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Coastal Areas at Risk from Storm Surges and Sea-Level Rise in Northeastern Italy*

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ABSTRACT

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Coastal areas of the northwestern Adriatic Sea, covering a surface of almost 2,400 square kilometers along over 300 km of coast between Monfalcone and Cattolica, are depressed below sea level. They are therefore exposed to the risk of flooding by sea surges and rivers. Man-induced or natural subsidence has affected most of these areas, especially near the Po Delta area, where an altitude of over 2.5 m was lost in some places during the past century. In this paper, an assessment is made of near-future relative sea-level changes which may occur during the next century, owing to unavoidable additional land subsidence and to the eustatic rise predicted by climatic models. Even in the absence of new human activities triggering land-subsidence processes, the additional loss in land level in relation to sea level is expected to vary by the year 2100 from about 0.5 m near the lagoons of Venice and of Marano-Grado to about 0.6 m near Ravenna and Cervia and to as much as 1.5 m in certain areas of the Po Delta. In a slightly deeper Adriatic Sea, tidal amplitudes will fortunately not increase and sea surges caused by Sirocco winds are not expected to become worse than today; they, however, will develop above locally higher sea levels. Many areas will be more at risk during the next century than today; a few significant case studies, each of them representing specific problems, are analysed: the Ausa-Corno industrial area inland from the Marano-Grado Lagoon, the historic center of the City of Venice, two sample areas in the Po Delta area, and the Ravenna-Ceria area.

ADDITIONAL INDEX WORDS: *Subsidence, sea-level impacts, flooding, coastal management, tidal changes, Adriatic Sea.*

THE INTRODUCTION

One main consequence of the near-future "greenhouse" global warming predicted by climatic models would be a rise in sea level and climatic changes; these conditions could induce an increase in the frequency and elevation of storm surges in certain areas. Sea surges in the shallow northern Adriatic triggered by atmospheric depressions associated with south winds (Siroccos) are already a frequent phenomenon which tends to raise the water level in the Gulfs of Venice and Trieste. In addition, many coastal sectors bordering the northern Adriatic are generally subsident and this can only worsen the negative effects of a sea-level rise.

The Intergovernmental Panel of Climate Change (IPCC), sponsored jointly by the World Meteorological Organization and the United Nations Environment Programme, is active in assessing future climate and sea-level change estimates and response strategies. Since the catastrophic predictions of the early 1980's, when the U.S. Environmental Protection Agency was expecting a sea-level rise in the year 2100 in the

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range 56–345 cm (HOFFMAN *et al.*, 1983), subsequent scenarios have foreseen a lesser eustatic rise. According to the IPCC (1990) assessment, the "best estimate" scenario for the year 2100 has anticipated a global sea-level rise of 66 cm, with high and low estimates of 110 cm and 31 cm, respectively. A later revision (WIGLEY and RAPER, 1992) considered a global sea level rise of 48 cm, with high and low estimates of 90 cm and 15 cm, respectively, as more probable for the year 2100. This 48 cm estimate will be used in this paper; more recent estimates (IPCC, in preparation) seem to prefer a sea-level rise of 37 cm by the year 2100, with a range of uncertainty of 10–54 cm.

Any land subsidence phenomenon would of course produce an additional local relative sea-level rise, to be summed to the global estimate. As a consequence, in any area where the relative sea level is expected to rise faster in the next century, changing vertical datums must be considered in the decadal-scale decision-making process. In such areas, especially if they are subsiding, it would be politically irresponsible to neglect these problems, although present-day uncertainty ranges of climatic models remain rather wide.

In this paper, we consider briefly the recent evolution and present situation in representative coastal areas of northeast Italy and attempt to assess possible changes which are liable to accompany a near-future rise in the relative sea level.

STUDY AREA

The coasts of the Po Plain and of the adjacent Veneto-Friuli Plain consist of over 300 km of low sedimentary shores, forming a crescent around the northwestern Adriatic Sea (Figure 1). Monfalcone and Cattolica are located on the two tips of the crescent, with the Po Delta projecting eastwards at its center. The continuity of the coasts is interrupted by several rivers and lagoons. In addition to the Po, the main rivers from north to south are the Isonzo, Tagliamento, Piave, Brenta, Adige, and Reno. From the administrative point of view, these coasts belong to three regions: Friuli-Venezia Giulia, Veneto, and Emilia-Romagna.

These coasts were described in Roman times as a continuous, almost impassable, sequence of lagoons, marshes and estuaries. Most of the marshes have subsequently been filled by sediments or drained by man. Among the lagoon basins remaining today, the largest ones are the Lagoons of Marano and Caorle (the Grado Lagoon developed in late Roman times) (MAROCCO, 1991), the Lagoon of Venice, the Comacchio fisheries ("Valli") and the Saline of Cervia.

Beach variations in the area considered have been studied in detail by ZUNICA (1971, 1990), CIABATTI *et al.* (1978, 1979a,b) and GEORGIOU and MARABINI (1978). According to the Atlas of Italian Beaches (CONSIGLIO NAZIONALE DELLE RICERCHE, 1985), all the beaches of the study area are sandy and the sea bottom close to the coast, up to the depth of 5 m, usually has gradients varying from 2 to 11 m/km (6,4 m/km on average); higher gradients (12 to 23 m/km) are reported only outside the southern part of the Lagoon of Venice, between the passes of Malamocco and Chioggia.

North of the Po Delta, the longshore drift of the sand occurs westward from the Isonzo River, eastward and westward from the Tagliamento River, and predominantly northward from the Brenta River; in such a system, the lagoons of Venice and of Marano and Grado should be two converging zones for the shore sand. Unfortunately, all the jetties constructed at the lagoon passes during the past century impede this natural circulation. Along the Emilia-Romagna coasts, the longshore drift is directed mainly northward, under the control of the prevailing southeastern winds (Sirocco).

Coastal defence structures have been built along about 60% of the coast (Figure 1): 56 km of groins and breakwaters, 36 km of protective structures, longitudinal or transversal, 55 km of seawalls, and 42 km of jetties or dikes (without taking into account all the embankments which do not face the sea directly). Erosion is active on the coastal sea floor and on the beach in several sectors (*e.g.*, north of the Tagliamento River mouth, between the mouths of the Brenta and the Adige rivers, near the Po di Levante mouth, between Volano and Porto Garibaldi, and near the Reno River mouth, Ravenna, Cervia, *etc.*).

In the last century, the entire shoreline was still prograding due to the mass of sediment supplied by the rivers. Significant regression began at the beginning of the 20th Century, especially after 1960. This was due both to land subsidence (see below) and to a poor sediment supply caused by the reduced suspended load along the rivers. This reduction can be attributed not only to the creation of artificial lakes (ZUNICA, 1990), on mountain basins many kilometers upstream, but also largely to gravel and sand quarrying from river beds and near the coastlines; this quarrying was particularly intensive after the Second World War.

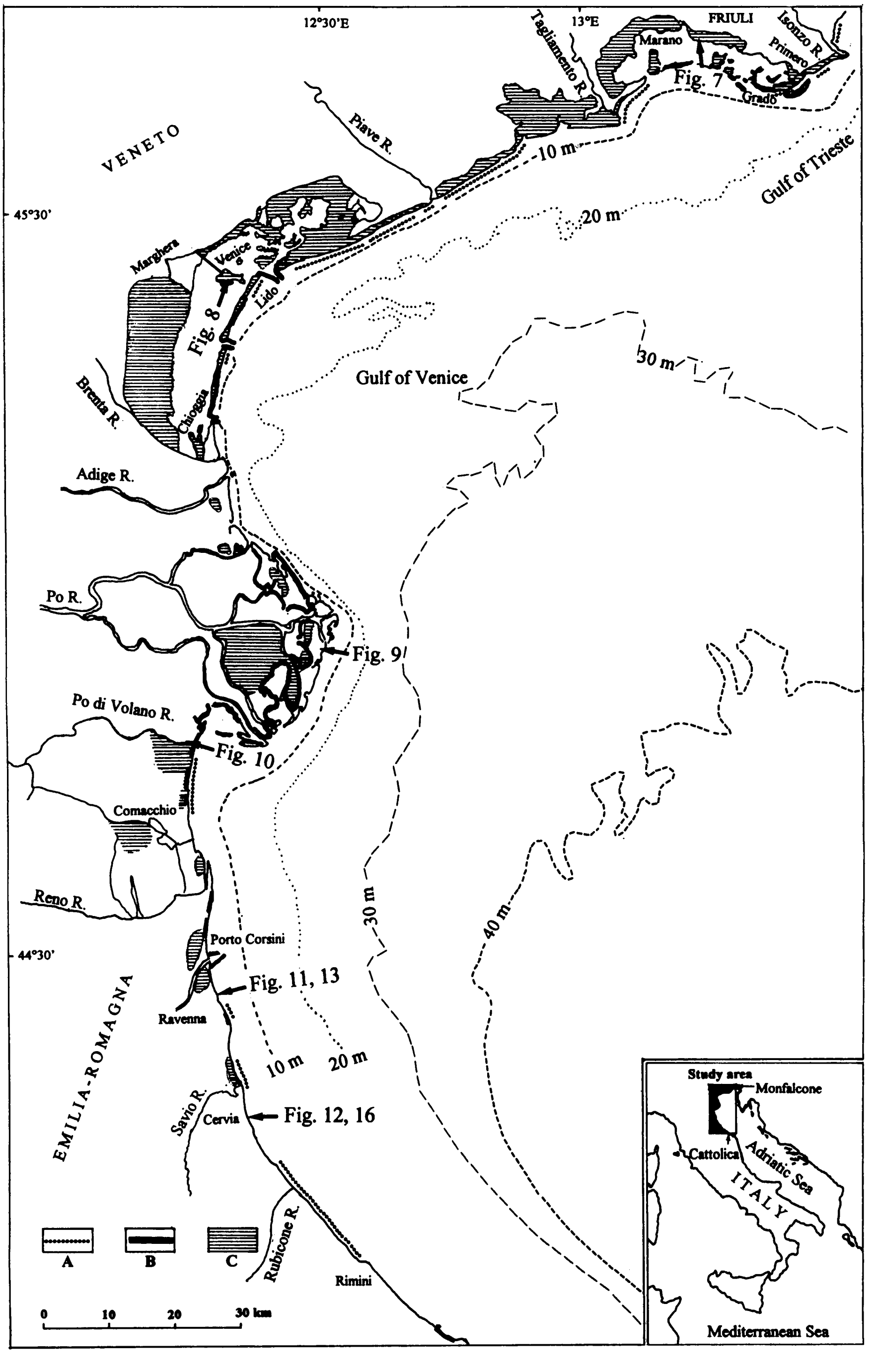

Figure 1. Location map of the study area. (A) groins, breakwaters; (B) seawalls, dikes, revetments; (C) approximate areas flooded by the November 1966 sea surge.

