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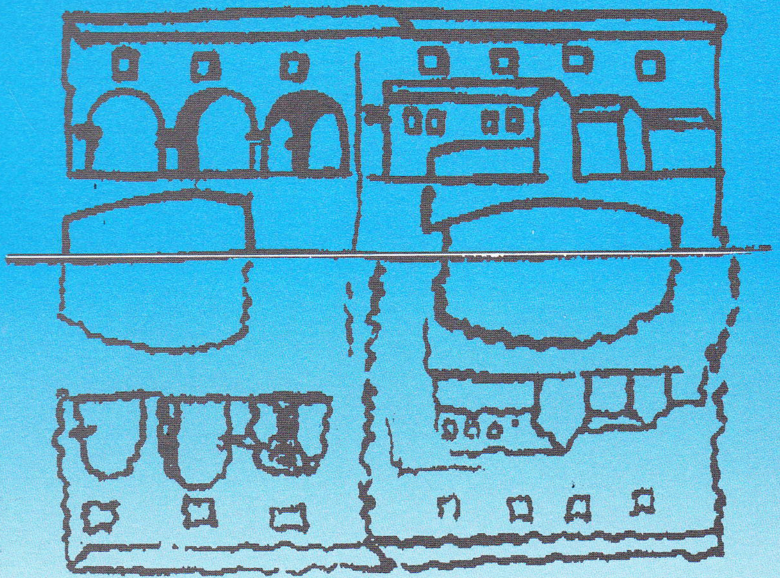
VENICE AND FLORENCE
A COMPLEX DIALOGUE WITH WATER



24 Maggio 1997

Sala delle Nazioni — Fortezza Da Basso
Firenze

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Symposium

VENICE AND FLORENCE: A COMPLEX DIALOGUE WITH WATER

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VENEZIA

THE PROBLEMS OF VENICE: AN INTRODUCTION

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ABSTRACT

The paper refers a few notes about the main problems of Venice and its lagoon.

1. - The problems that the conservation of Venice and its lagoon faces nowadays are many and fairly complex. Through the centuries such problems have attracted the interest of scientists and practitioners, in particular - in the last two centuries - through the longstanding interest of the School of Hydraulics of the University of Padua and of Istituto Veneto di Scienze, Lettere ed Arti, though gaining widespread visibility, and specific attentions from the government, only after the major flooding of Nov. 4, 1966. During such infamous event, the maximum tidal elevation recorded at Punta della Salute reached +1.93 m above the 1897 m.s.l. measured there (some 23 cm less than the current m.s.l.) and, should we say luckily, in times of low astronomical tide.

The problems revealed by the flooding - far from new, tied as they are to man-made works some dating back to 150 years - were of various nature. The one perhaps most evident concerns high tides and their possible control, but many more are conceivable. Among less evident, but rather crucial, issues one recalls:

- the ratio of the lagoonal environment with a widely exploited and inhabited runoff-contributing mainland;
- morphological matters related to erosive powers of tidal streams and to the structure of tidal channels and networks, capable as they are to alter naturally developing landforms;
- navigation issues and the role and future of economic activities whose sustainability is widely debated.

2. - The protection of downtown Venice and of the inhabited Lagoonal islands from recurrent flooding was initially discussed in terms of the simplest conceivable approach. The debate focused then on the most suitable interventions solely at the tidal inlets and yet capable to introduce head losses suited to reduce the frequency of high tides to the acceptable values of the early '900: in the average 7-8 times a year vs the current 40 (relative to the flooding threshold of +0.80 m a.m.s.l. which warrants safe circulation through most of the city - with the notable exception of the S. Marco area). Nevertheless, the size of the restrictions at the inlets which would have granted such conditions proved immediately incompatible with both an above-survival port activity and an acceptable exchange of water volumes with sea. This bears obvious impacts (far from obvious to quantify) on lagoonal water quality. With inlet cross-sections reduced to 100x12 m^2 at Lido, 120x15 m^2 at Malamocco and 50x7 m^2 at Chioggia, early (1972) studies showed that +0.80 m floodings could have been reduced from 40 to 8 for 1968 and from 52 to 10 during 1969, though with unacceptable impacts as discussed before.

From such a tenet, the basic design idea has developed, i.e. that of mobile barriers at the mouths for tidal control. It came immediately to mind a related, nontrivial problem: if the number of closures per year increase above some threshold, a considerable reduction in the exchange of water volumes between sea and lagoon would occur and - although not as seriously like in the case of permanent closures - serious environmental impacts were foreseen. Also, management problems would have surfaced because of the number of closure operations even considering the probability of false alarms due to imprecise forecasts of high tides - far from unthinkable.

Through these observations, some 20 years ago, a solution was engineered that could couple the obvious advantage of protecting from extreme surges and at the same time could provide a safe and manageable operation. The key factor was the design of a topographic threshold elevation of *insulae* (i.e. islands) above which closure would be granted. The *insulae* project was then originated: local protections are pursued via a careful topographic inspection and a connected set of intertwined locking systems aimed at reducing the frequency of inlet closures to acceptable values, with obvious advantages on both the management of the barriers and on in-town housing values (due to the acquired certainty of survival of ground-elevation flats and structures).

3. - The value +1.93 m above the mean (1897) sea level was attributed a return period of 200 years. Such result was obtained by a statistical analysis of the time series of maximum annual values from 1872 to 1972, once the series has been made stationary by subtracting the loss of elevation (about 23 cm) due to sea-level rise and subsidence accurately evaluated independently. The computations were therefore referred for each year to its current mean sea level: thus +1.70 m a.m.s.l. in 1966.

The fitting function adopted allows a few interesting remarks. In fact, the return period (or frequency of exceedence) of predefined events, referred to the ancient m.s.l. of Punta della Salute, can be computed as:

altezza [m]	Tr (anni)
+1.00	<1
+1.40	≈ 6
+1.60	≈20

Another interesting elaboration, extended from 1950 to 1993, shows the time distribution of events larger than +0.60, +0.80 and +1.00 m referred to m.s.l. of Punta della Salute. The results are interesting one the one side because they extend the observational basis to the last 44 years; and on the other because they allow the evaluation of the number of floodings underwent by S. Marco's square - whose threshold is as low as +0.60 m a. (current) m.s.l. In fact:

per h > 0.60 m 200 times (r.m.s. $\sigma = 68$)
per h > 0.80 m 40 times (r.m.s $\sigma = 16$)
per h > 1.00 m 6.6 times (r.m.s. $\sigma = 5$)

Such results show that the protection of the square against relatively minor events (≤1.00 m a.m.s.l.) may considerably reduce the number of floodings, with the obvious implications towards the research of a feasible solution .

4. - Downtown Venice and the islands do not share the same topographic elevations. Nor is uniform the spatial distribution of significant artwork and architectural treasures - there is no doubt, though, that the insula within S. Marco, unfortunately the lowest, deserves a greater attention than other still valuable areas. The threshold elevation for protection of each insula depends on local conditions, in the widest sense, aimed at keeping the control elevation the highest possible. Unfortunately the minimum control elevation, defined by the above conditions, also defines the operations at the barriers once possibly in operation. This is precisely the case of the insula in S. Marco: the most fragile environment, the lowest, is the richest in history and art, truly the heart of Venice. For S. Marco the control up to (+1.00) - (+1.10) would currently yield without operations at the inlets, the frequency to the values of the early '900 s.

The protection of Venice and its lagoon is therefore an ancient and well-known problem. It was declared is the past, since the 16th century (Cristoforo Sabbadino 1487(?)-1560) - but by some people still nowadays - that the main enemies of Venice were (and are?) the rivers, the sea and the man. This statement is only partly true. Without the sea Venice would perhaps not exist; or, though existing, it would be a town like many others. But also without men Venice would not exist for two fundamental reasons: because it was built and then defended. And men, still today, are required for its protection against high tides on the one hand and, on the other, against sediment transport within the lagoon and its related morphological transformations .

A great advantage distinguishes out times with respect the ancient ones: nearly everything we know about lagoonal phenomena has been defined and explained in the last 15 or 20 years, with due respect for venetian hydraulics of the past, of course.

5. - The conclusions of these concise notes as an introduction shows that the final solution of the problem must be found by different and complementary operations: the *insulae* against relatively low tides (<+1.00 m); the mobile (and invisible) barriers against higher tides; but also accepting a quite different social and economic model for the activities agricultural as well as industrial - of the its runoff-contributing mainland (≈1800 km^2 wide) which drains into the lagoon through its channel network.

PROTECTION OF VENICE AND OF THE OTHER INHABITED AREAS IN THE LAGOON FROM HIGH WATER

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ABSTRACT

The causes for the worsening of the high water phenomenon in Venice are illustrated and the projected works at the mouths to protect the town and the other inhabited areas of the lagoon are described. In particular, the hydrodynamic problems relating to the design of the sluice-gates which will form the mobile barrriers against exceptionally high tides are explained.

1. INTRODUCTION

Having evolved just before the year 1000 from the old defensive settlement of Rivoalto, Venice turned in a relatively short time from an agricultural community into an enterprising sea town (Bosio, 1986). As its economic power increased, following remarkable commercial expansion, hydraulic engineering and coastal works were carried out to adapt and preserve the lagoon as the port basin of Venice (Zorzi, 1980).

The first problem the Republic of Venice had to solve concerned the *physical conservation* of the lagoon to prevent it from silting up as a result of the sediment transported by the *rivers flowing* into it. Therefore, within a couple of centuries, in particular between 1500 and 1700, the mouths of the Brenta, the Bacchiglione and the Piave were diverted from the lagoon through radical hydraulic transformation works (Fig. 1).

The second problem to be faced, closely linked to the first, was how to maintain the *vitality* of the lagoon, necessary to ensure an acceptable quality of the water by renewing it. The inflexible legislation passed by the "Serenissima" to protect the integrity of the lagoon, combined with the authoritative action of the "Magistrato alle Acque" in enforcing it, contributed to the attainment of this objective (Rompiasio, 1733).

A third problem which has always been connected with the commercial development of Venice concerns the *navigability* of its inlets. The already reduced water depths at the mouths, due to the formation of sand bars produced by the littoral currents, proved to be totally inadequate with the advent of steamships. The problem was substantially solved through the construction, between the middle of the 19^{th} century and the beginning of the 20^{th} century, of jetties to protect the mouths (Noli, 1990). Subsequently, limited dredging work was sufficient to maintain the water depths.

The lagoon of Venice is separated from the Adriatic Sea by a thin littoral barrier. After the low and mid course of the Piave river were relocated, it received - through the littoral currents - insufficient renewal of the sediments which were eroded by the waves. Towards the middle of the 18^{th} century, in view of the precariousness of the repeated attempts to *protect the littoral* by using flexible systems of piers, branches and stones, a stable defence of the more exposed littoral at Pellestrina was designed and built using blocks of stone from Istria bound together by Pozzolana cement (Zendrini, 1743). This imposing work, known as the "murazzi", has effectively survived up to the present day (Gottardo, 1976). Some extraordinary repairs were necessary after the sea-storm of 1825 and, in particular, after the one in 1966 (Tomasicchio, 1983). On that occasion, the reinforcement was made by adding an impermeable diaphragm down to a deep clay level so as to be able to temporarily isolate the lagoon from the sea at different levels without the risk of siphoning.

During the second half of this century, an old problem which previously had not caused particular concern, became more and more serious: *the protection of the towns in the lagoon and in particular of Venice from high tides (called "high water") and, above all, from exceptionally high tidal levels.* Connected with

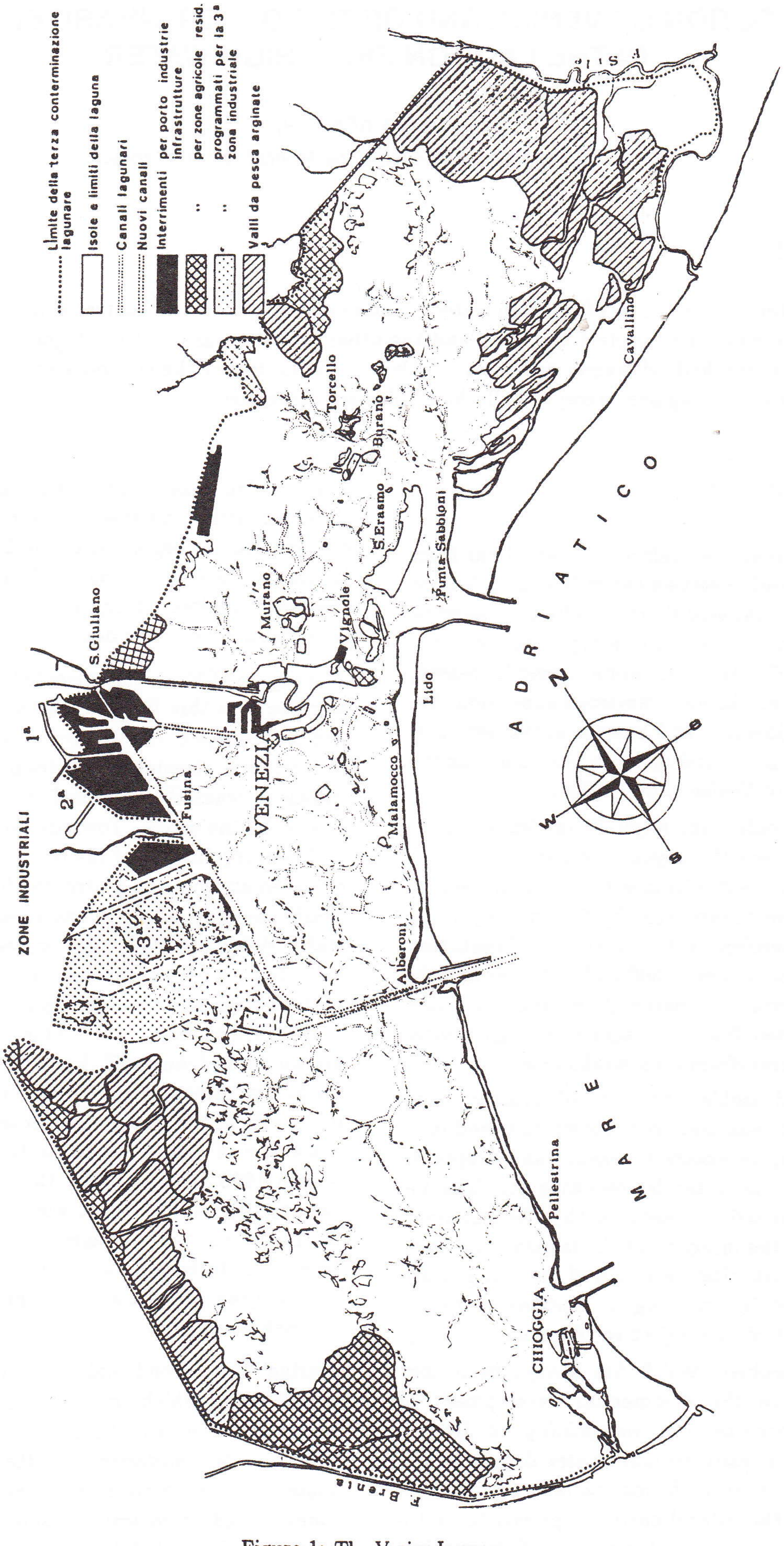

Figure 1: The Venice Lagoon.

this problem, in so far as the causes are to a large extent the same, is the morphological change of the lagoon, with the disappearance of low-lying lands (called "barene" and "velme"), and the weakening of the marine littoral of the lagoon. In order to understand the mechanisms which form the basis of the above-mentioned phenomena, it is necessary to provide some information concerning the processes which have a decisive influence on these phenomena: the tides, eustasy and subsidence of the lagoon region.

2. TIDES

The tides in the Adriatic Sea (Tenani, 1935; Defont, 1961) are generally of an astronomic nature and their principal component is semi-diurnal. The average annual range of amplitudes is about 60 cm, varying between 40 cm in the quadrature and 70 cm in the syzygy. The effects of the seiches of the Adriatic and, above all, the actions due to atmospheric phenomena, such as the wind and low pressure, can be superimposed on the astronomic tide.

The tides enter the lagoon of Venice through the three inlets of Lido, Malamocco and Chioggia and they propagate mainly along the ramified network of submerged channels. The tide levels in Venice are measured by the gauge at Punta della Salute whose zero mark is anchored to the mean sea level of 1897. High water means water whose level exceeds 0.70 m, which corresponds to the height in the lowest zones of piazza S. Marco, and exceptionally high water ("acque alte eccezionali") is that exceeding a level of 1.10 m. The flooding area of Venice, due to progressive tide levels, is shown in Table 1 (Frassetto, 1976).

The tides of Venice (Punta della Salute) have been increasing this century as regards both the values of the maximum elevation reached and the frequency with which the various levels are exceeded. Fig. 2 shows the annual distribution of the tides ≥ 1.10 m at Punta della Salute in the period between 1923-1996 (Centro Previsioni a Segnalazione Maree del Comune di Venezia, 1997). A strong increase can be seen between 1950 and 1960 followed by subsequent relative steadiness.

Considering that the amplitudes of the tides in the Adriatic have not undergone any statistically appreciable modifications, the causes of the increases can only be the following:

(a) increase in "amplitude" of the tides inside the lagoon:

(b) increase in the "difference in height" between the lagoon territory and the mean sea level.

The first factor derives essentially from the influence of the lagoon inlets (called "mouth") on the reduction of the tidal wave. The construction, between 1850 and 1920, of the embankments of the three inlets, from Malamocco to Lido, was certainly influential in reducing the tide at the entrance to the lagoon (Adami, 1974). Other concurrent causes are related to the lowering of both the waterways and the lagoon basin as a whole. However, this fact is of secondary importance to Venice as it is already very close to the mouth of Lido. The correlation between the tide in the Adriatic, at the Lido pier, and the tide at Punta della Salute is, in fact, already well rep-

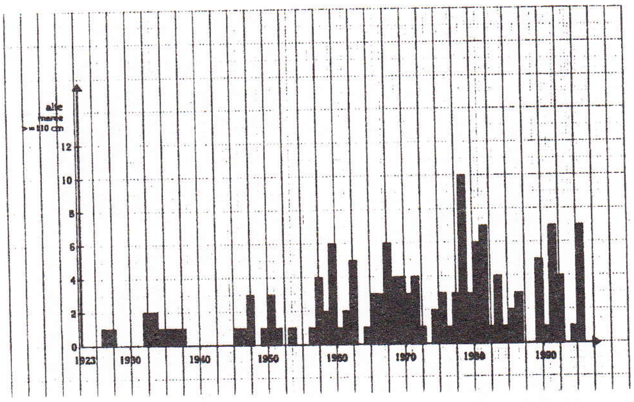

Figure 2: Tide levels ≥ 1.10 m at "Punta della Salute" in the period between 1923-1996.

Tide levels	Area	
m	Ha	%
0.90	1.1125	0.29
da 0.91 a 1.00	13.8763	3.56
da 1.01 a 1.10	45.8017	11.74
da 1.11 a 1.20	137.3544	35.18
da 1.21 a 1.30	268.4702	68.75
da 1.31 a 1.40	352.2110	90.19
da 1.41 a 1.50	379.1634	96.33
da 1.51 a 1.60	387.6498	99.27
da 1.61 a 1.70	389.4623	99.74
da 1.71 a 1.80	389.9061	99.86
da 1.81 a 1.90	390.4311	100.00
1.90		

Table 1: Flooding areas of Venice for progressive tide levels.

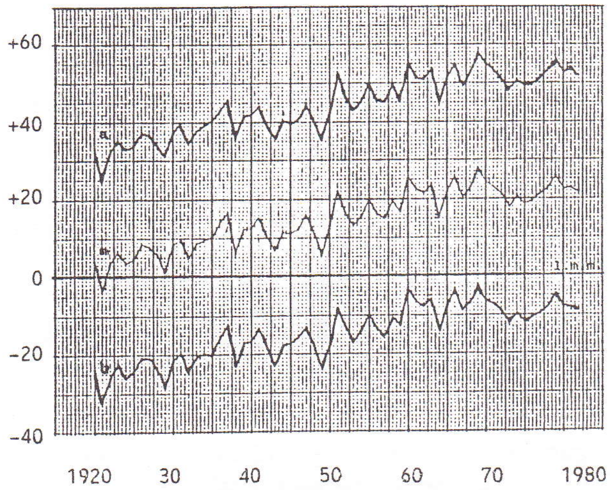

Figure 3: Trend of the annual mean levels of high tides (a), low tides (b) and of the mean sea level at "Punta della Salute" in the period 1920-1982 (from Canestrelli et al., 1983).

resented by a mathematical model of the *static* type which considers only flow resistance in the channels of the mouth as effective for the purposes of propagation (Ghetti, 1979, 1991).

The propagation of the tidal wave *inside* the lagoon has been studied using both *one-dimensional* mathematical propagation models, starting from the studies of Supino (1955), Pezzoli (1958, 1970) and Dronkers (1969, 1972), and *two-dimensional* propagation models (Datei, 1972), based on the finite difference method, among which I recall, in particular, the DHI model (Consorzio Venezia Nuova, 1987-88), or based on the finite element method (Consorzio Venezia Nuova, REA 1989). These models were used to examine the consequences of some modifications to the lagoon basin, such as digging the "oil canal", opening up of the marshes for fishing to the tidal flow, etc., all of which revealed a modest influence on the maximum levels in the centre of Venice.

The average trends of the high and low tides (Fig. 3, from Canestrelli et al., 1983) indicate that their difference, that is to say the average range of amplitude, increased at the most by 3 cm after 1920. Such an insignificant change does not justify the considerable variation which occurred during the same period in the maximum levels, which rose (together with the minimum levels) by more than 20 cm on average. Thus, cause (b) is *decisive*, that is to say the increase in the difference in height between the land and the mean sea level, an increase which derives from "eustasy" and "subsidence" phenomena.

3. EUSTASY AND SUBSIDENCE

An average rise - eustasy - in the order of 1 mm a year since the beginning of this century has been recorded in the mean level of the Adriatic Sea. From a comparison with the situation of the Adriatic at Trieste, a rise of 9 cm in the level has been estimated from the end of the 19th century to 1970 and a more or less stationary level subsequently.

This is a considerable variation; however, the most important contribution to the change in the difference in height between the land and the mean sea is attributed to the phenomenon of *anthropic subsidence* (Gambolati et al., 1973-74; Supino, 1978), mainly due to groundwater withdrawal for indrustrial purposes in the area of Porto Marghera (suspended at the beginning of the Seventies). The assessment made by the CNR (Carbognin et al., 1981) and recently confirmed (Carbognin et al., 1996), leads to the assumption of a lowering of approximately 13 cm from 1900 to 1980, reduced to 11 cm following an elastic recovery after withdrawal was stopped. *Natural subsidence* - compaction of the underlying layers - is to be added to the above value and for this century can be evaluated as being 3 cm. Lowering of the ground for the latter reason occurred naturally also in previous centuries and this can be seen in Venice from the thresholds of the oldest buildings which today are at mean sea level, whereas at the time of construction they must have been at least at the level of the mean high tides (Marchi, 1986).

On the whole, observations confirm the belief that the mean sea level with respect to the land at Punta dalla Salute has risen by 23 cm since 1897.

Fig. 4 shows, in a semilogarithmic diagram, an interpolar straight line of decennial frequency of the maximum tide levels at Punta della Salute between 1966 and 1994 (data obtained by the municipality of Venice, 1996). The very good alignment of the points indicates a reliable exponential distribution. In the same figure, a straight line has been dashed parallel to the previous one translated towards the bottom by 23 cm. It can be seen that the frequency variations noted on the new line substantially correspond to those which occurred last century.

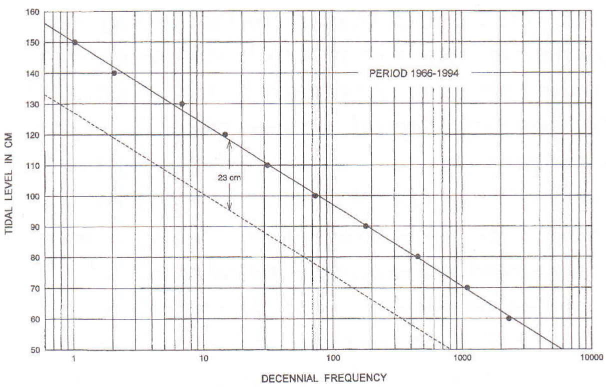

Figure 4: Decennial frequency of the maximum tide levels at "Punta della Salute" between 1966 and 1994.

For example, the level of 1.10 m, the beginning of exceptionally high water, which is now reached on average 30 times in ten years, under the conditions at the beginning of this century was only reached 4-5 times, as confirmed by the dashed line.

4. PROTECTION WORKS

The problem of flooding in Venice, which until the end of the 19th century - as already said - had been a marginal problem due to its exceptional nature, is of primary importance today. It is sufficient to think of the damage and inconvenience caused even last autumn when the 1.10 m level was exceeded 7 times and there were two tides of more than 1.30 m at Punta della Salute. The consequences of the exceptional event in November 1966 were particularly serious when the high water reached a maximum level of 1.94 m, flooded the whole town of Venice and, due to the aperiodic form of the tide (see Fig. 5), remained for 12 hours at a level above 1.40 m. Extremely huge works from the technical and economic points of view (Ghetti et al., 1983) are needed to protect Venice and its lagoon from undesidered tidal effects, while at the same time respecting the conditions which will ensure the exchange of sea - lagoon water, navigability of the inlets, stability against localised erosion and last but not least, the requirement that the works do not alter the landscape of the lagoon.
Conceptually, the criteria for the works at the inlets can be of two different types, based respectively on passive defence from the tides or on their control. Therefore, they consist in the following choice:

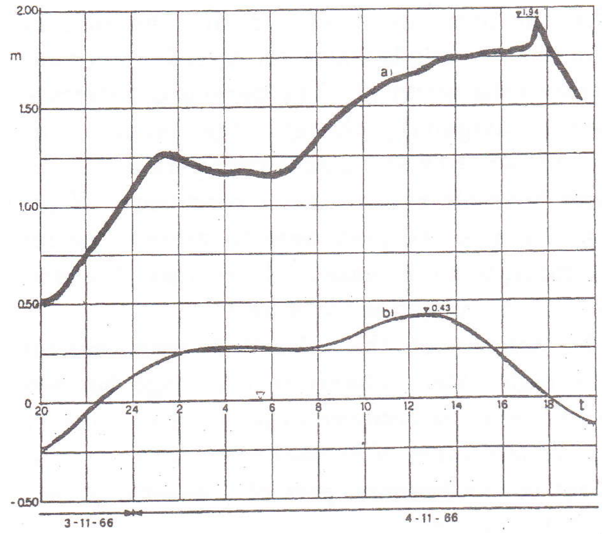

Figure 5: The exceptional high tide in November 1966: a) measured levels at "Punta della Salute"; b) astronomic prediction (from Ghetti, 1979).

1) create flow resistance in the sea-lagoon mouths through fixed works, barrages, narrowings or other, so as to reduce the amplitude of the tide in the lagoon with respect to that in open sea;

2) install mobile floodgates at the mouths such that they do not interfere with the ordinary flow but can completely stop the tidal flow when it is about to reach the maximum limit considered acceptable for Venice.

The first process, in order to obtain an appreciable reduction of the levels in the lagoon, requires very considerable narrowings in the three mouths. This involves reductions of the same order of magnitude on the tidal flows and consequent negative effects on the quality of the water and also on the hydrodynamic balance of the lagoon, because the area of the sections of the mouth channels is commensurate with the tidal prism and thus with the surface of the lagoon basin (Jarrett, 1976; Marchi, 1990). Moreover, the reduction effect which is caused by artificial narrowing on the ordinary oscillatory tides ceases to be effective with regard to exceptional aperiodic tides which are the most dangerous because they remain positive for more than one cycle (Ghetti et al., 1972).
The second course of action - that of mobile floodgates - appears on the whole to be preferable as it is possible to interrupt sea-lagoon communication only when necessary and closure is thus limited to a few hours a year, without compromising the quality of the water (considering

that the phenomena occur during the autumn and winter periods which are already of considerable tidal activity). The periods of interruption of navigability, though longer because they include warning and manoeuvring time, still appear bearable under present conditions. If penalisation of the port were to worsen due for example, to an increase in the eustasy, it is foreseen that navigation locks be used.
The defence of the inhabited areas against mid-high water, roughly in the range between 0.70-1.00 m, is however to be achieved through the construction of embankments and arrangement of the borders, part of a general project called "insulae".

5. PROTECTION AND ENVIRONMENTAL RE-EQUILIBRIUM PROJECT

The Ministry of Public Works, after the negative outcome of a contract put out to tender in 1975, entrusted in 1980 the task of drawing up a feasibility project of the works for the protection of the lagoon of Venice from high water to a group of experts which I had the honour to be part of. The project was drawn up within the time limit of eight months and presented at the end of May 1981 (Comune, Comprensorio e Provincia di Venezia, 1981) and approved by the "Consiglio Superiore dei LL.PP." in 1982. The qualifying points of the feasibility project were: the choice of mobile floodgates at the mouths to control the tides and the indication of the type of barrier, consisting of 20-25 m long empty elements, placed close together but independent, hinged to the foundations in the seabed and which can be lifted by buoyancy produced by the introduction of compressed air (Agema et al., 1983).
Through law no. 798 dated 29.11.1984, the need was recognised to carry out studies, experiments, projects and works to construct not only the defence from high water along the lines indicated in the feasibility project but also to establish the re-equilibrium of the lagoon environment, considerably compromised in the last fifty years. A grant was chosen as the most suitable means to attain these objectives and the Ministry indicated the "Consorzio Venezia Nuova" as the body to which this grant was to be awarded.
I will limit myself here to illustrating synthetically the *mobile floodgates* project. However, I would like to recall that in the last twenty years specific research and in depth studies concerning the knowledge of not only hydrodynamic but also *geomorphological, sedimentological, vegetational* problems and of the *evolution of the lagoon of Venice* (Di Silvio et al., 1990) have multiplied. They have made it possible to program works aimed at the morphological re-equilibrium of the lagoon system and at the protection of the littoral and borders of the lagoon; the pertinent works have already been partially carried out and others are under way. Thus, the reconstruction of the islands which are only submerged by high water and which are called "barene" has been undertaken and is still in progress. They are of fundamental importance for the conservation of the lagoon fauna and to preserve the original appearance of the lagoon. Other naturalistic engineering work concerns the return of filled in zones previously intended for industrial development to humid and lagoon areas. Reconstruction of the beach using groynes and supplies of sand has been carried out on the eroded littoral of the Cavallino and is also foreseen at Lido and Malamocco (Consorzio Venezia Nuova, REA, 1989).
As regards the works for the real protection of Venice and the other inhabited areas in the lagoon from the tides, the project developed by Technital, on behalf of Consorzio Venezia Nuova, also foresees the use of mobile floodgates at the mouths, as in the feasibility project of 1981, but differs from it for what concerns the mobile elements and, above all, as regards the planimetric development of the barriers.
The feasibility project foresaw the insertion of the mobile part of the barrier in openings included between two fixed trunks rooted to the jetties of the mouths and positioned the dam as far away as possible from the sea opening so that the surface waves would reach the barrier in considerably weakened form. The configurations proposed now, which can be seen in Figures 6, 7 and 8, foresee an entirely mobile floodgate so as not to alter in any way the existing flow - with the floodgate open - and not to create vorticity sources which are dangerous for the channel bottom even at a considerable distance from the barrier. In order to make the barriers shorter they have been placed inside the mouths, thereby taking them closer to the sea outlet. The change has been made possible on the basis of the results of the numerous experimental

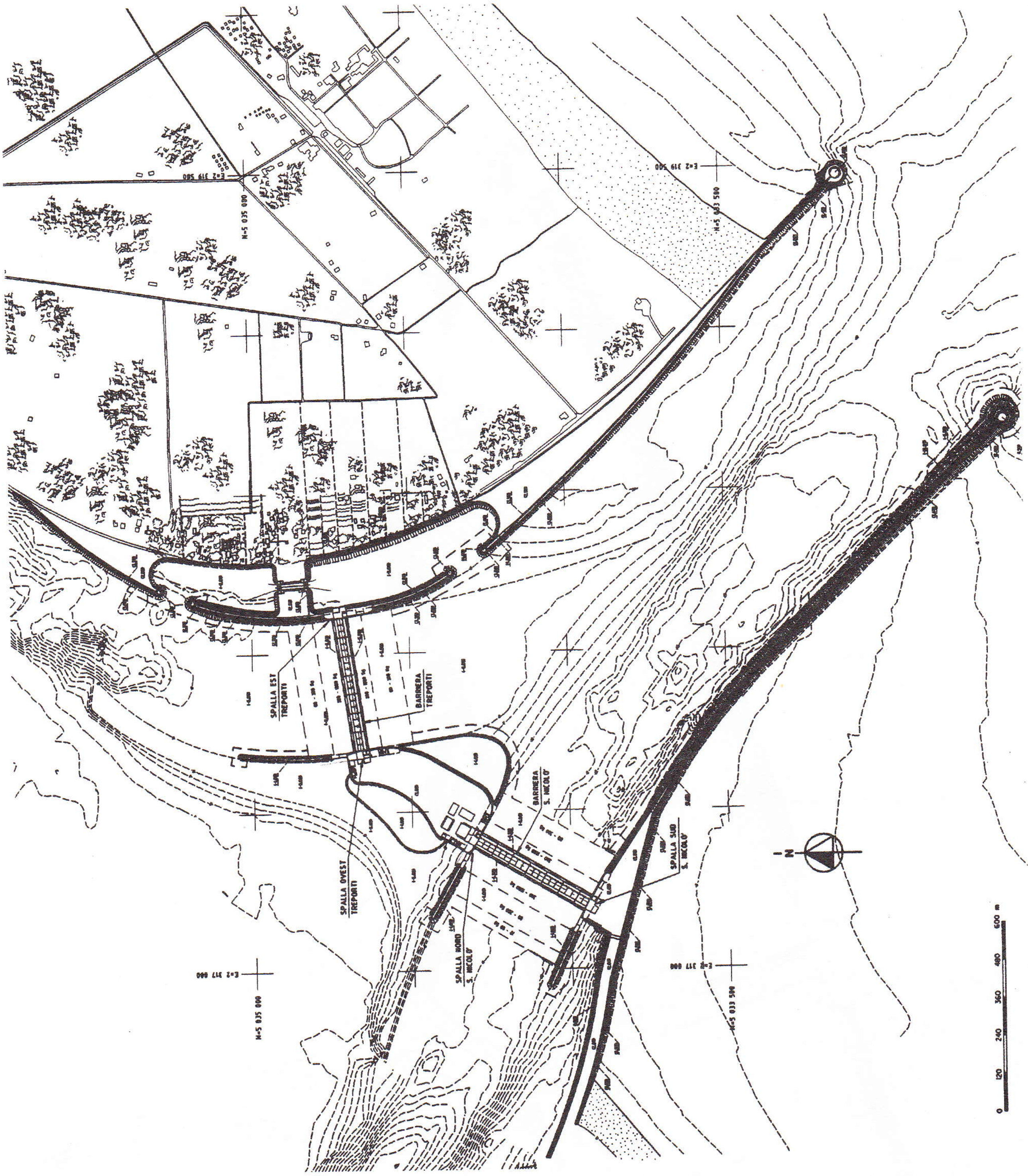

Figure 6: Design of the Lido mouth project.

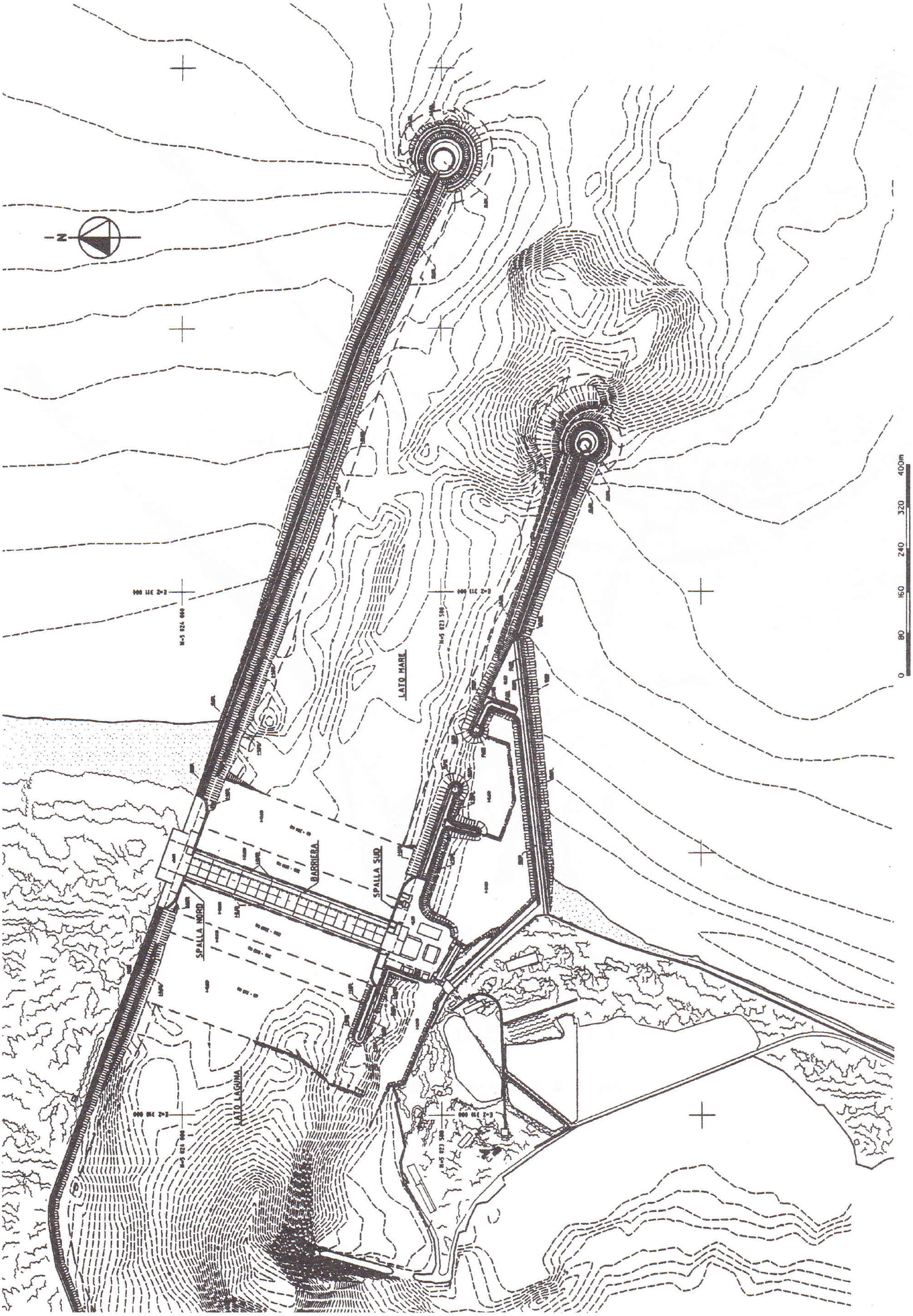

Figure 7: Design of the Malamocco mouth project.

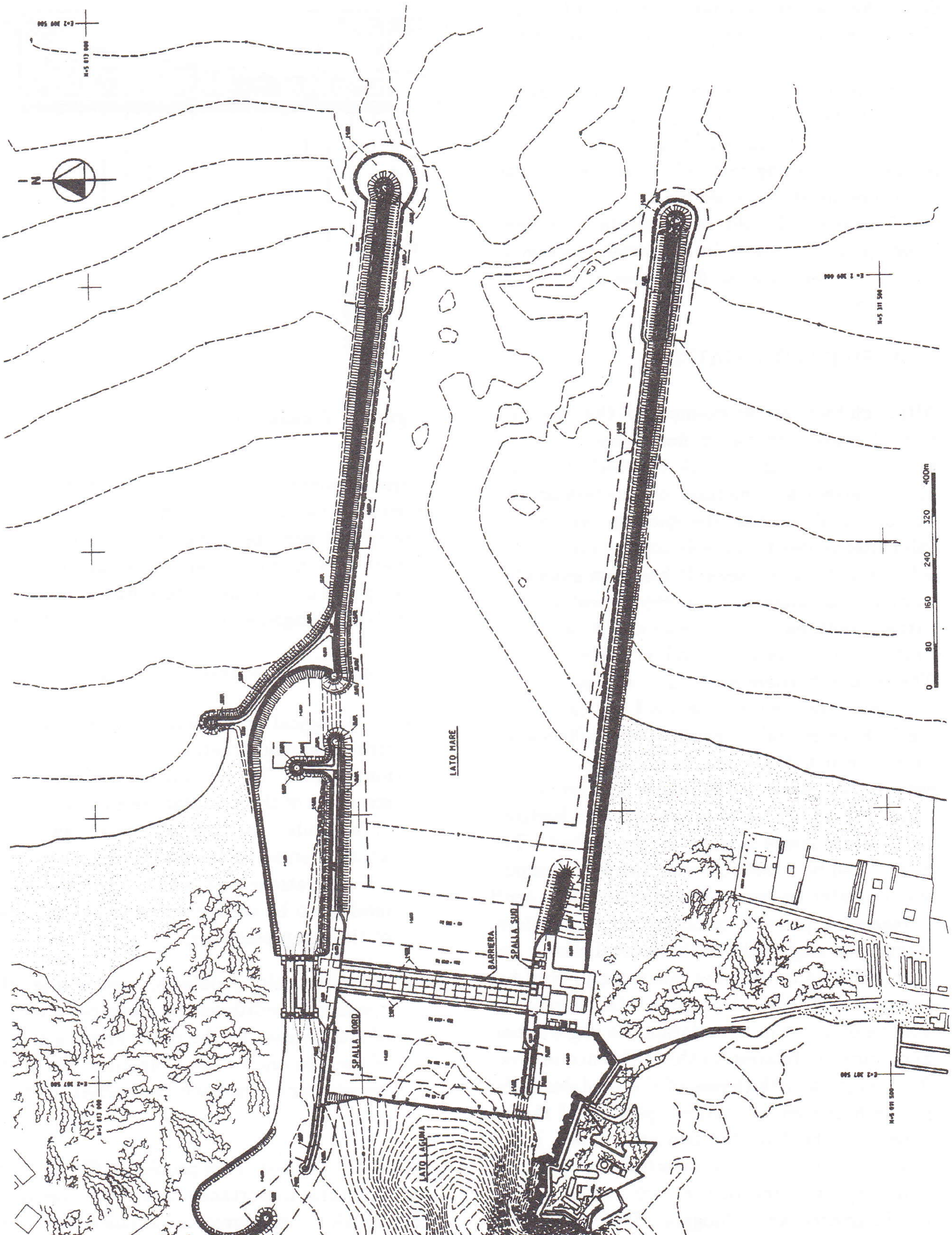

Figure 8: Design of the Chioggia mouth project.

tests which have been performed in recent years and which, as will be seen, have highlighted in detail the operational characteristics of the mobile system to deal with the surface waves of the sea.
As can be seen in Figures 6, 7 and 8, installation of the mobile floodgates at each mouth is connected with the construction of a port of refuge for returning craft which at the moment of closure are still in open sea.
At the mouth of Lido, in particular, the construction of an island in a central position is foreseen to separate the floodgates at S. Nicolò and Treporti.

6. MOBILE FLOODGATES

Although there are no examples of the construction of mobile buoyancy floodgates, which in terms of size, water depth in which they are placed, stress and method of functioning can be compared to those designed for Venice, no valid alternatives to this solution are known. Besides, also for this reason it has been subjected to numerous analytical and experimental verifications, both on reduced scale models and on a prototype of an isolated module, called MOSE.
The mobile barriers essentially consist of independent empty elements which I will call "modules". Each module consists of a parallelepiped caisson which takes up, horizontally, a 20 m space and is fixed to the seabed by two hinges. When it is full of water, it remains in a horizontal position inside a niche on the seabed. The caisson can be raised following the partial expulsion of water by means of compressed air, until it reaches a position of controlled equilibrium, forming an angle with the horizontal clearly less than 90° able to bear the difference in level between the sea and the lagoon. Of course, the volume of air let in to maintain the angle of balance varies in relation to this difference in level.
The height and thickness of the modules differ in the four communication openings of the lagoon with the Adriatic: two are foreseen in the mouth of Lido - in the directions of S. Nicolò and Treporti - and one in each of the mouths of Malamocco and Chioggia. Their design has undergone several modifications in order to improve the response and ensure the following requisites are met:
a) rapidity and ease of assembly and replacement of each module in the barrier;

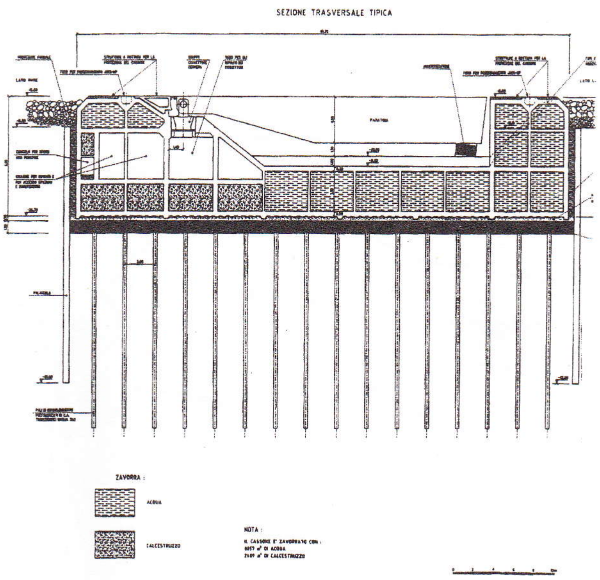

Figure 9: Foundation structure of the floodgate.

b) unsurmountability of the dam even when the waves and tides are exceptional;
c) restricted passage of water in the interspace between two modules even when they oscillate out of phase due to the surface waves;
d) reliability against overturning towards the sea.
The problems to be faced are of two types:

- technological problems, concerning the structure, construction and laying of the foundations in reinforced concrete, the structure of the modular steel caissons and, in particular, the construction of the hinges which must be suitable to hook up with marine operations and which must allow the module to be connected to the supply line of the compressed air;
- hydrodynamic problems, concerning the operating conditions and response of the set of sluice-gates to the quasi-static strength of the tide and to the dynamic stress of the waves which can reach the barrier from the outside.

As regards the first set of problems, Fig. 9 shows the structural importance required of the foundations which, moreover, are smaller than those of caissons already used abroad to build underwater tunnels. The use of craft is foreseen for the assembly (or dismantling) of each module which is fixed to the foundations by means of a couple of self-centering hinges (Fig. 10).

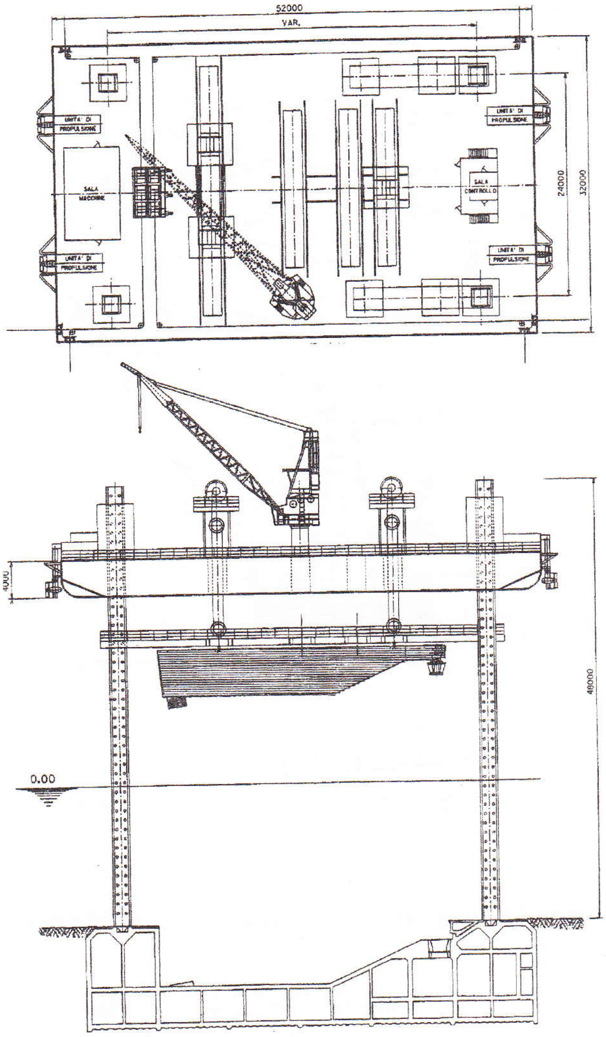

Figure 10: Assembly of a sluice-gate.

For what concerns the hydrodynamic problems, the first to be taken into consideration relates to the *minimum time* needed to *close* the barrier interrupting the rising tide current. In fact, if closure were to occur suddenly, it would give rise to an elevation of the water level such as the Joukowsky pressure increase in the water hammer phenomenon due to a rapid closure. To extend the time of closure, in view of the fact that the lifting speed of the individual module cannot be controlled, it is necessary to perform a gradual lifting distribution over time of the different modules. The overall minimum time required for the entire operation turns out to be half an hour and insertion of the modules must occur with a progressive increase in delay between one and the other starting with the lifting of the first to that of the last in order of time.

Not all the hydrodynamic phenomena connected with a set of mobile sluice-gates were easy to foresee. Whereas the conditions of *static equilibrium* were obviously known from the choice of the solution under review - as was the stability of the individual module under the action of the surface waves which can generally reach it - the implications relevant to the *behaviour of a "set" of sluice-gates* necessitated experimental studies and specific theories. Model tests in a *glass channel* were performed at the Estramed laboratory in Italy and at the Delft laboratory in Holland and were concluded in 1992. The possibility of motion of the modules asynchronous among themselves, with the same period or with double oscillation periods with respect to that of the waves, was well highlighted experimentally and analytically interpreted through a series of theoretical studies (Blondeaux et al., 1993; Mei et al., 1994; Vittori et al., 1996).

From the summer of 1992, tests were made on *physical models* reproducing the *three mouths* of the lagoon of Venice and pertinent floodgates at the Voltabarozzo laboratory of the Ministry of Public Works. The reduction scales of the lengths were 1:60 for the mouth of Chioggia, 1:80 for Malamocco and 1:64 for Lido.

With reference to the model tested at Delft, attention was focused on examining the phenomenon of *sub-harmonic oscillation of the set of sluice-gates* and on the reactions on the hinges caused by the surface waves. For this reason, a wave was simulated with a peak period close to halfway of the actual period of oscillation of the sluice-gates. The scale chosen, 1:30, made reliable evaluations possible also of the forces involved. Thus, simulation was limited to the set of sluice gates and to a part of the inlet channel, with the wave maker placed in the same channel. Having taken into account the transformation of the wave spectrum from the open sea to inside the mouth, the characteristics chosen for the primary wave to be simulated were: significant height Hs = 3.5 m, maximum height Hmax = 7.0 m, peak period Tp = 10 - 12 s. The associated long wave turned out to be: Hs = 0.80 m, Hmax = 1.3 m, Tp = 80 - 120 s.

At Voltabarozzo, by reproducing smaller scale models, it was possible to follow the propagation and transformation of the primary wave from outside to inside the channel, even with only one directional characteristics. Experimental observations confirmed the height of the primary wave assumed at Delft, but highlighted the

Mouth	Wave in open sea	Wave outside the mouth	Wave at the barrier
Chioggia	7.6 m	5.2 m	3.2 m
Malamocco	7.6 m	5.2 m	3.3 m
S. Nicolò	7.6 m	5.2 m	1.6 m
Treporti	7.6 m	5.2 m	1.5 m

Table 2: Transformation of the significant height of the primary wave

formation of a long wave with a height double that found at Delft.

For what concerns the primary wave with a return period of 1000 years, the transformations of the significant height passing from open sea outside the mouth to the floodgates are shown in Table 2.

Transversally, the wave in front of the floodgates showed considerable differences in height due to concentration effects towards the south part of the mouth. The values shown in Table 2 are on average those relevant to the zone of major concentration.

As regards *long waves* which can intervene in the process, it is necessary to specify that they are of two types: those which derive from non-linear interaction among the components of the primary wave and thus are closely correlated to it, and those which are generated by some discontinuity in the propagation domain, such as seabed variations, obstacles, currents etc. Experiments on the model of the mouth of Chioggia (Fig. 11) show that the development of long waves in that situation mainly depends on the bathymetry of the seabed and on the geometry of the mouth and is influenced very little by the characteristics of the primary waves (Adami et al., 1995). The evolution of the long wave, proceeding from the wave maker to the barrier, highlighted an amplification factor of the significant height equal to ~ 3.0 at Chioggia, 1.3 at Malamocco, 1.2 at S. Nicolò and 1.4 at Treporti. The first experimental tests carried out at Voltabarozzo had shown the possibility that the establishment of long waves, in conditions of resonance inside the inlet channel, could lead to the overturning of some modules of the barrier towards the sea. In the subsequent series of tests, which were particularly exacting for the barrier of Chioggia, the effects of some alternative modifications to the height, thickness and operative angle of balance were examined to identify the best solution.

The new characteristics chosen are shown in table 3 (see also Fig. 12).

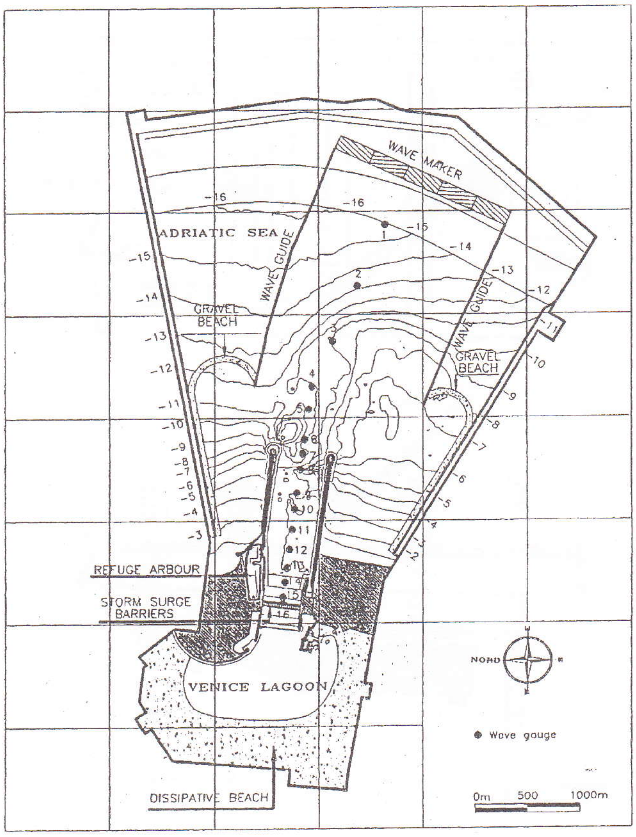

Figure 11: Layout of the Chioggia mouth physical model.

	Working angle	Module height (m)	Module thickness (m)
Chioggia	42.5	26.0	5.0
Malamocco	45.0	30.0	4.5
Lido S. Nicolò	45.0	23.0	4.0
Lido Treporti	40.0	18.0	3.6

Table 3: The new sluice-gate dimensions.

Models of the sets of sluice-gates with the above dimensions were made at Voltabarozzo according to the previously mentioned scales. The results of the tests were compared with those of a mathematical model, calibrated on the basis of the average of the maximum values of oscillation of the sluice-gates obtained experimentally.

Bearing in mind the experimental results and the integrative evaluations made with the mathematical model, a value was deducted equal to ~ 2 of the ratio between the maximum height of the waves calculated in the limit overturning condition and the maximum height of the foreseeable long waves with a millenary return period at the barrier of Chioggia. It should be added that the situations of the model, due to the one directionality of the

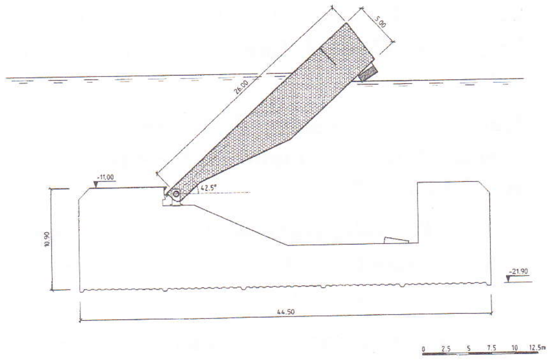

Figure 12: Vertical section of a sluice-gate (Chioggia).

wave generated and to the containment of the surface waves within the vertical wave guides enhance the height of the long waves associated with extreme events compatible with the water depths at the mouths. This effect further increases the *safety factor* of the sluice-gates in a real situation.

7. CONCLUSIONS

Considering the need to preserve the quality of the water in the lagoon (and therefore the vivacity of the basin), the navigability of the mouths, the natural environment and the features of the landscape, and in view of the untouchability of the morphological unity of the lagoon which imposes the simultaneous interruption of the tidal flow at the three mouths, it is very difficult to conceive of a system of mobile barriers which is conceptually and executively simpler than that designed.

This project involves considerable financial and technical commitment, not only during the construction phase, which is certainly the most delicate and complex, but also during the management phase as it requires careful and continual maintenance which has already been planned.

In any case, in order *not to aggravate* the situation in Venice, it is essential that two measures be taken:

- *eliminate the oil tanker traffic* from the lagoon;
- *prevent any form of drilling* in the Adriatic Sea for the extraction of liquid or gas from the subsoil in a range of at least 50 km from Venice.

For that concerns the problem dealt with here it can justifiably be said that scientific knowledge of the phenomena connected with the problems of the lagoon and the technical design of the artificial structures to defend Venice from the sea - *its sea* - which at times has become too dangerous, have reached a very high level of quality, adequate to the naturalistic, historical and artistic value of the area to be protected.

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THE JURIDICAL ASPECTS OF THE SAFEGUARDING OF VENICE

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ABSTRACT

The report outlines the legislative measures that established the procedures for the interventions made in order to safeguard Venice and its lagoon from the dangers caused by high seas.

The special legislation for Venice was introduced into the national legal system in order to cover the needs that emerged following the serious flood in 1966.

In fact, that year the actual fragility of the ecosystem of the Lagoon and therefore the dangers to which the city of Venice was exposed became quite clear.

The need to moderate and progressively eliminate the high water phenomenon brought the Lagoon of Venice to the attention of the Legislator as an environmental system to be recuperated through a process of socio-economical development.

Essentially, until the catastrophe of 1966, the Lagoon had been the object of legislative regulation (Law 366/63) but without evaluating, providing for, and regulating a phase of overall environmental recuperation.

In 1973, Law 171 was passed, based on the principle according to which "the safeguarding of Venice and its Lagoon is declared a problem of pre-eminent national interest" with the consequence that "the Republic guarantees the safeguarding of the landscape, the historical, artistic, and archaeological environment, protects the environment from atmospherical pollution and guarantees the socio-economical vitality within the frame of general development and the territorial layout of the Region."

On the grounds of the special legislation in the above-mentioned Law 171/73, the Minister of Public Works opened an international competition for a contract to provide for the determination of the works finalised to the elimination of the high water phenomenon, followed by their execution.

It is important to keep in mind that the initiation of the international contract competition was possible due to the fact that Law 171/73 provided for interventions for the purpose of "reducing the sea level in the Lagoon ..." might be undertaken even if not expressly mentioned in the district plans which, according to the legislation, should have constituted the groundwork of the whole safeguarding action. Said plans were to be approved by the Veneto Region.

