an underestimate of the actual river input. This should have been greater than 1 million m$^3$ of sediments per year in average, with values four times larger during very fast accretional phases (Franzini, 1991).
These figures agree with the results of hydraulic studies of the river. Milano (1986) considered the river's suspended load during the period 1847-1883 to be as much as 5.2 million m³/year; an additional 10% for the bed-load must be computed, according to the Author, to obtain the total river input. Paris (1991) gave a value of 6.5 million m³ of sediments for the river input in 1830.

The reduction in the river input (down to 1.7 million m³/year after Milano in the 1935-1972 period, and to 1.2 million m³/years after Paris in the 1953-1973 period) was the main cause for the beach erosion that started in the second half of the Nineteenth century. It is worth stressing that these volumes are those actually carried by the river to its mouth, and do not include the sediments laid within the coastal marshes for the reclamation works performed during that time through the river diversion. Data on the reclamations are not easy to obtain; Milano computed that 655,000 m³ of sediments per year were subtracted from the river load in 1847-1883 and 865,000 m³/year in 1883-1955. Paris gave a mean value of about 1.5 million m³/year for the period 1830-1952.

River diversion was the first factor responsible for the coastal erosion here as in many other parts of Italy. On the Ombrone coastal plain the last river diversion was closed in 1957, but beach erosion continues today at a higher rate. During the last thirty-four years the causes of beach erosion have become different from those that primed this process.

**THE DELTA EROSION**

**The beginning of the last erosional phase**

Dating the beginning of the last erosional phase is a very hard task, since this was preceded by shoreline fluctuations and also because cartographic documents do not cover this stretch of time continuously. Mori (1937), on the basis of ten surveys performed between 1821 and 1937, stated that the phase of maximum delta progradation was preceded by an erosional phase that moved back the 1821 shoreline (as much advanced as the 1883 one) to a position that will be reached late in 1926. In fact, a precise day in which the erosion starts does not exist! We assume that this happened during the second half of the Nineteenth century.

**From 1883 to 1929**

Shoreline changes that occurred in this period (fig. 3) show that the erosion of the delta was in its initial stage. This assertion is based more on the limited length of coast affected by the process than on the rate of the apex retreat.
Figure 3 - Shoreline changes (m) and relative rates (m/y) for the 16 sectors under study, between 1883 and 1929.

Figure 4 - Shoreline changes (m) and relative rates (m/y) for the 16 sectors under study, between 1929 and 1954.
Only a little more than one kilometer of beach was eroded in the northern lobe (sectors n. 8 & 9) and half a kilometer in the southern one (sector n. 10). However, the beach retreat reached in some places the value of 500 m (10.8 m/y) on the northern beach and of 350 m (7.6 m/y) on the southern one. Mean values for these sectors are respectively 0.7, 7.2 and 1.2 m/y. The remaining part of this coast was still in accretion, as suggested by the model of cuspatte delta erosion (Pranzini, 1989), at a rate varying from 2 to 5 m/y.

During these 46 years, the erosion on the whole delta was not very strong even if the apex had to adjust to the reduced sedimentary input. This erosion process is not different as to extent and rate from the one affecting the same area in the XVII-XVIII centuries, when the apex eroded while the delta wings continued in their progradation (Innocenti & Pranzini, 1993).

It seems that the land reclamation work did not cause a relevant reduction of the river input, since the delta continued its progradation during the initial phases of the work and the erosion of the years around 1900 was not so strong when compared with that affecting the area during the last thirty years, when the river diversion was closed.

The lack of bathymetric data suitable to analyse the submerged delta evolution in this period make it difficult to exactly quantify this erosion that probably was showing its effect on the submerged part of the delta. The amount of sediment feeding the lateral beaches was greater than that eroded at the apex. Sure is that part of this material was still coming from the Ombrone basin, since, until the second decade of this century, the river input was greater than 2 million m$^3$.

