Barrier island evolution in relation to sea-level changes: the example of the Grado Lagoon (northern Adriatic Sea, Italy)

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Abstract. Air-photographs, maps and repeated field surveys dated from 1882-1990 were used to define the evolutionary patterns of the new coastal barrier of Grado Lagoon between Porto Buso and Grado. The shoreline retreat model ("generalized Bruun Rule") was tested. This model can be used as a first approximation in prediction of shoreline movement following the sea-level rise, and considering the general prevalence of the transverse movement in this specific area. The results achieved allowed the authors to modify the Bruun-based model for prediction, in specific cases, of the alongshore sediment movement. Differences between the model and observed values in several cases are rather high and are interpreted as a result of tidal movements and alongshore sediment transport.

1. Introduction

The way beaches and barrier islands, which separate terrigenous lagoons, will respond to possible future global changes, and especially to the probable global sea-level rise, is one of the main issues in coastal management that will need to be addressed in the near future. In order to define possible defence strategies, a series of models of the coastal evolution in different physiographic areas have been proposed. It is important to apply some of these models to the north Adriatic coast, where, apart from important cities and tourist resorts, there is a succession of deltas and lagoons of primary environmental interest. The whole coastline consists of beaches composed usually of fine sands. At present, most (about 70%) of the Adriatic coast has been stabilized with transverse and other specific defence structures. The few relatively free sectors of the coast show great mobility, mainly due to natural factors. One of these areas, although highly affected by anthropogenic activity, is the new barrier island of the Grado Lagoon which extends

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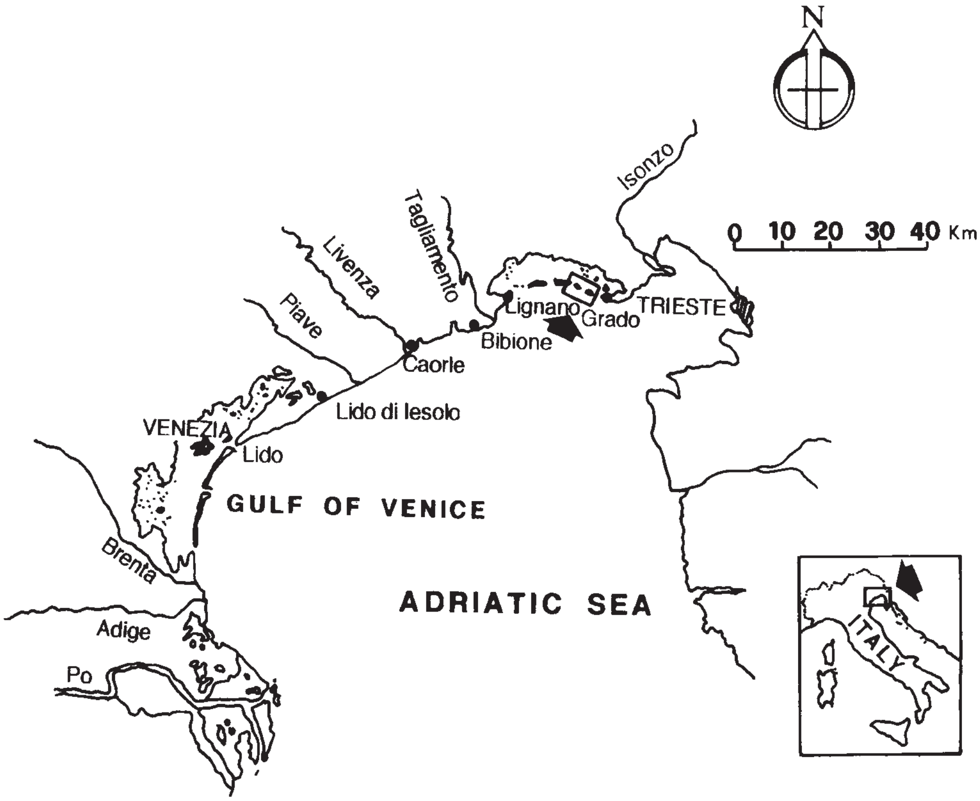

Fig. 1 - General location of the Grado Lagoon in the north Adriatic Sea.

from the inlet of Porto Buso to Grado. Morphological and sedimentological studies were carried out in this area as well as a series of topographic and bathymetric surveys. Therefore, the area can be used as a test bench to assess the validity of evolutionary models dealing with coasts subject to sea-level rise.

The main objectives of this study can be summarized as follows:

i) to study coastal changes for clarifying the general tendencies, patterns and main factors of the coastal evolution of the region;

ii) to verify the existing model (Bruun Rule) of coastal response to sea-level changes in a sort of back-prediction on the basis of the existing cartographic and field measurement data, and to discern sea-level changes from among a variety of factors relating to coastal change;

iii) to anticipate the general trend of coastal evolution for the region under the anticipated future sea-level rise induced by the "greenhouse effect".