The Minister of Public Works, although he valued the proposals received, did not think it was possible to assign the activities to a bidder, due to the fact that the hypothesised projects had to be carefully considered and verified through specific investigation and study, considering the complexity of the technical and scientific questions to be faced and solved.

Nonetheless, by means of a special expenditure authorisation, the Legislator allowed the Minister of Public Works to proceed with the purchase of the plans presented in the contest in order for them to be the groundwork for the overall visualisation of the specific problems.

Later, the Minister of Public Works named a Committee of distinguished University professors to proceed with the writing of a feasibility study - which, drawn up in view of the solutions planned in 1976, was favourably evaluated by the Superior Council of Public Works with vote number 209 in 1982.

The solutions outlined in said feasibility study should have been carefully verified, according to the specifications of the Superior Council of Public Works. Actually, in 1982, the same problems remained that had made development of the plans inadvisable in 1976.

In order to get around the problems that had arisen, which had, in fact, been the cause of not being able to arrange, evaluate, and then fulfil a plan of interventions intended for the safeguarding of the city of Venice in 1973, the Legislator emanated a second special Law for Venice (number 798/84) which, besides providing for the use of considerable sums of money, introduced significant innovations.

In particular, it was established that, for the fulfilment of the works with the highest degree of difficulty and their interconnection with those of their own competence, the State Administration could operate through the attribution of a single concession which rooted both the propaedeutical actions: those for studies and experimentation, and those concerning projects and their fulfilment, in the head of the Agency (see Law 798/84, comma 3).

The same Law pointed out a series of interventions as city administrational responsibilities aimed at recuperating the historical sector of the city centre, as well as utilisation of resources for the industrial reconversion of the area of Venice.

Furthermore, Law 798/84, on the grounds that the allotted financial aid would not have covered the program of interventions to be carried out, provided for periodical new financing, starting in 1987.

Moreover, said Law (in Article 4) prescribed that a mixed Committee preside over the safeguarding, with the responsibilities of direction, co-ordination, and control. This Committee, whose members were those Ministers most directly interested in the safeguarding of Venice, in addition to the President of the Veneto Region and the mayors of Venice and Chioggia, besides the representatives of the city councils of the Lagoon canal area, is presided over by the President of the Council of Ministers and makes executive those acts that are on a high administrative level inasmuch as they are aimed at transforming legislative outlines into operative decisions.

It is on the grounds of the second special Law that the Administration of Public Works made arrangements for a plan of interventions and therefore, thanks to the information acquired through the studies and experiments carried out, a general plan including the whole of the interventions which are to be carried out in order to guarantee the physical safeguarding of the Lagoon.

Said general plan has made it possible, in one sense, to have a final and certain picture of the financial resources to be employed to fulfil the goal established by the Legislator; furthermore, it has made it possible to outline clear contract conditions with the Agency. In fact, a general convention was stipulated for the purpose of regulating the relations with the Agency for the duration of the interventions included in the plan.

It is clear that having arranged a plan of overall interventions has been a positive innovation because it has made it possible to proceed, keeping in mind a series of certain references on the basis of which to establish a priority list from one occasion to the next, suggested by the condition and requirements of the Lagoon's ecosystem.

It must be said that to reach the arrangement of the overall plan of interventions, co-ordination with the Boards involved was continuous, especially regarding the Veneto Region, in order to guarantee the compatibility of the interventions within the realm of State and Regional competencies.

The necessity of co-ordination was felt also in order to avoid the ever-present possibility of interventions that overlap and are redundant, where they regard the same environment.

The further development of the special Legislation for Venice was obtained with the emanation of Law 5.2.1992 number 139, by which it was decided that the interventions for Venice were to be financed through a system of loans, therefore calling on Credit Institutes, with amortization left to the State.

The same Law 139/92, in consideration of the need for a growing co-ordination, established that the Veneto Region, the City Administration of Venice, and the Waters Magistrate carry out the interventions of digging out the canals according to the terms of the established agreement.

Furthermore, it established that the general plan for the interventions, entrusted to the sole Agent, or the Waters Magistrate, should be carried out in order to guarantee the activation of the works with the highest degree of environmental importance.

To this end, the Law specified that 25% of the finances were to be employed for environmental projects.

Afterwards, in 1994, the Government, taking advantage of the specific proxy included in the financial Law for the year 1994, emanated Legislative Decree number 62, promoting the formation of a joint stock company called "Agenzia per Venezia S.p.A." (Agency for Venice), to whom the planning, study, research, and co-ordination of the action of the Boards with diverse titles involved in the fulfilment of the safeguarding of Venice would be entrusted.

It has to be referred that the Veneto Region, the City Administrations of Venice and Chioggia, and the Ministry of Public Works were to share the social capital of said company.

Actually, the "Agenzia per Venezia S.p.A." (Agency for Venice) was not constituted for a series of reasons which hindered the application of the Legislative Decree.

In the first place, many of the activities which should have been assigned by the "Agenzia per Venezia S.p.A." (Agency for Venice) had already been completed; secondly, the local Boards felt that the co-ordination that said Company was to

guarantee could be more ably provided by means of constant liaison between Administrations.
It was at the time of the emanation of Legislative Decree number 62/94 that the competent Boards in the fulfilment of the safeguarding programs established an "Institutional Co-ordination Table" through which it was possible to establish a common line of action, in order to guarantee the highest level possible of co-operation and the greatest degree of integration of the diverse knowledge and technical-operative resources.

The activity guaranteed by the "Institutional Co-ordination Table" ensures constant technical action, allowing the Committee for the Co-ordination and Control of Direction to make its own decisions at an investigational level, bearing in mind the overall picture of diverse requirements and operational needs in the general safeguarding action.
In this picture, therefore, the plans are being carried out for the safeguarding of Venice.

THE VENICE LAGOON PROJECT

MOBILE BARRIERS AT THE LAGOON INLETS FOR CONTROLLING HIGH TIDES

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ABSTRACT

Situated in the largest lagoon of the Mediterranean Sea the city of Venice is in danger of extinction: the subsidence and the eustasy have led to increasingly frequent flooding.
The final solution to this problem would be - as it has been realized and demonstrated - the construction of a barrier system capable of temporarily stopping (4 hours during the predicted 8 closing operations a year - at today's sea level conditions) the tidal flow at the three inlets of the lagoon.
The paper describes, by an engineering point of view, the barriers system in the precinct of the environmental principles which have guided the whole of the Venice Lagoon Project.
General information on the project, including costs, have been supplied as appropriate.

1. INTRODUCTION

By 10 p.m. on November 3rd, 1966, the water had already invaded Venice. Six hours later, the tide was still rising and by five o'clock in the morning on November 4th it had reached a level of 1.16 m [1]. By midday, it was 1.76 m, and at 6 o'clock in the evening the high water level was a historical 1.94 m: Venice was submerged. The flooding of the city and of the other towns and villages in the Venetian lagoon, Fig. 1, lasted a full 22 hours and such high water levels lasting for such a long time were the worst ever recorded (the tides normally vary between about +0.5 and -0.6 m and last 6 hours).

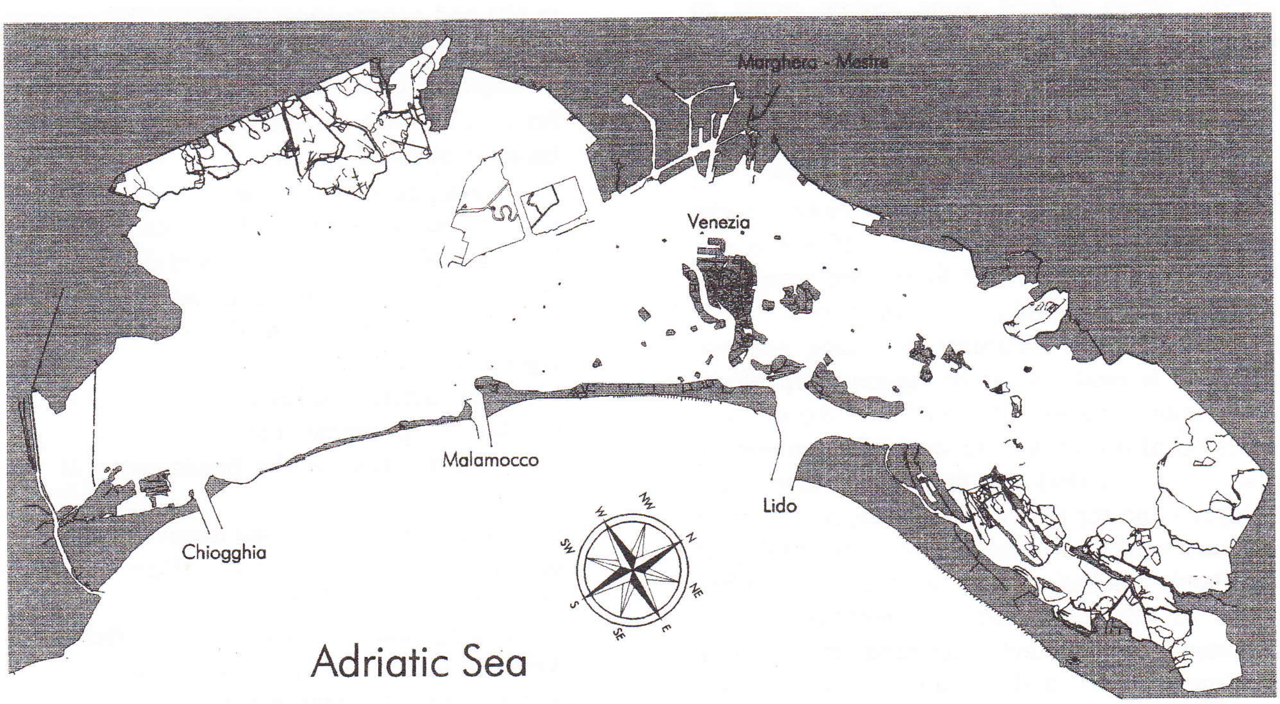

Figure 1 The Venice Lagoon

As many people will still clearly recall, there was an exceptional combination of two natural events in November 1966, in addition to the normal tidal effects, i.e. very heavy and persistent rainfall over northern and central Italy and a violent sirocco-driven wave motion along the Veneto coastline. This latter phenomenon was responsible for extensive damage to the Veneto beaches, especially on the islands of the Lido and Pellestrina, where the seaward defenses broke down in three places and the sea surging through the gaps wrought havoc on several villages (3000 people had to be evacuated from San Piero in Volta and Pellestrina).

The resulting destruction, not to speak of the damage to Venice's population and immaterial goods, was enormous. The city's vulnerability became known worldwide, prompting the Italian Parliament to pass the first of its Special Laws for Venice in 1973 (followed by others in 1984, 1992, etc.).

An extremely lively debate developed - first on a local scale, but soon expanding, and still in full swing - as to feasible ways to ensure that suchsituation as the one occurring in 1966 could not lead to such a disaster in future.
The discussion has always revolved around opposing convictions as to how Venice can be protected against flooding due to high tides: some recommend resorting to *diffuse*, or indirect, measures mainly affecting the morphology of the lagoon; others suggest using *mobile works* to achieve a temporary, physical separation of the lagoon from the sea during high tides.
It is worth emphasizing that the two basic types of action - i.e. *diffuse measures* and *mobile works* - are only mentioned here in very concise form. As we shall see later, for example, the mobile works (the financing and implementation of which will be the responsibility of the State) are planned to be associated with and to form an integral part of a series of other measures, including seaward defenses, re-establishing the lagoon morphology, stable improvements in the quality of the lagoon's water; local *insula* defense works (please refer to point 4 hereinafter) for the lagoon towns and villages - and for the city of Venice, in particular (all said works will also be the responsibility of the State). In addition, there are plans to open fish farms to tide expansion (by interrupting the continuous earth mound which separate them from the lagoon itself) and to eliminate the oil-tanker traffic from the Venetian lagoon.
It is also assumed that these works will form part of a more extensive operation, which includes pollution abatement schemes for the lagoon's watershed and the conservation of the historical buildings. As we shall explain later, such measures will be under the responsibility of others (mainly the Veneto Regional Authority and the Municipalities of Venice and Chioggia), though they will receive State financing.

Since the disastrous events of 1966, several laws have been passed for the purpose of ensuring that Venice and the Venetian lagoon are safeguarded, and financing for this objective is being progressively made available by the State. As mentioned above, the main bodies responsible for safeguarding Venice, as established by the laws concerned, are the State (i.e. the Ministry for Public Works, the Magistrato alle Acque di Venezia and, on its behalf, the Consorzio Venezia Nuova [2]), the Veneto Regional Authorities, the Municipalities of Venice and Chioggia, and to a lesser degree, several other institutions.

2. THE WORKS FOR SAFEGUARDING VENICE UNDER THE RESPONSIBILITY OF THE MAGISTRATO ALLE ACQUE DI VENEZIA

A great deal has been done since 1987 [3]: on behalf of the State, the Consorzio Venezia Nuova has prepared and virtually completed:

- a complex series of study projects (about 160 in all) and experimental trials for the purpose of ensuring a full understanding and proper management of the lagoon ecosystem;
- the creation of a database relating to the sea-lagoon-watershed system;
- the development of all the following general projects, based on the understanding acquired by means of the above-mentioned studies;

- the re-establishment of the lagoon morphology;
- stable improvements in the quality of the lagoon waters;
- coastline defense schemes (using protected beach recharge operations);
- the reconstruction of the breakwaters at the lagoon inlets;
- local *insula* defenses for the urban areas;
- opening the fish farms (albeit without disrupting their production activities);
- eliminating the oil-tanker traffic from the Venetian lagoon (but preserving the industrial activities of Porto Marghera);
- the MOBILE BARRIER WORKS at the lagoon inlets for controlling tidal flows.

At this point, it becomes necessary to emphasize that the project for the MOBILE BARRIER WORKS represents the *core element* in the system for protecting Venice from flooding.

In fact, though some people claim that *diffuse measures* of a morphological nature in the lagoon - such as filling the lagoon's shipping channels, raising the sea bed at the inlets, changes in the geometrical configuration of the breakwaters, restoring the lagoon's morphology to what it was several centuries ago, opening the fish farms, opening new channels through the *reclaimed areas* created in the sixties for the development of new industrial zones - would be sufficient to avoid at least an important part of the flooding in Venice, all the research confirms, without a shadow of doubt, that the only way to prevent flooding for good is by means of a *temporary separation* of the lagoon from the sea by means of mobile barrier structures.

Clearly, on the strength of sound scientific and technical motives [4], the Consorzio Venezia Nuova (which has conceived and designed the mobile works) - like the author of this paper - strongly supports the temporary physical separation of the lagoon from the sea, granting the diffuse measures a virtually negligible capacity to reduce the effects of high tides, and the consequent flooding of Venice.

above-listed series of projects which, together with the mobile barrier works, constitute a global environmental design scheme.

3. DEFENDING VENICE FROM HIGH TIDES

3.1. Venice's environmental, physical, human and economic context

Situated in the largest lagoon in the Mediterranean, the historic city of Venice is in danger of extinction. Subsidence and a rising sea level have led to increasingly frequent flooding in the city, Fig. 2, while trading, industrial and shipping-port activities have brought pollution up to critical levels in the surrounding lagoon.

Anthropic subsidence is now under control because subsurface water pumping has been forbidden since the seventies. Natural subsidence is still continuing, however (at a rate of 0.05 to 0.1 millimeter a year) and the rising sea level is a potential hazard.

Any increase in the gap between the water and the land - due to natural subsidence and the rise in sea level - would have a significant impact on the city of Venice because of the currently very limited clearance: it would take only a 0.3 m increase for St. Mark's Square to be flooded every day.

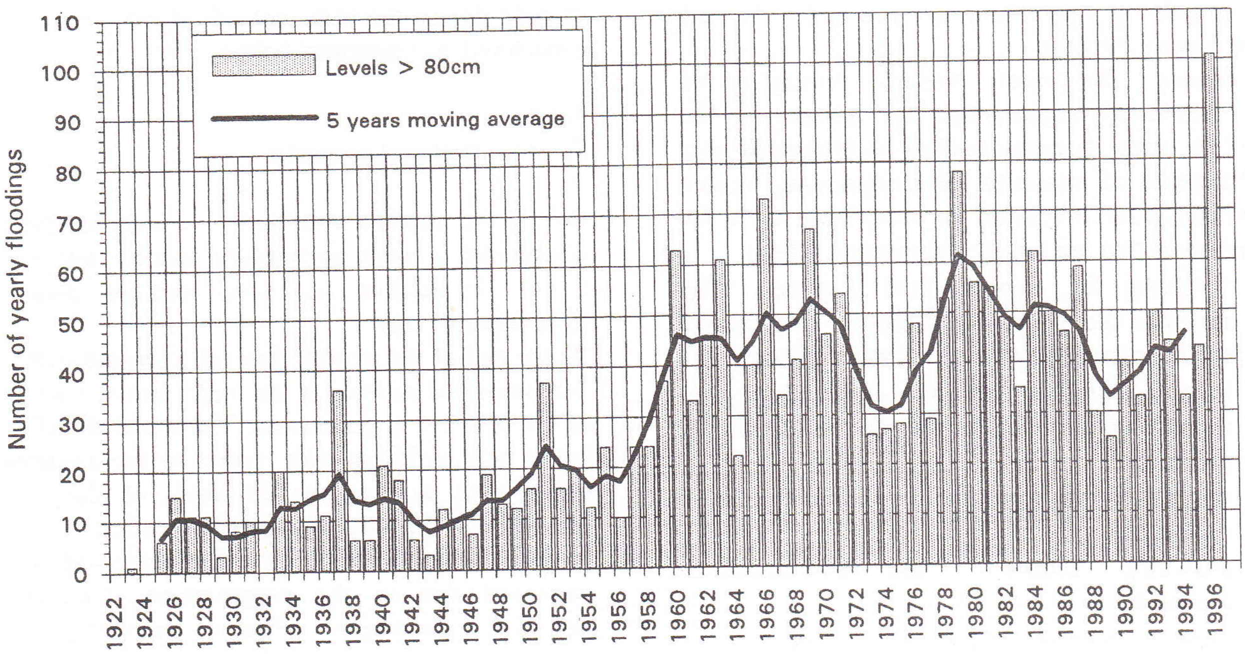

Figure 2 Increase in frequency of high tides during the XXth century

It must also be said that the position of the Consorzio is far from purely and simply "technocratic" - and proof of this lies in the

In the very early decades of this century St. Mark's Square used to be flooded seven times a year; today flooding occurs at least forty times a

year, and sometimes even far more often (67 times in 1967).
In November and December 1996, Venice was flooded twelve times, with a peak water level of 1.34 m.

It is easy to imagine the amount of distress and damage caused by flooding in Venice and the other lagoon towns and villages (Chioggia, Sottomarina, Pellestrina, Lido, Treporti, Burano, Murano) and its effects on the lagoon's trading, industrial, harbor and fishing activities.

It is extremely difficult, however, to precisely estimate this type of damage, particularly as concerns its effects on the *immaterial goods* (of a cultural, monumental, historical, archeological and environmental nature) that contribute to the value of Venice.
Such considerations form part of a series of Studies on the Environmental Impact of the Project for the Mobile Barrier Works (1996-1997): evaluating such matters - inasmuch as this is feasible - could provide an economic indication against which to measure the advantages of the works involved (in the sense of what it would cost *not* to perform the works for protecting Venice against high tides).

3.1.1. The guiding environmental principles behind the Venice Project

Following the most modern principles of environmental engineering, the project for the mobile works is considered as an integrated part of a series of measures for safeguarding Venice and has been developed in compliance with the guidelines that are briefly summarized below:

- involving the environmental engineers who designed the works in the process of focusing on the relevant purposes (holistic approach);
- keeping public opinion, including the specialists, informed as regards the role of the project;
- integrating the project in a consistent system of measures;
- analyzing economic and environmental measures;
- using sustainable technologies, procedures and programming;
- extensive and multi-disciplinary participation during the design stages.

The above has always involved - and will continue to do so, up until the completion of the works and beyond - baseline data collection, environmental auditing-reporting based on eco-indicators, monitoring programs, material flow programs (producing more with less), i.e., the development and application of suitable technological systems, the use of advanced materials and industrial systems, the extension of manufacturers' responsibilities, pollution prevention and control, waste management, transport systems, the minimization of impact and effects, eco-efficiency, continuous re-orientation of engineering towards sustainability.

3.2. Natural subsidence and a rising sea level

As already mentioned in paragraph 3.1, natural subsidence due to the consolidation of the terrain beneath the self weight of Venice is a predictable phenomenon. It can be estimated with a fair degree of accuracy on the basis of information collected over several centuries.
As for the global rise in sea level, a criterion was adopted that refers to the indications of the Intergovernmental Panel on Climate Change (IPCC), 1995, and the technical life of the mobile works (100 years).
Three scenarios were considered which could be defined respectively as: optimistic, realistic and pessimistic. For each of these, the possible attitude during the technical life of the work was considered, as illustrated below.

3.2.1. First (optimistic) scenario

During the hundred-year period considered, there is expected to be no appreciable eustasy, but only a rise in relative sea level due to natural subsidence (4 cm).
At the end of the period, this will coincide with a very marginal increase in the mean annual number of barrier-closing operations. There will therefore be no new problems with respect to the situation today, even as concerns the needs of shipping, inasmuch as the latter is known or predictable.
In the meantime, the quality of the water will have improved due to the programmed, necessary pollution abatement schemes involving the lagoon's watershed and the lagoon itself.

3.2.2. Second (realistic) scenario

During the coming century, there will be a rise in sea level comparable with the trend measured over the past hundred years. The natural subsidence will be the same as for the first scenario. Here again, there will be no reason for concern: the mean annual number of barrier-closing operations could increase by comparison with the present day, but still within limits compatible with the current or future maritime traffic (as may be reasonably predictable for the medium term).

3.2.3.
Third (pessimistic) scenario

According to the hypothesis of the IPCC, there will be a rise in sea level during this coming century of between 27 and 54 cm due to eustasy. The natural subsidence will be the same as for the first scenario.
Since a rise in sea level of between 20 and 30 cm (as a result of eustasy and natural subsidence) would pose problems - e.g. for the shipping in the lagoon - it would become necessary, as and when this situation should arise, to take steps to restrict the mean annual number of barrier-closing operations.
The measures to be taken - if and when such a need should arise - would depend on the general and particular conditions pertaining at the time. The political decision-makers would consequently have to implement suitable action after redefining, or adjusting, the purposes they intend to achieve.
Presumably the main objective would still be the survival of Venice, which is *irreplaceable* - rather than the survival of any other *replaceable* values, even if the action deriving from having established such priorities were to prove extremely costly in economic and social terms.
Clearly, any such action would have to be planned well in advance of the crisis threshold being reached (always make a move before you have to!) and could involve further *insula* measures for the towns and villages, and for Venice in particular (involving +20 to 30 cm, even at the cost of *extreme solutions* for the urban fabric), or the construction of at least one shipping lock, or the division of the lagoon into two parts (or sub-basins), or still other steps, or combinations of steps (the above list merely offers some examples).
Clearly the above-described positions may well be of a technical nature, but they carry considerable political weight. It is also self-evident that a wait-and-see attitude to deciding on any further corrective measures *in the event of the third scenario coming about* would be suicidal if the barriers had not already been installed in the meantime.

3.3.
The effect of *diffuse measures*

It has already been said that the *diffuse measures* would be practically irrelevant in terms of any reduction in the high water level in Venice in the event of even only moderately high tides. This is not to say that such measures are unnecessary. On the contrary, there are dozens of valid reasons for proceeding with them without delay - or rather, for continuing to go through with them.
Through the Consorzio Venezia Nuova, the Magistrato alle Acque di Venezia has already built, and is continuing to build, local *insula* defenses; it has begun work to re-establish the lagoon morphology (the technical and scientific reasons to justify said operations are not given here for the sake of brevity [5]) and to stop any further deterioration of the lagoon environment, deal with its causes, and reverse such tendencies (in other words, to ensure a substantial and long-term improvement in the quality of the water in the lagoon). Other operations include extremely important coastal defense measures (recharging the beaches and reinforcing the breakwaters at the lagoon inlets); opening fish farms (there is a pilot project already underway); and opening channels in the *casse di colmata;* plus special projects such as a scheme to get the political decision-makers to eliminate the oil-tanker traffic from the Venetian lagoon.
It is only right to add that several different proposals, generally defined as *diffuse measures,* have been recommended as alternatives to the mobile barrier works by several people (even of some authority) who disapprove of the barrier solution; these "alternatives" include changing the geometric configuration of the breakwaters, filling the so-called "Petroli" (oil-tankers') channel, or reducing the depth of the sea bed at the lagoon inlets. Although the utility of such measures is not entirely clear, their costs are prohibitive, and their potential negative consequences are often disastrous (to the point that they could in some cases be defined as *extravagant measures*), the environmental impact study for the Venice Project has nonetheless taken these proposals into account, since they form part of the expected comments and observations from the pubblic consultation.
Be that as it may, it is important to bear in mind that the cumulative effects of the diffuse measures, including those considered in the environmental programs (and the re-establishment of the lagoon morphology, in particular), in

combination with the above-mentioned *extravagant measures,* would generally contribute to a reduction in the high water level in Venice of less than 6 cm (and the single and/or cumulative effect would be even smaller in the case of steep tidal flows).

At each of the lagoon inlets, an array of independent flap gates will be installed, hinged to the foundation structures and positioned adjacent to each other, Fig. 3.

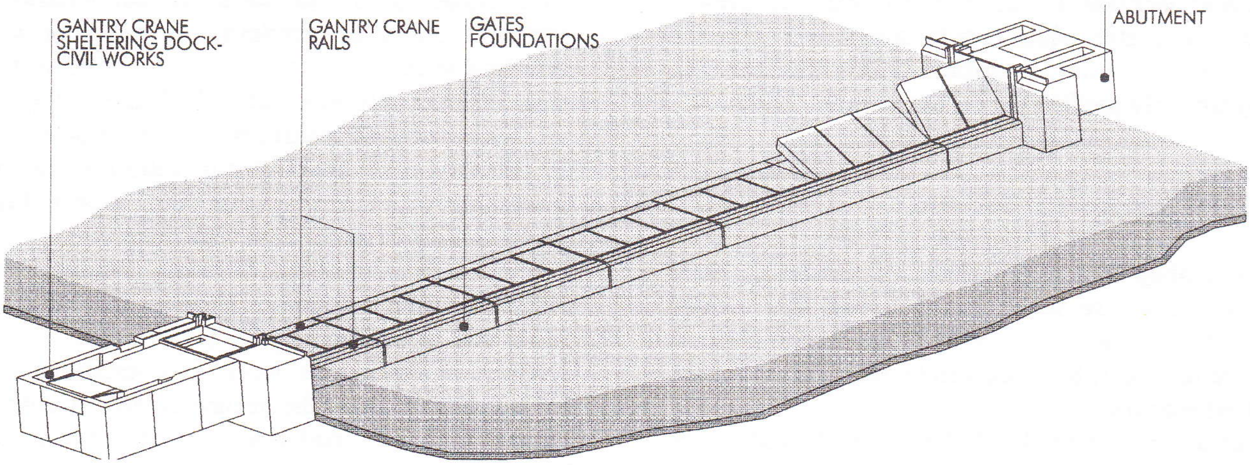

Figure 3 General view of the gates

4. THE PROJECT FOR THE MOBILE BARRIER WORKS [6]

Apart from the ample economic reasons, it has been realized by now, and demonstrated, that a final solution to the problem would be the construction of a barrier system capable of temporarily stopping the tidal flow at the three lagoon inlets (for 4 hours during each of the predicted 8 closing operations a year - at today's sea level conditions).

Obviously, in terms of providing physical protection against high water, the mobile barriers must be combined with the *Insulae Project*, i.e. the terrain on which Venice stands, including St. Mark's Square, must be raised to an elevation of at least +1 m, so the barriers would only close for high tides above this level. Otherwise the barrier closing operations would grow from 8 to 50 a year, which would be no problem in terms of the sea-lagoon and lagoon-sea water exchange (and the consequent quality of the water), but would mean growing problems (albeit still tolerable for the time being) in terms of the needs of the port of Venice.

4.1. The components of the barrier system

4.1.1. The gates

Each gate consists of a steel caisson which rests, when it is filled with water, inside a special recess created in its foundation structure below the sea bed. By introducing compressed air, water can be expelled from the gate so that it begins to lift, taking up a position which tilts at a 40-50 degree angle to the horizon. As long as the sea water level increases, air will be continuously introduced in order keep the gap between the sea and the lagoon levels up to 2 m, Fig. 4.

Depending on the depth of the canals where the gates are installed, the gates will vary between 20 and 30 m in length and between 3 and 5 m in thickness, while they will all be 20 m wide to facilitate maintenance and transport operations and to reduce to a minimum any loss of water-tightness due to the failure of a single gate.

The weight of the gates varies from 200 t at the Treporti inlet, which is 6 m deep, to more than 300 t at the Malamocco inlet, which is 15 m deep.

To reduce maintenance requirements to a minimum and to increase the reliability of the system, the number of accessory components for the gates has been limited to three, namely the hinge-connector units, the inclinometers to monitor the gate's position and the rubber shock absorbers.

The hinge-connector unit, Fig. 5, is undoubtedly the most significant element. It has to allow for the gate's rotation, the passage of air for its operation, the passage of connections for monitoring the gate's position, and for the locking and releasing of the gate from the foundation structure without resorting to the use of divers.

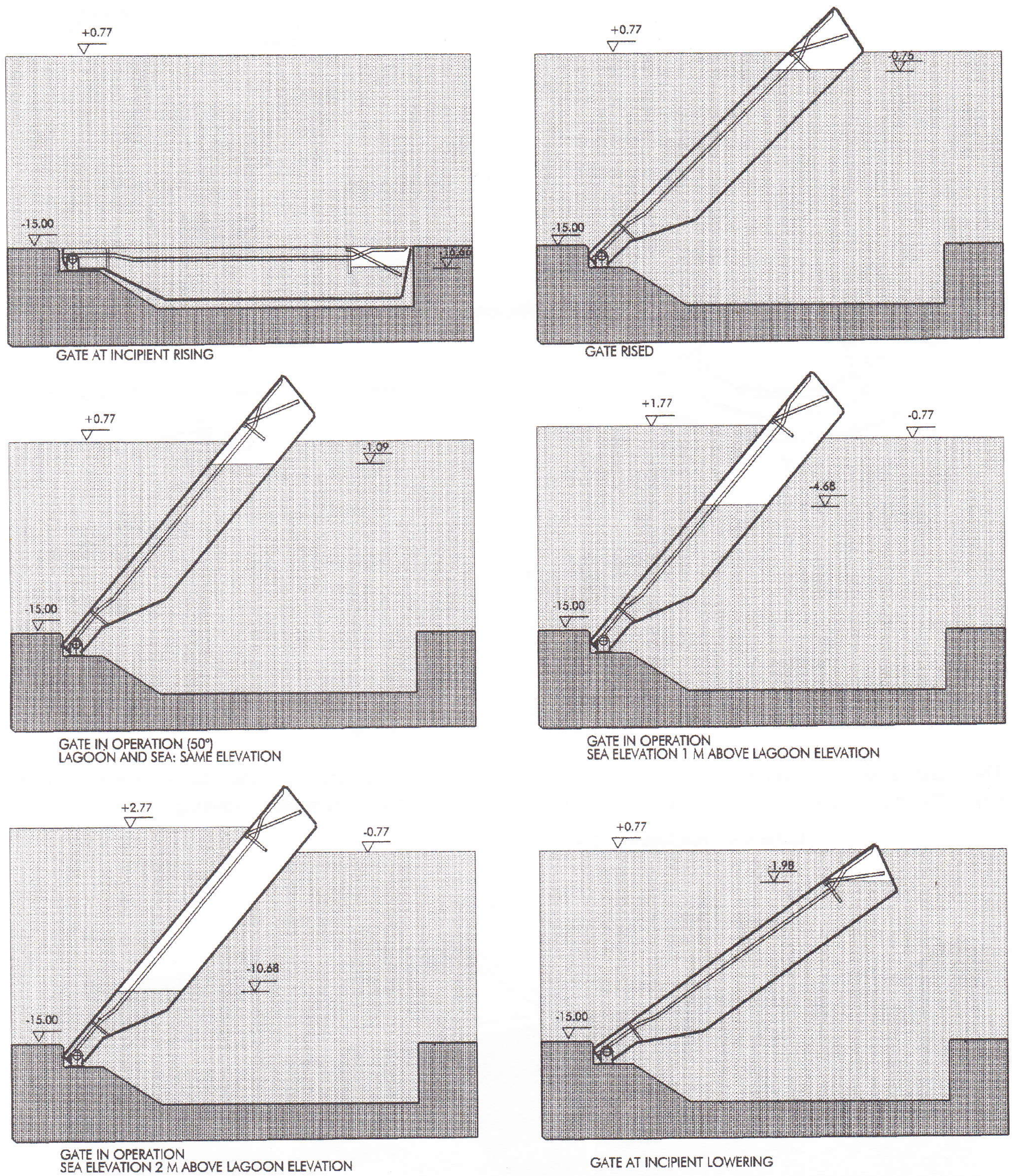

Figure 4 Gates operation (Malamocco inlets)

A system has been arranged for routine maintenance on the gates, which is capable of replacing a gate in less than 8 hours using gantry cranes, the rails of which are installed on the foundation works, Fig. 6.

4.1.2.

The civil works for supporting the gates

The civil works and structures where the gates and maintenance equipment are installed consist of prefabricated cellular reinforced concrete (r.c.) units, or caissons. The dimensions of these elements have been chosen to ensure as even as possible a distribution of the loads on the foundation ground and to limit the environmental impact during the construction period.

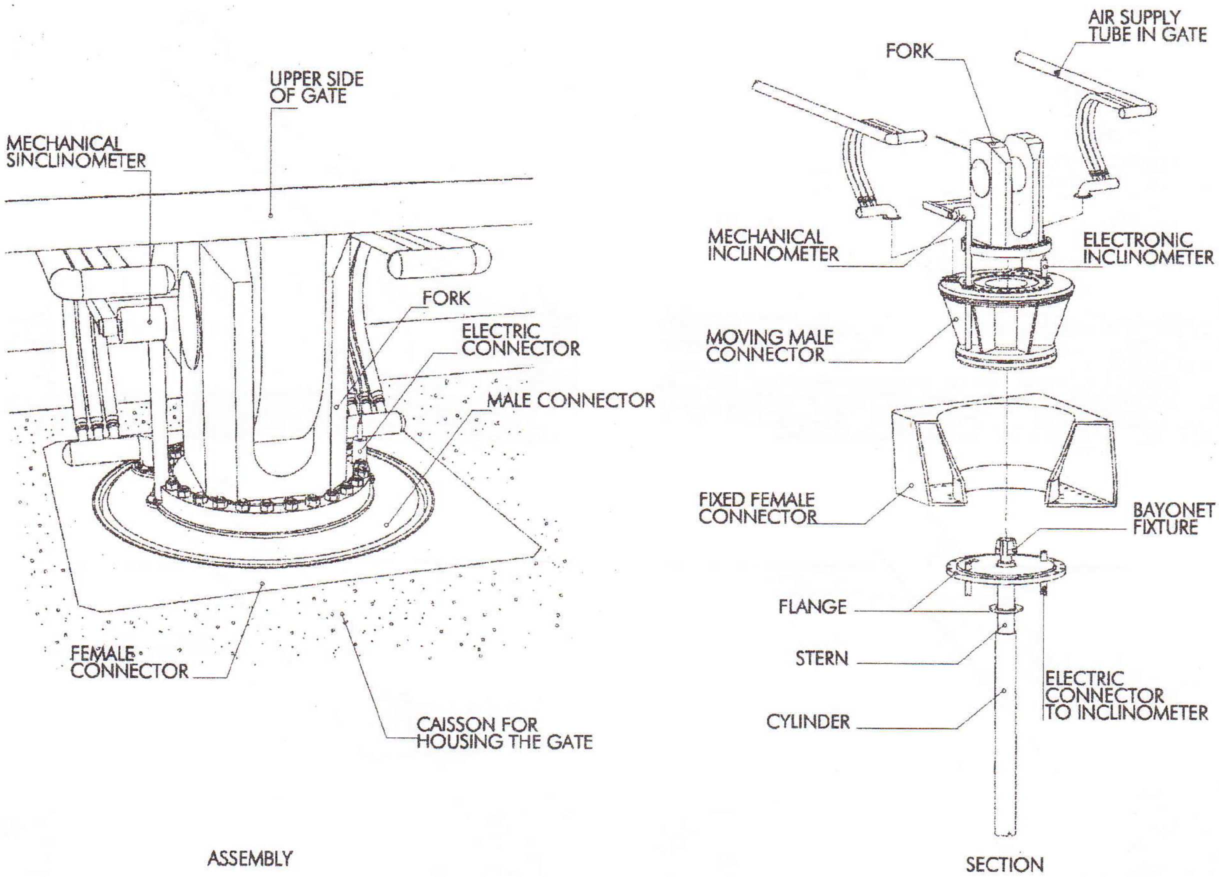

Figure 5 Hinge-connector unit

The main structures can be divided into three types: the foundations for the gates, the abutments and the sheltering docks for the maintenance equipment, see again Fig. 3.

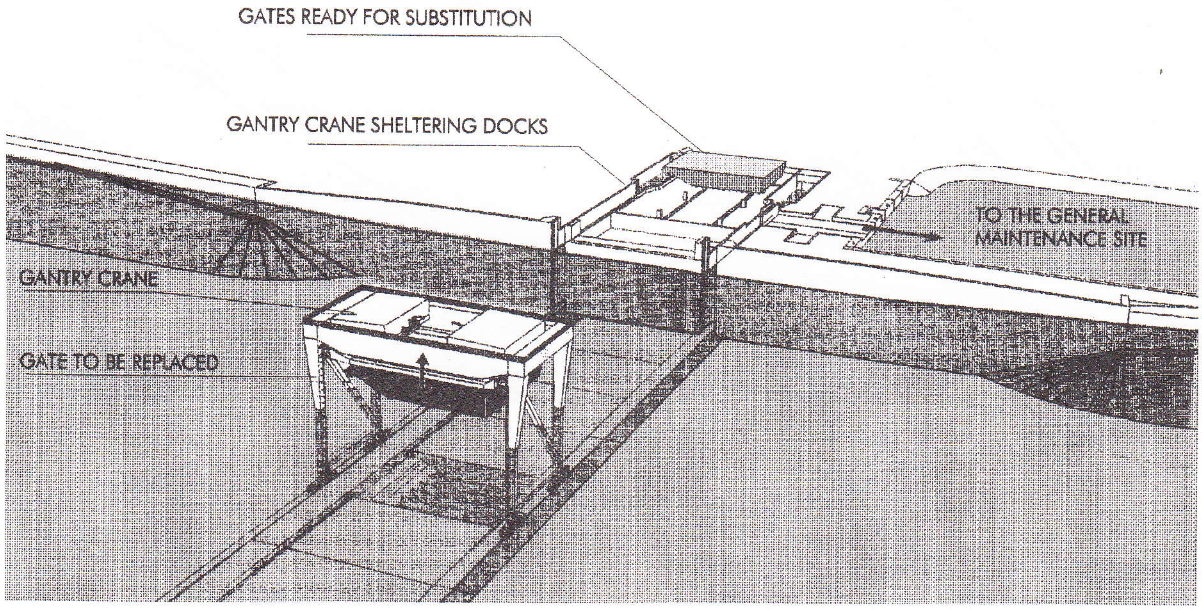

Figure 6 Gates maintenance equipment

The foundations for the gates contain three independent tunnels housing the various equipment, cables, control sets and the piping for conveying air from the compressors to the connectors on each gate, Fig.7.

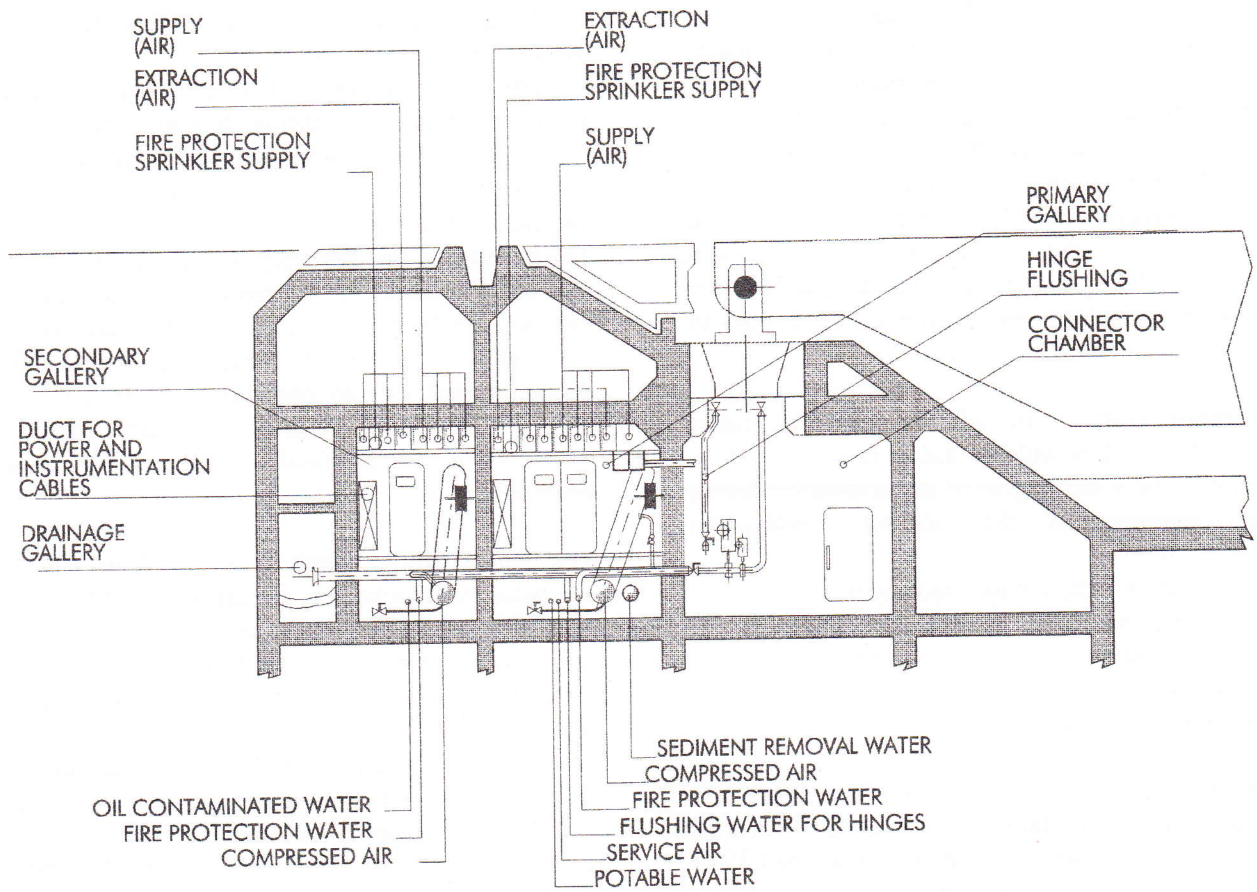

Figure 7 Electromechanical equipment to be installed inside the foundation (cross section)

While the height of the foundation structures is roughly the same for each inlet, measuring 10.5 m, the other dimensions vary, between 30 and 50 m in width and between 40 and 60 m in length, depending on the actual cross section of each inlet.

The inlet bottoms are at -6 m (Lido Treporti), -11 m (Lido San Nicolò), -15 m (Malamocco), and -11 m (Chioggia); the length of the inlets varies between 360 and 420 m.

The tunnels can be accessed by staff in charge of the system's management and maintenance, so they are equipped with all the necessary safety devices. For example, two sets of the various equipment are installed in two separate tunnels, so that a serious failure can occur in either of the tunnels without bringing the whole system to a halt.

The third tunnel collects the air expelled by the gates during the sinking operations. The air (which may be mixed with water) is thus channeled towards the vertical abutments and released into the open air.

4.2.

Construction methods

The design project has opted for a construction method that minimizes the construction method that minimizes the impact on the environment and on shipping traffic.

Gates Operation (Malamocco inlet).The method adopted provides for the break-down of the structures into a number of r. c. elements of limited size that can be prefabricated in special docks, situated even some distance from the inlets, for their transport while afloat and subsequent sinking for installation on the sea bed, which is dredged and graded to the design levels.

Solutions of this kind, based on prefabricated r. c. units, are in widespread use, ensuring a high level of reliability, in the construction of large underwater road and railway tunnels and in sea-water cooling systems for thermoelectric power plants.

By comparison with the traditional solution whereby the elements are built locally inside cofferdams, the solution using prefabricated units offers the advantage of avoiding changes to the inlet's cross section during the construction period. In fact, the works required at the inlet (using floating mobile equipment) before the installation of the prefabricated units include: installing sheet piling for the trenches, underwater excavations and driving prefabricated r. c. piles to reinforce the foundation soils.

Maritime traffic will still be able to transit through the inlets with the aid of tugs, since there will only be some degree of inconvenience during the operation of the floating construction equipment.
This solution calls for the creation of one or more dry docks where all the r. c. units can be prefabricated, which must be deep enough to house the elements when they are floated for transport (i.e. about 10 m).

The principal structures at the three inlets are made up of 157 prefabricated r.c. units of variable dimensions depending on the inlet concerned 25 of which for the construction of the foundation structures for housing the gates (maximum dimensions 60 m x 49 m x 12 m) and the other ones for the abutments, the main sheltering docks for the gantry cranes, the secondary gantry cranes, quays, buildings, tanks, etc.

4.3.
The joints between the prefabricated units

The joints connecting the prefabricated units are of vital importance in that they must guarantee the watertightness of the service tunnels inside the foundation works.
The selected system has already yielded excellent results in hundreds of different applications and in more than 50 years of service (i.e. in submerged tunnels and underwater hydraulic piping).
It consists of two separate rubber joints, both of which ensure watertightness, but each having a specific and complementary function, Fig. 8. The outer joint, which ensures the first connection between two adjacent prefabricated units soon after they have been placed on the foundation layer, is called a "Gina". It is fixed to one of the two heads of each caisson when the caisson is in the prefabrication dockyard.
Watertightness is obtained by pressing the joint against the head of the facing caisson in two steps. A first level of watertightness is obtained at a low compression level by simply placing the two units one against the other.
The purpose of this first step is to empty the space between the joint and the temporary diaphragms installed inside the caissons, near the joint itself, in order to mobilize the horizontal hydrostatic thrust exerted on the opposite side of the last caisson installed. This additional, strrong compressive force finally makes the joint watertight.

The second joint, which is required to ensure complete watertightness, is called an "Omega". This joint is installed on the inside of the previous seal, so that it can be inspected from inside the caissons (in a dry environment) and, if necessary, replaced.
The "Omega" joint is installed, after the tunnels have been drained, by securing it to the caisson structures by means of metal flanges. It is designed to withstand all the stresses that may occur during the life of the gate and is the fundamental long-term sealing element. The "Gina" joint also has to be in good working order throughout the life of the gates to allow for the replacement of the "Omega" seal, should this become necessary.

4.4.
Differential settlement of the caissons

Containing caisson settlement has proved the most critical criterion in establishing the type of foundation.
In view of the geotechnical conditions of the foundation ground, characterized by alternating layers in varying thicknesses of cohesive and incoherent soils, the choice of the type of foundation was based on a prudential schematization of the ground's behavior, and particularly on an attempt to assess differential settlement.
The long-term differential settlement of a given prefabricated foundation unit, or of two adjacent units (considered together with their typical tolerances), must be limited to 3 cm over 60 m and must never exceed 6 cm in order:

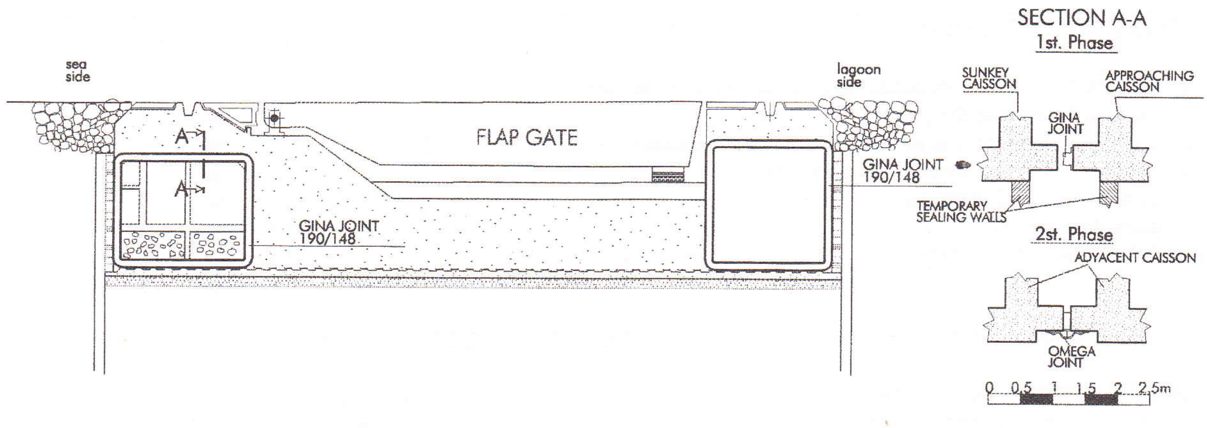

Figure 8 Joint between prefabricated foundation elements

- to preserve the watertightness of the "Gina" joint in the long term;
- to avoid contact between the gates installed on two adjacent caissons, which are 20 cm apart;
- to allow for transit of the gantry crane for maintenance operations, which can move along the rails attached to the caissons at a maximum slope of 1%.

4.5.
Risks of losing watertightness at the caisson connecting joints

In the long term, i.e. after a substantial decompression of the rubber has taken place, the "Gina" joint will still allow for a certain degree of compression loss without affecting watertightness. In particular, the traditional "Gina" element maintains watertightness even after a decompression of 4 cm.

4.6.
Risks of contact between gates installed on adjacent foundation caissons

The gap between two adjacent gates must be wide enough to prevent them from touching each other. At the same time, this distance must be small enough to restrict the quantity of water entering the lagoon when the gates are in operation, i.e. raised.
An average gap of 15 cm has been considered for adjacent gates installed on different caissons, with a maximum of 20 cm at their free ends.
In the case of gates installed on the same caisson, however, the gap will measure only 10 cm.

4.7.
Risks of faulty operation of the maintenance equipment

Ground settlement can interfere with the smooth operation of the gantry cranes by hindering their movement from one caisson to the next.
However, the rails are equipped with a 4 m-long connecting section between the caissons in order to convert any difference in level or axis into a gradual and acceptable change of direction. Considering the limited use envisaged for the traveling gantry cranes and their very low speed, a maximum difference in axis of 1% will be allowable.

4.8.
Critical factors for the operation of the system

It is evident that proper operating conditions depend not only on controlling the settlement and horizontal strains, but also on the construction tolerances for the gates and the foundation and abutments caissons, on their installation and on the thermal strains that the structures may have to withstand.
For safety's sake, the preliminary design assumes that each construction operation is carried out with an imprecision equating to the maximum accepted tolerance, that the maximum strains occur and that no corrective action is taken on the dimensional errors that may be found.
Fig. 9 shows the contributions of tolerances relating to construction and installation, thermal strains and differential settlement, i.e. the three factors that can affect the proper operation of the system. These data refer only to the Malamocco inlet.
The construction and installation tolerances were defined on the basis of experience acquired in the construction of similar works, including large-sized prefabricated elements installed under water and subject to limitations on settlement for functional reasons, such as in the case of railway tunnels.

	A		B		C
I) CONSTRUCTION TOLERANCES AND DEFORMATIONS					
1.5 cm: distance between the opposite between surfaces of the two caisson for setting the joints			1.5	cm	
1 cm: additional distance due to deformations of the surfaces as above	1	cm	0.7	cm	N
5 cm: radial offset of the spherical hinges center			5	cm	
1 cm: deformation and shrinkage			1	cm	
0.5 cm: gates dimentions			0.5	cm	
1 cm: deformations of the gates			0.5	cm	
Total:	1	cm	9.2	cm	N
II) INSTALLATION TOLERANCES AND MAXIMUM DIFFERENTIAL SETTLEMENTS					
2 cm on 60 m: bearing caisson surfaces	0.05	cm	2.0	cm	
3 cm on 60 m: differential vertical settlements	0.07	cm			N
3 cm on 60 m: differential horizontal settlements	0.08	cm	0.03	cm	N
1 cm: vertical differential displacement at the joints (% on the vertical surface)			0.25	cm	
1 cm: horizontal misalignement at the joints (% on the hotizontal surface)			0.25	cm	
Total:	2.0	cm	5.03	cm	0.25%
Cumulate effects I) and II)	3.0	cm	14.05	cm	0.25%
Maximun value cionsistent with the functionality of the gates:	4	cm	20	cm	1 %

A = lost of tightness due to GINA joint decompression
B = mobility reduction due to the gap reduction between two adjacent gates
C = reduced capability of the maintemance gantry cranes due to rails misalignement
N = negligible

Figure 9 Construction and installation tolerances and settlements (Malamocco inlet)

Even if the components shown in the above-mentioned tables are combined together, the total figures would not reach limit values sufficient to prejudice the operation of the system, which would still retain an adequate safety margin. For instance, assuming a symmetrical rotation of two adjacent caissons, a differential settlement of up to 6 cm over 60 m would be tolerable, which is twice as much as the maximum allowable limit established by the project.

4.9. Loads transmitted to the ground

Each of the barriers at the three lagoon inlets will certainly be a large infrastructure, not only because of the function that it is required to carry out, but also in terms its overall size and the numerous layers of ground that will be affected.
Considering the excavation volumes and the springing levels of the structures, the loads on the ground will be limited, however, and will be, to a large extent, lower than they are today. The caissons where the gates are installed and the abutment caissons are placed at the various inlets inside a trench about 10 m deep, and the effective pressure at that depth is now about 9 t/m².

In the most critical case, i.e. the Malamocco inlet, the mean effective pressure associated with the permanent loads of the foundation caissons and abutment works will be 6 t/m², with a low variability due to live loads (15% at most), and hence always well below the current effective pressure.
As for the caissons for the maintenance equipment sheltering docks, higher effective pressures than exist at present may be reached, because a deeper excavation is needed to reach the installation level. Generally speaking, in the different situations at the three inlets, these prefabricated units are installed in a trench between 11 and 20 m deep, where the current effective pressure is between 10 and 18 t/m². At these levels, the mean effective pressure transmitted by the structures to the foundation ground will be 15 t/m², and will thus rise locally by 5 t/m².

4.9.1. Geotechnical conditions, load-bearing capacity and settlement

Analyses revealed a complex geotechnical situation, characterized by a continuous alternation of cohesive and sandy layers of varying thickness. On the basis of the measurements available, a precautionary

reconstruction of the load-bearing capacity and deformability of the foundation soil was made, selecting the lowest values obtained from the laboratory tests and adopting the greatest thicknesses of deformable layers found by geotechnical investigations for the reference stratigraphy.
In particular, for the estimation of differential settlement, a precautionary procedure was used, assuming that the joint between two adjacent caissons rests on the "most deformable" of the layers found during testing, with the opposite ends of the caissons resting on the "least deformable" layer, and that the geotechnical parameters of the "least deformable" ground could be 30% higher than the precautionary values considered for the stability calculations.

4.9.2. Comparison between different solutions

A comparison was made between the following solutions, which offer a progressively greater degree of protection against differential settlement, Fig. 10 :
- direct bearing;
- direct bearing on previously-reinforced ground;
- indirect bearing by anchoring the structures to deep foundations.

The settlement phenomena were calculated both by traditional methods and using a two-dimensional finite elements model (the **PLAXIS** code) in which the structures were represented with their actual rigidity and ground characteristics in an elasto-plastic form.
For the direct bearing solution, the absolute settlement per foundation and abutment caisson was estimated at 9 cm, while the differential settlement over a 60 m length (calculated, as explained, on the assumption that both the soil layers and the geotechnical parameters were variable proved to be about 6 cm, and consequently higher than the maximum allowable limit of 3 cm. The surveys also showed that 65% of these settlements is attributable to the uppermost cohesive layer which is present at all the inlets in thicknesses of about 20 m, starting from the resting elevation of the caissons.

These results suggested the solution of a direct bearing on reinforced ground, altering the geotechnical features of the first layer. The deformability features of this layer will be improved by means of r.c. piles 40 to 24 cm diameter, arranged in a mesh at 3 m intervals and reaching through the whole thickness of the layer (down to a depth of 20 m). This approach was selected after considering other possible solutions and was designed to ensure a gradual load transfer to the piles in the surrounding ground.

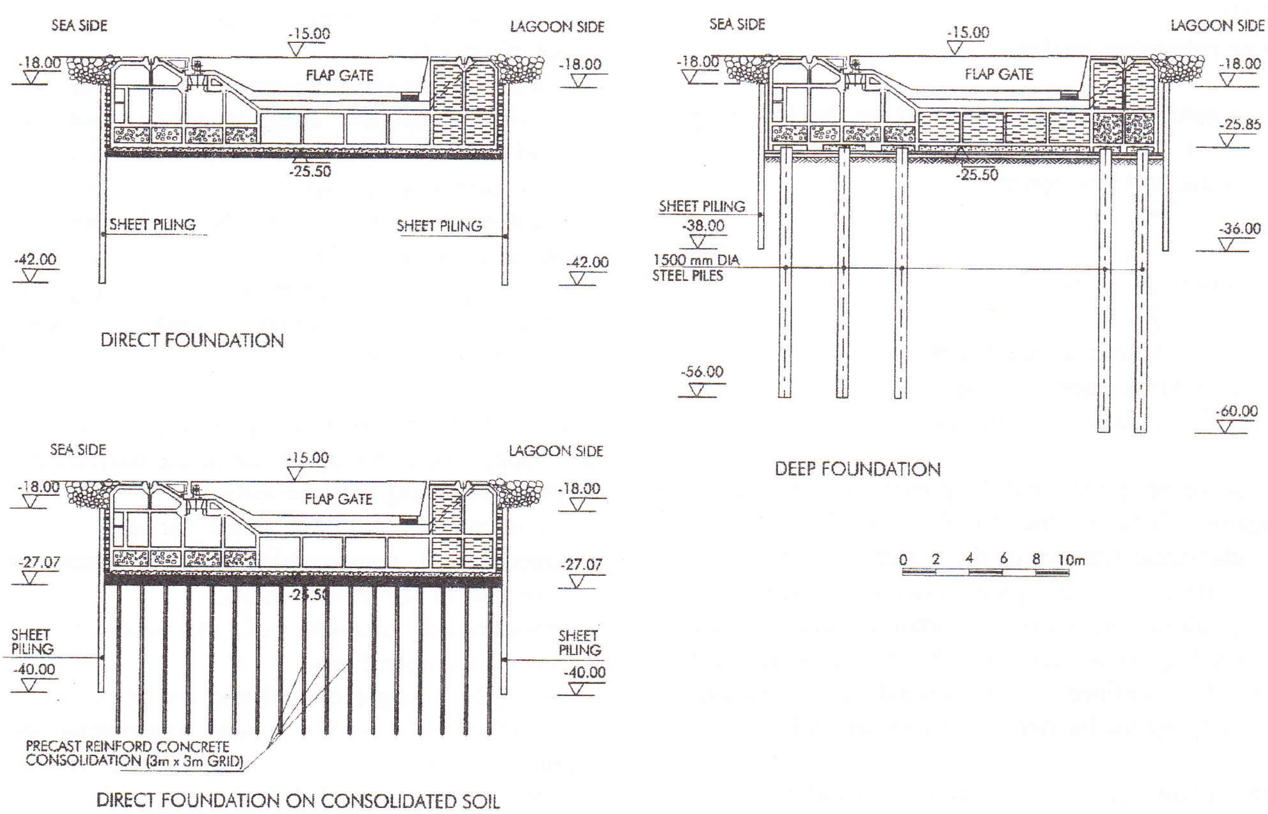

Figure 10 Types of foundation considered

It was calculated that this improvement in the ground's features would enable a ten-fold increase in the shear strain modulus of the first cohesive layer (from 460 t/m² to 6000 t/m²), reducing the absolute settlement to 4.5 cm and the differential to about 3 cm.
The last solution considered was to place deep foundations on large-diameter piles. Considering the depth reached by the piles and the need to contain the construction time to avoid blocking the inlet canals for too long, 1.5 m diameter steel piles (22 mm thick) were proposed, arranged in 5 rows along the cross section of the foundation caissons at 5 m intervals.

