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GEOMORPHOLOGICAL HAZARDS IN THE PO DELTA AND ADJACENT AREAS (**)

Abstract: BONDESAN M., *Geomorphological hazards in the Po Delta and adjacent areas.*

Man has played an increasingly important role in the geomorphological evolution of that part of the wide coastal belt occupied by the present and ancient deltas of the Po River. Over the centuries, man has identified and faced various types of geomorphological hazard, from flooding to the threat of silting-up of the mouths of the Lagoon of Venice by sediments discharged into the sea from the Po. In order to control the river network, first embankments were built, hindering sediments from compensating the effects of subsidence: the course of the Po has been diverted several times. Colonization was completed with the draining of marshlands and lakes.

However, still today, this area faces a whole series of geomorphological hazards, some due to natural phenomena, such as geological subsidence and the eustatic rise in sea level, and others connected to man's activities. The unnatural altimetric conditions caused by the stabilization of the river network have been aggravated by artificial subsidence, due to reclamation itself or to other activities altering the state of underground waters. At present, almost the entire territory is under sea level and drainage is only made possible by the constant efficiency of a large number of pumping stations. The risk of breaching, now well under control, is accompanied by possible flooding due to drainage difficulties and above all by invasion by the sea. In recent decades, yet another cause of hazard has been the reduction of solid transport by the river, again due to man's activities (mainly gravel and sand quarrying from riverbeds). This reduction has given rise to a general tendency to beach and riverbed erosion, which not only considerably lowers the tourist value of the beaches but also increases the danger of invasion by the sea.

KEY WORDS: Coastal plains, Subsidence, Action of man, Morphodynamics, Po Delta (Italy).

Riassunto: BONDESAN M., *Condizioni di rischio geomorfologico nel Delta del Po e nei territori adiacenti.*

Nell'evoluzione geomorfologica della fascia litoranea comprendente l'attuale e gli antichi delta del Po, l'uomo ha giocato un ruolo via via più importante. Ha individuato e affrontato, nel corso dei secoli, diverse condizioni di rischio geomorfologico, dalle esondazioni fluviali fino alla minaccia di ostruzione delle bocche della Laguna di Venezia da parte dei sedimenti scaricati in mare dal Po. Per controllare la rete fluviale sono stati innalzati argini, impedendo ai sedimenti di compensare gli effetti della subsidenza; il corso del Po è stato più volte deviato. La colonizzazione è stata completata con il prosciugamento di paludi e stagni.

Ma ancor oggi quest'area è interessata da una serie di rischi geomorfologici. Le cause sono costituite solo in parte da fenomeni naturali, come la subsidenza geologica e l'innalzamento eustatico del livello marino; per il resto si tratta di cause connesse proprio alla stessa attività antropica. L'innaturale assetto altimetrico dovuto all'irrigidimento della rete fluviale è stato infatti aggravato dalla subsidenza artificiale connessa con la stessa bonifica idraulica o con altre attività che hanno alterato le condizioni delle acque sotterranee. Attualmente il territorio si trova quasi interamente in condizioni di depressione assoluta e lo scolo delle acque è reso possibile dalla costante efficienza di un gran numero di impianti idrovori. Al rischio delle esondazioni fluviali, oggi ben controllato, si è quindi affiancato quello di temporanei allagamenti per difficoltà di drenaggio, e soprattutto il rischio di ingressione di acque dal mare. Negli ultimi decenni è intervenuta un'ulteriore causa di rischio, la diminuzione di apporto solido fluviale, anch'essa conseguenza di attività antropiche, soprattutto dell'estrazione di materiali dagli alvei. Tale diminuzione ha determinato, oltre ad erosioni negli alvei fluviali, una generale tendenza alla erosione dei litorali. Questo fenomeno, oltre alla perdita del bene economico rappresentato dalle spiagge, comporta l'aggravamento del pericolo di ingressione marina.

TERMINI CHIAVE: Pianura costiera, Subsidenza, Azione dell'Uomo, Morfodinamica, Delta del Po.

THE TERRITORY AND ITS HYDROGRAPHIC EVOLUTION

An alluvial plain, inhabited by man since pre-historic times like the Po Plain (1), is generally considered to be subject to limited and well-controlled geomorphological hazards. The same cannot be said for the belt nearest the sea, where risks are particularly serious, due both to the rapid evolutional capacity of the territory itself and to man's activities.

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(1) The Po Plain also includes the Friuli and Romagna plains, which are not part of the Po hydrographic basin. The Po Plain covers 46,000 km^2 and occupies 270 km of coastline along the Adriatic.

(2) The actual annual mean discharge of the Po (hydrographic basin more than 70,000 km^2) is about 1500 m^3/s; its overall solid transport is 10.5 million tons/year.