2. Description of the study area

2.1. Geomorphological conditions

The coastal barrier between the inlet of Porto Buso and the town of Grado consists of a series

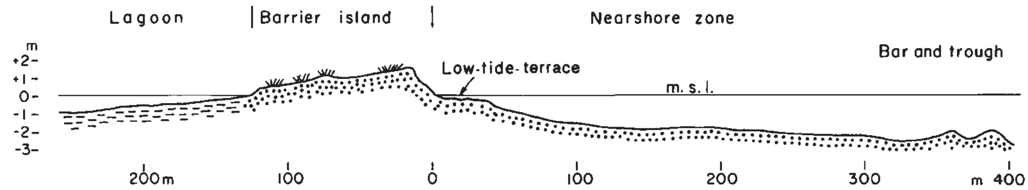

Fig. 2 - Generalised morphological profile of the new coastal barrier of the Grado Lagoon.

of barrier islands (about 10 km) alternating with tidal flats that define a small paralagoonal basin (about 6 sq km) (Figs. 1 and 2). The barrier island is narrow (100-150 m), generally lacks dunes (except for the easternmost area) and presents a morphology typical of tidal beaches (Figs. 3, 4, and 5). In particular, a low tide terrace, a foreshore and a backshore with several berms (summer and winter) can be distinguished on the barrier (Fig. 2). Occasionally, eolian depositional bodies occur (shadows and incipient foredunes). In winter the barrier island in subject to severe erosion during storms by washover and shoaling processes across the barrier island to the paralagoonal basin. Vegetation in the backshore is scanty and not sufficient to stabilize the blanket of sand continuously blown away by the wind. However, at the back of the beach, lagoonal vegetation *(Spartina, Salicornia)* stabilizes surficial sediments. On the tidal flat at the back of the barrier island, the pelitic sediments are dry. This results in the formation of mud hardpans with typical toast and mud cracks. In the case of erosion, mud pebbles form. At times these mud hardpans become visible on the seaward part of the barrier, pointing out the recent transgression of the sandy bodies over lagoonal deposits.

The gentle coastal slope (0.2 - 0.6‰) is characterized by the existence of submerged bars. Offshore from the bar and trough zone the sea bottom is covered with *mattes* of marine phanerogams *(Chymodocea* and rarely *Posidonia oceanica).*

2.2. Hydrometeorological conditions

The study area lacks permanent stations for the observation of sea parameters, such as mean water surface level, waves and tides. According to Brambati (1974a), Brambati and Candian (1976), Catani and Marocco (1976) and Brambati (1987), ENE winds (Bora) generally prevail in this region of the North Adriatic sea, while SE winds (Scirocco) play a secondary role. The resulting mean wave-inducing wind direction near Grado is SSE (160-165 degrees), the mean effective wind speed being 4.7 m/s.

During a Bora, the mean observed wave height is 20/30 cm, the length 10 m and the period 6 s, while during a Scirocco the respective values are 30/40 cm, 7 m and 5 s. The maximum observed wave parameters in the period 1970-1973 were 145 cm, 15 m and 7 s (Brambati, 1974a). Under the generally smooth coastal slope conditions, these waves produce significant storm surges reaching 1.6-1.7 m. The greatest storm surge recorded was in Trieste in December 1969 and was 2.09 m above mean sea level (msl) (Mazzarella and Palumbo, 1991).

Fig. 3 - Air photograph of recent barrier islands near Grado: general view of Banco dei Tratauri and Banco d'Orio.

Long-term data on tides in the Adriatic Sea demonstrate their semi-diurnal character. Mean spring tidal range is 86 cm whereas the neap tide is 22 cm; the extreme tidal range is estimated at 1.1 - 1.2 m. The rates of the tidal currents in the Grado and Marano inlet are 35-53 cm/s.

Reliable uniform tide-gauge time series on sea levels are available for Trieste and Venezia, extending back in time to 1905 and 1872 respectively. The mean rate of sea level rise is 0.132 cm/year (Stravisi and Ferraro, 1986) and 0.39±0.10 cm/year (Mazzarella and Palumbo, 1991). However, due to distinctive differences in the geodynamic conditions along the coast, the use of the data from these tide-gauge stations is rather problematic. Fast subsidence in the Venice area is well-known, both from geological (Fontes and Bortolami, 1973; Colantoni et al., 1979; Pirazzoli, 1991) and instrumental data (Pirazzoli, 1981; Carbognin et al., 1981; Mazzarella and Palumbo, 1991). There are no direct data on the vertical deformations at Trieste. Since, the rate of the sea-level rise at Trieste is similar to that for the mean global sea-level. The sea-level data at Trieste may be considered appropriate for our studies (Fig. 6).

Estimates of vertical land movements in the study area are unknown. Recent topographic surveys in the coastal area (R.F.V.G., 1990) produced evidence for a series of vertical movements of the pier (mean value 3.92 mm/yr). However, these movements are possibly of local nature and result from positive and negative movements of the foundations on the embankments.

The updated version of the tide-gauge data for Trieste was kindly provided by the Istituto Sperimentale Talassografico of Trieste. The temporal alternation of sea-level rise and fall (Fig. 6) presents an opportunity for the analysis of coastal responses to changes in the water-level regime.

Fig. 4 - Air photograph of Banco dei Tratauri and the pier embanking the Grado channel.

