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Seabed Morphology and Pollution Along the Bagnoli Coast (Naples, Italy): a Hypothesis for Environmental Restoration

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With 6 figures

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Abstract. The interaction of coastal and submarine morphology with the hydrodynamic regimes exerts a control on coastal dynamic processes, conditioning the dispersion of sediments and potential pollutants existing in the area. Thus, the study of such parameters is useful in order to define environmental threats. Within the submerged sector of the Bagnoli coast and particularly in the southern part of the investigated area, there are sediment groups composed of very fine sands located in low-energy zones due to wave refraction and diffraction; they can also be found on the sea bottom and on the man-made structures typical of this zone. These areas show high pollutant levels of N, P, Cu, Fe, Mn, Ni, Pb, Zn, Cd, polyaromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs). The northern area, a place of high-energy hydrodynamic processes, also shows high concentration levels of pollutants due to the presence of secondary cell circulation.

Morphological research and analysis of textural characteristics of bottom sediments along the Bagnoli coast allowed the actual processes and their evolution in space and time to be defined. It has also been possible to correlate such processes to the seabed morphology system, the wave formations which affect the coast, the complex system of sediment transport, as well as to the man-made interventions in the area. The results of recent chemical analyses of beach sediments and bottom sediments off the Bagnoli coast were also incorporated. They prove the presence of heavy metals, PAHs and PCBs in high and sometimes very high concentrations. Finally, based on the results of research and analyses, a hypothesis for an intervention for environmental restoration has been formulated in order to renaturalise the coast through dredging and treatment of the sand, both on the seabed and on the emerged beach.

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Geomorphological framework

The Bagnoli Plain extends within the volcanic district of the Phlegrean Fields, which also includes the islands of Ischia and Procida and the submerged volcanic conduits in the northwestern part of the Gulf of Naples. The Phlegrean Fields, located on the south-western margin of the Campania Plain, consist of a complex polycrateric area, still active but quiescent. The volcanic activity here, which is presumed to have started about 50,000 years b.p., is attributed to bradyseismic phenomena, the slow vertical soil deformation, clearly observable in the historical town centre of Pozzuoli and the neighbouring areas (Luongo *et al.*, 1998).

The Bagnoli Plain is a coastal plain arranged on a morphostructural depression of volcano-tectonic genesis, located on the margin of the Phlegrean Fields' caldera. It ranges between the Posillipo hill and Agnano plain and it connects the urban centres of Naples and Pozzuoli (Fig. 1). It has a smooth morphology, surrounded by phlegrean pyroclastic reliefs which constitute the skeleton of both towns. The plain, lying a few meters above the present-day sea level, is delimited to the E by the cliff of Posillipo hill and to the W by the slopes of Mt. Sant'Angelo and Mt. Spina; it extends in a NE-SW direction for about 4 km from the Soccavo-Fuorigrotta depression as far as the Bay of Pozzuoli, to which it opens with a sandy beach about 3 km wide.

The entire plain is highly urbanised all the way to the shoreline. In fact, the western suburbs of Naples stand on it (Bagnoli, Fuorigrotta, Rione Traiano and Cavalleggieri); near the coast, in the central part of the plain, there is the former industrial area which, in places, even stretches out into the sea. The areas on the margins of the plain, however, are scarcely inhabited due to unfavourable conditions of the pyroclastic land, a steep slope, and terraces for agricultural purposes. The present-day subtriangular shape of the Bagnoli Plain and the coastal concave physiography with a NW-SE orientation reflect various endogenous and exogenous processes that took place during the Late Pleistocene-Holocene (De Pippo *et al.*, 1998).

The plain faces the Gulf of Pozzuoli which constitutes the submerged southern margin of phlegrean caldera formed 37,000 years b.p. The gulf represents the most depressed area in the Phlegrean Fields; its margins are composed of both emerged and submerged volcanic structures and has been affected by marine sedimentation for at least 10,000 years (Pennetta *et al.*, 1984; De Pippo *et al.*, 1988).

The Gulf of Pozzuoli constitutes a rough morphological element: at its bottom a coastal platform (De Pippo *et al.*, 1984) extends almost from Miseno Cape to Nisida Island and has a central, subcircular depression that is about 100 m deep. This depression originated from a volcano-tectonic collapse probably between 18,000 and 6,000 years b.p. Furthermore, it is almost completely barred towards the open sea by a subcircular wall of submerged volcanic structures, composed of the Miseno and Penta Palummo banks (earlier than 18,000 years b.p.) and the Nisida Bank, located at 50–70 m depth. The Nisida Bank, more recent than the others, with its morphological rise, has determined the bifurcation of the valley axis of the Dohrn Canyon. Towards the open sea, beyond these banks, a gradually declining continental platform develops with a gradient of about 0.5 °; its edge lies at depths between 165 and 125 m. From the edge, engraved by the heads of the Dohrn and Magnaghi canyons, begins a steep slope. The characteristics of the platform can be assimilated to a marine abrasion platform