**From 1929 to 1954**

During these 25 years a longer stretch of coast was eroded, even if at a reduced rate (fig. 4). The most seriously stressed part remained the northern lobe (sector n. 9; 5.6 m/y), but the erosion became strong also in the southern one (sector n. 10; 2.2 m/y) and reached the sector n. 11 that shows a mean retreat of 4.3 m/y, whilst it was in accretion in the previous period. All the remaining sectors are in accretion at a rate similar to that shown in the preceding years, except for sector n. 5 where the mean retreat is 50 m (2.1 m/y). In 1929 in this area there was a convexity absent in 1883 and in 1954. This could be related to mega-cusps moving longshore as observed in more recent years (Innocenti, 1990).

**From 1954 to 1973**

The analysis of the coast evolution following 1954 (fig. 5) is more reliable thanks to the availability of restitution of aerial photographs at the scale 1:5,000.
Figure 5 - Changes in the shoreline (m) and relative rates (m/y) for the 16 sectors under study, between 1954 and 1973.

Figure 6 - Changes in the shoreline (m) and relative rates (m/y) for the 16 sectors under study, between 1973 and 1979.

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During this lapse of time - even if too long to properly analyse the delta evolution - the trend shown in the previous years was confirmed. The delta apex retreated at a mean rate of 9.7 m/y and at places the total erosion was greater than 300 meters (about 16 m/y). The beach of Marina di Alberese (sector n. 12) was eroded at a rate of 1.9 m/y, whilst it was accreting at 0.6 m/y in the period 1929-1954. The same occurred in the northern lobe, where the beach of sector n. 8 passed from an accretion of 1.6 m/y to an erosion of 5.7 m/y.

The stretch under erosion, 2 kilometers long in the period 1881-1954, was almost 5 kilometers in the following period.

The beaches more distant from the apex went on in their accretional phase with a global mean value of 20 - 30 meters.

From 1973 to 1979

The above evolutionary trend was confirmed also in the 70's, when the erosion affected 11 out of the 16 studied sectors (fig. 6).

To the right of the river mouth the erosion rate was 8.7 m/y, but at some places the actual value was 13 m/y.

Accretion was present only on the southermmost sector and on the first two sectors, where the shoreline advanced of about 12 meters (2.1 and 2.0 m/y).

A remarkable beach progradation occurred on sectors 5 and 6 with the formation of a lobe similar to that present in 1929. Such lobes were described by Mori (1935) as being inclined and enclosing pools similar to those portrayed in ancient maps. Mori asserted that they would rise, grow and disappear in three years. The cause for their formation must be found in the energy reduction of the longshore currents in the lee-side of the apex. This causes the approach to the coast of the bar present in the breaking line. The rectification of the delta could have determined the migration of the areas where the conditions for this process are present. Notable is, at this respect, that Innocenti (1990) observed a similar natural lobe in 1989, where a limited beach nourishment was carried out.

From 1979 to 1984/85

The delta evolution in this period (fig. 7) confirms the evolutionary trend performed since mid-Nineteenth century: erosion went on at greater speed on the northern apex (with rates that can exceed 20 m/y in some points of sectors 6 and 7) while in the northern beach the accretion rate was halved. The lobe present in 1979 in sectors 5 and 6 is located further north and reduced in dimension.

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Figure 7 - Changes in the shoreline (m) and relative rates (m/y) for the 16 sectors under study, between 1979 and 1984/85.

Figure 8 - Changes in the shoreline (m) and relative rates (m/y) for the 16 sectors under study, between 1984/85 and 1990.

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On the southern beach the erosion affected the first 3 kilometers from the river mouth with mean values reaching 8 m/y. More to the south, accretion occurred with values of about 2-3 m/y. The 14.7 m/y performed by the southern sector (n. 16) may be attributed to incorrect survey.

From 1984/85 to 1990

The seriousness of the erosion in this part of Italy is outstanding if figure 8 is analysed. Of the 16 sectors in which the coast was divided, 12 were under erosion. Unfortunately, a shoreline survey of the two southern sectors is not available, but an accretional trend should be confirmed.

The erosion rate was 10.2 m/y in sector n. 7, while it was reduced in those areas that experienced the most severe erosion during the previous period. This can be explained by considering that the mega-cusps that move northwards make the shoreline retreat a non-linear process.