Using such deep foundations, the absolute settlement turned out to be no more than 3 cm and the differential settlement dropped to about 2 cm.

Though they were carried out using the approximations typical of the preliminary stages when different options are compared, these estimates demonstrated that resorting to deep foundations is unnecessary if the barrier rests on reinforced ground. This also allows for solutions which do not involve connecting large-diameter pile heads to the prefabricated concrete structures, an underwater operation that would pose obvious difficulties and risks for the system's reliability.

4.10. The reliability analysis

The gate's operation is ensured by the following systems:
- control and monitoring;

- pneumatic plants;
- electric plants;
- sediment removal equipment;
- gate maintenance equipment;
- auxiliary plants and utilities.

Reserve equipment and the provision of protection against failures due to fire or flooding are fundamental features of the system, which is why they are located in separate chambers and tunnels (e.g. along the gates' foundation caissons, see again Fig. 7) so that the effects of any accident can be confined to a defined area, without prejudicing the barrier's operation as a whole.

The plant, utilities and systems located in the foundation caisson tunnels run as far as the abutment structures at the two ends of the barrier. The delivery and discharge of compressed air and the auxiliary systems only reach one of the abutments, where the compressed air and energy production plants and the control room are located. Conversely, ventilation is provided symmetrically between the two abutments in order to reduce the size and number of ducts to install in each tunnel.
The tunnels housing the plant and equipment are also used for maintenance and to reach the chambers from where the gates hinge connectors are made ready for gate locking and releasing operations.
The abutment structures contain the plant, equipment and piping systems for the air supply to the gates and its subsequent removal, the tunnel ventilation systems and the auxiliary services.
The structures are provided with stairways and lifts leading from the ground floor, situated 3.5 m above sea level, to the tunnel levels, Fig. 11.
A sheltering dock is provided for a gantry crane for use in replacing and transferring gates to the maintenance yard, located at the abutments; the main abutment also includes areas for the storage of a spare gate.

5. CONTROL AND MONITORING SYSTEM [6]

The operation of the mobile gates involves three types of activity:
- data acquisition (external data on the environmental and socio-economic conditions and internal data on the system and the structure's operation);
- data processing to guide the performance of gate operations and maintenance;
- carrying out operations according to established procedures (gate raising, maintenance, etc.).

The control and monitoring system has been developed so that the operation of the barriers can meet the following requirements:
- simultaneous control of all the barriers;
- unequivocal responsibility for the operating procedures at the three inlets;
- coordinated planning of maintenance and inspection operations.

As a result, a single control and operation center has been planned with a central supervising and monitoring station, while the mobile barrier operations are controlled and monitored by the three control rooms located in the abutments of each barrier, Fig. 12.

The main control center is located on the artificial island at the Lido inlet and controls the general coordination of the barrier opening and closing operations by means of a supervision system subsystems in order to achieve a "scattered control" which ensures the utmost flexibility. Every single system (air compression, power generation, sediment removal, etc.) has its own

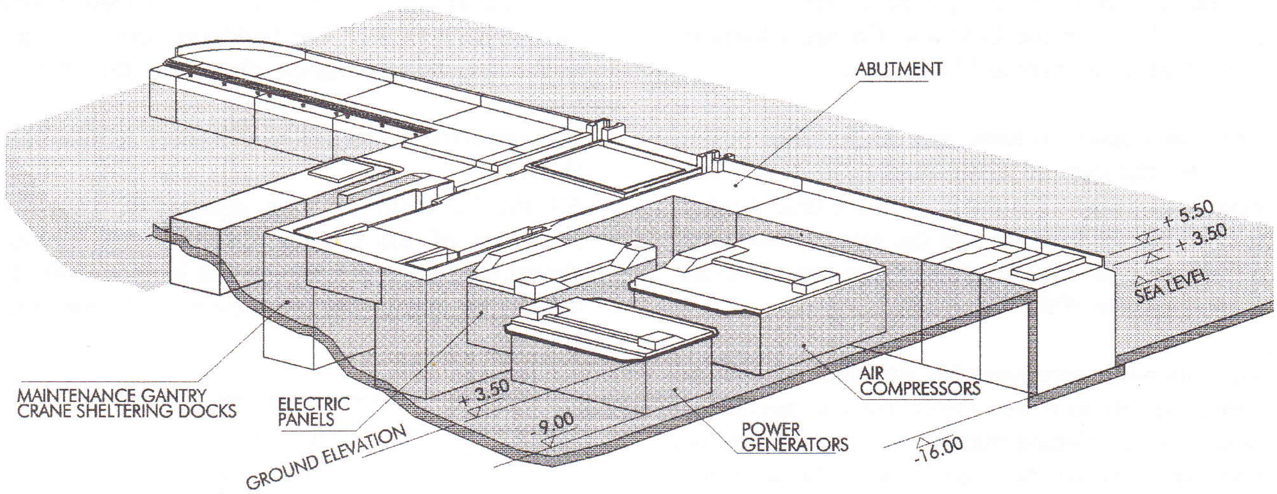

Figure 11 Electromechanical equipment and civil works

linked to the three control rooms. This central station receives all the information needed for a global control of the barriers.
The central station also issues the instructions that start barrier closing or opening sequences so as to ensure that said commands are unequivocal.
The control and monitoring systems installed in the control rooms are for ensuring the smooth operation of the gates during the various stages and to check that the systems are kept in good working order.

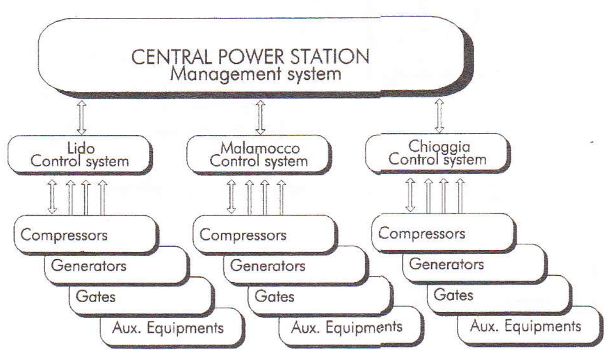

Figure 12 Control sistem chart

The control and monitoring system relies fundamentally on the use of equipment working at different hierarchical levels through decentralized decentralized control and monitoring equipment. All signals coming from the peripheral units converge on the control room, where they are represented in the form of synoptic charts. It is therefore possible, in the control room, to select various degrees of automation by means of simple procedures.
In general, the control and monitoring system will operate in different modes according to the need and at the operator's discretion. Three operating modes have been envisaged for gate operation, depending on three different control panels:
- automatic mode;
- manual mode;
- "stand-by manual" mode.

6. PLANT AND EQUIPMENT [6]

6.1. Air compression system

Gate raising and adjustment takes place by introducing air in the quantity and at the pressure most suitable for the depth of the sea bed, the dimensions of the gate and the difference in level required between the sea and the lagoon.
Altogether, it takes 57,000 Nm³ of air to raise the gates of all three barriers and a further 150,000 Nm³ to achieve the maximum difference in level envisaged by the project, which equates to 2 m

(42% of the air at the Lido inlet, 35% at the Malamocco inlet and 23% at the Chioggia inlet).

The air must be supplied to the system at a pressure sufficient to push the water out of the gates, which lie at depths that differ from one inlet to another, by overcoming load losses, i.e. 3.12 absolute bars for the Lido and Chioggia barriers and 3.6 absolute bars at Malamocco.

The compression system, and its installed power and the number of compressors, in particular, have been designed in the light of the time it takes for the barrier to close and the rate at which the difference between the sea and the lagoon levels grows because of the rising tide.

The minimum recommended time for raising the barrier is 30 minutes; faster closing operations would risk producing marked level oscillations on both the sea and the lagoon side. On the other hand, the longer the closing time, the longer the waiting time for the merchant ships entering and leaving the lagoon (if closing operations were to take 45 minutes instead of 30, the waiting time for shipping would increase by 15%).

The air compression system has consequently been to ensure a closing time of 30 minutes.

For compressed air production, eight potential solutions were considered, which can be divided into three groups:

- direct air production (the output of compressors correlates directly to the delivery piping); four options were compared, each using a different number of compressors, i.e.
- mixed solutions, in which some compressors create a stock of compressed air for gate raising, while others are directly connected to the gates to keep them in position while the difference in level between the sea and the lagoon increases;
- the production of high-pressure air to be stocked and used both to raise the gates and to keep them trim.

The most cost-effective solution proved to be a direct production by means of 6 compressors at each of the three inlets, two of which are on stand-by, Fig. 13.
The total electric power required to raise all the gates is 15 MW.
The centrifugal compressors are of the oil-free air type and are coupled by means of an overgear to 6 kV synchronous electric motors with outputs ranging between 500 kW and 1100 kW.
The air flow rate ranges from 7,000 Nm^3/h to 14,000 Nm^3/h, with maximum pressures reaching 3.6 absolute bars.
Compression stations have been located directly in the main abutments of each inlet to reduce load losses inside piping. The buildings containing the electric power generation plant and the electric panel.
The auxiliary plants are also located in the main abutments.
All the buildings housing equipment, with the exception of the control stations, are situated almost entirely under the ground level in order to reduce the impact on the lagoon landscape, Fig. 13.

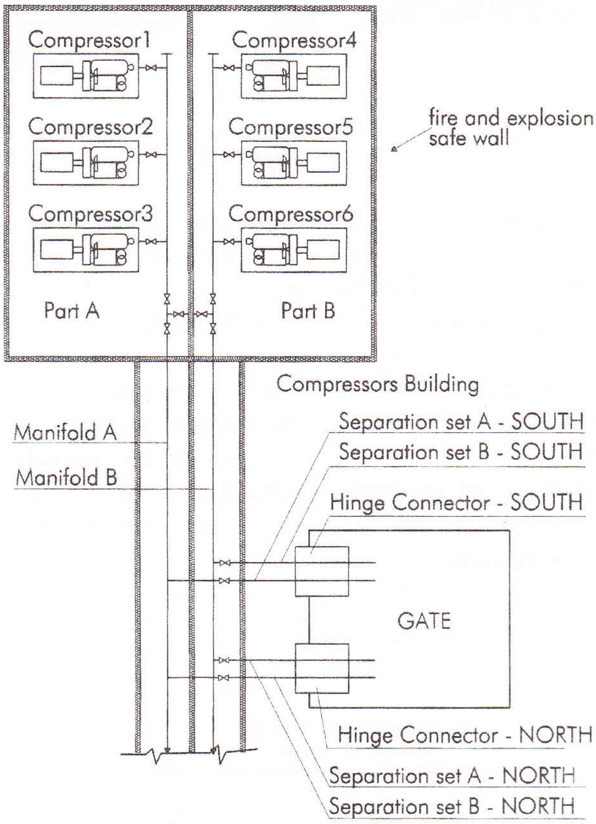

Figure 13 Air compressors scheme

6.2. Electric system

An output of 15 MW is necessary for operating the compressors and the auxiliary equipment. Considering the predictably limited number of barrier-closing operations per year, the power supply from the Italian National Electricity Board (ENEL) is the main source of electric power; its reliability is ensured by two independent sources

(each of the three barriers can be supplied from the south by the Brondolo substation and from the north, by the Cavallino substation, with a 20 kV voltage) and from emergency generator sets.
On the basis of the results obtained in the feasibility analysis, the solutions adopted cater for the supply of each inlet from three different stations, each of which is provided with three emergency generator sets plus a stand-by set.
The electric systems are located in two different chambers with two generator sets each, and there are two electric distribution boards to avoid the risk of a total power cut due to explosion or fire.
The wiring diagrams for the three inlets are illustrated in Fig. 14.

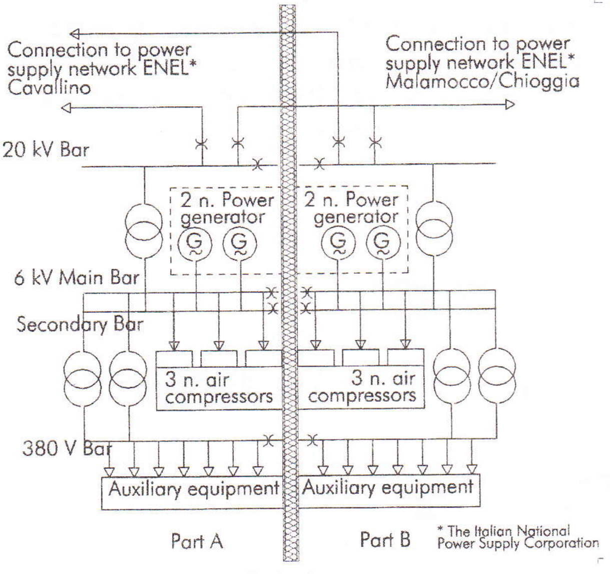

Figura 14 Electric system

The system consists of a 20 kV section, including the electric power supply from the national ENEL network and the input and output panels for the 20 kV lines; a 6 kV section comprising the generator sets, the compressor motors and the electric distribution boards; a 380 V section for supplying auxiliary plants; the electric power supply control and monitoring system.
The different voltages are obtained through a double transformation: from 20 to 6 kV and from 6 kV to 380 V.
According to the project, the ENEL lines will supply the maximum required power of 15 MW, 44% of which is needed to operate the gates at the Lido inlet, 32% for Malamocco and 24% for Chioggia.

In the event of need, the electricity supply can provide an overall power of 20 MW, divided as follows:
- four 2 MW sets, totaling 8 MW, at the Lido
- four 1.5 MW sets, totaling 6 MW, at Malamocco
- four 1.5 MW sets, totaling 6 MW, at Chioggia

Three stations will be connected by a double medium-voltage electric line. Should the power supply from both the ENEL sub-stations be cut off, the three stations will be enabled automatically and will work as a single system.

7. RELIABILITY ANALYSIS [6]

The reliability analysis consists of calculating the system failure probabilities in terms of the average number of failures per time unit, on the basis of the failure probabilities of the individual components.
The reliability analysis is used for an objective comparison of potential solutions, so that the most suitable one can be identified. For instance, the actual functional advantage achievable by increasing the complexity of the system or introducing reserve units for the components most prone to failure can be verified.
The barrier system comprises a large number of components (79 gates, 158 hinge connectors, 316 connections for introducing air in the gates, etc.).
The purpose of the reliability analysis for this particular system is to establish how much to backup the main systems and the features of the housing structures, by selecting the most cost-effective solutions.
The analysis considered solutions that provided for the probability of a whole barrier not rising once every 10,000 years and for one gate not rising once every 1000 years. In addition, the probability of any failure producing a high tide in the lagoon in excess of 130 cm must be lower than once every 1000 years.
The aim of the procedure is to find combinations of the minimum number of component failures capable of bringing the system to a halt.
For this study, a "failures tree" was used, i.e. a flow chart describing the interrelations between the failures of each component and the failure of the whole system at different aggregation levels (a compressor does not start, a gate does not rise, etc.).

Compiling the failure charts calls for the definition of the system and sub-system failures and the identification of all potential causes of failure, considering the components individually. The probability evaluations on the failure charts were done with the ORCHARD code of the Atomic Energy Authority, U.K.. The component failure rate was calculated by the database of said Authority.

Although the reliability analysis was carried out only considering the main components of the system, more than 300 components had to be included in the failure chart and the minimum number of failure combinations that can lead to the complete breakdown of the gates exceeds 4000.

In particular, the influence of ordinary and extraordinary gate maintenance operations on the system's reliability was evaluated.

The solutions adopted in the preliminary design phase assume that there is one probability every 10,000 years of the level of 110 cm being reached in the lagoon as a result of gate malfunction during high tide. This solution is characterized by two fundamental features:

- all the systems are located in physically separated chambers;
- all the main plant (power, air compression and supply, monitoring and ventilation systems) has full backup capabilities.

As an example, Fig. 15 shows a flow chart illustrating the failure of a compressor cooling system.

8. GENERAL INFORMATION

The project for the mobile barrier works is currently under consideration by the Committee for Evaluating Environmental Impact, which is expected to issue its verdict before the end of 1997.

From then onwards, it will be possible to implement the executive project so that the works can begin in the year 2000; they are expected to take 8 years to complete.

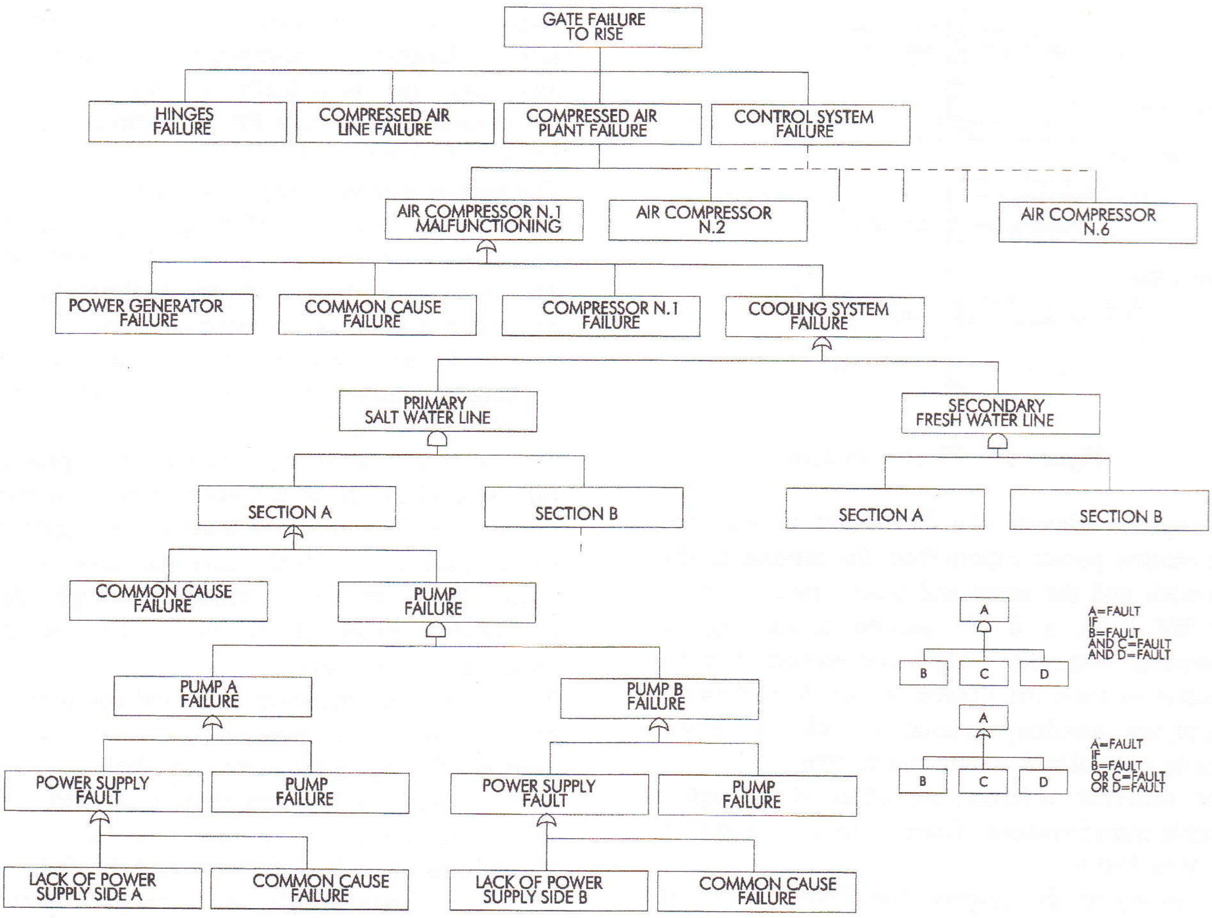

Figura 15 Air compressor cooling system, fault tree analysis

The net cost of the works is estimated at around 3,000 billion Italian lire; the gross value, including the cost of design, works management,

concessions, contingencies, other burdens and VAT, amounts to 5,350 billion lire.
It has also been estimated that the annual cost of managing the system and ordinary and extraordinary maintenance will come to about 0.7% of the cost of the works. This amount is considered consistent when compared with the running costs of other hydraulic systems.

NOTES

[1] The high water levels and elevations mentioned in this paper generally refer to the tide meter at the Punta della Salute, which is 23 cm below the mean level of the lagoon.

[2] The Consorzio Venezia Nuova is a private pool of Italian building contractors of national and regional standing, which has been entrusted by the State under a specific concession for the performance of the following:
. preparatory studies and experiments, including *post operam* monitoring;
. the design and construction of the works involved in the project by the building companies belonging to the pool;
. supervision of the works under the control of the State, of the Magistrato alle Acque di Venezia, and of specially-appointed Testing and Commissioning Boards.

[3] As at the end of 1996, the State had issued the sum of 1,860 billion lire to the account of the Magistrato alle Acque di Venezia, 93% of which has been reserved for executive projects and 63% has been spent on the projects that have already been completed or on projects that are currently underway.
The global cost of all the schemes for safeguarding Venice, including the mobile barrier works, amounts to about 8,000 billion lire (1996 estimate), which includes the above-mentioned 1,860 billion. The estimated time for the completion of the works, assuming there are no hold-ups in the financing, is 10 years: 2 years for the preparation of a first part of the construction project for the mobile works and 8 years for their actual construction.
This is on the understanding that all the other measures for safeguarding Venice are taken in the meantime.

[4] The work of the Consorzio Venezia Nuova is based on science and knowledge, and in particular on studies, experiments, general design projects, and international experience (e.g. flood prevention barriers for the River Thames; the mouth of the Eastern Schelde River; the Waterweg in Rotterdam), and on the work that it has done or is in the process of doing (1997) for the Venice Project, the project for mobile barrier works at the lagoon inlets for controlling tidal flows.

[5] See the special issue of the "Quaderni Trimestrali" of the Consorzio Venezia Nuova, May 1995.

[6] Points 4 to 7 refer in particular to the paper presented by M. Gentilomo and G. Cecconi to the 7th Conference on "Offshore and Maritime Engineering Association, AIOM", University of Pisa, October 1994.

PROTECTING ST. MARK'S SQUARE FROM HIGH TIDES

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The situation presented here, concerning the city of Venice requires the invention of a *dam* so unusual, unobtrusive thin and invisible, that it cannot compare I believe with anything discussed in this meeting.

At present, St. Mark's Square is more exposed to high tides than any other zone in Venice. This situation is very difficult to deal with as it is not solely dependent on natural phenomena. In addition to the factor of global rise in sea level over recent centuries, it also depends on the ancient will to respect St. Mark's Basilica as supreme political-religious emblem of the Republic.

Modifications have been carried out to the Basilica over the centuries in terms of external and internal decoration, whereas its doorways have been in place since the 1300s at the very same elevation. Recent measurements confirm that the public paved areas in front of the central arch are 58.9 cm above current mean sea level; this means they are below normal tide level, which is approx. 70 cm in Venice. The level around the doorway that gives into the Piazzetta dei Leoncini is a mere 73 cm. During the Republic, the Procurators of St. Mark's, responsible for the Basilica and its surrounds, attempted to save the square from high tides by raising the public paved area. This is still the most effective and widely-used way to deal with the problem. In alternative, constructions such as the Zecca (Mint), Marciana Library and the Procuratie Nuove, dating back to pre 1537, were placed on a stylobate or higher step. In 1723 when the traditional red-brick paving of St. Mark's Square was replaced with the grey and white stone work which is still in use today, the possibility of saving the entire square and its monuments from flooding by exceptionally high tides was examined. As however the problem was considered from the viewpoint of natural gravitational hydraulics, no solution was found. Mechanical pumps for rapid removal of water from the basins or flooded countryside were not available, only hand pumps, and it would have been impossible to design an efficient system.

Can today's technology and advanced scientific know-how make it possible to deal with the flood risk for St. Mark's Square without altering the time-honoured image of this unusual symbolic and monumental complex? This in essence is the difficult question to be answered by "The Works for Safeguarding the Insula of St. Mark's" as per the Preliminary Project approved by the Committee of Experts of the Venice Water Authority on 10/2/1995, drawn up by a group of consultants under the Consorzio Venezia Nuova, and which now must be transformed into the Executive Project.

To understand the reasons behind the preliminary project, it is important to know that scientific investigations have confirmed that flooding takes place when the water rises in the square in one of three ways: a) overflow: when, during the incoming tide, the sea and lagoon water overflow the canaledging walls of the public paved area; b) reverse flow: as is common in similar squares, there are underground channels beneath the paving for draining rainwater, they function in the reverse sense when the tide rises, and let water in instead of out; c) filtration: like the rest of Venice, the subsoil of St. Marks's Square in composed of several layers of permeable filling, and if the underground channels or the outer border walls are not perfectly sealed, water can filter through the paving. Keeping track of these three different but concurrent causes has been the major concern of those responsible for the project design.

Accurate plano-altimetrical measurements of the existing paving made it possible to identify the exact zones that are progressively submerged as the water level rises, as per the graph. As regards the descriptions of the solutions proposed, it must be emphasised that previous work has revealed the square to be a sort of "basin", as the level of the paving is +1.00 m and over, for most of the perimeter. Thus, if the other more general systems could be relied on for protection against the higher tides, it would be possible to limit the safeguarding of the square to one metre.

Were the existing raised outer walls to be completed, a system based on the paving itself could be designed for overflows, and other systems studied for flooding through reverse flow or filtration.

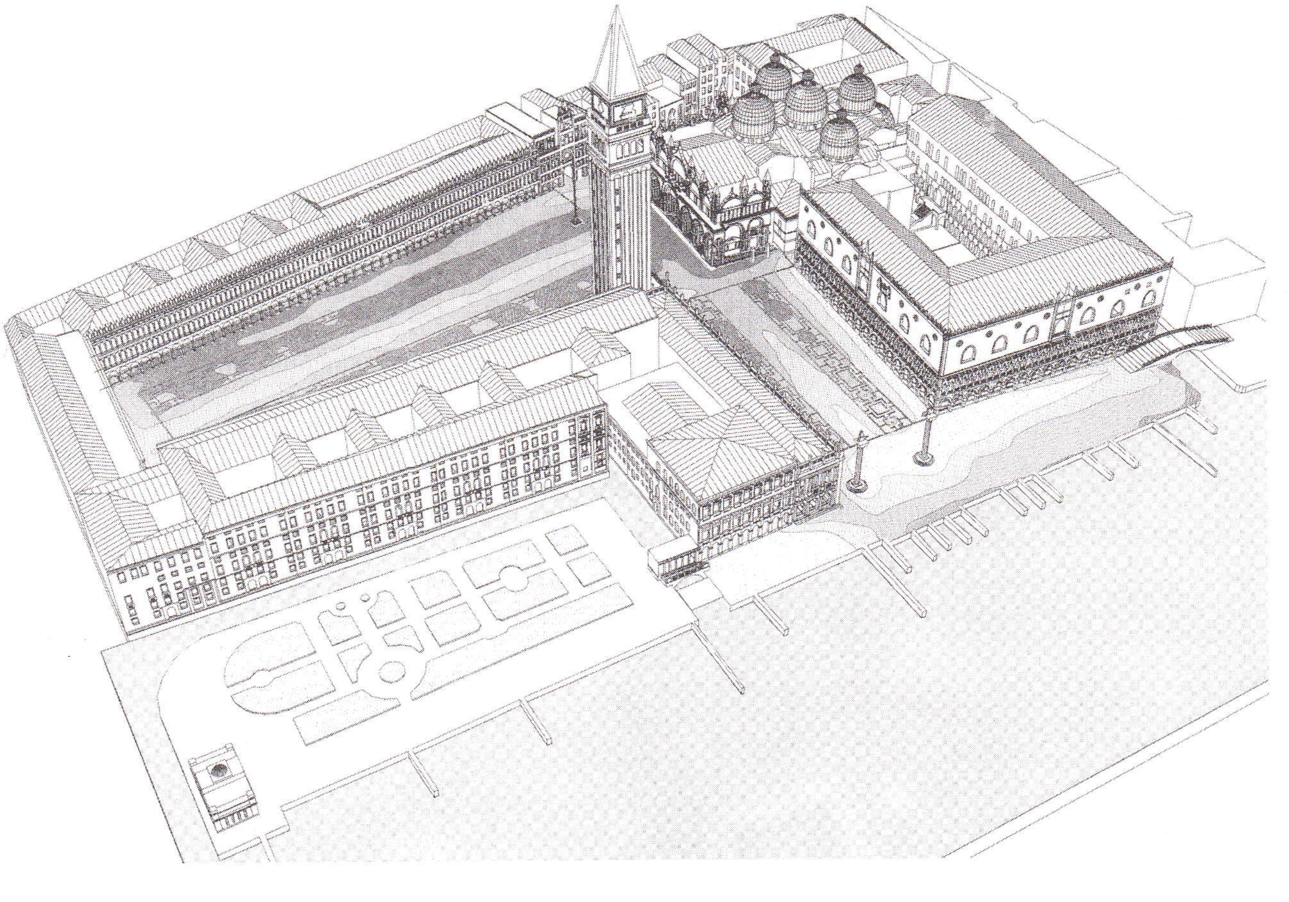
At this point a brief overview of the surroundings is in order, with +1 m as the reference level for safeguarding. The south-western region, located at +1.22, and over, gives no cause for concern, while the north-east zone encompasses difficult sites below one metre. As already mentioned, the area around the Basilica is one of the lowest, and requires special solutions. The picture is rosier in the vicinity of the Ducal Palace Piazzetta, though the level of the paving drops along the waterfront towards the Paglia bridge.

All in all the basin form of the paving means few adjustments are required to cover a rise up to one metre in the level of the tide. A brief mention of the subsoil is necessary, in terms of the flooding through reverse flow and filtration. The survey of the underground channelling showed that they are made of bricks and lie some 1.50 m below pavement level, and are 1.20 m wide at most. There are problems involving the archaeological finds as non-destructive investigation is needed. Some work has been carried out, but completion is necessary in view of the executive project. A detailed underwater survey of the outlets showed they are placed haphazardly and vary widely. The geo-technical survey showed that the permeability of the material examined varies considerably from layer to layer and the piezometric survey suggested that infiltration coincides for the most part with the incoming tide, that is to say, it lets the water in rather than out. In light of what has been said so far, it is clear that a projects is needed to deal in a global manner with the three above-mentioned causes of flooding, namely overflow, reverse flow and filtration. Theoretically, global project types might involve: a) the construction of new permanent or mobile works either on the surface or underwater, to form a perimetral barrier to intercept the water; b) the transformation of the existing structures into structures with the same characteristics but treated in such a way as to halt reverse flow and filtration. It goes without saying that the historical-architectonic and monumental importance of S. Mark's Square mean that only type b) solutions are possible. In summary, project requisites are as follows: a) in order to deal with flooding due to overflow: a modest rise in the perimetral paving, where necessary and architectonically possible; b) in order to deal with flooding due to reverse flow from the channelling: structures restored, sealed off and integrated with a new system for removing water, including one for pumping rainwater out into the lagoon; c) in order to deal with flooding due to filtration from the subsoil: the addition of waterproofing coverings below the paving and where it comes into contact with the lower part of the buildings.

The question of St. Mark's Basilica

involves the Procurators of St. Marks's, the most legitimate and competent heir of Venetian traditions. To date only general ideas have been put forward. Seen as a whole, the preliminary project can be defined as a programme for regenerating, reinforcing and coordinating all the elements both above and below the surface, conceived since the creation of St. Mark's Square, so that the public will be able to move from one place to another without getting their feet wet. There were once several wells in the Square for collecting and purifying the rainwater for drinking purposes or domestic use. The last of these wells was closed in the 1600s. All had underground cavities for collecting rainwater, and were waterproofed from below by a layer of thick compact clay taken from the geological stratifications on the bottom of the lagoon. These layers of clay kept the dirty salt water separate from rainwater, and thus served the same purpose the project assigns to the thinner waterproofing covering for the entire complex to be added below the present-day surface of St. Mark's Square. Similar to the covering used in roofing restoration, these protective layers serve to stop water leaving the subsoil via the square unless by way of restores underground or new channelling. However, more importantly, it is a question of technical proposals that are compatible with the maintenance and workable preservation of all the environmental, formal and functional components that go to make up the unique historic heritage of the complex.

The preliminary project mean withdrawing the square from the pathetic atmosphere of "curiosity" that mortifies it today, restoring it to the condition for which it was constructed, namely that one of the most beautiful, place of collective social, cultural life to be found anywhere in the world.



GEOTECHNICAL PROBLEMS FOR THE MOBILE BARRIERS

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ABSTRACT

The selection and design of the mobile barrier foundations require an accurate knowledge of the geotechnical parameters of the Venetian quaternary basin and particularly of the cohesive formations, which are the most responsible of the settlements and displacements induced by the barriers in to the ground. To this purpose a comprehensive geotechnical soil characterization has been carried out by site and laboratory investigations. This paper presents some relevant aspects of the geotechnical characterization of soils and discuss the barrier foundation related problems.

1. INTRODUCTION

It is probably world-wide recognised that the city of Venice shows a precarious equilibrium and that the margin of security is being eroded annually at an increasing rate. The rate of deterioration is being accelerated by the increasing frequency of the flooding of the old city, by the increase of pollution of both the lagoon and the atmosphere and by the reduction of the freeboard of the city as a result of the eustatic rise in sea level coupled with a subsidence of the general lagoon area (Ricceri and Butterfield, 1974).

In the early eighties, the Italian Government decided to finance the design of special mobile barriers - located at the three inlets of the lagoon - which should be able to protect the old city and the entire lagoon against the flooding due to the high tides.

The selection and design of the barrier foundations require an accurate knowledge of the geotechnical parameters of the upper quaternary basin, particularly of the cohesive formations, which are the most responsible of the settlements under the barriers.

To this purpose a comprehensive geotechnical investigation was carried out in two phases.

The first phase was considered as a preliminary investigation (to be used for the preliminary design of the barriers) and was performed in correspondence of the three lagoon inlets by using some standard investigations.

The second phase was decided in order to characterize more accurately the Venetian subsoil.

However, the high costs of boreholes and laboratory tests suggested a more extensive use of the less expensive in situ tests.

Unfortunately, in situ tests not always provide direct determination of soil parameters but require empirical correlations or interpretation methods in order to transform the in situ measured quantity (e.g. the tip penetration resistance in the case of cone penetration test) in the selected design parameters.

In order to establish reliable correlations or to validate available interpretation methods, a calibration between in-situ-determined quantities and soil parameters, accurately estimated from laboratory tests on undisturbed samples, was considered as necessary.

Therefore, before beginning with the second phase, a special geotechnical investigation was planned: the so called "Geotechnical Calibration Station" (GECAST). In a limited area at the Malamocco inlet, deep boreholes together with piezocone, dilatometer, selfboring pressuremeter, screw plate and cross/down hole tests were carried out on nearby verticals. In addition, in order to obtain high quality undisturbed specimens, it was decided to used also a new large diameter sampler.

This paper discuss some aspects of the geotechnical investigation and characterization of Venetian ground, together with the selection of soil parameters. More particularly the paper considers the cohesive soils, which are the most responsible of settlements under the barriers and discuss the geotechnical problems related to the selection of barrier foundations.

Other aspects will be considered in future research.

2. HISTORY OF THE VENETIAN LAGOON

2.1 Geological history

During the Pliocene, more than one million years ago, the sea level was much higher than today. The entire Padana plain, where the sediments coming from the erosion of the emersed land were being discharged, was entirely submerged by the Adriatic sea (fig. 1a).

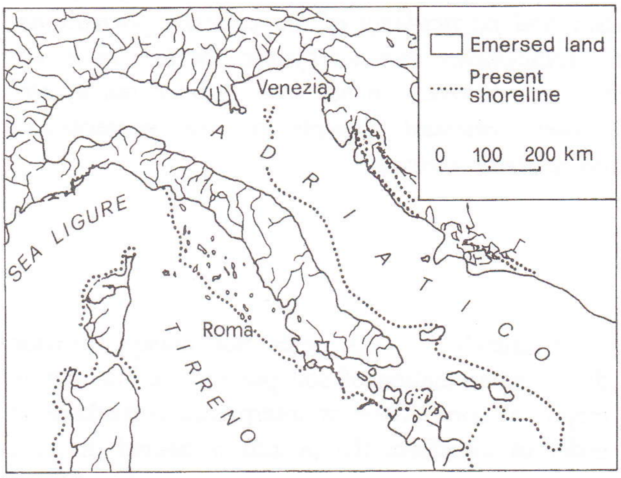

Fig. 1a. North Italy during the Pliocene.

The Pleistocene was characterized by several glaciation and interglaciation periods with alternating lowering and raising of the sea level. During the last Wurmian glaciation, between 120,000 and 8,000 B.C., the sea level was lowered of about 90 m with respect to the present level and, therefore, the Padana plain and a part of the Northern Adriatic have been emersed (fig. 1b).

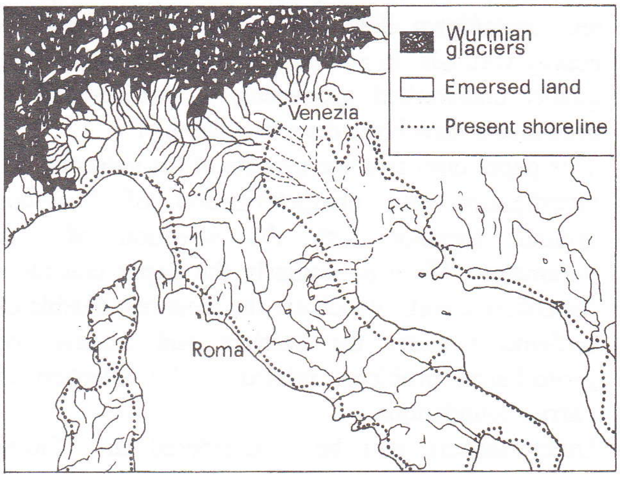

Fig. 1b. North Italy during the Pliocene.

The last 10,000 years are characterized by a raising of the sea level, reaching, between 5,000 and 3,000 B.C, a value slightly higher than the present one.

The quaternary deposits of the Venice Lagoon, extending until a depth of approximately 900-950 m below mean sea water level, have been formed throughout the Pleistocene.

They are composed by a complex system of interbedded sands, silts and silty clay sediments. Their accumulation took place in different phases, during which marine regression and transgression alternated and the rivers transported materials coming from the nearby Alps.

At the inlet of Malamocco, where very extensive geological investigations have been carried out, four main environmental phases have been distinguished (Curzi, 1995):

- from ground level to 10-15 m: deposition due to the present lagunar cycle;
- from 10-15 m to 50-60 m: complex interbedded sedimentation during the last glacial period;
- from 50-60 m to about 300 m: alternated marine, lagunar and continental deposition;
- from 300 to 950 m: marine sedimentation of lower Pleistocene.

A general view of the Venetian lagoon is shown in figure 2.

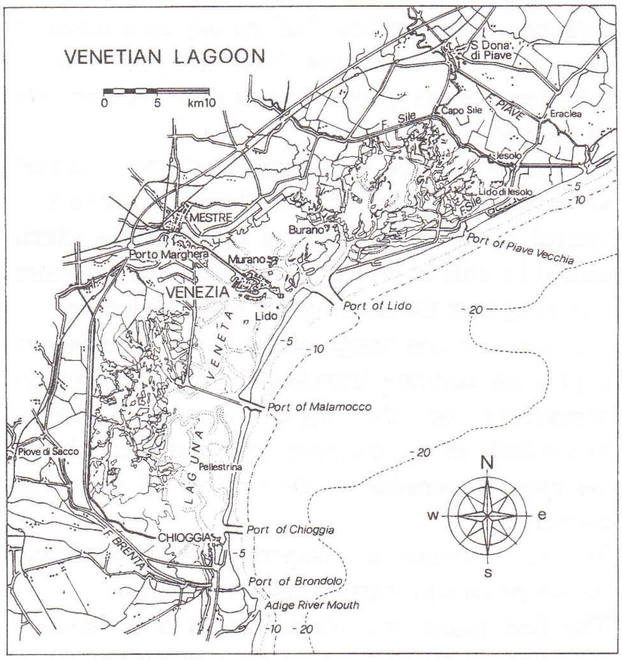

Fig. 2. General view of the Venetian lagoon.

2.2 Anthropic action

Various type of anthropic actions voted to the increase of the safety and efficiency of the Venetian harbour have been carried out since the twelfth century, when the first future citizens settled on the islands.

The littoral was protected by using simple earth nourishments reinforced with oak piles ("tolpi"). Particularly devastating storms occurred during 1346-1347 suggested the use of "Istria" stones, placed between two lines of piles connected by chains. Two or three adjacent lines were used to protect the more exposed sites. These works have been integrated with several 100 m - long groyne, which were made using the same technique described above. In 1560, about 200 groynes have been realized along the Venetian littoral.

One of the most important problem for the Venetian citizens was the preservation of efficient communications between lagoon and sea.

These were seriously compromised by the rivers Brenta, Sile, Piave and others, which discharged waters and sediments into the Venetian lagoon. In order to prevent this, the rivers were diverted into extensive canals around the lagoon periphery. In addition, other interventions have been performed: in order to increase the navigability of Lido, S. Erasmo inlet was closed in 1351 and, after 9 years, reopened.

Pile-works were also realized in order to divide the waters of S. Erasmo inlet from those of S. Nicolò inlet; the total length of these pile works was increased up to 900 m. In 1519 these were destroyed and, subsequently, after 15 years, it was reconstructed and reinforced. Figure 3a shows the morphological evolution of the Lido inlet, from 1552 until today. Figures 3b and 3c show the evolution of Chioggia and Malamocco inlets from the beginning of XIX century to the present (Colombo, 1970).

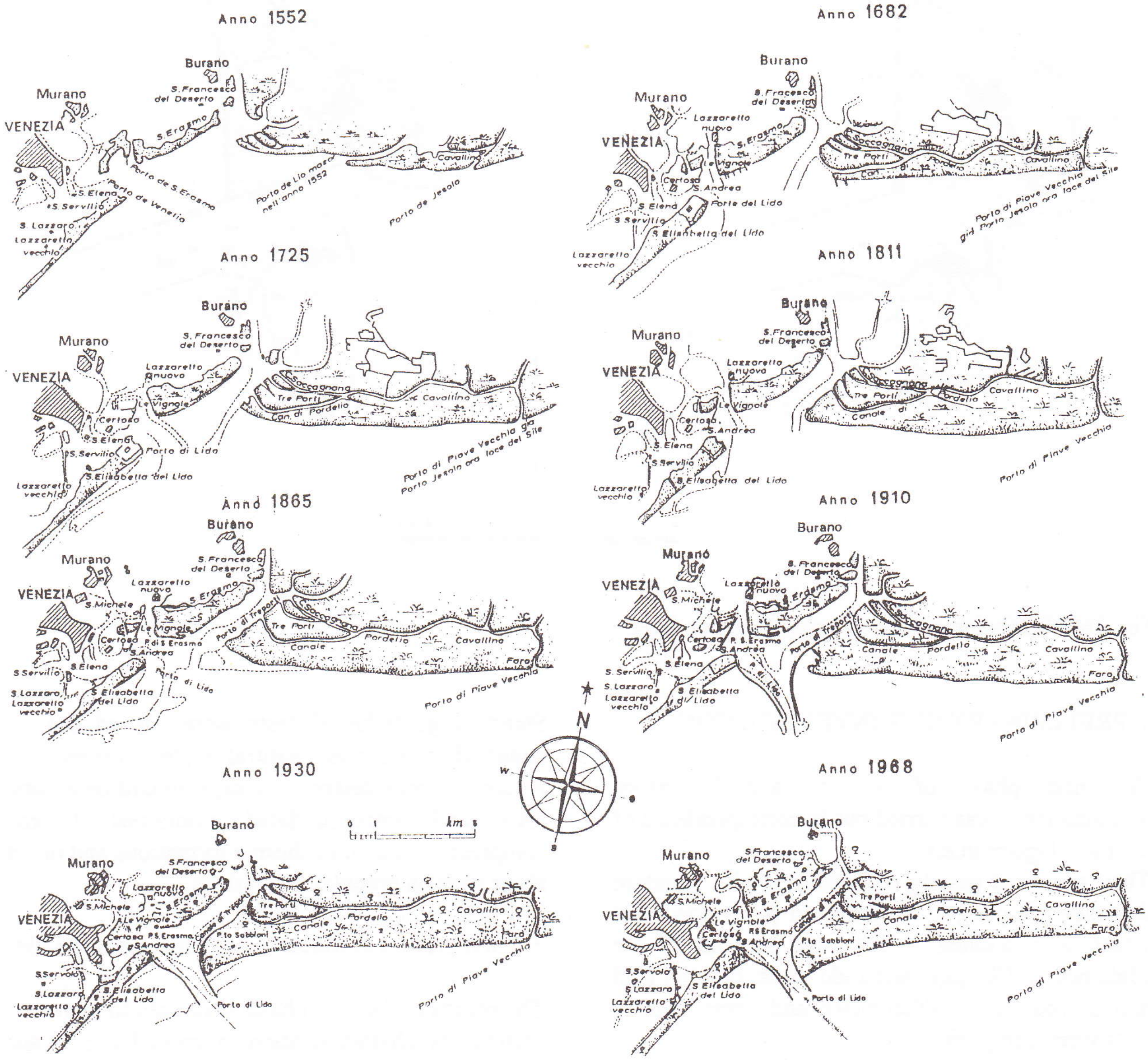

Fig. 3a. Morphological evolution of Lido inlet.

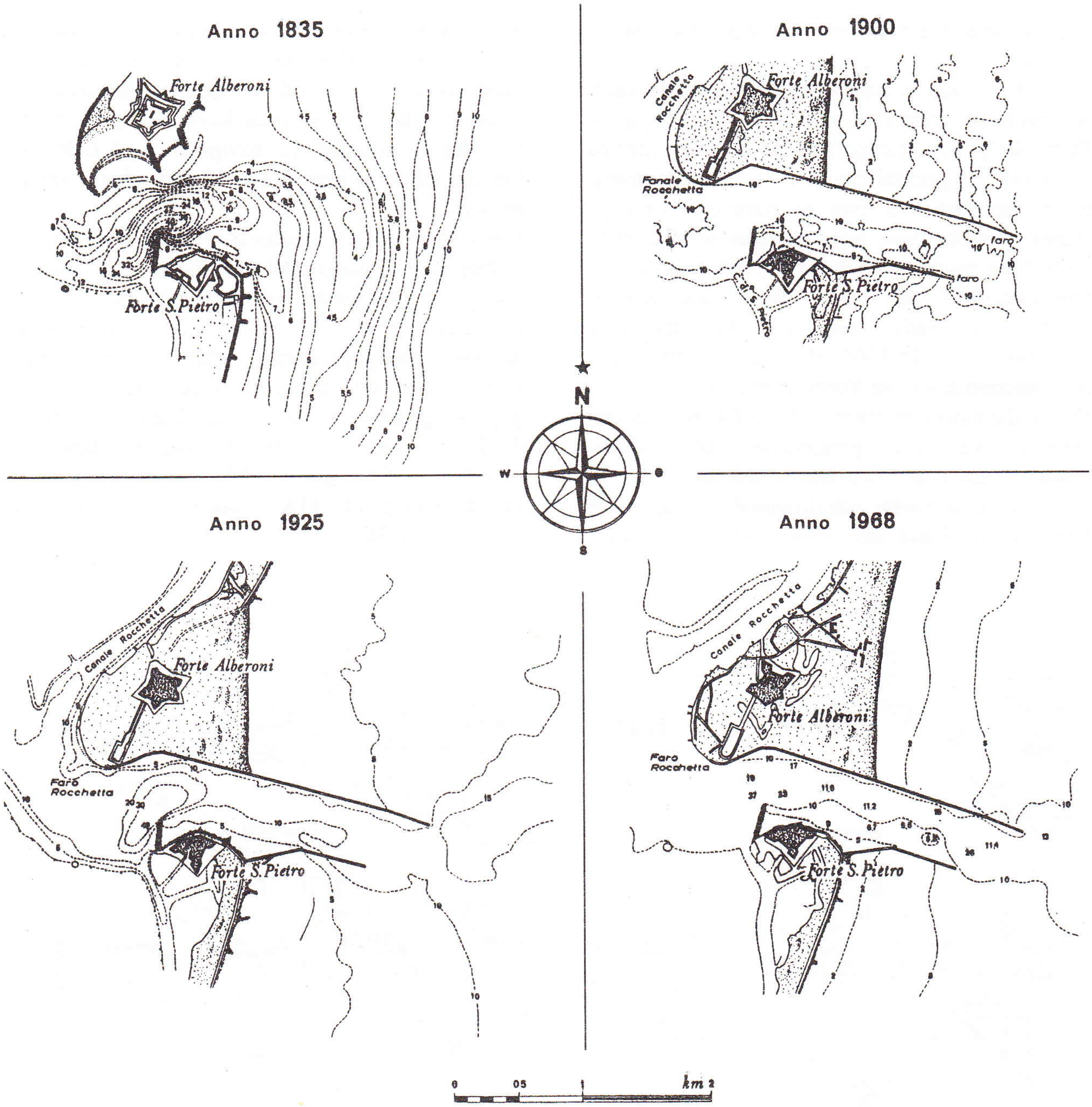

Fig. 3b. Morphological evolution of Chioggia inlet.

3. PRELIMINARY SITE INVESTIGATIONS

The first phase of in situ and laboratory investigations was carried out in correspondence of the three lagoon inlets.
They consisted mainly of boreholes with standard diameter sampling (100 mm) and piezocone tests, which were located at the cross sections of the Malamocco, Chioggia and Lido inlets, both on land and at sea. Some dilatometer and pressuremeter tests were also performed.
The location of the in situ tests at the three inlets is shown in figure 4a,b,c.

Standard geotechnical tests were carried out on undisturbed samples: natural water content and Atterberg limits determinations, standard oedometic tests and unconsolidated undrained triaxial compression tests on cohesive formations and direct shear tests on granular formations.

3.1 Soil profiles at Malamocco, Chioggia and Lido

The results of the first phase were used to provide a preliminary characterization of ground profile and an estimate of the most relevant geotechnical parameters involved in the barrier design.

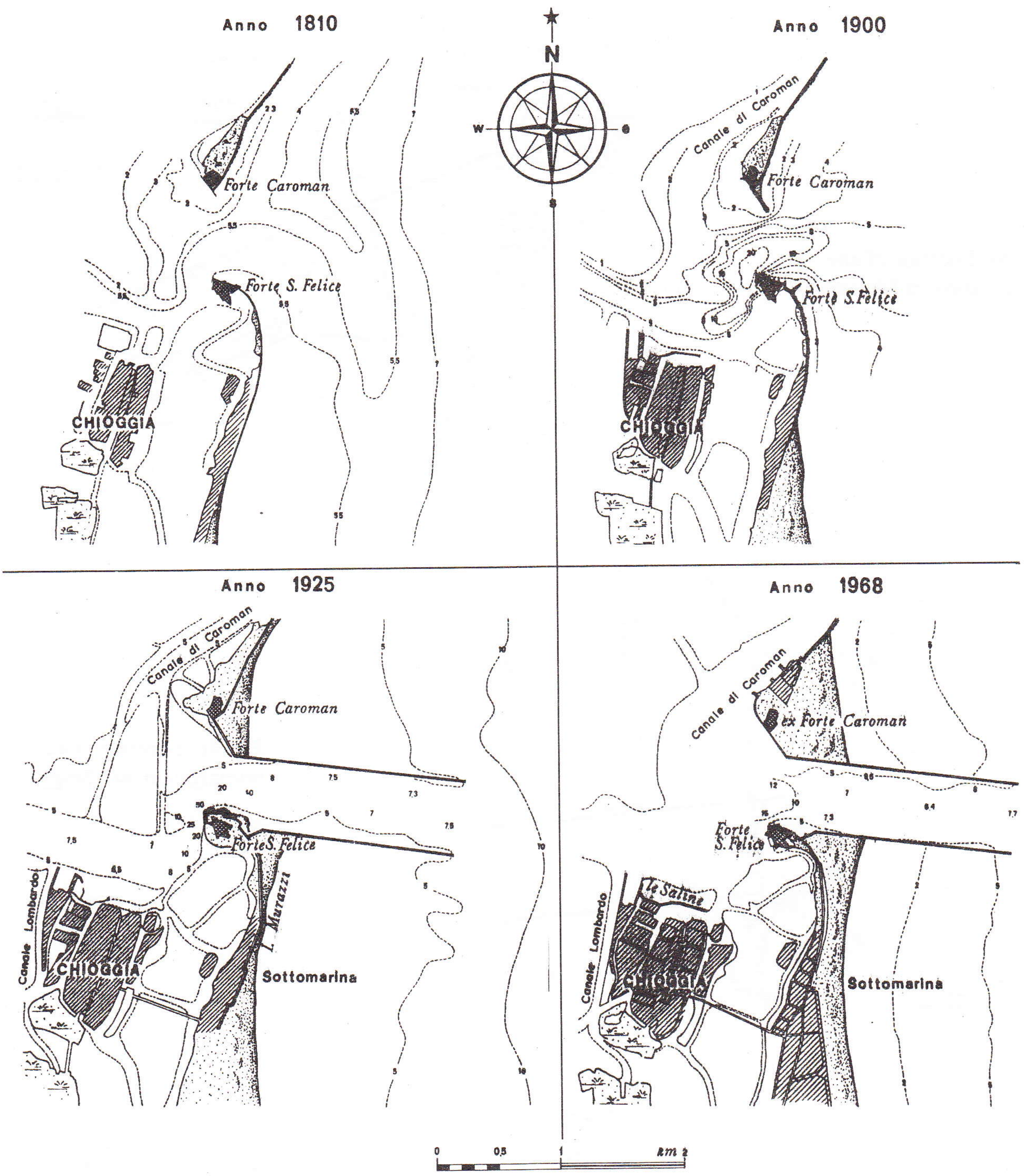

Fig. 3c. Morphological evolution of Malamocco inlet.

Due to the very complex geological history, the sediments exhibit a great non-homogeneity with a significant variation of the particle size distribution even in a few centimetres long sample.
Therefore it was very difficult to schematise a soil profile within which the different formations (cohesive/granular) can be clearly distinguished.
To this purpose the piezocone tests were used to distinguish between mainly cohesive or granular formations. On the basis of the trend against depth of pore pressure (measured at the tip of the cone during penetration) three tentative soil profile at the lagoon inlets were drawn. Figures 5a,b,c show the soil profiles at Malamocco, Chioggia and Lido, where the formations are divided in two categories: the formations with predominant cohesive fraction and the ones with predominant sandy fraction.
On the basis of the laboratory test results a more complete characterization of soil properties was performed. This characterization was particularly aimed to estimate the stress history, discussed in the following paragraph.

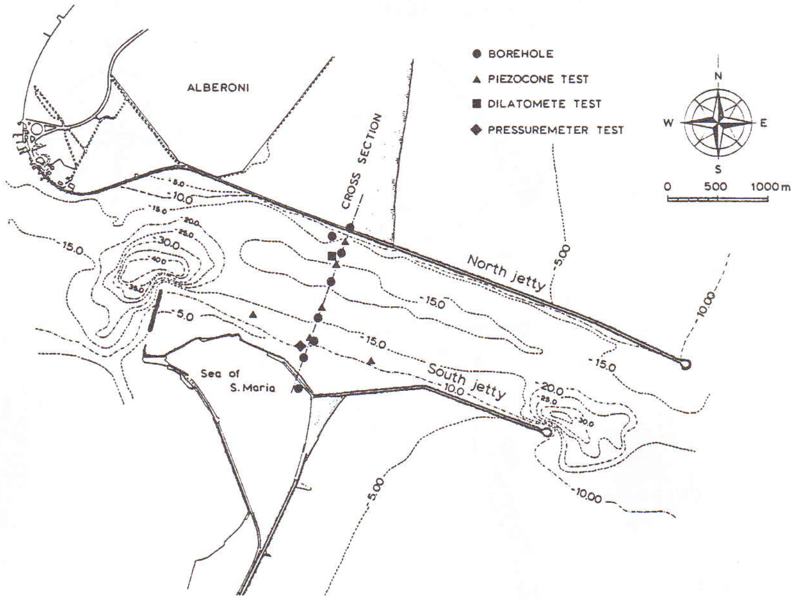

Fig. 4a. Location of site investigation at Malamocco.

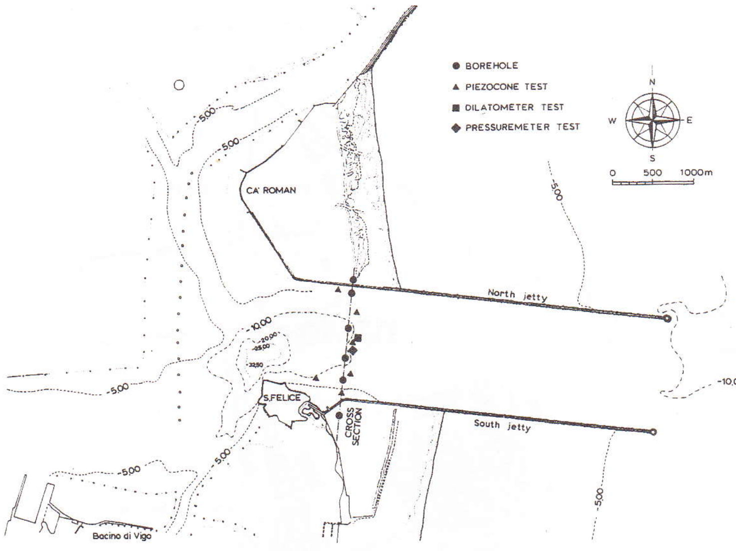

Fig. 4b. Location of site investigation at Chioggia.