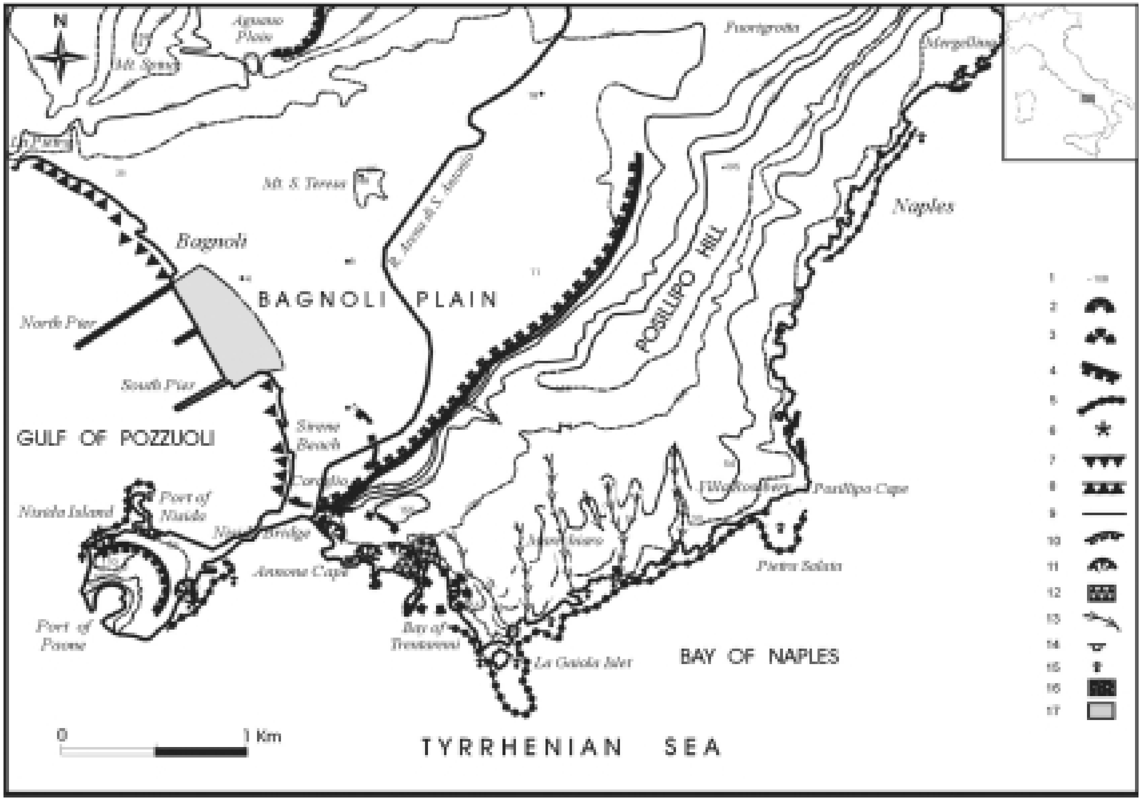

Fig. 1. Geomorphological scheme of the investigated area. 1) altitude; 2) rim of crater; 3) presumed rim of crater; 4) edge of volcano-tectonic depression; 5) submerged ancient coastline; 6) emerged stack; 7) prograding coastline; 8) receding coastline; 9) stable coastline; 10) edge of erosion cliff; 11) rockslide hollow; 12) rockslide pile; 13) V-shaped valley; 14) abandoned quarry; 15) Roman period archaeological ruin; 16) dumping; 17) land reclamation.

modelled most probably during the fall and the low-stand of the sea level, as low as –120 m, about 18,000 years b.p. during the last Würm glacial.

Other significant morphological elements within the gulf are some strips of terraces cut in pyroclastic products, at various depths, on banks and near the current shoreline (Cocco *et al.*,1988). A few terraced surfaces are also found, some only in part and others continuing down to 15 m depth. Those at 10/15 m are attributed to Roman period, whereas those at 5 m to the medieval period. Other surfaces are found at a depth of about 20/30 m and 30/40 m. Their current depth is linked to volcano-tectonic and bradyseismic phenomena still active in the area, which usually take place both before and after paroxysmal eruptive events; the last of these, the Mt. Nuovo eruption of 1538, concludes the phlegrean explosive volcanic activity.

Seabed morphology

The highly detailed bathymetrical map (Fig. 2) allows the area under study to be subdivided into three sectors with different morphological seabed characteristics: a northern sector between Pozzuoli and Bagnoli, a central sector between Bagnoli and Nisida Island, including the zone facing the reclaimed land of the former industrial area, and a southern sector between Nisida Island and Annone Cape.

Moreover, these sectors show morphological characteristics inherited from volcano-tectonic phenomena which affected the Phlegrean Fields area in various times. The first coastal sector has quite sinuous bathymetries down to 10 m. In this zone, down to 5/8 m depth, boulders of lava resulting from a landslide from the cliff behind (Mt. Olibano) are found on the seabed together with strips of marine abrasion platforms, both outcropping and submerged, modelled in pyroclastic deposits. The latter sometimes seem to be cut crosswise by gullies connected to a sub-aerial hydrographic network and probably created by surface runoff during periods of emersion. The trend of isobathic lines within the –10 m belt leads to the hypothesis of the presence of secondary cell circulation; this is most probably due to an embayment effect in the area and to the presence of various man-made structures, both parallel and oblique to the coast. Beyond this depth and down to 40 m, about 1300 m off the coast, the bathymetric curves are more regular and parallel to the coastline. Between 40 and 100 m, the isobathic lines show a trend attributed to a paleomorphology inherited from volcano-tectonic phenomena that affected the area.

At the central coastal sector, the isobathic lines down to 10 m show a less sinuous trend than the previous one, especially within the 5 m belt, where strips of beachrocks are observed, both on the emerged beach and on the sea bottom. Within this belt there are breakwaters parallel to the shoreline, both adjacent to and distant from it; the latter have determined the genesis of sand tombolos in the area behind them. Between the North Pier and the South Pier of the former iron and steel industry, however, where the artificial land reclamation has been carried out, the isobathic lines are extremely regular and parallel to the shoreline. The morphology of the seabed down to 15 m has been influenced by these structures, which determined the wave diffraction and reflection. Beyond this depth and down to 70 m, the seabed morphology is very rough; this is probably due to buried volcanic structures which represent seamounts down to 40 m, separated by NE-SW oriented gullies. Note that in this area, the10 m bathymetrical line