Sector n. 1 - the beach of Marina di Grosseto north of the San Rocco canal - was accreting at a rate of 1.3 m/y, but this figure derives from two different trends: in the southern part of this sector erosion was present - for the first time - while in the northern one accretion was still prevailing. The erosion of the beach placed on the right-hand side of the canal outflow is to be ascribed to the effect of the construction of a jetty in order to prevent the shoaling of the canal. The limited projection of this structure does not stop the longshore drift, since it is possible to see that during the sea-storms a bar runs northward from the head of the jetty parallel to the beach and approaches the shoreline more to the north.

MORPHOLOGICAL EVOLUTION OF THE SUBMERGED DELTA

The sedimentary body constituting the submerged delta is huge, since its cuspatte shape is detectable on bathymetric surveys down to -60 meters at 4 kilometers from the present shoreline.

The offshore part of the delta, from -20 m down, maintains its original shape acquired during the accretion phase since it is not subject to wave action. On the contrary, onshore beaches suffer a rapid erosion.

Where the shoreline was running in 1883, a depth of 5 meters is present in 1977 (Bartolini & Franzini, 1985). Similar erosion occurred down to -5 meters (now at -10 m). This erosion is reduced offshore at the present -15 m contour, and is almost imperceptible at -20 m.

This situation refers to the apex of the delta, while on the wings the accretion still remains, with values reaching 4 m at Marina di Grosseto. This accretion is more likely to be produced by the materials eroded at the apex than to those coming from the river basin (Franzini, 1989).
However, numerical model applied to the morphologic conditions of the delta in the years 1883 and 1977 shows that the delta erosion is followed by a reduction in longshore transport at the apex and by an increase in longshore transport rates at the wings (Aminti & Pranzini, 1990).

The present morphology - as depicted from 1987 surveys - is characterized by a concave profile with a 1.6% - 0.6% incline from the shoreline to -5 meters, and 0.9% - 0.4% from -5 down to -10 meters. The slope is lower in front of the river mouth, where the erosion is dismantling the deltaic apparatus in its prominent part; a steeper profile is present in the other erosion sectors, where the lack of an original extended beach derives from their remoteness from the river mouth.

On the offshore a more constant slope is present. The steepest part is the southernmost part of the studied area, where a rapid sedimentation occurred recently, since sediments could overtake the Collelungo headland once this was completely silted.

Within the -5 m contour, the profile is less steep in the northern lobe than in the southern one. This could be explained with the presence, in the former area, of well developed sand-bars, absent from the southern beach. These sand-bars, formed by coarser sediments (Innocenti & Pranzini, 1993) are to be associated with a northward offshore drift caused by south and south-west winds, the strongest in the area.

The comparison between 1977 and 1987 bottom surveys shows that the erosion proceeded at an increased rate and expanded nearly to all the study area, with values of about 18-23 cm on the delta wings and 82 cm at the delta apex. Only in the first two kilometers of coast (the northern beach) an accretion - similar to that present from 1883 to 1977 - occurred.

Bottom lowering occurred even in those sectors where the shoreline advanced. This is a sign of an overhanging erosion of these sectors.

From 1977 to 1987, a loss of 830,000 m$^3$ of sediment per year occurred in the eroded areas, whereas a gain of 200,000 m$^3$/y closes the sedimentary budget in the sectors still in accretion. These figures refers to the changes occurred inside the -10 isobath, where not all the couples of profiles connect, and must therefore be regarded as underestimated.

THE CAUSES OF THE EROSION

As previously said, the Ombrone River delta formation was mainly determined by the reduction of forest cover inside the river basin and by the consequent increase in the river sedimentary input. The present erosion can find its causes both in the river input reduction and in other causes not related to the river basin.
A study of the wind direction and strength in the period 1857-1976 (Meini et al., 1979) proves that no significative changes occurred to support a climate dependence of this process. Furthermore, a change in the occurrence of seas-storms from the various directions could have determined the erosion of one delta wing, but the accretion of the other one. Limited climatic changes could have happened (both in wind strength and direction and in precipitation values); in fact, they could only have reduced or increased the processes, but they could not have determined the long-term evolutionary trend of the beach.

