Evolutionary trends in the beaches of the Tagliamento river delta

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ABSTRACT The morphodynamic analysis of the beaches of the Tagliamento river delta (from Punta Baseleghe to the Lignano inlet) showed that some littoral zones are undergoing endemic erosion while others seem to be advancing or stable. These results, based on 132 topographic and bathymetric profiles collected perpendicular to the coast, were obtained in the study area in 2002 and 2003 and compared to the 1987 bathymetric profiles. From the analysis of the bathy-morphological data, the areas prone to great changes are located near the river mouth where a series of detached breakwaters have been placed for stabilization. These defences have partly stopped or generally slowed the erosive processes but have given rise to conditions of instability in the adjacent areas. Important erosive processes are evident, more westwards, in the area denominated Lame di Revelino - Pineta Punta Faro, where a progressive withdrawal of the beach, the disappearance of the low-tide terrace and the thinning of the upper shoreface zones is currently occurring. The central and western part of the Bibione shore display different characteristics. Here, the beaches are essentially characterized by a stable or advancing regime. The beach, in correspondence to the Baseleghe inlet, initially thins in width which has nothing to do with erosion, and shows an important development seawards and further expansion westwards. This kind of behaviour of the beach further highlights a trend towards an occlusion of the Baseleghe inlet. The eastern lobe of the delta is represented by a beach with a concave geometry, marked by the presence of groins. These structures have captured and stabilized the sand within the cells between pairs of adjoining groins. At the same time, however they also prevent the drift of sediments towards the east, determining a substantial decrease of the sedimentary flow toward the beaches in that direction. The central portion of the Lignano shore shows a typically stable character with natural progradation phases which were also confirmed by a long time-series of observations. Instead, the coastal belt close to the Lignano harbour fairway is slightly unstable; a series of groins and seawall revetments are located in this area.

1. Introduction

The present paper summarizes the data and conclusions of a series of studies that were designed to provide a synoptic definition of the main characteristics of the coastal environment of the Tagliamento river delta in the north Adriatic Sea (Ramella *et al.*, 2004). As described in Gordini *et al.* (2006), these studies consisted of detailed analyses of environmental information on the beach and upper shoreface in the area. Here, the data gathered during the studies have been

re-analyzed, and the results compared to those obtained from earlier investigations into the mechanisms underpinning the observed local phenomena. This approach permitted a better characterization of the more recent changes occurring in the study area.

In the past, many authoritative studies have been conducted on the Tagliamento delta beaches, and a great deal of sedimentological and morphological data (Zunica, 1971; Brambati, 1987; Fontolan, 2004) among others is therefore available for the area. The new data, obtained with state-of-the-art technologies, have not only confirmed many of the results of these older studies but have also thrown some light on ongoing processes. The data were gathered by means of a series of topographic and bathymetric surveys conducted perpendicular to the beach toward the ends of summer 2002 and winter 2003. Thus, two fundamental evolutionary regimes of the shore - erosive in winter and depositional during summer - could be studied. The analysis of the data helped to define the morphological variations of the beach, which could be related to changes in some seasonal meteo-marine characteristics. Subsequently, the comparison of the recently acquired data with those presented in the earlier studies permitted a quantification of the erosional rates and a better understanding of the stability and the depositional beach trends.

The knowledge base obtained can be considered an important tool for subsequent environmental assays of evolutionary trends in this economically sensitive area. It will also provide baseline information useful for actions aimed at improving and restoring eroded zones.

2. Physiographic and meteo-marine setting

The investigated coastal area, located in the northern Adriatic Sea (Fig. 1), is characterized principally by the fine sand beaches of the Tagliamento river delta that extends from Punta Baseleghe to the Lignano inlet. The orientation of the coastline exposes these beaches to different wind and wave regimes. The prevailing winds are those that blow from the I quadrant, mainly the Bora from the ENE (Carrera *et al.*, 1995) in the fall and winter. The entire area is also affected by the northern winds (diurnal in character) caused by thermal variations, and less frequently, by the Scirocco and the Libeccio winds from the southwest (Catani and Marocco, 1976; Brambati, 1987).

The tidal variations observed along the coast are particularly large. The maximum amplitude is observed during spring-tide, with an average semidiurnal shift of 86 cm near Trieste (100 cm at Venice). The minimum amplitude is noted during the mean neap-tides, with diurnal shifts of about 22 cm and 20 cm at Trieste and Venice, respectively (Dorigo, 1965; Polli, 1970). However, the concomitance of spring-tides, seiches, south-easterly winds and low atmospheric pressure can cause an exceptional event, described locally as "acqua alta", that has exhibited values of 130 cm with peak values of about 200 cm (Marocco and Pessina, 2000). Mean significant wave heights during the year are lower than 0.5 m (Dal Cin and Simeoni, 1994), while the highest offshore wave height, recorded for storms generated by both the Bora and Scirocco, is about 5 m (Cavaleri *et al.*, 1996). The mean basin circulation is cyclonic.

3. Geologic settings and evolutionary considerations of the area

The area is characterized by sedimentary deposits interpreted as transgressive systems, late

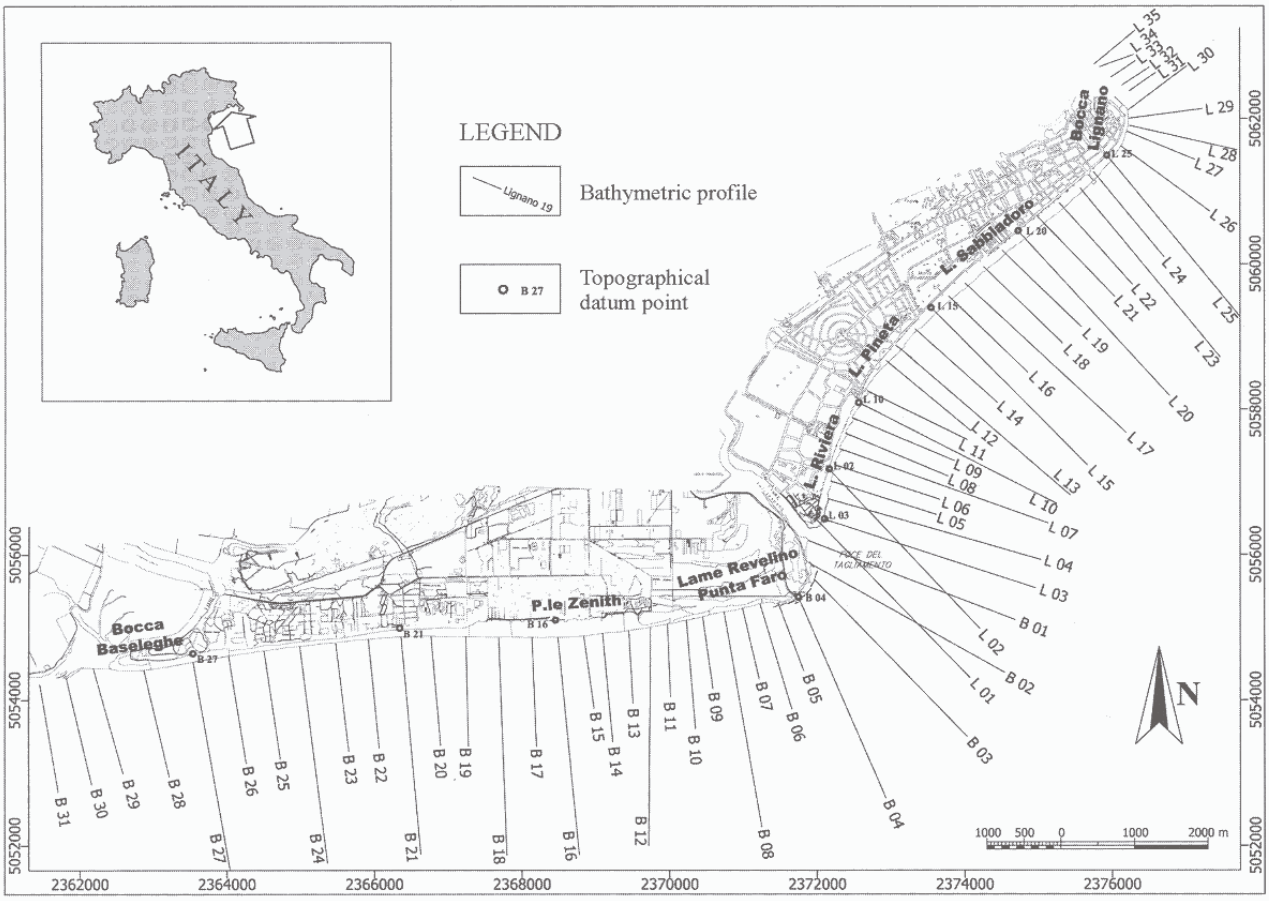

Fig. 1 - Tagliamento river delta: location of the bathymetric profiles and topographical datum points.