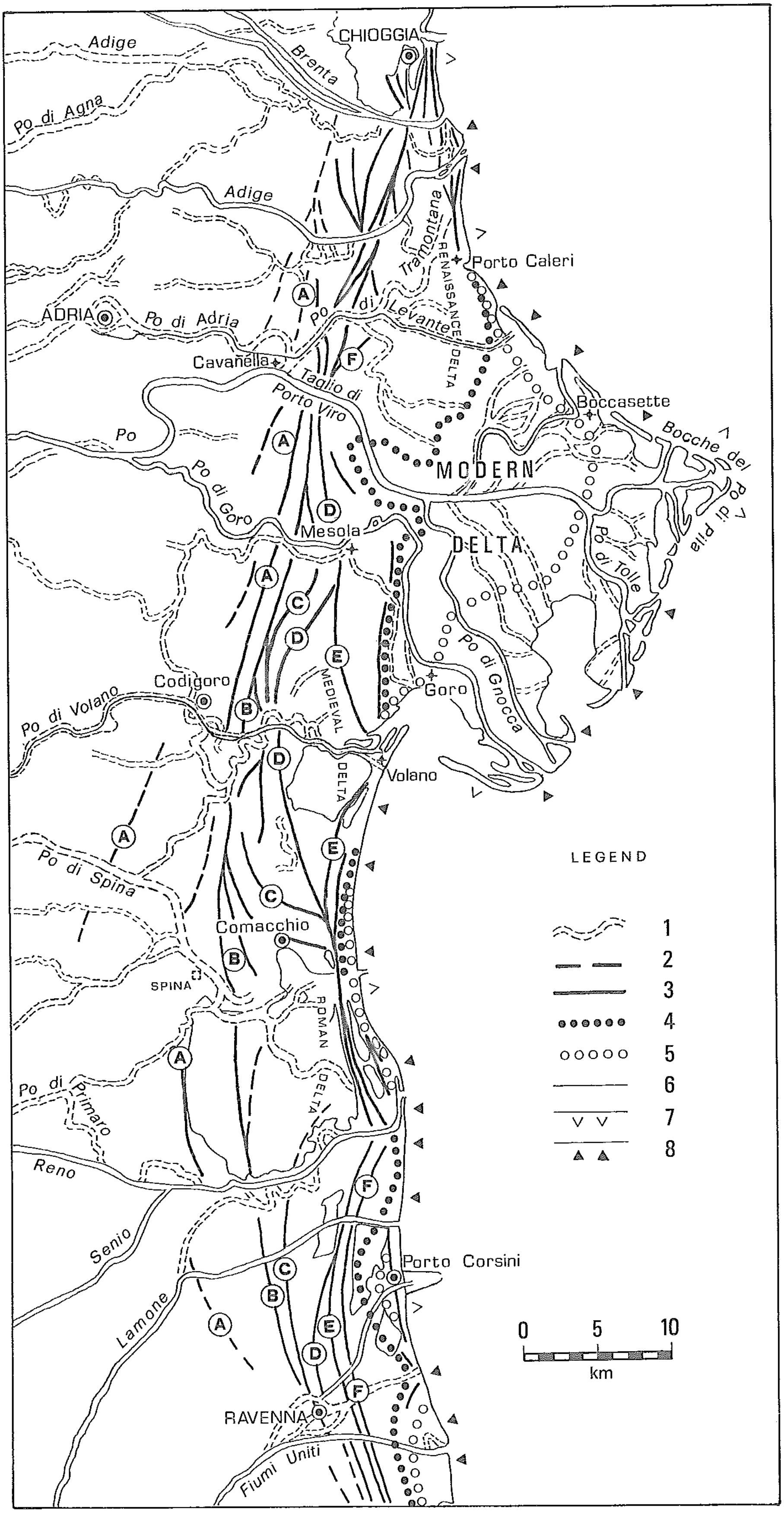

FIG. 1 - Geomorphological map of present-day and ancient mouths of the Po:
1) main paleo-riverbeds
2) buried beach ridges
3) outcropping beach ridges, with ages:
   A - earlier than 6th cent. B.C.
   B - 6th - 4th cent. B.C.
   C - 1st - 2nd cent. A.D.
   D - about 5th cent, A.D.
   E - about 10th cent. A.D.
   F - 13th - 15th cent. A.D.
4) coastline at end of 16th cent.
5) coastline in 1730-1740
6) present-day coastline
7) currently advancing beaches
8) currently eroding beaches.