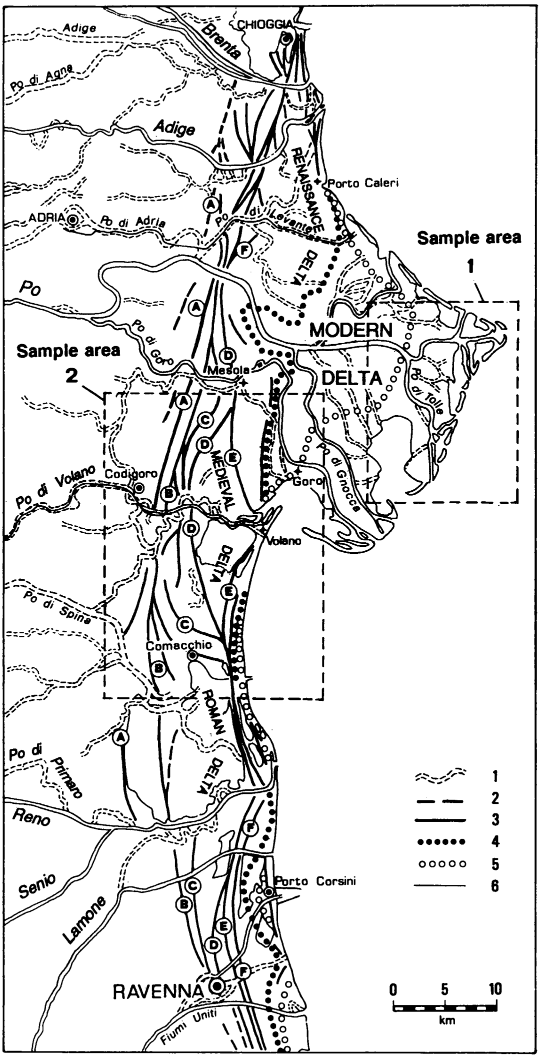

Figure 2. Geomorphological map of present-day and ancient mouths of the Po River (sample areas indicated). (1) main paleo-riverbeds; (2) main buried beach ridges; (3) main outcropping beach ridges, with ages: (A) earlier than 6th c. BC, (B) 6th-4th c. BC, (C) 1st–2nd c. AD, (D) about 6th c. AD, (E) about 10th c. AD, (F) 13th–15th c. AD; (4) coastline at end of 16th c.; (5) coastline in 1730–1740; (6) present-day coastline.

Territorial and geomorphological problems are particularly varied and severe in many coastal areas of the northwestern Adriatic, especially near the lagoon of Venice and the Po Delta. The recent evolution and certain potential impacts of a new sea-level rise in the Venice area have recently been summarized by PIRAZZOLI (1991) and FAVERO (1992). The general situation of the Po Delta will be briefly described herein.

The evolution of the Po Delta area has been extremely complicated, especially if we consider as deltaic territory not only the present-day delta, but the whole area affected by the various mouths of the Po in historical times. For example in the Middle Ages, the two main branches of the Po were the Po di Primaro and the Po di Volano (Figure 2), which flowed many kilometers further south than the river today. It was only in the 14th Century that the present-day main branch of the Po predominated over the other two. Until the end of the 16th Century, its main mouths lay further north than they do now, very close to the mouth of the Adige. The Venetians, fearing that discharged sediments could close the mouths of the Lagoon of Venice, diverted the Po to the southeast, excavatng a bed more than 5 km long. It was from these works that the modern delta began to develop.

In 1604, the old branches of the Primaro and Volano were detached from the active network of the Po. The former was later used to lead the Reno to the sea; the latter was used as a navigable canal and to convey water from wide areas inland. Especially in the last thousand years, the whole area involved in the diversions and flooding of these branches of the Po has been subjected to substantial reclamation works to improve land use. The control of rivers, with the construction of high containing banks has made increasingly larger areas available for agriculture. In these areas, already subject to natural subsidence, the land between the various rivers became increasingly depressed due to the termination of sediment loads. The river beds have become increasingly high, like the Mississippi River in the U.S.A., and breaches are rarer and more catastrophic when they occur. The former balanced situation between rivers and the adjacent territory has deteriorated from a physical, landscape and social perspective. In the delta itself, the deltaic branches have been overextended. The marshland has been reclaimed by facilitating the natural outflow of waters or (more rarely) by controlling fluvial landfill and by pumping in the last 130 years, even in the salt marshes. Reclamation too has produced negative effects. For example, it has caused considerable reduction of the soil level (less in the case of controlled fluvial landfill and more in that of pumping); sediments have been compacted due to reduced hydrostatic reactions, adding to the effects of peat oxidation. Recently, considerable sinking has also been recorded in inland areas (these had remained above sea level for thousands of years) due to the forced drainage to which they were subjected to control the phreatic surface.

The negative effects of other anthropic activities were also observed in the last century, such as further artificial soil sinking; this was attributed to the lowering of the piezometric surfaces of confined aquifers by excessive pumping of water for various uses and chemical alteration of groundwaters. In the present complex altimetric situation, it is now not only necessary to pump water from areas which lie under sea level throughout the modern delta, but also to raise water from inland areas where channels cross zones that have recently sunk. All these phenomena combine in various ways in the areas of the delta, so that there is no sector of the territory which is the same as another, nor does one sector have all the problems at any one time.

In order to highlight the negative consequences which a future rise in sea level might have in the Po Delta, two sample areas among other case studies, are considered below (Figure 2): (1) in the modern delta and (2) in a relatively ancient part of the delta.

LAND SUBSIDENCE

Depressed areas are very frequent in the outer fringe of the plains. Tracts below sea level can be found at more than 40 km inland from the present shoreline. Areas more than 2 m below sea level are especially widespread around the Po Delta. Figure 3 (Appendix) summarizes information deduced from detailed regional maps and processed during the survey for the new general geomorphological map of the entire Po Plain (Castiglioni, 1994; Castiglioni *et al.*, 1995). These areas cover 2,375 km^2, much more than previously thought (Table 1). If we also consider the areas defined by the +2 m contour, we can observe the very extensive continuity of lowland in the coastal and deltaic belt (Figure 3, Appendix). Some important differences in altitude and morphology between the various sections which compose the belt itself can also be observed, so that a subregional scale can be used to help understand the evolution of land subsidence.

These already topographically depressed areas became even more so after having been reclaimed, owing to compaction phenomena and to the lack

Figure 3 is included on enclosed map.

Figure 3. Elevation of the low Po and Veneto-Friuli Plains. (Scale 1:500,000) Appendix to coastal areas at risk from storm surges and sea-level rise in northeastern Italy.

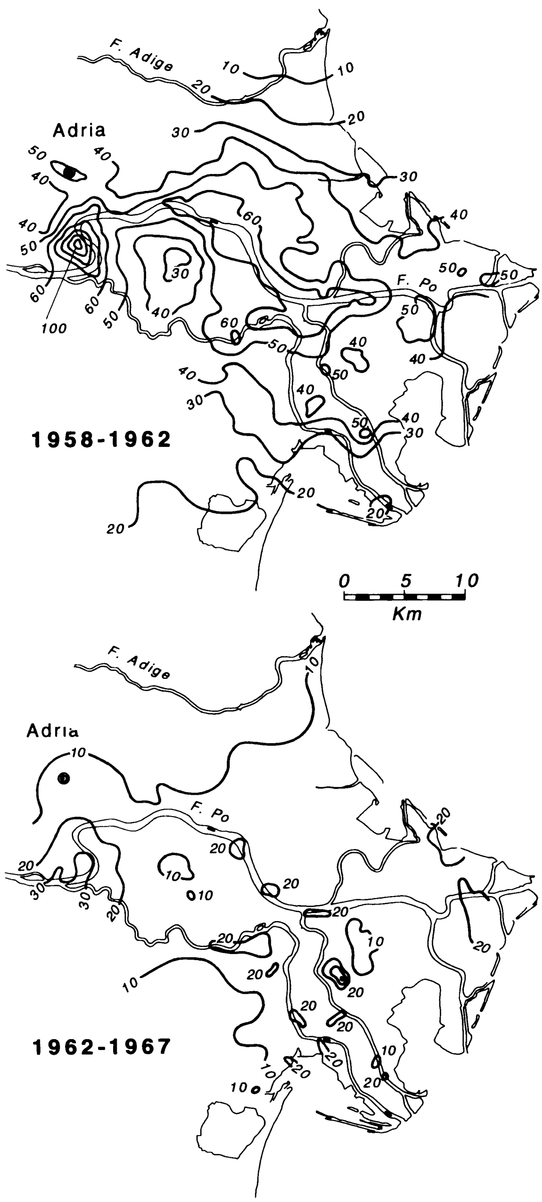

Figure 4. Countour lines showing land subsidence in the Po Delta are (in cm): (a) between 1958 and 1962; (b) between 1962 and 1967 (after Caputo *et al.*, 1970; Bondesan and Simeoni, 1983; Bondesan, 1989).

of a regular sediment supply from floods. Out of the 730 km² of the Po River Delta, for example, 600 km² are reclaimed land and the remainder are brackish lagoons (MARABINI, 1985). From the 1950's onwards, land subsidence caused by the pumping of underground water and gases became the predominant deteriorating factor, especially in the Po Delta (Figure 4).

In the northernmost sector of the area considered (Friuli Coastal Plain), natural subsidence rates are probably very low (0.1 to 0.2 mm/yr); however, higher rates have been reported near river beds (2.2 mm/yr on average near the Isonzo and 1.8–2.0 mm/yr near the Tagliamento). In addition, construction loads may cause local compaction (*e.g.*, 3.3. mm/yr near the Isonzo mouth, 1.3 mm/yr between Primero and Grado, increasing to about 3.5 mm/yr between Grado and Porto Buso, whereas relative stability is reported west of Porto Buso (REGIONE AUTONOMA FRIULI-VENEZIA GIULIA, 1990). Land reclaimed here from former lagoon areas is usually about 1 m below present nearby lagoon floors, also indicating recent compaction (estimated at about 0.3–1.5 m in the last 60 years by FORAMITTI, 1990).

In the Venice area, where natural subsidence can be estimated at 0.3–0.4 mm/yr since the early Quaternary and 0.5–0.7 mm/yr since the last interglacial period (PIRAZZOLI, 1987), local compaction phenomena have certainly been significant when the upper layers of muddy sediments were laden down by the construction of heavy buildings. On the other hand, the eustatic sea level seems to have remained almost stable in the Mediterranean during historical times (FLEMMING and WEBB, 1986), but may have increased between 5 and 12 cm during the last century (SHENNAN and WOODWORTH, 1992; PIRAZZOLI, 1993). During the last century, the Venice tide gauge recorded a relative MSL rise of 25 cm, compared with 14 cm on the Trieste tide gauge at the northern end of the Adriatic. During the same period, hydrodynamical effects triggered by morphological changes produced by human intervention are estimated to have caused an additional rise of extreme surge levels, above the MSL of at least 14 cm in Venice (PIRAZZOLI, 1987). The total rise in the sea-surge levels during the last century can therefore be estimated to be at least 16 cm along the Friuli coasts, 39 cm in Venice, 42 cm at Marghera and 25 cm at the Lido pass. During the last century at Chioggia, subsidence has probably been 3 cm greater than in Venice (L. CARBOGNIN, *personal communication*, November 1994), *i.e.*, about 28 cm.

Table 1. *Coastal areas below sea level between the main river courses in northeastern Italy. Inner water basins are not included (after* CASTIGLIONI, *1994, with data provided by A. Bondesan.*

Area	km²
Isonzo to Tagliamento	34.09
Tagliamento to Livenza	232.45
Livenza to Piave	181.14
Piave to Sile	73.27
Sile to Brenta	63.05
Brenta to Adige	200.86
Adige to Po di Pila	309.93
Po di Pila to Po di Goro	686.65
Po di Goro to Reno (except water basins)	560.39
Reno to Savio	29.95
Savio to Rubicone	3.70
Total	2,375.48

In the Po Delta area, long-term natural subsidence can be estimated to be of the order of 1.0 ± 0.2 mm/yr (*e.g.*, ELMI, 1984). Historical changes in the development of the Po Delta have been traced in detail from morphological and historical evidence (CIABATTI, 1967; VEGGIANI, 1985; FABBRI, 1985; SESTINI, 1992). The development of the modern Po Delta has taken place mostly during the last four centuries. No long tide-gauge records are available in the area. When the first leveling network covering the area was established in 1957, heavy subsidence phenomena caused by gas extraction were already active in a wide region (CALOI, 1967; CAPUTO *et al.*, 1970; BONDESAN and SIMEONI, 1983; BONDESAN, 1989). Methane extraction started in 1938 and continued until 1964. Although subsequent levelings have indicated a decrease in subsidence rates since 1964, the southern part of the delta was still being affected by rapid compaction phenomena in the 1970's, with subsidence rates varying between 5 and 20 mm/yr (BONDESAN *et al.*, 1986; MINISTERO DELL'AGRICOLTURA & CONSORZIO PER IL CANALE EMILIANO-ROMAGNOLO, 1990). More recent information suggests that subsidence rates decreased very little in the 1980's and even increased in some cases, probably in relation to the present land use (forced drainage after copious irrigation). On the whole, the change in the relative sea level during the last century can be estimated to be 254 cm at Polesine Camerini, 248 cm at the Tolle Hydrometer, 269 cm at Porto Tolle, 169 cm near the Donzella mouth, and 138 cm at Volano and 107 cm at Codigoro.