3. Recent evolution of the barrier island

An analysis of topographic maps and air-photographs for the area demonstrates three evolutionary phases for the new coastal barrier. These phases are determined essentially by the engineering works in the coastal zone. An early evolutionary phase of the primitive sandbanks is recognized for the period before construction of the embankment on the old beach ridge and of the piers at the inlet. The second phase covered the period of engineering works, and a third and last phase began after the construction of the piers and during the relative stabilization of the present coastal system.

3.1. First phase (1882-1938)

The position of the ancient barrier island of Grado Lagoon is well documented in the topographic maps of 1882, 1896, 1917 and 1927. At the beginning of this period a set of small (unnamed) sandbanks extended from the Morgo inlet towards Grado and moved seaward in a sinusoidal manner from the ancient barrier island. In general, the new ridge of semisubmerged sandbanks extended for 4300 m with a minimum width in the western part (80 m) and a maximum width in the centre-east (300 m). Mean width of the bank was equal to 150 m.

During the period 1896-1917, the morphology of the banks changed considerably (Fig. 7). The single sandbank named Banco d'Orio formed and shifted westward along the coast, separating the mouth of the Morgo channel from the sea. The bank extended by 3700 m and its width

Fig. 5 - Detailed view of Banco dei Tratauri.

ranged from 100 m at its east to 420 m in the centre-west, the mean width being 270 m. Thus, during these years, the original sandbanks unified, moved seaward and westward, and considerably increased in area.

In 1928-1934, the 1200-meter long pier was built south-east of the island San Pietro d'Orio. Another pier extended in a south-western direction from Grado. The piers, which embank the channel of San Pietro d'Orio and the channel of Grado, ensured permanent navigation from the Grado Lagoon to the open Adriatic Sea and protected the western sector of Grado from erosion.

The piers reached out to a water depth of 2.5-3.0 m in the open sea and intercepted most of the prevailing westward alongshore transport of sediments. Together with other morphological features and the general pattern of the currents (Mosetti and Lavenia, 1969), the presence of the submerged bank, known as the Banco d'Orio, indicated a high intensity of longshore sedimentary movement (Zenkovich, 1967; Boldyrev, 1992).

The construction of the piers produced a drastic change in the evolution of the barriers.

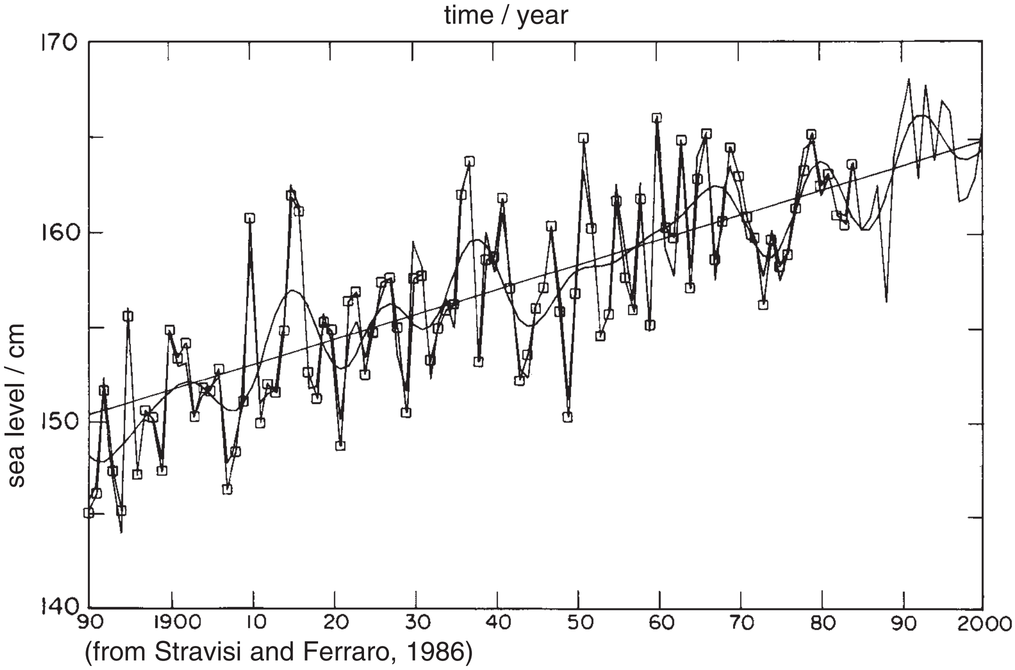

Fig. 6 - Tide-gauge data on sea-level changes at Trieste.

3.2. Second phase (1938-1964)

A new bank called Banco dei Tratauri emerged west of the piers. After several years, the new bank, as well as the old Banco d'Orio, shifted eastward losing its width. The new barrier extended in the form of an arch reaching 5100 m with a maximum width of 320 m (eastern end), a minimum width of 40 m (the tongue of sand at the opposite end and a mean width of 146 m (Figs. 7 and 8). In 1952, the Banco dei Tratauri extended for about 200 m westward maintaining its width. The Banco d'Orio also extended westward and reached 3900 m in length and 120 - 130 m in width. The westward extension of the Bank was at the expense of its width and height. The two banks together formed a tongue of sand of 5900 m length interrupted only by an inlet of about 400 m in width.