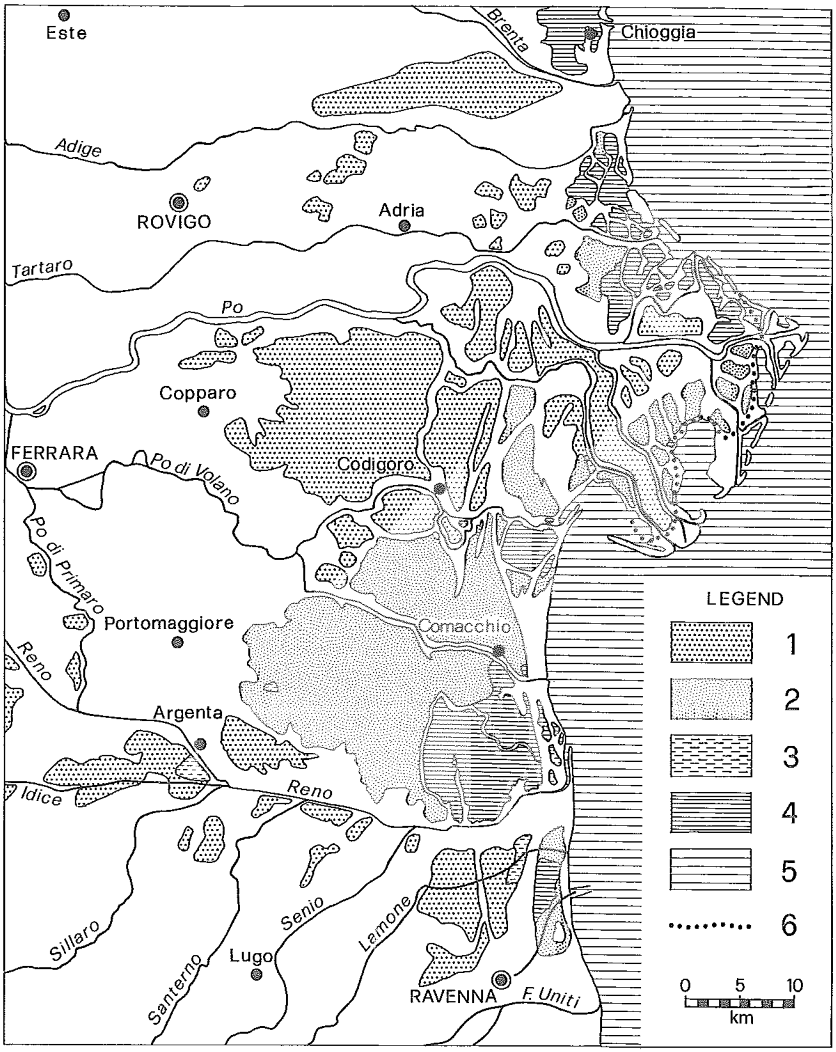

FIG. 2 - Bodies of water, reclaimed after 1870 and present-day:
1) reclaimed bodies of fresh water
2) reclaimed brackish lakes
3) present-day freshwater basins
4) present-day lagoons and brackish lakes
5) coastline in 1870.

These problems are clearly represented in the Po Delta [2] and in adjacent areas.

From the geographical viewpoint, by Po Delta we currently mean the peninsula between the Sacca di Goro (South) and Porto Caleri (North). However, if we consider the area covered by the mouths of the Po in the last 5,000 years, we see that it extends at least from around Ravenna as far North as Chioggia. The problems to be discussed later, although particularly noticeable in the present deltaic peninsula of the Po, characterize the whole coastal belt, which is of more recent formation.

In the Pleistocene and Holocene the Po tended to shift its lower course northwards, although this migration did not occur regularly and the current course is not the most northerly of those which have formed until now. One course of the late Bronze Age Po has been reconstructed, flowing further North than the present one through Rovigo and Adria (VEGGIANI, 1974), with one branch running from Rovigo towards Chioggia, into which the Adige may also have flowed (CASTIGLIONI, 1978). This course became extinct after a large breach near Sermide around the 8th century B.C. (FERRI, 1985). Most of the courses of the Po thus turned towards the location of present-day Ferrara. Much later, after a series of major breaches near Ficarolo around the 12th century A.D., the actual lower course of the Po began to predominate and, until the Renaissance, debouched near the actual mouth of the Adige (*Renaissance Delta*).

Between 1599 and 1604 the hydraulic engineers of the Republic of Venice, fearing that the sediments of both the Po and the Adige would cause the mouths of the Lagoon of Venice to silt up, diverted the Po near Cavanella into an artificial bed running South-East.

These works, called *Taglio di Porto Viro (Porto Viro Cut, or New Cut)* (fig. 1) caused the construction of the *Modern Delta*. In 1612 the branch of the most northerly of the mouths of the Po (Po di Tramontana) was closed, and in 1625 the entire *Renaissance Delta* was cut off from the hydrographic network of the Po. Only one branch of this network, the Po di Levante, is still active, bringing to the sea the river Tartaro, which is practically without solid transport (fig. 2).