South of the Po Delta, subsidence phenomena have been reported all along the Romagna coast, as far as Rimini (VIANELLO *et al.*, 1982). During the period 1968–1978, subsidence rates have varied from 15 mm/yr between the Po Delta and Ravenna to 5–10 mm/yr farther to the south (CONSIGLIO NAZIONALE DELLE RICERCHE, 1985). Detailed information on subsidence trends in the Ravenna-Cervia area will be given below.

In many cases, coastal instability increased due to the construction of jetties interfering with longshore currents, the dismantlement of coastal dunes, and the rapid urbanization.

RECENT AND NEAR-FUTURE SEA-SURGE FLOODING LEVELS

Areas Flooded by the 1966 Sea-Surge and Near-Future Changes in Land-Level

Flooding events, often reported in the coastal areas of the Po Plain, may result from river overflow or from sea surges. Great sea surges are generally related to deep atmospheric depressions and are often accompanied by heavy rain and in certain cases by river flood; therefore, during the most devastating coastal floods, it is usually difficult to distinguish the boundary between water coming from the sea from that of the river. In November 1966, for example, at the time of the greatest storm surge of this century in the North Adriatic, river flooding occurred in many wide inland areas, mainly in northeast Italy (CNR and ISTITUTO DI GEOGRAFIA DEL MAGISTRATO ALLE ACQUE DI VENEZIA, 1969). The areas marked in Figure 1, flooded by the 1966 sea surge, are therefore approximate and result from a simplified compilation from the above sources as well as from STEFANINI *et al.* (1979), CALEFFA *et al.* (undated), VIANELLO *et al.* (1982), ILICETO (1992), and other unpublished information which may show contradictory mapping indications. For more detailed information concerning flooded areas in the Po Delta, see Figures 9 and 10.

To estimate possible near-future changes, we used land sinking scenarios which assume that: only the natural component of subsidence will be active north of the Po Delta and south of Ravenna; the anthropomorphic component will decrease gradually to zero by 2020 near Ravenna; and artificial subsidence will remain significant in the delta area, reaching by 2100 a total amount of 70 cm at Polesine Camerini and Idrometro Tolle, 50 cm at Porto Tolle and Donzella, even increasing to 100 cm in the southern part of the delta (Codigoro-Volano area). With a "greenhouse" eustatic sea-level rise of 48 cm by the end of the next century, this would give a relative MSL rise of 50 cm near the lagoon of Marano-Grado, 53 cm near the lagoon of Venice, 98 to 148 cm in the Po Delta area and about 60 cm near Ravenna and Cervia.

The Influence of Subsidence and Eustasy on Sea Dynamics

The possible sinking of coastal land and the sea-level rise can be considered separately and summed up at the end for the overall effect (as done above); this is, however only a "static" conclusion. Indeed, these facts can have an influence on sea dynamics and modify such phenomena as tide and storm surges. However, we can anticipate that any modification will be very slight, since the order of magnitude of the subsidence in the Northern Adriatic area and the sea-level rise result in very small perturbations of the sea motion.

The short-term fluctuations of the sea level around its mean value are due to astronomical and meteorological forcings. In the Adriatic, astronomical forcing produces an almost complete "co-oscillation" with the Mediterranean (continuous driving from the southern inlet and negligible local direct forcing from the moon and sun). The meteorological action, on the other hand, consists in a surface push of the wind and the hydrostatic effect of atmospheric pressure; indeed, where the pressure is high, it will push down the sea and create a bulge where the pressure is low. The wind effect is largely dominant in the Northern Adriatic, due to the channel-shape of the sea; storms from the southeast can easily pile up water at the dead end.

To start with the problem from the beginning, the expected sea-level rise due to eustasy can be seen as a general increase of the sea depth; the coastal sinking should give only a local deformation of the sea bed, but both effects seem to go in the same direction.

A detailed description of the sea dynamics is possible by using well-known mathematical expressions. The equations of fluid dynamics expressing the conservation of matter and linear momentum are "tailored" in different ways when particular aspects are studied; the relations considered here (the long wave equations) (WELANDER, 1961) disregard, for example, the diffusivity term or swell description. Once the equations are given, modeling is concerned with prac-

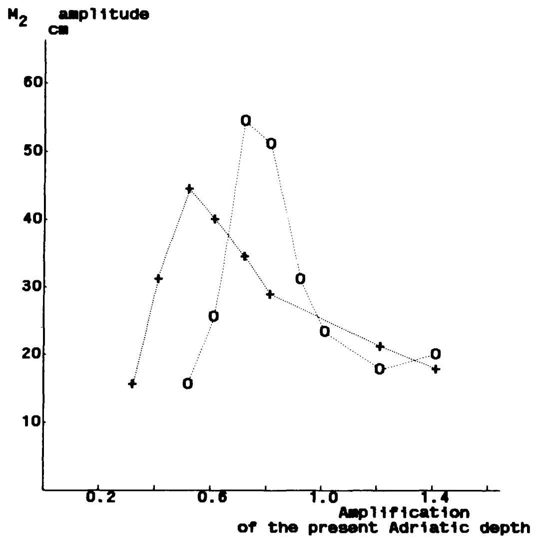

Figure 5. Numerical models show how the tide would change off the Venice lagoon (amplitude of M2, in cm), should the depth of the sea change according to a certain factor (x-axis). Crosses refer to the changes in the whole Adriatic, while circles concern the N-NW part of the Adriatic only. The highest values indicate a resonance of the basin due to the forcing tide.

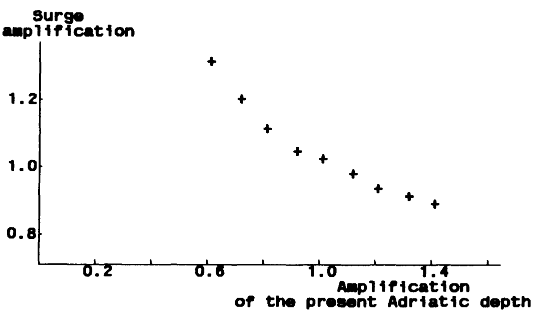

Figure 6. The surge generated by a constant wind decreases when the depth of the sea increases, but, contrary to the preceding figure, shows no resonant peak.

tical numerical aspects. In the Northern Adriatic, a lot of study and experience was required in order to understand and predict floods (ROBINSON *et al.*, 1973), but a special development is given here; the effects of possible changes in the morphology of the sea basin are also considered.

The model used to simulate the hydrodynamics of the Adriatic is a finite-difference scheme, similar to that already used by HANSEN (1956); it consists of a rectangular grid approximating the geographic coordinates on a plane surface, where the space derivative of the relevant functions (level and current) are approximated by the differences between two point-values. Non-linear terms are not considered and the bottom friction is simulated linearly. The numerical technique used here was first proposed by DAZZI and ZECCHETTO (1985) and can be classified as explicit-implicit. The actual grid mesh is 12′ in longitude and 6′ in latitude, so that the points of level estimation are about 800. Even a low-level personal computer can be used to run it. This type of model is suitable for investigating both tidal propagation and wind effect; the former is simulated by imposing the known local oscillations at the southern boundary and the latter by figuring a steady wind stress from the southeast all over the Adriatic. For practical purposes, only the trend shown by the model can be of real interest, but the results are quite relevant from a theoretical point of view.

First of all, it is clear that both wind effect and tidal propagation depend on the depth of the water basin; and since land sinking and sea-level rise both correspond to a deepening of the sea, something is bound to change. The numerical scheme has been run by simulating the winds of the Adriatic as they exist, then on a new Adriatic pattern, where a large "belt" on the northern and northwestern sides has an increased depth. The complete modeling confirms what could be easily estimated from the equations, an increase in depth produces smaller surges when there is no change in the wind.

The tidal motion will now be considered. Again (but for independent reasons), the models show that the tidal wave in the direction of the tidal propagation from the south would be reduced in the case of a deeper sea. We can conclude that a threat to the fate of the land and the sea can be anticipated (*e.g.*, owing to water invading the coast) though surges and tides would not necessarily worsen as a consequence.

The tidal wave observed in the Northern Adriatic depends very closely on the morphology of the sea floor. The local tidal range observed (close to one meter) immediately appears to be much larger than elsewhere in the Mediterranean (usually less than 0.3 m). One good way of accounting for this is to point out that the tidal periodicities (12 and 24 hours) are very close to the main resonant periodicities of the Adriatic concerning free oscillations (11 and 22 hours); the connection be-

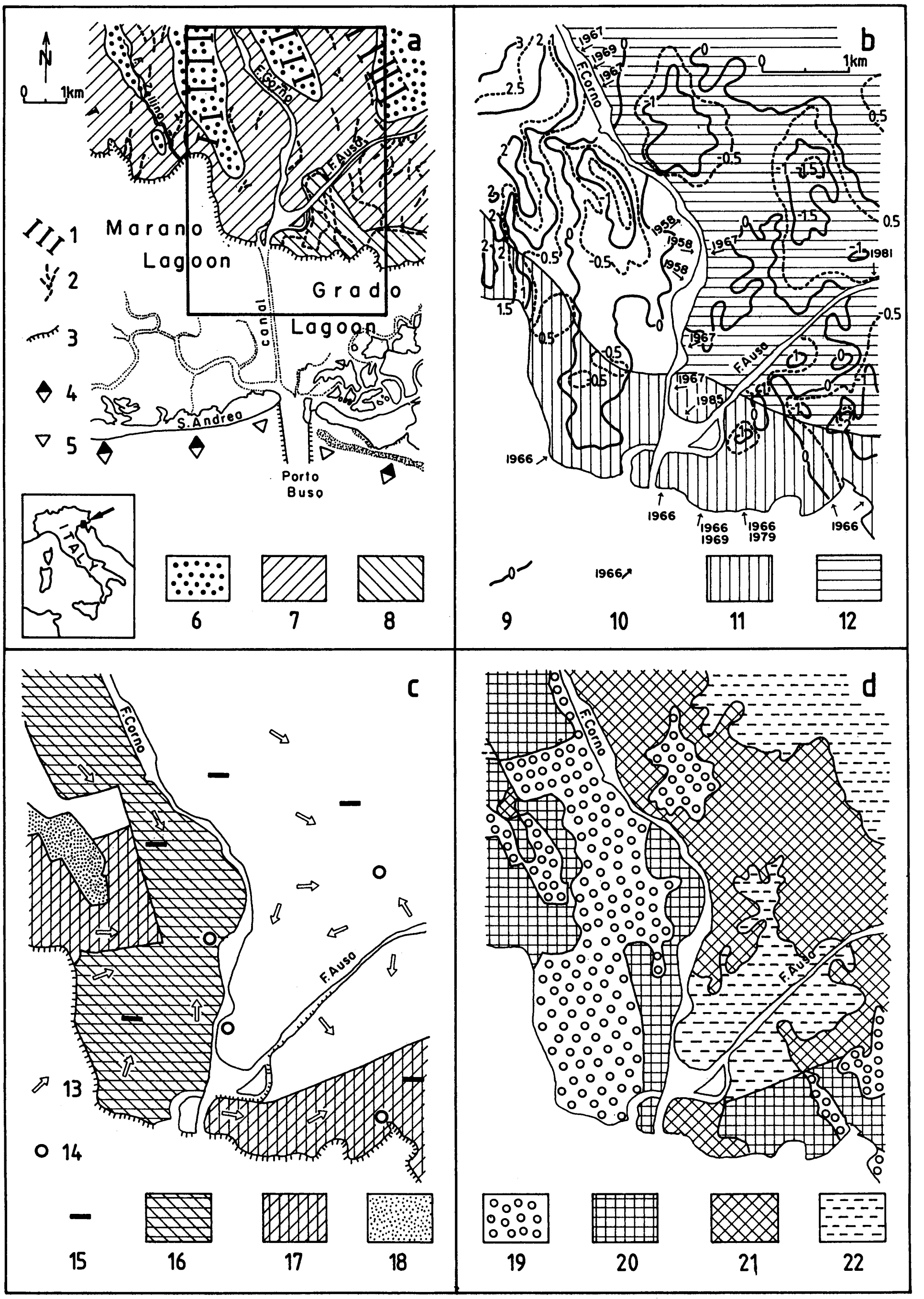

Figure 7. The coastal risk in the Ausa-Corno industrial rea (Friuli-Venezia Giulia, Italy).