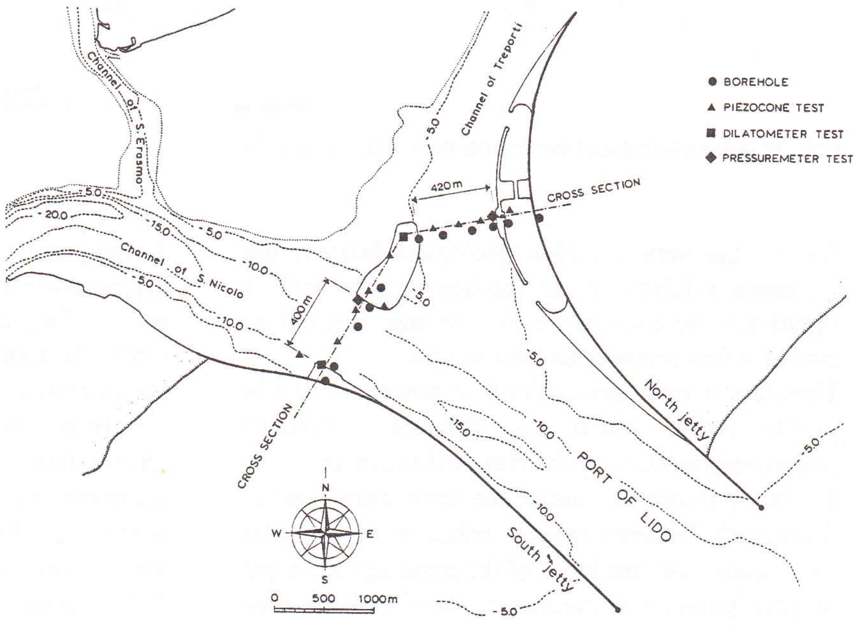

Fig. 4c. Location of site investigation at Lido.

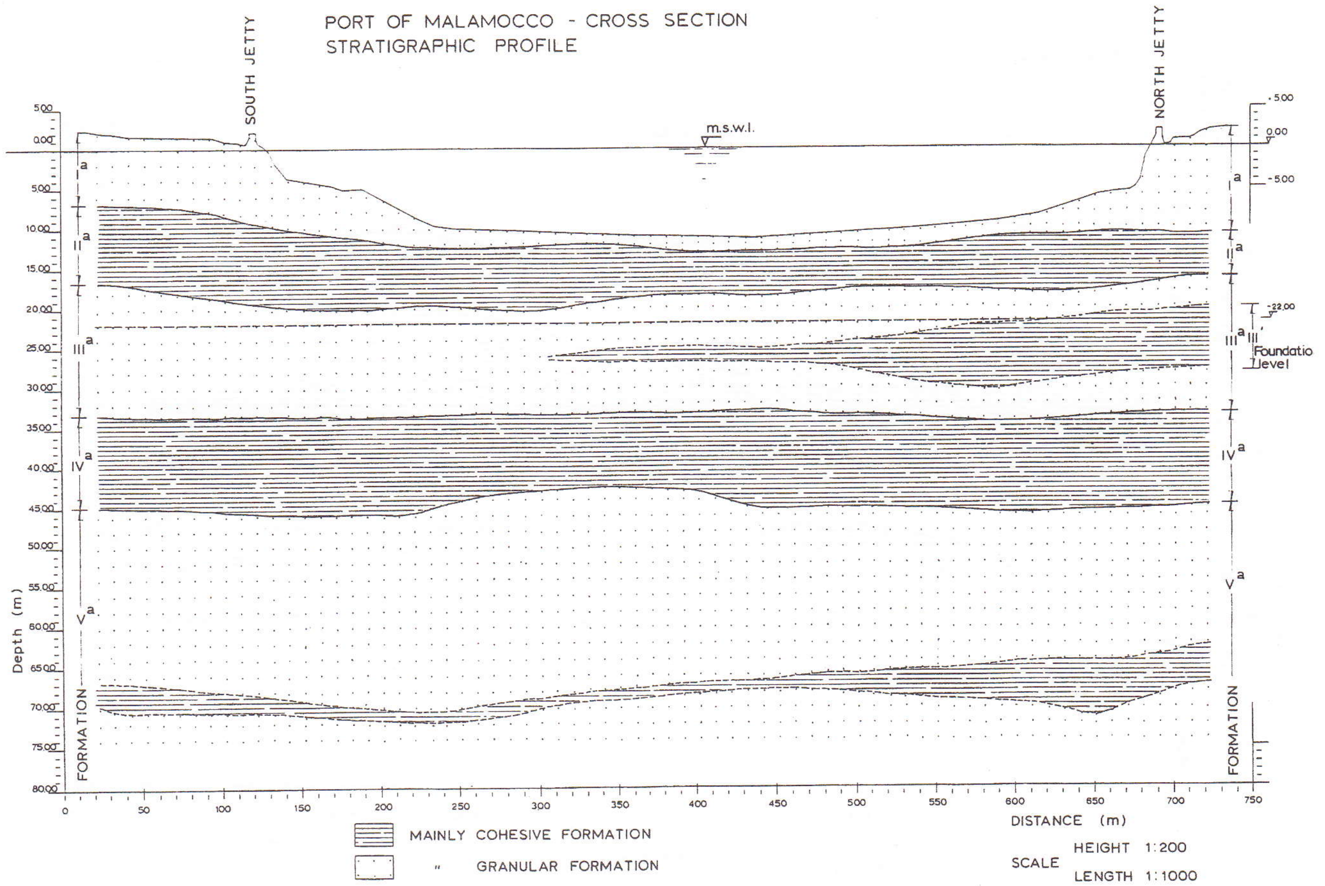

Fig. 5a. Soil profile at Malamocco inlet.

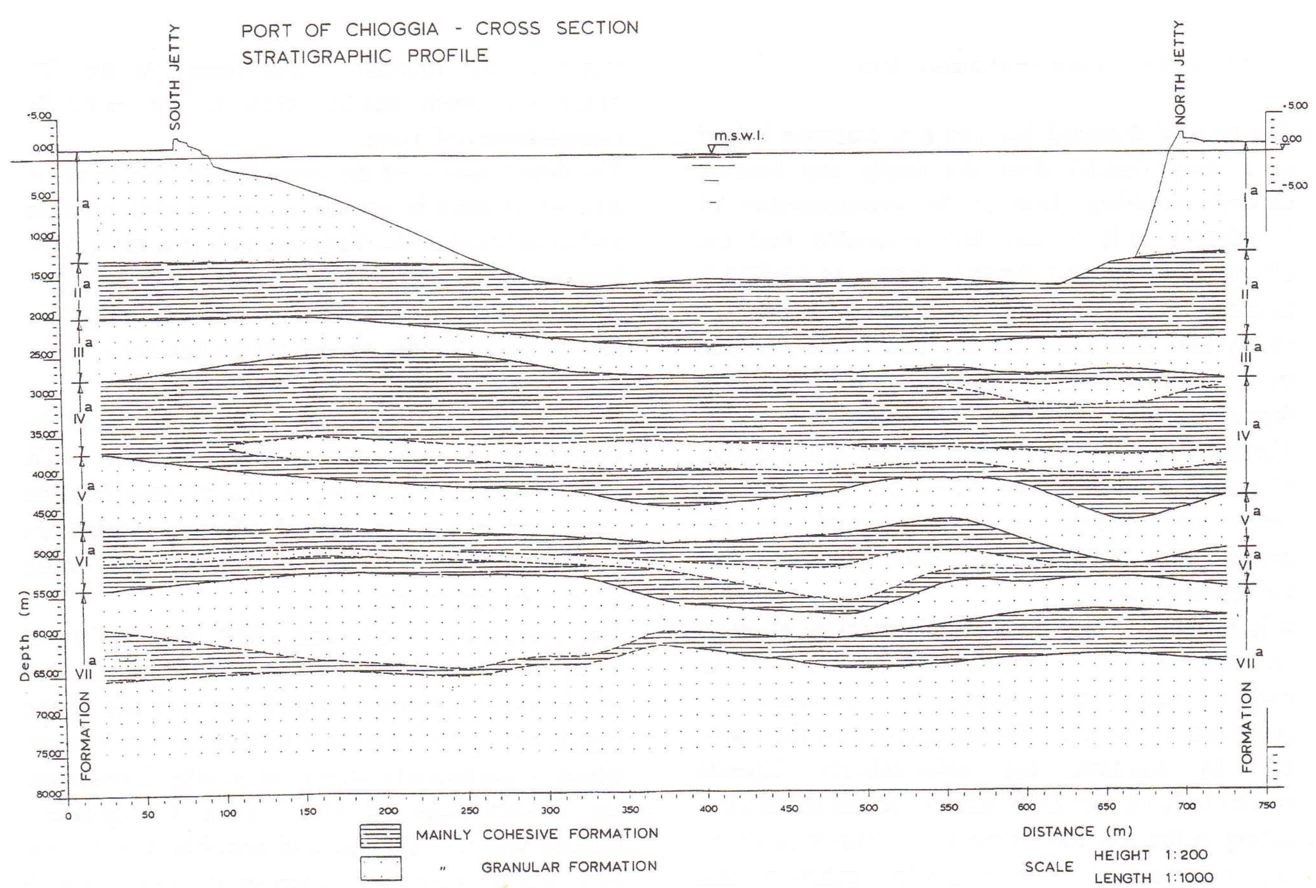

Fig. 5b. Soil profile at Chioggia inlet.

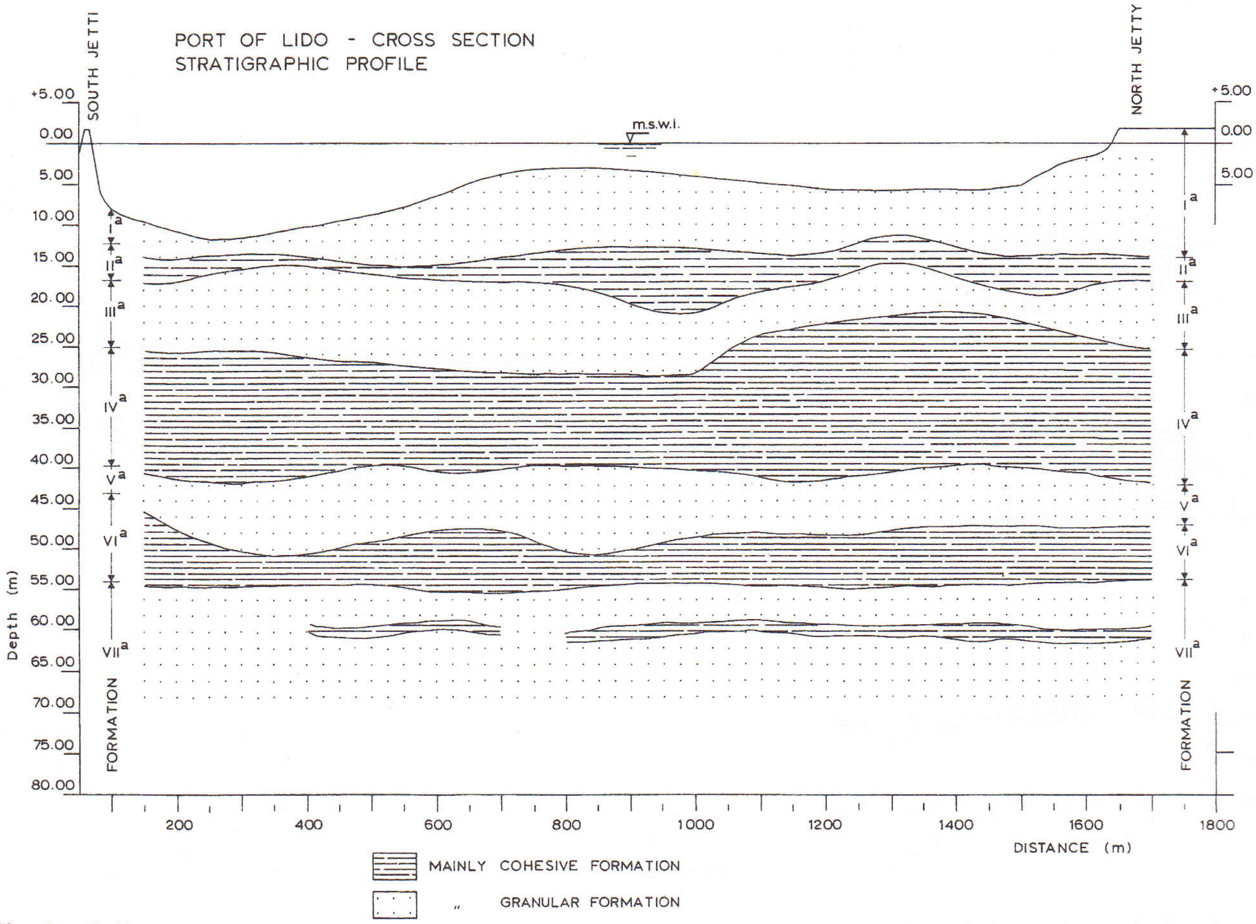

Fig. 5c. Soil profile at Lido inlet.

3.2 Stress history and overconsolidation

The type of designed barriers (i.e. caissons lodged in a deep trench) does not imply any bearing capacity problem. Due to the characteristics of foundation soils it was also estimated that the effects of cyclic and dynamic loads are negligible in comparison with the oscillation eigenfrequency of the system. Moreover, no soil liquefaction, caused by a sudden increase of pore pressure in the sandy formations, was considered to be possible.

Therefore, the most important aspect in the design of barrier foundations is the correct evaluation of settlements, which, in turn, depend on the deformability of all the formations (particularly of the cohesive ones).

It is recognised that the soil deformability depends on many factors, namely the type of soil, the mineralogical composition, the presence of cementation, the type of water permeating the voids, etc. In addition, the deformability depends particularly on the stress history, on the stress state acting in the soil and on the stress path induced by the construction. For example, cohesive and granular soils are usually much stiffer when stressed in the overconsolidated (OC) range; therefore, the foundation settlements in the OC range are much smaller than in the normally consolidated (NC) one.

The determination of the stress history and of the in situ stress state is usually a complicated problem and in the case of the Venetian soils it is more over, because the soils at the inlets have undergone a very complex history of unloading and reloading (due also to the anthropic action) which has been shown to be very difficult to reconstruct precisely.

For practical purposes, the stress history can be synthesised in the overconsolidation ratio *OCR* ($OCR=\sigma'_p/\sigma'_{vo}$, where σ'_p is the preconsolidation stress and σ'_{vo} is the vertical effective overburden stress) which was preliminary determined by using laboratory test results.

The evaluation of σ'_p, and *OCR* was performed using the results of oedometric tests. However, due to the non-structured nature of the soils and to the significant stress relief due to sample disturbance, which is particularly important in silty formations, the determination of *OCR* using Casagrande's method was troublesome and possible only for the more plastic samples (Ricceri et al., 1985). Fig. 6 shows the trend of *OCR* against depth at the three inlets.

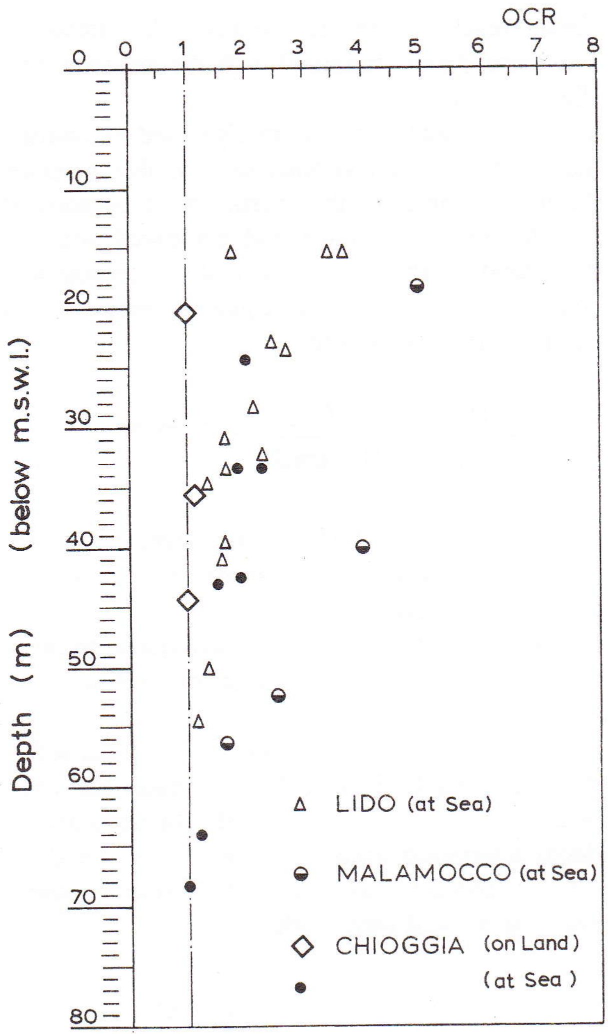

Fig. 6. Trend of *OCR* against depth from oedometric tests.

Another way to estimate the trend of *OCR* is to use an empirical correlation linking the undrained shear strength to *OCR*. This method is less accurate than the direct evaluation of σ'_p from oedometric test. The undrained shear strength c_u can be expressed by the empirical relation (Ladd and Foott, 1974; Ladd et al., 1977; Ladd, 1982):

$$\frac{c_u}{\sigma'_{vo}} = S(OCR)^m \qquad (1)$$

where $S = c_u/\sigma'_{vo}$ at $OCR=1$ and m is an empirical-experimental parameter, which may be taken equal to 0.8 when c_u is determined from undrained triaxial compression test, as given in the above references. The *OCR* can then be determined from the relation:

$$OCR = \left(S\frac{c_u}{\sigma'_{vo}}\right)^{1/m} \qquad (2)$$

The well accepted Skempton equation (1957) can be utilized to express S as:

$$S = \frac{c_u}{\sigma'_{vo}} = 0.11 + 0.0037PI \qquad (3)$$

where *PI* is the plasticity index. For plasticity index of about 20, which is a typical value for the Venetian cohesive soils, S is 0.18.

Fig. 7 shows the trend of the ratio c_u/σ'_{vo} against depth both at sea and on land.

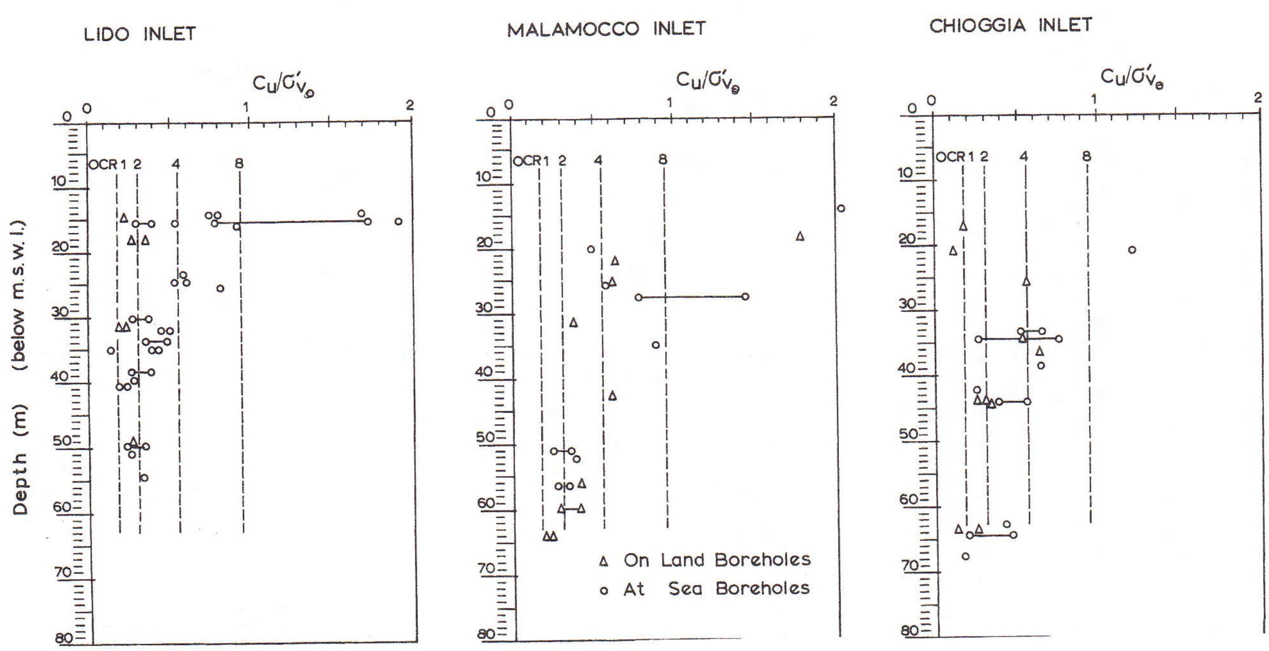

Fig. 7. Trend of ratio c_u/σ'_{vo} against depth both at sea and on land.

Note that this ratio decreases with depth and it is always higher at sea then on land.
The *OCR* was determined also from the in situ test results.
In particular, two types of test have been selected for the analysis of the stress history, namely the piezocone and the pressuremeter tests.
In the piezocone test the overconsolidation ratio is obtained from the ratio between the excess pore pressure and the cone resistance measured at the tip during penetration. Among the empirical formulas proposed in the past (Lacasse and Lunne, 1982; Tumay et al., 1981, 1982; Wroth, 1984), the correlation proposed by Wroth seems to be the most reliable. Considering the ratio $\Delta u/(q_c-\sigma_v)$, where Δu is the excess pore pressure, q_c the tip resistance and σ_v the total vertical stress, Wroth (1984) stated the following correlations:

$$\Delta u/(q_c-\sigma_v)=0.7\,;\ OCR\approx 1 \quad (4a)$$
$$\Delta u/(q_c-\sigma_v)=0.4\,;\ OCR\approx 2 \quad (4b)$$
$$\Delta u/(q_c-\sigma_v)=0.3\,;\ OCR\approx 4 \quad (4c)$$

The values of the ratio $\Delta u/(q_c-\sigma_v)$ determined using the results of several piezocone tests are plotted vs. depth in fig. 8.

These results seem to confirm the trend of overconsolidation measured with the previous tests (figs. 6 and 7) .
The pressuremeter tests were also used to estimate the degree of overconsolidation. To this purpose, the in situ values of the coefficient of pressure at rest K_o were determined and compared with the theoretical value for normally consolidated condition. The following equation proposed by Schmidt (1966) was used:

$$\frac{K_0(OC)}{K_0(NC)}=\frac{K_0(OC)}{(1-sin\phi')}=OCR^{sin\phi'} \quad (5)$$

where K_o(OC)and K_o(NC) are, respectively, the coefficients of pressure at rest for OC and NC soil and ϕ' is the friction angle.
Fig. 9 sketches the *OCR* values determined from the pressuremeter tests carried out at the three inlets.

From the above considerations the Venetian soil at the inlets, up to 50 m below the mean sea water level, is mostly over consolidated. The trend against depth determined from all the tests here considered (in the laboratory and in situ) shows a general decrease of *OCR* with depth.

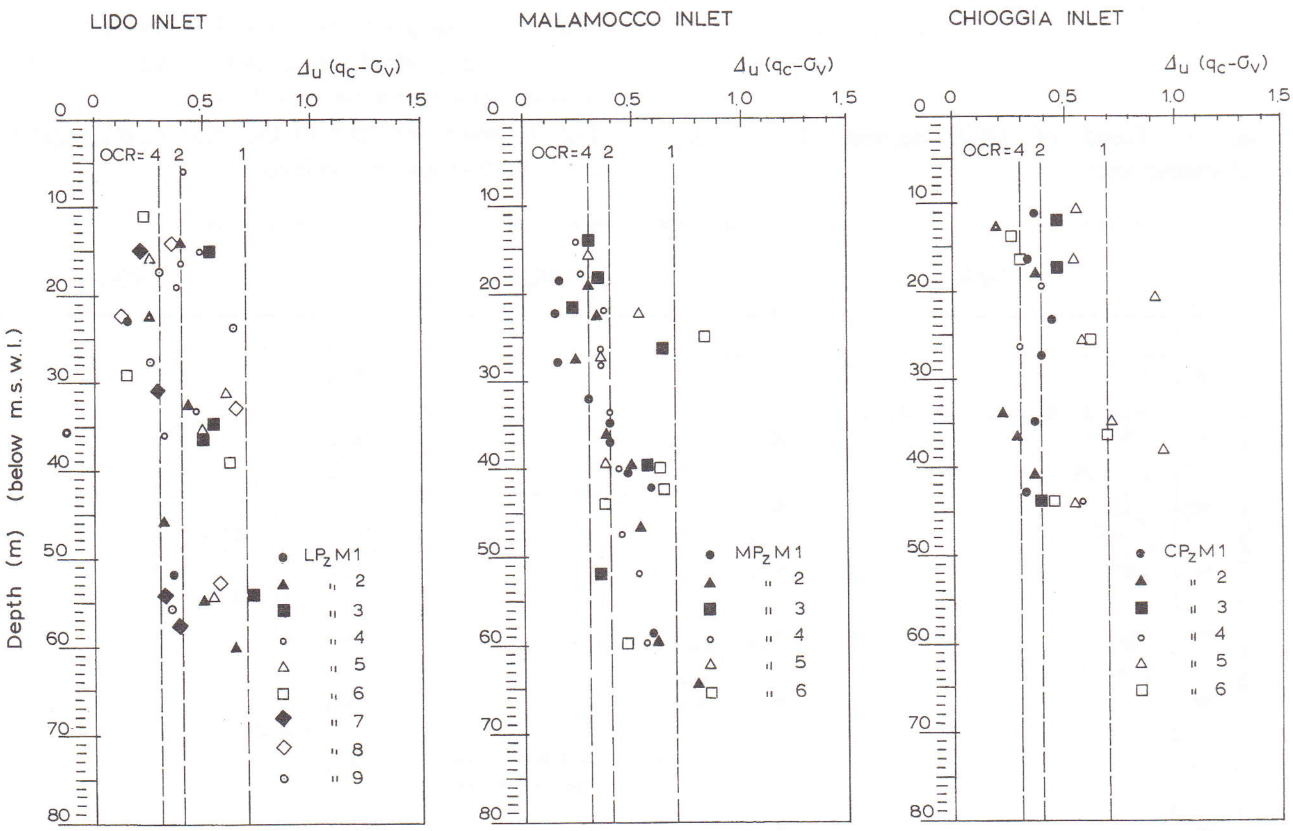

Fig. 8. Trend of the ratio $\Delta u/(q_c-\sigma_v)$ from the results of piezocone tests.

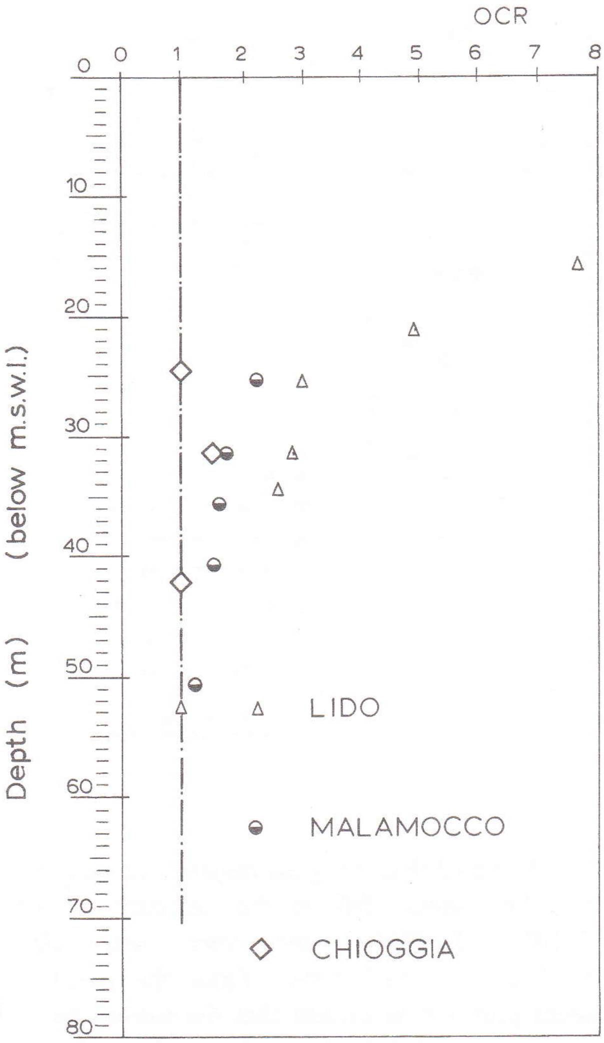

Fig. 9. *OCR* values from pressuremeter tests.

3.3 Strength, deformability and consolidation

The evaluation of the parameters governing the stress-strain-time behaviour is a difficult task especially when dealing with non-homogeneous soils as the Venetian ones.
Since the deformability parameters play a key role in the barriers design, our research mainly considered this aspect.
A preliminary soil-deformability characterization was performed using the results of the first phase of investigation. It was observed that oedometric and standard triaxial tests do not lead to a satisfactory and reliable estimate of the stiffness, especially in the strain range induced by the loads due to the barrier foundations. More accurate laboratory investigations were carried out on the samples coming from the boreholes of the GECSAT. This argument will be discussed in paragraph 4.4.
It has been estimated that the consolidation of soil under the loads applied by the barriers does not require long times. This is due to the non-homogeneous nature of the cohesive soils, characterized by alternating layers of fine silty sand within the cohesive matrix. The high permeability of the thin sand layers increases the in situ consolidation coefficients, which are, consequently, much higher than those measured in the laboratory. In addition, the soil is mostly overconsolidated and, therefore, consolidation times reduce even more.

4. THE GEOTECHNICAL CALIBRATION STATION

The Geotechnical Calibration Station was located in a restricted area at the Malamocco inlet, where the following types of test have been carried out:
- standard boreholes;
- large diameter boreholes;
- piezocone tests;
- dilatometer tests;
- selfboring pressuremeter tests;
- screw plate tests;
- down hole tests;
- cross hole test.

The geotechnical laboratory investigations were carried out by the University of Padova and ISMES of Bergamo in co-operation with the Magistrato alle Acque and the Consorzio Venezia Nuova (Magistrato alle Acque, Ministero dei Lavori Pubblici, 1994).
Figure 10 shows the location of the in situ tests at the GECAST.

4.1 Soil profile at the GECAST

Figure 11 depicts a tentative soil profile, up to 60 m below mean sea level, determined from a borehole log, compared with the results of a piezocone test (q_c = tip resistance; u_w= pore pressure), carried out on a vertical close to the borehole.
In this case, a more detailed criterion was used to distinguish between cohesive and granular formations.
On the basis of the comparison between the results of the piezocone test and the borehole log, 11 basic formation were selected.
Figure 12 sketches the variation with depth of some soil characteristics determined on samples coming from standard and large diameter boreholes:
- Particle size composition;
- Bulk density (γ_{sat});
- Atterberg limits (*LL*, *PL*);
- Natural water contents (w_o).

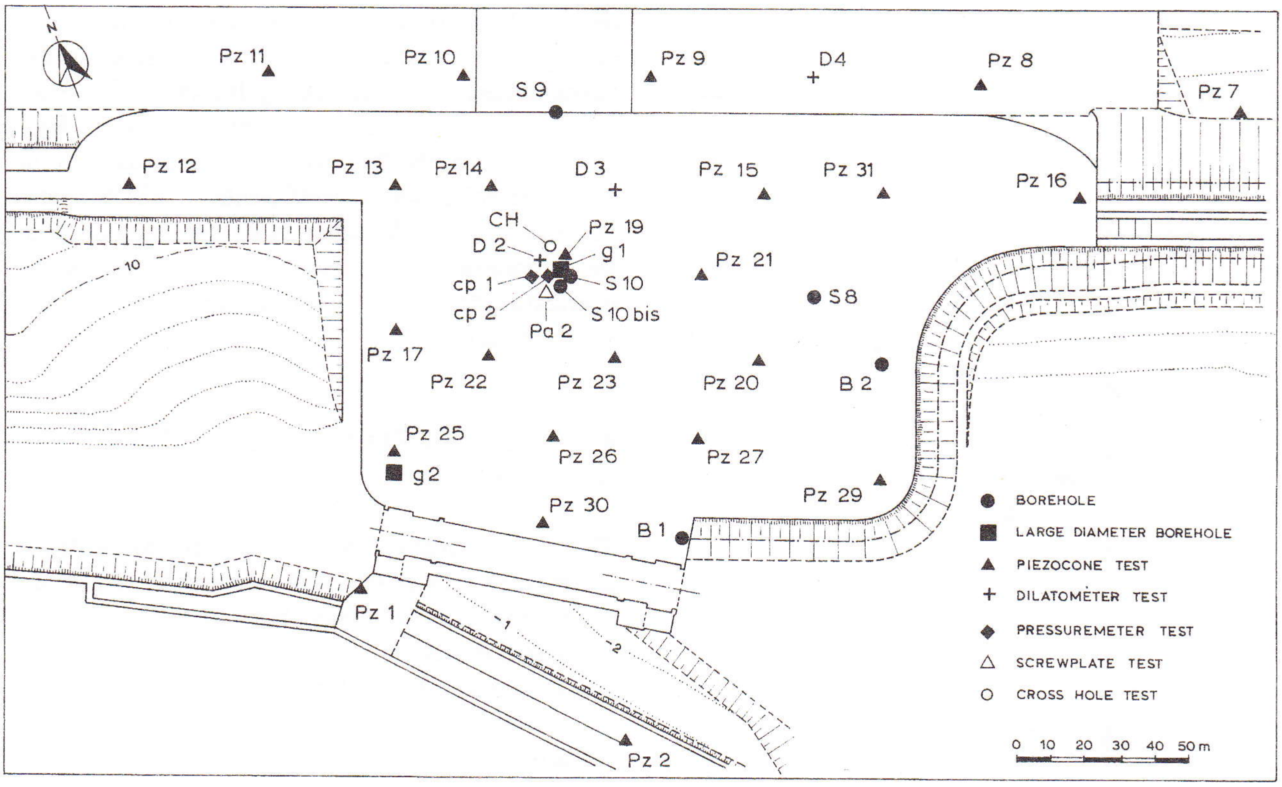

Fig. 10. Location of the in situ tests at the GECAST.

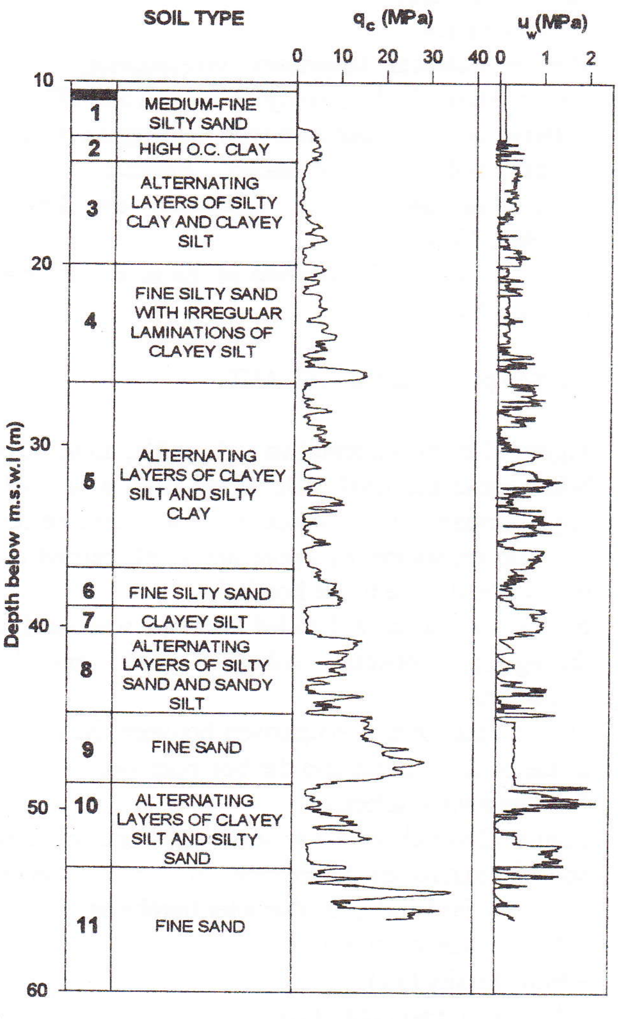

Fig. 11. Soil profile at the GECAST

It can be noted that the great majority of samples, other than sands, fall in the category of silt ($PI \leq 10\%$, $LL \leq 35\%$) and very silty clay ($10 \leq PI \leq 25\%$, $35 \leq LL \leq 50\%$). From the moisture content profile it is evident that the subsoil has a water content slightly decreasing with depth but always above the plastic limit.

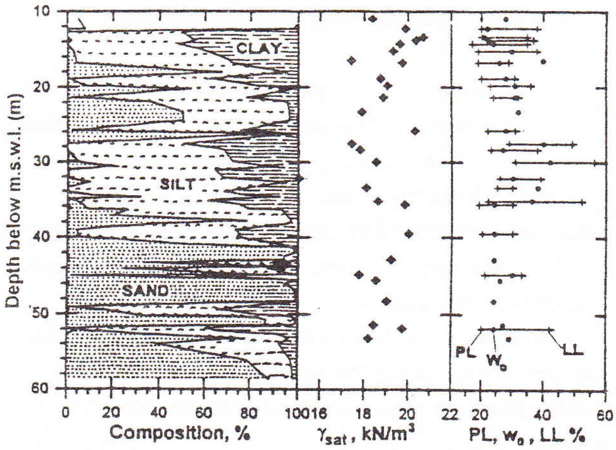

Fig. 12. Variation with depth of some soil characteristics.

4.2 Soil stress history

The stress history was reconstructed at the GECAST using both laboratory and in situ tests.

The trend of effective overburden stress σ'_{vo} with depth, estimated using the values of bulk densities determined in the laboratory from the large-diameter borehole samples, is reported in fig. 13.
Fig. 13 also shows the values of preconsolidation stress determined from oedometric tests (using Casagrande's method).
Calculated laboratory values of *OCR* are plotted on the same figure and compared with those estimated using the results of a dilatometer test (DMT) and a seflboring pressuremeter test (SBPT), both carried out close to the large diameter borehole.
An appreciable decrease of *OCR* was clearly noted, thus confirming the results of the preliminary investigation. The high *OCR* values (>10) in the formation 2 are characteristic of the well known *caranto*, an high OC oxidated clay on which most historical venetian buildings are founded.

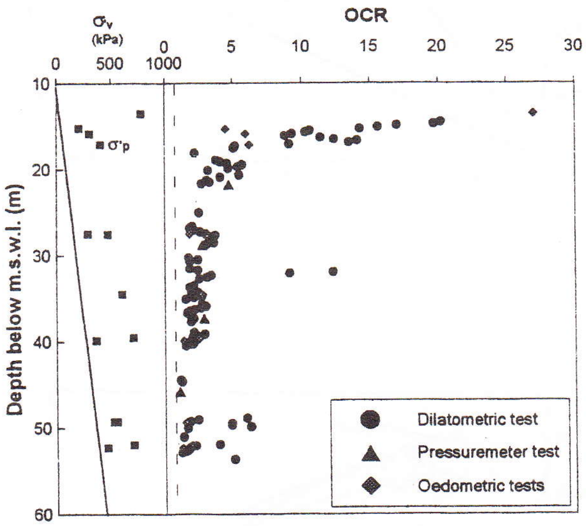

Fig. 13. Overconsolidation against depth.

4.3 In situ stress state

The in situ stress state was estimated by considering the coefficient of pressure at rest K_o at various depths in the ground. K_o was determined from dilatometer and selfboring pressuremeter tests and from uni-axial reconsolidation stage in computer controlled CK_0D/U triaxial tests. The K_o values from triaxial tests showed to be independent on depth and always lower than DMT and SBPT ones. This is probably be due to the effects of laboratory reconsolidation (Mayne and Kuhlhawy, 1982) and to the stress relief induced by sample disturbance (particularly important in silty formations) .
The effect of *OCR* on the horizontal stress can be clearly appreciated in fig. 14. Down to 20 m K_0 is higher than unity and then decreases strongly, approaching 0.4-0.6 at great depths.

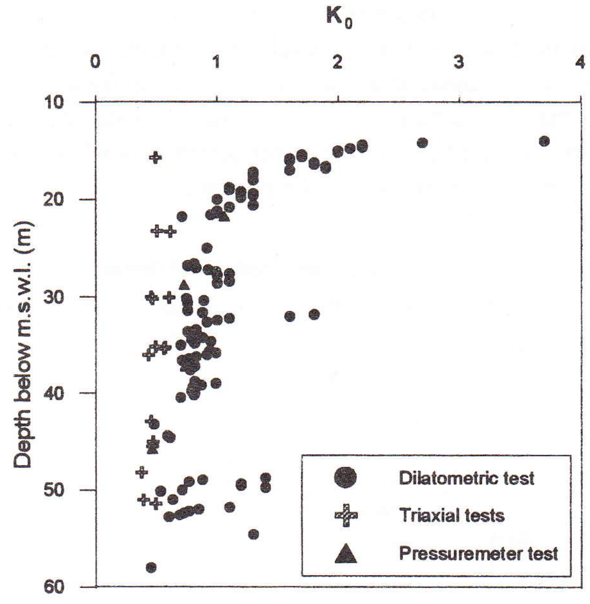

Fig. 14. Trend of K_o against depth.

4.4 Stiffness

The evaluation of soil stiffness can be performed using many methods, both in situ and in the laboratory.
Considerable differences are often seen among the deformability values obtained from the different methods; in some cases the differences could be ten-fold or even more. For example, the stiffness determined from shear-wave velocity measurement may be too large in estimating the settlement under static working loading conditions, whereas the one from pressuremeter tests may be to small. This is due to the highly non-linear nature of the stress-strain relation and to the dependence of the soil stiffness on the stress history of soil.
In order to estimate the stiffness of Venetian cohesive soils at the GECAST several in situ and laboratory tests were carried out.
Here, the results of the following tests are reported and discussed:
- oedometric tests;
- special strain/stress controlled triaxial tests;
- dilatometer test;
- cross-hole test.

4.4.1 Oedometric tests

The reliability of stiffness determined from oedometric tests when used to calculate settlements of overconsolidated soil is still argument of debate.
Nevertheless, the stiffness was determined from the results of all the oedometric tests carried out on all the undisturbed samples.

The values of oedometric modulus M, determined in an unloading-reloading cycle in correspondence to the in situ overburden stress, is plotted in figure 15. It may be noted a general increase of modulus with depth, except that in the upper formations where the higher values are due to the *caranto*.

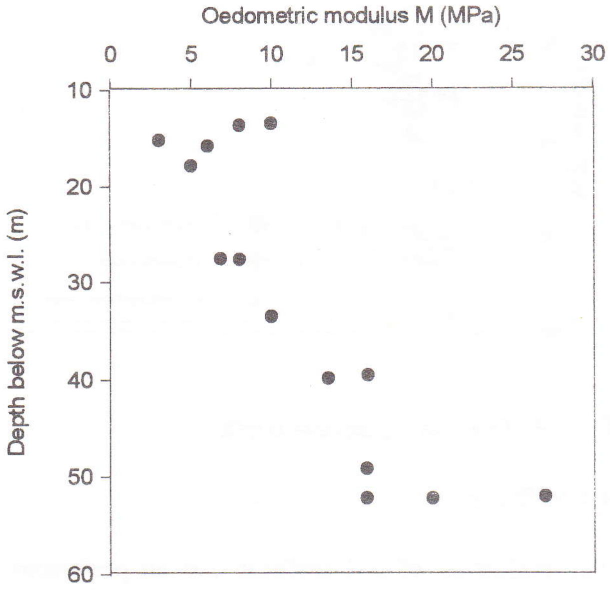

Fig. 15. Oedometric modulus vs. depth.

4.4.2 Triaxial tests

Several standard compression and extension triaxial tests were carried out. Some tests were performed at the University of Padova on large specimens using an automated computed controlled stress/strain path triaxial system. In order to improve the precision of the measure, the triaxial system is equipped by a special triaxial cell, able to measure local deformations on soil samples (Ricceri, Simonini and Cola, 1997).
The CK_0U triaxial compression and extension tests were carried out on the cohesive soils coming from formations 3 and 4 (fig. 11) and drawn up in the large-diameter borehole G2. The specimens were consolidated under the estimated in situ vertical stress and driven to failure with a strain rate of 0.008%/min.
Figure 16 shows two typical stress paths (samples VE4-VE8) for the Venetian silty formations (p' is the mean effective stress and q is the deviatoric stress). Note the very low pore pressure - characteristic of silty soils - developed during shear. The critical state line was determined at axial deformation of about 4-5%: the line slope is characterised by M_c=1.34 that means ϕ_{cv}=33°, typical values for the silty formations.

The trend of secant shear modulus G determined using internal measurements is reported in fig. 17 for four specimens trimmed from two samples (VE4-VE8). The advantage of using local measurement can be appreciated especially for shear strain levels γ below 0.0001.
The maximum values of G are reported in fig. 18.

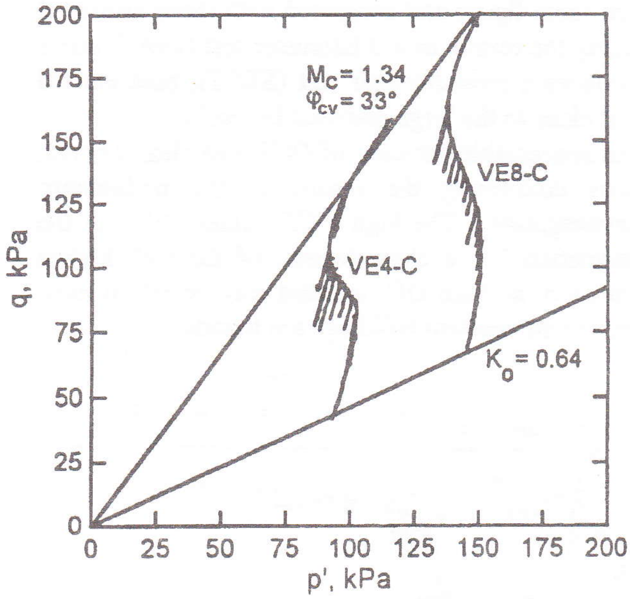

Fig. 16. Typical stress-paths for the Venetian silty soils.

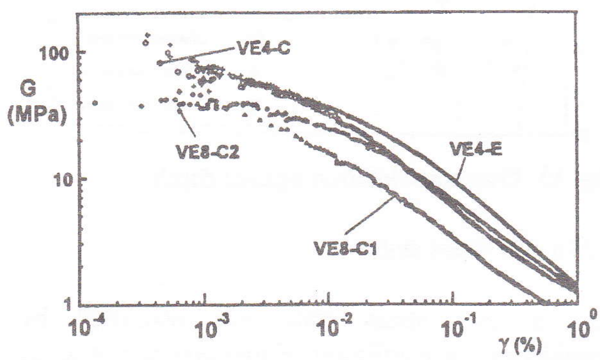

Fig. 17. Shear modulus against shear strain.

4.4.3 Resonant column tests

The resonant column can measure the soil stiffness in the range 0.0001%- 0.01 %. All tests have been performed at ISMES laboratory.
The maximum values of the shear modulus were calculated and expressed as a function of overburden stress acting in the soil. These values, plotted on figure 18, are relatively high and are similar to those determined with the cross-hole test.

4.3.4 Cross hole test

A cross-hole test has been carried out on three verticals and its results have been plotted in terms on shear modulus G against depth in figure 18.
A general increase of the modulus with depth can be observed. No particular scatter exists up to 40 m below m.s.w.l.; at greater depths, and especially around 50 m, a sharp decrease in the modulus due to the transition from a thick layer of sand to alternating layers of clayey silt and silty clay can be noted (formation 9 - formation 10).

4.4.5 Dilatometic test

The advantage of the dilatometric test is a quasi-continuos measurement of some significant soil properties. The results of the test can be also used to determine the oedometric modulus of the soil. In order to compare the dilatometric stiffness with those determined from other tests, the dilatometric modulus has been transformed in the shear modulus G by the relation:

$$G = M\frac{\left(1-\nu-2\nu^2\right)}{2\left(1-\nu^2\right)} \quad (6)$$

where ν is the Poisson's ratio of the soil. The shear modulus (plotted in fig 18) shows a trend against depth similar to that given by the cone penetration resistance with the highest values measured in the sandy formations.
Figure 18 also sketches the trend of cone penetration resistance with depth. Observing the various trends of shear modulus it can be noted that the cross-hole test and resonant column tests lead to the highest values of shear modulus. On the contrary, the lowest values (calculated using relation (6)) are those from oedometric tests. Intermediate values seem to be those of dilatometric test.
The shear moduli calculated from the triaxial tests are similar to those determined with the resonant column apparatus.
These different moduli are of course related to the different strain levels induced into the soil by the various type of investigations. It's author opinion that the relations existing between the deformability parameters and strain levels should be carefully considered since it influences strongly the results of any analysis of the interaction between barrier foundations and surrounding soil.

5. ALLOWABLE SETTLEMENTS OF THE BARRIERS

During the life of the barriers, absolute and differential settlements (both horizontal and vertical) may occur. These are due to the variable loading conditions or to the non-uniformity of soil characteristics along the barriers. The settlements must be kept within the limits imposed by the barrier serviceability, which is ensured by:
- the preservation of the hydraulic seal of the joint GINA between two adjacent caissons;
- the possibility of free oscillations of mobile gates avoiding any mutual contact;
- the alignment of the guide rails for the traveling gantry crane .

In particular, the serviceability of the gates is provided if and only if the maximum long term differential settlement between two adjacent caissons does not exceed 6 cm.
Among the three barriers, the one of Malamocco showed the most critical conditions with respect to differential settlements. It was calculated that the maximum vertical stress applied by the caissons to the soil is in most cases smaller than the overburden stress presently acting in the soil at the foundation level. In fact, the excavation works (the caissons are installed in a trench about 10 m deep) necessary to reach the foundation level induce a stress decrease of about 90 kPa. The maximum contact pressure applied by the gate caissons to the soil have been estimated to be about 65 kPa, thus slightly lower than the present vertical effective stress. A different situation was examined for the lateral caissons (for the maintenance keeping), where a deeper excavation is needed to reach the foundation level. These caissons transmit to the soil a vertical stress of about 150 kPa. For the lateral caissons, the overburden stress, at depths of excavation between 11 and 20 m, ranges from 100 and 180 kPa.
Therefore, it may be noted that in most cases the loads applied by the barriers do non increase the current stress state acting in the soil.
In addition, it was pointed out in sections 3 and 4 that the soil at the three inlets, both on land ad at sea, is overconsolidated, at least up to a depth of about 50 m below mean sea water level.
From the above considerations follows that the soil loaded by the caissons deforms mainly in the overconsolidated range (i.e. no yielding of soil occurs), thus implying quasi-elastic behaviour at relatively small deformations, and, consequently, small settlements.

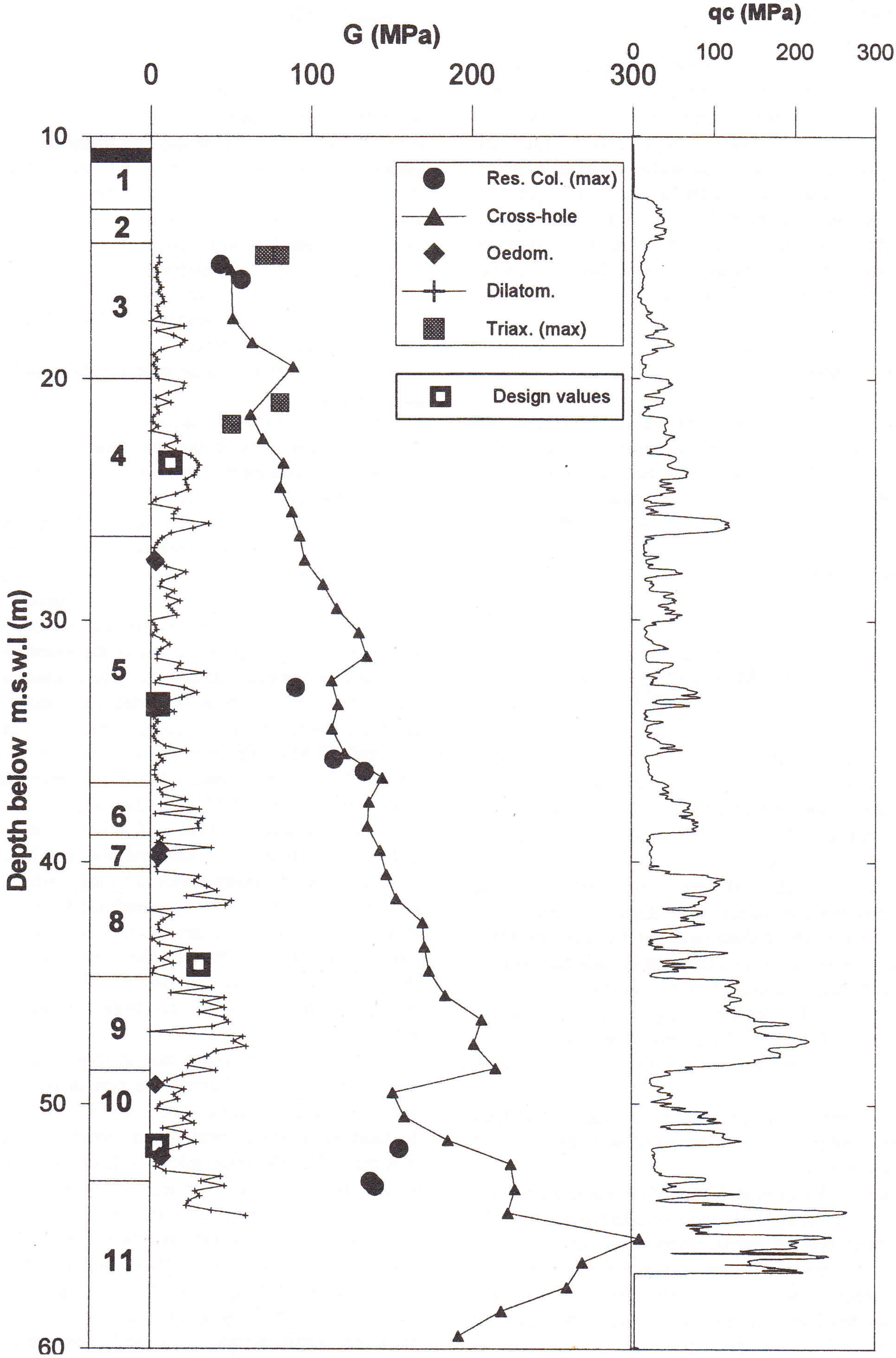

Fig. 18. Shear moduli determined from the various tests at the GECAST as a function of depth.

On the basis of these considerations, the following solutions for the barrier foundations have been considered during the prelimnary design stage:

- direct foundations on natural soil;
- direct foundations on improved soil;
- large diameter piled foundations.

As pointed out above, the crucial problem to be solved in the geotechnical design of the foundations is the correct estimation of absolute and differential settlements.

To this purpose, a soil-structure interaction analysis has been performed using a simplified two-dimensional elasto-plastic finite element model (PLAXIS F.E. program), whose parameters have been selected on the basis of the results of preliminary investigations. The average values of deformability parameters adopted in the model, expressed in terms of shear modulus *G*, are sketched in fig 18. It can be noted that the values are significantly smaller than the maximum values of *G*, determined from cross-hole and resonant column tests.

Nevertheless, the settlements determined on the basis of these values are relatively small: in the case of foundations directly posed on natural soil, absolute and differential vertical displacements of 9 cm and 6 cm have been respectively determined.

Therefore, direct foundations have been selected but, in order to reduce the settlements to more acceptable values, an improvement of the first cohesive soil layer by using driven piles has been considered. The piles, having length equal to the depth of the layer, are installed at the nodes of a 3 m square mesh.

It has been calculated that this type of soil improvement may lead to a significant increase of shear modulus *G* of the first cohesive layer under the foundation (posed at -26 m below m.s.w.l). The equivalent elastic shear modulus of the improved soil turned out 13 times larger than the natural one.

In the case with soil improvement, the finite element analyses have shown a sharp reduction of both differential and absolute settlements, which were reduced to an half of the previous ones.

Due to the satisfactory results given by this solution, the deep foundations on large diameter bored piles was considered neither economically attractive nor necessary.

It should be noted that settlement calculations have been performed by considering that two adjacent caissons rest on the "most deformable" profile and on the "least deformable" profile: in this case the maximum differential settlement at the joint occurs. This represents a very cautelative assumption in the design.

6. CONCLUSIONS

On the basis of the above considerations, the following preliminary conclusions could be drawn:

- future site investigations may be planned by excluding the bearing piles as possible foundations for the mobile barriers;
- the preliminary results of the Geotechnical Calibration Station will help in the selection of economical site investigation to determine more carefully the stratigraphic profiles and strengh/stiffness parameters of the soil at the three inlets;
- the site investigation should be located at the nodes of a mesh covering the whole area of the barriers, as suggested by the Eurocode design rules (1988): in that way a three-dimensional geotechnical model could be provided for the soil under the barriers.
- further research is needed to establish reliable correlations and interpretation methods for the in-situ tests. These will be necessarily based on the analysis of data form the Geotechnical Calibration Station;
- the question if the upper cohesive soil must be improved with driven piles (which is of economical relevance in the design) is strongly dependent on the reliability of the stratigraphic profile, on the type of numerical model and related soil parameters, used to simulate the behavior of the soil-barrier interaction. It's author opinion that three-dimensional effects of the barriers must be considered in numerical modeling. Moreover, in order to predict reliable settlements for improved and unimproved soil, the selection of deformability parameters should be take into account the soil strain range under the barriers.

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THE ENVIRONMENT OF THE VENICE LAGOON AND MEASURES FOR ITS CONSERVATION

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ABSTRACT

The lagoon of Venice is one of the most important wetland areas of the Mediterranean Basin. The importance of wetlands is second only to rainforests as reservoirs of biodiversity and natural productivity. The lagoon of Venice is progressively losing its typical natural characteristics due to erosion processes and water eutrophication determined by the intensive anthropic use of its territory. The most visible indicators of the lagoon degradation are the disappearance of tidal marshes and the occurrence in the warm season of extensive macroalgae blooms. The measures which have been proposed, and that partly are in progress, to stop degradation and preserve the lagoon natural characteristics are presented in this article.

1. INTRODUCTION

The Venetian lagoon (*Figure 1*) is the largest coastal lagoon of the Mediterranean Basin. It has an average depth of approximately 1 m and is connected to the sea through three inlets. Its surface covers approximately 550 Km^2, distributed among islands, tidal marshes, tidal flats, shallow areas, channels and fish farms, as follows:

	Level (with respect to mean sea level) (m)	*Surface (Km^2)*
Islands+land	> 0.5	≈ 100
Tidal marshes	0 ÷ 0.5	≈ 30
Tidal flats	-0.3 ÷ 0	≈ 40
Shallow areas	-2 ÷ -0.3	≈ 230
Channels	< -2	≈ 60
Fish farms		≈ 90

Water levels and currents are regulated by the tidal excursions of the Adriatic sea. The tide has an amplitude ranging from approximately 20 cm in ebb conditions to 100 cm in spring conditions. Particular meteorological situations can increase the maximum level of the tide, causing the flooding of the urban centres.

The lagoon of Venice is an unique example of man's integration with nature, its present configuration being the result of both natural factors and human interventions. In the absence of human interventions the lagoon of Venice would have disappeared or would have assumed a configuration vastly different from the present one.

Coastal lagoons are in fact very unstable systems. They originate from the interaction of the sediments transported from the rivers to the sea with the marine currents. Their shape evolves continuously, if the sediment fluxes from the rivers are too abundant, the lagoons tend to silt up and to become part of the terrestrial system, viceversa if the sediment fluxes are scarce, the lagoons tend to become part of the marine system.