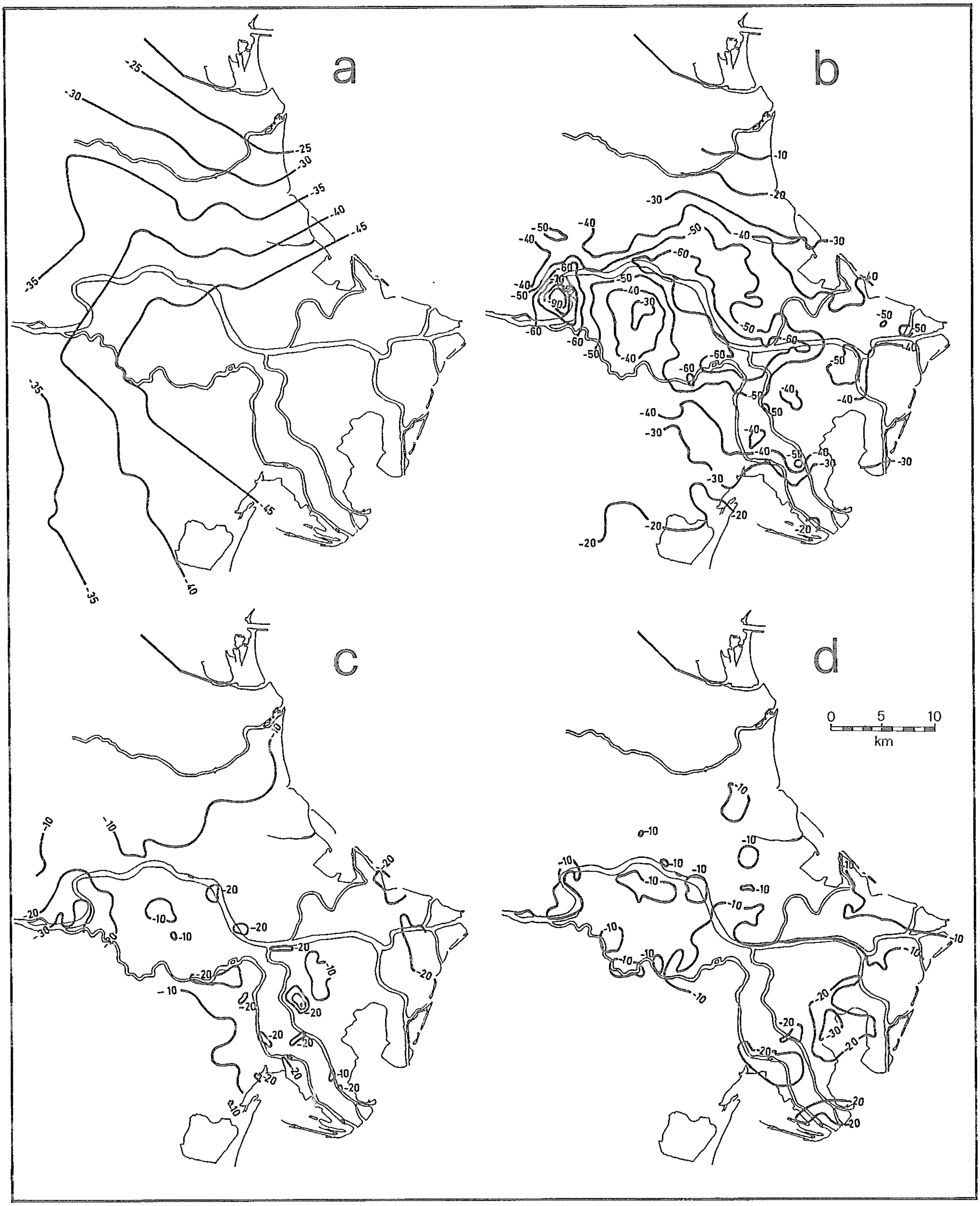

FIG. 3 - Contour lines showing soil lowering (in cm) at various periods in 20th century:
a) between 1900 and 1957 (CAPUTO & *alii*, 1970)
b) between 1958 and 1962 (CAPUTO & *alii*, 1970)
c) between 1962 and 1967 (CAPUTO & *alii*, 1970)
d) between 1967 and 1974 (BONDESAN & SIMEONI , 1983)

South of the abandoned delta, the new Po fan began to grow, with sediments brought by Taglio di Porto Viro and by the pre-existing Po di Goro (CIABATTI, 1967). The growth of the *Modern Delta* was characterized by many new branches, on which the Venetians continued to work to stabilize the more important branches flowing South (Gnocca, Tolle), at the expense of those flowing North. Later, in the 19th century, the Venetians almost completely closed the major branch, the Po di Maistra, concerned by the new mouth which the Po di Maistra had opened towards the North after the Boccasette breach (1827).

It is thus clear that the formation of the *Modern Delta*, which took place in less than 400 years, has been strongly influenced by man's activities (ZUNICA, 1971). However, this is only one of the numerous factors which demonstrate the close link between the presence of man and the morphology of this territory.

Other signs of this interaction may be seen in the radical transformation of the whole landscape of this area. Like most of the hinterland, the coastal plain had always been characterized by extensive marshlands, mainly produced by large-scale flooding due to breaches. Many of the lagoons and brackish lakes were also formed when small seaward bays were cut off by banks of sediments transported by longshore currents, or by seawater invasion on to already emerged or marshy land. Sometimes, however, it was man himself who, several centuries ago, created these bodies of water — mainly involuntarily, by favouring soil sinking. Most of these wetlands have now practically completely disappeared (fig. 2).

THE MAIN CAUSES OF HAZARDS

Man's presence in this area has mainly been a battle against nature, and against water in particular: geomorphological hazard has always existed, and man has constantly fought against it in order to defend his economic activities. But their excessive impact has now created other new hazards — the result of the very operations which man has carried out on the territory.

The most important situations and phenomena causing these hazards are:

- natural subsidence;
- rise in average sea level;
- rigidity of the hydrographic network;
- artificial subsidence;
- reduced solid transport by rivers.

Natural subsidence. Natural subsidence is due to the geological origin of this area and in particular to the conditions of the substrate. For example, the fact that, even in very recent times, subsidence has occurred at different speeds in different areas is not only due to the different compressibility of the sediments, but also to the shape of the substrate of the alluvial plain and to the movements to which it is still subject (neotectonics): it should be recalled that the southern part of the coastal belt rests on buried structures of the Appennine (PIERI & GROPPI, 1980).

Subsidence has been at work for millions of years, as shown by the fact that marine sediments, although always indicating shallow-water facies, overlap in some place to form banks several hundreds of metres thick. The velocity of natural subsidence in this area is estimated at 1-3 mm/year; the higher values are found in the *Modern Delta*.