Quaternary in age (Gordini *et al.*, 2002). They are represented by LST (Lowstand System Tract) alluvial clays and sands of continental origin. Such deposits are buried by sediments displaying different thicknesses that constitute the TST (Transgressive System Tract) deposits, mainly characterized by "barrier-lagoon-estuary " systems. The HST (Highstand System Tract) deposits are located in correspondence to the actual shoreline or sometimes even more inland. These denote the maximum level reached by the sea during the last sea transgression. The deposits are constituted by the sands of the coastal sedimentary prism distributed along a narrow coastal band and also by delta, prodelta and lagoon deposits with variable granulometry.

Sedimentological analyses performed on cores acquired in the Tagliamento delta (Giovanelli *et al.*, 1985; Marocco, 1988, 1991; Gordini *et al.*, 2002) have shown that the substrate is constituted by pelitic-sandy alluvial sediments of the flood plain, attributable to referable swampy episodes of the Tagliamento, Isonzo, Natisone and Torre paleo-rivers. This particular genesis is confirmed by the presence within such sediments of mineral traces typical of these rivers (Gazzi *et al.*, 1973).

The alluvial deposits reveal alternating sandy and pelitic sedimentation phases, followed by erosive phases related to the eustatic sea-level rise. This evolutionary pattern has caused some lateral variations in the superficial sediment. Near the actual shoreline, there is a clear transition

from a continental environment to that of a sea-shore. In the north, however, a typical transition towards a lagoon environment can be noted. The development and successive accretion of a delta above the lagoonal sediments has led to the separation between the Caorle and Marano paleo-lagoons (Marocco, 1989). The mineralogical composition of the sandy sediments in this last evolutionary phase is similar to that observed in the actual Tagliamento system. Therefore, it is probable that the Tagliamento river started to flow in this area only recently.

The present Tagliamento delta was formed about 2000 years ago with a non gradual progradation, but characterized by rapid accretion with alternated erosive and stable phases (Marocco, 1991).

The analysis of the historical cartography performed by Zunica (1971) shows that from 1644 to 1868, the delta has suffered substantial changes, partly determined by natural factors and by the sea state and partly by human intervention. The latter, involving reclamation work, the filling of depressed areas, the construction of embankments and continuous regulation of the river-flow, has strongly modified the territory. The comparison of the maps indicate that the greatest modifications occurred on the right side of the delta. The shore here evolved from a stumpy and convex seaward geometry (the 1822 situation) to an accentuated concavity in a time interval of only 46 years. The concavity is particularly evident in the western-central portion, denoting erosive events. A migration of the terminal segment of the river is also noted with a modest rotation first towards the east and then towards the west – the current situation. Zunica (1971) also underlines that the maximum backspace occurred in a very short period, from1822 to 1833. Progressive advances brought the shore in 1868 to the initial condition, which was afterwards surpassed in 1903. Meanwhile, the other parts of the shore appears more stable, although a strong accretion occurred at the end of the century.

The analysis of the various editions of the I.G.M. Map (from 1937 to 1951) confirm the coastal trends deduced from the more ancient maps, with a great dynamism on the right side in comparison to the left side. The latter evidences continuous periods of conspicuous nourishment alternated by others of intense erosive activity. The different I.G.M. Map editions underline the mechanism of the delta accretion. This involves a progressive fusion of sandy bars with the swash zone and the migration of the submarine bars towards the west. Brambati (1987), on the basis of the comparison between the 1891, 1978 and 1985 shorelines, confirms the evolution of the left side of the Tagliamento, underlining the eastern mouth lobe development. This is opposite to the pattern occurring along the shoreline portions up to the Lignano Riviera where an erosional phase is observed. More to the east, a strong progression of the beach is recognizable up to the Lignano mouth over the last century.

4. Methodology applied to the definition of the beach and shoreface

132 topographic and bathymetric profiles (66 for each seasonal period) were collected perpendicular to the backshore, foreshore and shoreface beach along 18 km of the coast, extending from Punta Baseleghe to the Lignano mouth, in September and October 2002 and May and June 2003. The spacing of the profiles was maintained at around 250 - 350 m, whereas the lengths of the resulting sections varied from 1.5 to 3.0 km (Figs. 1 and 2). The profiles comprised a depth interval of 0.5 m to 10 - 12 m.

Fig. 2 - Some meaningful examples of topographic and bathymetric profiles acquired in correspondence to the beaches of the Tagliamento river delta; see Fig. 1 for the locations of the profiles. The depth is referred to the mean sea level, whereas the distances are referred to the closest topographical datum point located along the coast.

The seafloor survey was performed using a Lowrance LCX - 18C echo sounder and navigation plotter with operating frequencies of 200 and 50 kHz. The echo sounder provided a graphic visualization of the profiles. The positions of the bathymetric profiles were obtained using a DGPS system survey.

Furthermore, in order to obtain a detailed reconstruction of the shoreline, LIDAR methodology was used to accurately define the morphologies of the backshore beach and the

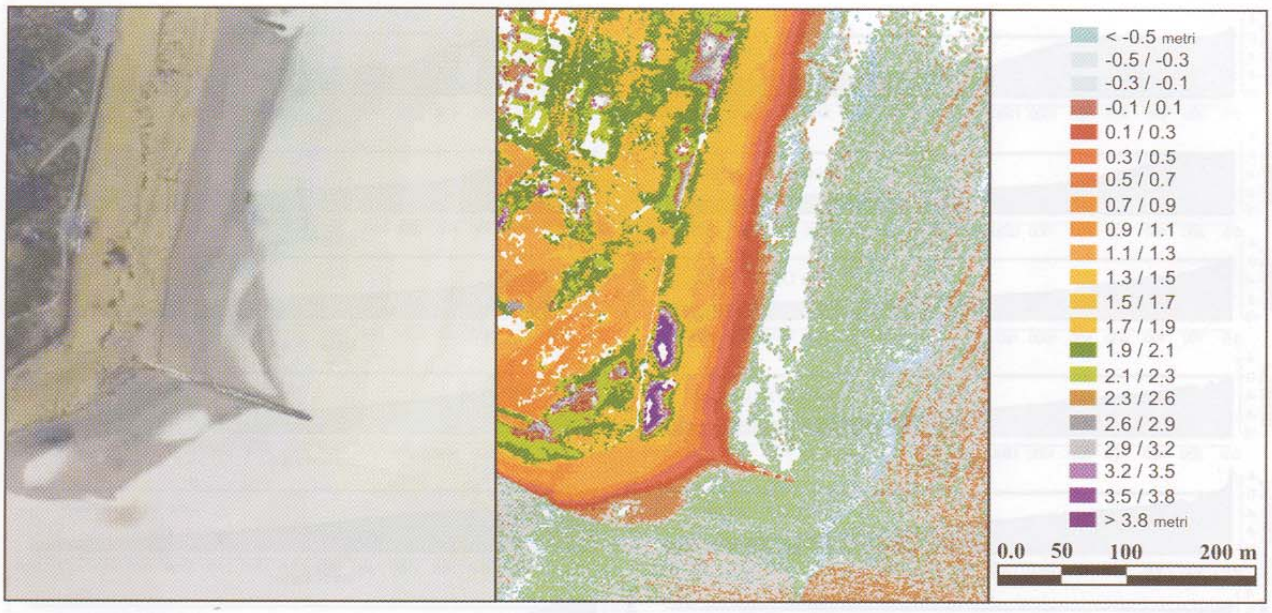

Fig. 3 - Orthoimage and Laser Scan mapping of the transversal groin at the Tagliamento mouth.

portion of foreshore beach not covered by the bathymetric surveys. The LIDAR system employed was a Helica S.r.l. ALTM3033, constituted by an infrared laser (λ =1063 nm) that sends impulses of light at a frequency of 33 kHz. The system was mounted on an AS350B2 helicopter supplied with an inertial system to compensate for signal variability caused by the pitch and roll of the instrument platform.