(a) Geographic and geomorphologic setting, natural and/or man-made landforms. (1) fluvial ridges; (2) palaeo-riverbeds; (3) continuous dams and piers. Beach evolutional trends (4, 5): (4) stable shoreline; (5) advancing shoreline. Lithology of the alluvial plain (6–8): (6) mainly gravelly-sandy soils; (7) mainly pelitic soils; (8) recently reclaimed lagoon soils.

(b) Microtopography, flooded areas and main embankment disruptions which occurred during the flood of 4–5 November 1966:

tween these two factors is well known (DEFANT, 1960). Any change in the depth of the sea (like any other geometric variation) would change the resonant period and consequently the observed tide due to the critical proximity of resonance and excitation.

While we insist that what is actually happening is presumably decreasing the observed tidal range, models confirm that the latter would increase should the sea tend to be filled, for example by deposits originating from the rivers (Figure 5). Indeed, the resonant period of a shallow Adriatic would initially move closer to the tidal period. A continuation of this trend would reverse the effect, when the two characteristic times separate again. Nothing like this would be observed in the wind-generated surge (Figure 6). In order to show the tide evolution even more clearly, the model also assumed depth variations (at the same percentage) for the whole Adriatic basin.

CASE STUDIES OF COASTAL AREAS AT RISK

According to SESTINI (1992, p. 429), "today the entire north-western Adriatic coast is in a state of physical instability because of subsidence and sediment starvation and must be classified as a high-risk zone in respect of the threat of accelerated sea-level rise." It is not possible to consider here in detail all the areas at risk between Monfalcone and Cattolica: however some significant case studies representing specific problems are analysed below.

The Ausa-Corno Industrial Area (Friuli-Venezia Giulia) (Figure 7)

The area selected for this study is located behind the Marano and Grado Lagoon and includes the industrial pole gravitating around the fluvial port of Porto Nogaro, on the River Corno. Created in the 1960's, this industrial area is a smaller-scale version of the industrial development of Porto Marghera in the nearby Venice Lagoon; a long and deep navigable canal crossing the lagoon and two routes along important spring rivers (Figure 7a) allow medium-tonnage vessels access to the area. In particular, the industrial area stretches along the western bank of the River Corno, with plots of land right on the waterfront, in order to make loading and unloading operations easier. Industries are small-sized (about 80 operative units) and are concerned with metalwork (iron and steel), mechanical engineering, leather tanning and wood processing.

From a geomorphological point of view, the area under examination is a partial relict of the vast alluvial plain created by the late-glacial rivers and, at a later stage, marginally affected by the Holocene transgression. Traces of the ancient riverbeds crossing the plain can still be identified, thanks to the presence of fluvial ridges stretching north to south and composed basically of gravel-sand deposits. The old overflow area can be identified by the presence of finer sediments (pelites) and traces of a buried hydrographic network, more developed near the inner border of the lagoon. At present, rivers crossing this area originate from the Friuli springs and flow in deep beds across the former overflowing area (Figure 7a). Following recent reclamation activity, the whole inner lagoon border has been surrounded and protected by an earthfill embankment covered with stone which reaches peak heights of ± 3 m or more above mean sea level. The barrier island of the lagoon is not characterized by coastal erosion phenomena, for it has been artificially stabilized by the construction of long piers at Porto Buso which prevent the coastal dispersion of sediments.

The microtopography of the region (Figure 7b) indicates the existence of vast areas below sea level with altitudes that are sometimes lower than the lagoon bed they overlook. The whole area is subjected to flooding caused both by rivers overflowing and inundation by lagoon waters brought about by the collapse of adjacent dams (see Figure 7b, a photograph of the situation after the 1966 flood). In all this part of the lowland, farming, the main resource of the area, is made possible by the constant operation of drainage pump systems

←

(9) contour-lines in meters (above MSL); (10) breached or damaged embankments and year of the event; (11) area affected by the lagoon water inundation; (12) area affected by a river overflowing the banks or dams.

(c) Hydrography and land use. Hydrography (13–15): (13) direction of water run-off; (14) main drainage pump stations; (15) areas with drainage difficulties. Land use (16–18): (16) industrial area; (17) areas of farming or of environmental interest; (18) environmentally protected areas; plain areas correspond to farm land.

(d) Coastal risk (C.R.) zoning (19–22): (19) very high C.R. areas; (20) high C.R. areas; (21) medium C.R. areas; (22) low C.R. areas.

(Figure 7c). During floods, it has been observed that natural or artificial obstacles (coastal roads, inland dams, *etc.*) close off certain areas, preventing the run-off of flood waters; in these areas with drainage difficulties, water stagnation can persist for a long period of time after the natural disaster has occurred.

The only bulwark preventing lagoon and river waters from flooding the depressed areas are unstable even though they were partially or totally reconstructed after the event of November 1966. With the aim of evaluating how they would respond in the near future (while recalling that these types of works were built to the standard of minimum return periods of floods of a few decades to one hundred years), a set of parameters has been examined to determine the stability of the bulwarks (over the past 30 years), *i.e.*, the maximum height and methods of construction, with particular reference to the material used (material found locally of poor geotechnical qualities, quarry material, *etc.*). To complete this survey on the territory with a view to evaluating the environmental risks, the use of the land was taken into consideration (Figure 7c). The most profitable use from an economic and environmental point of view was considered.

By attributing a specific value to each identified class of vulnerability and the current use of the land (maximum value 6, intermediate 4 and minimum 2), the Coastal Risk (C.R.) value has been calculated in the event of floods caused by lagoon or river waters washing away the land or overflowing the lagoon and river embankments. The calculation has taken into account three types of vulnerability related to the topographically depressed situation, the drainage difficulties of the area, the stability of the defence works and the current use of the land. Figure 7d outlines the topographic conditions and water run-off problems, as well as the high economic value of the Ausa-Corno industrial area due to the presence of production plants. This industrial area is classified as high-risk from the environmental point of view, especially in the event of damaged embankments or water overflowing the banks of the River Corno. This risk would naturally be greater if the sea level were to rise in the near future.

The Historical Center of the City of Venice

Beginning in the Sixth Century A.D., the city of Venice was built gradually on 119 alluvial-tidal islets in the middle of a lagoon; the natural muddy layers of the islets were strengthened with millions of wooden posts to support the foundations of buildings. When constructing heavy buildings in this very dense urban conglomeration, insufficient foundations were frequently a problem. This created compaction phenomena and local subsidence on many occasions, causing certain buildings to settle more than others (PIRAZZOLI, 1974) and even to lean over slightly. In some parts of the city, evidence can be found that the ground level has been raised more than once to cope with land settlements.

Compaction effects of pumping water from underground sources, mostly for industrial use in the port of Marghera, were especially extensive during this century until 1975. Geodetic surveys show that from 1952 to 1969 land settlement was about 14 cm in Marghera and 10 cm in Venice, corresponding to a piezometric decline of 13 m and 5 m, respectively (CARBOGNIN *et al.*, 1976).

Due to these successive decreases in land level in relation to MSL and to the slight sea-level rise which took place during the first half of this century, the ground level in certain parts of the city is today very near to the high tide level (the average tidal range is about 0.6 m and the spring tidal range slightly above 1.0 m) (PIRAZZOLI, 1991); sea surges also penetrate more easily into the lagoon and reach higher levels than in the past because of recent dredging of the lagoon passes and navigation channels to Marghera. In particular, the lowest point of the city (in St. Mark's Square, just outside the basilica) is now only 0.4 m above the present MSL (which is today 22 cm above the Venice Datum), almost 60% of the city at the street level is situated at elevations between +0.9 m and +1.1 m and over 90% is below +1.2 m (in relation to the present MSL). In comparison, flooding levels higher than or equal to 1.10 m above the Venice Datum have occurred 140 times during the past century (from 1893 to 1992), with 93 occurrences during the last 30 years. In an attempt to eliminate the effects of sea-level rise and subsidence, data were considered above the running MSL; among the 79 occurrences of floods above +1.0 m during the last 100 years, 38 events have taken place during the last 30 years. This represents an increase in frequency from 0.59 to 1.27 times per year, on average; this increase cannot be ascribed to changes in the vertical reference level, but rather to the morphological and hydrodynamical changes which took place in the lagoon.

The altimetry (related to the Venice Datum) of

Figure 8. Map of the central part of the City of Venice: (1) itineraries where temporary higher emergency paths for pedestrians are usually set up in the case of flooding; (2) altimetric contour lines at street level, in cm, above the local datum; (3) local altimetric measurements.

the central part of the city of Venice, between St. Mark's Square and the Rialto is based on data by FRASSETTO (1976) and SBAVAGLIA (1977), and is shown in Figure 8. The routes along which a 60 cm-higher emergency path for pedestrians can quickly be built with trestles and planks when a flood is forecast (CANESTRELLI *et al.*, 1983) are also traced in Figure 8. In most places where no emergency measures are taken, activities come to a stop for several hours during each flood. Trestles and planks cannot prevent ground floors from being flooded, with subsequent damage to furnishings and buildings.

The effects of a new near-future relative sea-level rise would be dramatic in the Venice area. With an additional new MSL rise of only 20 cm, the return period of a +1.4 m flood (above Datum, *i.e.*, +1.18 m above present MSL) would decrease from 4.1 years to 1.5 years; sea water would be washed into St. Mark's Square by 55% of the high tides (*i.e.*, each day on average) and would stagnate there for 1,283 hours per year (15% of the year). Other scenarios corresponding to higher sea-level rises have been analysed by PIRAZZOLI (1991).

Engineering projects to remedy the present situation were proposed during the last decades (PIRAZZOLI, 1987). The latest project sponsored by the Italian Government, which is now in the process of being evaluated in draft form, includes three parts (CONSORZIO VENEZIA NUOVA, 1992): (1) The construction of a series of mobile gates at the lagoon passes, which will be closed when the tide height threatens to reach the level of +1.0 m (above Datum, *i.e.*, +0.78 above present MSL). Each gate, 20 m long, will lie on the floor of the lagoon passes in normal times, but can be raised by injecting compressed air to partially seal the openings. The gates will be constructed to oscillate with waves, independently one from the other; thus, narrow passages for water will remain open all the time and the barrier will not be completely watertight. This protection would contribute to defending the lagoon from storm surges at the first stage, when durations of closure at the lagoon passes remain brief. It seems doubtful however that such a barrier will be sufficient to protect the lagoon against flooding in the case of a near-future sea-level rise, when closure durations will increase. (2) There is a plan to raise the level of certain streets, most frequented by pedestrians, to +1.0 m (above Datum), in parts of the city which are now below this level. In other parts of the city where this will not be possible (*e.g.*, for architectural reasons), it has been proposed to raise the street level only along the canals. This would mean that rain and sewage waters which now flow directly into the sea will have to be collected and pumped away. Unfortunately, a complete map of the entire canalization network does not yet exist. (3) A series of works is also planned along the outer coast, to strengthen the littoral bars and to decrease present erosion rates and pollution levels in the lagoon.