Eustatic rise in sea level. The sea level has been rising since about 1850, and in recent decades has been estimated at around 1.4 mm/year. Many climatologists predict that it will gradually increase still further, due to the well-known *greenhouse effect*.

Rigidity of the hydrographic network. This stabilization, or rigidity, is due to the practice of building artificial embankments to contain the rivers. Although essential to protect man's towns and economic activities, this type of operation has prevented sedimentation in the interfluvial areas, and the river beds have consequently been brought to exaggerated levels. All the flood levels and high-water beds of the rivers crossing the low plain are far higher than the surrounding land. The same practice has also favoured the rapid growth of the peninsula of the *Modern Delta*, and has made the mouth branches of the river excessively long.

Artificial subsidence. In the studied area, artificial subsidence has had considerable effects (fig. 3), mainly due to disturbances in the water-bearing strata (BONDESAN, MINARELLI & RUSSO, 1986).

The following problems are particularly noticeable:

1) Strong lowering of the piezometric levels of confined aquifers, caused by the withdrawal of such large quantities of water that the aquifers cannot recharge them. The entire territory has been submitted to considerable pumping from artesian aquifers, particularly for agriculture and industry. Moreover, exploitation of methane-bearing waters from the Quaternary layers, mainly in the *Modern Delta* and surrounding areas, between 1938 and 1963, caused very considerable sinking of the soil, velocities sometimes exceeding 20 cm/year (CAPUTO, PIERI & UGUENDOLI, 1970).

2) Permanent lowering of the phreatic surface, caused by reclamation of saltmarsh or by operations connected with agriculture in general. These practices have caused sediment compaction, for both hydrostatic reasons and the chemical reactions which took place in the organic components of the sediments themselves (e.g., peat oxidation). Further artificial lowering of the watertable in order to maintain cultivable areas then led to further soil sinking, a vicious circle which has caused lowering exceeding 2 m in some areas.

3) Chemical alteration of groundwaters, particularly phreatic water-bearing strata, due to variations in the thickness between the saltwater-bearing layer and the overlying freshwater one, sometimes caused by forced drainage. In other cases, these phenomena are due to the introduction of liquids into the aquifer (sewage, industrial waste, percolation from garbage dumps, etc.).

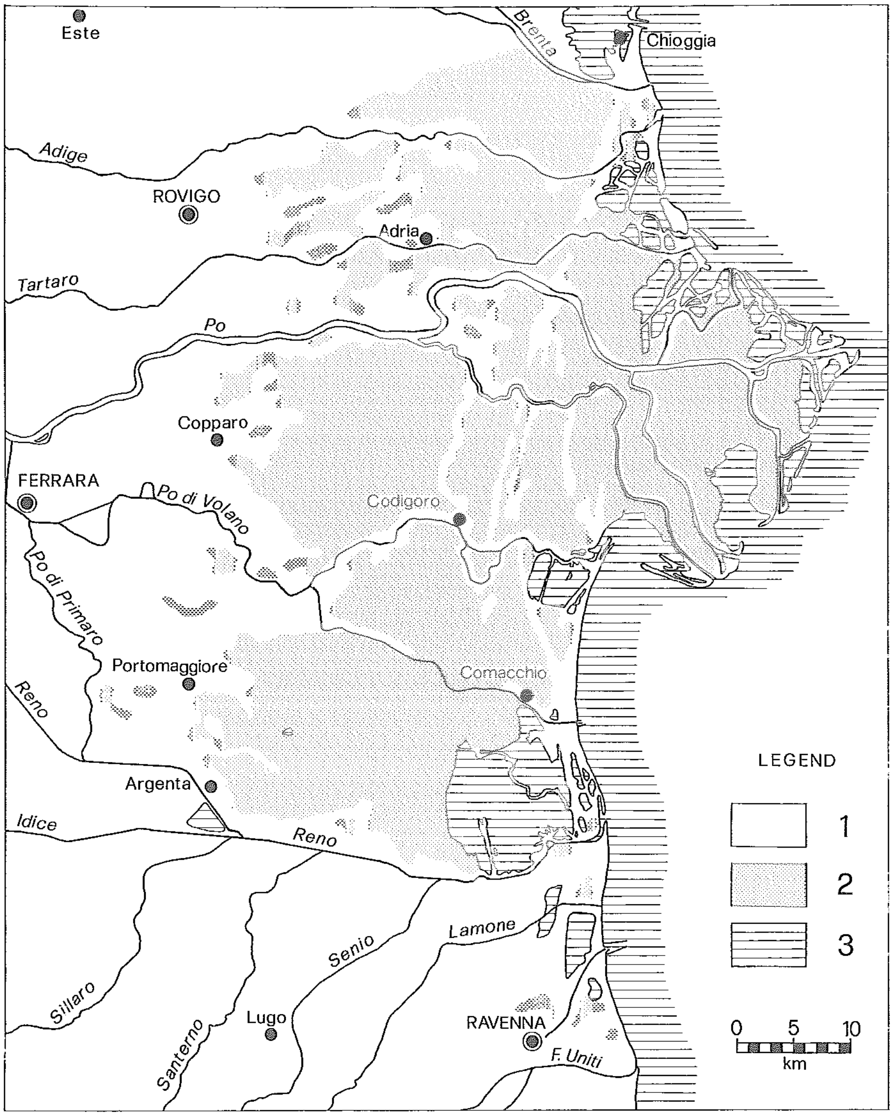

FIG. 4 - Altimetric situation of mapped area:
1) areas above sea level
2) areas below sea level
3) present-day lagoons and coastal lakes.