The investigation allowed us to obtain an average density of points greater than 1.5 points/m^2. During the LIDAR acquisition, a photographic survey using a Rollei digital camera (model 6008) was also performed.

5. Bathymetric setting and seabed morphology of the Tagliamento river delta

The Tagliamento river delta system is characterized by an irregular, triangular geometry, with the two side lobes showing some peculiarities which help to reconstruct the formation mode, the recent evolution and the actual dynamics of the related shores. The two side lobes will be described separately below.

5.1. Eastern coastline zone (from the Tagliamento mouth to the Lignano Inlet)

The eastern sector of the Tagliamento delta highlights a sinuous coastline, characterized by a seaward development of the mouth area. The mouth shows a marked convexity, evidence of the typical progression of a delta formation in the accretion phase. The particular seaward development (physiological of a river delta in the active phase) is also aided by the presence of a transversal groin formed in 1963 (Fig. 3) that has partly prevented the natural radial dispersion of the delta by different meteorological and marine conditions. This has resulted in the accumulation of new sandy sediments at the mouth constituted by the solid matter load of the

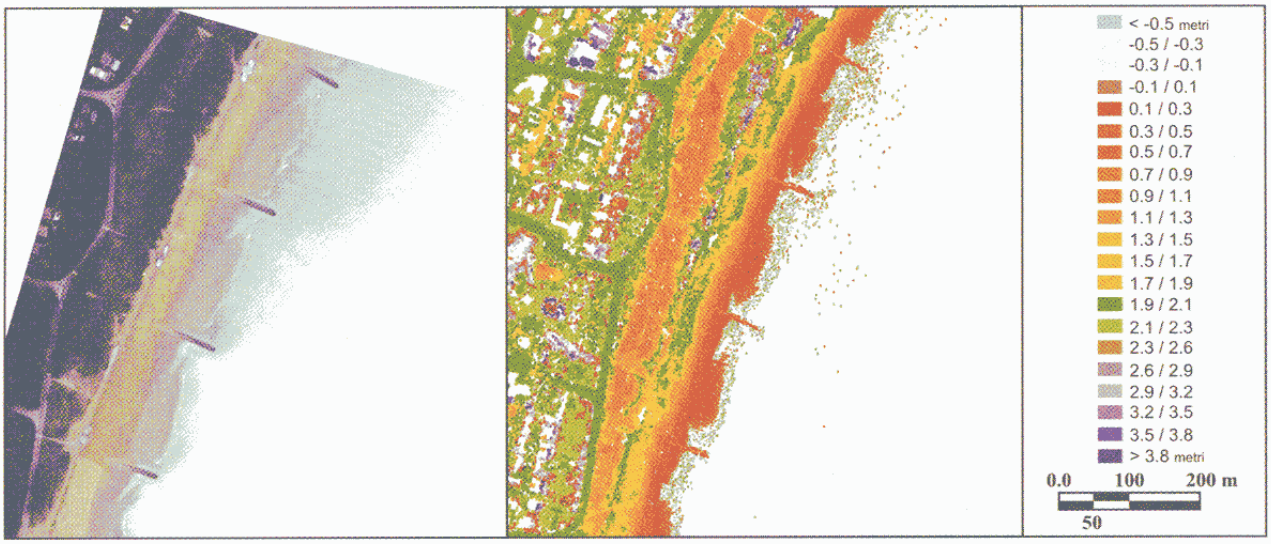

Fig. 4 - Orthoimage and Laser Scan mapping of the transversal groin present along the Lignano Riviera shore, highlighting the limited extension of the backshore.

Tagliamento. These new sediments nourish the oriental sector of the delta structure.

The backshore of this zone is around 100 m wide and is delimited landwards by coastal barchan dunes and small eolian accumulations. These latter structures, which are particularly noticeable after intense storms, present signs of erosion at the bases caused by the removal of sand and their redistribution in the neighbouring areas or on the seabed when the foreshore and portions of the backshore beaches are almost completely submerged.

The foreshore is slightly wider than the upper shoreface (around 120 m). It presents an ample sub-horizontal zone in the form of a foreshore between the 1.0 and 1.5 m-depth levels where the swash bars and other typical accumulation sedimentary features of a river mouth can be observed. These last appear southwestward oriented (Fig. 2, lines L01 and L03).

Away from the mouth zone, the coastline displays a continuous concave pattern (coastline in regression), marked by the presence of numerous seawall (transversal groins) that partially modify its natural course (Fig. 4). The largest sand accumulations on the western side of the groins suggest the predominance of longitudinal sediment transport towards the east unlike in the rest of the northern Adriatic Sea where the opposite is true. Thus, the zone is mainly nourished by the sediments of the Tagliamento river outflow during Sirocco-driven storms. This peculiar behaviour of the transport is due to the particular development of the Lignano channel delta caused by the ebb-tides that divert part of the sediments towards a seawall and fix the rest in proximity to the mouth. However, the limited extension of the beach (around 50 m, the only place of the whole shore with such width) underlines the continuing erosive trend in this sector of the coast notwithstanding the defense works that at best, tend to maintain the actual situation but do not adequately deal with the underlying causes.

This sector of the shore is also characterized by an almost entirely absent or a very limited foreshore (roughly 10-15 m). Between the foreshore and the upper shoreface, only one intertidal bar is present, followed by a depression (a longshore trough) leading to the inferior limit of the