The present-day depths of navigation channels are indeed excessive for a muddy lagoon and incompatible with its hydrodynamic and sedimentary equilibrium. For political reasons (the fear of penalizing maritime traffic), this project does not envisage the possibility of decreasing these depths substantially. Since excessive depths facilitate the penetration of storm surges into the lagoon, the gates would have to be closed more frequently than if these depths had been decreased. Thus, maritime traffic will be penalized anyway and the hydrodynamic and sedimentological balance in the lagoon will not be restored.

A new even slightly relative sea-level rise would greatly endanger present-day life and activities of the lagoon; for an additional MSL rise greater than 20 cm (in the present situation) or greater than 40–50 cm (if the whole project presently proposed by Italian State Agencies is carried out), it will become necessary to separate the lagoon shores from the sea in a more effective way.

Po Delta Sample Area 1 (Modern Delta)

Sample Area 1 lies in the SE sector of the modern delta (Figures 2 and 9). It includes: a) Isola Camerini, *i.e.*, the area between the sea, the Po di Pila and its right branch (called Busa di Scirocco), and the Po di Tolle and its left branch (called Busa del Bastimento); and b) Isola Bonelli, *i.e.*, the area immediately south, between the sea, Busa del Bastimento and the terminal stretch of the Po di Tolle.

These two areas can be treated together, because their creation and development ran parallel (both formed between approximately 1730 and 1930). Several reclamation works were carried out between 1730 and 1930. The entire modern delta was in fact characterized by early settlement and many of the place-names recall the noble Venetian families who were granted ownership of the land as it gradually came into existence. The whole area is one of the most important cases of early settlement and reclamation operations involving

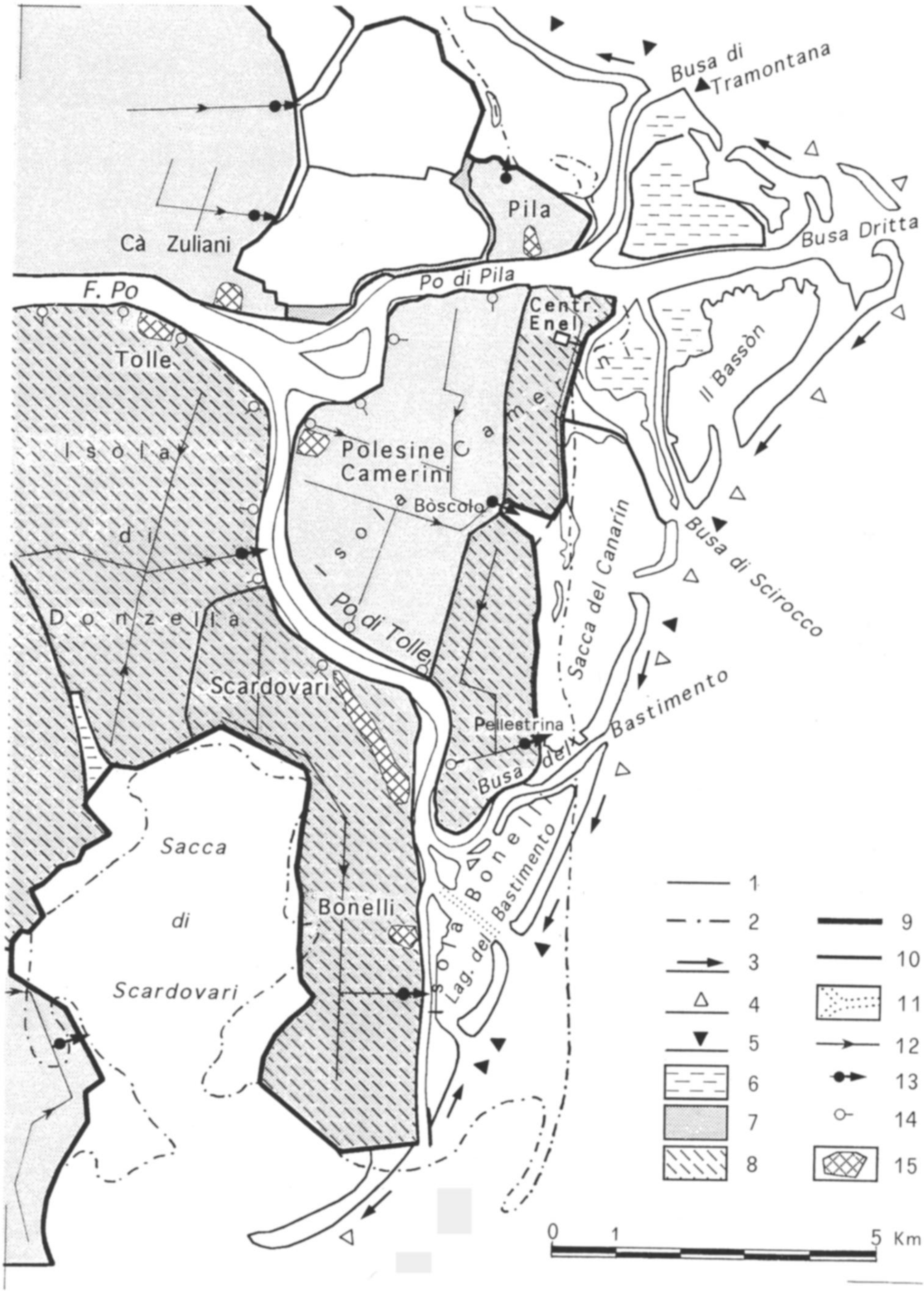

Figure 9. Po Delta: sample area 1 (Modern delta). (1) present coastline; (2) coastline in 1893; (3) direction of longshore sediment transport; (4) tendency of coast to advance; (5) tendency of coast to retreat; (6) marshland; (7) areas below sea level; (8) areas flooded by sea water in November 1966; (9) sea and lagoon dams; (10) river and other inland embankments; (11) lagoon canals (artificial); (12) main inland canals (and direction of water outflow); (13) pumping station (discharge); (14) freshwater intake; (15) built-up areas.

pumping that had been accomplished by the early years of the 20th Century.

Soil sinking has been considerable. Records show values between 7 and 10 cm/year in the period 1958–1962, falling to between 1.5 and 3 cm/year between 1970 and 1974. In addition to natural subsidence, severe and inevitable sinking is the result of reclamation in such a recently formed area; moreover, the extraction of methane-bearing waters during the Second World War (although to a lesser extent than in the rest of the low Po plain) did not help. The pumping stations were abandoned towards the end of the war, and most of the territory was again invaded by the sea, mainly due to the rise of the water level in the adjacent lagoon (Sacca del Canarìn).

During the post-war period, the sea and lagoon banks were rebuilt, almost always farther inland and both areas were again reclaimed. They are now almost completely under sea level and form two of the many polders of which the delta is now formed. Both areas were then badly affected by flooding from river breaches and invasion by the sea. Between 1951 and 1966, Isola Camerini was flooded ten times and Isola Bonelli six, in spite of frequent bank reinforcements. Reclamation operations in Isola Bonelli, less densely populated and more difficult to protect, were finally abandoned (in 1956) and the area has now been taken over again by the sea and is called Laguna del Bastimento. The waters of the Po di Tolle enter this lagoon through various breaches.

Today, Isola Camerini is protected by high banks and is under intensive cultivation, although the suspended branches of the Po mean that further flooding is still possible. Two banks far inland subdivide this polder into three sectors. The network of canals which, with some difficulty, drain the waters are served respectively by the Boscolo and Pellestrina pumping stations, both discharging into the lagoon facing them (Figure 9).

The large thermoelectric power station at Porto Tolle (Centr. Enel) was built in the northern sector in the 1970's. Its main structures rest on substantial foundations specially made for them. The main village is Polesine Camerini in the western sector.

Recent coastal dynamics have been dominated by beach retreat due to large-scale land subsidence; beach erosion has also occurred. The Po di Tolle, the main deltaic branch in the last century, was supplanted by the Po di Pila and now carries little sediment. From the beginning of this century until about the 1960's, this situation had already caused considerable beach retreat to the south (Isola Bonelli). Today, this trend is greatly reduced because the longshore current runs mainly from NNE to SSW, towards the mouth of the Po di Tolle (now protected by breakwaters); and sediment supply is ensured by the mouths of the Po di Pila, in which sediment impoverishment in the last few decades has been less serious. However, the most southerly beaches are now being influenced by the negative consequences of the partial closure of Busa del Bastimento.

A salt-water wedge occurs in the branches of the Po di Pila and Po di Tolle (it extends for almost 30 km in the Po Grande) and obtaining water for agriculture and for the Porto Tolle power station already presents problems. In this area too, any future rise in sea level would have important effects. Considerable expense would be involved in the following main operations: (1) repositioning water intakes from rivers, for industrial and agricultural use (measures to hinder the rise of the wedge could only be carried out on the Po di Tolle branch, not on that of Po di Pila); (2) increase in the power of pumping stations; and 3) raising the height of banks to lagoons and rivers.

On the other hand, an eustatic increase would not harm fishing in the lagoons. On the contrary, increased salinity would be advantageous, especially in the Laguna del Bastimento which currently receives too much fresh water from the Po. However, salt water infiltrating the watertables of the reclaimed areas (partly due to an increased hydrostatic load) would have disastrous effects on agriculture.

Po Delta Sample Area 2 (Volano)

This area includes the delta of the Volano, formed in medieval times, and the land which was later added to it (Figures 2 and 10). The southern part of the delta, less affected by human activities, has two salt marshes: Valle Bertuzzi, used for fish-farming, of which only the southern and western parts were reclaimed in the 1950's, and Lago delle Nazioni, used for water sports, created in 1963 from the larger Valle Volano.