Reduced solid transport by rivers. The reduction in sediment transport by the Po has been particularly marked in recent decades, although it cannot be attributed to reduced liquid transport. To some extent it is due to the hydrogeologic pattern of the mountain basins and to dam construction (artificial lakes, etc.), but its main cause is the quarrying of gravel and sand from riverbeds, particularly intense after the Second World War.

The total solid transport of the Po fell from $16.9 \cdot 10^6$ tons/year (1956-64) to $10.5 \cdot 10^6$ tons/year (1965-73), a reduction of 38% (DAL CIN, 1983). Similar reductions have also occurred in very many other rivers. Sand transport at the mouth of the Reno, for instance, is now practically nil.

CURRENT CONDITIONS OF HAZARDS

The present situation is mainly the combined result of the above operations and problems.

One example of this combination is the altimetric situation which in itself represents an important geomorphological hazard. The stabilization of the drainage network had already raised the riverbeds above the surrounding areas, so that during the last few centuries breaches have been less frequent but more catastrophic. The last great flood of the Po at Occhiobello in November 1951 almost entirely submerged the central-eastern part of the province of Rovigo (99,500 ha).

In the area examined here, reclamation has mostly been carried out by direct pumping from marshlands and brackish lakes (3). Even in areas where the soil is not already

(3) Before the introduction of pumping, reclamation mainly involved the use of river sediments, i.e., the diversion of particularly turbid rivers (mainly the Appennine ones) into the areas to be reclaimed, which were then made into sometimes extensive water-meadows by carefully built external embankments. This system, which imitated the natural process, caused slight artificial subsidence, but it was very slow.

under sea level, artificial subsidence has led to this state. The only exceptions are the beaches, small strips of paleo-riverbeds, and the largest ancient beach ridges (fig. 4). Instead of being convex, the *Modern Delta* is now concave, with central depressions up to 4 m under sea level. Some sectors of the coastal belt have therefore become real polders, and waters draining from it (low waters) and generally also those coming from inland canals (high waters) must be pumped upwards in order to be brought to the sea.

Artificial subsidence often inverts canal gradients, requiring the partial rebuilding of canal networks, and the construction of new pumping stations and the reinforcement of existing ones. Obviously, breakdowns can cause serious damage. One significant case occurred in August 1979, when a violent storm caused the temporary failure of some of the main pumping stations South of the Po: enormous areas were flooded for more than two days (fig. 5). *Reclamation* here must therefore be considered not so much as an accomplished fact as a constant activity, and the more the sea level continues to rise and artificial subsidence proceeds, the more expensive this activity becomes.

As well as breaching, now well under control, one of the most serious risks is now invasion by the sea. Large dams have had to be built, both in direct contact with the sea and further inland.

Other geomorphological risks have been caused by reduced solid transport by rivers. The present solid transport of the Po is mainly composed of erosion products which the river removes from its plain bed. Although on one hand this type of erosion reduces the danger of breaching, on the other it threatens the stability of embankments and other artifacts (bridges, etc.). However, its most evident effect is accentuated beach erosion (BONDESAN & SIMEONI, 1983; DAL CIN, 1983).

Combined with artificial subsidence, beach erosion has practically halted the growth of the Po Delta in the last 40 years. In any case, it has aggravated the problem of invasion by the sea throughout the coastal belt, and has favoured the drowning of marshlands or areas which had emerged and in some cases had even been cultivated (fig. 6).

Breakwater systems have been built to protect the beaches along the southern part of the coast. However, these defences have mainly had exclusively local aims in view, as urgent remedies to contingent situations. Their benefit has