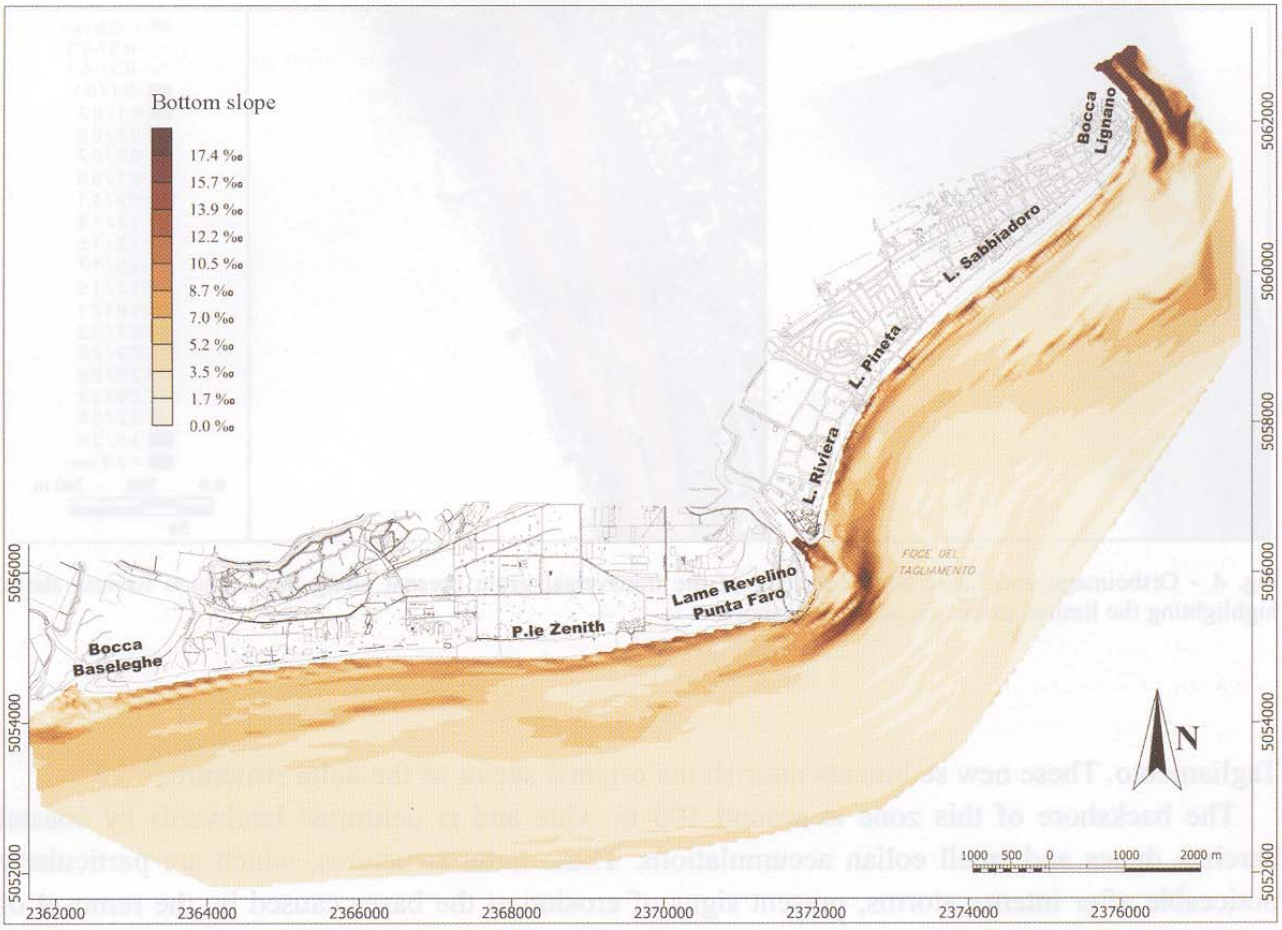

Fig. 5 – Acclivity map of the foreshore and shoreface beach of the Tagliamento river delta.

transversal groin (Fig. 2, lines L07; L13 and Fig. 5). Sometimes, the intertidal bar is not present at all.

The central and eastern portions of the investigated shoreline (from the Lignano Riviera to Lignano Sabbiadoro) show a convex development, with an ample backshore beach (180 m), and foreshore one (340 m). The low-tide terrace is wide, around 40-60 m. It indicates a stable shore sector, with phases of natural progression (Fig. 2, lines L15; L17; L20; L21; L25 and Fig. 6). The superior limit of the beach is represented by a foredune parallel to the shoreline that varies in height from around 4 to 5 m. In the adjacent areas, concrete seawall revetments are present.

The coast, in the vicinity of the access channel of the Lignano harbour, is characterized by a series of anthropic seawall structures (transversal groins and seawall revetments) constructed to safeguard the harbour itself and the urbanized area behind it (Fig. 7).

The backshore is narrow (around 60 m wide) and strongly anthropized. In the fore-shore area, a low-tide terrace, roughly 40 m wide, is present. This sub-horizontal or little tilted zone of the foreshore beach is interrupted by the seawall extremity of the transversal groin, where a strong inclination indicates the beginning of the dynamic upper shoreface (Fig. 5).

The shoreface (between the 0.5 m and the 1.0 m depth levels) displays its maximum extension

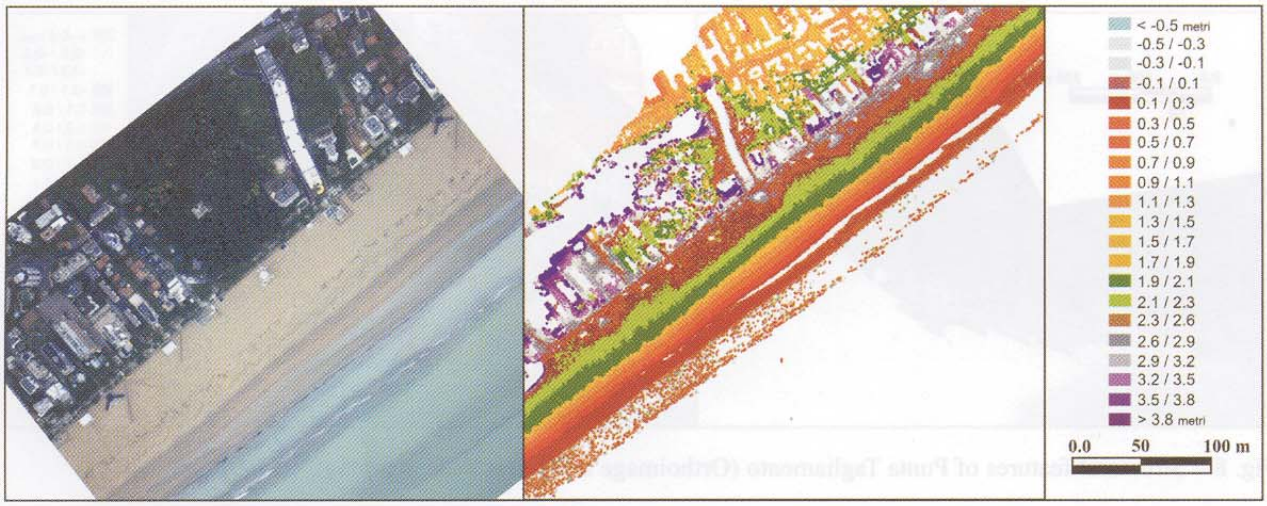

Fig. 6 - Orthoimage and Laser Scan mapping acquired in correspondence to the Lignano Sabbiadoro shore; the backshore and foreshore in this coastal sector highlight the maximum extension.

inside the mouth of the lagoon, near the breakwater of the Lignano harbour. Its outer boundary delimits the inlet channel of the delta (Fig. 2, lines L27 and L30).

5.2. Western coastline zone (from the mouth of the Tagliamento to Punta Baseleghe)

The western bank of the delta mouth has been subject to rapid recession during these last years. This area is protected by numerous maritime structures that have radically transformed the landscape and the coastal hydrodynamics (Fig. 8). These structures are constituted by rubble-mound seawalls of different dimensions oriented in different directions. Sometimes, big sacks of

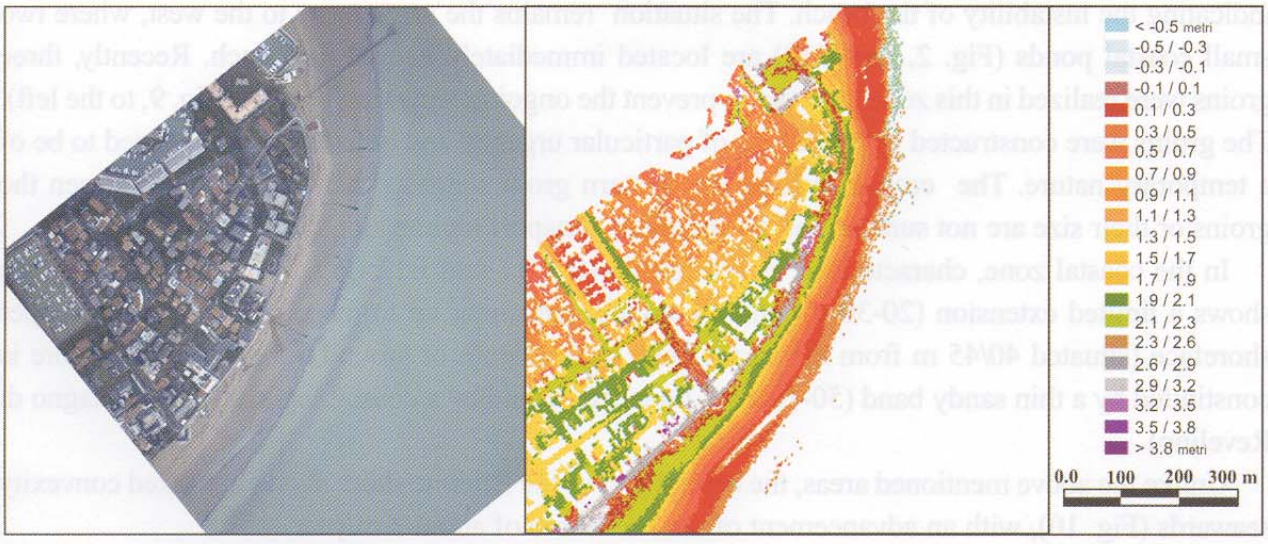

Fig. 7 - Details of the transversal groins present in proximity to the access channel of the Lignano harbour (Orthoimage and Laser Scan mapping).