Water turnover in these basins is ensured by sluices and pumps communicating with the mouth of the Volano. Seawards, the area was first modified by erosion of the deltaic cusp and later by sedimentation due to longshore currents which run here from south to north and have thus created spits and beach ridges which extend increas-

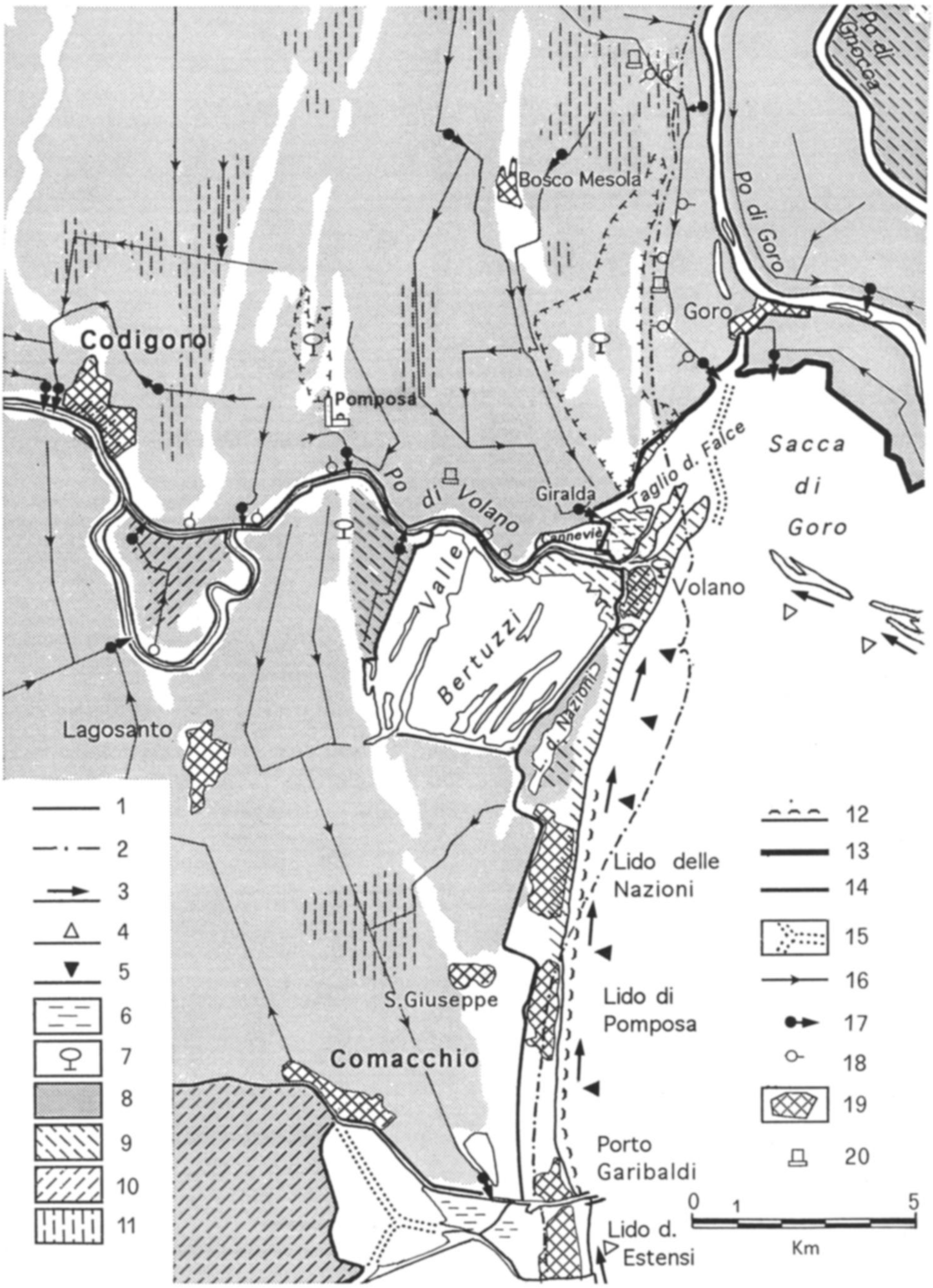

Figure 10. Po Delta: sample area 2 (Volano). (1) present coastline; (2) coastline at end of 16th c.; (3) direction of longshore sediment transport; (4) tendency of coast to advance; (5) tendency of coast to retreat; (6) marshland; (7) main wooded areas; (8) areas below sea level; (9) areas flooded by sea water in November 1966; (10) areas flooded by river water in November 1966; (11) main areas flooded in August 1979, due to an electricity breakdown at pumping stations; (12) breakwaters; (13) sea and lagoon dams; (14) embankments to rivers and other inland embankments; (15) lagoon canals (artificial); (16) main inland canals (and direction of water outflow); (17) pumping station (discharge); (18) freshwater intake; (19) built-up areas; (20) buildings of great historical and artistic value.

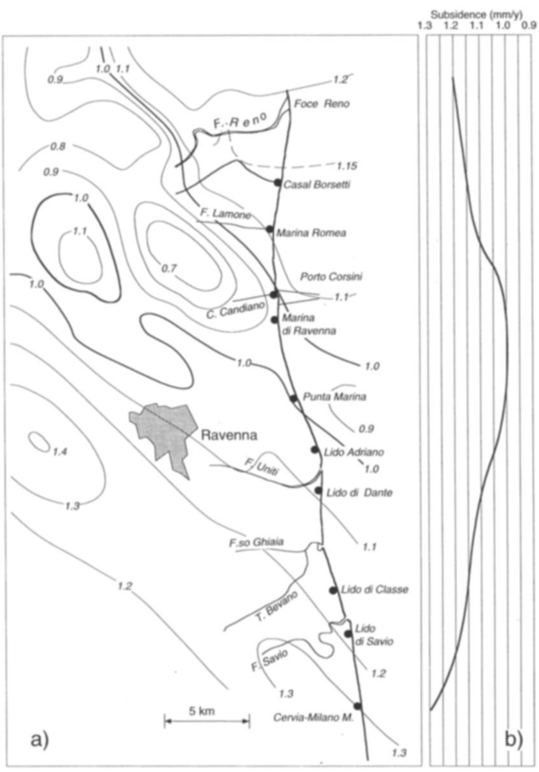

Figure 11. (a) The Ravenna area. Contour lines: Quaternary average subsidence rates in mm/yr. (b) Quaternary subsidence rates along the coastline.

ingly northwards. A pine wood was planted in the 1930's on one of these ridges and a small tourist resort (Volano) was built. The ridge further south includes the much larger resorts of Lido delle Nazioni and Lido di Pomposa.

The northern part of the delta was also covered by large bodies of water, drained between 1958 and 1969. Only a small marsh near the mouth of the Volano (biotope of Valle Cannevié) was saved. To the NE is the forest of Mesola, covering deltaic land which was formed from the Po di Goro in late medieval-Renaissance times. This forest like the mouth of the Po di Volano adjoins the Sacca di Goro, a marine bay which the advance of the modern delta has now transformed into a lagoon, often subject to sea surges.

This territory contains many areas of great natural beauty and buildings of historical interest and is one of the main parts of the future Po Delta Natural Park. Inland are the ancient monastery of Pomposa, with its famous Romanesque abbey, and the village of Codigoro, on the Volano.

In addition to geological subsidence, the entire territory suffers from serious problems of man-induced land sinking, partly caused by recent reclamation works. Notable examples of sinking (more than 6 cm/year) were recorded in the Codigoro area between the 1940's and 1966, probably caused by the pumping of methane-bearing water during that period. Other recent examples of sinking are due to pumping water for agricultural and industrial use, the ascent of the salt-water aquifer or dispersion of liquids in the soil (civil and industrial wastewaters, liquids from waste dumps, perhaps also chemicals used in agriculture).

At the present time, almost all the territory lies under sea level, partly because the most recent reclamation works emptied basins whose bottoms were already under sea level. The coast does not receive sediments from the Po. There are no beaches north of the mouth of the Volano and the coast has retreated due to land subsidence. The beaches to the south are eroding, especially the Lido delle Nazioni and Lido di Pomposa, because longshore transport of sediments brought to the sea by the Reno is hindered by the jetties of Porto Garibaldi (Figure 10). The Reno also currently transports only very small quantities of sediment to the sea. Efforts to remedy this erosion have been made by constructing rubble mounds parallel to the coast.

Invasion by the sea has occurred several times in past centuries, seawater sometimes pouring over the stretch of beach between the mouth of the Volano and the Forest of Mesola. This breach, called Taglio della Falce, was definitely opened in 1822 with the construction of a canal carrying seawater to the inland marshes in order to transform them into fish-farming basins. The final result was a lagoonal mouth which allowed communication between the Sacca di Goro and the inland bodies of water. In order to reclaim them, this mouth was closed with a dam, on which the Giralda pumping station was built and which still brings drainage waters today from the reclaimed land to the Sacca di Goro. South of the Volano, too, storm waves often breached the beach ridge, especially at Valle Volano; in order to prevent flooding of the very low-lying agricultural land near the beach, an inner bank was constructed in the 1970's between Volano and Porto Garibaldi.

This same area was also subject to bad floods from the main branch of the Po and the Po di

Goro, one dramatic example occurring in 1705. The Po di Volano too can cause floods although it is no longer linked to the Po, for it carries large volumes of water (up to 200 m^3 sec in cases of heavy rainfall over the entire basin), and when there is a sea surge in the Sacca di Goro, the water cannot be contained. The banks have therefore had to be raised even higher as far as 20 km from the mouth, except within the limits of the town of Codigoro itself; there, the unattractive aspects of the bank and their environmental impact would be intolerable. Plans have also been made for controlled washland, even though this would mean sacrificing much agricultural land.

The Po di Volano also contains a salt-water wedge which sometimes travels as far as 15 km from the mouth, beyond Codigoro. The dams facing the lagoon (*e.g.*, those of the former Taglio della Falce) lie on particularly permeable soil, and the salt-water aquifer is also particularly high here, especially in the most low-lying areas.

The entire territory is dependent on pumping to remove rainfall runoff. Since many pumping stations are exclusively powered by electricity, black-outs can cause partial flooding, as happened during the storm of August 18, 1979.

A possible future rise in sea level in such a complex territory would also have complex consequences, and at the present time it is not easy to predict what measures would be necessary. The following effects would certainly be inevitable: (1) a further ascent of the salt-water wedge in rivers and other watercourses, which would make it extremely difficult to procure fresh water for irrigation and other uses; (2) shallowing of the salt-fresh water interface, both directly (near the sea) and also as an effect of the rise in the salt-water wedge in the rivers, all probably worsening land subsidence; (3) an increase in the difference in height between the water levels in drainage channels and sea level—all these problems would have negative effects—prolonged in time but still pronounced—on the vegetation, as regards woodland and other natural environmental assets, and on agriculture—they would also require drainage and irrigation networks to be restructured, with an increase in the power of existing pumping stations and the construction of new ones—sluices and pumps serving fish-farming basins would also have to be restructured; (4) increased vulnerability of the territory to invasion by the sea and flooding by rivers, leading to the need to raise the height of existing dams and river banks—the beauty of the landscape would be greatly impaired; and (5) worsening of problems due to sea surges.

For example, the need to raise the banks of the Volano, even inside Codigoro, would become inevitable. This picturesque village, now lying right on both banks of the river, would be split into two by high banks preventing any view of the water, as has already happened in many other towns and villages in the Po Plain. Social life and scenic vistas would be affected and proper town planning impeded. If the construction of a pumping station for the Volano became necessary, it would be the largest in Italy and one of the largest in Europe.

The Ravenna-Cervia Sample Area (Figures 11–17)

The area considered includes parts of the Po Plain and the coast between the Reno River mouth and Cervia-Milano Marittima (Figure 11). It is highly urbanized, with residential, economic and industrial settlements, including one of the most important harbors of the Mediterranean. The whole area is therefore subject to a very great environmental hazard. It has been affected by an important regional natural subsidence, active throughout the Quaternary, and by a man-induced subsidence chiefly due to water pumping for civic use and subordinately to methane extraction. In the last decades, subsidence has attained peaks of high risk. Abundant geodetic measurements are available, mainly for the town of Ravenna and the nearby littoral zone; two sample localities have been selected, namely Ravenna-Porto Corsini and Cervia-Milano Marittima, where almost continuous measurements have been recorded since 1949.

Natural Subsidence

During the whole Quaternary (and with different rates also during the Pliocene), the zone has undergone a steady natural subsidence. Its amount can be estimated from data of the AGIP gas wells (SELLI and CIABATTI, 1977; PIERI and GROPPI, 1981) as ranging from a minimum of 0.9 mm/yr (Punta Marina) to a maximum of 1.3 mm/yr in the Cervia-Milano Marittima zone (Figure 11b).