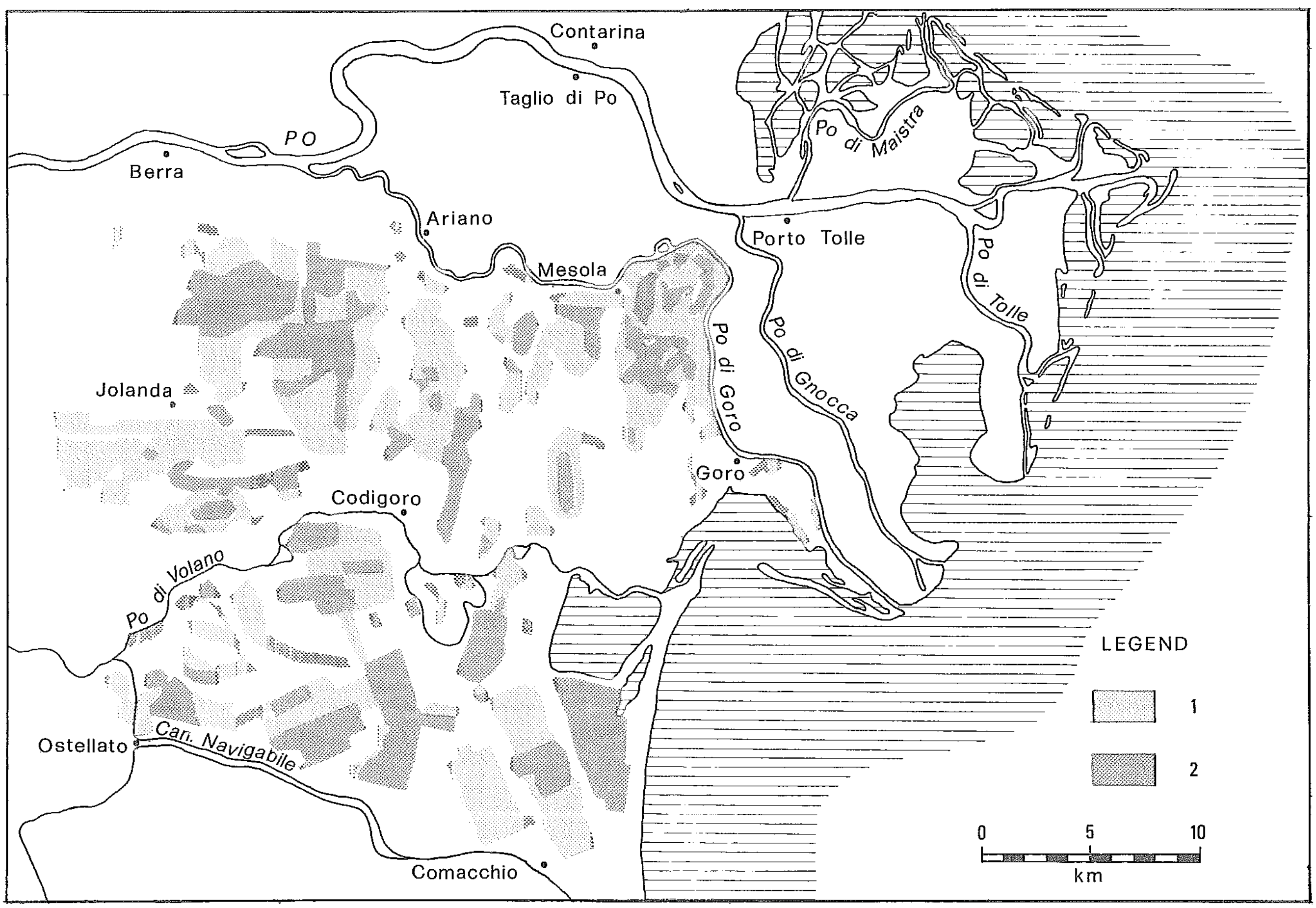

FIG. 5 - Flooding due to storm of August 18-19, 1979:
1) areas flooded for less than 48 hours
2) areas flooded for more than 48 hours.