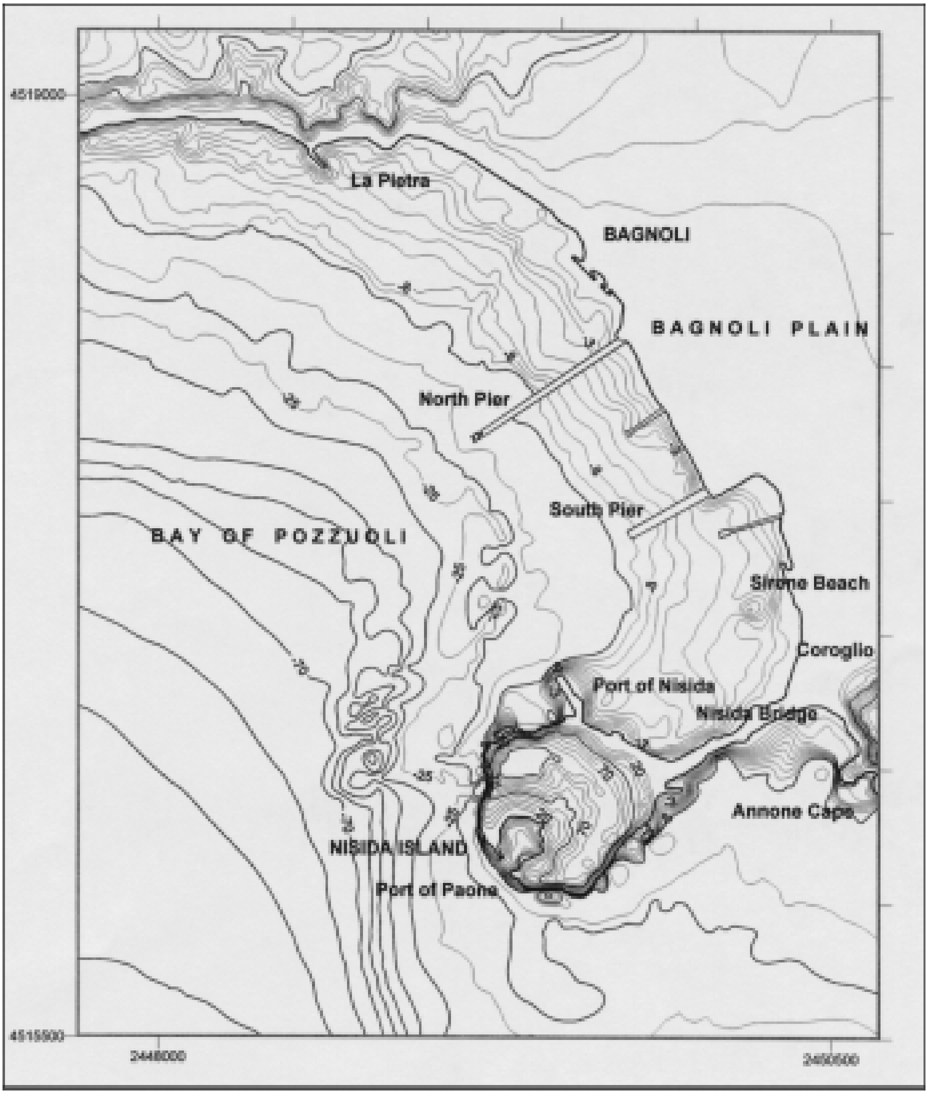

Fig. 2. Bay of Bagnoli bathymetrical map.

is located far from the shoreline, indicating a probable zone of sediment accumulation. This process is still visible within the area facing the Sirene Beach, where there is a clear progradation of isobathic lines down to 6 m depth. This progradation phenomenon, together with a depression observed in the same zone, suggests the presence of a secondary cell circulation caused by the embayment effect and also by secondary compensation effects due to the breakwater located there.

Moreover, the seabed morphology of this sector is characterised by the presence of the Nisida Island volcanic structure at its centre. In fact, along the perimeter of the island, the sea bottom rapidly drops to 20 m. Near the stacks of Ponente (W) and Levante (E) the depth varies between 2 and 10 m where the sea bottom is composed of piles of large pyroclastic boulders collapsed from the cliff. Furthermore, shallow waters with a depth of 2 to 5 m and isobathic lines with a centripetal trend are recorded inside the Port of Paone, which represents the relict of the caldera depression of the volcanic structure. Off the Port of Paone, up to about 500 m southward from the cliff, the depth does not exceed 20 m due to the presence of the Nisida Bank, a relict of another submerged volcanic structure.

Sediment analysis

The mean distribution of sediment frequency (M_z) has allowed a zonation (Fig. 3) which practically subdivides the area under study into four sectors, proceeding from NW towards SE. The first identified sector is the one between Pozzuoli and Bagnoli, where gravelly and sandy sediments are present (from very coarse to fine). Their distribution indicates that only at the northern end of the area between Pozzuoli and La Pietra does the succession conform to the morphodynamics of the coastal environment; this is reflected by a progressive decrease of grain mean diameter towards the open sea because it is controlled by ordinary coastal processes (waves and currents). In the same area, however, the presence of coarser materials at greater depths, within 10 m depth, indicates a high-energy zone where the bottom currents oblique to the coastline are active.

In the area between La Pietra and Bagnoli, a distribution, attributed to the presence of intense cell circulation due to the embayment effect, is observed. Note that the presence of such sediments indicates a high-energy level, this sector being more open to waves coming from the second and third quadrants. Moreover, the presence of secondary cell circulations is evidenced by an inversion of distribution, with materials becoming gradually coarser towards the open sea.