Other engineering works carried out during that or later times just behind the new coastal barrier and near Porto Buso were aimed at the increase and regulation of water flow across the old coastal barrier, and at the improvement of access to the river harbour of Porto Nogaro. The following works were implemented:
- closing of the Morghetto channel by a pier (1950);
- closing of the channel Valerian by a pier (1951);
- closing of the channel Lipan by a pier (1960);
- construction in two stages of the piers of Porto Buso (1960-1964).

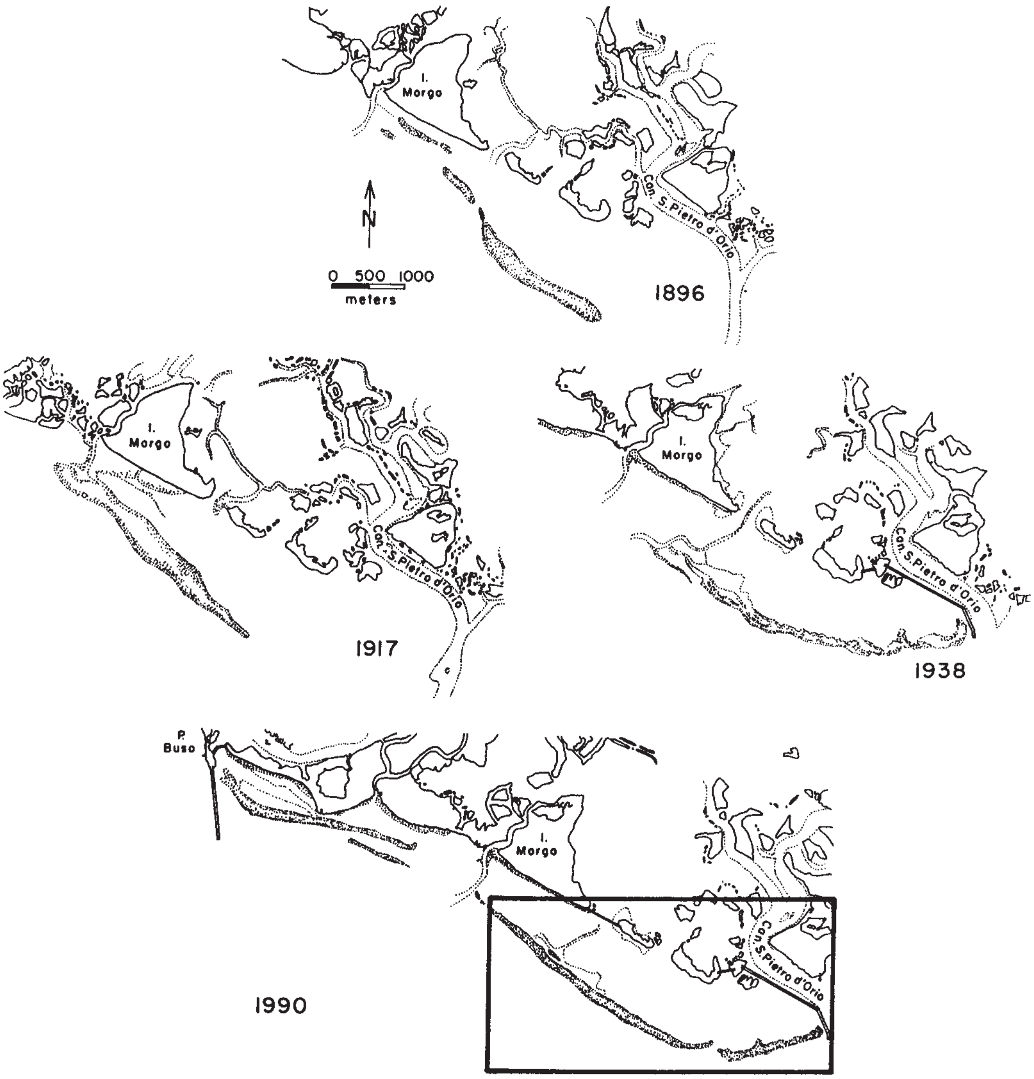

Fig. 7 - Planimetric data on the coastal changes in the Grado Lagoon for various years. The area of the detailed studies is shown on the last map (1990).

3.3. Third phase (1964-1990)

In 1971-1973, the original Banco d'Orio divided into two separate islands (Banco d'Orio "A" and Banco d'Orio "B") (Brambati, 1974a) (Fig. 8). It also shifted landward by a conspicuous 100 m on the east side and 250 m on the west. The Banco dei Tratauri maintained its original position except for slight advances and withdrawals of its shoreline and an extension to the west that greatly reduced the inlet between the Banco dei Tratauri and the Banco d'Orio "B" (Brambati, 1974b). In the western part of the area, near the eastern pier of Porto Buso, the sand