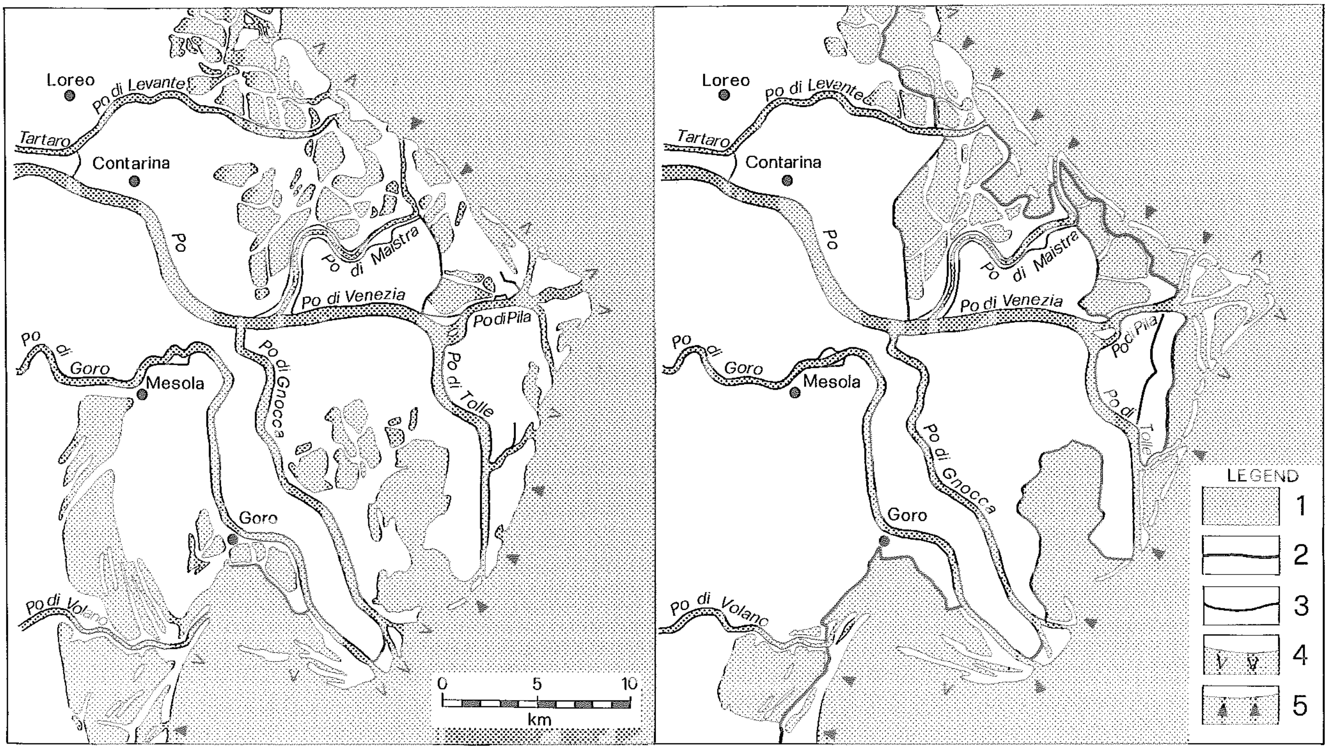

FIG. 6 - Comparison between situations in last 50 years:
1) sea and inland waters
2) main protective embankments
3) secondary protective embankments
4) currently advancing beaches
5) currently eroding beaches.
Note reduction of flooded area inland (reclaimed) and expansion of lagoons and brackish lakes in advanced part of delta.

therefore also been only local, but they have accentuated the erosion of nearby beaches (BONDESAN, CALDERONI & DAL CIN, 1979).

The breakwaters also degrade the very beaches they are supposed to protect, being both ugly and favouring seawater eutrophization near the coast. Other beach defence systems with less environmental impact are now being experimented, but the problem is difficult to solve when the river cannot bring down sufficient sediments.

CONCLUSIONS

The coastal belt of the Po deltas presents an interesting series of geomorphological hazards. Its management cannot neglect these problems — in the same way that it cannot neglect pollution, nor forget the need to protect the natural beauties of the area, many aspects of which are unique in Italy and rare in Europe.

As regards geomorphological aspects, at the current time man can and must concentrate his efforts on the negative phenomena he produces. For example, artificial subsidence has been greatly reduced by the fact that the withdrawal of methane-bearing waters, practised from the Second World War until 1963, has been discontinued. Other negative factors must now be minimized — decisions which can be taken by local authorities. The problem of reduced solid transport by rivers is different, and depends on the behaviour of entire hydrographic networks.

It is in any case essential to define a list of priorities to be followed when using the resources of both the hydrographic basin and local territories. Hydraulic security comes at the top of this list, but other land resources must be carefully evaluated, and possibly left to future generations.

The coastal area of the Po Delta must pass from its actual rigid tendency to a more elastic one. The creation of a natural park, integrated with existing activities and respecting the characteristics of its environment, may be the form of land exploitation which is the most compatible with its peculiar geomorphological problems.

REFERENCES

BONDESAN M., CALDERONI G. & DAL CIN R. (1979) - *Il litorale delle province di Ferrara e di Ravenna (Alto Adriatico): evoluzione morfologica e distribuzione dei sedimenti.* Boll. Soc. Geol. It., *97*, 1978, 247-248, 14 ff., 4 tt., 3 tabb.

BONDESAN M. & SIMEONI U. (1983) - *Dinamica e analisi morfologica statistica dei litorali del delta del Po e alle foci dell'Adige e del Brenta.* Mem. Sc. Geol., *36*, 1-48, 20 ff., 1 t., 14 tabb.

BONDESAN M., MINARELLI A. & RUSSO P. (1986) - *Studio dei movimenti verticali del suolo nella provincia di Ferrara.* St. Idrogeol. sulla Pianura Padana, *2*, 1-31, 16 ff., 1 tab.

CAPUTO M., PIERI L. & UGUENDOLI M. (1970) - *Geometric investigation of the subsidence in the Po Delta.* Boll. Geof. Teor. Appl., *13* (47), 187-207, 15 ff.

CASTIGLIONI G.B. (1978) - *Il ramo più settentrionale del Po nell'antichità.* Atti Mem. Acc. Patav. Sc. Lett. Arti, *90*, 157-164, 1 f.

CIABATTI M. (1967) - *Ricerche sull'evoluzione del delta padano.* Giorn. Geol., Ser. 2, *34* (2), 1966, 381-406, 4 ff., tt. 38-39.

DAL CIN R. (1983) - *I litorali del delta del Po e alle foci dell'Adige e del Brenta: caratteri tessiturali e dispersione dei sedimenti, cause dell'arretramento e previsioni sull'evoluzione futura.* Boll. Soc. Geol. It., *102*, 9-56, 22 ff, 1 t., 5 tabb.

FERRI R. (1985) - *Geomorfologia antica del territorio di Sermide (Mantova) attraverso lo studio del microrilievo.* Ann. Univ. Ferrara, *9* (1), 1-17, 8 ff., 1 t.

PIERI M. & GROPPI G. (1980) - *Subsurface geological structure of the Po Plain (Italy).* C.N.R., Prog. Fin. Geodinamica, s.p. Modello Strutturale, *414*, 13 pp., 6 tt.

VEGGIANI A. (1974) - *Le variazioni idrografiche del basso corso del Po negli ultimi 3000 anni.* Padusa, *1-2*, 39-60, 5 ff.

ZÙNICA M. (1971) - *Le spiagge del Veneto.* C.N.R., Ricerche sulle variazioni delle spiagge italiane. Centro St. Geogr. Fis. Padova, *8*, 144 pp., 18 ff., 18 tt., 20 tabb.