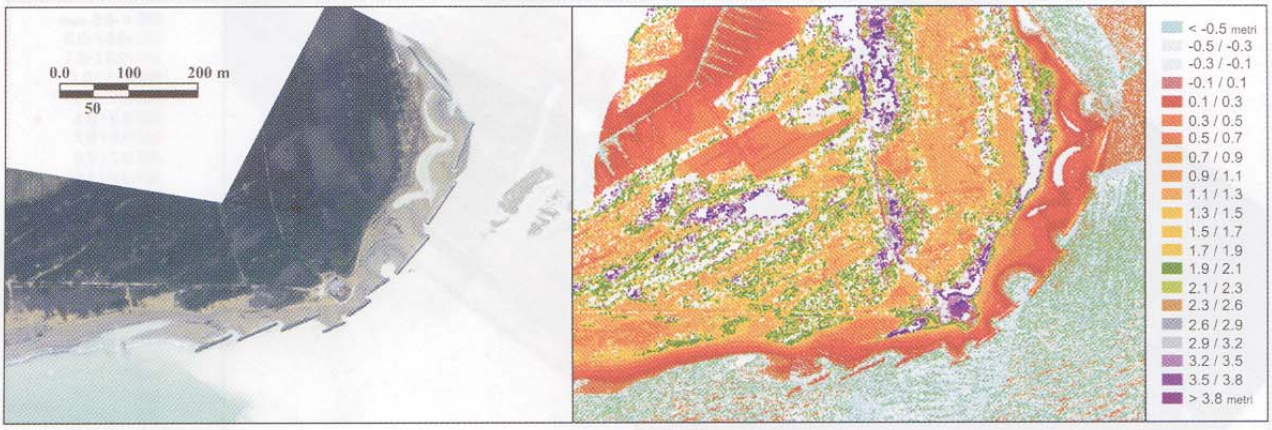

Fig. 8 – Structural features of Punta Tagliamento (Orthoimage and Laser Scan mapping).

sand located behind the swash zone are present. Note that the coastal dune system of the delta apex has suffered from erosive phenomena.

A flat and narrow beach is present in this area, characterized by the typical shoreline geometry of successive cusp-like formations contiguous to the offshore breakwaters (Fig. 2, lines B02, B03 and B04). The construction of the littoral barriers has greatly altered the natural aspect of shore's landscape. On the other hand, the presence of the barriers has provided a satisfactory stability for the shore.

In the areas adjacent to the littoral breakwaters, a recession of the swash zone can be observed. This has led to a reduction in the width of the backshore (<of 50 m, Fig. 9), delimited landwards by a naturally depressed area (Lame di Revelino).

The profile of the beach shows the complete or near absence of the foreshore and some development of the upper shoreface (Fig. 2, lines B08 and B12). In this coastal zone, the transition from the swash zone to the remaining part of the foreshore beach shows a strong inclination (Fig. 5), indicating the instability of the beach. The situation remains the same more to the west, where two small coastal ponds (Fig. 2, line B12) are located immediately behind the beach. Recently, three groins were realized in this zone, in order to prevent the ongoing recession process (Fig. 9, to the left). The groins were constructed in conditions of particular urgency and initially were supposed to be of a temporary nature. The erosion behind the western groin suggests that the spacing between the groins or their size are not suitable for the sediment transport regime along the shore.

In the coastal zone, characterized by the lines B10, B11 and B12 (Fig. 1 and 2), the foreshore shows a limited extension (20-30 m) and a constant deepening up to the upper limit of the upper shoreface (situated 40/45 m from the swash zone with a depth of around 0.9 m). The foreshore is constituted by a thin sandy band (50-100 m) bounded behind by a coastal lagunary pond (Stagno di Revelino).

Unlike the above mentioned areas, the central part of the Bibione shore shows a marked convexity seawards (Fig. 10), with an advancement of the backshore of about 3 m/year.

The low-tide terrace is characterized by a notable width (about 60 m), and slopes gently towards the 70-80 m-wide dynamic band of the shore. The upper shoreface shows a regular inclination

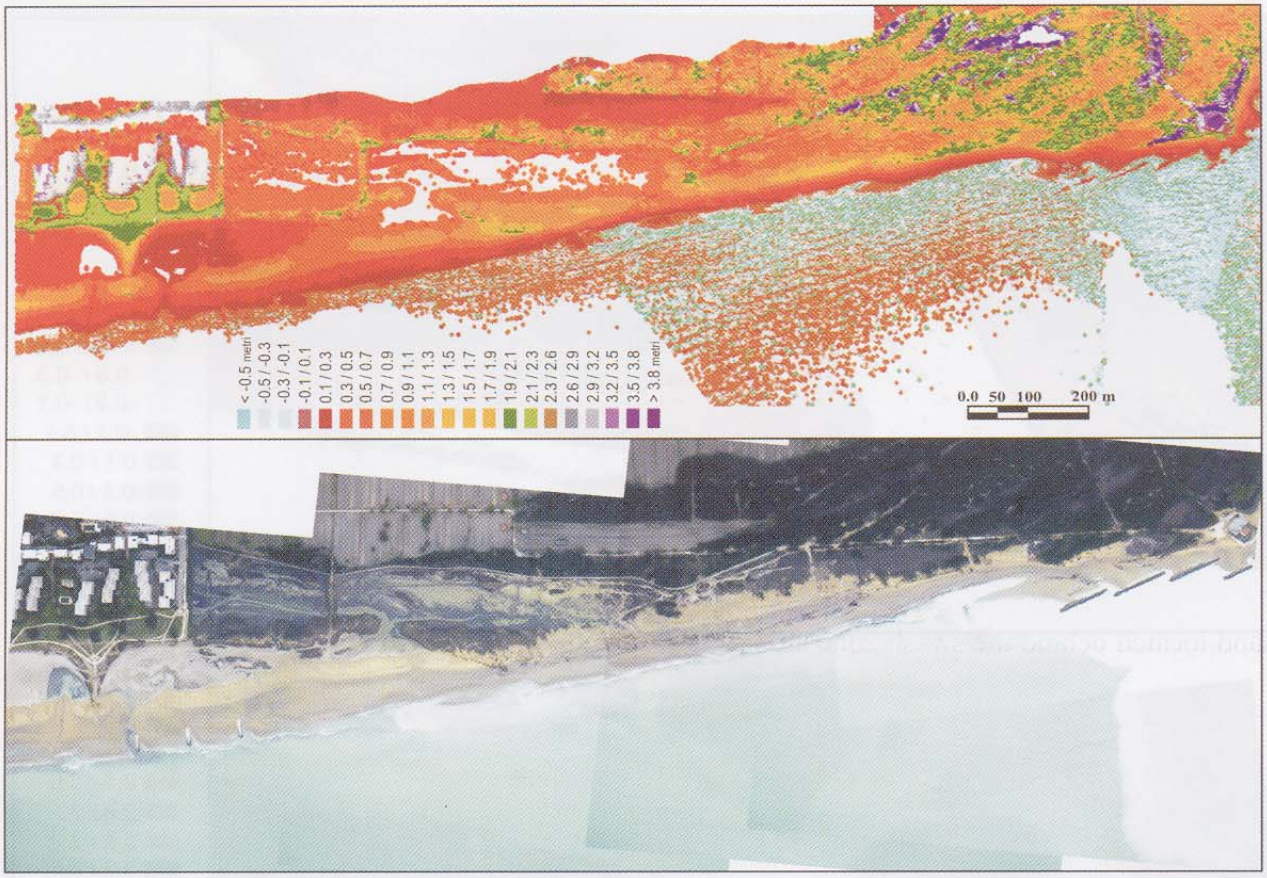

Fig. 9 - Orthoimage mosaics and Laser Scan mapping of the Pineta Punta Faro - Lame di Revelino shore, showing thew recession of the beach in the areas adjacent to the offshore breakwater of Punta Tagliamento.

