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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.

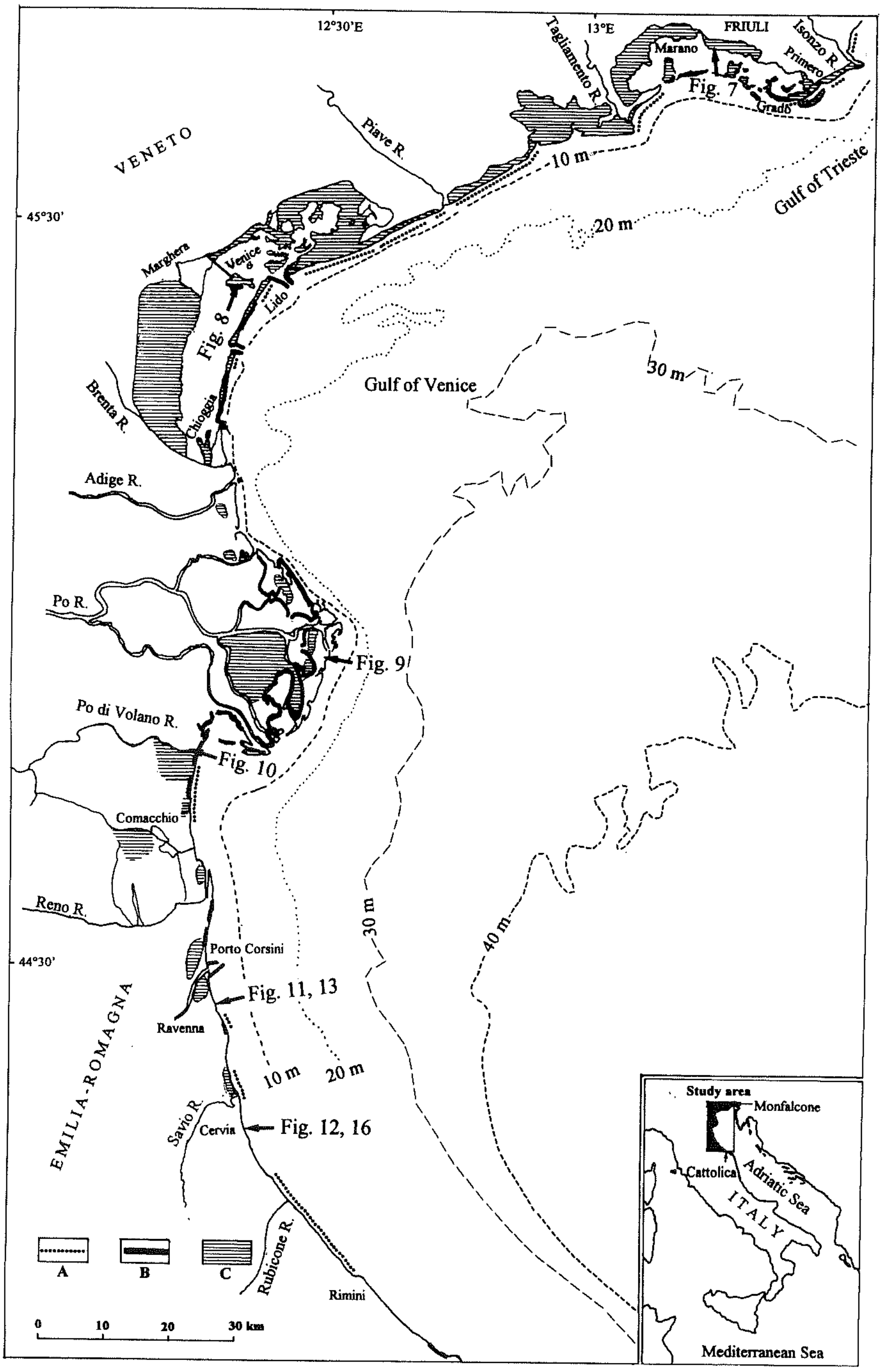

Figure 1. Location map of the study area. (A) groins, breakwaters; (B) seawalls, dikes, revetments; (C) approximate areas flooded by the November 1966 sea surge.