The origin of the Venetian lagoon can be dated to 6000 years ago, when the sea level stabilised around the present coastline. The first written citation of the lagoon is attributed to Tito Livio, from whom we learn that human settlements existed in the area 300 years b.C. (Dorigo, 1995). Archaeological findings date the presence of human settlements in the area to the fifth century b.C. (Canal, 1995). The reconstruction of the development of the human settlements in the area still presents many gaps and uncertainties, for more information on this subject the interested reader can consult the above quoted articles by Dorigo and Canal.

The city of Venice began to develop at the beginning of this millennium. At that time, the setting of the lagoon was very different from today: the littorals presented eight openings through which the lagoon was exchanging water with the sea; the deltas of the rivers were penetrating inside the waters of the lagoon and the transition from the marine to the terrestrial environment was very gradual and characterised by the presence of swampy areas. Although the environment was surely very rich as to flora and fauna species, it was not the most convenient for the life of the human communities established in the area.

At the beginning of this millennium the transport of sediments from the rivers to the lagoon was progressively silting up the lagoon: the depth of the lagoon was decreasing and the part of the lagoon replaced by land was rapidly increasing.

The Venetian considered the progressive silting of the lagoon a catastrophe. Not only their security was in danger because of the possibility that enemies could quickly reach the city by land, but also their economy which, being mostly based on commerce of goods on water, was in serious peril of a very fast decay should the lagoon becoming inadequate for harbouring the Venetian fleet.

The Venetians reacted to these threats by diverting to the sea the major rivers which were flowing into the lagoon.

Not everybody was in favour of this solution, the discussions begun around the year 1300 and the diversion of the rivers was completed only towards the end of the 16th century.

The diversion of the rivers was taken by the Venetian as an opportunity to reclaim the swampy

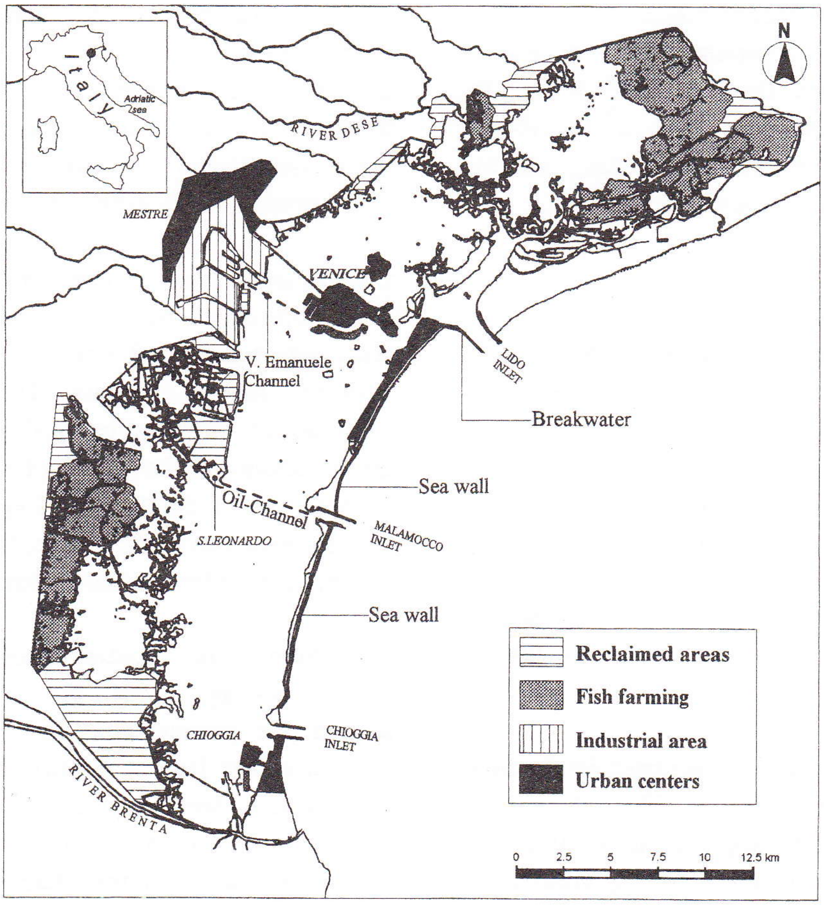

Figure 1 - The lagoon of Venice

areas which were bordering the lagoon. With this operation, the Venetians reached the objectives of eliminating areas considered unhealthy, at the same time creating areas suitable for agriculture on the immediate border of the lagoon and clearly defining the limit between land and the lagoon water. This limit was formally marked with the realisation of the "conterminazione lagunare" initiated in the year 1611 and terminated in the year 1700 with the positioning of 99 markers. See on this subject the proceedings of the conference held in the year 1991 by the "ISTITUTO VENETO DI SCIENZE, LETTERE E ARTI".

The problems faced by the Venetians in the past, did not concern only the interaction with the land alone, but also with the sea. Only very narrow islands protected the lagoon from the sea waves. It was necessary to create a "sea wall" to avoid the lagoon becoming incorporated into the sea and to protect the people, mostly fishermen, who had established their home on these islands. The construction of the sea wall took from 1738 to 1785; without this wall the waves of the high water episode of November 1966 would have swept away the majority of the houses located on the island of Pellestrina.

The maintenance of navigation through the openings connecting the lagoon with the sea had been always a major concern for the ancient Venetians and also a major problem, since the formation of sand bars was periodically obstructing the openings. An effective solution was found only in 1845 when it was decided to protect the opening of Malamocco through the construction of breakwaters. This solution proved so effective that it was replicated at the other two openings. By the year 1935, all the three inlets were protected by breakwaters, and the Venetian had thus achieved the configuration of the lagoon, shown in *Figure 1*, for which they had been aiming since the year 1300, that is to have a body of water:

* navigable for all its extension
* having nearby a fertile land;
* well separated from the mainland;
* well protected from the sea and
* connected to it through openings not subject to siltation.

The actions taken in the course of approximately 700 years, from the 12^{th} century to the beginning of this century were aimed at enhancing the use of the lagoon as a commercial port and creating the conditions for the industrial, urban and agricultural development of the territory bordering the lagoon.

The environmental problems from which the lagoon suffers today have their roots in the past, when the understanding of how lagoon systems function was practically nil and each intervention was evaluated in relation to the specific problem to be solved, without considering the possible consequences of the intervention on other aspects of the lagoon.

The diversion of the major rivers was effective in preventing the siltation of the lagoon, but also tended to make the erosion processes prevail over sedimentation. This trend was enhanced by the littoral protection works. The construction of the breakwaters deprived the lagoon of the sediments previously entering the lagoon from the sea. Today the lagoon has a net loss of sediments which is around one million tons per year and is evolving towards becoming a marine bay. But this is not the only problem.

Coherently with the line drawn in the past, at the beginning of this century, an industrial area began to develop at the edge of the lagoon on the land directly opposite Venice, and a commercial port developed in the area of Marghera. To provide access to this port, it was necessary to dredge a navigation channel, 10 meters deep, named Vittorio Emanuele, after the king of Italy of that time (*Figure 1*).

The growth of Marghera progressed rapidly after the 2^{nd} World War and the decision, taken in the fifties, to develop a petrochemical industry in the area with the creation of the second largest refinery of Italy, led to the need to provide the condition for the big oil tankers to enter the lagoon. A new navigation channel, 12 meters deep, was excavated connecting Malamocco inlet directly with the inner part of the lagoon. This channel is known as the 'oil-channel' (*Figure 1*).

The dredged sediments were used to reclaim the tidal marshes at the border of the land facing the

Malamocco mouth. The port to receive the oil tankers, named San Leonardo, was built directly in the reclaimed area (*Figure 1*).

The dredging of the navigation channels contributed to accelerating the erosion of the lagoon.

In fact these channels, not being in equilibrium with the local conditions, tend to trap the sediments which are put into suspension from the nearby shallow layers and to maintain them navigable must be periodically dredged. Until a few years ago, the dredged sediments were deposited to the sea, thus causing a net loss of sediments from the lagoon.

Parallel to the development of the industrial and commercial activities, the nearby village of Mestre grew up to become one of the largest urban areas of the whole Veneto Region, with a population today of around two hundred thousand, more than three times the population of the historical centre.

At the same time, urbanisation, industrialisation and intensive agriculture developed throughout the whole basin which discharges in the lagoon.

The intensive growth of the human activities around the lagoon and on its drainage basin has degraded the quality of the water and of the sediments of the lagoon. This has posed the problems of the recovery of the contaminated areas and the depuration of the pollutants produced, whose solution is fundamental to the conservation of the lagoon environment.

Figure 2 summarises the major events which determined the present state of the lagoon of Venice.

The episode of high water on 4th November 1966 demonstrated the vulnerability of Venice.

Although concern about the deterioration of the lagoon was present in the public debate before this episode, it was the event of November 1966 which triggered the ongoing process aimed at repairing the errors of the past and identifying those actions which can, within the limits of our present understanding, safeguard Venice and conserve the ecosystem of the lagoon.

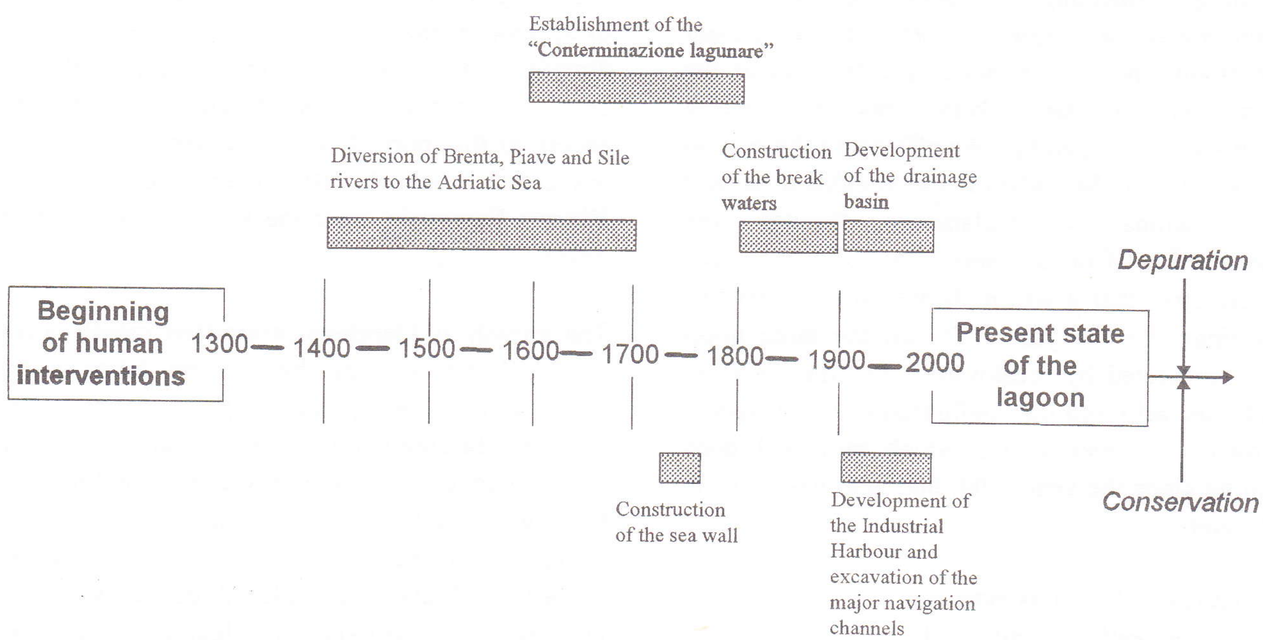

Figure 2 - Human interventions in the lagoon of Venice

2. THE ENVIRONMENTAL CHARACTERISTICS OF THE LAGOON OF VENICE

The lagoon of Venice like all coastal lagoons belongs to the wetland areas. Wetlands are "areas of marsh, fen, peat land or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine waters, the depth of which at low tides does not exceed six metres".

The importance of wetlands is second only to rainforests as reservoirs of biodiversity and natural productivity. Furthermore they play important roles in vital planetary processes such as the hydrological cycle and the servicing of migratory fish and birds. The importance of wetlands was officially recognised at international level in 1971, when a group of countries in the Iranian city of Ramsar signed a Convention for the conservation of wetlands.

The nations which are contracting parties of the Ramsar Convention are obliged to formulate and implement the national land-use planning so as to promote the "wise use" of wetlands in their national territory. The Convention defines "wise use of wetlands" as "their sustainable utilisation for the benefit of humankind in a way compatible with the maintenance of the natural properties of the ecosystem". In addition, contracting parties are obliged to designate at least one wetland for inclusion in the "List of Wetlands of International Importance" according to criteria established by the Convention on the species hosted by the wetland. The inclusion of a site in the list of the wetlands of international importance obliges the country to manage the site according to the principles of the Convention.

To date the Convention has been signed by 93 nations (36 in Europe) and 800 sites, for a total of approximately 5300 Km^2, have been nominated wetlands of international importance. Italy has nominated 36 sites; one of these sites is an area of the lagoon of Venice, originally used for fish farming, known as "Valle Averto".

The natural importance of coastal lagoons derives largely from being areas of transition between the marine and the terrestrial environment. This determines the presence of different type of habitats and therefore a great variety of species. *Figure 3* shows schematically the different habitats which are found in the lagoon of Venice proceeding from the land to the sea. In the same figure it is shown how the ecosystem will simplify if the lagoon will become a marine bay.

The circulation induced by the tidal excursion of the Adriatic Sea plays a fundamental role on the ecology of the lagoon of Venice. Using a popular expression it can be said that it is responsible for the "vivification of the lagoon". It contributes to

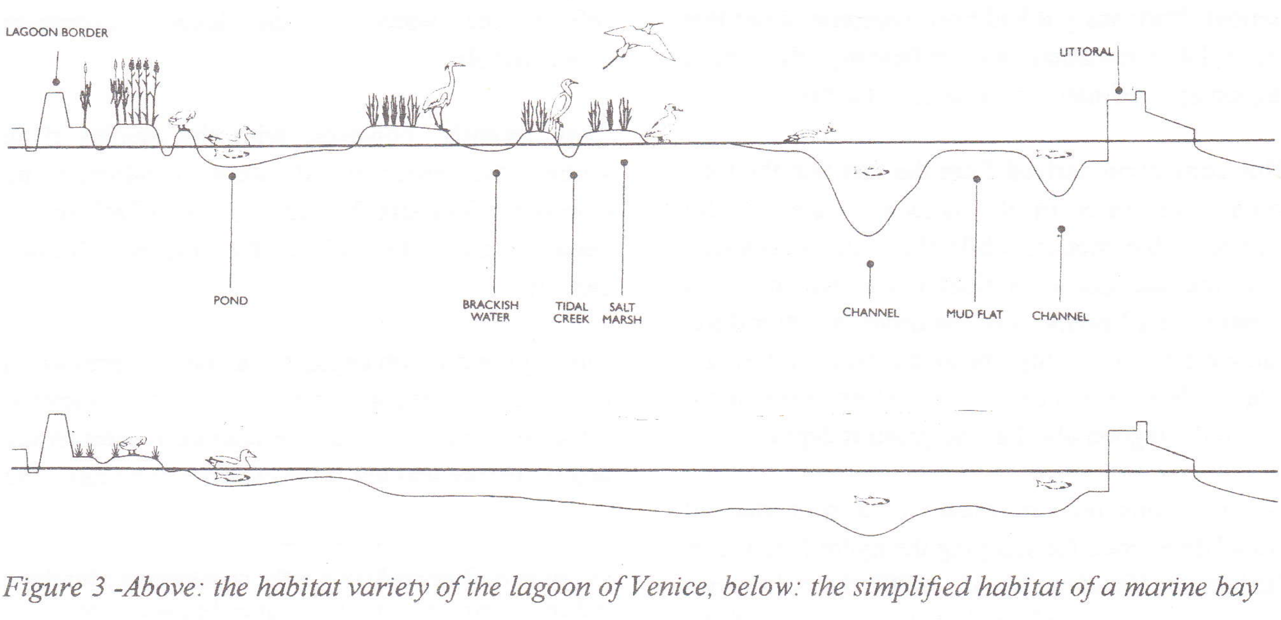

Figure 3 -Above: the habitat variety of the lagoon of Venice, below: the simplified habitat of a marine bay

the life of the lagoon in different ways, in particular it:

1. determines the variation of salinity from the sea to the land by diluting the fluxes of fresh water flowing into the lagoon from the drainage basin, and in this way, because certain species can only survive within a given salinity range, influences strongly the variety of species present in the lagoon;

2. transports and disperses nutrients and other substances which are either discharged in the lagoon water or produced by the physical, chemical and biological processes, taking place within the water column;

3. enhances the exchange of oxygen between the bottom sediment layer and the overlying water column, and therefore in the areas where circulation is more vivacious it is improbable that the water column become anoxic.

One of the most important aspects of the tidal circulation is its capacity to dilute the residual discharged into the lagoon. This matter acquired importance after the growth of the human activities in the territory surrounding Venice determined a dramatic increase in the amount of residuals discharged into the lagoon.

The pollution produced by the discharged residuals made evident that the capacity of the lagoon to dilute the residuals discharged into its water was limited. Previously it had been common belief that the tidal circulation was refreshing the entire lagoon approximately in a period of a day.

This conviction derived from the fact that the total volume of water of the lagoon is around 600 million cubic metres, while the water exchanged with the sea during a tidal cycle, which has a duration of 12 hours, is of the order of 200 million cubic metres. In reality, the area refreshed during a tidal cycle is only a limited area close to the inlets, where the lagoon also has the greatest depth.

To prove this fact, by means of a mathematical model developed for studying the hydrodynamic of the lagoon (Umgiesser et al., 1988), the trajectories of water particles released at the entrances of the three openings have been studied. As seen in *Figure 4,* drawn from the work done to define the interventions to improve the quality of the lagoon (CVN-Technital, 1993). the distance travelled by the particles, during the six hours of rising tide, is limited to the outlets area.

Figure 4 - The maximum distances covered by the sea water particles entering the lagoon in a tidal cycle

Moving from the inlets towards the inner border of the lagoon the capacity of the tidal circulation to refresh the water of the lagoon decreases progressively.

Only recently, however, with the studies done within the program of work conducted by Consorzio Venezia Nuova[1] (CVN, 1994) has it been possible to define the lagoon dilution capacity.

The lagoon dilution capacity has been expressed in terms of the average time a pollutant particle, released from a point of the lagoon, resides in the lagoon before leaving it through the openings. The

[1] *Consorzio Venezia Nuova* is the concessonary for the Italian Government of the design and construction of the works to save Venice and its lagoon.

computation of this residence time, which is function of the point from which the pollutant particle is released, has required the application of the two-dimensional mathematical hydrodynamic model coupled with a two-dimensional dispersion model (Postma, 1992). The results for the whole lagoon are reported in *Figure 5*, which, in particular, shows that the area of the lagoon in front of the industrial area, direct recipient of the industrial residuals, has the highest residence times.

The map in *Figure 5* shows that the substances discharged into the lagoon from the inner border tend to reside in the lagoon more than 10 days. This is a time sufficient for these substances to deposit and to enter the biological processes which take place in the lagoon. It is because of this fact that lagoons tend to trap nutrients and other substances, and have a productivity which is ten times that of the marine environment.

Because of the natural tendency of lagoons to trap substances, the lagoon waters are very susceptible to eutrophication, with effects which contribute heavily to the degradation of the lagoon, as explained in the next chapter.

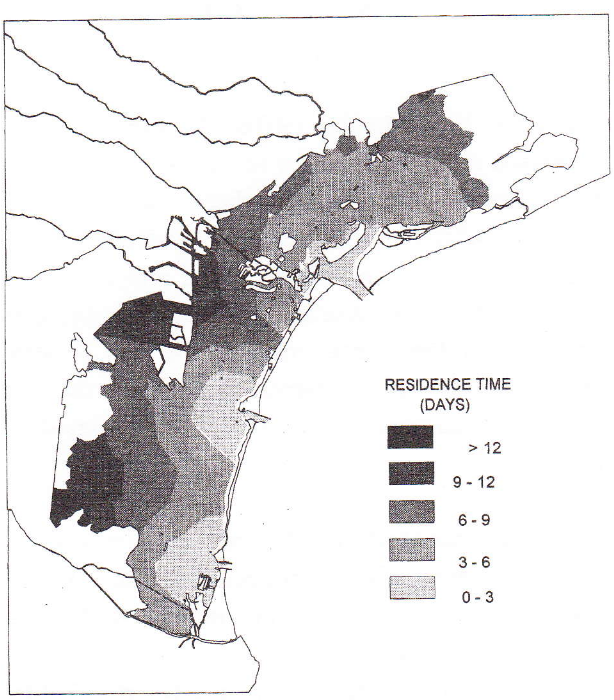

Figure 5 - Residence time in the lagoon of Venice

3. THE DEGRADATION OF THE LAGOON

The degradation of the physical system

The objective systematically pursued since the year 1200 has been to make the lagoon a very safe port accessible to large ships. The diversion of rivers, the construction of breakwaters at the openings and the dredging of the channel Vittorio Emanuele and of the "oil-channel" to allow the entrance into the lagoon of the oil tankers, have all acted in this direction.

The pursuing of this objective saved the lagoon from silting, but made the lagoon rapidly evolve towards becoming a marine bay. The mechanism through which this is occurring is as follows.

The loss of significant inputs of sediments from the land and from the sea, resulting from the river diversion and the construction of the breakwaters, means there is no replacement of those sediments put into suspension in the shallow areas by waves induced by the wind or motorboats and ultimately lost to the sea.

The sediments are transported to the sea either directly by the fluxes exchanged through the openings or indirectly as a result of the dredging operations which must be done periodically to clear the navigation channels of the sediments from the shallows which have deposited on their bottom. In this process the shallows tend to become deeper.

This increases the strength of waves on the structures present in lagoon and in particular on the edge of the tidal marshes, whose extension (also as a result of the fact that, due to land subsidence and increased sea level, there has been a 25 cm loss in height in this century) has diminished from 72 km^2 in 1930 to 48 km^2 today (including reclaimed land). In the work done to find measures which could stop the erosive trend of the lagoon (CVN-Technital,1992), on the basis of experimental data and of mathematical models, it has been estimated that the net loss of sediments is approximately one million tons on a yearly basis: 700 tons are lost naturally and 400 by dredging.

In the cited work it has been also shown that the excavation of artificial channels worsen the situation. The local currents, in the shallow areas where artificial channels are dredged, tend to remain the same as in the unmodified situation and, normally, they are too weak to avoid the sedimentation in the channel of the suspended sediments which originate from the neighbouring shallow areas.

Thus, these channels have the effect of subtracting sediment from the shallow areas and require frequent dredging in order to keep them navigable. This is not happening with the natural channels because the current velocities are in equilibrium with the section of the channel, and therefore natural channels do not normally tend to trap suspended sediments.

The loss of the marshlands and the deepening of the shallow areas will make the lagoon lose its wetland character completely. The biodiversity of the lagoon ecosystem and its high productivity will therefore be lost. This will have consequences on the acquaculture and fishing activities in the lagoon. In addition, given that wave intensity growths with the square of water depth, all the banks and the buildings directly exposed to waves will be subject to a faster degradation, and to ensure their stability, maintenance will have to be done more frequently.

The degradation of the aquatic system

The degradation of the lagoon morphology has been accompanied in the second half of this century by a progressive decrease in the quality of the aquatic system as a result of the increased pollution load from the drainage basin.

Before the growth of the activities in the drainage basin, the only pollution load discharged into the lagoon was the one produced by the lagoon urban settlements. The load was therefore almost exclusively organic and reached the lagoon untreated, since the lagoon urban centres, as is still the case today for most of them, did not have a sewerage system. This load was not negligible, given that the population of Venice alone at the end of the second world war was around 170,000 inhabitants. However, with the exception of the local effects which this load creates still today within and nearby the city, it was compatible with the lagoon self depurating capacity.

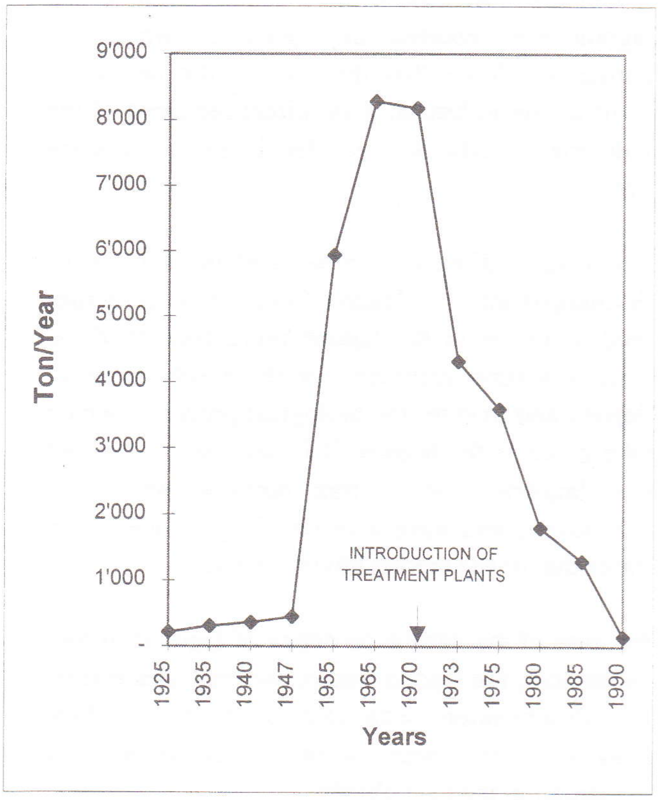

Figure 6 - Discharges of Nitrogen from the Industrial Area of Marghera

From the 1960s to the 1970s, the pollution load increased dramatically as a result of the growth of the industrial area of Marghera. As shown in *Figure 6* which uses Nitrogen as indicator of the time evolution of the load from the industrial area, only with the implementation of treatment systems, imposed by the introduction in the 60s of strict regulations on environmental pollution, the load from the industrial area decreased to the levels of the '50s.

Until the introduction of strict regulations, the industrial area also introduced in the lagoon significant loads of heavy metals and toxic substances, in addition to nutrients and organic compounds. There are no official estimates, but the effects of these loads are evident in the sediments in front of the industrial area. These sediments present the highest concentration of heavy metals.

In the 50s, the lack of consciousness of the damage chemical compounds could produce to the environment also led to the disposal of industrial residuals without taking any precaution in several locations within the lagoon.

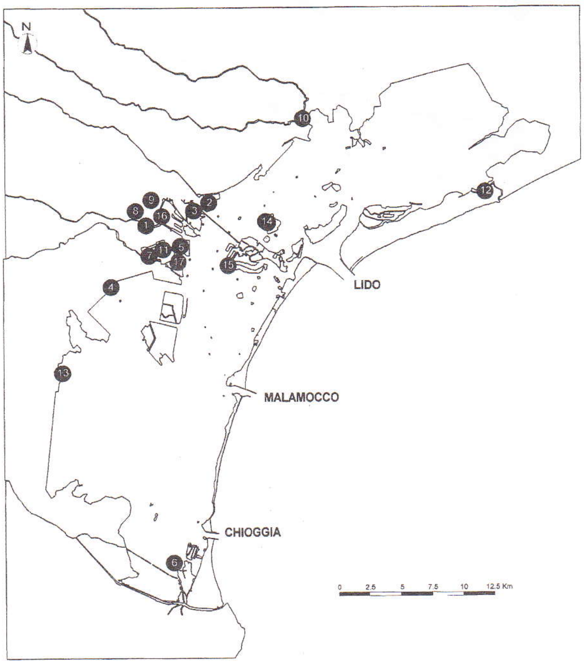

Figure 7 - Abandoned dump sites

The "illegal" waste disposal sites identified today are shown in *Figure 7*, and one of the major action to reduce the degradation of the lagoon of Venice is to intervene in these sites to ensure that in the future their content is not lost to the lagoon.

While the load from the industrial area was decreasing, activities all over the drainage basin were growing at a very fast pace, especially in the agricultural sector, as shown from *Figure 8*, shifting the problem from the control of point sources to that of non point sources. Thus, despite the effort undertaken in both the public and private sector to reduce the load discharged into the lagoon, the amount of nutrients and organic compounds reaching the lagoon is amply sufficient to make the system eutrophic. In the work done (CVN-Technital, 1993), it has been estimated that, on a yearly basis, over 7000 tons of nitrogen and over 1000 tons of phosphorus are still discharged in the lagoon environment from the drainage basin and from the urban and industrial areas situated within the lagoon.

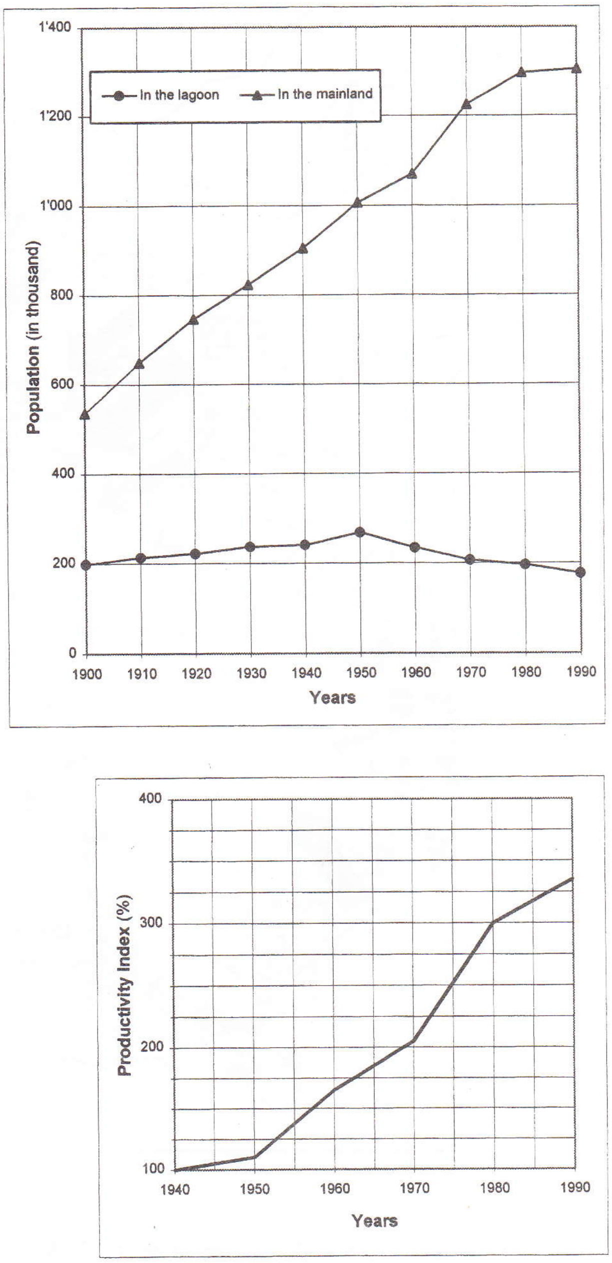

Figure 8 - Above: the evolution of population in the drainage basin and in the lagoon; Below: the fast growth of agriculture productivity in the drainage basin.

The distribution of the organic (BOD_5) and nutrient (Nitrogen and Phosphorus) loads expressed on a daily basis is given in *Figure 9*.

The excess of nutrients in the water column has caused a series of algae blooms. In the seventies they were typically phytoplancton blooms, similar to those observed in the Adriatic sea, but subsequently macroalgae, in particular nitrophilous opportunistic species like Ulva rigida, have become the dominant primary producers.

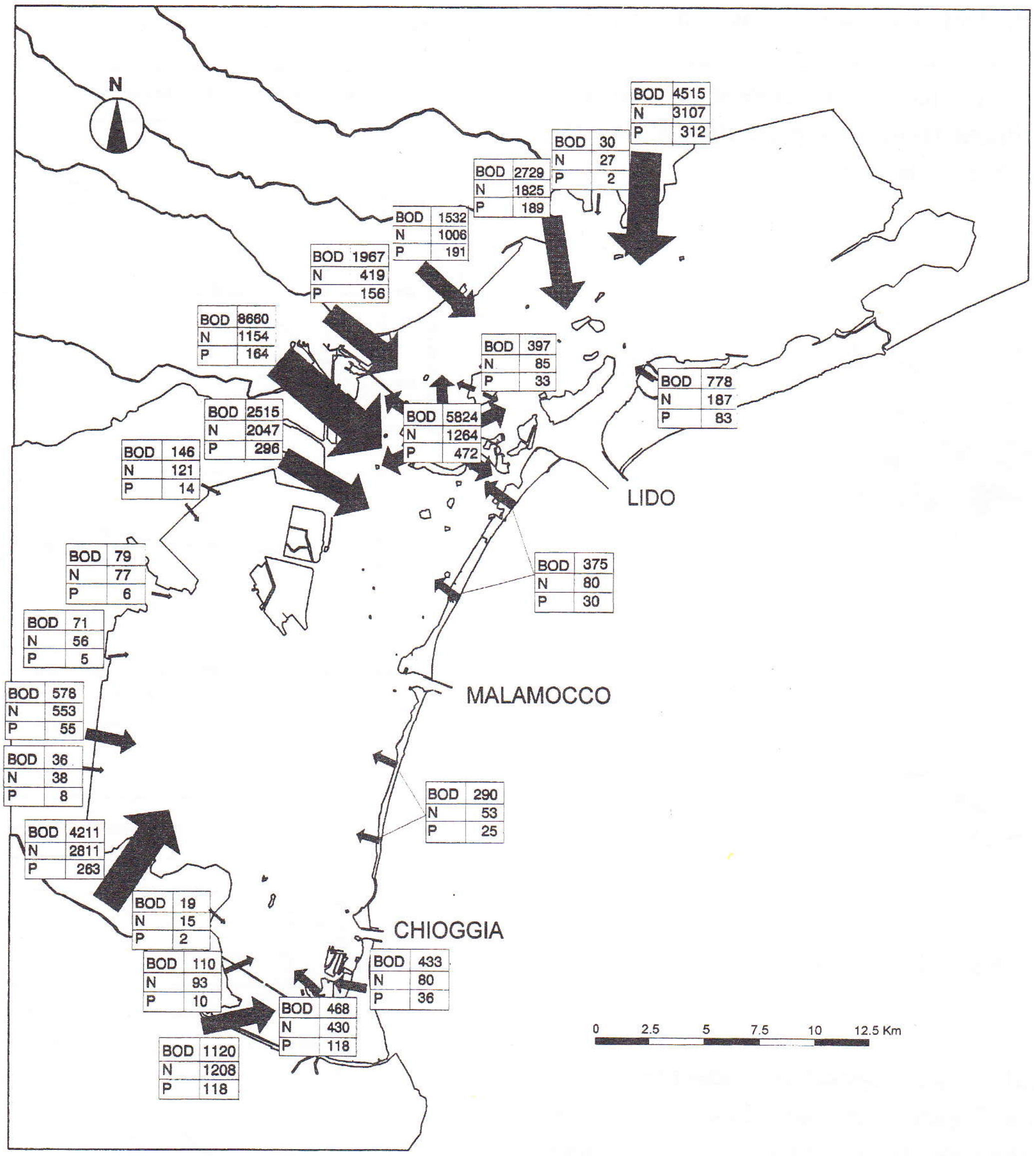

Figure 9 - Distribution of BOD, N and P loads (in kg/day) in the lagoon of Venice
(the arrows are proportional to the BOD load)

The factors which favour the development of Ulva with respect to phytoplancton have not been completely identified.

Based on the present knowledge (Jonkers et al.,1992), the following three factors seem relevant:

1. the overwintering of Ulva: a certain biomass of Ulva due to the climate of the area remains throughout the winter season and takes up virtually all the spring runoff of nutrients before the phytoplancton can respond and develop a bloom;
2. the ability of Ulva to take up and store more nitrogen than it needs for immediate growt when nutrients are in excess. If nitrogen becomes the limiting nutrient, growth of phytoplancton is reduced whilst growth of Ulva may continue for a certain period of time;
3. the morphology of the lagoon: the evolution of the shallow areas due to the on-going erosion has favoured Ulva. In the areas with depth around 1m Ulva is little transported with the tidally induced water circulation and receives relatively high light intensities. Phytoplancton on the contrary is transported with the tide into deeper areas such as gullies and canals and consequently receives lower average light intensities.

The principal negative effects of Ulva dominance, summarised in *Figure 10*, are:

- **Disappearance of large quantities of eelgrass beds.** The presence of macroalgae in the water column reduces the light availability. Eelgrass has disappeared totally in the areas where the macroalgae dominate. The former meadows of submerged rooted vegetation in the lagoon have been reduced to restricted areas around the port entrances.

- **Anoxic water and hydrogen sulphide release.** Fast decay of macroalgae biomass, especially when present in large quantities (e.g. over 5 kg/m^2 ww), occurring in poorly refreshed areas during unfavourably meteorological conditions (high temperature and absence of wind) has often resulted in oxygen depletion in the water column and in the release of H_2S in the atmosphere.

- **Reduction in species diversity.** The temporary disappearance of zoobenthos and fish due to local anoxic conditions has favoured an increase of few tolerant species.

- **Erosion of marshes.** In the widespread areas where macroalgae are dominant, macroalgae are deposited on the marshland edges at high water. The deposition of these dense mats of macroalgae causes the vegetation on the marshland to die. Without the protective cover of the emergent vegetation, including their rootnet, the erodibility of the marshland edges increases.

- **Nutrient release from sediments.** Part of the organic matter in algae and plants is transformed back to nutrients during mineralization in the water. Another part is deposited on the sediments where it is mineralised throughout the year releasing nutrients to the water column . The release rates of nutrients from sediments can be as important as the loads from the hinterland and from the city of Venice (Sfriso et al., 1989).

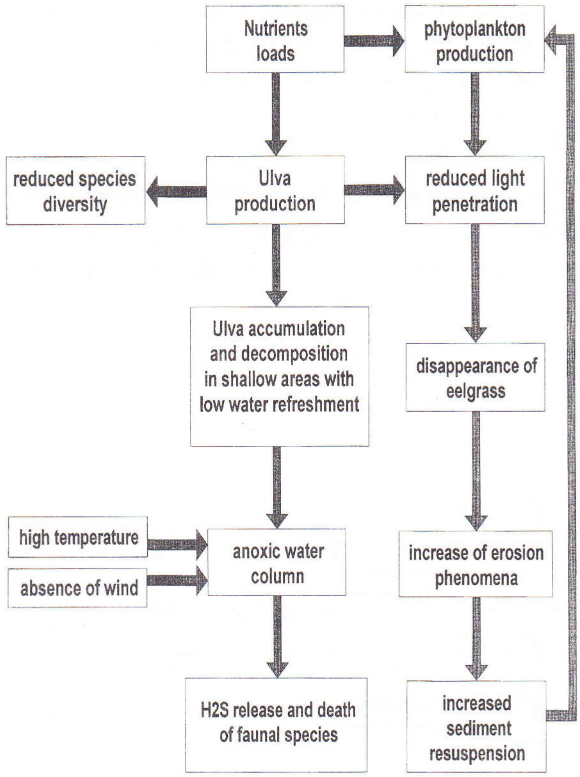

Figure 10 - Main eutrophication phenomena in the lagoon of Venice

4. THE INTERVENTIONS FOR THE CONSERVATION OF THE LAGOON ENVIRONMENT

The GIS and the mathematical models which have been developed

The definition of the measures for the conservation of the lagoon environment requires the identification of the causes of the lagoon degradation and the understanding of the relations existing between the causes and their effects. to this purpose a specific framework of analysis has been built. This framework organises and condenses the available knowledge and allows for the reproduction of the principal relations. It comprises two integrated parts:

- a GIS component to describe the spatial distribution of the relevant parameters and to understand through their overlapping which are the main relations and where the most critical conditions occur;

- a set of mathematical models developed at a level of detail sufficient to compare the effectiveness of alternative interventions in relative terms.

The scheme applied to identify the critical areas of the lagoon by overlapping through the GIS the relevant parameters is reproduced in *Figure 11* (Bettinetti et al.,1996).

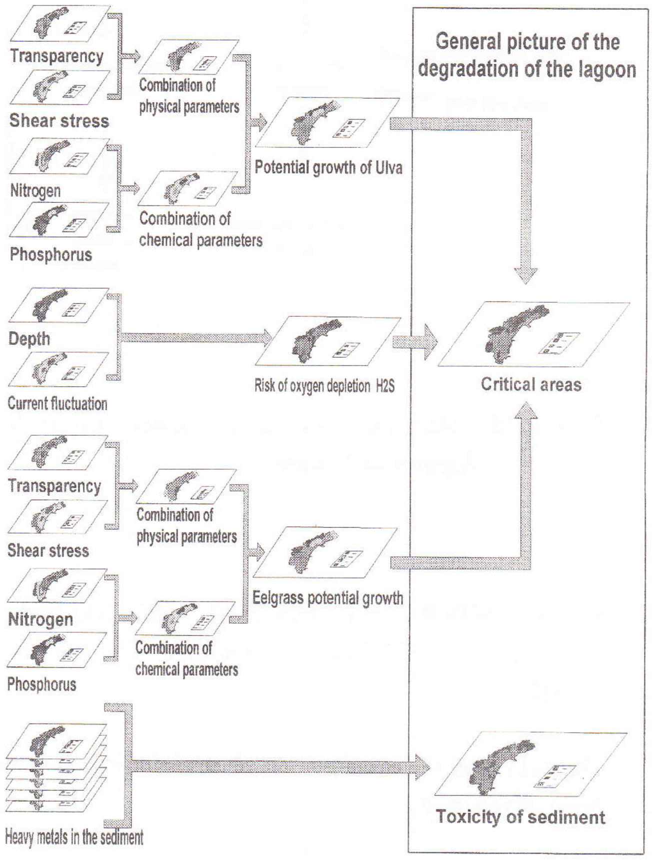

Figure 11 - Scheme applied to identify the critical areas of lagoon of Venice

In order to assess the effects of actions which affect the lagoon environment, the mathematical modelling must be sufficiently advanced to describe the ecological processes which are relevant in the lagoon of Venice (Runca et al., 1996).

The present version of the ecological model developed for the Venice lagoon consists of 108 cells. The model is linked to the hydrodynamic and to the dispersive model quoted above. *Figure 12* shows the grid of the three models. Within each computational element of the ecological model, in addition to model standard quality processes, the specific processes related to the dominance in the lagoon of Venice of macro-algae are calculated according to the scheme presented above in *Figure 10.*

The use of the ecological model has in particular shown that, in order to solve the eutrophication problem of the lagoon of Venice, the amount of nutrient and organic load today discharged into the lagoon must be reduced by at least 60% (CVN-Technital, 1993). This results has proved that also the load originated by non point sources must be reduced.

By applying the ecological and other more traditional models the interventions considered necessary for the recovery of the lagoon have been identified. Although the interventions which have been selected constitute an integrated plan, they have been divided into two groups, according to whether they are more effective on morphology or on quality.

The interventions selected for the restoration of lagoon morphology

- Input of sediments from the sea
  It is foreseen to dredge the sediments deposited outside the Lido inlet and place it using barges or a jet-pump in selected locations within the lagoon.
- Disposal of dredged material within the lagoon boundary
  Use of the sediments dredged for navigation purposes within the lagoon to create artificial marshes as a compensation for those lost as a consequence of erosion phenomena.
- Reduction of the erodibility of the lagoon bottom
  It is foreseen to recreate in selected areas of the lagoon the eelgrass beds that have disappeared as a consequence of the decrease of environmental quality. These plants in fact create a dense rootnet that stabilises the bottom, while their leaves contribute to smooth the wave action. This intervention is strictly linked to those aimed at improving the water quality in the lagoon.

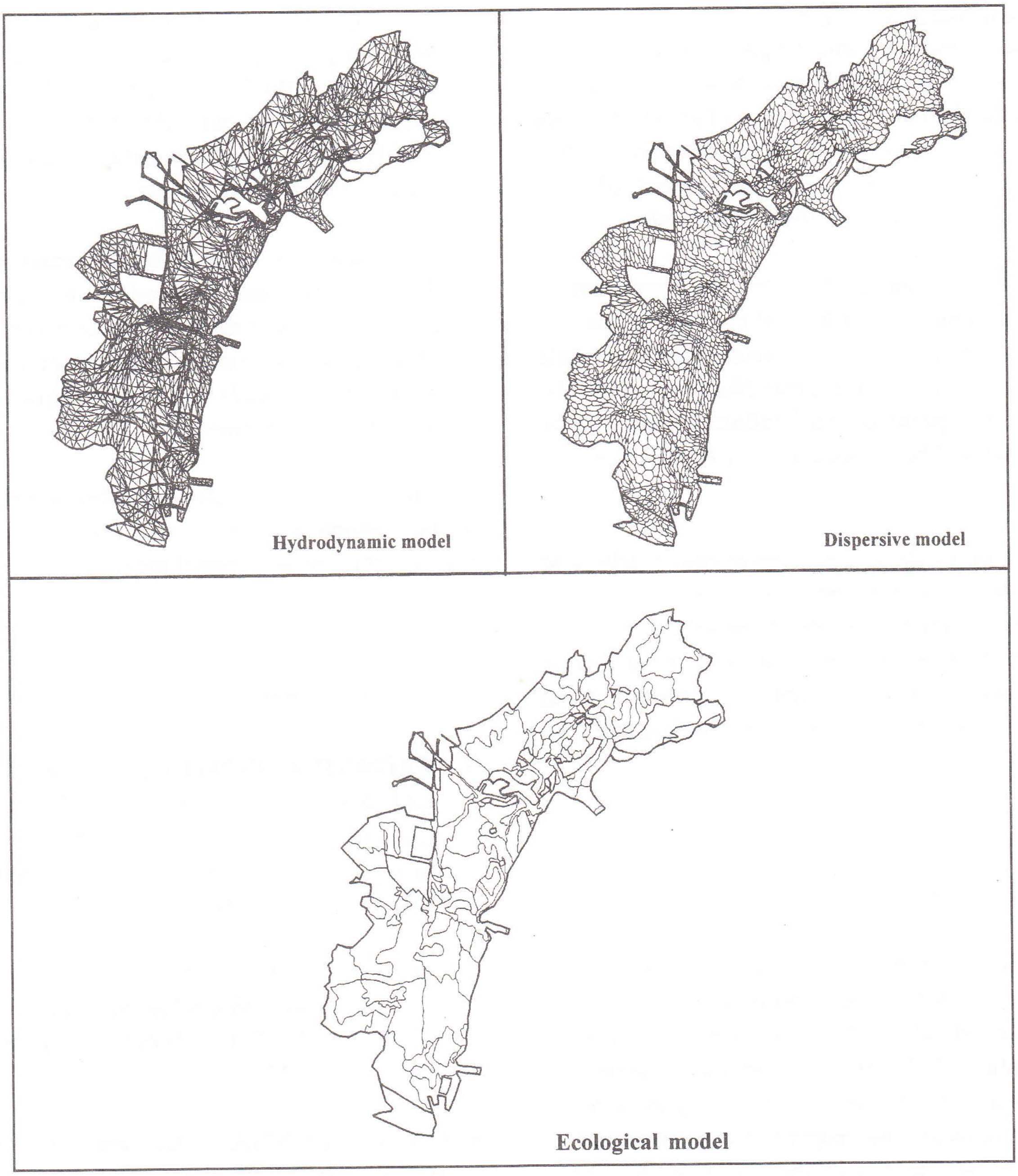

Figure 12 - The grid of the mathematical models

Implementing these measures will result in a global reduction of 80% of the present sediment loss (CVN-Technital, 1992).

Interventions selected for the restoration of the environmental quality

- Reduction of nutrient inputs from the drainage basin
  In addition to complete the interventions to reduce the load from point source, it is planned to realise a series of artificial wetlands around the lagoon border in order to treat the pollution load deriving from agricultural run-off that cannot be collected and treated in traditional treatment plants.
- Intervention on the morphology to reduce macroalgae development
  It is foreseen to create artificial tidal flats around the city of Venice to reduce the water depth in order to create unfavourable conditions (from the hydrodynamic and ecological point of view) for the macroalgae growth .

- <u>Emergency interventions</u>
  These include macroalgae harvesting and oxygenation of the water column and aim to reduce the risk of occurrence of anoxic episodes and H_2S release in the water column in sensitive areas of the lagoon, in the period of time necessary to complete the recovery plan.

It has been estimated that the implementation of these actions will reduce the nutrient load to approximately 30% of the present situation while the extent of the critical areas (those dominated by macroalgae presence and influenced by anoxic episodes) will be reduced by 90% (CVN-Technital, 1993).

In addition to the above interventions finalised to solve the eutrophication problem of the lagoon, work is in progress on the abondoned dump sites. Two of them have been completely isolated from the lagoon by sheetpile diaphragm driven down to reach a soil bottom layer of sufficiently low permeability.

5. CONCLUSION

The conservation of the lagoon environment requires that actions be taken in several directions. The planned interventions will not only improve the quality of the environment and maintain its ecological character, but by preventing the shallow areas from becoming deeper will also contribute to reducing the intensity of the waves on the fragile buildings of the city.

In order to ensure that interventions produce effects in the right directions, the lagoon must be monitored on a regular basis. Specific attention, in addition to quality, must be given to the lagoon sediment balance, since its changes affect the physical stability of the system and its ecological character.

On the basis of the work done for the lagoon of Venice, it is important for the conservation of a coastal lagoon subject to anthropic pressure:

- to keep "buffer" areas around the aquatic body to filter the pollution produced in the catchment basin by human activities. The "buffer" areas will also provide environmental services such a recreation, wild life protection and landscape enhancement and will therefore improve the quality of life for the population and increase the general value of the area;

- to evaluate the capacity of the water body to disperse pollutants released from existing or planned anthropic activities, since accumulation of pollutants decreases the quality of water and sediments and leads to a rapid degradation of the natural environment.

The method and the related tools developed for the Venice lagoon are general and can be applied to similar estuarine and coastal areas.

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Seconda sessione

FIRENZE

FLOOD RISK IN THE ARNO BASIN: OVERVIEW OF THE SITUATION AND SUMMARY OF THE ACTIONS ENVISAGED IN THE BASIN PLAN

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Secretary General of the Basin Authority

ABSTRACT

The River Arno, with a catchment basin of 8228 Km^3, is a torrential river with flows that in the Florence stretch may vary between a minimum of 3-4 m^3/sec in the period from July to end September (hence below the "minimum vital" flow, which is 8 m^3/sec), to a maximum in Autumn and Spring of 2000-2200 m^3/sec (in 8 events which occurred during the Fifties), with peaks of over 4000 m^3/sec in the case of catastrophic flooding as happened in 1966.

1. NATURAL CAUSES

Historic data document both directly and indirectly that various flood events occurred even in the past: the effects of the latter together with the study of the more recent inundations (in particular the 1966 flood) indicate that such events have occurred, and will hence continue to do so, when rain falls on the whole of the catchment basin or on most of it and exceeds a given threshold in intensity and duration. Indeed, in such cases the amount of flowing water cannot be contained within the banks or the artificial embankments of the river.

The plains of the Casentino, Val di Chiana, Valdarno, Pistoia, Prato, Florence, Val di Nievole and the Marshes of Fucecchio, Bientina and of the Pisa coastal zone, as well as the plains of the main tributaries to the River Arno, are geologic evidence of the numerous alluvial events which occurred in historic and prehistoric eras, when rivers were free to overflow into the surrounding territory depositing and arranging the silt and debris that they had eroded and transported down from the hills of the catchment basin.

2. PAST INTERVENTIONS THAT AGGRAVATED THE ARNO WATER SYSTEM

In the course of time, the natural flooding of the river, caused by the intensity and by the regular recurrence of rainfall and by the geological and geomorphological characteristics of the territory gradually turned into greater and greater risk factors because of the large water works carried out, documented from the early 14th century and which continued in time (especially in the late 18th and early 19th centuries): indeed, such interventions transformed the breadth of the river and led to changes in its flow capacity.

It must be recalled that starting from the 14th - 16th centuries, and in particular towards the end of the 18th century, the situation was worsened even further because the waters from the Siena and Arezzo portion of the Chiana Valley, that had hitherto flown into the Tiber, were diverted and made to become tributaries of the River Arno as a result of the reclamation of the swampy land around the Chiusi and Montepulciano Lakes owned at first by the Medici and then by the Lorena; this raised the flows to the Arno to values between 350 and 650 m^3/sec in the case of major flooding events.
Indeed, as early as 1342 the rulers of Arezzo began to excavate the rock sill that separated the Arno valley from the Chiana valley hence shifting the origin of the Chiana whose waters flowed into the Arno, by some 8 Km towards Arezzo, in the vicinity of Policiano. In the mid-16th century, the waters of the

Chiana from the Brolio area flowed into the Tiber, they were almost stagnant waters from Brolio di Pigli whereas from Pigli they descended towards the Arno. The Medici began the reclamation works of the Chiana Valley. Towards 1780 with the agreement signed by the Lorena and the Pope defining their respective boundaries, the waters that flowed into the Arno were made to originate from the Tresa Valley, just below Chiusi, by means of the Chiana canal that was over 50 km long.

Moreover, as early as the 14th century, the Arno's course was straightened by creating several canals that eliminated many of the river's natural meanders, and the width of the riverbed was progressively reduced to a few tens of metres so as to be used for transport purposes in particular for the timber coming from the Casentino and Valdarno forests that were to be transported to the downstream areas; this was done especially in the months of March and April, but also in Autumn when the flow rates of the river were such as to make this easier. The artificial narrowing of the river bed which was undertaken systematically from the mid 16th century (the most recent intervention which caused the present situation, especially between Florence and the river mouth, dates back to around 1840) and its progressive straightening have led to a situation where, in the segment downstream from ENEL's Levane dam (Ar), the Arno can contain within its embankments and natural banks water flows of the order of 2500-3000 m^3/sec, apart from some stretches where the width is reasonable but not sufficient for the disposal of flood waters.

3. PAST CORRECTION

The Arno's greater liability to flooding as a result of the straightening of its course was offset by the fact that the surrounding areas were farmland and hence the river's waters could overflow without producing any damage.

In the vicinity of villages the river was divided into two or three branches (called *bisarni*) that would circumvent the village and then flow back together into a single course downstream from the village. Such measure obviously aimed at making sure that in the case of floods the villages would not be damaged.

In some cases as in the Pisa plain, in the 14th century "overflow" channels were arranged so as to enable flood waters to flow towards uninhabited and morphologically lower areas without producing any damage.

Parallel to this a network of canals was built towards the end of the 18th century by the Lorena family so as to lengthen outflow time and reduce the level of flood waters as well as to reclaim and enable better crop growing in the plain.
Later, starting from 1820, and particularly after the early decades of this century innumerable, forest and water management interventions and river-bed correction works (dikes) were carried out. Over 2700 such measures have been counted by the census made during the preparation of the Plan

4. THE RISK OF FLOODS IN THE BASIN

There has always been a risk of floods in the Arno basin in all historic eras.

An analysis of historic documents shows that from 1177 onwards Florence experienced 56 floods with the urban area being directly involved, eight of which were particularly

disastrous. These are the floods that occurred in 1333, 1547, 1557, 1589, 1740, 1758, 1844 and 1966.
In the case of the flood which occurred on 4 November 1966 the average rainfall for the whole basin was about 170 mm, with peaks in some places of 300-350 mm.

Besides the Florence area, the flood also struck, with disastrous consequences, the Casentino, the Upper, Middle and Lower Valdarno and the city of Pisa.

During the last 50 years smaller sized events have occurred, without flooding Florence (transit flow at the Ponte Vecchio section being around 2000-3200 m^3/sec) which however caused extensive damage to the territory. During this period both before and after the 1966 flood there have been eight major events (1949, 1951, 1961, 1973, 1980, 1987, 1992, 1993) with an average rainfall in the basin of some 70-90 mm with peaks of 200-250 mm in some places.

As will be seen in the following, the risk of floods is not restricted only to this type of rainfall; today there are innumerable risk situations which are recurrent, especially along the tributaries, as witnessed by the eleven events that have occurred during the last five years in the Arno and Serchio basins.

5. THE 4 NOVEMBER 1966 FLOOD

During the 4 November 1966 flood in Florence the river exceeded a flow of 4000 m^3/sec as against a flow capacity of just over 2500 m^3/sec.

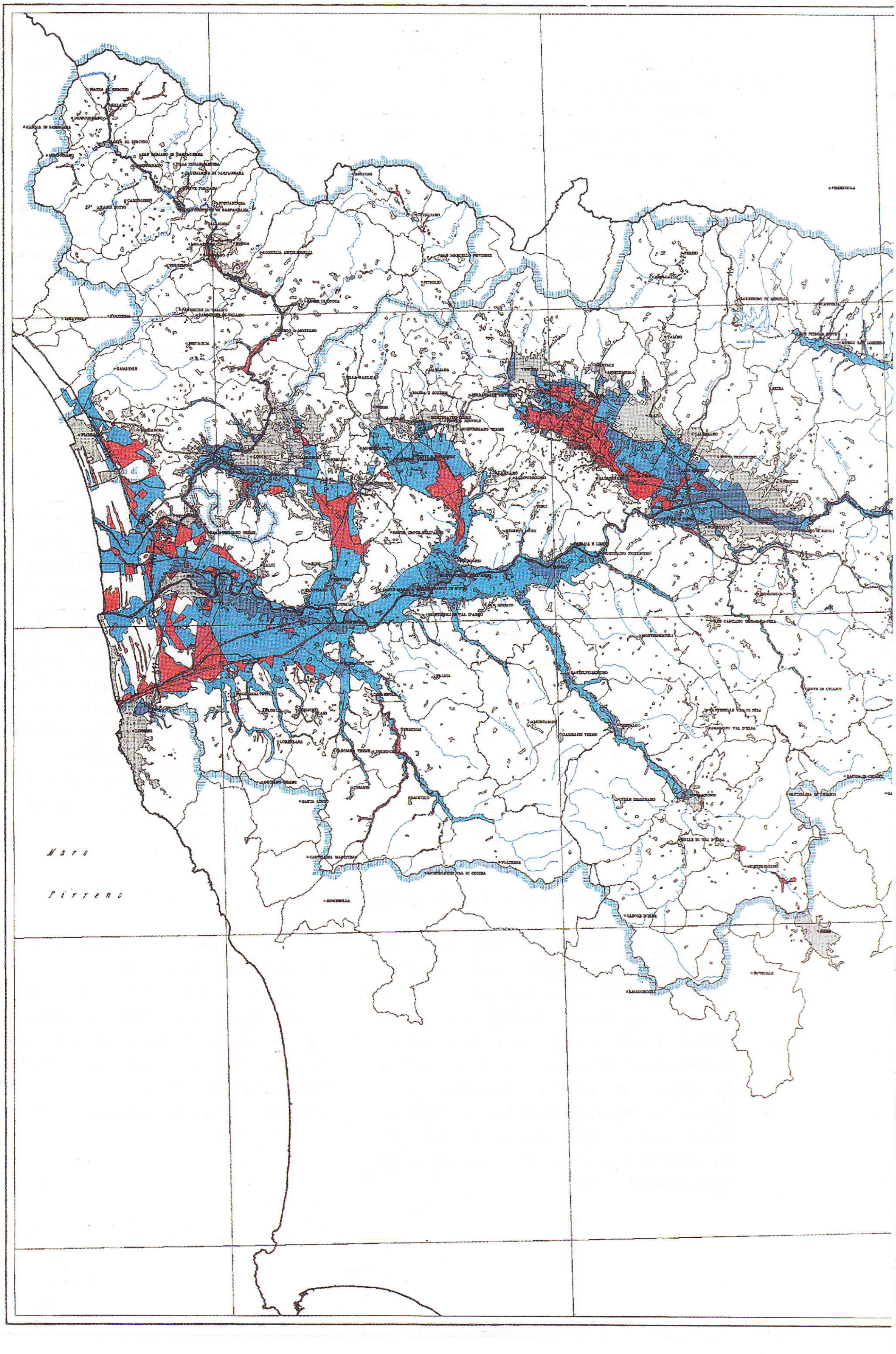
The flooding waters had already undergone some lamination upstream as a result of the overflows into the Casentino and Upper Valdarno areas.