In the sector near the Sirene Beach, the distribution of sandy sediments, from medium to very fine, indicates an area with low environmental energy highlighted by a major presence of fine sediments. A secondary cell circulation determined by the embayment effect, due to the deep curvature of the coastline and evidenced by a distribution controlled by the currents, is located at the southernmost sector; it is characterised by sediments ranging from coarser to finer in relation to the depth. The sediment distribution within the area facing the artificial land reclamation, between the North Pier and the South Pier, clearly indicates the presence of a low-energy area; this is evidenced by the presence of fine and very fine sand. The disposition of fine sandy sediments might indicate the existence of a wide secondary cell circulation, attributed this time to wave diffraction and reflection coming from SW, near the North Pier. Behind this pier, a narrow strip of medium sand is also present, extending in SW-NE direction.

The disposition of very fine sand to the N of the piers could indicate the closing of the coastal cell located in the area facing the urban centre of Bagnoli; to the S of the reclaimed land, however, the sediment distribution, extending in a narrow strip in E-W direction, might be linked to a minor cell. In this area, high concentrations of bituminous materials deriving from the former iron and steel activity are mixed in the sandy sediments. Finally, the presence of coarse sand sediments behind the dock of Nisida

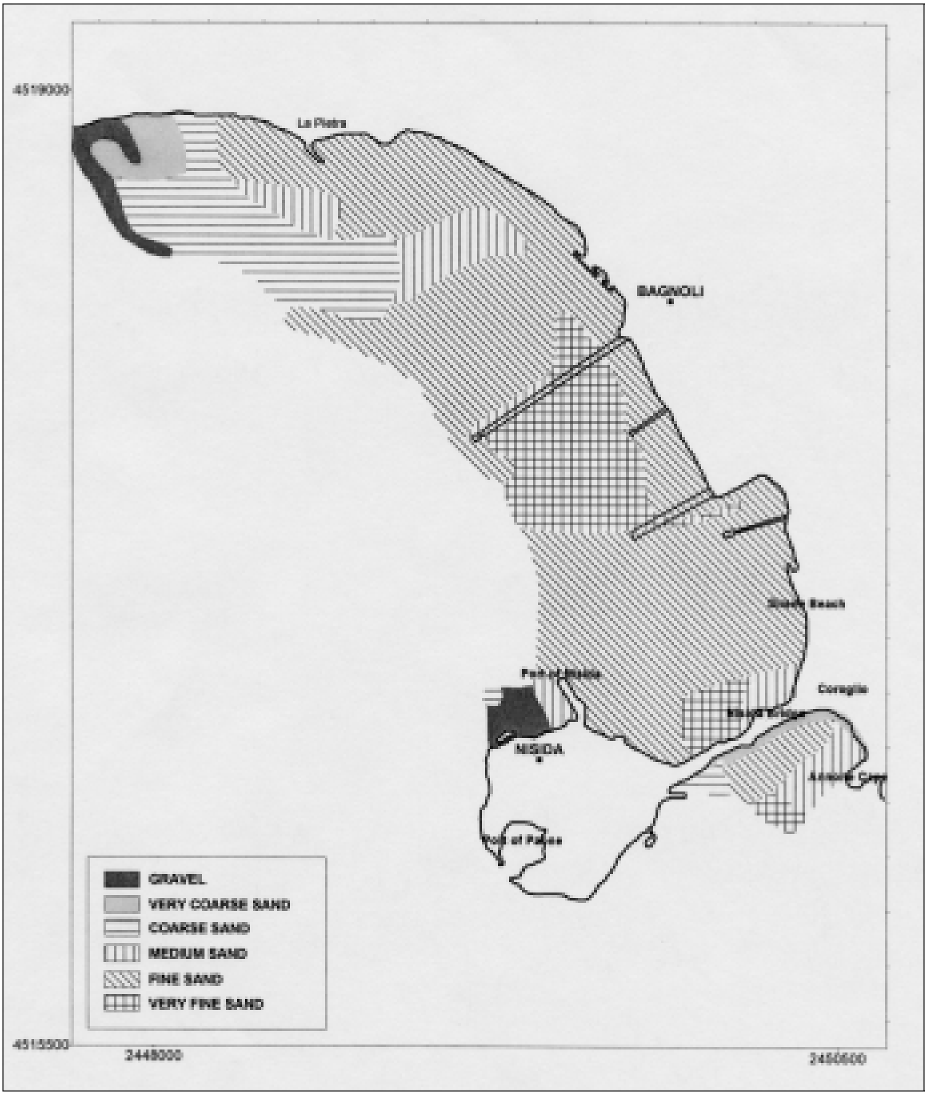

Fig. 3. Distribution of granulometric facies along the sea bottom of the Bay of Bagnoli.

lighthouse indicates a high-energy area where diffraction and reflection take place along the sides of the volcanic structure and near the jetty of the small harbour.

Sediment transport

The sediment transport along the Bay of Bagnoli coast, inside the wider Gulf of Pozzuoli, is directly influenced by marine currents (longshore and rip currents) generated by different wind directions and intensities as well as by interference between waves and the sea bottom morphology.