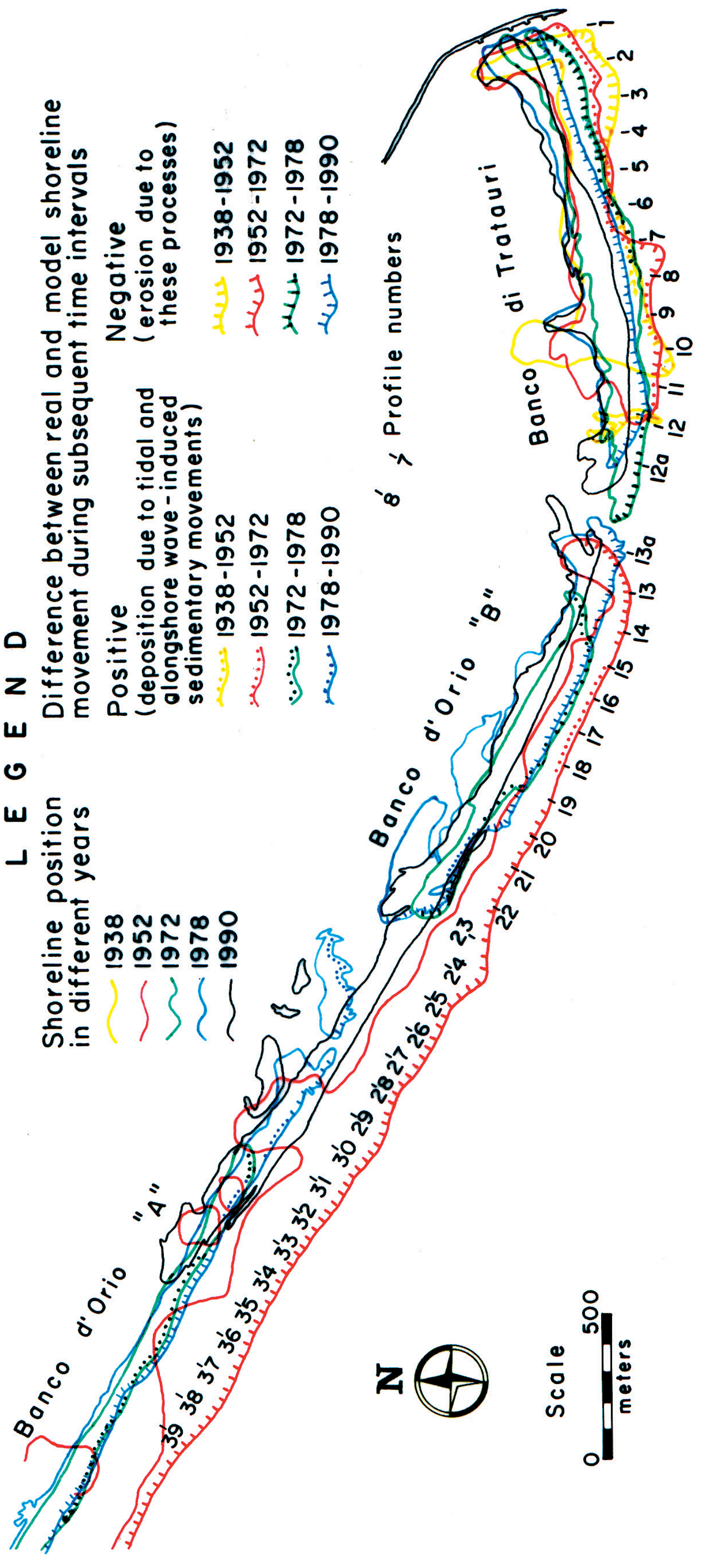

Fig. 8 - Shoreline changes in the study area in 1938-1990. See position of the area in the index map (Fig. 1).

bars consolidated and emerged, forming a new sandbank that grew progressively eastward to the inlet of the Morgo channel. This new bank (named Banco d'Anfora) completed the coastal arch of the new barrier. In 1974, only a few years after construction of the Porto Buso pier, this bank was about 3000 m long, 150 m wide and of modest height.

With the formation of the Banco d'Anfora the new barrier of the Grado Lagoon took its present shape, with the two main banks "hinged" to the piers (though separated from them by two narrow channels) and a central body represented by one or more banks that unite or divide in response to the hydrometeorological conditions. The general shoreline contour of the area assumed a sinuous form (sinuosity = 1.06) conditioned by the orientation and the extension of the piers at the extremities that contain and support the system. In particular, near the eastern pier, the banks of the Banco dei Tratauri and the eastern tip of the Banco d'Orio are of typical arcuate form, anchored and bound to the pier. The same is true for the western part of the Banco d'Anfora. In the central part of the area, the shoreline is fairly straight, although slightly concave in the easternmost part of the Banco d'Anfora, corresponding to the bank of the Morgo inlet.

The latest topographic and bathymetric surveys of the area demonstrates the relative stability of the Banco dei Tratauri (Brambati, 1987; Gatto and Marocco, 1993) and a progressive tendency to an increase in area, especially in the western part, for the Banco d'Anfora. The remaining banks are in state of continuous change and represent the critical part of the system. Instability in this tract of beach ridge is due to Bora sea that tends to smooth the coastal arch and bend it to the west, and to the Scirocco and Libeccio swells that tend to move especially the central part especially of the beach ridge back towards the lagoon. These movements together with the discharge from the Morgo channel (behind the banks) support the coastal barrier and protect it from degradation.