The overflow of 70 million m^3 which flooded Florence laminated the crest of the flood for the areas downstream hence attenuating somewhat the violence of the rushing waters but also the damage caused in the lower part of the basin was in any case severe for a number of reasons; the construction works of the Pontedera overflow channel were still underway, the tributaries to the Arno contributed huge amounts of water, hydraulic jumps caused by the excessive height of the waters of the River Arno and finally, throughout its course which was almost entirely artificial, there were innumerable points where the river section had been narrowed excessively with bottlenecks having a capacity of only 1700 m^3/sec, as in the town of Pisa.

6. PROJECTS AND MEASURES TAKEN AFTER 1966

Following the disastrous 1966 flood, an Interministerial Committee, also known as "De Marchi Committee" was set up to look into the issues of water management and soil defence. Its aim was to work out strategies for defending the country from floods. Within the framework of the Committee, Prof. Supino led the Arno and Serchio Working Group, and so the body of interventions suggested by this Committee is known as the "Supino Plan" (1974).

The plan provided for a feasibility study for the adoption of actions in the Arno basin to be able to counter floods of the size of the 1966 flood; the plan envisaged the construction of 23 reservoirs along the main river and along its tributaries of which 17 to be built upstream from
Florence, for a total capacity of 240 million m^3.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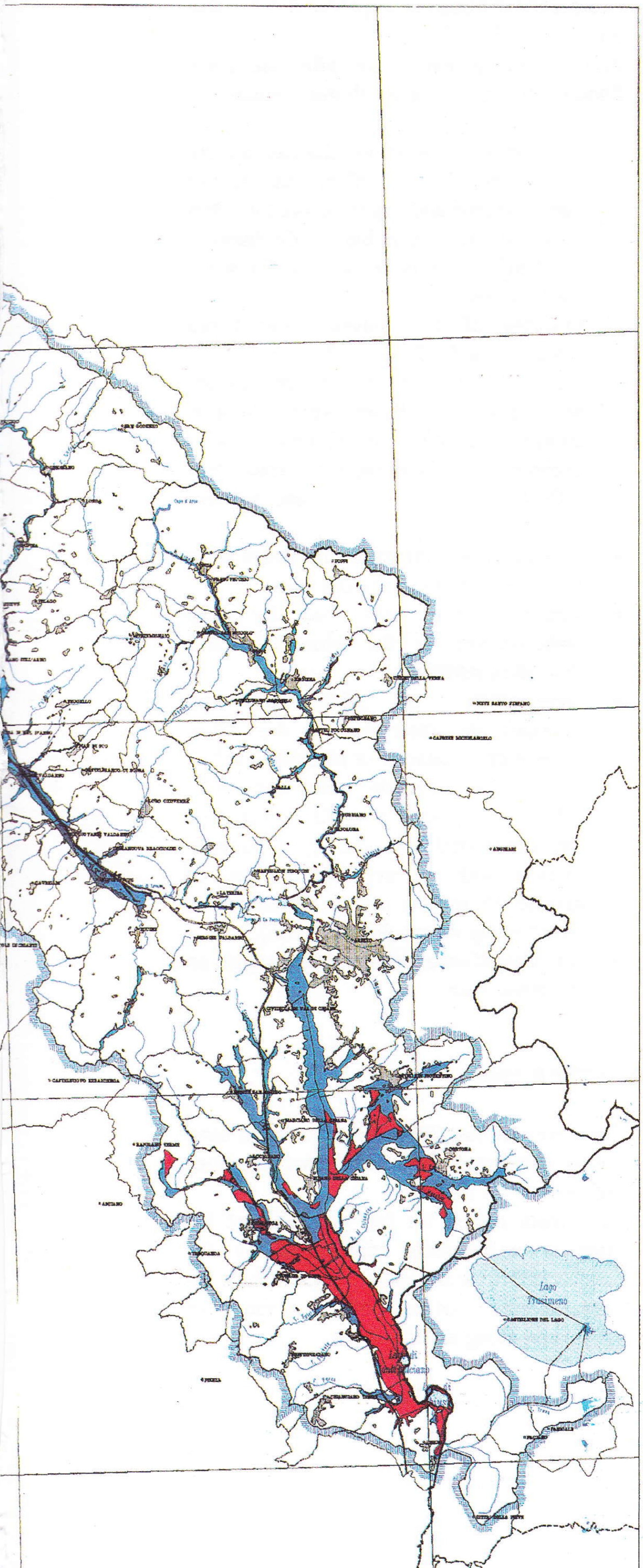


Regione Toscana

Autorita' di Bacino
DEL FIUME ARNO

Autorita' di Bacino
BACINO PILOTA DEL FIUME SERCHIO

Legge 183/1989 (art. 30) – Legge 253/1990 (art. 8)

D.M. 1 luglio 1989

Carta guida delle aree inondabili

Redatta sulla base degli eventi alluvionali significatifi degli ultimi 30 anni

Scala 1 : 200.000

0 km 4 8 12

Proiezione U.T.M.

Zone soggette ad inondazioni eccezionali

Zone soggette ad inondazioni ricorrenti

Limite amministrativo Autorita' di Bacino del F. Serchio e del F. Arno

Limite di Comune

Limite di Provincia

Limite di Regione

Reticolo idrografico

Centri e nuclei abitati

The project envisaged a diversion canal upstream from Florence running from the Arno to the River Greve, and another one on the River Elsa, as well as overflow tanks on the River Elsa and in the Fucecchio Marsh.

Later, with a view to the multiple use of water (laminating floods, water supply for domestic, irrigation and industrial purposes, water quality), the Studio Lotti Firm of Rome (1975) was assigned the task, by the Ministry for the Budget and by the Region of Tuscany, to rehabilitate the River Arno Basin envisaging the construction of 11 multipurpose reservoirs for a total capacity of some 400 million m^3 of which 117 for flood lamination.

The project was based on the achievement of the best degree of defence, as established by a cost-benefit analysis. For Florence and Pisa the measures to be taken were gauged to ensure full protection from floods of the size of the 1966 flood.

Other studies and projects (Grazi, Evangelisti, College of Engineers of Florence, etc.) proposed the construction of other reservoirs, supplemented if necessary by overflow tanks and diversion canals, as efficient defence actions.

Only a small proportion of the innumerable proposals, studies and projects that were made successively in time, have been turned into practical measures capable of defending the territory from floods.

Amongst the actions taken after the 1966 flood the following are worth mentioning:

- the Pontedera overflow channel on the River Arno. This overflow channel had been designed and begun before the 1966 flood and it is capable of discharging 1400 m^3/sec; it is being used for some 1000 m^3/sec.
- lowering of the shelves under Ponte Vecchio and Ponte alle Grazie in Florence and raising of the embankment walls along the River Arno where it crosses the city of Florence hence expanding the flow capacity from 2500 (10966) to 3100-3400 m^3/sec without clearance;
- reshaping the river course upstream from Florence up to the Albereta zone;
- stabilising the river bed by dike embankments in the Montelupo and Pontedera stretches;
- construction of the Bilancino multipurpose reservoir on the River Sieve with a capacity of 80 million m^3 of water (it is currently being completed: 1997-1999) useful also for ensuring a "minimum vital flow" during the summer months with an expected volume of around 15 million m^3 to accommodate overflowing waters during floods).
- the Castelfiorentino diversion canal on the River Elsa.

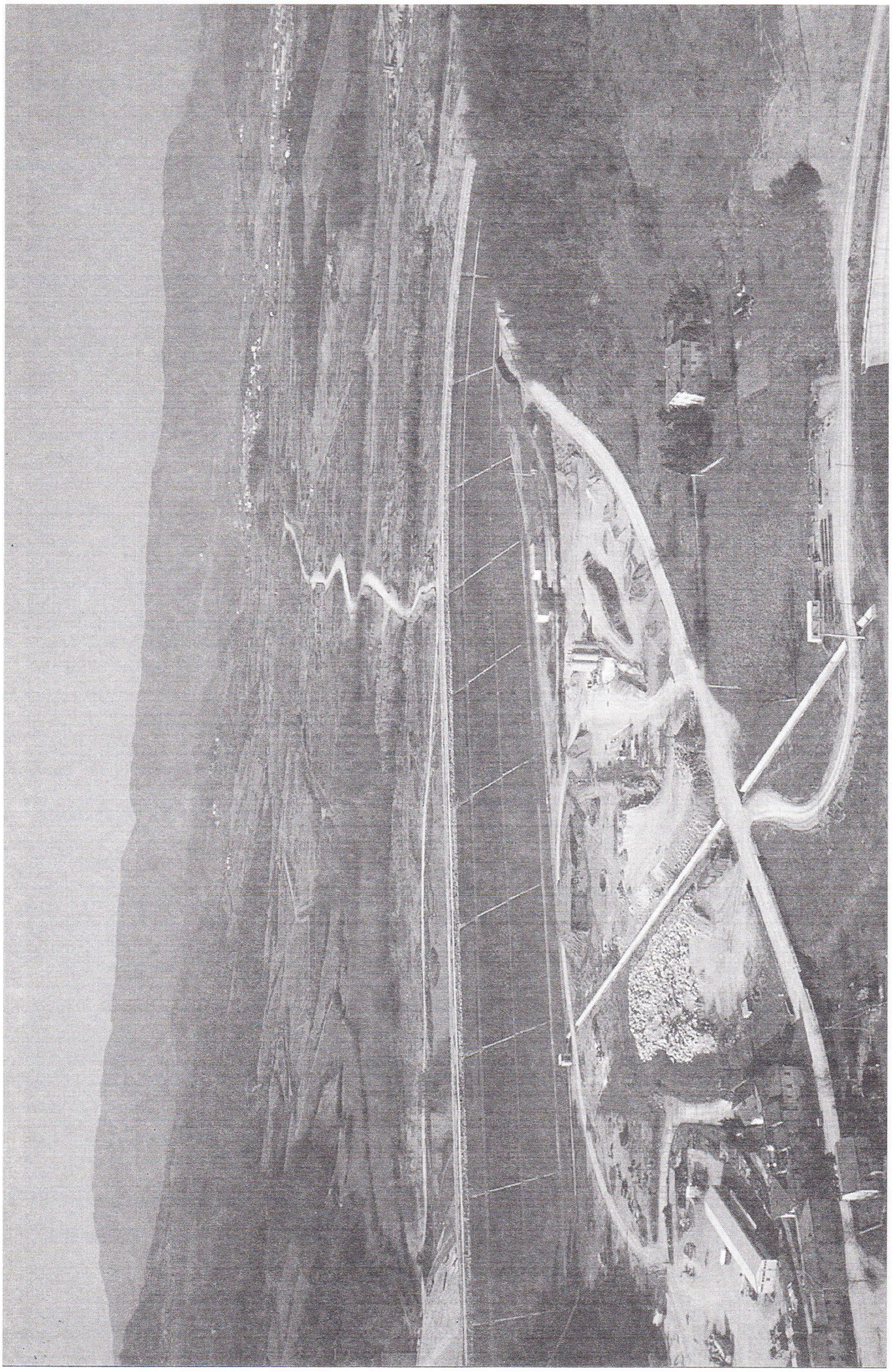
7. WORSENING OF THE RISK OF FLOODS AFTER 1966

In recent decades the social and economic changes have radically changed the level of Italy's development in general and of the Arno Basin in particular.

In general the risk of floods in the Basin after the catastrophic event of 1966 has greatly increased in particular as a result of the anthropic activities that have been carried out over the last 30-40 years and that have often devastated the natural characteristics of most of the territory.

The main reason for the worsening of the risk is undoubtedly represented by the unchecked urbanisation in fluvial areas or in areas at high flood risk both along the River Arno and along its tributaries.

The spillway of Arno river near Pontedera (Pisa)



Reservoir of Bilancino, on Sieve river

8. URBANIZATION FROM 1954 TO 1966

The documents collected show that in 1954 the level of urbanisation corresponded to an "ancient" and longstanding pattern.

Various surveys suggest that 1967 (the year following the very severe flood that involved Florence and many other flat lands of the basin) was the year when urbanisation of the areas at risk began or at least it was the year when the projects for the larger built-up areas were made.

This was undoubtedly the consequence of the issuing of Act n° 765/1967, the so-called "Bridge Act", a major town-planning act that was approved under the emotional drive of the tragic events that had occurred at Agrigento, where an entire section of the town collapsed under the weight of unauthorised buildings.

Paradoxically enough, with the declared aim of relaunching the economy, this Act provided authorisation for one year to build houses anywhere throughout the territory, even without building permits in the municipalities that had not developed effective town-planning instruments.

And indeed as of 1973, as much as 70% of the current built-up areas in the fluvial areas which have not taken into account the characteristics of the territory, had already been built.

Beginning from the late 1970s and early 1980s there was a slowdown in the unchecked and disorderly urban and industrial expansion which had taken place in the areas of greatest flood risk which nevertheless continued to grow.

From a more general standpoint, as happened in other European Countries (refer to the remarks by G. Garry and J. Grassin at the 23rd Conference of the Société Hydrotéchnique de France - September 1994), it can be estimated that 80% of the buildings located in areas subject to floods have been built during the last 40 years and that for a variety of historic, economic and social reasons this urbanisation process has not yet been brought to a stop in these areas.

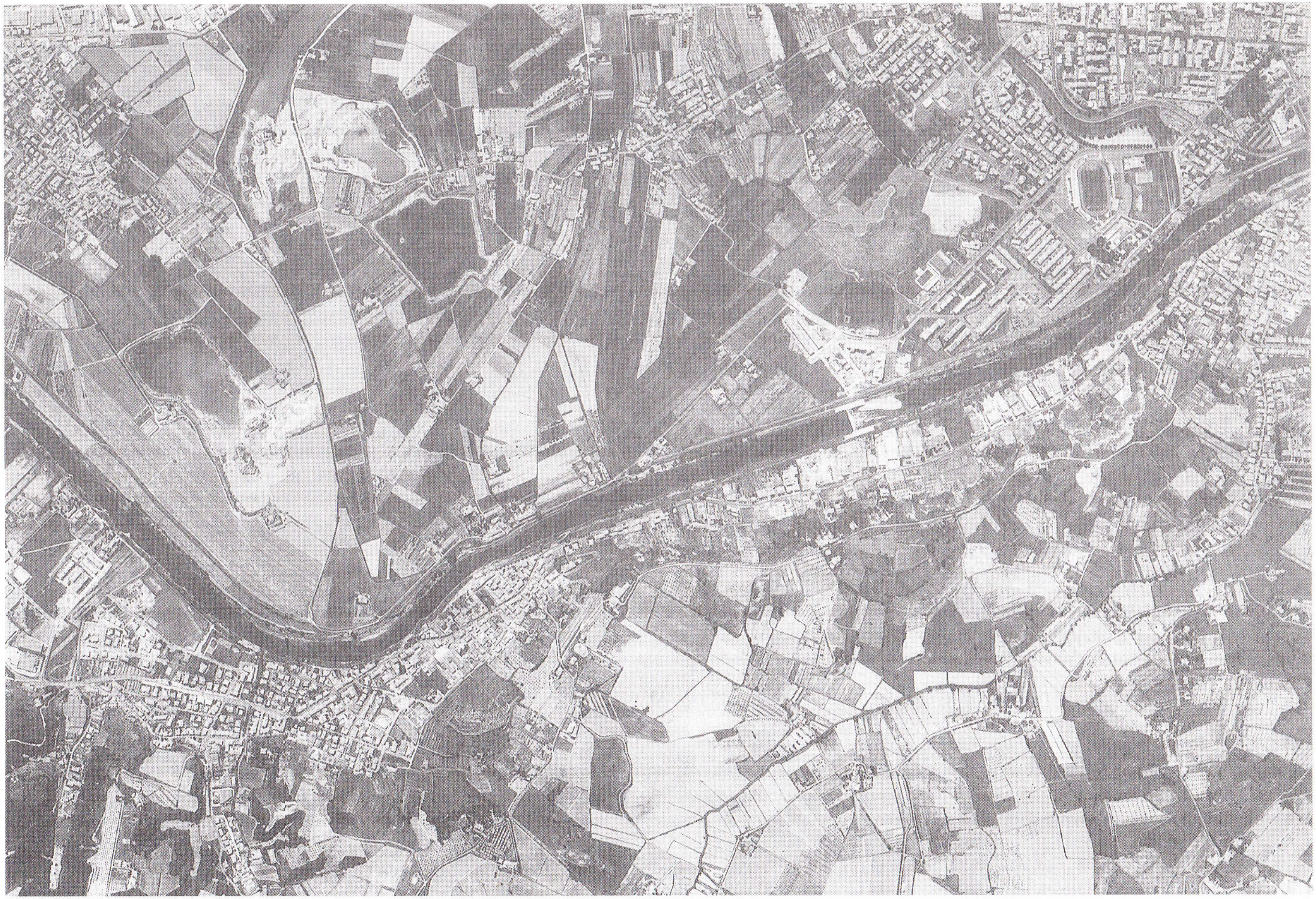
It is a vicious circle which begins with the relatively low cost of the soils and the ease of construction, which then carries with it the need for infrastructure and additional facilities such as shopping centres, schools, restructuring of the town centres which leads to the attraction of more inhabitants who demand a higher level of protection since the whole process has raised the vulnerability and risks in the area.

9. CHANGES IN FARMING PRACTICES, ABANDONMENT OF MOUNTAIN AREAS AND OTHER CONTRIBUTING CAUSES

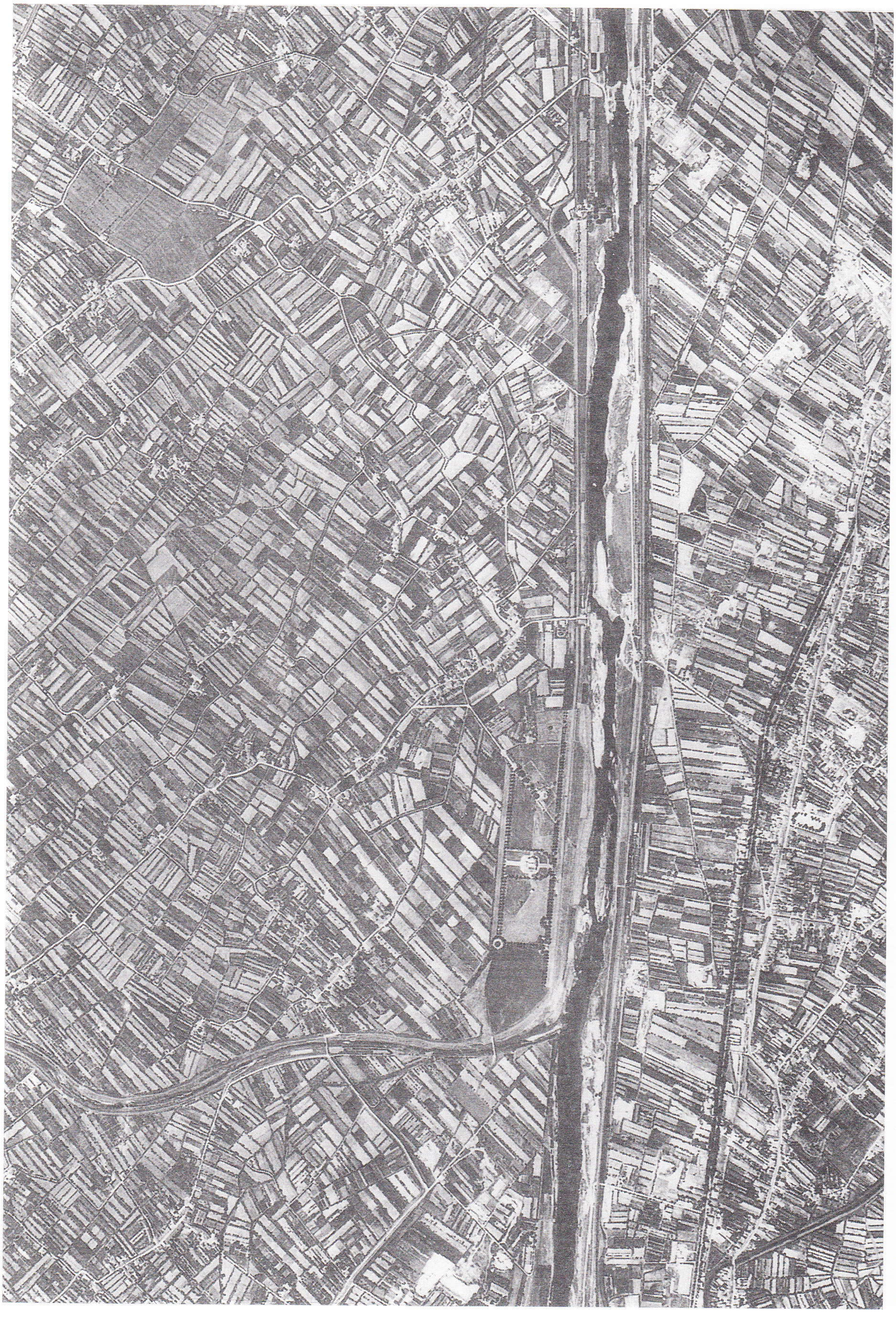
Besides the expansion of settlements in the fluvial areas, other causes which worsen the level of risk are:

1. disappearance of the minor and farming network of canals in the plains that had been built by the Lorena family at the end of the 18th century. From the data that have been collected this network of canals were still effective and in perfect working conditions in 1954; today these canals are unrecoverable;
2. the progressive loss of efficacy of the water and forest development and soil defence measures in the mountain and hilly areas that were the result of organic management interventions in the mountain basins, that had begun in the first half of the 19th century and developed in the early decades of this century. In this sense it is worth recalling that over 2700 dikes and embankments have been counted in the Basin, of which 900 present medium-to-

Land transformation: Arno river near Ugnano, downstream of Florence, in 1993



Land transformation: Arno river near Limite, upstream of Empoli (Florence), in 1993. Visible the old meander



Land transformation: Arno river near Ugnano, downstream of Florence, in 1954

Land transformation: Arno river near Limite, upstream of Empoli (Florence), in 1954. Visible the old meander severe damages and over 700 are partially damaged;

3. waterproofing of vast flat lands (for instance as a result of the establishment of flower and plant nurseries, an activity which has developed massively in the area) which together with the expansion of concrete throughout the territory have negatively affected the water inflow system;
4. uncontrolled development of vegetation in the riverbed with the ensuing large amounts of dry wood and uprooted trunks which in the case of floods are a cause of risk for bridges and engineering works, they reduce the hydraulic section of the river and cause temporary hampering to the discharge of waters;
5. local obstructions in the river bed especially in some tributaries caused by the unauthorised dumping of rubble, worsened in many cases by the foundations of dikes, crossings and bridges with small spans which are an obstacle to the flowing of flooding waters
6. reduced ordinary and special maintenance resulting from the intertwining of competencies, lack of adequate financial resources and loss of operational capacity of the competent authorities.

In conclusion, today, depending on the areas, there is a risk of floods even in the case of cumulated rainfalls of about 110-120 mm per event; this severe situation has come about several times over the last five years both in the Arno and Serchio basins where eleven floods have occurred which, albeit limited with respect to the entire territory and not as severe as events of the 1966 type, have nevertheless caused damages estimated to run at 1400 - 1800 billion Lire.

10. CHANGES IN THE BED OF THE RIVER ARNO OVER THE LAST 40 YEARS

As concerns fluvial dynamics, mention must be made of the changes in the river bed which have occurred over the last 40 years downstream from the ENEL Levane and La Penna dams (AR).

Moving downstream the following can be observed:

the Levane dam - Figline Valdarno stretch: mild erosion which tends to decrease downstream;
the Figline Valdarno - Incisa stretch: average lowering of around 1-1.5 m;
the Incisa - Rignano stretch: lowering greater than 2 m;
the Rignano - Le Sieci stretch: lowering less than 1 m;
the Le Sieci - Florence valley stretch: lowering of the river bed up to 5-8 m with variations that tend to flatten out near Signa;
stretch between Signa and just upstream from Pontedera; average lowering of around 3-4 m;
the Pontedera - Pisa stretch: lowering of around 2 m and less which tends to disappear near Pisa;
last stretch of the Arno; raising of the riverbed which started in 1969 (when the prohibition to remove aggregates from the riverbed was introduced).

Silting up in the end portion of the River Arno are due to the depositing of solid debris transported by the river and to the accumulation of marine sediments pushed in by the waves, in particular at the mouth.

The lowering of the river bed up to Pisa suggests that the volume increase is of around 12 Mm^3 which cannot be immediately translated into reservoir capacity for flood lamination.

The poor contribution in terms of solid debris transported by the river to its mouth as against the sediments pushed in from the sea shore causes a coastal erosion of around 300,000 m^3/year, and accounts for some 6 Mm^3 of mud and solid deposits of the river that make up the 40 year-long silt up of the ENEL reservoirs of Levane and La Penna whose construction was completed in 1958 and 1957 respectively.

11. WATER MANAGEMENT AND ADMINISTRATIVE COMPETENCES

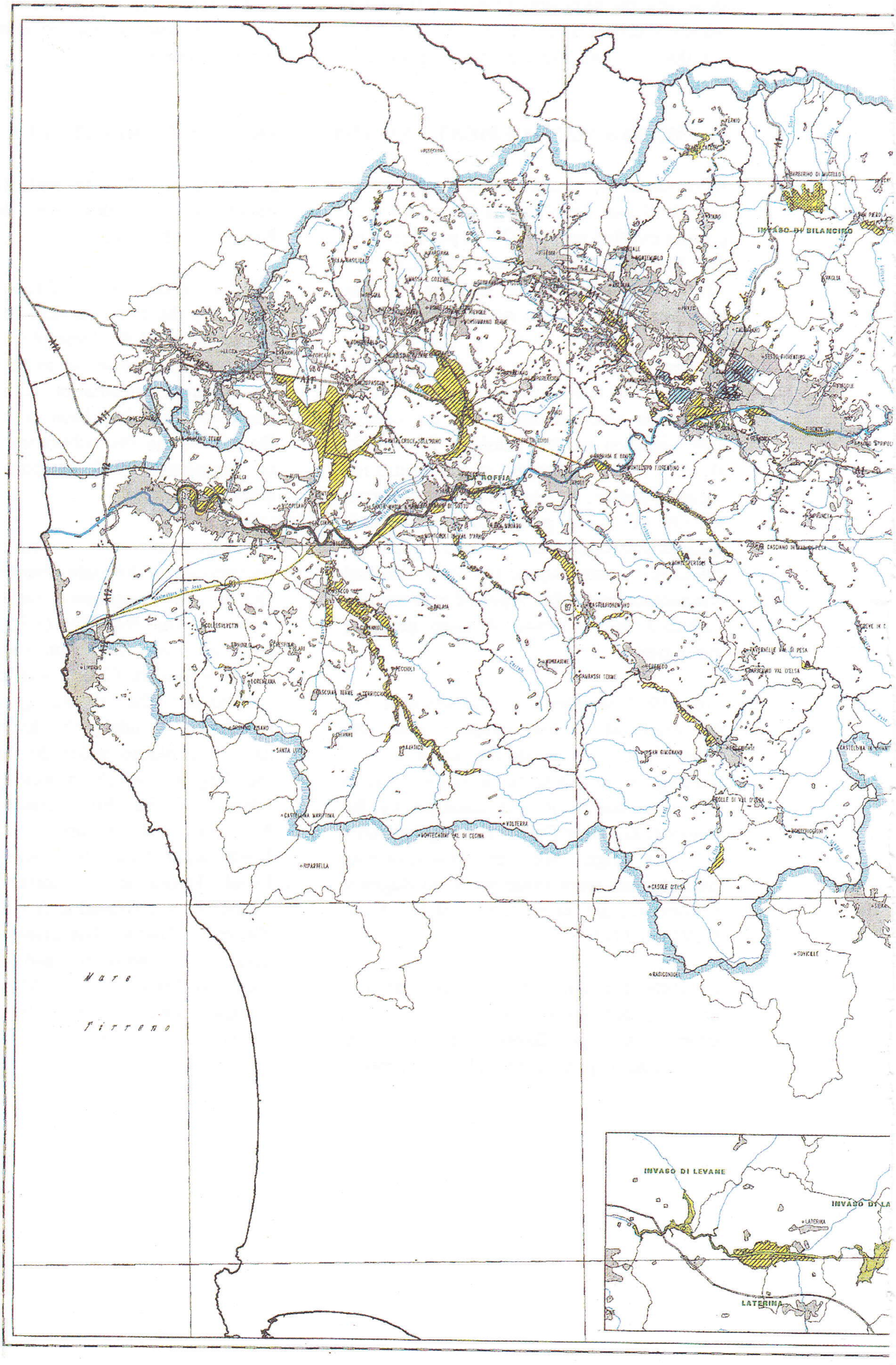
As concerns the administrative competencies over the River Arno and its tributaries it is pointed out that up to 1977, in pursuance of the Consolidated Act of the R.D. n° 523/1904 (and subsequent additions) it was up to the State to carry out interventions on water management works: at first through the local offices of the State Engineering Corps which were based in each Province but which reported directly to the central administration of the Ministry for Public Works; later as a result of administrative decentralisation, through the Provveditorato alle OO.PP. (Local public works authority). Besides exercising its competence on the "classified" water works, the State also had competence over other types of intervention, including the approval of town planning instruments.

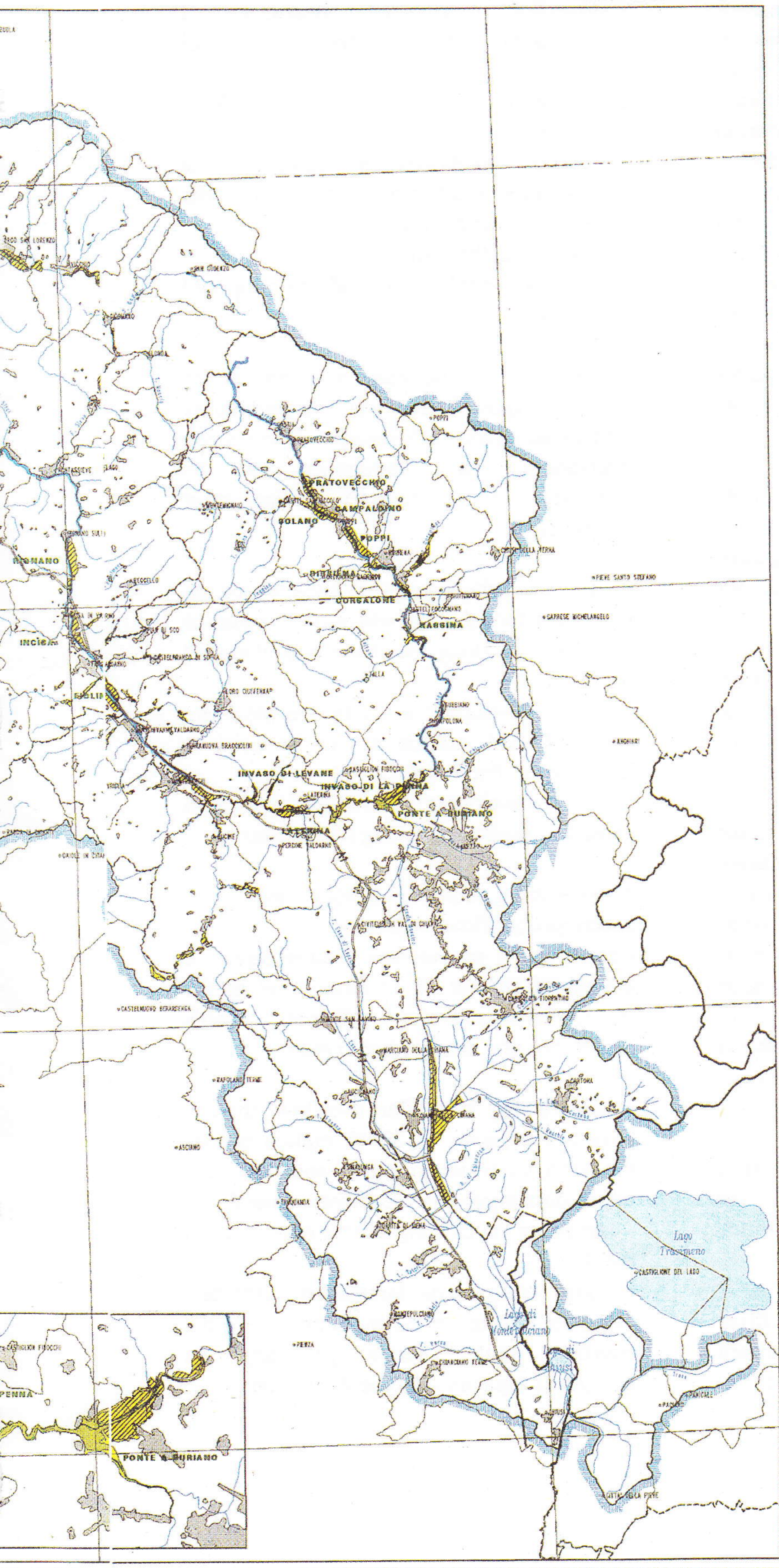
From 1977, together with its tributaries and the whole of its hydrographic basin, the River Arno came under the jurisdiction of the Regions, and in terms of implementation and authorisation it was managed by the Regional Engineer Corps. Funding is mainly of State origin. Also the town-planning competencies were assigned to the Regions, as they still are, in pursuance of D.P.R. n° 8/1972 and 6/1977.

In 1989 the Arno River was classified amongst the eleven basins of national interest and a Basin Authority was established as programming body; hydraulic problems, soil defence and water quality issues instead are dealt with jointly by the Region and the State.

For the implementation of the actions to be taken, for the flood service, etc., as of 1st December 1993 the hydraulic competencies have been reorganised so as to eliminate the pre-existing fragmentation: competence over the River Arno has been taken on by the State, whereas the tributaries come under the competence of the Regions of Tuscany and Umbria.

In particular, as a result of this reorganisation, the State (Provveditorato alle OO.PP.) has competence over the course of the River Arno from Stia (AR) to its mouth, and includes the Pontedera overflow channels, Val di Chiana and the first level tributaries. The remaining network of tributaries including the hydraulic works have been placed under the competence of the Regions which operate through the offices of the Engineering Corps, the Mountain Communities, and the Reclamation Consortia. Now, as the III Level Hydraulic Consortia have been dissolved as envisaged in Act n° 183/89, the Region of Tuscany has classified the whole area as reclamation land and through Regional Act n° 34 of 5 May 1994 it has assigned major hydraulic functions to the Reclamation Consortia.


INVASO DI BILANCINO
ROFFIA
Mare
Tirreno
INVASO DI LEVANE
LATERINA



Autorita' di Bacino
DEL FIUME ARNO

Carta degli interventi proposti per la riduzione del rischio idraulico nel bacino dell'Arno

Scala 1 : 200.000

0 km 4 8 12

Proiezione U.T.M.

P1 Aree golenali e di prima pertinenza fluviale.

Aree residue umide e/o di pertinenza idraulica nella pianura PT - PO - FI

Opere esistenti

Invasi Enel di Levane e La Penna (Ar)

Tratto con ampliamento sezione idraulica (Firenze) (post 1966)

Canale Scolmatore dell'Arno (terminato post 1966)

Canale diversivo dell'Elsa (Castelfiorentino)

Invaso di Bilancino (F. Sieve) (in corso di ultimazione)

Interventi proposti

Aree di espansione e casse di laminazione

Serbatoi di laminazione

Interventi di laminazione con "bocche tarate", etc.

Scolmatore Arno - Padule di Fucecchio

Scolmatore Arno - Padule di Bientina

Diversivo del F. Era

Tratti con adeguamento della sezione idraulica

N.B.: A - Interventi alternativi

Limite amministrativo Bacino Arno

Limiti di Comune

Limiti di Provincia

Limiti di Regione

Reticolo idrografico

Centri e nuclei abitati

12. DEVELOPMENT OF AN EFFECTIVE HYDRAULIC DEFENCE SYSTEM FOR THE ARNO BASIN (BASIN PLAN)

The Basin Authority has developed a draft Plan for the River Arno Basin aimed at containing the hydraulic risk within limits that are possible on the basis of a realistic analysis of the present environmental situation as far as the physical, social, economic and productive aspects are concerned. The aim of the structural interventions is to laminate the floods of the River Arno and of its tributaries (even in rare events of simultaneous flooding of both the main river and its tributaries, which usually occur separately), and to eliminate the critical stretches where the discharge capacity is insufficient.

The draft Plan, adopted on 17 July 1966, was preceded, as said earlier, by the reorganisation of the water management competencies, which are instrumental for maintenance works (Decree of the Ministry of Public Works of 1 December 1993), by the programming and funding of real-time hydrometeorological monitoring (completion of the system built on the Arno by the Region of Tuscany a few years ago which is efficient especially upstream from Florence), by setting building restrictions along the Arno in the stretches at risk and in the areas that are still available to allow the river to overflow. Such restraints have been issued by both the Basin Authority, with Act n° 493/1993 (19 July 1994) and by the Region of Tuscany and they apply to the whole of the territory including the tributaries (Decision of the Regional Government n° 233 of 21 June 1994).

This draft has been drawn up on the basis of a series of studies (listed in the "References"), the most important of which concern:

1. the hydrologic behaviour of the River Arno in the presence of significant meteorological events, the effects of the overflow areas on flood lamination, and hydraulic testing of the river control actions;
2. hydraulic risk along the first level tributaries;
3. current conditions of repair of the hydraulic and forest management works in the mountain areas;
4. rainfall in the basin
5. environmental impact of the proposed actions.

The strategy of the Plan is based on the following types of structural interventions as well as on adequate *hydraulic maintenance* interventions and resumption of the *hydraulic and forestry management measures*.

a) enhancing the lamination capacity of the remaining fluvial areas where overflowing is still possible along the Arno and along its tributaries by:

- developing areas to accommodate some 140-155 million m^3 to be used to laminate the flood wave;
- developing areas to accommodate some 152 million m^3 along the tributaries;

b) developing additional storage capacity to accommodate flood waters by

- constructing an overflow channel having a storage of at least 28-34 million m^3 on the Arno, upstream from Empoli, which discharges into the Fucecchio marsh;

- constructing a similar overflow channel having a capacity of 30-40 million m^3 on the Arno, upstream from Pisa and Pontedera which discharges into the Bientina marsh;
- upgrading the existing overflow channel on the Arno;
- constructing some lamination reservoirs along the tributaries, as an alternative to the overflow tanks, hence providing an additional capacity of some 24 million m^3;

- raising the height of the Levane and la Penna ENEL dams (AR) adjusting the bottom discharge and desilting facilities in the existing reservoir to create a maximum lamination volume of 43 million m^3 (depending on the various intervention proposals);

c) upgrading the capacity of the river bed by:

- building appropriate embankments in the critical stretches, lowering the high water beds, widening the hydraulic section of the river where needed, envisaging for instance, the creation of underground caverns that can be flooded near historic towns where there is still some residual risk of inundation, etc.

Such interventions meet the twofold need of optimising the present possibilities of reducing the risk of inundation by using urban-free areas for flood lamination, and protecting the urban areas that are now at risk of inundation.

Out of a total of over 9,000 Km^2, which is the area covered by the Arno basin as reported in Act n° 183/1989, the surface area that has been inundated during the flood events that have occurred since 1966 totals around 1200 km^2.

The possibility of controlling the floods over a territory at risk of some 200 km^2, will protect the remaining 1000 km^2 of flat land. The floods which have been occurring in the former area have also been due to the lack of a co-ordinated strategic plan.

The overall effect of risk reduction will in any case be dependent on the size of the lamination interventions that will be adopted.

The ultimate goal will be pursued in a stepwise manner through structured interventions to be carried out in three phases over a total fifteen-year time frame: each phase envisages its own objective in terms of floods containment, namely controlling the more significant events which have occurred during the last few years (1966-1992).

Emergency and civil protection plans will also be set up, carried out and updated during the period of implementation of the Plan.

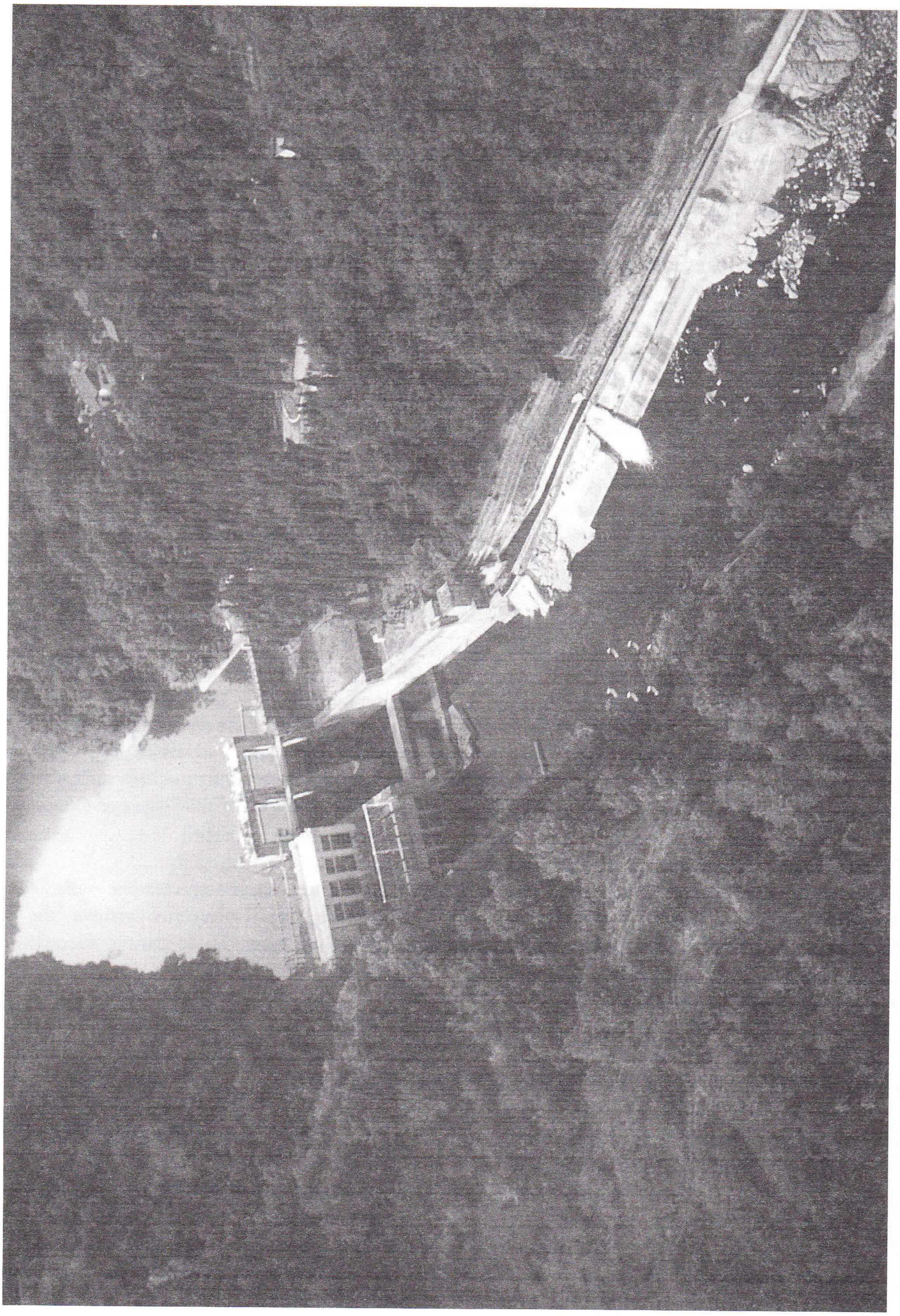
In order to ensure full efficacy, the structural interventions will be accompanied by initiatives aimed at rationalising the political, administrative and management system with regard to:

adopting adequate management criteria;
streamlining procedures and simplification of the regulatory system;
enhancing and co-ordinating the operational structures (Provveditorati OO.PP., Offices of the Engineer Corps, Reclamation Consortia).

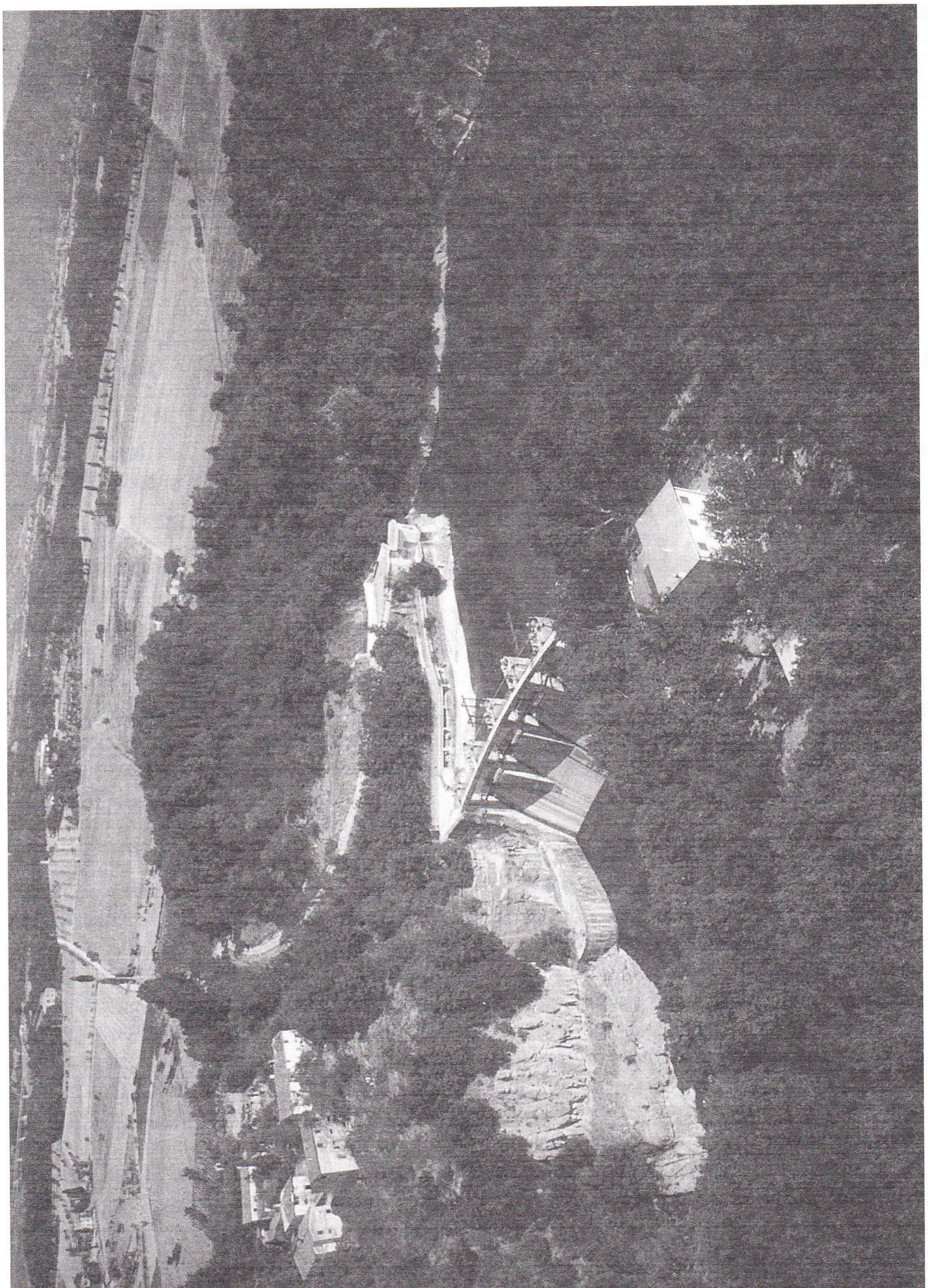
Besides the structural interventions and the emergency and civil protection actions, the Plan envisages also the following specific instruments:

13. POLITICAL AND ADMINISTRATIVE REGULATIONS

1. reorganisation of the water management competencies, already implemented by the D.M. of 1st December 1993 but further improvements are required;
2. upgrading the existing protection measures so that they are in line with the actions envisaged in the Plan, with special protection of the areas that are still available for future water control measures;
3. regulations at the municipal level of the areas at risk;
4. insurance policies and solidarity fund for adequate compensation in case of catastrophe.



Levane Dam (Arezzo)



La Penna Dam (Arezzo)

14. MANAGEMENT CRITERIA

1. criteria for building the overflow tanks and lamination facilities; degraded areas are to be selected and excavation works and landscaping measures are to be envisaged;
2. criteria for ordinary and special maintenance; actions are to be taken to rebalance the situation between erosion areas and those where sediments and debris have accumulated;
3. criteria for maintaining river bed and riparian vegetation;
4. criteria and plans for ensuring protection in the most critical stretches.

15. ORGANISATION AND MANAGEMENT OF THE MONITORING AND CONTROL SYSTEMS

The systems currently available which offer real time data transmission (systems for hydropluviometric, hydrometeorological and environmental recordings; weather radars, etc.) are a great many but they are managed by different bodies that do not communicate with one another. By integrating them it will be possible, in the short run, to produce an expert warning and flood prediction system that will assist the civil protection bodies in their decision-making process in the case of risk and they can also be a source of information for the citizens.

In particular, as concerns the protection measures relative to the building restrictions in the areas at risk of floods and/or to be used for discharge purposes, the draft Plan confirms the areas identified in Decision n° 46 of 19 July 1994 (and subsequent modifications and supplements) of the Institutional Committee, recalled previously; they will be maintained until approval of the Basin Plan.

With the adoption of the Plan it is envisaged that the state, regional and territorial bodies are to inform the Basin Authority of the public works they will be carrying out and of the building permits issued or envisaged within the area (about 200 Km^2) where water control measures are to be carried out.

Upon approval, the Plan will decide whether the building restraint is to be extended to a broader area (around 400 km^2, the so-called "extended protection") to be protected not only from the risk of floods but more in general for hydrogeological purposes, so as to ensure the recharging and protection of the ground water in the plains, the stagnation of waters and capacity to keep such waters around the water courses during very heavy rainfall.

After having examined the observations that have been received, the Plan will decide which of the alternative actions will be adopted as variations to the draft Plan itself (see Appendix), and in particular decisions will be taken as to how the Levane and La Penna ENEL reservoirs are to be used to laminate the Arno floods depending on the intervention proposal that will be selected.

The implementation of the structural and non-structural interventions to reduce the flood risk which according to the Plan are to be carried out over a fifteen-year period will require an overall cost of some 3000-3500 billion Lire.

THE BASIC PLAN OF ARNO'S RIVER IN THE CONTEST OF TERRITORIAL AND ENVIRONMENTAL PLANNING

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ABSTRACT

The territorial planning has to meet the necessity of safety measures for the areas with an high risk level along the watercourses of Tuscany.

The law n. 183/89 and the launch of Arno's basic plan are the occasion that can harmonize development and environmental preservation needs.

The Arno river is typical of extremely variable discharges so that in the urban Florentine fluvial course the flow changes from 3-4 mc/sec in the summer season to 1500-2000 mc/sec in the autumnal season until to reach 4000 mc/sec and over in occasion to disastrous events.

In the drainage basin of Arno river, nearly 8000 km^2, there are 20 large dams and about 800 small ones.

The point of division between "large" and "small" ones consists according to the Italian regulation, in an height of fifteen metres and a storage capacity of 1 hm^3

After the flood in 1966 a Commission was established to find the best solution for defence from extraordinary flood events.

The plan proposed by the Commission foresees the realisation of 23 dams on the main river course and on affluents, 17 of them upstream of Florence.

The plan considered also the possibility to realize a diversion canal of Arno river upstream the city, with flow discharge in Ema torrent an affluent of Greve river which in due course discharge again in Arno river downstream of Florence. This hypothesis was discarded because the river's contiguous areas was already remarkably built.

Such a plan was adapted afterwards to demands of multiple type, considering drinking water or irrigation necessities.

The works foreseen by the above mentioned plan and already realized are the lowering of Ponte Vecchio and Ponte a Santa Trinita' floor in Florence city, the completion of the diversion in Pontedera and the building of Bilancino dam on Sieve river.

Environmental Problems make the Regional Administration believing that the realization of dams is not the only way to solve the problem of hydraulic risk of Florence city, and of the rest of Tuscany territory. The regional administration is sensible, in particularly, to the problems of interception of solid transport because the Tuscany coasts are in erosion with a deficit value near 400.000-600.000 mc of materials. This deficit is not only caused by dam's interception, but also to uncontrolled excavations.

The two dams, on Arno river, Levane and La Penna, are actually dedicated to electric energy production.

The Regional Administration consider that energetic production should be subordinate to the hydraulic security management, that is one of the criteria and objectives established by law n. 36/1994, in the matter of water resources when refers to "liveability environment" and to "expectation of future generations to avail itself of a patrimonial environmental" as its aim.

To dedicate these two dams prevalently to hydraulic security is absolutely necessary an adaptation of bottom outlets, to made dams more transparent so that they can floods, in such a pass the medium way as to utilize completely the storage capacity to flood control and a removal of sedimentation that was deposited during years of exercise to recover total capacity.

As regards sedimentation removal if it is realized with mechanic aid of eddying is necessary to ascertain with precision the problems that could be transferred on the river, and the restitution formalities which could not be very different from flood events. Obviously, whichever would be the removal method, it will be necessary to verify again the researches already made on the qualitative characteristics of such sediments.

It is moreover indispensable to provide along all Arno river main course and on principal affluents, many areas of possible river expansion and of storage capacity for flood control. They should have in their totality the maximum possible storage capacity to compensate for the missed dams construction.

Our Region has foreseen specific areas, with legal obligation, or encumbrances, adjacent to the rivers more exposed to risk, imposing, according to cases, one or two risk classes.

On the most critical affluents, and where orographic and anthropic conditions will permit, it would be suitable to build check dams with calibrated outlets to control the major floods.

Moreover we need to programme again a careful use of soil in the hill and mountain zone that should keep in account hydraulic-forestal and agrarian landscaping.

Finally we shall develop and try some non structural interventions. As Regional Administration we have prepared a riskiness map on flooding, map which is basic to ascertain the most critical situations with the aim to optimize the territorial programming and to predispose safety plans.

We shall develop, then, flood alert systems. We can not limit ourselves only to the monitoring of actual events but we need also to try our best in the forecast of hydro meteorological events, due the peculiarity of our rivers and torrents.

Besides meteorological and flood forecast remain anyhow not at all determined the programming aspect and above all emergency co-ordination.

In fact it is essential to arrange some certain and standardized procedures that shall permit to all responsible subjects of flood management to become acquainted with what all other subjects have executed till that moment and of some possible operation choices that could be offered to them.

THE HYDROLOGY OF THE ARNO RIVER FLOODS

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Professore di Costruzioni Idrauliche, Università, Firenze

ABSTRACT

Considering the problems correlated with River Arno flooding, and particularly in City of Florence, the historical and geographical characteristics are described. Then, considering the actual state of the Art in the defense means as well as the works undertaken by the Italian and the Tuscany Region governments, the needs for a civil protection city plan and an alarm system are emphasized.
The possible systems for real-time flood forecast are introduced in terms of meteorological and hydrological monitoring networks and the corresponding structure for alarming and defending on the flooding is draw down.

1. INTRODUCTION.

Nobody can forget the terrible flooding of Florence on November the 4th, 1966. A big scare has been traced on the face of our history and culture and the whole Word promptly came to help Florence to reestablish herself and hers monuments.
During a meeting called at the end of September 1985 to discuss the drought problem in Florence, the Civil Protection Minister, Giuseppe Zamberletti, ascertained that the prevention and mitigation natural measures for the city of Florence in the case of flood was still incomplete and charged the Prefetto of Florence, Giovanni Mannoni, with the responsibility of establishing a civil protection plan relative to the possible flooding of the Arno or its tributaries, with particular attention to the city of Florence.
The problem of the flooding of any urban center, and even more in the case of a city like Florence with great historical and cultural importance, cannot be handled with only the traditional technical means but requires the extension of factors to be evaluated to include social and cultural spheres.

Man tends to lack the valid working memory in the face of flood phenomenon which would allow him to make intelligent choices; it pursues, therefore, a great degree of room for irrational thinking when faced with a pending crisis. History shows however that by studying past phenomenon a flood behavior pattern appears in which floods are shown to be completely natural moments in a chain of events; in the same way changes in the face of the earth are considered normal by scientists working in geological sciences.
Experience shows that two types of measures can be taken to mitigate the effects of these sudden "calamities": structural measures with the purpose of in some way containing or limiting the impact of the phenomenon, and non-structural measures designed to limit to a minimum the damages caused by the flood, such as laws, emergency plans, information and organization networks, etc.. The water sciences play an important role in both of these phases by studying and planning the physical structures which can alter the course of the phenomenon and by offering dynamic reconstruction models of flood behavior to be used in developing realistic approach to the problem.
The Mediterranean area of the European Common Market countries, most specifically, and some of the Atlantic regions as well, show a particularly rapid response to intense precipitation. The time factor involved, from the beginning of the flooding to peak discharge, ranges from 1-2 hours to 12-24 hours for major streams.
For hydrologic events with a return period of approximately 100 years, that is to say with the yearly odds of flooding 1 to 100, most of the streams and Mediterranean rivers produce periodically unexpected flooding in the low sloping terminal branches or in the intermediate plains, historically covered by swamps and marshes, and now inhabited.
In such areas, which have been the site of the most productive human activities and the most intense settlement during the past centuries, every flood produces widespread material damages and victims. The great number of waterways included in this category creates a condition in which during any rainy season, while the probability of flooding remains relatively low if considered individually, the total number of floods in the common market countries as a whole ranges in the hundreds.

The structural control measures undertaken by every country in the community must be considered only as long term projects involving several generations and cannot potentially eliminate flood risk completely.

It has therefore been necessary on the short term basis to develop non-structural prevention and mitigation programs which have a variety of names according to the country involved:

- Plan exposition risques inondation, Delegation aux Risques Majeur, FRANCE;
- Flood Emergency Plans, Federal Emergency Management Agency, U.S.A.;
- Piani di bacino, Dipartimento di Protezione Civile, ITALY.

They all require an adequate warning system in order to carry out their own civil protection function.

Forecasting, warning and emergency preparedness measures are integral parts of a well-balanced flood-plain management system. Adequate warning allows time for the preparation of temporary flood-proofing closures and the evacuation of people and building contents from hazardous locations. This is, in part, a technical issue of concern to meteorologists and hydrologists and, in part, an administrative issue requiring a system or emergency planning, organization, communication, and public education. An event such as the flooding of the Arno river cannot be considered as limited to the city of Florence, even if the possible flooding of Florence is an event which draws particular national and international public interest. It is necessary, therefore, to take into consideration in this prevention and mitigation plan also other river front communities as well as those positioned along the various tributaries which show more frequent danger of overflows than the main river itself.

Flood-proofing is applicable to historic buildings, to essential facilities that are not suitable for alternative locations, and to areas in which the capital investment in the existing urban infrastructure requires continued occupation of a hazardous location. This strategy is especially suitable where moderate flooding with low stage, low velocity and short duration is experienced.