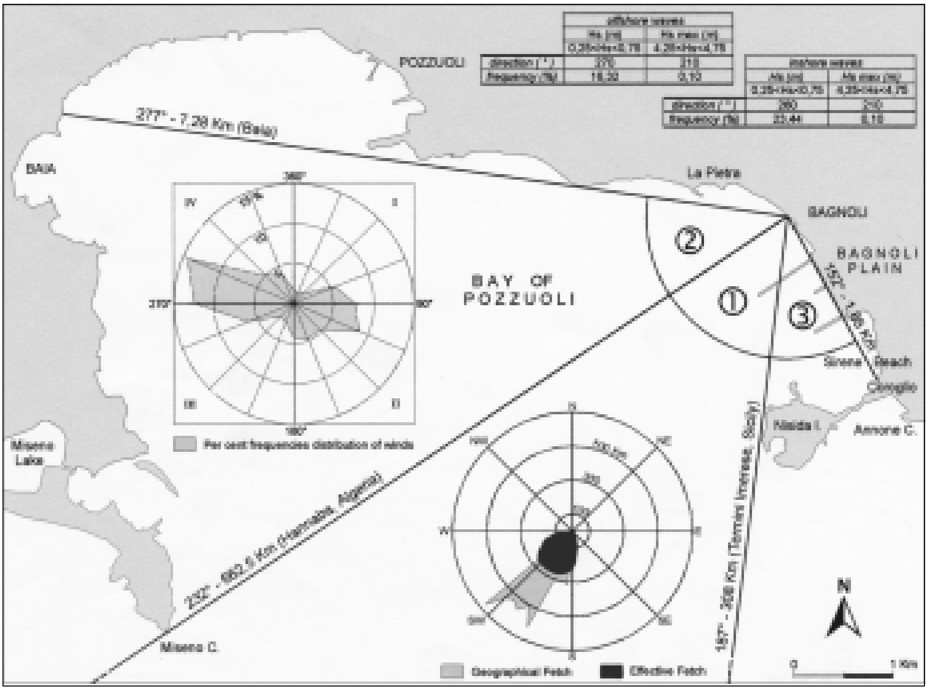

Fig. 4. Wave-exposed coastal sectors, wind frequencies, fetch areas and wave parameters along the coast between La Pietra and Nisida Island (Bay of Bagnoli). Bold segments indicate the three sectors of wave-exposed coast: ① main (amplitude 45 °, average direction SW, average distance 485.2 km); ② second (amplitude 45 °, average direction W, average distance 7.4 km); ③ third (amplitude 35 °, average direction SE, average distance 2 km). Polar diagram showing distribution of wind frequencies in percentage, calculated for each sextant on the basis of 1951–1998 period data, registered at the anemometric station of Ponza Island (Lazio province, central Italy), omitting calms (12.78 %): NNW and W winds (IV quadrant) are dominant, while ESE (II quadrant) are prevalent. Polar diagram of geographical and effective fetch areas indicates a main southwestern direction of wave trains, moving from offshore towards inshore. Two tables indicate both direction and frequency of offshore and inshore waves, referring to minimum ($0.25 < Hs < 0.75$ m) and maximum ($4.25 < Hs$ max < 4.75 m) heights: the former is 270 ° (SW) with 16.32 % frequency for offshore waves, the latter is 260 ° (WSW) with 23.44 % frequency for inshore waves, while both maximum waves show a direction of 210 ° (SSW) with a 0.10 % frequency.

In order to understand the coastal dynamic processes, the shallow water of coastal wave-exposed sectors of Bagnoli, the wind frequencies, the fetch areas, as well as the offshore and inshore wave parameters along the coast between La Pietra and Nisida Island have been analysed (Fig. 4). Three angular sectors of wave-exposed coast are identified: the main one has an amplitude of 45 °, a southwesterward direction and an average distance of 485.2 km; the second shows equally an amplitude of 45 ° but has a westward direction and an average distance of 7.4 km; finally, the third sector is 35 ° wide with a southeastern direction and 2 km of average distance.

The polar diagram shows the distribution of wind frequencies in percentage and was calculated for each sextant on the basis of 1951–1998 period data, registered at the anemometric station of Ponza Island (Lazio province, central Italy), omitting calms (12.78%). It indicates that NNW and W winds (IV quadrant) are dominant, while ESE (II quadrant) are prevalent. The polar diagram of geographical and effective fetch areas, the latter calculated by dividing into 5 ° slices the whole wave-exposed sector and widening ± 45 ° over its geographical limits, according to Milano (1977), indicates a main southwestern direction of wave trains, moving from offshore towards inshore.

The two tables indicate both the direction and frequency of offshore and inshore waves, *Hs* (0.25 ÷ 0.75 m) referring to minimum heights and *Hs max* (4.25 ÷ 4.75 m) to maximum heights. Offshore wave direction is 270 ° (SW) with 16.32 % frequency, while that of inshore waves is 260 ° (WSW) with 23.44 % frequency at breaking point; both maximum waves show a direction of 210 ° (SSW) with a 0.10 % frequency.

The modal analysis carried out for each sediment sample, both from the waterline and the sea bottom, and of their frequency of occurrence, have enabled identification of the granulometric subpopulations which contribute to sedimentary dynamics within the area under study. Based both on the identified subpopulations and on the mean modal formula, it is deduced that granulometric populations contributing effectively to the sedimentary dynamics in the area are gravels, very coarse sands, coarse sands, medium sands and fine sands, while very fine sands appear only subordinately (Fig. 5).

In order to identify the shifting patterns of sandy materials along the entire coast, vectors of transport were reconstructed for various identified subpopulations, according to Cortemiglia (1978) and De Pippo (1988). The disposition of vectors of transport for gravels and very coarse sands confirms the presence of a high-energy secondary cell circulation in the northern sector and the shifting of materials towards greater depths, even if confined within the 10 m bathymetry. The sediment shifting apparently occurs just near the area where the bathymetries tend to show a convexity towards the open sea, which confirms the presence of ongoing accumulation phenomena.

In the southern sector between Nisida Island and Annone Cape, the vectors of transport indicate a sediment shifting affected by longshore currents. It should be stressed that near the jetty of Nisida, the materials tend to shift towards the open sea due to wave diffraction and reflection coming from SW, both on the jetty itself and on the sides of the Nisida volcanic structure. From the analysis of the vectors of transport of coarse sands found near the facing Musa Quarry, a shifting of sandy sediments is deduced, essentially due to the action of longshore currents following a E-W direction, slightly oblique to the coast. Between Bagnoli Dazio and Bagnoli, the sediment transport indicates a movement generated by rip currents and also confirms the existence of a secondary cell circulation and a high-energy environment. Coarse sands clearly do not interfere in the dynamics of the area between Bagnoli and Nisida and their contribution to the dynamics of the Annone Cape zone seems to be negligible, even if a slight movement attributed to longshore currents is observed.