Within this context we decided to analyze only the eastern part of the new barrier in the Grado Lagoon for the following two main reasons:
- there are more frequent test surveys for this area;
- the clear evidence of shoreline movement that is possibly partially a result of sea-level changes.

4. Description of the shoreline retreat model

The currently well-known model of shoreline variations under sea-level changes was proposed by Per Bruun in the USA and Vsevolod Zenkovich in Russia in the late 1950's on the basis of the general theory of coastal hydrodynamics. According to this model, known as the Bruun Rule, a shoreline retreat (advance) R is proportional to the sea-level change U, and to the width of the wave-induced zone of the sea-bottom B, and inversely proportional to the maximum depth of this zone D:

$$R = UB/D. \tag{1}$$

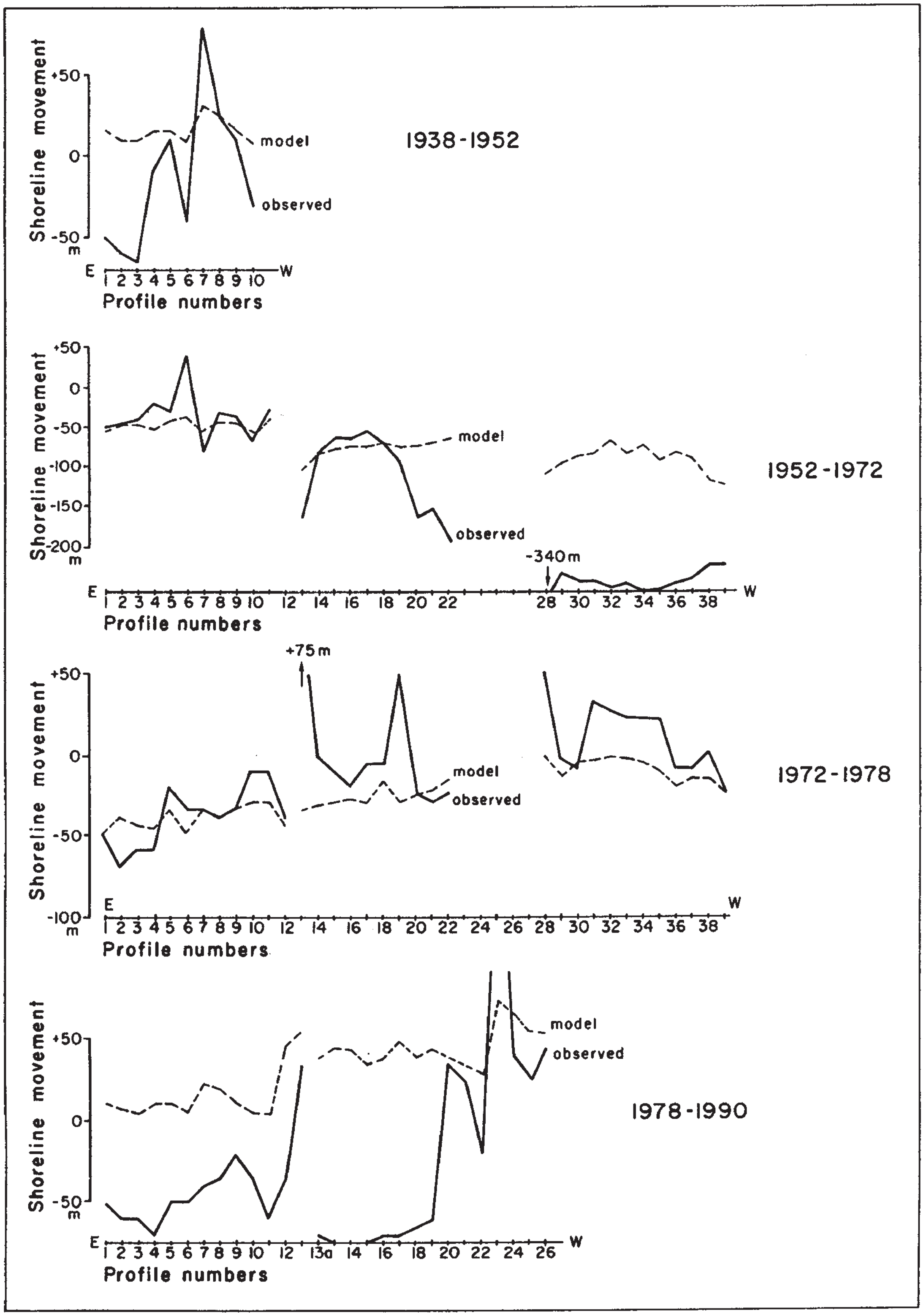

Fig. 9 - Observed and model values of shoreline movements in the study area over different time periods.

Therefore, the Bruun Rule postulates the dependence of shoreline movement on the underwater coastal slope. The model showed good correlation with observed shoreline changes on the Great Lakes and in many other coastal areas. For its great simplicity and because it contains easily-measured parameters, the Bruun Rule has interested a great number of scholars. However, since Bruun Rule-based predictions have often differed from observed changes (by a factor of 2-5), various authors have tried to establish limitations to its application by defining boundary conditions, and by proposing changes to account for additional factors involved in the process of coastal reformation. The modification proposed by Weggel (1979) is an attempt at accounting for the reformation of coastal dunes while the so called generalized Bruun Rule proposed by Dean and Maurmeyer (1983) accounts for the sedimentary washover to a lagoon:

$$R=U\,(B+W+Bl)\,/\,((D+h)-(Dl+hl)), \tag{2}$$

where

h is the elevation of the beach berm, Bl, Dl and hl are the respective parameters of a landward (lagoon) slope on a barrier island, and W is its width.