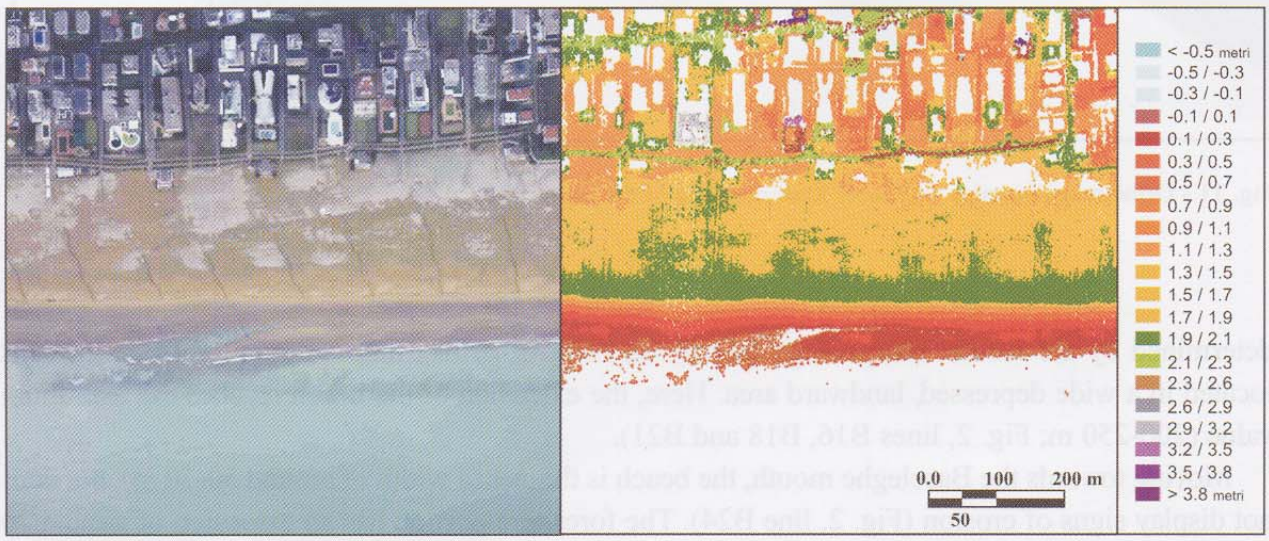

Fig. 10 – The central portion of the Bibione shore, showing the large extension of the backshore and foreshore beach (Orthoimage and Laser Scan mapping).

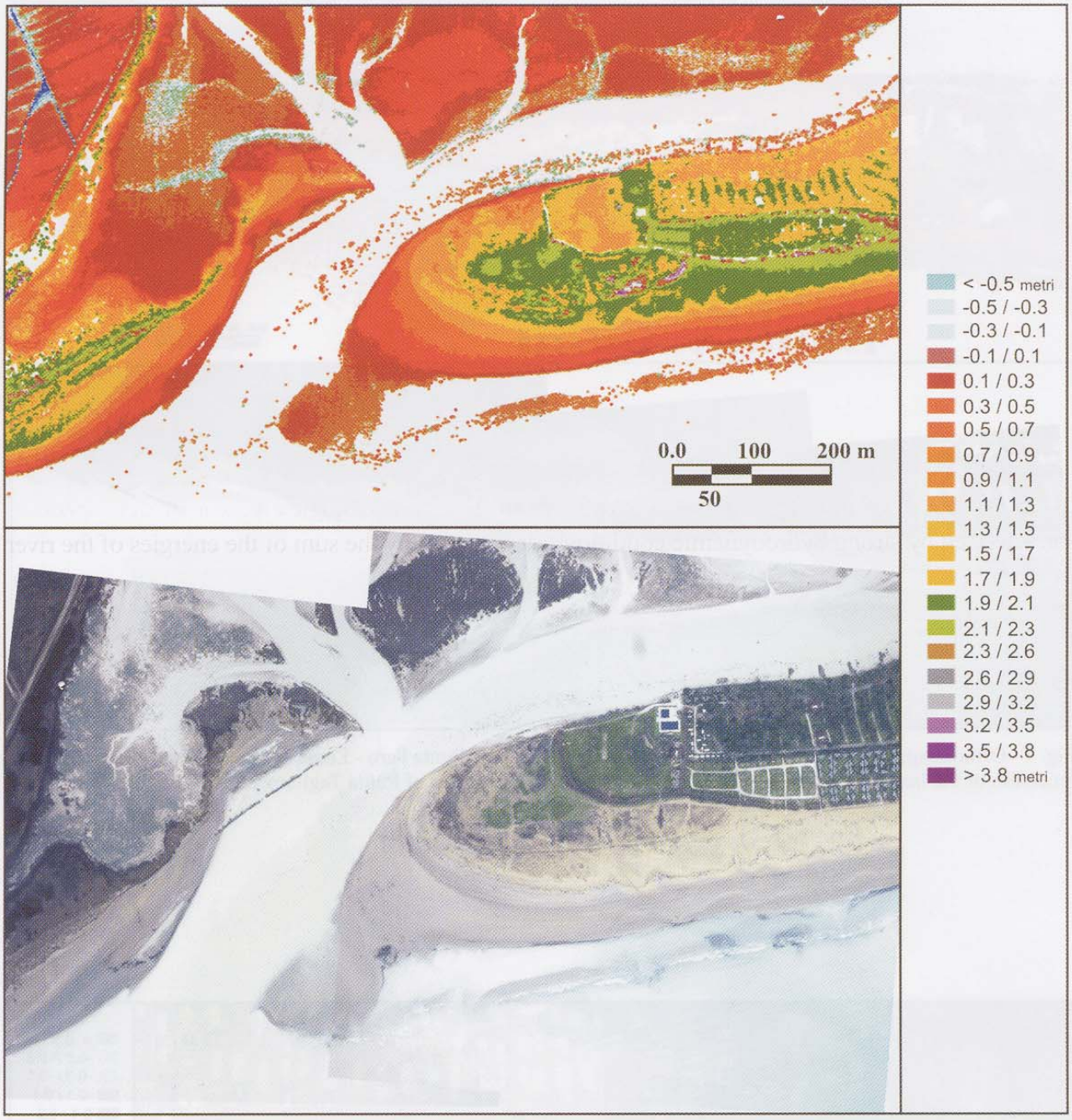

Fig. 11 - Orthoimage mosaics and Laser Scan mapping of the Baseleghe mouth.

determined by the natural morphology (swale and storm berms), and is delimited by revetments located in a wide depressed, landward area. Here, the extension of the beach reaches the maximum value (200-250 m; Fig. 2, lines B16, B18 and B21).

Moving towards the Baseleghe mouth, the beach is thinner (a width of around 50-70 m), but does not display signs of erosion (Fig. 2, line B24). The foreshore portion has an extension of around 70 m, with an evident low-tide zone delimited by a bar (set at a depth of 0.7 m).