The existence of secondary cell circulations in the northern part of the beach and subordinately in the central part is confirmed by the disposition of the transport axes of the medium sands. The transport of this material is generally limited to the northern area, with a clockwise movement caused by the combined effect of longshore currents and rip currents. Such sediment transport is most probably attributed to the effect of incidence of wave motion coming from southern quadrants. Moreover, there is a visible movement of medium sands in the sector characterised by the artificial land reclamation, where the shifting of sediments towards the shallow areas between the piers might take place in an anti-clockwise cell circulation.

The sediment movement might be controlled by wave diffraction and reflection in the areas facing the jetty of the Port of Nisida and by longshore currents near Annone Cape, although the role of rip currents is also identifiable; they tend to remove the sedi-

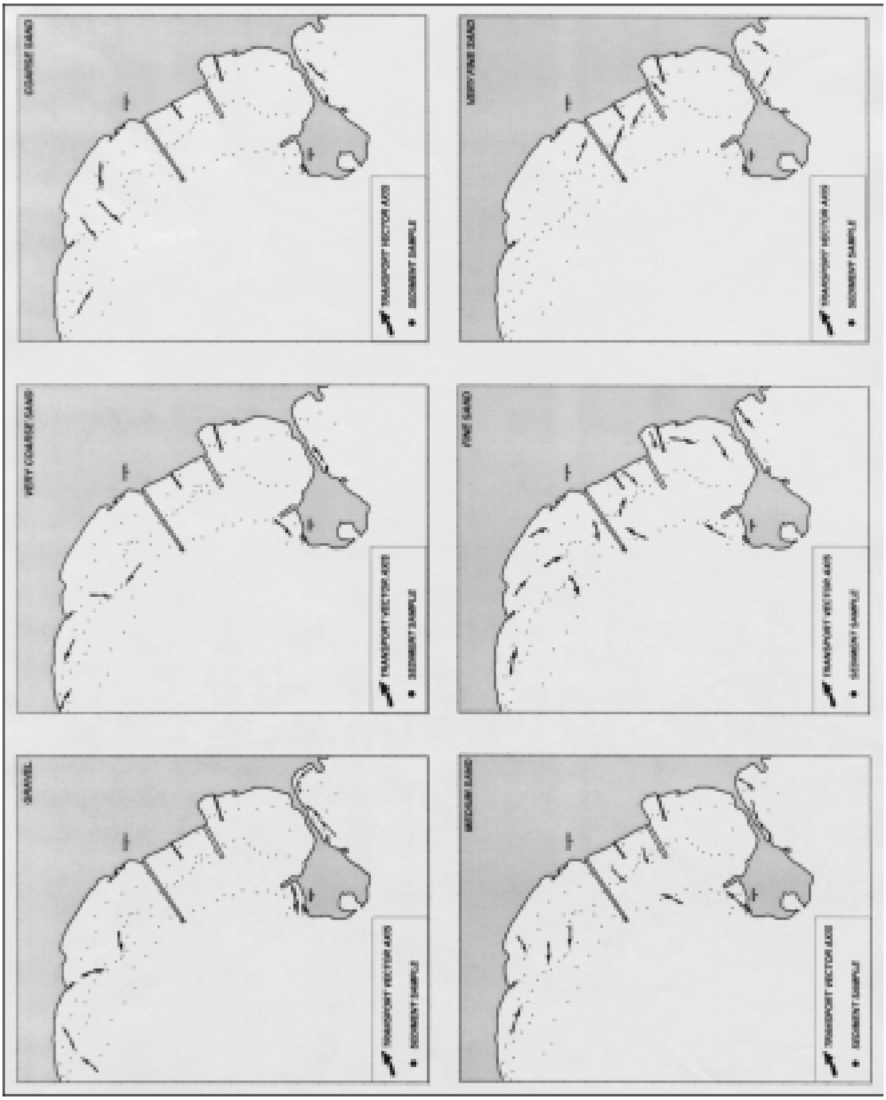

Fig. 5. Direction of sediment transport vector axes along the sea bottom of the Bay of Bagnoli.

ments from the coast facing Mt. Coroglio, moving them offshore. The disposition of the vectors of transport of fine sands confirms the presence of a clockwise cell circulation in the northern sector, whereas the cells in the central-southern areas this time seem to show a clockwise direction and a confinement to shallow areas.

In the area facing the Sirene Beach, the disposition of the vectors of transport confirm the shifting of material, with sediment accumulation and progradation of the bathymetry. In this case, the circulation in the northern sector is dominated by the presence of a high-energy environment with a combination of longshore and rip currents contributing to the formation of an identified secondary cell circulation.

In the area facing the Sirene Beach, the circulation is essentially attributed to the embayment effect produced by a deep curvature which characterises the shoreline configuration. In the zone facing the artificial land reclamation, the sediment shifting is due to intense wave refraction and reflection phenomena produced by the presence of numerous piers. Between the South Pier and the smaller one located to the N of the Sirene Beach, the sediment transport might indicate an oblique shifting potentially explaining the recession of the shoreline.

The disposition of the transport axes of very fine sands has also been analysed, although they do not contribute as efficiently as the other subpopulations to the littoral dynamics of the Bagnoli coast. In this case, the sediments visibly move obliquely to the coast, along the Annone Cape and the Nisida Bridge area, in perfect harmony with the dynamics of a high-energy coastal sector, showing an offshore evacuation of fine sediments. In the central areas, on the other hand, such sediments remain affected by a secondary circulation in a low-energy environment influenced by the presence of man-made structures.