Sea-level rise could be considered as one of the causes of the present beach erosion (Bruun, 1983). The sea-level rise of 13 cm that occurred during the last one hundred years forced 4.500.000 m$^3$ of sediment to move offshore in the stretch of coast under study. If a linear trend is considered, a loss of 45.000 m$^3$ of sediment per year is obtained. In addition, land subsidence is to be considered. A regional value of 3 mm/y has been computed for this area, giving a loss of 100.000 m$^3$/y.

As a whole, a loss of 145.000 m$^3$/y is determined by the relative sea-level change. This value is a relevant part of the 830.000 m$^3$/y sedimentary deficit of the area, which appears from the comparison of 1977 and 1987 bathymetric surveys. The reported value for the land subsidence must be considered as minimal, since the groundwater use has increased since 1957.

If, for the delta formation a sedimentary input greater than 1 million m$^3$ was necessary, others must be the causes of the erosion.

Those who first studied the problem when land reclamation was still on or just concluded saw it as the main cause. Sure is that they greatly influenced the coastline evolution in the period, but the prograding of the erosion even after the end of the relocations make the problem more complex than those Authors thought. Actually, the erosion in the period 1883-1954 affected a very limited part of the delta and the river must have been able to feed the beach. The same may be inferred from data concerning the river input (Paris, 1991).

The story of the delta during the last forty years shows that land relocations played a secondary role in the shoreline evolution, in opposition with the ideas of those who studied the delta at the beginning of this century. Land relocations actually reduced sedimentary input, but this reduction was even lower than that induced by present human impact on the river basins.

Although the volumes now considered refer to the total river load, whilst the fraction useful for beach nourishment is mainly the sandy one, the comparison between historical and present-time data is reliable since the proportion among different grain-size classes is unchanged. The good fit between the volume obtained from the delta shape and hydraulic computations derives from the fact that the former includes also the finest part of the sediments, since it considers the delta down to -50 meters.

The amount of the coarse part of the river load computed by Milano (1986) and Paris (1991) is similar, also becau-
se they share the same sources. According to Milano, the useful load for the period 1955-1979 is 352.000 m$^3$/y - to be compared with a volume of 1.136.000 m$^3$/y for the period 1847-1883 and 748.000 m$^3$/y for the period 1883-1955. Paris gives values of 382.250 (1926-1951) and 265.172 (1952-1973). The last data are theoretical and refer to the volume that would be transported if the sediments were available; a condition considered impossible by this Author since the river-bed has been widely exploited to obtain building materials. However, these figures are consistent with the estimated sedimentary deficit of the delta (830.000 m$^3$/y) when considering that the balance should be reached with 1 million m$^3$/y.

The erosion was therefore caused by the drop of the useful river load by approximately 3/4 from mid Nineteenth century to nowadays. This reduction was only marginally caused by river diversion, and today - thirty years after the closure of the last diversion - it must be ascribed to different causes.

The main cause is probably the reafforestation of large part of the river basin performed after World War II, which reduced soil vulnerability to erosion over wide areas. Additional works, such as the building of small dams, reduced the part of the basin able to produce useful sediments. As concerns river-bed quarrying, it is not possible to quantify the amount of material extracted, but a zero sedimentary input to the beach has been suggested by Paris (1991) as a consequence of this exploitation.

CONCLUSIONS

Data for shoreline retreat and bottom erosion fit well and show that a conspicuous sedimentary deficit affects the Ombrone River delta. The present trend shows, as well, that this process is still in act and that the erosion will shortly affect areas now in accretion.

The lack of sediments is so large that no artificial beach nourishment is possible at the present cost of borrow materials. The protection of these beaches with coastal defences, on the other hand, is not advisable, since they are part of a Regional Park (Parco Naturale della Maremma) where human artifacts are almost lacking.

The only alternative strategy is one oriented to promote an increase in the river sedimentary input; i.e. favour landslides, soil erosion, deforestation, etc. Here is present-day absurdity of environmental management!

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