Special measures have been planned for the preservation of the cultural heritage of Florence; in particular, the many art works in Florence have been given special consideration. An emergency plan for painting and statues in danger has been drown down by the Prefetto and the Supervisor for the protection of the arts and historical monuments.

The plan for the restructuring of the data-sensing and measurement system in the Arno River basin, with transmitting raingauges and radar is an example of the integration of several different organizations (the aforementioned Group, the Tuscany Regional Government, the Prefettura of Florence and the Department for Civil Protection) each having the specific responsibility, in order to achieve availed hazard management program.

The Arno project is now starting to present the work lines prepared to reach the maximum possible reliability in such kind of hydrologic forecasting. To this extent new technologies are required to prepare an experimental apparatus able to link the efforts of Italian Public Administrators, Researchers and Industry in order to achieve a higher security level for Florence.

2. THE ARNO RIVER FLOODING PROBLEM

2.1. The Geography.

The geography of the river Arno valley can be described by the drawn of Fig. 1 in which the structure results as a cluster of ancient lakes, now quite totally filled up of sediments, connected by gorges. Owing to the relative interdependence of this morphology, at present the upper "lakes" are in erosional phase while the lower ones has been stopped in their filling by the land reclamation techniques and training works started in 1500. The basin area is bounded by the Apennine Mountains range that describes an arc from North to East having average elevation of 1000 m above the sea with maxim of about 2000 m, south wise the water divide consists in the Chianti Hills formation which picks never trespass 900 m of elevation. The interference between the basin catchment exposure and the local climatic tendencies produces the highest flooding risk in the period from September to January in which the south-west winds dominate.

The particular geological and geomorphologic aspects of flooding in Florence have been analyzed in the studies by: Lo Sacco [1962], concerning the morphological situation of the plain, Conedera and Ercoli [1973], for the photointerpretation of past waterways configuration, Piccardi [1956] analyzing the evaluation of the river bed, and Capecchi and al. [1976] concerning analysis of underground and hydro-geological aspects. When analyzing the combined evidence resulting from the various studies, it becomes evident that the geomorphologic condition of the Arno basin has, in recent geological periods, been subject to a high degree of evolution with the formation of lacustrine depression subsequently filled with sediments carried by surface water. In the

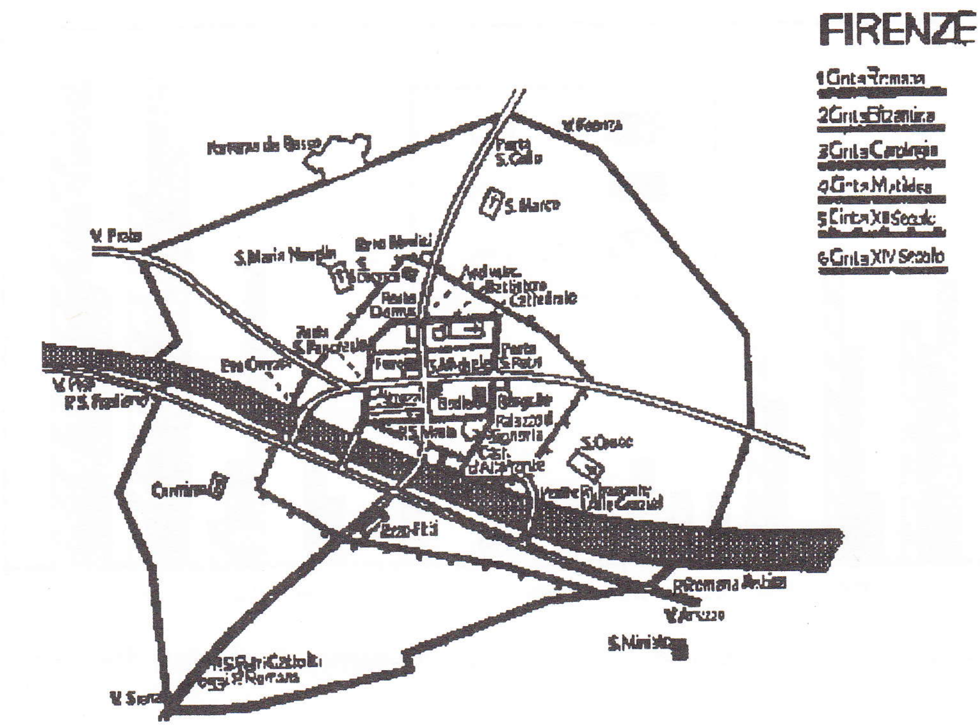

Fig. 1 - The evolution of Florence city walls from the roman age.

past, part of the plane on which Florence is situated, was covered by the remnants of a former lake living the swamp known as "le padule". Only at the end of the 1800's with the completion of the land reclamation project (Sesto Fiorentino, Prato, Pistoia) did the entire plane assume its current aspect. In fact, the agricultural plane has a history of only about eighty years in the current configuration. In the Arno basin, as the flooding damages were becoming serious, as the problem of flood forecast has been developed. In ancient times observations have increasingly been made that are reported in chronicles and regional history. The river stage recording started in 1861, but only since 1921 we find complete data reports. The hydrological characteristics of River Arno catchment area are described in the reports from Ministry of Public Works Hydrological Service.

2.2 The History.

First the famous hydraulic works that in late Roman Empire moved the Chiana stream from south-sloping to north-sloping disconnecting it from the Tiber R. while connecting to the Arno as a new tributary. It seems this intervention produced some serious disadvantage for the city of Florence, but in lack of data we can only deduce that the catchment area has been increased of about 700 km^2. The first historical record of city flooding arises in 1173. In the Table II the classification of historical floods by damages is made, as reported by Morozzi[1761]

In Renaissance times, due to the development of the City and the strong modification in land use, the increase of flooding frequency produced a lot of scientific observations by physicists and architects, and various hypotheses have been developed regarding river upgrade, debris transport and land use effects on flood frequency. Until 16th century the basin land use was mainly pastureland, with a small percentage of agriculture only for local needs. In this age the river bed was wide, according to drawings by Leonardo, and only few training works seem to be applied to like small dikes and levees that arise from ancient Roman colonization.
The development of industrial activities at the first Medici period, and the strong effort in agriculture starting then with Cosimo the 1st, have produces a continuous fight with the River by closing it in even narrow bed. We can thus say that the present river bed is only about one tenth in width of the original one. This big change in river training may explain the increase in flooding frequency starting at the beginning of 16th century. However, as far as the geometry is concerned, it does not appear that the overall layout of the river bed has changed much since the seventeenth century, perhaps with the exception of some widened bridge spans during the various reconstruction. It seems that the total water discharge capacity has remained substantially

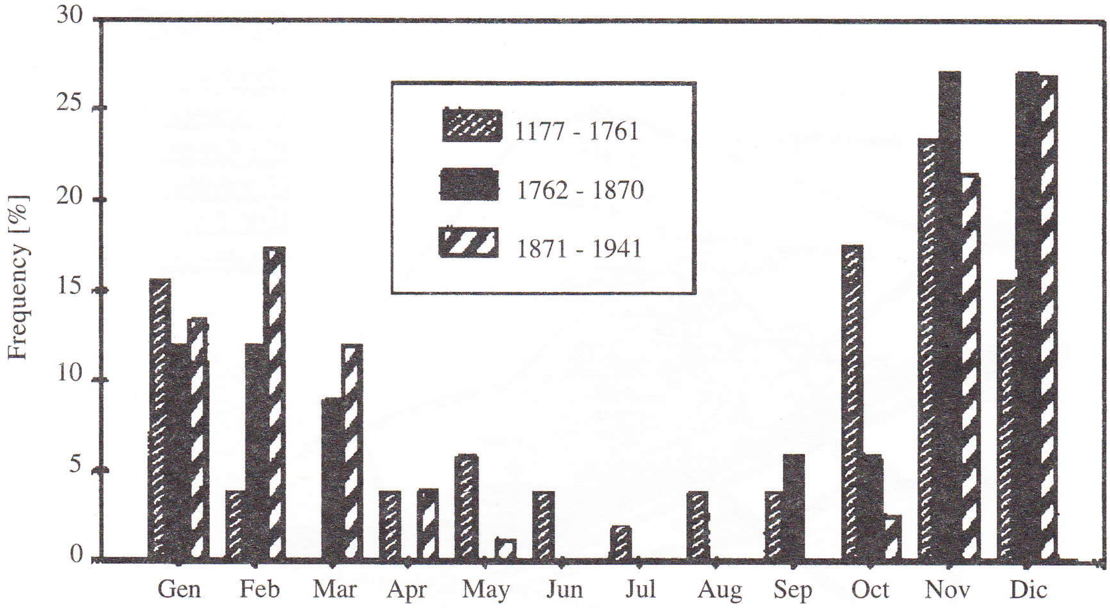

Fig. 2 - Seasonal evolution of Arno R. floods frequency in the last 500 years.

unchanged since the seventeenth century. A slight reduction in the section involved in the completion of the riverbank reinforcement walls may have occurred in the 1700's, but that is of minimal importance when compared to the regularization created by the wall.

The quantity of information available allows for a variety of reconstruction's and interpretations. Many

TABLE I
(Flood damages in Florence form 1177 to 1761)

from Morozzi [1761]

DATE	DAMAGE	DATE	DAMAGE
04-11-1177	XXXX	15-11-1544	XXXX
13-08-1547	XXXXXX		
??-10-1261	XX	08-11-1550	XX
01-10-1269	XXXX	13-09-1557	XXXXXX
15-12-1282	XXXX	31-10-1589	XXXXXX
02-04-1284	XXXX		
05-12-1288	XXXX	??-01-1621	XX
09-11-1641	XX		
??-??-1303	XX	06-11-1646	XXXX
??-01-1305	XX	??-01-1651	XX
01-11-1333	XXXXXX	04-11-1660	XX
05-12-1334	XXXX	11-05-1674	XX
06-11-1345	XXXX	11-10-1676	XXXX
??-11-1362	XX	19-02-1677	XXXX
01-11-1368	XX	18-05-1680	XXXX
21-07-1378	XX	20-04-1683	XX
20-10-1380	XXXX	26-01-1687	XXXX
08-12-1688	XXXX		
??-05-1406	XX	02-06-1695	XX
??-12-1434	XX	??-01-1698	XX
18-10-1456	XXXX		
16-01-1465	XXXX	11-10-1705	XXXX
19-01-1490	XX	28-02-1709	XXXX
10-06-1491	XX	22-10-1714	XXXX
06-09-1715	XX		
08-01-1515	XXXX	??-11-1719	XXXX
28-08-1520	XX	03-12-1740	XXXXXX
15-12-1532	XXXX	19-10-1745	XX
??-??-1538	XX	01-12-1758	XXXXXX
06-11-1543	XXXX	15-11-1761	XX

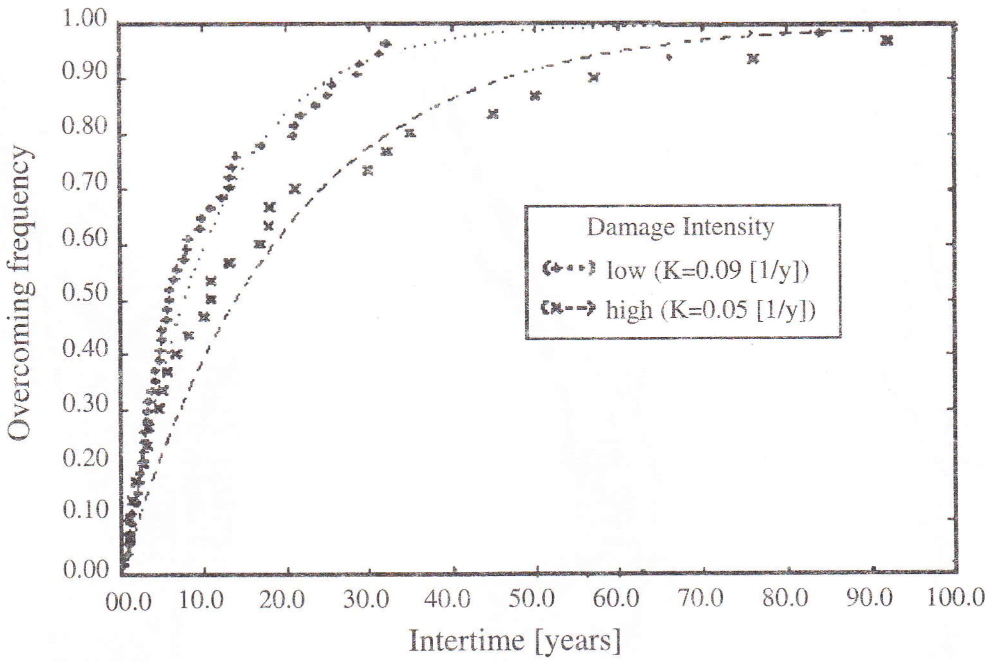

Fig. 3 - Overcoming frequency for floods occurence classed by damage intensity according with Morozzi for the period 1173-1761.

of these in the past were concerned especially with comparison of different flow stages in most important floods (1226, 1333, 1557, 1844, 1966). However, when considering that: 1) the available information is often fragmentary, 2) changes in the urban complex can greatly influence the absorption capacity of settled areas; then such a comparison often distort the overall view while giving too much importance to detail

Another useful tool in determining flood probability can be based on the study of statistical information, once each flood is considered as an independent event statistically distributed according to the classic Poisson distribution. A data base for statistical analysis is provided by the invaluable work by Morozzi [1761], in which each flood between 1173 and 1761 is carefully recorded and divided in to three magnitude levels on the basis of damage caused (see Fig. 2). The reconstruction of the statistical series can be made using return period analysis criteria, which in the case of Poissonian analysis must be distributed according to exponential law. If we study the high flooding water flows of the Arno river in Florence from 1872 to 1941 (Natoni data) we find in fact that the actual return periods are distributed quite closely along the aforementioned law. This is shown in Fig. 3, where the curves of cumulated frequency of return periods for high water stages of 4.50 to 5.00 [m] are reported, which were obtained by the former warning stage at the Acciaioli gauging station now out of service. When the Morozzi reports are subdivided into two periods, 1173-1500 the first and 1500-1761 the second, we see that the first period follows the Poisson distribution quite closely whereas the second period does not .

A very summary analysis of the history of Florence shows that the period of frequent high water stages corresponds to the period of agricultural development, started under the Repubblica Fiorentina and continued under the government of the Medici. The radical influence this period had on the evolution of the river is demonstrated by the following maps in Fig. 5, where the state of the Arno river in the branch immediately downstream of the town are shown at times of Leonardo (1500), of Viviani (~1670) and beginning of this century. In the work of Natoni all ancient and modern data are collected up to the 1941: when adding modern information, only up to 1972 published, it results:

- that the river flooding threshold in Morozzi historical report can be estimated around 2000 m^3/s in Florence and 2500 in Pisa, close to the mouth;
- that the actual river status produces a correlation lag between rainfalls and discharge of 5.5 hours in Florence and about 11 in Pisa;
- that the average absorption for a given rainfall can reach up to a maximum of 200 mm, but expected values are lower reaching 80 mm in the case of wetted basin.

Leonardo 1500 Viviani 1700 I.G.M.I. 1900

Fig. 4 - Three images of the Arno River downstream of Florence: in Leonardo's time (1500), in Viviani's time (1700) and at the beginning of this century.

2.3 The present state.

Today, on the basis of the studies and terrible experience of the remote and recent past, the current state of the Arno river is well defined.
The studies carried by the Governmental Commission 'De Marchi - Supino' [1968] suggested to increase the river storage capacity by means of 25 reservoirs (18 upstream) of Florence having 226 Mm^3 of total storage capacity, but only few of these being on the main river course. The others lye over the tributaries system, due to both the difficulties in finding proper space in the morphology described above and the constraints of historical and econom-

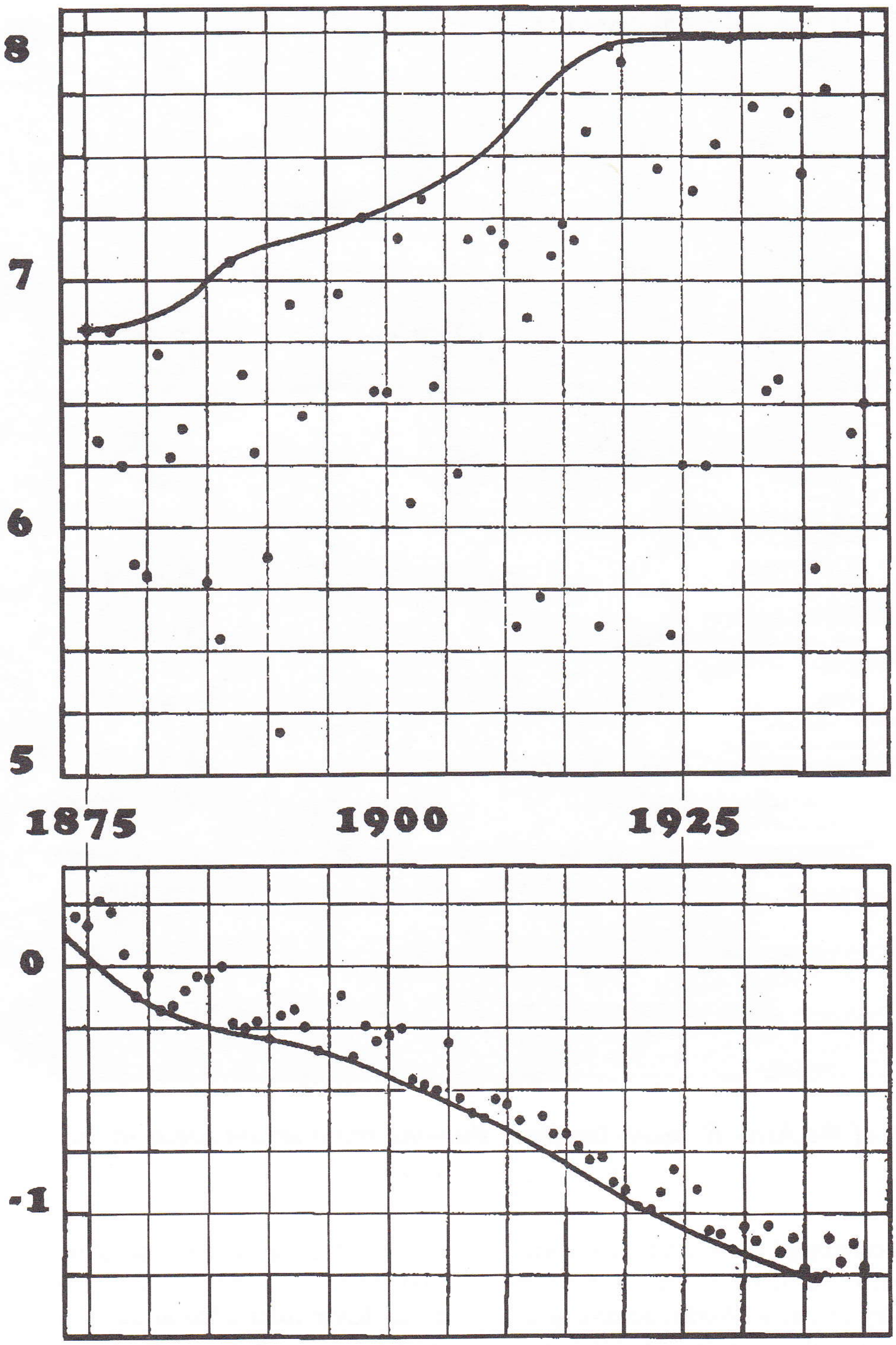

Fig. 5 - Evolution of annual maxima and minima at theArno R. stage recorder in Sostegno at Pisa for the period 1874-1941 (from Natoni 1943).

ical resources. In response to the proposal of the De Marchi plan, the Tuscany Regional Government commissioned the Arno Pilot Plan to Studio Lotti [1976], aiming at a global regulation of the runoff while increasing the basin water retention and thereby limiting high water risks. The Pilot Plan by Lotti [1976], while considering such limitations, proposed 11 multipurpose reservoirs, 4 of them upstream of Florence, with 97.5 Mm^3 for flood damping.

The work projects called for in the Arno Pilot Plane have gotten underway only recently and they are so far limited to the construction of the Bilancino reservoir (Upper Sieve). It is not easy to predict

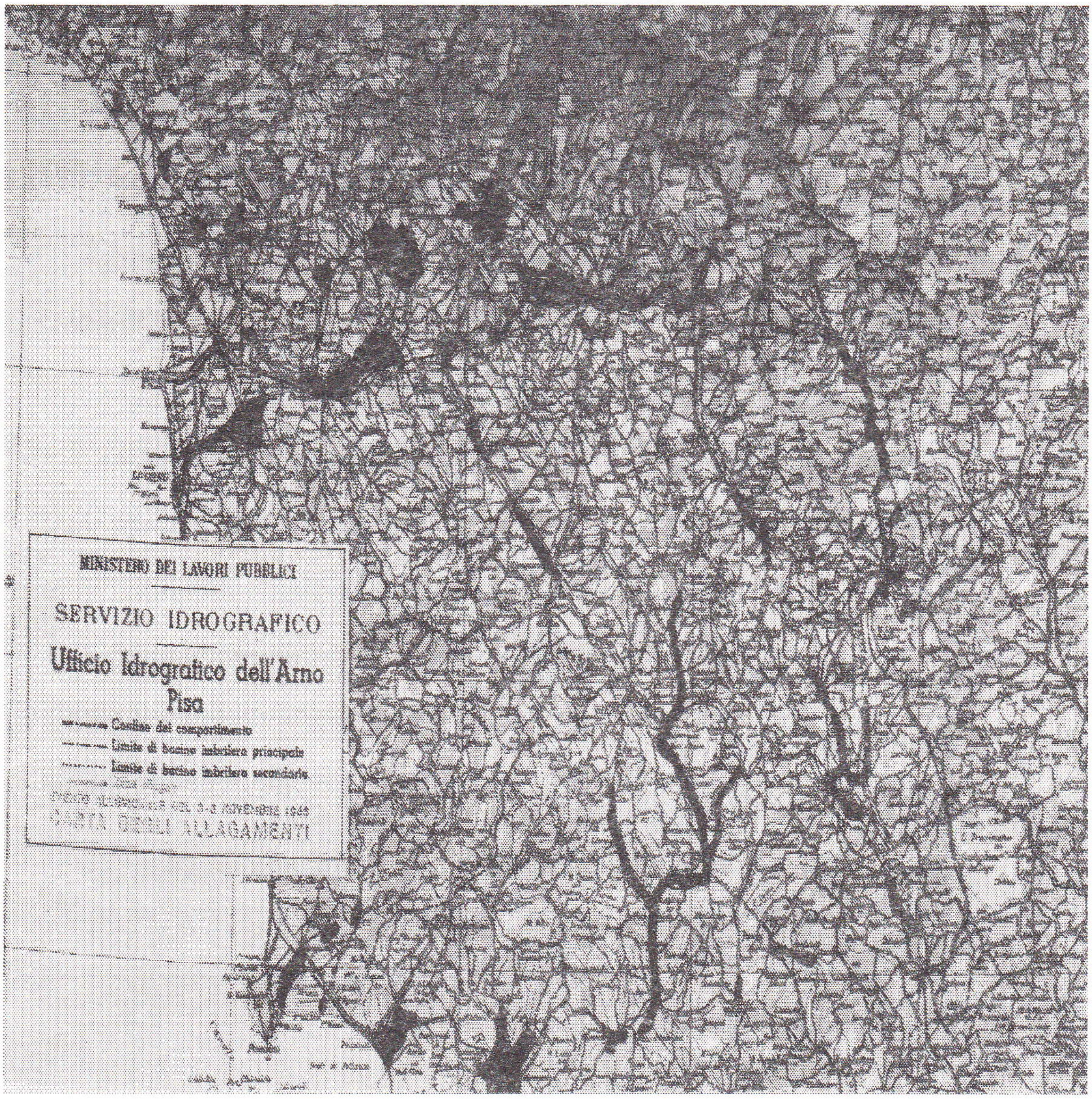

Fig. 6 - Map of the Arno R. basin territory showing the inunded areas in the 1966 flood (from Bendini [1967]).

when they will be completed and when the river will have storage capacity sufficient to take in highest peaks. The Ministry of Public Works, according to the results of the physical model studied at Bologna University by Cocchi, provided for one meter lowering the bridge threshold of Pontevecchio and Ponte a Santa Trinita, as reported by Canfarini [1979]. It is not possible to evaluate with any precision the statistical risk factor of floods with a danger level similar to the 1966 one. At present only the Bilancino Reservoir in the upper Sieve tributary valley is under construction: once completed it will present a volume of 17 Mm^3 for flood mitigation over 150 km^2 of catchment area.

While the structural defense is under preparation, only two improvements in flood defense have been completed: 1) the lowering of the ancient Florence bridges edge that, on the basis of hydraulic physical modelling, it should increase the discharge capacity of the River from 2700 to 3400 m^3/s; 2) the Arno bypass able to divert up to 900 m^3/s upstream of Pisa. From the available data one would predict an average flood return of 120 years, which could be extended to 150 when considering the work done on the bridges thresholds: this, 120 years later, would finally satisfy Giorgini's desires [1851].The expected return period represents however only the probability of a flood with a risk coefficient much greater than that used in the planning the safety of an airplane or a nuclear power plant. It is essential therefore that the problem of the safety of Florence, Pisa and other minor towns, be considered in terms of non-structural defense, at least until the structural defense projects are finally able to reduce the return

period to such a long time to be neglected. Even though the recent structural improvements reduced the flooding risk for the cities of Florence and Pisa, the repetition of a 1966 like flood would produce even bigger damages if no care is posed in:
- preparing flood plans,
- setting up alarm systems based upon hydrological and meteorological forecasting.

With this in mind the National Group for the Defense on Hydrological Hazard (GNDCI), a national scientific organization for hydrogeological disasters prevention, of the Italian National Research Council (CNR), operating under the auspices of the Civil Protection Ministry, has undertaken a series of initiatives with the purpose of creating a disaster preparedness program capable of minimizing the damaging effects such those caused by 1966 flood, this study has been presented recently by Becchi et A. [1986] . A cooperative effort has been created among the Ministry for Civil Protection, Tuscany Regional Government, the City of Florence and other local agencies coordinated by the Prefetto of Florence with the participation of the GNDCI.

This aims at creating a non-structural defense plan for the City. It would consist in a hazard warning system and an overall action plan for City services, public officials, police and citizens. The technical and scientific steps necessary are based on the present state of the monitoring system as setup by the Genio Civile. This consists of a small number of river stage gages (Subbiano, Montevarchi, Fornacina, Uffizi) connected through a transmitting system susceptible to breakdown. With such a system, while assuming to have a sufficiently accurate flood warning not more then three hours of forecast lead time can be generated. In Fig. 6 the relative positions of the measuring stations now operating are indicated along with some former gaging station.

2.4 The hydrological forecasting.

I.B.M. carried out a scientific study together with the University of Pavia group (Maione and A.) on the generation and propagation of floods along the Arno River. This model has been developed considering the flood formation by means of unit hydrograph technique for each major tributary and a flood routing model utilizing the whole dynamics scheme of the De Saint Venant's equations through several digitized river cross sections.

The IBM [1977] study utilizing CLS method for hydrograph inference shows that in the Arno valley there are different hydrologic response due to the different geographic situation. The Tuscany Ragional Government thougheter with the Ecosystems Inc.[1976] started to study for a hydrological parametrical model of the Sieve R., one of major Arno tributaries. Recently, utilizing published data, Becchi and Bemporad [1985] shown that in various Arno tributaries the absorption rate can be important also for wet season storms.

From such studies as well as from previous analysis of Natoni it is clear that the hydrological behaviour of the Arno is particularly sensible to the soil moisture as well as to the distribution of the rainfall in the valley. Due to the short time in flood formation and to the high risk level for the cities of Florence and Pisa, a hydrological forecasting technique should consider various steps in the alarm definition.

Starting from the Natale [1977] definition of the risk level, considering that not only the river stage but also rainfall and meteorological data should be considered, as in Kytanidis and Bras [1980], a complete monitoring system should be set up in order to reduce the risk level. According with Nemec [1984] classification, the Arno River case represents a limit case in terms of hydrological response time and up to now no real time forecasting of this type has applied. But the inestimable cultural and historical values of the City are to be preserved so, while preparing structural defense, an experimental monitoring system can reduce the total risk to acceptable values.

In 1989 an experimental meteorological RADAR station start in operation and some important rainfall field features have been studied in last five years during severe and dangerous storms. In the mean while the Italian National Hydrographic Service developped a real time monitoring system that now a days account for 70 raingauges and 18 stage meters.

In 1990 the Arno River Autority has been set up by the Ministry of Public Works and some major problems begin to be regulated.

In particular in 1996 the Arno River Autority promoved the Basin Flooding Risk Plan, that included several intervention measures. In the basin risk plan some new floods regulation storage capability are detected divided in two main groups.

The first group accounts for dam reservoirs, and is scheduled by five major works, including Bilancino dam that is now in way to be ready and some change in La Penna and Levane reservoir capacity, to reach a total available storage capacity of about 120 Mm^3.

The second group is accounting for regulated inundable areas, equally distributed in between the major stream and the tributaries, this this storage capacity is evaluated of about 110 Mm^3 maximum. Owing the big effort of finding storage capacity able to mitigate the flood intensity the overall available volume still results limited, also considering that the formerly evaluted volume of 210 Mm^3 needed for flood mitigation in 1966 now are increased to 380 Mm^3 considering the soil storage capacity lost in the last 30 years by cause of the urban development, and the expected construction time requires up to fifhteen years of works. In the mean while to protect the Arno valley population some non-structural activities are started.

The Ministry for Civil Protection organized a series of technical alarms, and the aforesaid GNDCI was carring out some new studies in soil moisture monitoring and in meteorological RADAR management in order to improve furtherly the time lag available for alarm and defence operations and also the reliability of the discharge predictions.

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LA PENNA AND LEVANE DAMS ON THE ARNO RIVER: THEIR CHARACTERISTICS AND THEIR POTENTIAL FOR FLOOD CONTROL

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ENEL SpA

Introduction

After the disastrous flood which hit the Arno Valley and Florence in 1966, several studies aimed at identifying possible means to control the floods of the river, have been carried out.

It has been found that a valuable contribution could be obtained by heightening the existing hydroelectric dams of Levane and La Penna.

The control volume thus made available would be of about 40 to 50 million m^3, enough to protect Florence against a flood of the same size of the one occurred in 1966.

In fact, in 1966 the maximum flow discharged from the dams was of about 2500 m^3/s while in Florence it was of 4200 m^3/s.

With the proposed modifications, it is possible to reduce the maximum flow discharged from the dams to 1200 m^3/s and consequently limit the flow crossing Florence to no more than 3500 m^3/s, which is a value compatible with the downtown river bed, as it is now after the ameliorative works carried out following the above mentioned event.

The existing dams

La Penna and Levane dams are located on

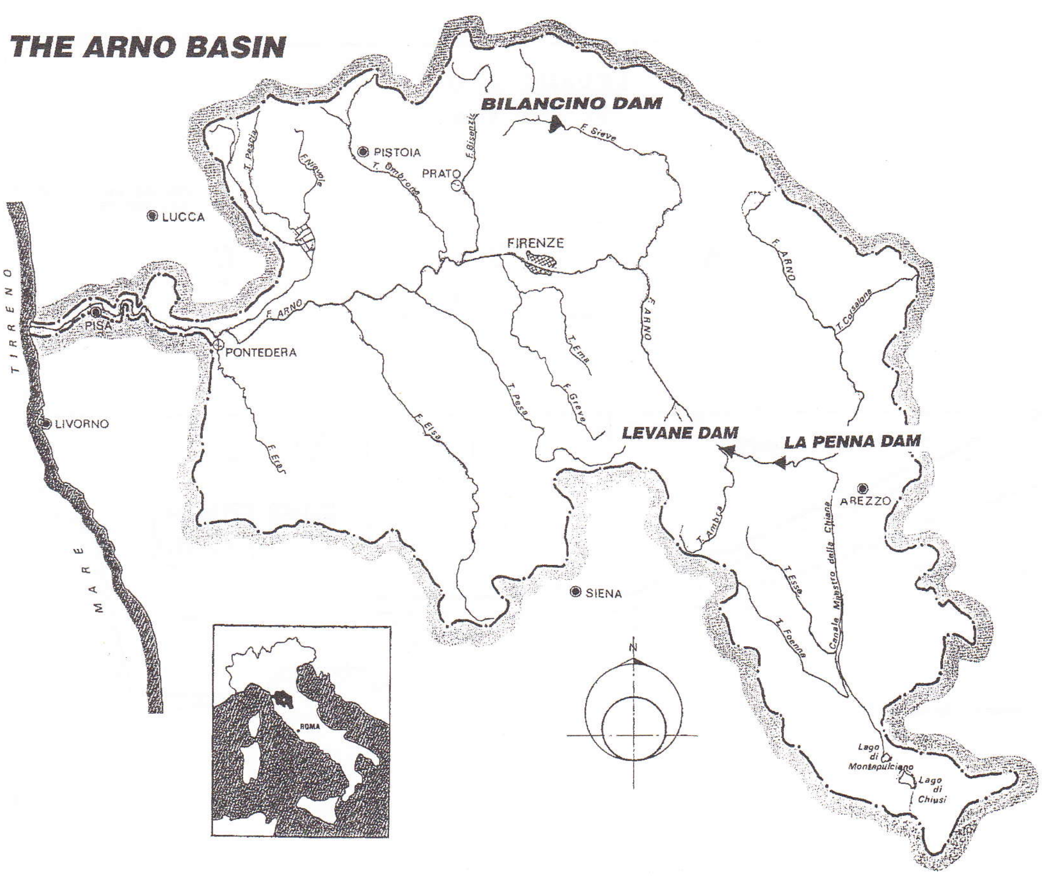


Fig. 1

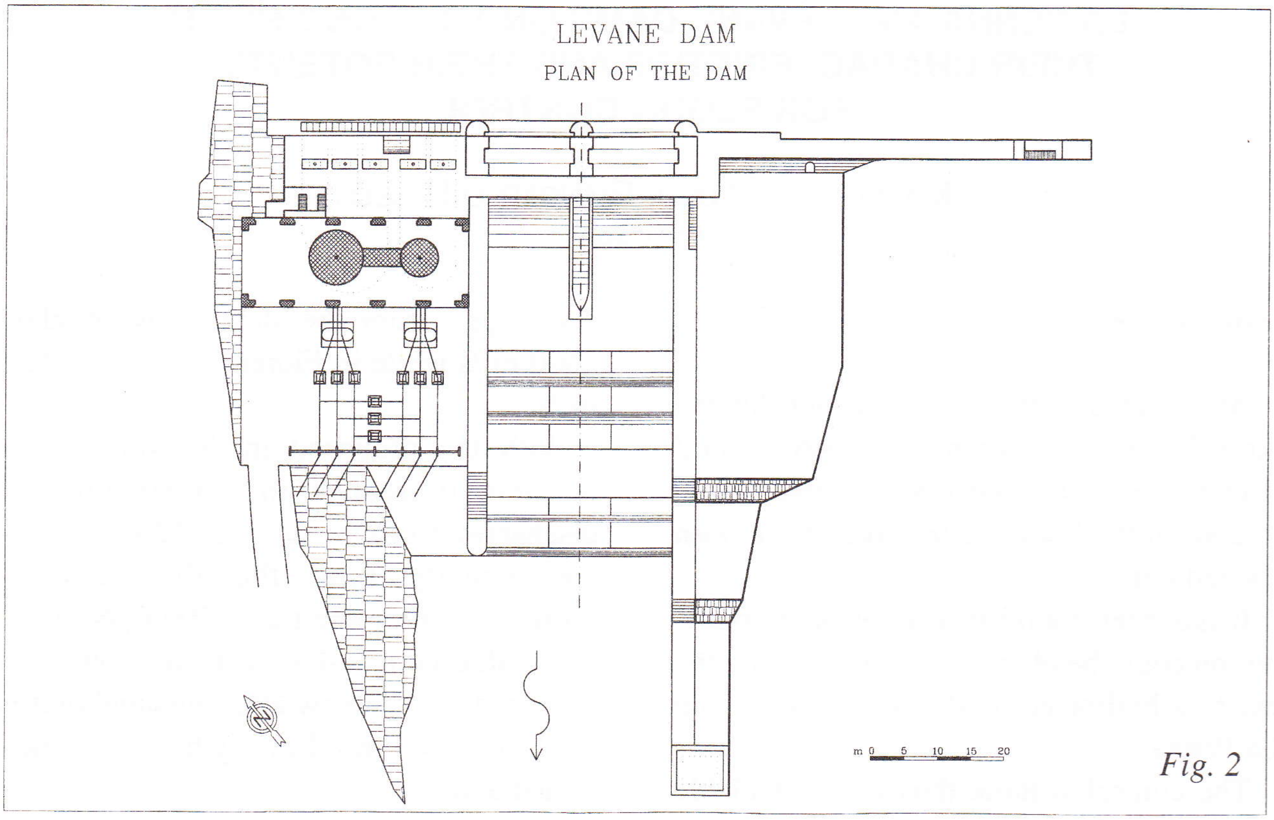


Fig. 2

the Arno river about 50 km upstream from Florence and determine two reservoirs in series (Fig. 1). Their catchment area is of 2400 km^2 while the total catchment area upstream from Florence is of about 4100 km^2.

Levane dam, located downstream from La Penna, is of the gravity type on the abut-

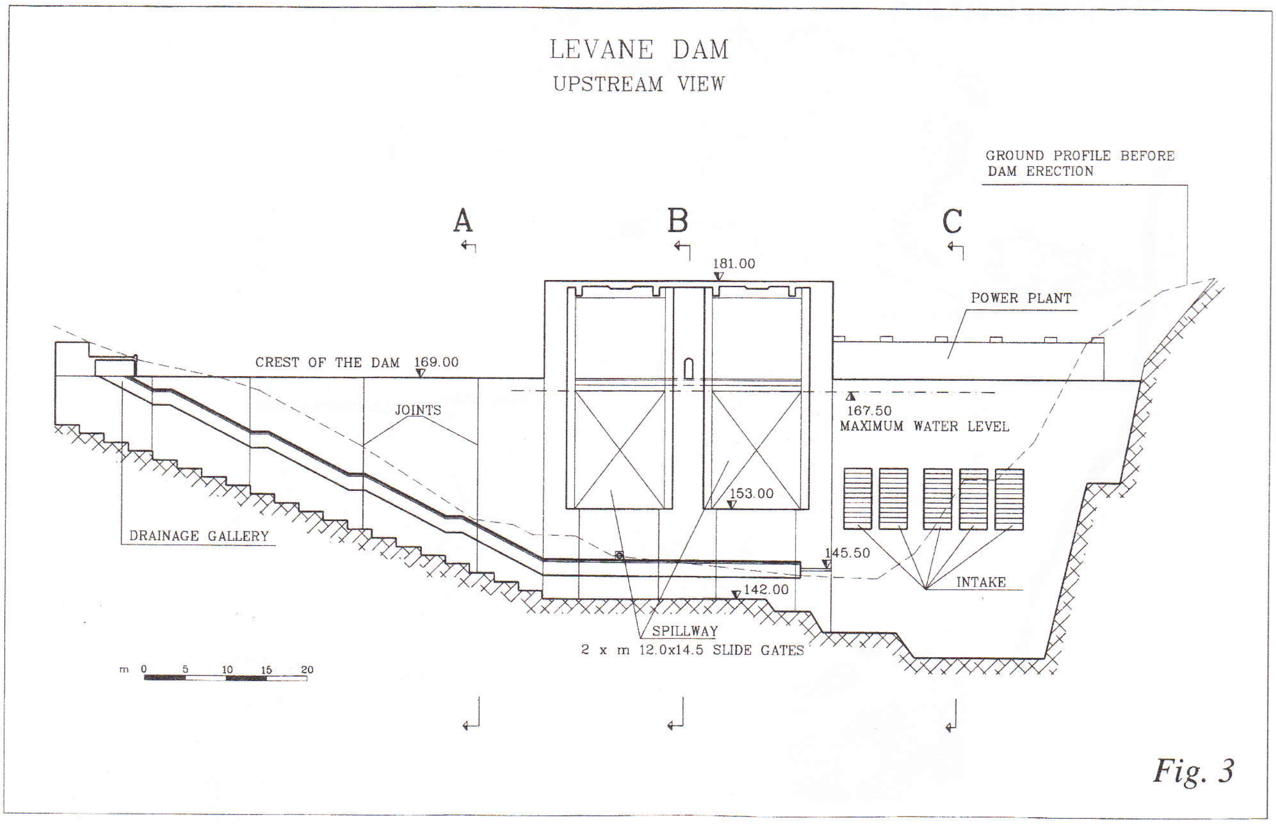


Fig. 3

LEVANE DAM
VERTICAL CROSS SECTION AT "A"

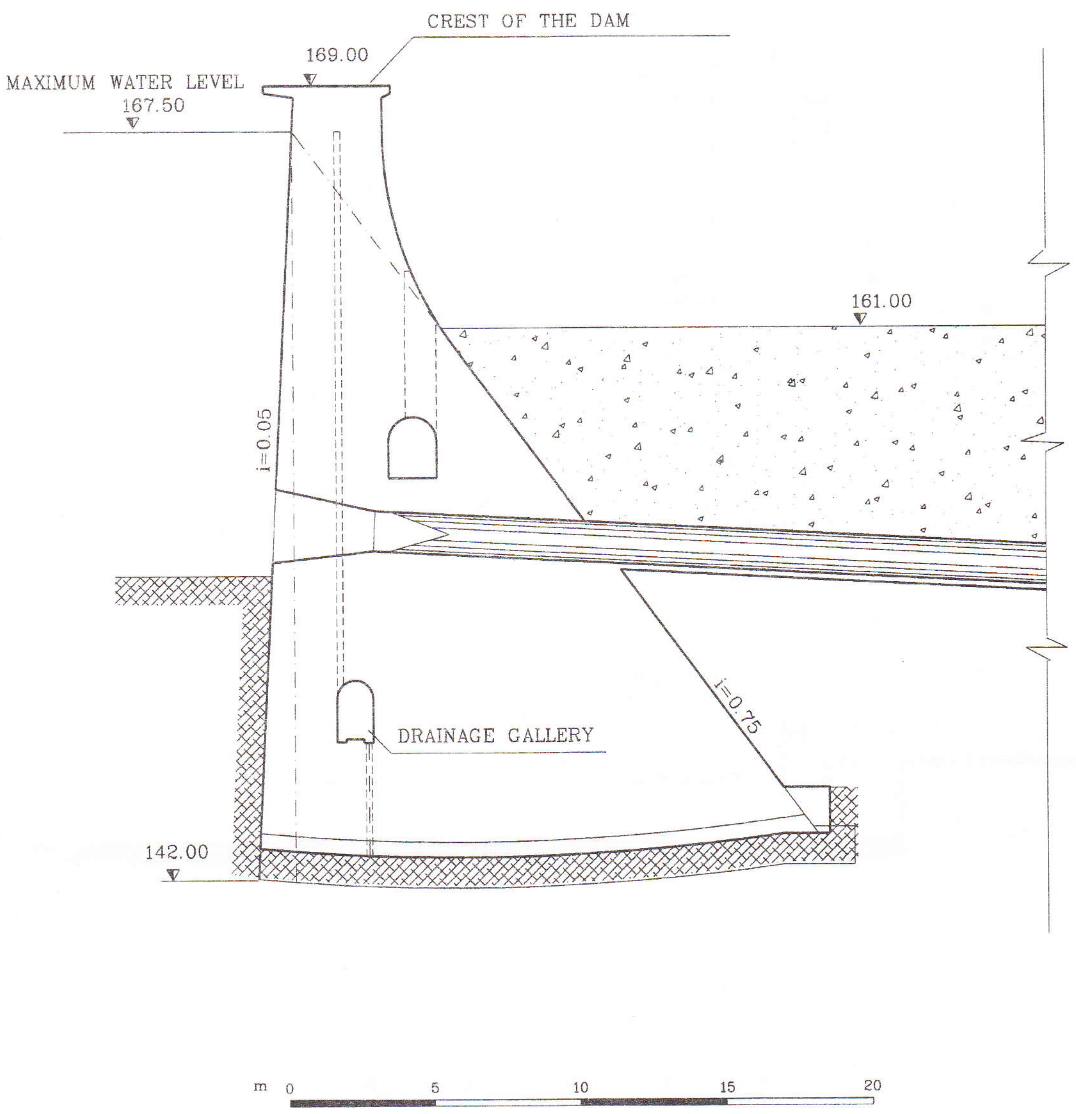


Fig. 4

LEVANE DAM

VERTICAL CROSS SECTION AT "B"

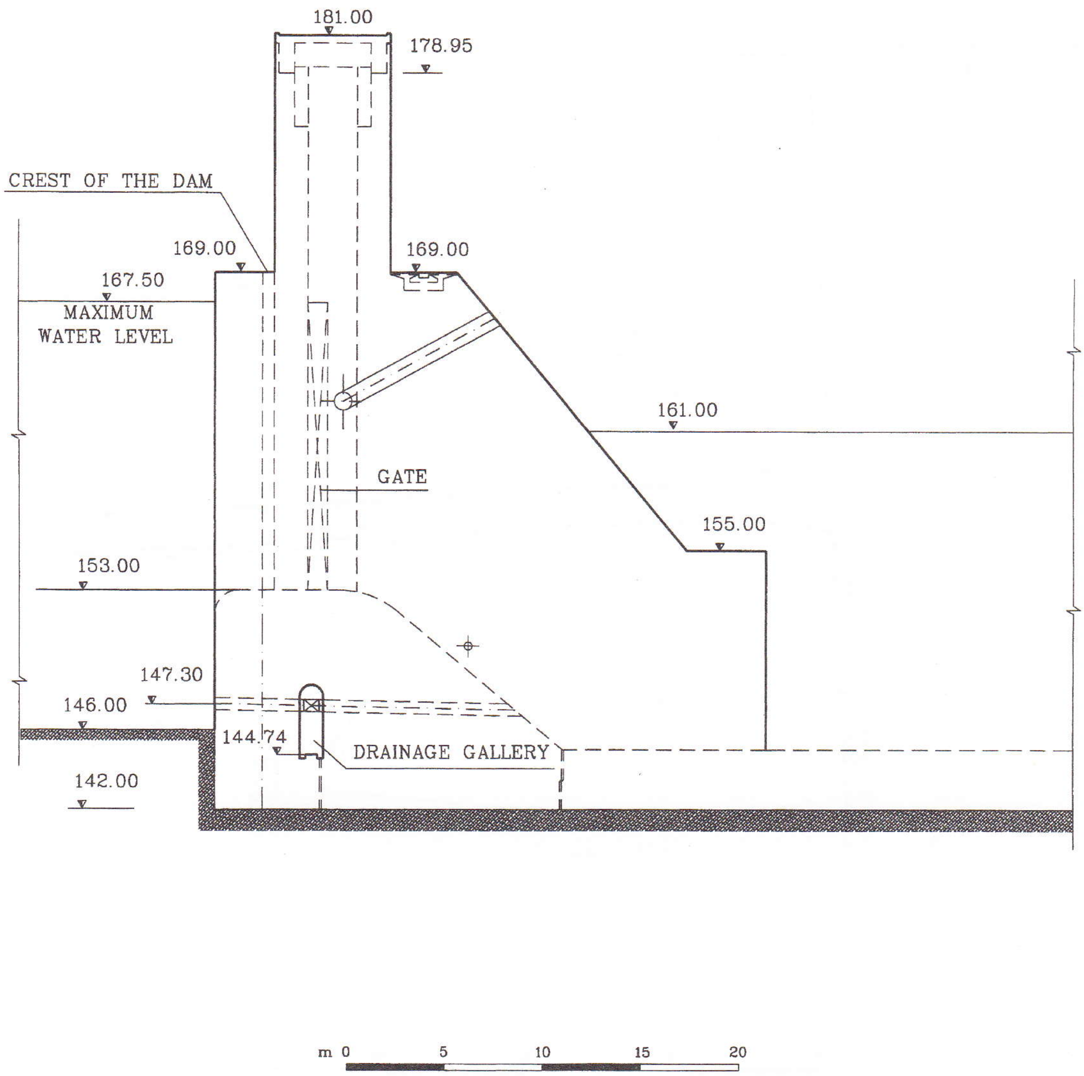


Fig. 5

LEVANE DAM

VERTICAL CROSS SECTION AT "C"

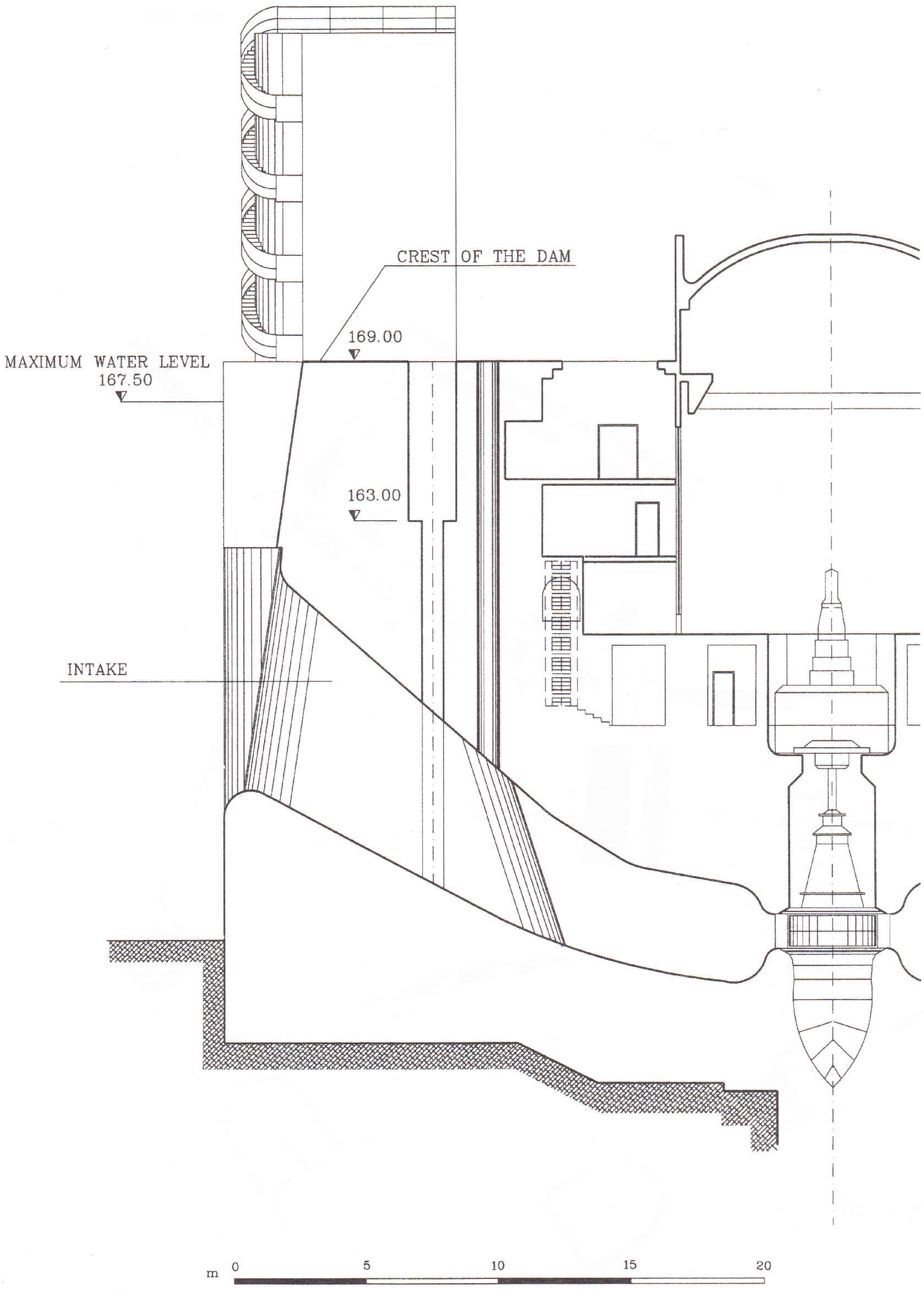
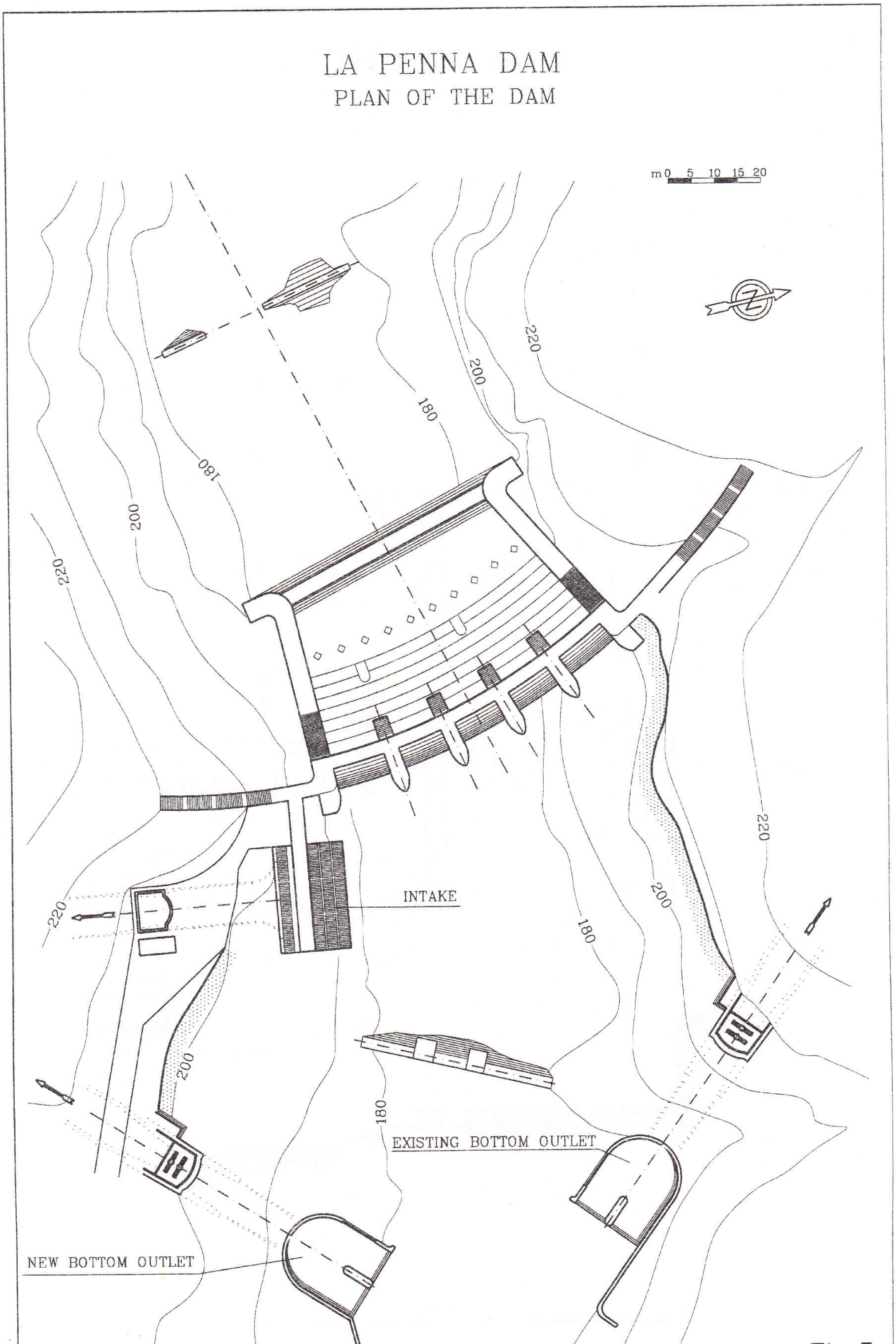


Fig. 6



LA PENNA DAM
PLAN OF THE DAM
m 0 5 10 15 20
220
200
180
180
200
220
INTAKE
220
220
200
180
200
180
EXISTING BOTTOM OUTLET
NEW BOTTOM OUTLET

Fig. 7

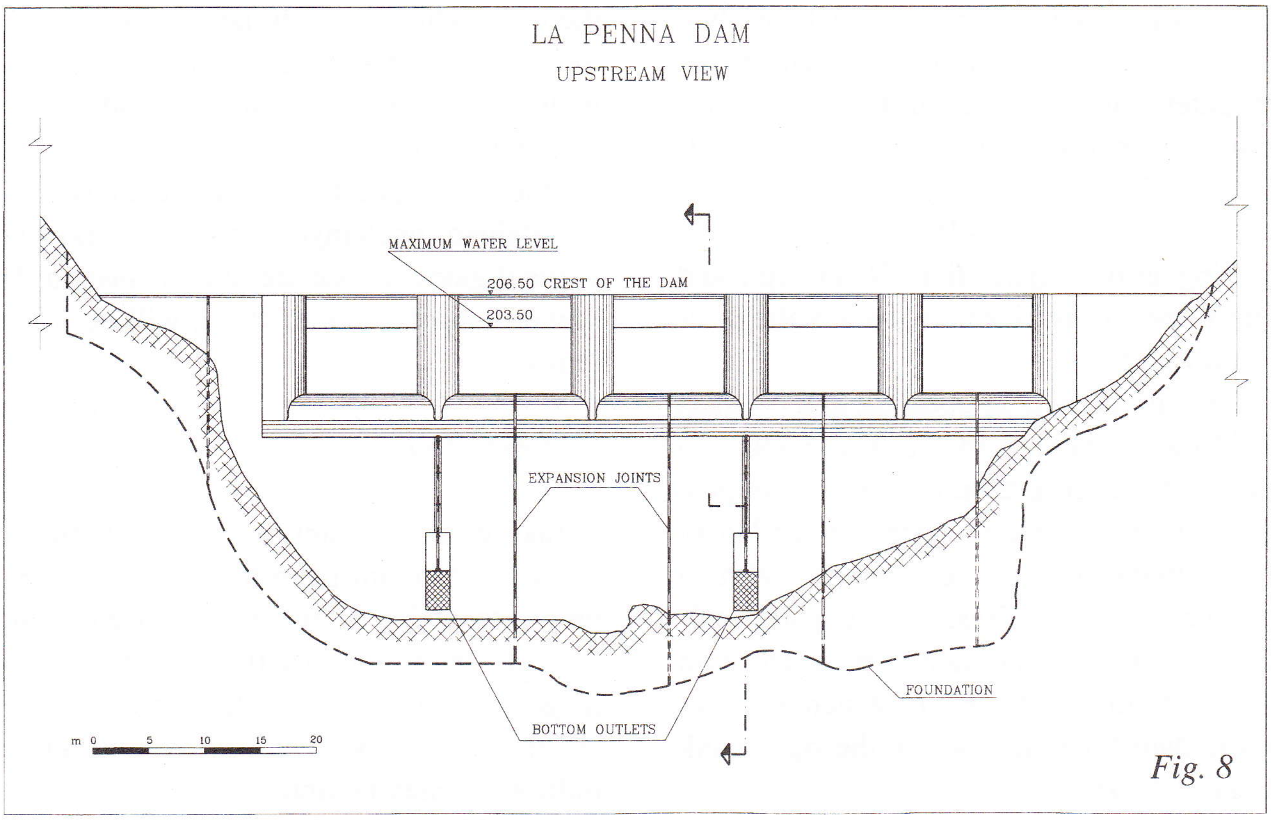

LA PENNA DAM
UPSTREAM VIEW
MAXIMUM WATER LEVEL
206.50 CREST OF THE DAM
203.50
EXPANSION JOINTS
FOUNDATION
BOTTOM OUTLETS
m 0 5 10 15 20

Fig. 8

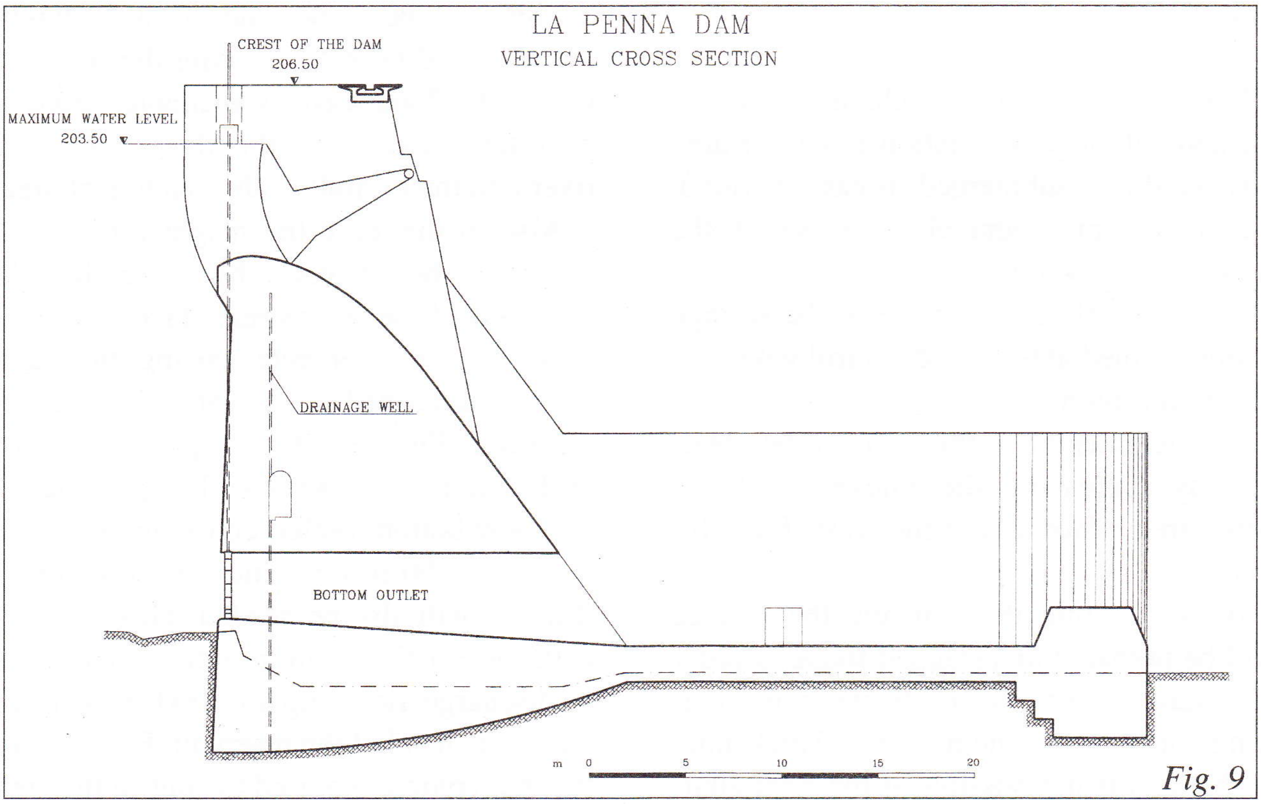

LA PENNA DAM
VERTICAL CROSS SECTION
CREST OF THE DAM
206.50
MAXIMUM WATER LEVEL
203.50
DRAINAGE WELL
BOTTOM OUTLET
m 0 5 10 15 20

Fig. 9

ments while the central part includes two large discharge outlets provided with vertical gates. The dam is 27 m high and determines a reservoir having a volume of 5 million m^3 (Figs. 2, 3, 4, 5, 6).