Distribution of pollutants

The analysis of pollutant distribution (Fig. 6) on the seabed and on the emerged beach confirms the connection between the morphological aspects, the distribution of fine granulometric facies and the role of cell circulation generated by longshore currents. The area containing high concentrations of heavy metals extends almost parallel to the coast in the entire zone between the North Pier and the South Pier and beyond, almost up to the dock of Nisida lighthouse. Moreover, high contents are recorded at the foot of the piers and in the sediments of the emerged beach, sheltered by adjacent breakwaters, located N of the North Pier. Another very small zone is identified along the emerged and submerged beach of the Sirene Beach, down to 4 m water depth, near the adjacent breakwaters.

The major PAH concentrations are found in an area to the N of the North Pier, stretching in a E-W direction from the emerged beach up to about 5 m, and then NE-SW oriented. A second area, less wide than the first one, is identified to the S of the South Pier, which is also NE-SW oriented. A third very small zone is confined within the bay between Annone Cape and the bridge that connects the coast to Nisida Island, at about 1/6 m depth, with the same orientation.

The areas with PCBs are located on the seabed to the N of the North Pier, between the North Pier and South Pier, and in the tract of emerged and submerged beach between the latter and the nearby small one located to the S. They are particularly present in the central zone between the two piers, both at the foot of the North Pier, between 1 and 3 m depth, and near the head of the South Pier, between 4 and 6 m. Moreover, PAHs are also identified to the S of the head of the North Pier. The only zones where these pollutants are found on the emerged beach are the extremely small area to the N, the area confined between the two small piers, extending down to about 4 m, and, finally, a very small area at the foot of Nisida Bridge. The area between the small piers is approximately E-W oriented, differing from the others, which extend approximately NE-SW.

High concentrations of nitrogen were recorded N of the North Pier and in the zone between the two piers. A limited zone exists within the inlet, in the shallows, between Annone Cape and Nisida Bridge. Except for the central area, which has an ogival shape

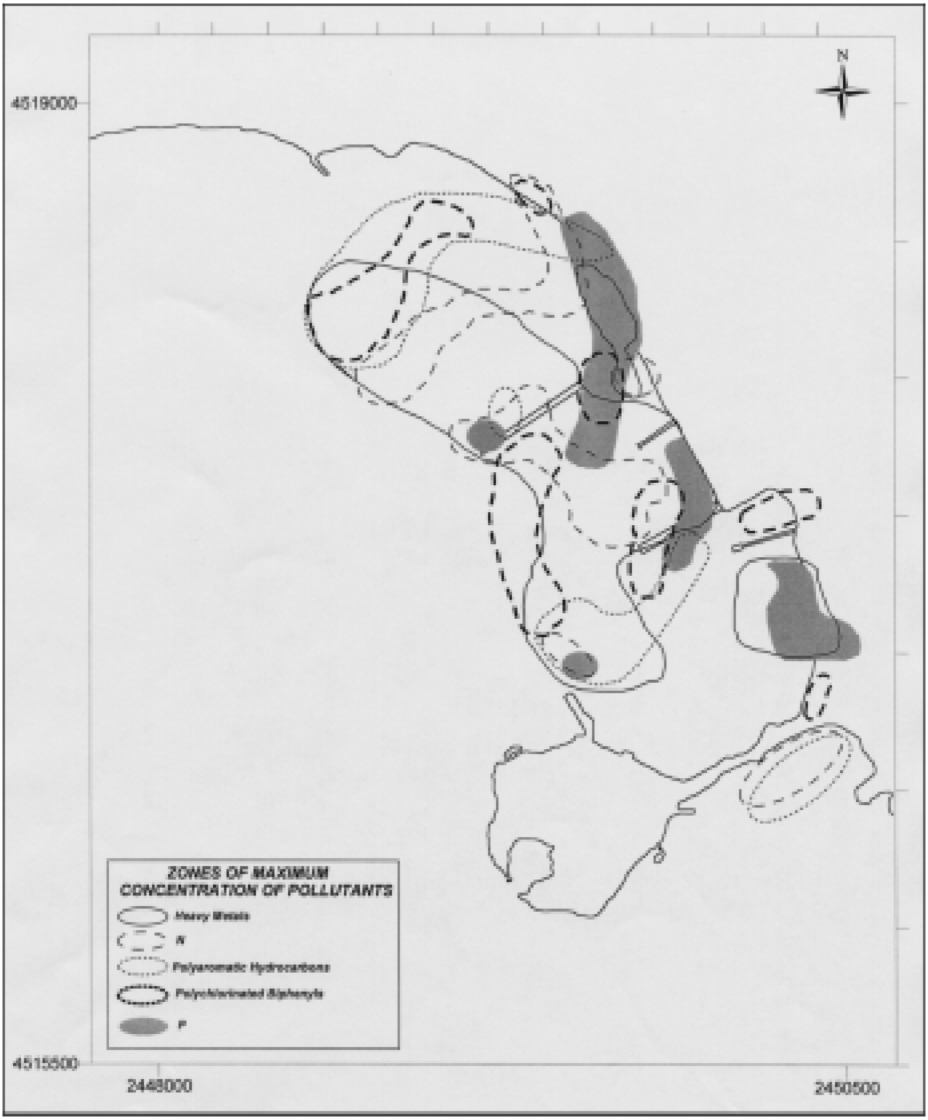

Fig. 6. Distribution of maximum concentration areas of pollutants on the seabed and beach of the Bay of Bagnoli.

extending in a NW-SE direction, the other zones are narrow and elongated: the northern one first NW-SE and then NE-SW oriented, the southern one approximately NE-SW.