In coincidence with the barrier spit that delimits the Baseleghe lagoon (Fig. 11), the backshore

beach widens to around 150 m and is marked by the presence of coastal dunes of modest elevation (1-2 m) parallel to the shoreline that constitute the boundary of the backshore beach. The classical morphologies of growth, typical of a barrier spit, are evident here. The swash zone joins the low-tide terrace (about 25 m wide) with a small inclination. The low-tide terrace, in turn, joins the dynamic zone with another low gradient. In the dynamic zone, typical morphologies related to the wave regime (the base of the spit, numerous swash bars and lobate forms due to the movement of the sandy sediments) can be recognized parallel to the isobaths (Fig. 2, lines B27 and B29). These extend predominantly towards the west, so much so that the Baseleghe mouth can be obstructed or diverted in this direction (Zunica, 1971; Catani *et al.*, 1978, 1982). To prevent this, today, as in the past, the access channel to the Baseleghe harbour is periodically dredged. The dredging operations maintain the navigability of the channel and furnishes a huge supply of sediments which can serve to replenish the eroded areas.

5.3. Morphological characteristics of the mouth of the Tagliamento

At the mouth of the Tagliamento, a series of sea-floor morphologies typical of delta systems characterized by strong hydrodynamic conditions, determined by the sum of the energies of the river (jet stream), the sea state and the tidal current, are present. The delta front (Fig. 5) is defined by an ample semicircular area and a weak inclination (Fig. 2, lines L01, L03, B02 and B03). It develops from the beach of Bibione to that of Lignano and is scoured by the mouth of the channel, partly natural and partly dredged to permit entry into the Lignano river harbour. The passage from the inside to the outside of the mouth is characterized by the presence of a well-developed ebb-tidal delta concretized by an imposing water flow ramp that passes from a depth of 6 m (in correspondence to the Marina Uno dock) to a depth of 1 m over a distance of just around 1,3 km (seawall). Proceeding offshore, the delta front is identified by the compression of the 1-6 m isobaths, indicative of an elevated inclination (maximum 1,3%). This variation of the inclination denotes the extreme limit of the solid matter transport of the Tagliamento river, and therefore, the most recent deposits of the HST system.

The Acclivity Map (Fig. 5) shows that the flat-lying zone described earlier is characterized by the presence of numerous bedforms that highlight the principal hydrodynamic features of this shore portion. In particular, a lengthened depression is present (a depth of 1.2 m) close to the base of, and parallel to, the more western offshore breakwaters set up to protect the Punta Tagliamento lighthouse. This canalization, entirely natural, although some dependence on the littoral barrier cannot be ruled out, represents the preferential path of the marginal river flows that carry the terrigenous inputs from the area of the river mouth. The main channel is delimited on both sides by linear bars of varying height (from 0,5 to 0,8 m) that are more developed on the western side. The bars are notably influenced by the periodic dredging operations performed for assuring access to the Marina Uno harbour.

Besides these active and passive bedforms, lobate forms (height of around 0.2-0.5 m) are also present in the principal directions of the sedimentary plumes (towards the west), along with numerous crescent-shaped and other irregular swash bars (heights of 0.4-0.6 m) in continuous evolution and transformation. The delta is characterized by a notable solid material supply that favours its seaward development, but this active pattern is contrasted by a significant wave-dominated component (sensu, Hayes, 1980).

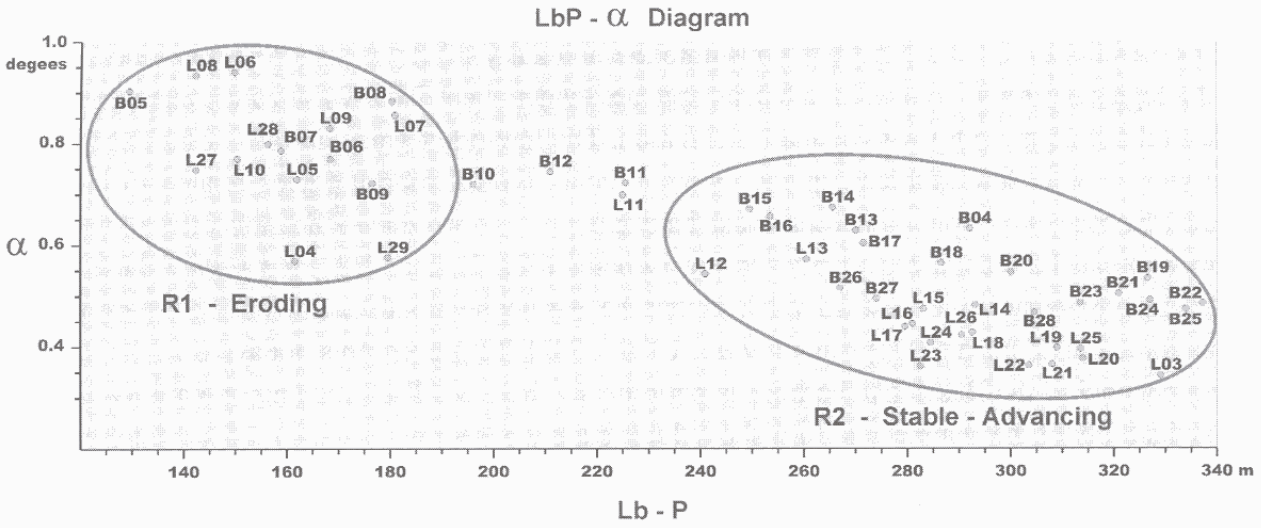

Fig. 12 – Diagram between the distance of the line of the swash zone from the base of the outer submarine bar (Lb-P) and the inclination α of the underlying plane (from Gordini *et al.*, 2006).

6. Quantitative morphological analysis of the beach

To complete this study, a brief quantitative morphological investigation has been conducted to define the sizes, the elevations, the inclinations and the particular morphological elements of the different zones of the backshore, foreshore and lower shoreface. The aim of this analysis is to characterize the different parts of the beach from the perspective of their stability (or instability).

Within the context of the fore-shore beach and the shoreface, the zone extending from the "swash zone" to the upper shoreface has been studied with great attention. The best results are obtained by analysing the relationship between the distance of the line of the swash zone from the base of the outer submarine bar (Lb-P) and the inclination α of the underlying plane (Fig. 12).

From Fig. 12, it can be seen that relationships of dependence exist between the size of the submarine zone (fore-shore beach + upper shoreface), its inclination and the conditions of erosion or overall stability of the shore. The points that represent these morphological parameters quantitatively, calculated for every topographic-bathymetric section, refer to the conditions present during the last survey of May-June 2003. The results indicate that where the shoreface beach areas are smaller, the inclination increases and vice versa. Thus, the inclination of beach areas with similar sedimentological characteristics is directly related to the stability. In this type of diagram, the state of a specific portion of the beach can be immediately recognized by noting where the points relating the measured parameters tend to cluster. Moving from left to right in such a diagram, in fact, one covers the entire progression of states, extending from that of prevalent erosion at one end to high stability/accretion at the other. Thus, in Fig. 12, the R1 grouping of points indicates one extreme, that is, erosion, whereas the R2 grouping represents the other, namely, stability/accretion. The R1 cluster refers to the following areas:

- the beach zone west of the littoral barrier protecting the lighthouse of Punta Tagliamento (lines