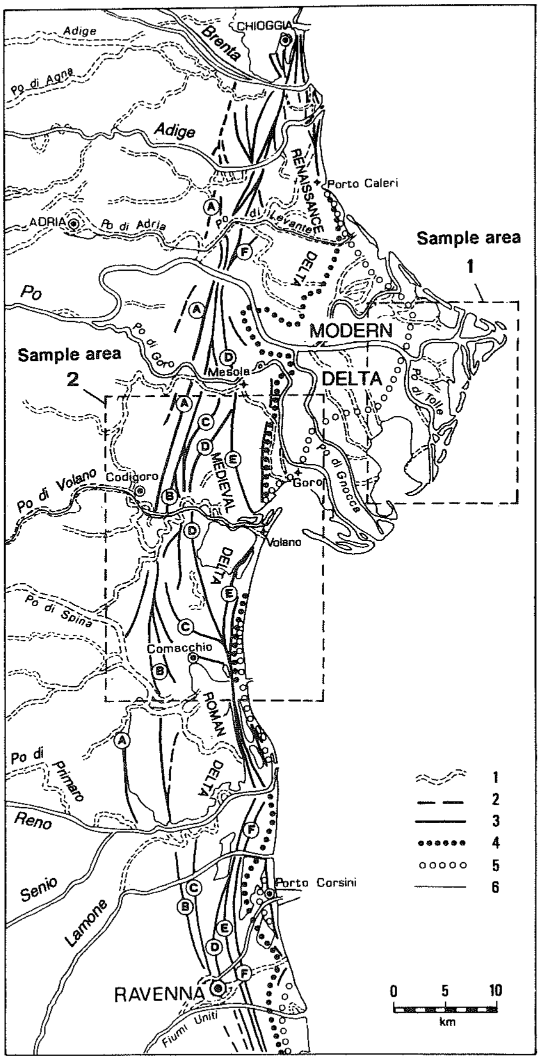

Figure 2. Geomorphological map of present-day and ancient mouths of the Po River (sample areas indicated). (1) main paleo-riverbeds; (2) main buried beach ridges; (3) main outcropping beach ridges, with ages: (A) earlier than 6th c. BC, (B) 6th-4th c. BC, (C) 1st–2nd c. AD, (D) about 6th c. AD, (E) about 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 km², 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.

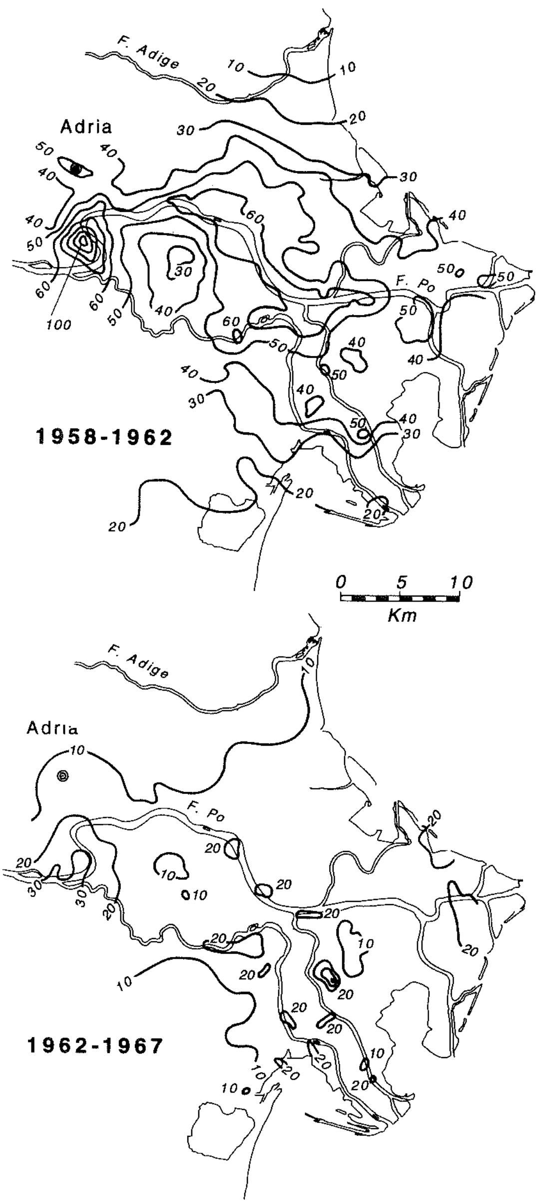

Figure 4. Countour lines showing land subsidence in the Po Delta are (in cm): (a) between 1958 and 1962; (b) between 1962 and 1967 (after CAPUTO *et al.*, 1970; BONDESAN and SIMEONI, 1983; BONDESAN, 1989).

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 45 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.