More recent movements can be estimated from geotechnical borings which have enabled the shoreline and the surface of the Flandrian transgression to be reconstructed (Figure 12a). In the Cervia zone at the point of maximum advancement of the shoreline, this surface reaches a maximum depth of 11 m (Figure 12b). As the age of

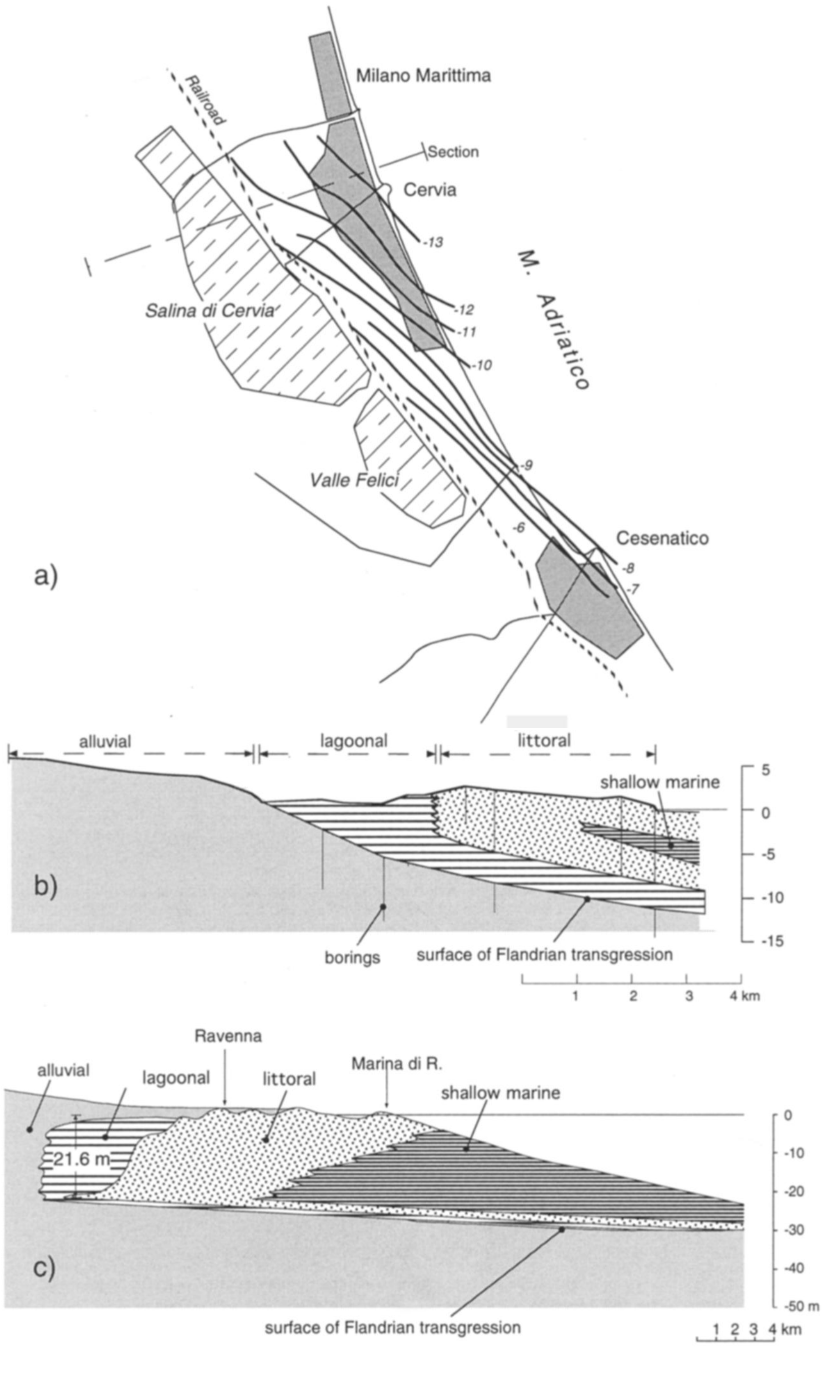

Figure 12. (a, b). The Cervia-Milano Marittima area: (a) depth (in m) of the Flandrian transgressive surface; (b) cross-section. (c) Section of the Ravenna beach ridge.

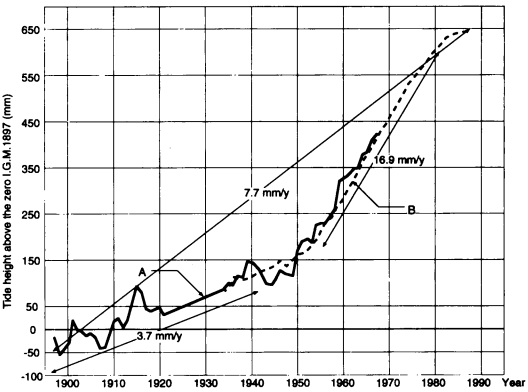

Figure 13. 1885–1988 MSL records at Ravenna-Porto Corsini, according to ANTONIAZZI, 1976 (A) and to SAPIR, 1992 (B).

the maximum Flandrian transgression can be estimated around 6,000 yr B.P., a subsidence rate of the order of 2 mm/yr can be deduced near Cervia.

In Ravenna, two kinds of information sources are available: the position of the transgressive Flandrian surface and the archaeological (Roman and Byzantine) data. The transgressive surface is about 22 m deep (Figure 12c), implying a subsidence rate of the order of 3.7 mm/yr. The same 3.7 mm/yr value can be obtained from the MSL trend recorded at the Porto Corsini tide-gauge station during the period 1885–1940 (Figure 13). The latter, however, includes both the subsidence and the eustatic rise that in the last century is estimated to be between 0.5 and 1.2 mm/yr (see above); a natural subsidence rate range of 2.5–3.2 mm/yr can be deduced therefore in the Porto Corsini area, which is of the same order of value as the 2.8 mm/yr obtained by RONCUZZI (1992) comparing levels of sewage system remains of Roman (Republican, Augustian and Teodorician) and medieval times in Ravenna.

Man-Induced Subsidence

Ravenna. The subsidence outline in the Ravenna coastal strip is more complex. Tide-gauge records at Porto Corsini (Figure 13) and geodetic measurements (Figure 14) show a sharp increase in land subsidence after 1950, with a maximum peak of 34–42 mm/yr in 1976. Between 1986 and 1992, the total subsidence rate was reduced to 6–10 mm/yr in the whole study area, except in the Lido Adriano zone, where values of 13–25 mm/yr

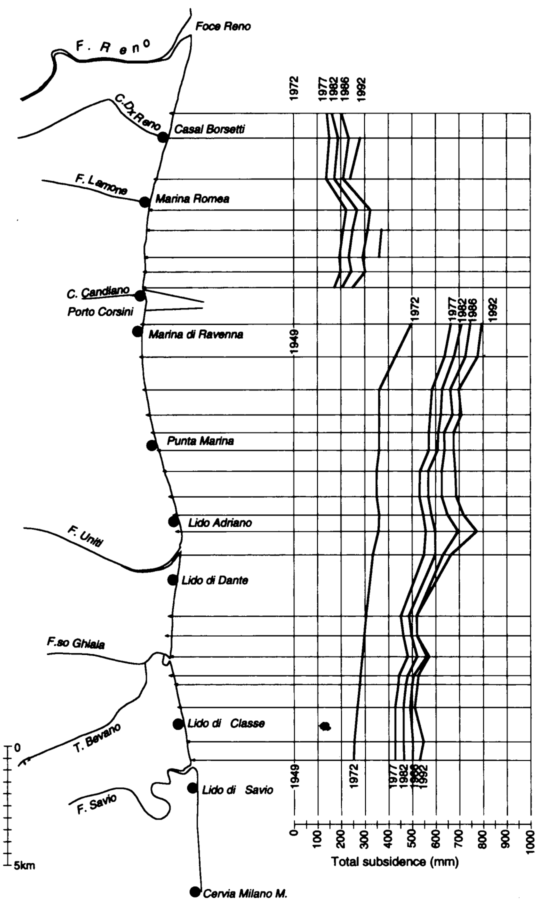

Figure 14. Total subsidence (1949–1992) along the coastline of the Ravenna-Cervia area.

were recorded in 1986, possibly corresponding to heavy methane extractions from offshore reservoirs (Figure 15).

More recent geodetic surveys (COMUNE DI RAVENNA, 1993) suggest that a drop in subsidence rates is occurring. If this drop is confirmed, subsidence rates very close to the natural ones can be expected in the near future. Recent subsidence rates are contributing greatly to an environmental and geomorphological deterioration trend in the whole coastal area (BONDESAN *et al.*, 1978; CARBOGNIN *et al.*, 1984; RONZANI, 1987), which implies the following:

(1) Shoreline retreat can only be partially mitigated by coastal defences (breakwaters), because its main causes have not changed, namely the

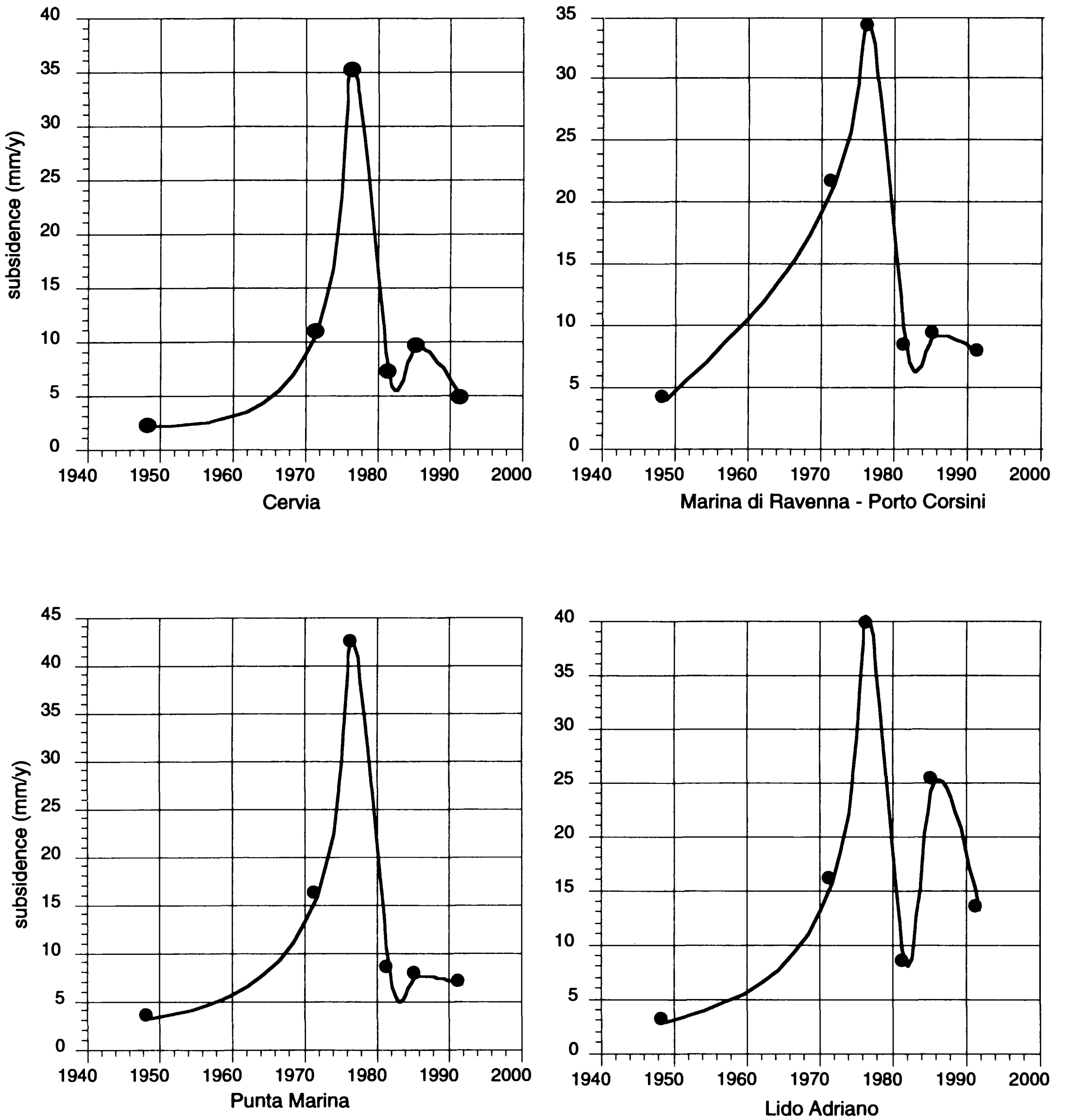

Figure 15. Subsidence rates at four localities along the coastline (for site location, see Figure 14).

reduced sediment supply by rivers, urban impacts, as well as deterioration of the beach and dune ridge; the latter, even if artificially rebuilt in some sectors, is already greatly impaired by several passages that were cut to the beach and to tourist facilities.