Finally, high contents of phosphorus are distributed both in areas surrounding the heads of the North Pier and the jetty of Nisida, and near the foot of the North and South piers, between the waterline and about 6 m depth. Within the tract to the N of the North Pier, the area extends up to the emerged beach, as is also the case near the Sirene Beach, where the phosphorus is distributed down to about 3 m depth. Generally, these areas are N-S oriented.

A hypothesis for intervention

Creating a touristic seaside resort in the area will require an intervention that applies innovative methodology to renaturalise the littoral prism (Motta, 2000). This will necessitate considering the coastal morphodynamical aspects of this area (De Pippo *et al.*, 1984; Cocco *et al.*, 1988) and implementing an environmental restoration with regard to high metallic contents, other pollutants and organic matters in the sediments of the seabed and of the emerged beach. In particular, dredging the surface of the submerged beach down to a sediment depth of at least 0.5 m is proposed, extending to the 5/10 m isobathic line; for the emerged beach, a decortication of the top layer to a depth of about 0.5–1 m is suggested.

Removed sediments might be treated both mechanically and with chemical processes to remove pollutants. The gravel-sand-pelite fractions and coarse polygenic inerts deriving from the former industrial activity can be separated out by sifting dredged material, subsequent sedimentation of sands in tanks and hydrocyclonation for recuperating fine sands (Merico *et al.*, 2000). The resulting parts, exposed to chemical and ecotoxicological analyses according to the type and the distribution of pollutant elements found (heavy metals, nitrogen, phosphorus, PAHs, PCBs), might be treated with specific processes, i.e. chemical and/or biodegradation to reduce toxicity and organic matter. This would reduce the time needed to restore the environmental equilibrium (Marrale *et al.*, 2000).

Subsequently, a protected beach nourishment is proposed for the emerged and submerged beaches. Marine sands, taken from sea bottom deposits, should be integrated into the previously treated sands. These marine sands, with mineralogical and textural characteristics similar to those that formed the coast, now degraded, might be taken from the sea bottom with a sand-pump dredger and transferred to the shore by means of a pumping system using floating pipes; they will then be used to model the beach with soil-moving machines. However, the sediments should be mechanically sifted beforehand in order to separate grains with greater mean sizes; this provides a better response against the erosive effects of wave motion and offshore transport by rip currents, minimizing the loss of material used to rebuild the beach and consequently the economic loss (De Pippo *et al.*, 2000a).

The base of the nourished submerged beach might be protected by placing artificial underwater barriers on the sea bottom, appropriately oriented, at about 5 m depth. For this purpose, the use of precast modular barriers with low environmental impact is proposed; they mimic natural underwater sand bars (De Pippo *et al.*, 2000b). Finally, the volume of sediments necessary to rebuild an emerged beach – an average of 60 cm deep, about 2 m high above sea level, and 1 km wide – is estimated at about 120,000 cubic metres.

Discussion

The research carried out in the Bay of Bagnoli enabled zones of different morphodynamical evolution to be identified. The influencing factors here were coastal configuration, the presence of emerged and submerged volcanic structures and the presence of numerous man-made structures. These create the incidence of wave motion refraction, diffraction and reflection, with a clear diversification in time and in space of the coastal currents they generate. Moreover, the modifications to the coastal regime induced by man-made structures (piers, breakwaters, jetties) are already absorbed by the environment. It can be considered in a situation of partial equilibrium in the southern and central zones of the area and continues to be evolving in the northern zones with high-energy environments.

The trend of isobathic lines within the 10 m belt indicates the existence of secondary cell circulations, most probably due to an embayment effect of the area and to the presence of numerous man-made structures, both parallel and oblique to the coast. Thus, the coast can be subdivided into three areas: the first, northwards, between La Pietra and the northern margin of the artificially reclaimed land of the former industrial area, followed by the whole area facing the latter, between the North Pier and the South Pier and, finally, the southernmost area near the Sirene Beach, which subtends the artificial bay in the shelter of the Nisida Island.

This study has revealed a high hydrodynamic energy environment in the northern area, with bottom currents oblique to the shoreline. The presence of intense coastal cell circulation with a clockwise orientation, due to the embayment effect, is identified in the same area; this is confirmed both by the morphology and distribution of granulometric facies and by the disposition of relative transport axes. This area shows a great concentration of N, Mn, total hydrocarbons and PCBs on the sea bottom and the emerged beach; this is attributed prevalently to the accumulation of fine sediments on the northern side of the North Pier, caused by the artificial embayment effect here. The central area is characterised by low energy and by a wide secondary cell circulation with a clockwise orientation, generated from wave diffraction and reflection between the North Pier and South Pier. Here, the pelitic fraction in the very fine sands is associated with high concentrations of N, P, Cu, Fe, Mn, Ni, Zn, PAHs and PCBs. In the southern sector facing the Sirene Beach, the distribution of medium-fine sandy sediments indicates an area of low hydrodynamic energy. This is supported both by a wide distribution of very fine materials and their textural characteristics and by the presence of a meadow of marine phanerogams that capture such sediments, fixing them to the substratum with their rhizomes. Finally, a secondary cell circulation causes the accumulation, on the sea bottom and at the base of the emerged beach, of a high concentration of all the pollutants previously described (Ministry of Environment, 2000) and also of Pb and Cd (Sharp & Nardi, 1987). Its clockwise orientation is determined by an embayment effect due to the deep curvature of the coastline and is evidenced by a current-controlled sediment distribution, i.e. by a normal coast-offshore sediment gradient from coarse to fine.

The restoration of the Bagnoli coast as a touristic seaside resort will be possible by means of a moderate intervention; it will involve sediments dredged from the seabed and the beach, preventive mechanical, chemical and biological treatment to reduce pollutant elements in the sand and, finally, a protected seabed and beach nourishment of the area.

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