As well as other Bruun-based equations, Eq. (2) is established on the following main assumptions:

1. The model in its traditional form predicts shoreline changes caused by a transverse wave-induced movement of sediments, i.e., it does not apply to alongshore sedimentary movements of any other origin or to transverse movements caused by non-wave factors (such as tides);
2. The model assumes the preservation of an equilibrium transverse profile of the coastal zone. It was demonstrated by Allison (1980) and by the SCOR Working Group (1991) that among other premises, the model requires relatively slow changes in sea-level U, as compared to a shoreline retreat (or advance) R, and a sufficient sediment supply;
3. A very important assumption is the exclusively seaward movement of sediments during periods of sea-level rise and a shoreward movement during periods of sea-level fall. Recent investigations (Kaplin, 1989; Kaplin et al., 1993; Selivanov, 1993) demonstrated that the Bruun Rule is obviously true only for the conditions of a relatively steep nearshore coastal slope (generally tan $a > 0.01$ for coarse sands and 0.003-0.005 for medium and fine sands). Nevertheless, Eq. (2) at least partially overcomes this limitation;
4. The model does not predict short-term shoreline changes, for example during a single storm. According to the SCOR Working Group (1991), the response time for a costal zone to reach equilibrium can be as long as several months. Our studies on microtidal coasts demonstrated that the total response time to major storms exceeds 1-2 years (Selivanov, 1989). Seasonal changes in sea-level, therefore, probably cannot be related to the above model, and it predicts only decadal or secular changes;
5. The model assumes a uniform pattern of sea-level changes (proportional, accelerating, or decelerating). Therefore, it can only be applied to periods of relatively steady sea-level rise in Trieste, which usually lasted for 7-10 years (Fig. 6).

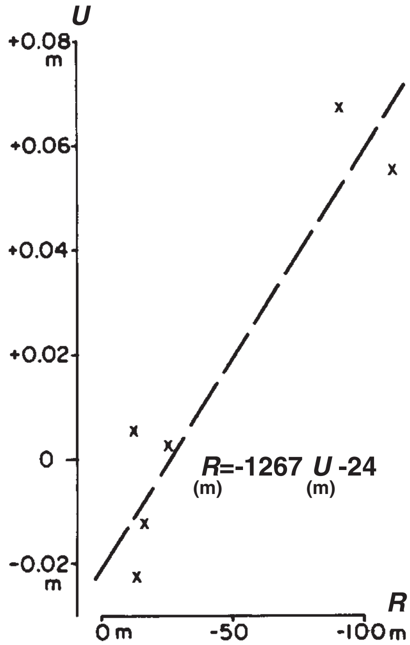

Fig. 10 - Correlation of shoreline retreat *R* (m) and sea-level change *U* (m).

5. General model testing approach and data used

The general prevalence of transverse sediment movement in the studied area allowed us to apply model (2) to this area.

In order to test the ability of model (2) to distinguish wave-induced transverse sedimentary movements in the coastal zone due to sea-level changes and to evaluate the relative significance of this factor among others, we used the valuable data on changes in the new highly variable coastal barriers west of Grado.

In an attempt to apply model (2) to the estimation of shoreline movements in the test area and to account for the observed changes in the width *W* of the barrier island, we modified the model by subtracting the shoreline retreat values *R*1 and *R*2 during the two consecutive periods:

$$R1 = U1(B1+W1+Bl1)/((D1+h1)-(Dl1+hl1)); \tag{3}$$

$$R2 = U2(B2+W2+Bl2)/((D2+h2)(Dl2+hl2)). \tag{4}$$

If the elevation of the barrier island and the parameters of the underwater coastal slope do not change, i.e., $B1=B2=B$, $D1=D2=D$, $h1=h2=h$, $Bl1=Bl2=Bl$, $Dl1=Dl2=Dl$, $hl1=hl2=hl$, and the sea-level change is proportional ($U1=U2=U$), then

$$R1\text{-}R2 = U(B+W1-W2)/((D+h)-(Dl+hl)). \tag{5}$$

The morphological parameters in Eq. (5) were taken from the respective maps. All measurements were carried out on nearly 40 transverse profiles spaced at a distance of 125 m from each other. According to the recommendations by Hallermeyer (1978), the boundary of the wave-induced bottom zone (the so-called "wave-base") was established at a depth of H = 2.5 heights of extreme breaking waves of 5% probability. Heights of extreme breaking waves were calculated from wind parameters by the empirical CERC equation (Komar, 1983) and were equal to 2.0-2.1 m. It is worth noting that an empirical approach by Niemeyer (1978) leads to a similar estimate. Therefore, the limiting depth of the wave-induced bottom zone in the study area can be estimated at 5-6 m.