(2) A continuous sequence of dense pine forest (dating back to the Middle Ages), with marshes and lagoons ("pialasse") behind the dune ridge, of great natural value, pertains to the Po Delta Natural Park. The forest is partially endangered by increasing salinity in the phreatic underground water. The marshes and lagoons (some of which were artificially modified in the last two centuries) are affected by modifications in water exchanges with the sea, caused by the dismantling of the

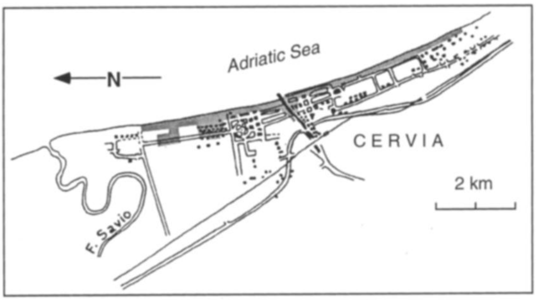

Figure 16. Areas flooded in Cervia by the 1986 storm surge.

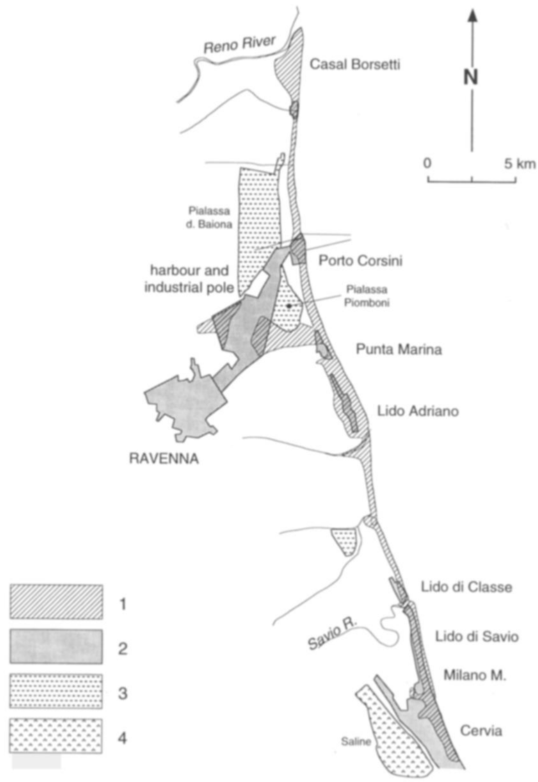

Figure 17. Areas liable to floods due to storm surges and river overflow in the Ravenna-Cervia area (after RONZANI, 1987, modified). (1) Likely flooded areas; (2) urban and industrial settlements; (3) lagoons and main marshes ("pialasse"); (4) Saline (salt marshes).

tideway network. The "pialasse" in particular now show a high risk of flooding: some parts of the industrial facilities close to Ravenna harbor have to be protected with long bulkheads.

(3) Reclaimed backlands with wide surfaces at or below sea level are protected only by a narrow dune and beach ridge. The entire area is being drained by a dense network of surface channels and pumping stations; the interruption of mechanical drainage would rapidly change the backlands into a wide marshy area with impeded runoff or permanent standing water. At the present time, areas liable to be flooded cover large strips, up to a maximum of 5 km (Figure 17). Storm-surges and water-flood hazards have certainly increased with the lowering of the dune and beach ridge protecting the backlands.

(4) Due to widespread land reclamation and to the continuous rise of the artificial levee, river channels are much higher than in the surrounding areas; there is no more sediment deposition balancing the subsidence of the floodplain. Furthermore, the narrowed stream sections are no longer capable of carrying the largest secular floods.

A near-future rise of the sea level and of brackish waters would certainly lead to a worsening of existing imbalances, building stability and security, *etc.* Such effects could reach critical thresholds within a short time, long before the end of the next century. If the eustatic rise reaches the revised IPCC high estimate (+25 cm by the year 2025, WIGLEY and RAPER, 1992) and subsidence rates remain the same as those recorded in the 1986–1992 interval, a total relative sea-level rise of 40–50 cm would occur in the study area as soon as 2025. On the other hand, in the case of subsidence rates close to the natural values and of a medium IPCC 1992 eustatic rise (+48 cm by 2100), the total sea-level rise will reach about 60–70 cm in the next century.

In both cases shoreline erosion will continue along the same trend, lead to a 50–70 m retreat of the beach due to beach-profile reshaping (GABBIANELLI *et al.*, in press). In some zones (Lido Adriano-Punta Marina), beach erosion will be even greater, up to 100 m or more, affecting tourist facilities.

Cervia. The local anthropomorphic subsidence is calculated by deducting the estimated natural subsidence from the total measured one. Topographical measurements were not available before 1950, but at that time effects of anthropomorphic activities can be considered as practically null. Levelings are available for the periods 1950–1980

(CARBOGNIN *et al.*, 1984) and 1984–1992 (COMUNE DI RAVENNA, 1993).

The former data concern the inner strip along the Adriatica highway for approximately 6 km and indicate a maximum subsidence on the southern side of the harbor with a value of 440 mm. For the interval 1984–1992, a total subsidence of 106 mm was measured in the Lido del Savio-Milano Marittima area, but about 4 km NNW of Cervia, with a rate of 13.3 mm/yr. By extrapolating this rate to 1980, a sinking value of 160 mm is obtained from 1980 to 1992 and a total subsidence of 600 mm (Figure 15), including 516 mm of anthropomorphic subsidence for the whole interval 1950–1992. Likewise, the total 1892–1992 subsidence is 716 mm.

As a consequence, flooding by storm surges is now a frequent phenomenon in the Cervia area (CARBOGNIN *et al.*, 1984; COMUNE DI CERVIA, *personal communication*) (Figure 16). The port wharves have been raised up with continuous walls and mobile bulkheads. A large part (about 2 km^2) of the Cervia territory, behind the littoral ridge (Salina di Cervia, Valle Felici), is now below sea level. According to recent and present-day trends, an additional 220 mm of residual man-induced subsidence is expected by 2020 when about 4 km^2 of land will be below sea level. Severe river flood risk is expected in the southern part of the territory and higher floods from sea surges in the old town centre.

CONCLUSIONS

Only a few sample areas could be considered in this study. They are sufficient, however, to give an idea of the diversity and extent of the problems which may occur locally as a consequence of climatic change. Potential dangers would be greatly worsened near river mouths, in lagoons, and along eroding parts of the coast by any rise in the relative sea level (whatever its cause, eustasy or land sinking). Finally, the frequency of sea surges would inevitably increase mechanically with a rise in sea level and even more so in the case of a more frequent passage of critically-deep atmospheric depressions (the same depressions which may also bring heavy rainfalls) and stronger winds.

During the last century, the loss in altimetric elevation has been very variable along the coast, changing from about 0.2 m in the more "stable" coastal areas to 2.7 m in the Po Delta. Owing to this and to increasing erosion processes, coastal defenses and river banks have had to be constructed or raised along long distances and certain exposed areas even abandoned to the sea. For the next century and even in the absence of new man-induced subsidence phenomena, a new altimetric loss of at least 0.5 to 1.5 m can be predicted, if the "best-guess" sea-level rise predicted by climatic models takes place. Most coastal lagoons will probably have to be closed or abandoned to the sea and continuous strong defenses constructed all along the remaining shore, to maintain activities in what will become more and more the "Italian Netherlands."

The low coastal area between Monfalcone and Cattolica has experienced, since at least Roman times, a common physical history under the influences of sea action, of river flooding and sedimentation and of human activities. Similar problems exist therefore for all this area, covering over 300 km of shoreline, in spite of several administrative boundaries.

There is a need to adopt an unified approach to deal with the common coastal problems of the next century. This work is intended as a first step towards the definition of a typology of coastal areas at risk in northeastern Italy.

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□ RIASSUNTO □

Lungo un tratto di oltre 300 km della costa dell'Alto Adriatico, tra Monfalcone e Cattolica, si trovano quasi 2400 km^2 di territorio situato sotto il livello del mare. Queste zone sono particolarmente eposte agli allagamenti provocati dalle onde di tempesta ("acqua alta") e dalle rotte fluviali. La subsidenza naturale o antropica è stata notevole in molte di queste zone, specialmente nel delta del Po, dove le perdite di quota assoluta hanno localmente superato 2,5 m nel corso dell'ultimo secolo. In questo lavoro vengono stimate le variazioni di livello relativo del mare che potrebbero verificarsi nel corso del prossimo secolo in seguito ad inevitabili fenomeni di subsidenza ed all'innalzamento eustatico del livello marino previsto da alcuni modelli climatici. Anche in assenza di aggravamenti della subsidenza di origine antropica, ci si può attendere entro l'amno 2100 una ulteriore perdita di quota di circa 0,5 m vicino alle lagune di Venezia e di Marano-Grado, di 0,6 m presso Ravenna e Cervia e di 1,5 m in certe zone del delta del Po. Un leggero aumento di profondità dei fondali dell'Alto Adriatico non comporterebbe, per fortuna, un incremento dell'ampiezza di marea e l'onda di tempesta causata dalle sciroccate non si aggraverebbe, ma agirebbe ad una quota relativamente piú alta. Tra le varie zone nelle quali il rischio di allagamento aumenterebbe nel prossimo secolo, si sono analizzati alcuni esempi significativi, corrispondenti a problematiche specifiche: la zona industriale Ausa-Corno dietro la laguna di Marano-Grado, il centro storico di Venezia, due zone campione nel delta del Po e la fascia costiera tra Ravenna e Cervia.

□ RÉSUMÉ □

Dans le nord-ouest de la mer Adriatique, le long de plus de 300 km de côtes entre Monfalcone et Cattolica, des régions littorales couvrant une superficie de presque 2400 km^2 sont situées sous le niveau de la mer. Ces régions sont susceptibles d'être inondées par des surcotes marines ou des débordements fluviaux. La subsidence, naturelle ou d'origine anthropique, y a été sensible dans le passé, surtout dans le delta du Pô, où depuis un siècle les affaissements on dépassé localement 2,5 m. Dans ce travail on tente d'évaluer des variations du niveau relatif de la mer qui pourraient se produire au cours du prochain siècle, du fait d'une présence inévitable de la subsidence (au moins naturelle) et de l'élévation du niveau eustatique de la mer prévue par des modèles climatiques. Même en l'absence de nouvelle subsidence d'origine anthropique, la perte prévisible d'altitude d'ici l'an 2100 varie de 0,5 m près des lagunes de Venise et de Marano-Grado, à 0,6 m près de Ravenne et Cervia, et jusqu'à 1,5 m dans certaines zones du delta du Pô. Dans une mer Adriatique devenue légèrement plus profonde, l'amplitude de la marée ne devrait heureusement pas augmenter. Quant aux surcotes provoquées par le sirocco, elles ne devraient pas croître, mais elles se développeront au-dessus d'un niveau marin localement plus élevé. Parmi les nombreux sites qui se trouveront exposés à des risques accrus au cours du prochain siècle, on analyse ici quelques exemples significatifs, correspondant à des problèmes spécifiques: la zone industrielle d'Ausa-Corno derrière la lagune de Marano-Grado, le centre historique de la ville de Venise, deux zones-type dans le delta du Pô et la région littorale entre Ravenne et Cervia.

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