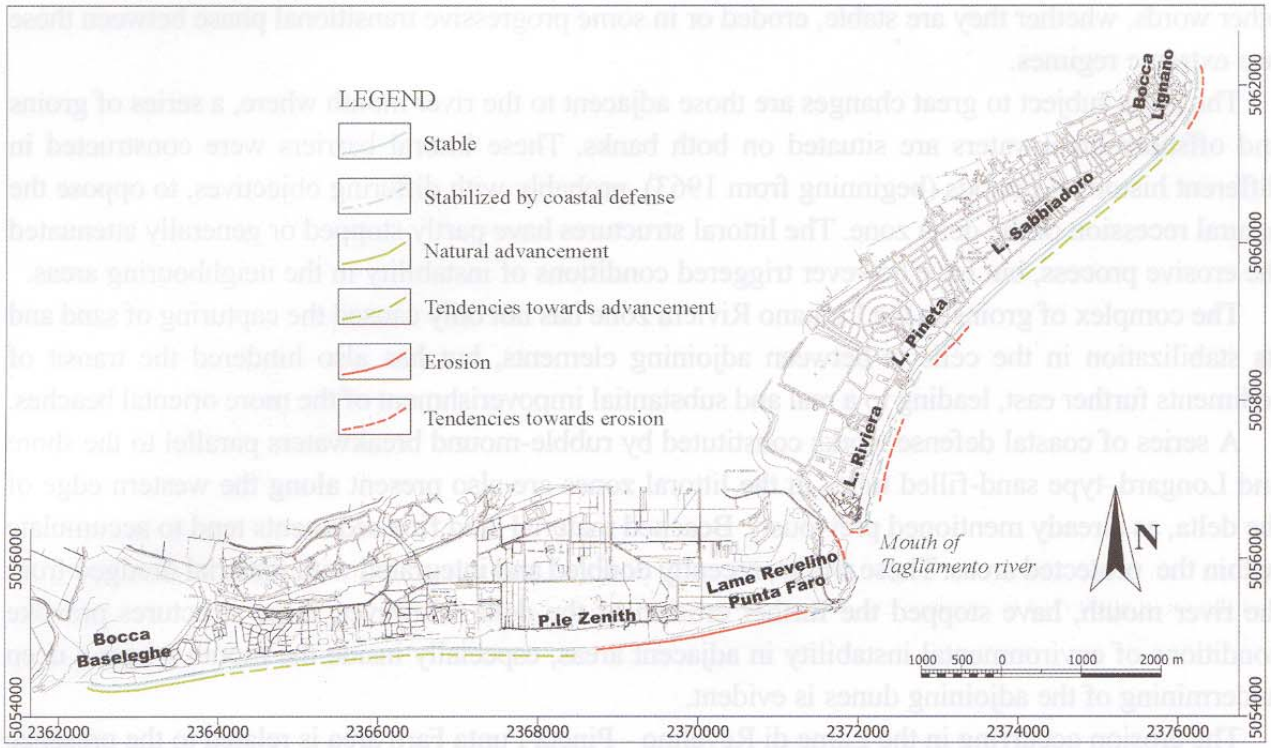

Fig. 13 - A scheme of the evolutionary trends of the beaches of the Tagliamento delta based on data gathered during this study and other historical data.

B5, B6, B7, B8 and B9);

- the beach zone to the east of the mouth of the Tagliamento (Lignano Riviera), protected by groins (lines L04, L05, L06, L07, L08, L09 and L10);
- the narrow beaches of the western side of the mouth of Lignano, characterized by the presence of groins (lines L27, L28 and L29).

Instead, the areas comprising the R2 grouping are as follows:

- the remainder of the investigated shorelines with the exception of the zone situated in the area of the lighthouse and Bibione (lines B10, B11 and B12) and the shoreline between the Lignano Riviera and Sabbiadoro (line L11).

The two data groups clearly stand out at the extremes of the diagram, nevertheless not all the points in the stable or progressive area are equivalent. This fact could be interpreted as their tendency towards stability or the opposite, towards erosion (for example, points relating to the lines L12 and L3 or in the case of the Bibione shore, B13 and B14).

7. Conclusion

The information obtained from the elaboration of bathymetric profiles performed along the beach and shoreface (Gordini *et al.*, 2006) together with observations of the backshore beach and those from a more general LIDAR survey allow a first morphodynamic interpretation of the beaches of the Tagliamento river delta that helps us to define the different states of the relevant shorelines. In

other words, whether they are stable, eroded or in some progressive transitional phase between these two extreme regimes.

The areas subject to great changes are those adjacent to the river mouth where, a series of groins and offshore breakwaters are situated on both banks. These littoral barriers were constructed in different historical periods (beginning from 1963), probably with differing objectives, to oppose the natural recession of the delta zone. The littoral structures have partly stopped or generally attenuated the erosive process, but have however triggered conditions of instability in the neighbouring areas.

The complex of groins in the Lignano Riviera zone has not only caused the capturing of sand and its stabilization in the cells in-between adjoining elements, but has also hindered the transit of sediments further east, leading to a real and substantial impoverishment of the more oriental beaches.

A series of coastal defense works constituted by rubble-mound breakwaters parallel to the shore and Longard–type sand-filled tubes in the littoral zones are also present along the western edge of the delta, as already mentioned previously. Beached material and fine sediments tend to accumulate within the protected areas. These works, recently doubled and integrated with material dredged from the river mouth, have stopped the further erosion of the delta. However, these structures provoke conditions of environmental instability in adjacent areas, especially inside the mouth where a deep undermining of the adjoining dunes is evident.

The erosion occurring in the Lame di Revelino - Pineta Punta Faro area is related to the presence of the coastal protection works located off Punta Tagliamento. Here, a progressive recession of the beach can be observed, accompanied by the near loss of the low-tide terrace and a thinning of the "bar and trough" zone (upper shoreface). For example, within a time frame of roughly a year, the foreshore terrace and the intertidal bars along line B08 in Fig. 2 nearly disappeared, and the sediments lost in this process were redistributed at greater depths. The shoreface is also characterized by the typical features of an erosion environment, showing pelitic deposits of lagunary origin, rich in organic material and the exposed root complexes of coastal vegetation in the swash zone.

The result of this erosion, transport and accumulation over short distances has been the formation of the sandy accumulation present on the seabed in front of Piazzale Zenith more to the west. Therefore, it can be reasonably assumed that the Lame di Revelino - Pineta Punta Faro area is subject to intense removal of sediments that are not sufficiently balanced by the coastal transport during storms when the presence of the coastal defense works lead to the establishment of anomalous reflection phenomena. The fact that this accumulation was found in 2003 as well as in 2004, reinforces the hypothesis that not only are the sediments which are removed from the beach lost permanently but the transport of new material to the area is greatly hindered, as mentioned, by the defense works of Punta Faro. West of the Lame di Revelino - Pineta Punta Faro area, where the two small coastal ponds are present, the recent removal of sands from the three rubble-mound breakwaters constructed specifically to stop the ongoing erosion suggests that the design and placement of these structures are not optimal.

Unlike the Lame di Revelino - Pineta Punta Faro area, the central and western part of the shore of Bibione is essentially characterized by a stable situation where the beach is advancing over time. This depositional pattern is evidenced by the convex morphology, the extension and inclination of the backshore, and the ampleness of the upper shoreface. The beach that continues towards Bocca di Baseleghe, narrows initially (without however actually receding), and then advances towards the sea and westwards where it tends to block the entrance to the lagoon. This is also confirmed by the

intertidal and submarine bedforms in the area.

As for the lobe of the delta, east of the Tagliamento, it is interesting to note its marked protrusion seawards, sustained by the transversal groin at the mouth created in 1963.

The shoreline traces a concave path as it moves away from the zone of the mouth. The presence of transversal rubble-mound groins confers a typical saw-tooth appearance to the coast, owing to the visual effect of the great accumulation of sands on their western sides. This area is primarily fed by the solid material load of the Tagliamento river, and the general east-to-west transport characteristic of the northern Adriatic plays only a small role. This is because of the significant development of the delta of the channel of Lignano which forces coastal sands to accumulate in front of the lagoon inlet or otherwise transit very far offshore. Despite the presence of the transversal breakwaters, the beaches are narrow, attesting to the inadequacy of these structures that, at best, trap sediments. Overall, however, this area can be considered stabilized, with local tendencies towards erosion, by the coastal defense works that are present (Fig. 13).

The beach of the Lignano Pineta area, immediately east of the breakwater zone, is not replenished by the two main transport regimes and therefore embodies a stable situation with temporary recessive characteristics. The poor replenishment is due to the shielding effect of the groins that prevents the arrival of new sediments from the river on the one hand and the deviation of the coastal transport far offshore by the strong outflow of the channel of Lignano on the other.

The central part of the shore of Lignano seems to be stable over time with phases of natural advancement. The typical profile of the beach in this sector shows a wide portion of backshore and foreshore beach that gently joins a large upper shoreface. This "bar and trough" zone is followed by a long flat-lying tract that continues seawards and unites with the ebb-tidal delta of Lignano.

The access channel of the Lignano harbour, characterized by a series of sheet-pile groins and seawall revetments, is affected by as light instability.

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