In order to minimize the non-uniformity of the sea-level curve for Trieste, and bearing in mind that models (2) and (5) refer to interannual changes in the coastal zone, appropriate sea-levels for the years of the coastal surveys were calculated as mean values for the three preceding years.

6. Results

An analysis of shoreline movement in the Banco dei Tratauri - Banco d'Orio area during the last century from all the existing data shows a general positive correlation between the mean value of shoreline retreat along the coast and the rate of sea-level change (Figs. 9 and 10). This clearly shows the importance of this factor in the coastal evolution of the area. This result is even more valuable when we consider that both periods of both sea-level rise and sea-level fall occurred during the time-interval. However, the general prevalence of the shoreline retreat is clear even for the periods of sea-level fall.

An application of model (5) to the back-prediction of shoreline movement during the periods of 1938-1952, 1952-1972, 1972-1978 and 1978-1990 which were better covered by maps at the scale of 1:5,000 (Fig. 7) gives results comparable to the observed shoreline changes. The comparison between the observed and model results for these time intervals is presented in Figs. 9 and 10. For the different periods and various coastal stretches the model describes 40 - 100 % of the shoreline variability. The correlation between the observed and model values is closer for the periods of sea-level rise, especially for the exceptional rise in 1952-1972.

From assumptions 1-5 that formed the basis for application of the model, it can be concluded that the differences between real results and model results reflect the contribution of other processes involved in coastal change. In this particular area they are primarily of transverse character. The difference, therefore, between predicted and real shoreline movement indicates the tendency and importance of the above processes: i.e., where shoreline retreat is greater than the "predicted" value, wave-induced alongshore, and tidal sedimentary transport tends primarily to erosion, and vice versa.

Thus the method can be used to distinguish between areas of tidal and longshore wave-induced deposition and erosion. Figs. 9 and 10 show that the zones of deposition and erosion by tidal and alongshore wave movement move along the coastline from period to period. However, while erosion tends to occur mostly in the eastern parts of the banks, deposition seems to prevail in the centre. This is in agreement with the conclusions by Brambati (1987) on the general character of the evolution of these depositional features.

The western extremities of these banks also represent zones where non-transverse wave-induced erosion prevails. The prevalence of flood over ebb tides is a possible explanation.

Another important feature of this methodology is the possibility to distinguish different patterns of shoreline evolution, possibly as a result of various tendencies and rates of sea-level changes, including among other factors:

1. Prevalence of erosion in the eastern segments of the banks and deposition in the western ones. This tendency is possibly directed by the westward longshore sedimentary movement and is reflected better during periods of slow sea-level and wave climate changes; for example, the fall in a relative sea-level in 1938-1952 and its slow rise in 1972-1978 and the respective relatively slow wave climate changes;
2. Clockwise "rotation" of the bank, i.e., the prevalence of deposition in the eastern sectors and erosion (less intensive than in pattern 1) in the western ones. During the period of intensive rise in relative sea-level in 1952-1972 this pattern was obvious. A higher supply of sedimentary material from the coastal slope during intensive sea-level rise is the possible reason for this evolutionary pattern;
3. Total prevalence of shoreline retreat several times exceeding the "predicted" model values in 1978-1990, notwithstanding the slow fall in relative sea-level.

7. Discussion and conclusions

The results achieved during implementation of the project allowed the authors to modify the Bruun-based model for prediction, in specific cases, of the alongshore sediment movement. The general results prove the conclusion that a possible accelerated sea-level rise would inevitably cause drastic changes in coastal evolutionary trends and patterns in the north Adriatic Sea. The young depositional coastal barriers would be among the most sensitive features to this process. If the rise in the global mean sea-level really accelerates to 0.3-1.0 cm/year, as was predicted by the Intergovernmental Panel on Climate Change (Houghton et al., 1990), then a drastic shoreline retreat and general erosion of these bodies will be inevitable. However, during the first stage of this process, a general mobilization of sedimentary material in the coastal zone and the resulting increase in the elevation of depositional barriers and possibly their clockwise rotation is possible. Nevertheless, the small width and volume of these depositional bodies will result in their narrowing to critical values (100-200 m) and their subsequent destruction in a couple of decades, as was directly observed in the Caspian Sea and the Sea of Azov under the rapid water-level rise (see Kaplin et al., 1993).

Intensive shoreline retreat will also occur along the depositional coasts at Grado and Lignano, which are protected from erosion by the artificial transverse structures. According to the model, the rate of shoreline retreat could reach extreme values of 4-5 m/year, which is comparable to or exceeds the observed shoreline retreat values over the last decades. This phenomenon could cause significant losses along the coasts in the area. The existing coastal defence structures would have to be totally rebuilt.

Our study obviously demonstrated the great importance of the problem of coastal response to sea-level changes. Such a response really does exist in the region. A possible future sea-level rise would inevitably cause significant damage to the population, industry, agriculture and infrastructures. The existing methodologies and their modifications as presented in this paper form the necessary basis for the distinguishing and quantification of the patterns of coastal change.

However, observations on sea coasts in the region need to be extended, and the existing surveys renewed. The studies should include all the coastal types in the region, in order to allow an analysis of the broad variety of coastal responses to sea-level changes.

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