The upper dam of La Penna is of the overflowing gravity type. It is 36 m high and determines a reservoir having a volume of 16 million m^3.

The dam body is in concrete and consists of blocks separated by vertical joints. To relieve the uplift pressures, the dam in provided with a drainage system extended to the foundation and connected with a peripheral gallery. Besides the gated spillway on the top, the dam is provided with three bottom outlets, two of which are built in the dam body and one in the right bank (Figs. 7, 8, 9).

The modifications proposed

Levane Dam

Taking into account the characteristics of the dam, of the power station and of the area that would be submerged in case of flood, the maximum acceptable increase of the water level is 4.5 m.

Consequently the increase of the storage volume aimed at the flood control would be of 9.6 million m^3.

The heightening of the dam will be obtained by increasing the thickness of the downstream face and of the crest (Figs. 10, 11).

Before casting the concrete the surface will be prepared in a stepped shape in order to assure a solid contact between the existing concrete and the new one. Thickening of the dam is not possible at the right abutment because of the presence of the power station. Therefore, the additional concrete volume must be concentrated on the crest of the dam, which is fairly large (Fig. 12). An increase of the number of drainage wells, including those located in the foundation, is also provided.

Since the operating water level will be maintained unchanged, also the existing vertical gates, which are able to sustain the higher loads in case of floos, will be maintained.

La Penna Dam

Taking into account the characteristics of the area upstream from the dam, the maximum acceptable increase of the water level (in case of exceptional flood) is 5.5 m. By heightening the dam of the same quantity, an increase in the reservoir volume of 25 million m^3 may be obtained.

An additional volume of 8 million m^3 may be obtained by a fast emptying of the reservoir some hours before the arrival of the flood peak.

This can be done only if a hydraulic model, capable of forecasting the propagation of the flood wave, is available, based on a system monitoring the flows along the river and the rainfall in the catchment area.

Also in this case the heightening of the dam will be obtained by increasing the thickness of the downstream face and of the crest. For the concrete casting the same method described for Levane dam will be followed (Fig. 13). An adequate extension of the drainage network will be provided.

A new bottom outlet, consisting of a tunnel about 700 m long and 8 m in diameter (Fig. 7), will also be needed. This, together with the existing bottom outlets, will allow to discharge flows up to 1000 m^3/s at the minimum level of the reservoir. By this way, the free volume required to control the crest of the flood will be maintened until the flood flow reaches values higher than 1000 m^3/s.

LEVANE DAM

VERTICAL CROSS SECTION OF THE NEW DAM AT "A"

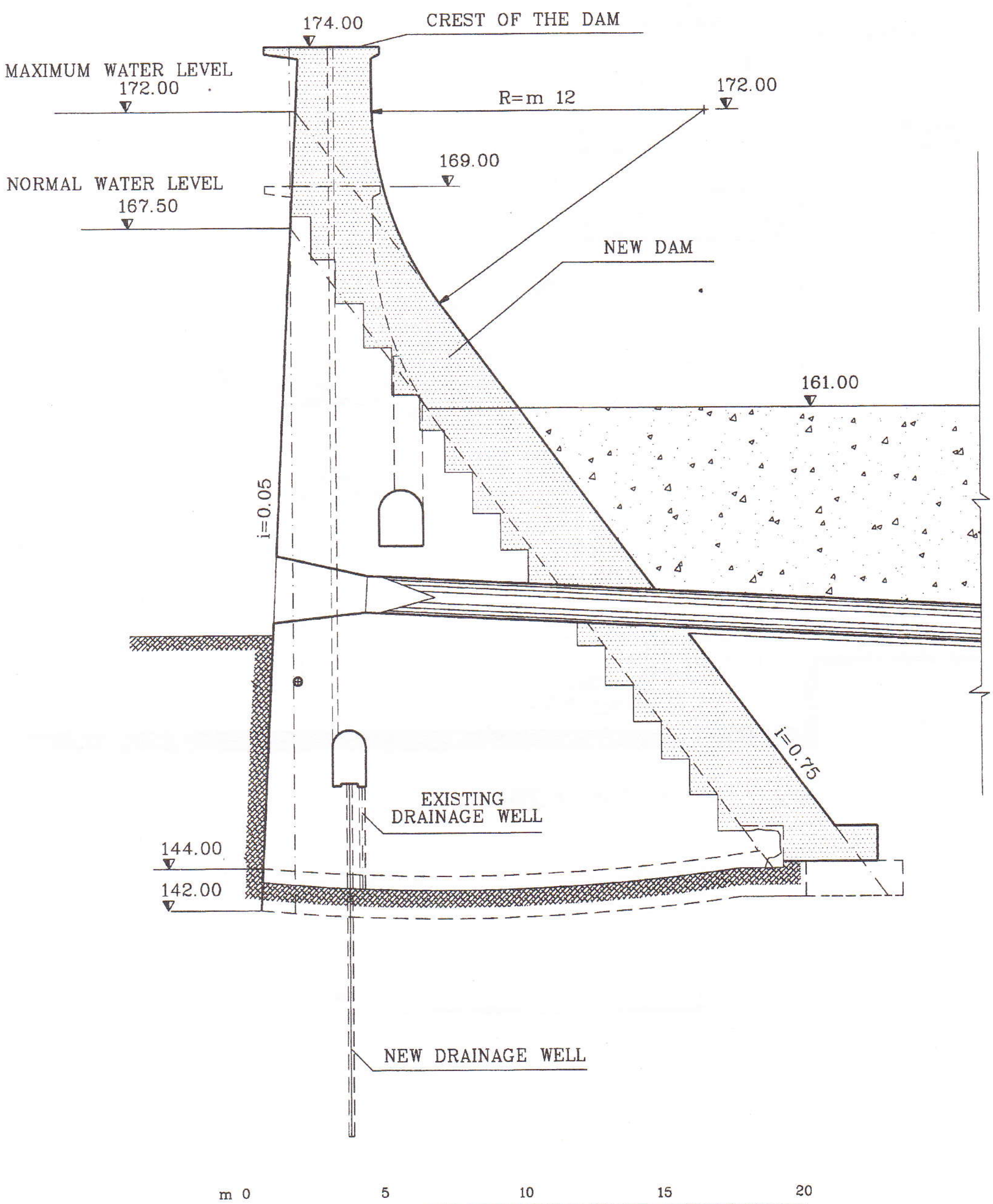


Fig. 10

LEVANE DAM

VERTICAL CROSS SECTION OF NEW DAM AT "B"

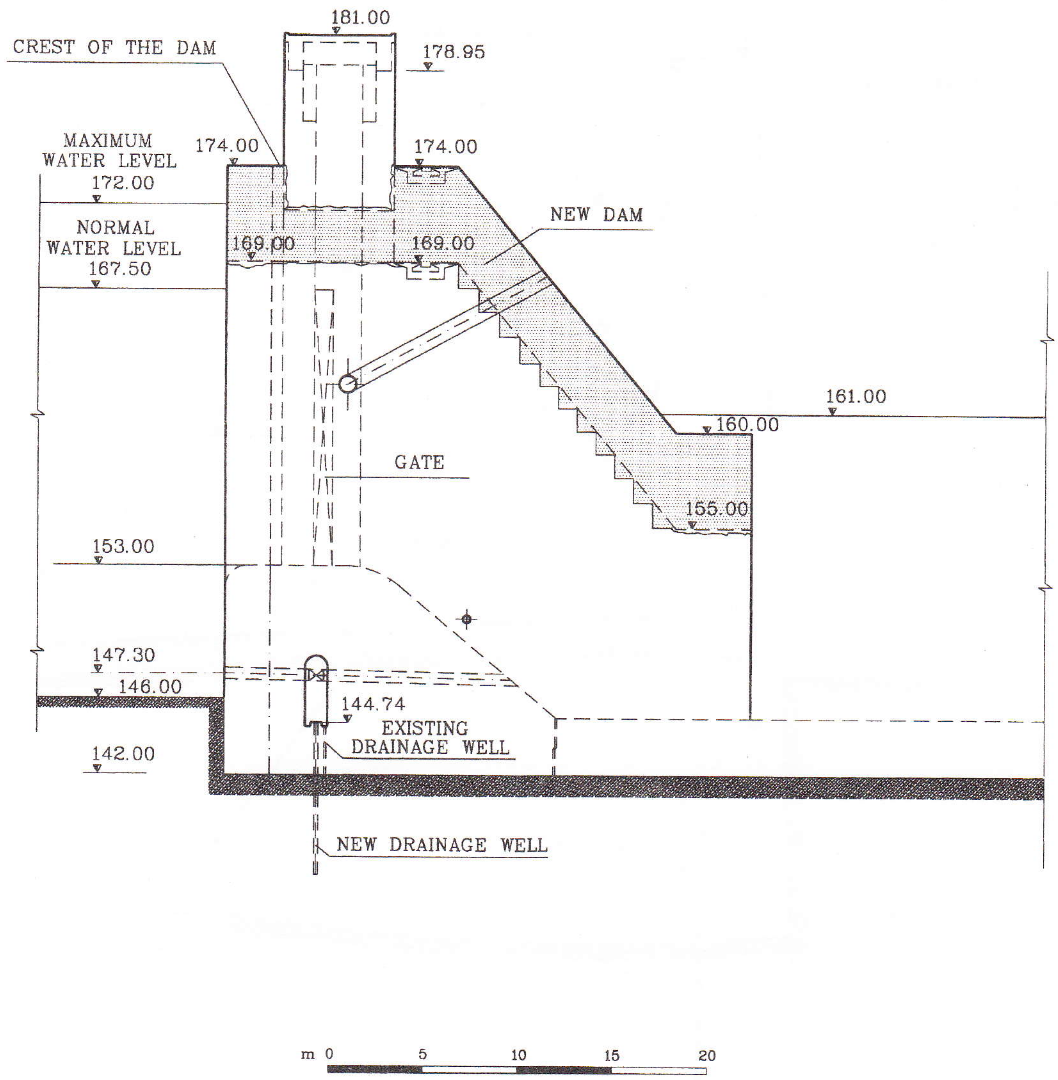


Fig. 11

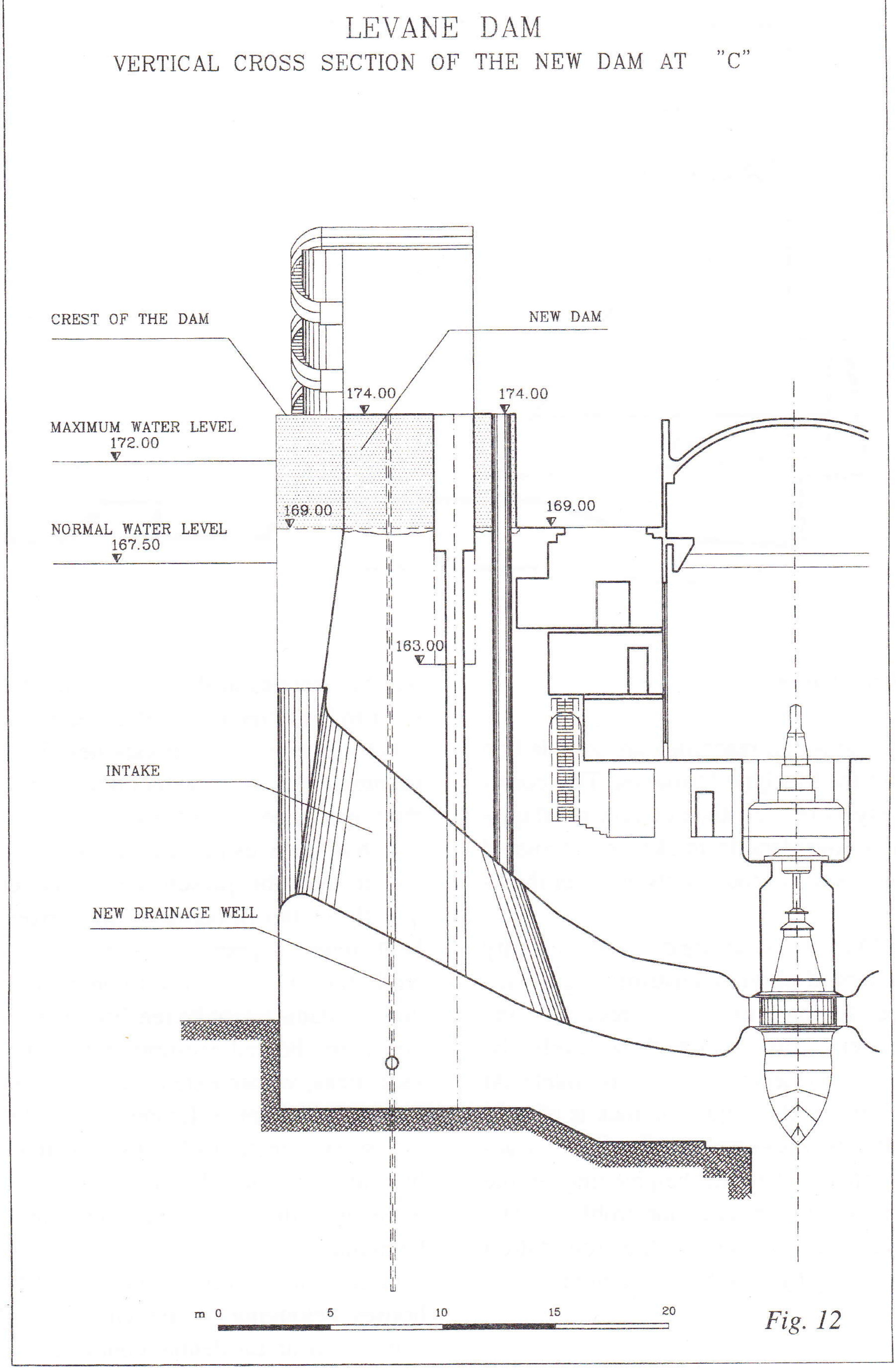

LEVANE DAM
VERTICAL CROSS SECTION OF THE NEW DAM AT "C"
CREST OF THE DAM
NEW DAM
174.00
174.00
MAXIMUM WATER LEVEL
172.00
169.00
169.00
NORMAL WATER LEVEL
167.50
163.00
INTAKE
NEW DRAINAGE WELL
m 0
5
10
15
20

Fig. 12

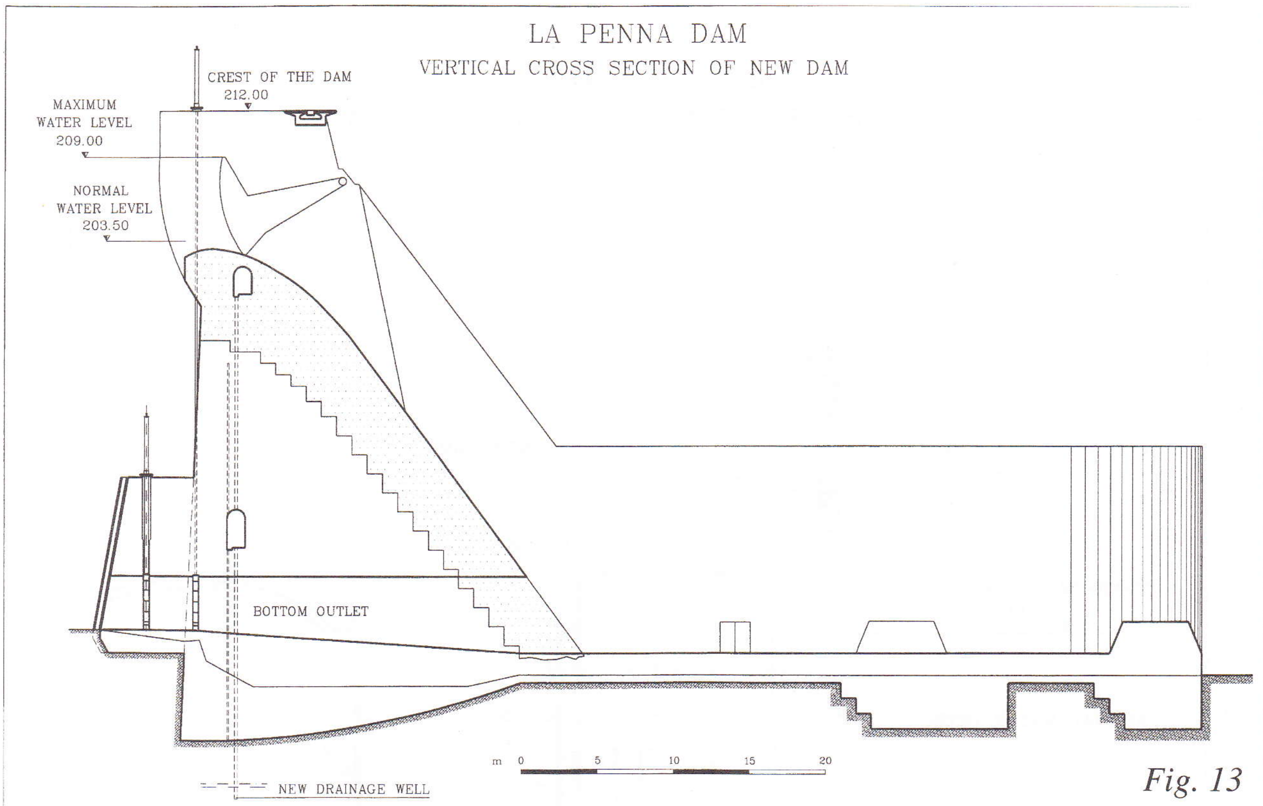


Fig. 13

Geological aspects

Both dams and reservoirs are founded on rocks of the Macigno formation. This consists of layers of sandstone of very good quality and considerable thickness, alternated with layers of scistous marls of lower thickness.

The Macigno rocks are covered with silty clay layers of pluvio-lacustrine origin wich will be, to some extent, interested by the new water levels. Also at these levels, the banks of the reservoir result to be stable. At the abutments the sandstone rock is of considerable thickness and is only slightly fractured, what makes the heightening of the dams feasible without major problems. The compressive stresses in the foundation increase only by less than 1.5 kg/cm^2.

Envirovmental impact

As it has been said before, the reservoirs will be operated at the same water levels as prior to the heightening of the dams.

Only during major floods new land will be submerged, to an extent depending upon the importance of the flood.

It has been estimated that water levels higher than the present ones, and consequently partial flooding of the surrounding land, might happen every 30 to 50 years, while the maximum level compatible with the new dams might be reached every 300 to 500 years. Forced expropriation of the relevant areas, whose extension is of 2 km^2 at Levane and 3 km^2 at La Penna, could not be necessary. Erection of houses or industrial buildings should obviously be prevented while agricultural and ohter activities could be maintained.

In case of maximum flood about twenty houses belonging to the village of Ponte Buriano, near La Penna, could be flooded. Two alternatives have been therefore envisaged: either demolishing these houses and rebuiliding them at higher levels, or constructing a bank capable of protecting the houses, together with a drainage tunnel to collect the surface water runoff.

Constraints during construction

The works at Levane dam will be carried out while keeping the plant in service. A relatively short outage will be required to modify the controls of the intake gates and of the screen cleaning machine.

At La Penna, it will be necessary to lower the water level during the heightening of the dam, while a total emptying of the reservoir will be required to build the new bottom outlet: these works will last about six months.

Taking into account that the two reservoirs are also used to supply drinking water to Florence, the works on the dams should be postponed to the impoundment of the new reservoir of Bilancino, which exploits the water of a tributary of the Arno river, with the aim to increase the drinking water supply to Florence in addition to La Penna reservoir.

Economic evaluations

The cost of Levane project has been estimated in 24 million $, of which 14 for the dam and appurtenances and 10 for the reservoir and land acquisition.

The cost of La Penna project has been estimated in 190 million $, of which 110 for the dam, its appurtenances and the new bot-

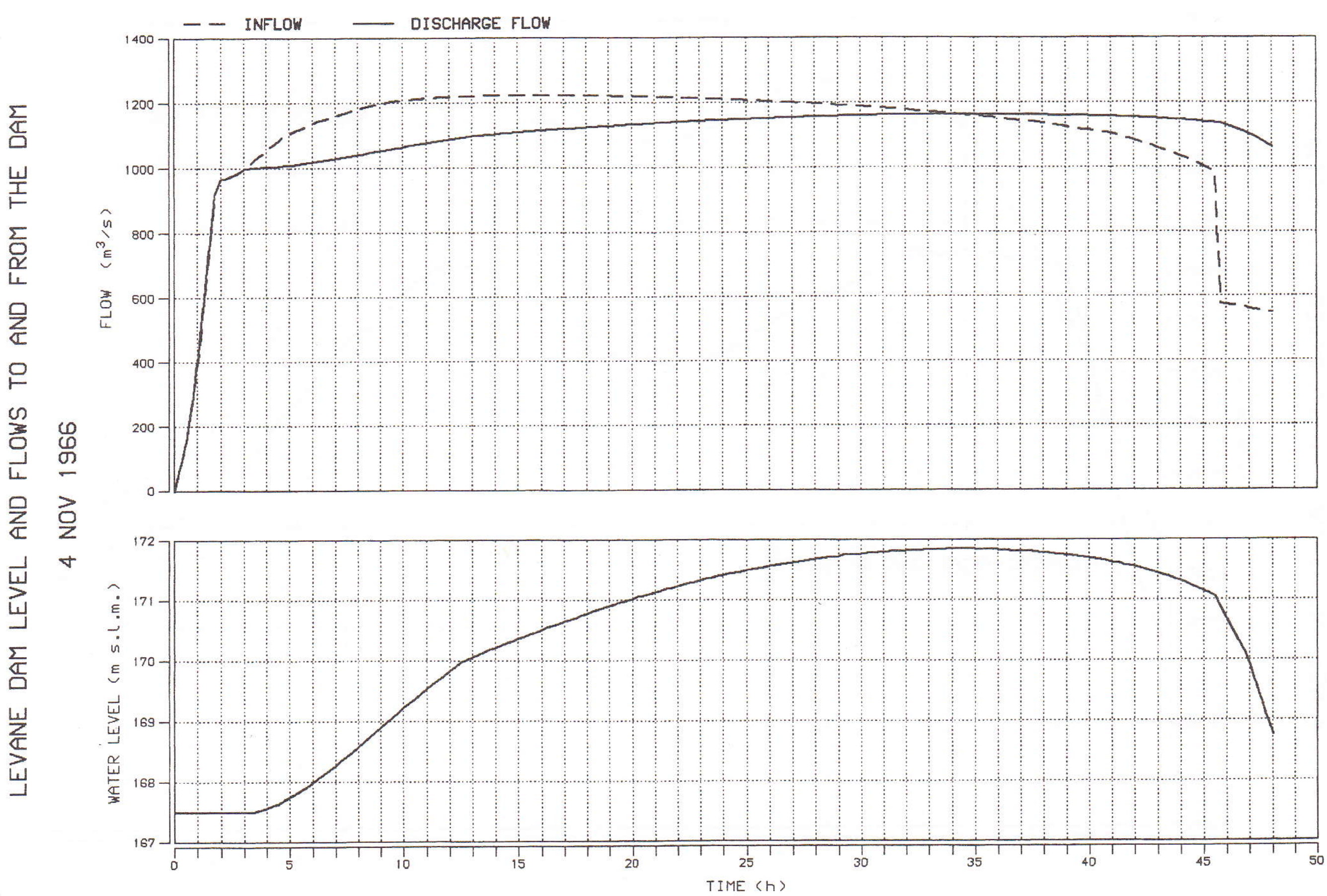


Fig. 14

LA PENNA DAM LEVEL AND FLOWS TO AND FROM THE DAM
4 NOV 1966

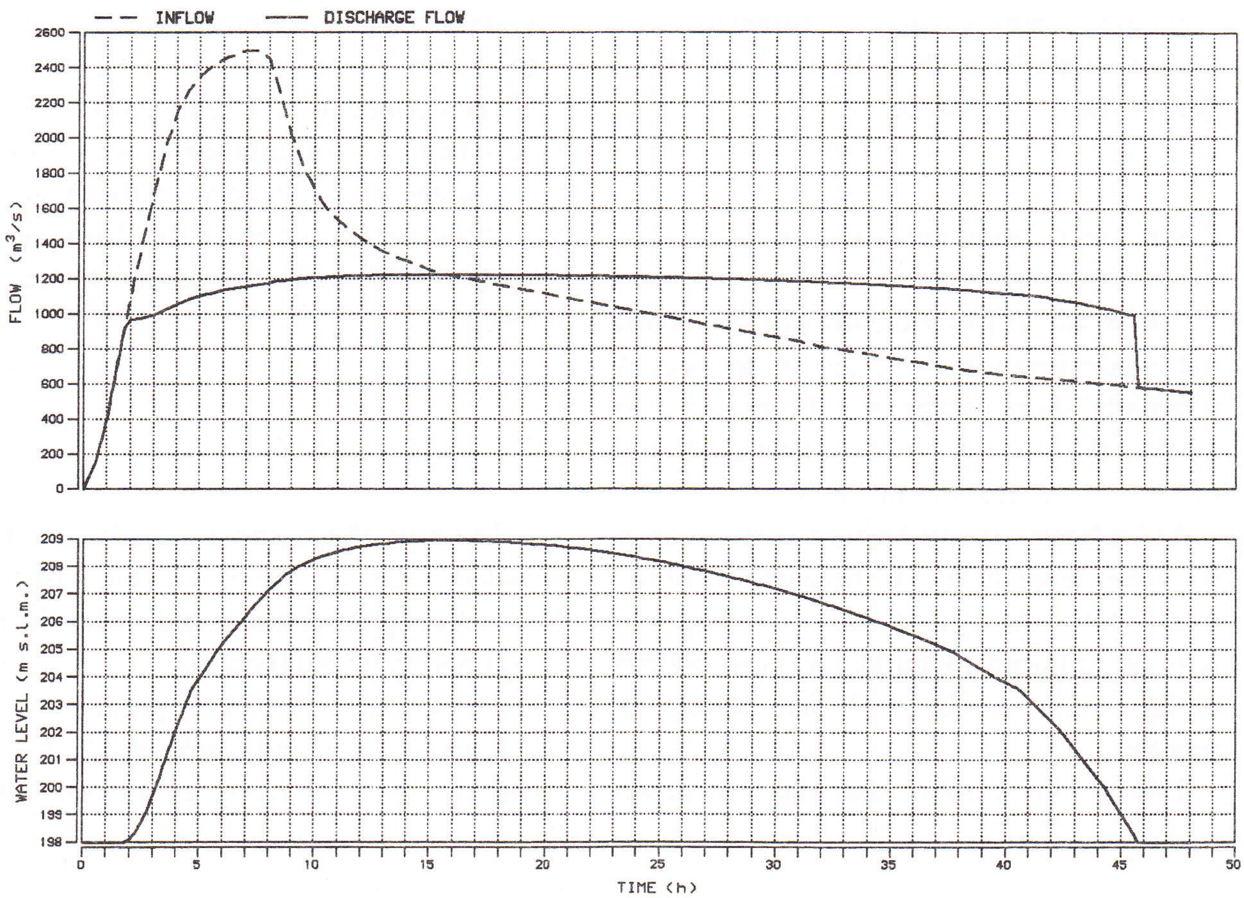


Fig. 15

4 NOV 1966 FLOWS IN THE RIVER AT FLORENCE

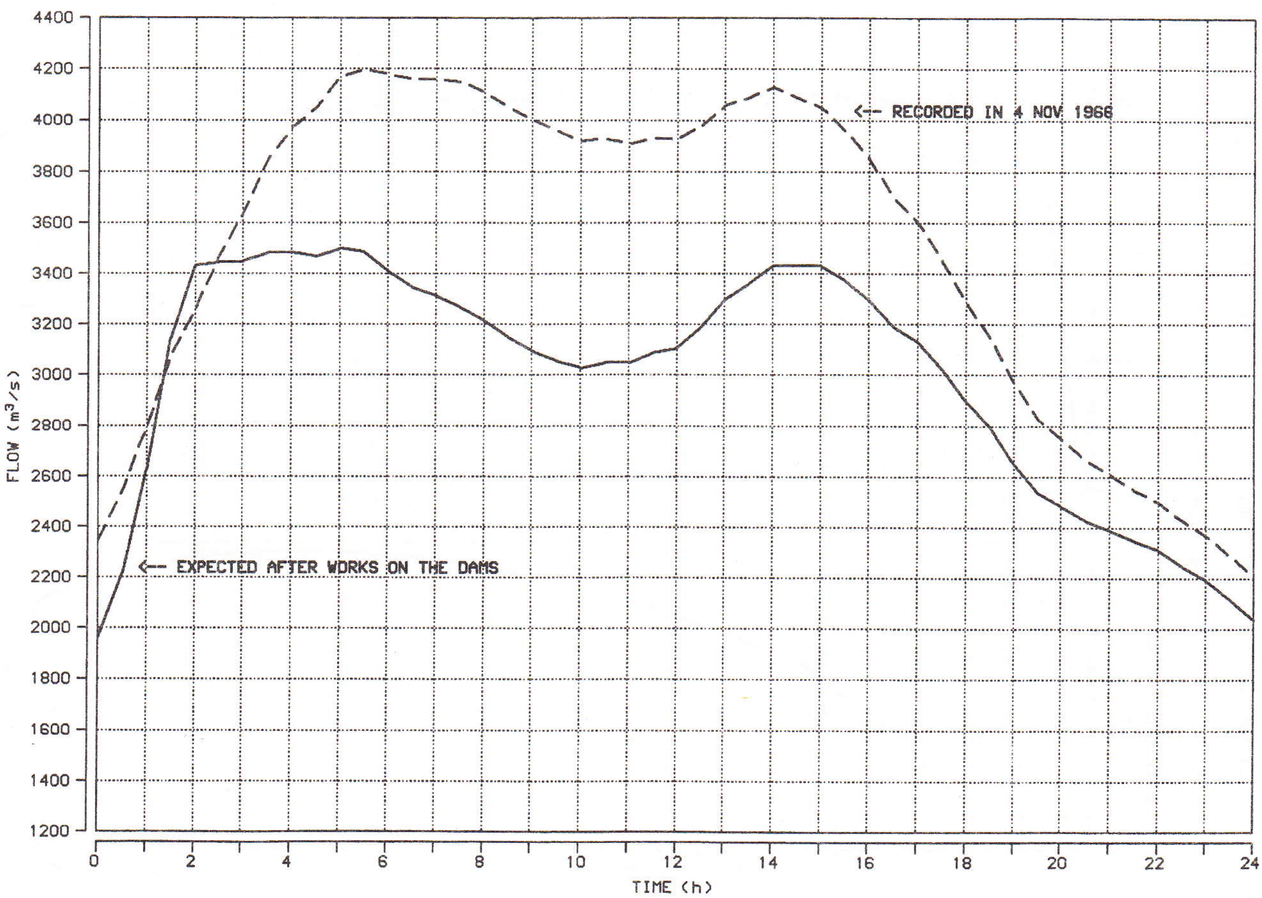


Fig. 16

tom outlet, and 80 for the reservoirs, land acquisition and other works aimed at the village protection.

Operating criteria

As mentioned above, the operation of hydroelectric plants will remain unchanged after the dam modifications.

During flood conditions, the bottom outlets will be opened in advance, based on the indications of the forecast model, in order to assure a suitable storage volume for the flood peak.

The maximum discharge flow from the bottom outlets will be about 1200 m^3/s (Figs. 14, 15).

By this way, the peak flow at Florence will be 3500 m^3/s (rather than 4200 as in 1966), which is a value compatible with the present characteristics of the downtown river bed (Fig. 16).

Conclusions

The feasibility study outlined above has been included in the basin plan set up by the Arno Authority, but of course other approvals of the local Authorities, as well as a detailed design before construction, will be required.

Any way, even not considering the damages due to the extreme floods, the cost of the project is lower than those produced by the minor floods occurred so far.

Levane dam - downstream view

La Penna dam - downstream view

HYDRAULIC CHECK OF THE PROPOSED INTERVENTIONS FOR ARNO RIVER REGIME CONTROL

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ABSTRACT

This paper analyzes the flood dynamics of the Arno River under hydrological stresses similar to those of November 1966 and October 1992 floods. The analysis is based on a distributed parameter hydrologic model and a hydraulic model to simulate unsteady flow conditions.
The purpose of the model simulation is to characterize the behavior of the fluvial system under different scenarios of the Basin Plan, i.e.:

- peak flow mitigation using the residual alluvial plain areas still available to be inundated;
- use of additional volumes to storage temporary flood water;
- improvement of river-conveyance capacity.

The Basin Plan includes interventions on the main stream and the tributaries of the Arno through the construction of flood expansion areas, new reservoirs and the enlargement of existing Enel (National Electric company) Levane and La Penna reservoirs.
The results indicate the possibility of achieving a significant reduction of peak flow and the associated flood volumes, together with an increase in peak time occurrence.

1. INTRODUCTION

- The increasing use of territory for productive and residential purposes resulted (at least in the last decades) in the occupation of areas pertaining to the river dynamics and naturally inundated during high flood flows. In order to protect man activities in such areas levees and embankments have been realized, but they remarkably affected the flood wave propagation (Paris and Rubellini, 1994). Such a situation is particularly relevant for the Arno whose hydraulic risks notably increased from November 1966 to present because of the considerable occupation of alluvial plain areas. One of the interventions proposed to control flood dynamics is therefore linked to the rehabilitation of these territories as flood lamination areas or, at least, to the setting of constraints to the use of riverside areas not yet occupied. The Basin Plan for the control of the Arno's hydraulic risks includes a number of interventions that can be summarised as follows:

a) improvement in peak flow lamination by the remaining alluvial plain areas still available to be inundated
b) finding additional storage volumes;
c) improvement of the river flood carrying capacity.

The interventions specifically regard:

type a:

- realization of controlled flooding areas through the construction of banks and spillways along the river sides for a total of approximately 163 million m³.

type b:

- realization of a diversion upstream Empoli to discharge a flood volume in the Fucecchio swamp of approximately 28-34

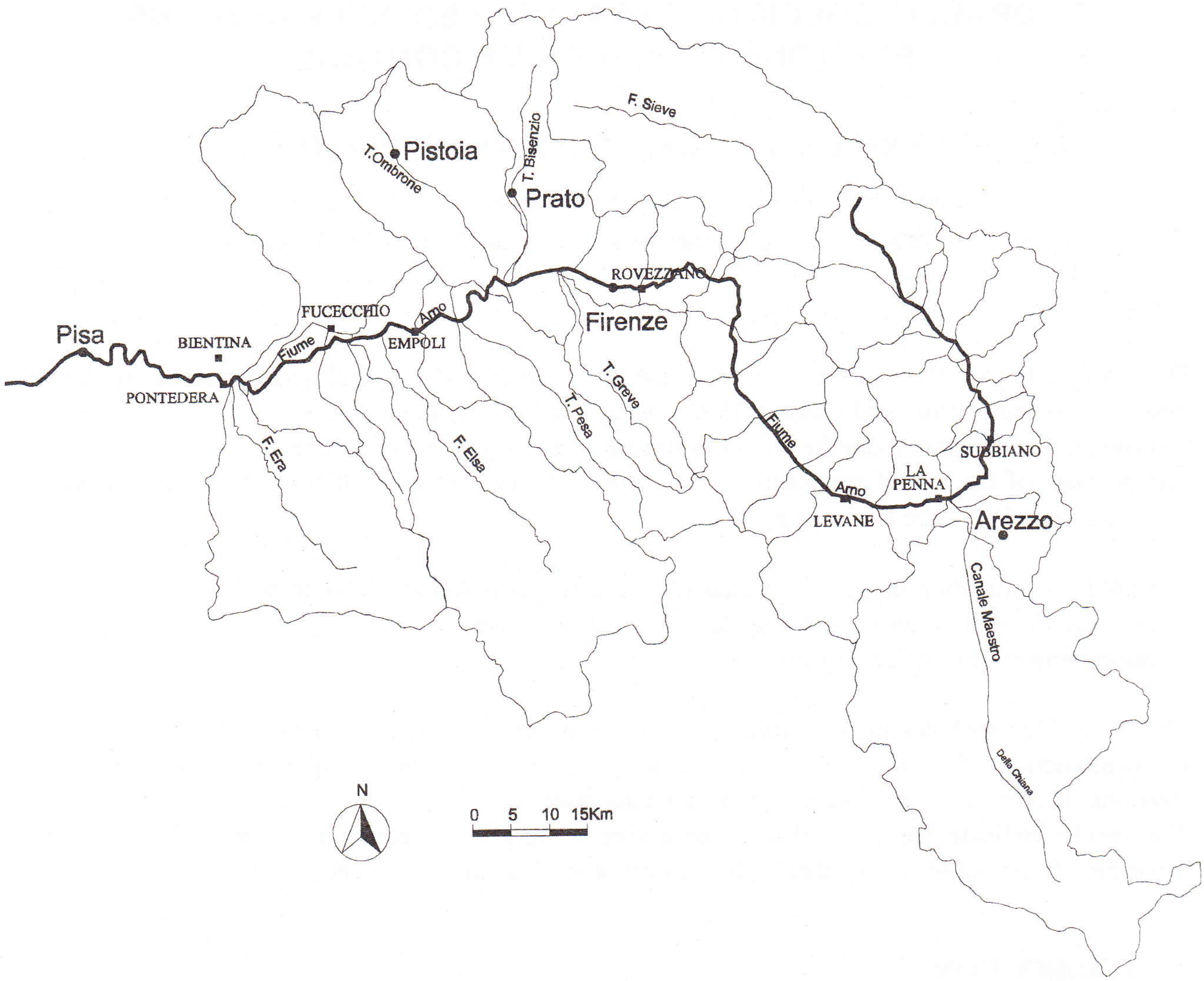

Figure 1. Arno River Basin

million m³

- a second diversion upstream Pontedera and discharging in Bientina swamp with a volume of storage of at least 30-40 Mm³
- increase of the discharge capacity of existing diversion at Pontedera.
- increase the storage capacity of the two existing dams of Levane and La Penna, to a volume of 43 Mm³

type c:

- improvement and restoration of the bank structurea in the critical river reaches.

2. FRAMEWORK OF ANALYSIS

2.1 Hydrologic model

The estimation of the flood discharge along the river reaches has been carried out through an hydrological rainfall model able to estimate discharges and their spatial and temporal variability from tributary areas.

The Arno basin was subdivided into approximately thirty sub-basins of variable dimensions, corresponding to the main tributaries and areas distributed along the river. Each sub-basin was discretized into elementary square cells 400x400 meter in size, corresponding to the mesh size of the Digital Terrain Model available for the regione toscana.

The DTM was verified and corrected in order to make it more suitable to hydrological simulations. In particular, the impluvium lines defining runoff pattern from a single cell up to the outlet of the basin were verified.

The hydrological model can be schematically definied as quasi-*distributed:* it can be distinguished components in the model of the *lumped* type (governed by singular parameters for the whole catchment) as well as of the distributed type (governed by parameters which are different from cell to cell).

From the conceptual point of view, runoff from each cell is simulated by a set of three elements:

- a linear model of the reservoir to represent the storage capacity of soil surface and drainage network;
- an infiltration model based on the equation of motion in unsaturated soil;
- a kinematic (or runoff) model according to which the contribution coming from the single cell is transferred to the river outlet with delay time proportional to the distance of the cell from the river outlet.

The model is based on a hydrologic balance, the time step being one hour.
The computational phases for each step of simulation are the following:

- estimation of spatial distribution of precipitations using statistical regression techniques applied to the available data;
- evaluation of infiltration;
- estimation of surface runoff;
- calculation of hydrograph at the outlet of the basin.

The model has been calibrated by evaluating a set of singular parameters in a heuristic way for each basin to minimize the spread between measured and calculated values.
With reference to Figure 2, the hydrological balance of the single cell can be schematically represented as follows.

The schematization of the processes of interaction between water and soil used in the model is derived from Green and Ampt (1911), and includes the application of Darcy's Law and the principle of the mass conservation.

Given the initial conditions of the soil water content W_O, at each time step *i* the balance of the volume of water that contributes to the efflux from every cell is up-dated in the following way:

(1) $$W_i = W_{i-1} - \left(\frac{W_{i-1} + W_i}{2}\right) KK + f_i$$

(2) $$W_i < 0 \Rightarrow \qquad W_i = 0;\ DD = W_i + I$$

(3) $$W_i > 0 \Rightarrow \qquad DD = KK\,(W_i + W_{i-1})/2$$

where*:*

W_i = unit volume at i-nth step [mm]
DD = hypodermic flow coefficient [mm]
KK = soil-saturation coefficient [-]
f_i = rate of infiltration [mm]

The rate of infiltration at the i-nth step is calculated as follows:

(4) $$I = f_i = K_s\left(1 + 2\frac{A}{W_{i-1} + W_i}\right)$$

where A [mm] is the soil capacity
This formulation is derived from Darcy's Law; for an unsaturated flow can be expressed as:

(5) $$V_z = K_h(\theta) - K_h(\theta)\frac{\partial\psi(\theta)}{\partial z}$$

where:

Vz = apparent velocity of water in downward direction [mm/h]
θ= water content [mm]
ψ= pressure head [mm H2O]
Kh = hydraulic conductivity [mm/h]

Expressing equation 5 in terms of finite differences, and applying between soil surface and the position *zf(t)* of wet front at time *t* , we have:

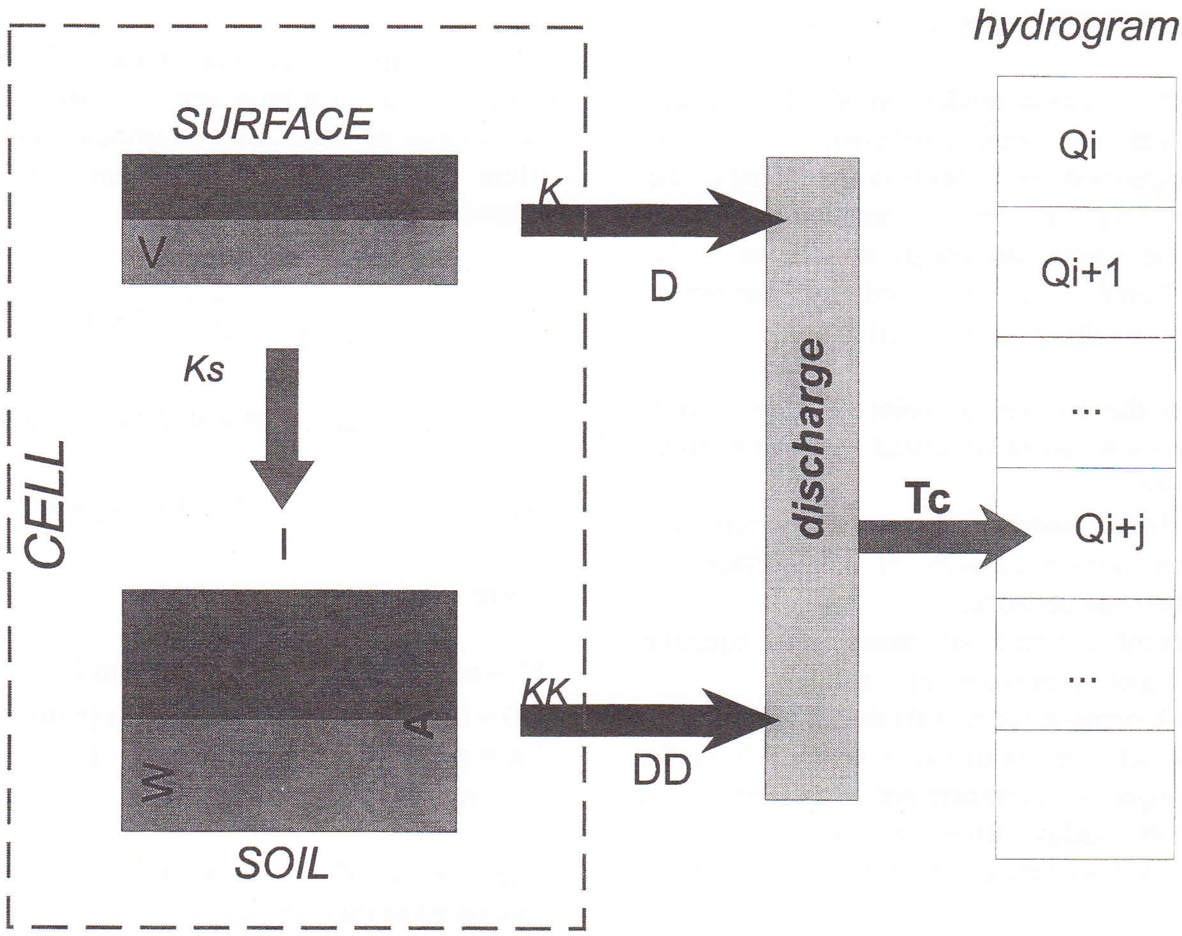

Figure 2. Scheme of the hydrological balance for a single cell

(6) $$V_z(0,t) = f(t) = K_h - K_h \frac{\psi_f - 0}{z_f(t)}$$

in which ψ_f is the effective pressure head at the wet surface . Keeping in mind that $\psi_f < 0$, equation 6 can be expressed as:

(7) $$f(t) = K_h \left[1 + \frac{|\psi_f|}{z_f(t)} \right]$$

Mass conservation principle requires that:

(8) $$F(t) = z_f(t)(\phi - \theta_0)$$

in which

F(t) = total amount of water that infiltrates at time *t* [mm]
θ_0 = initial water content[mm]

Therefore we have:

(9) $$f(t) = K_h \left[1 + \frac{|\psi_f|(A - \theta_0)}{F(t)} \right]$$

Equation (9) allows the calculation of the infiltration rate as a function of the total infiltration occurring at time *t*.

The second term in square brackets of equation (9) is a function of the ratio between the availability of soil storage and the quantity of water infiltrated in the soil. The numerator is replaced by parameter A, related to the characteristics of the soil; whereas in the denominator appears the water-soil content (average value between *i*-1-nth and *i*-nth time step).

Similarly to the soil balance, the evolution of surface volume is calculated as follows:

$$(10) \quad V_i = V_{i-1} - \left(\frac{V_{i-1} + V_i}{2}\right) K + p - I$$

$$(11) \quad V_i < 0 \Rightarrow V_i = 0 \; I = V_i + p \; D = 0$$

$$(12) \quad V_i < 0 \Rightarrow \qquad D = K(V_i + V_{i-1})/2$$

where *DD* and *D* are the two components of flow from each cell, and p is the precipitation [mm]. The contribution of each cell is transferred to the outlet taking in account the concentration time in the calculation of hydrograph.

The parameters of calibration are the following:

t_{corr}	concentration time coefficient [-]
K_s	infiltration coefficient in saturated conditions [mm/h]
A	soil capacity [mm]
W_o	initial soil-water content [mm]
KK	soil saturation coefficient [-]
K	surface saturation coefficient [-]

These parameters are characteristic of each basin and are calibrated in the application phase together with the hydraulic model in order to minimize discrepancy with measured hydrographs available in several gauge stations of the Arno river.

2.2 Hydraulic Model

A hydraulic unidimensional model has been set up to simulate unsteady flow conditions along the main stream.

In particular, the hydraulic model is based on the equations of De Saint Venant to describe the motion and the continuity for the water flow:

$$(13) \quad \frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} + q(x) = 0$$

$$(14) \quad \frac{\partial H}{\partial x} = -\frac{1}{g}\frac{\partial U}{\partial t} - J$$

where

- A = cross section [m²]
- Q = discharge [m³/s]
- q(x) = lateral inflow [m²/s]
- H = total head [m]
- g = acceleration of gravity [m/s²]
- U = average current velocity [m/s]
- J = head loss
- x = spatial coordinate [m]
- t = time [s]

Under the assumptions for the validity of equations (13) and (14), head losses are estimated as follows:

$$(15) \quad J = \frac{U|U|}{gC^2 R}$$

where R is the hydraulic radius and C is the nondimensional Chezy coefficient related to Gauckler-Strickler's coefficient Ks $[m^{\frac{1}{3}} s^{-1}]$ by the relation:

$$(16) \quad C = \frac{KsR^{\frac{1}{6}}}{\sqrt{g}}$$

In order to take in account the dissipitative effects induced by geometry variations of sections, such as expansions or contractions, the additional head loss ΔH has been calculated with the following formula:

$$(17)\quad \Delta H = \frac{Q^2}{2g}\xi\Delta(\alpha / A^2)$$

in which α is the kinetic energy coefficient and ξ can assume values between 0.1 and 0.8.

Solution of the above-described equations has been carried out by an implicit finite difference numerical scheme with appropriate boundary conditions. The total length of the mein stream has been divided in sub-reaches where the downstream boundary condition was in the form:

$$(18)\quad Q = a(h - h_0)^c + q_0$$

where a,b,c and q_0 are parameters of the rating curve.

3. CALIBRATION AND VERIFICATION OF TEH EVENT OF NOVEMBER 1966

The hydraulic and hydrologic models have been used to simulate the hystorical event of November 1966. To this purpose, hydrology, hydraulic, fluvial geometry and flood control works are all referred to conditions of 1966. Additional data have been collected from ENEL (1994), from Ministry of Public Works and from Ministry of Agriculture and Forestry (1969).

Particularly, hydrographs in the following sections were available: La Penna dam, Levane Dam, Rovezzano. Furthermore, estimations of the maximum water levels heve been collected at several sites upstream of Florence. It is worth to note that during the 1966 event, most of the gauge stations in the Arno basins were destroyed by the flood. The available hydrographs were therefore estimated on the basis of flood level marks.

The calibration of the hydraulic model has been based on the estimation of the roughness to attribute to the different fluvial reaches to get the best agreement with the available data.

For the reach Pratovecchio - Levane dam , a Gaukler-Strickler's coefficient equal to 24 gives the best results in terms of water levels and flood celerity. For the downstream reach a value of Gaukler-Strickler's coefficient of 30 was considered appropriate (this value corresponds to the one used in the IBM Mathematical Model of Arno Flood Study, 1978)

Ustream Levane and La Penna dams, the hydrologic-hydraulic model was calibrated using data at the Subbiano gauge station and the estimated hydrographs of discharges downstream La Penna dam.

From the flood levels at Subbiano, the Hydrographic Service estimated a flood peak of 2250mc/s, while the simulated value is approximately 1900mc/s. Figure 3 shows a comparison between estimated and simulated discharges downstream La Penna.

Hydrographs show a rapid rising phase, followed by a peak value of about 2500 mc/s, and a decreasing phase relatively slow.

Figure 4 shows the estimated and simulated hydrograph downstream Levane dam. In both cases the agreement can be considered good.

Figure 5 shows the comparison between estimated hydrograph by prof. Cocchi [..] and that one simulated by the model. An optimal agreement is observed.

In Table 1, the calculated and estimated water levels values are shown.

Even if some discrepancy exists, it must be remember the uncertainty connected to the available data and to a precise recontruction of the territorial, morfological and hydrological conditions of 1966.

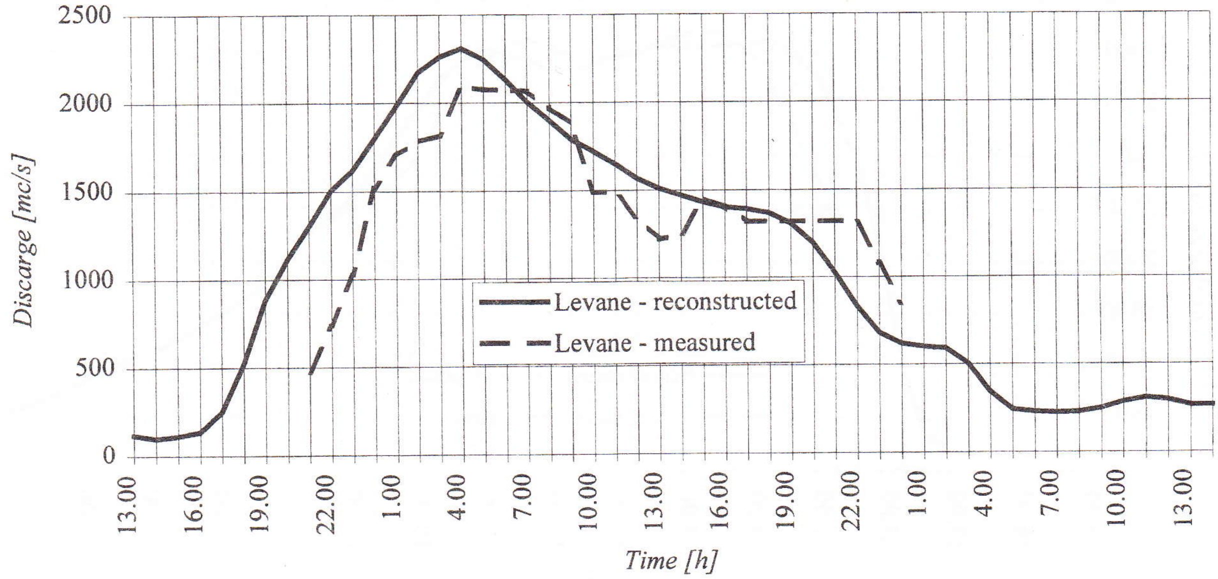

Figure 3.Arno at Levane - Measured and simulated hydrographs

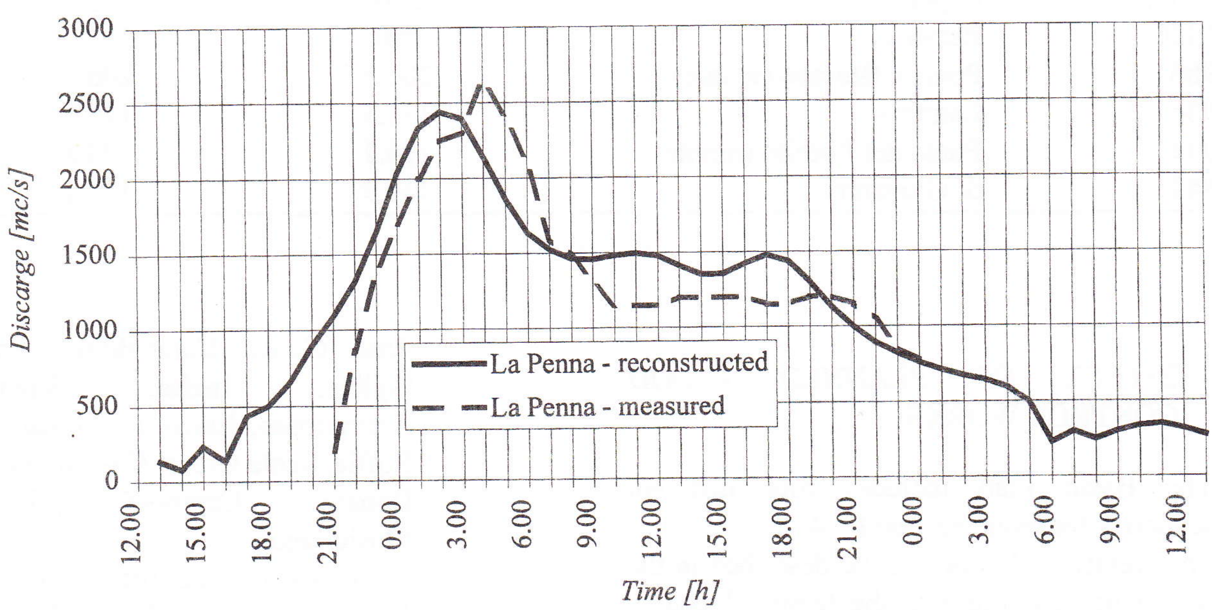

Figure 4 .Arno at La Penna - Measured and simulated hydrographs

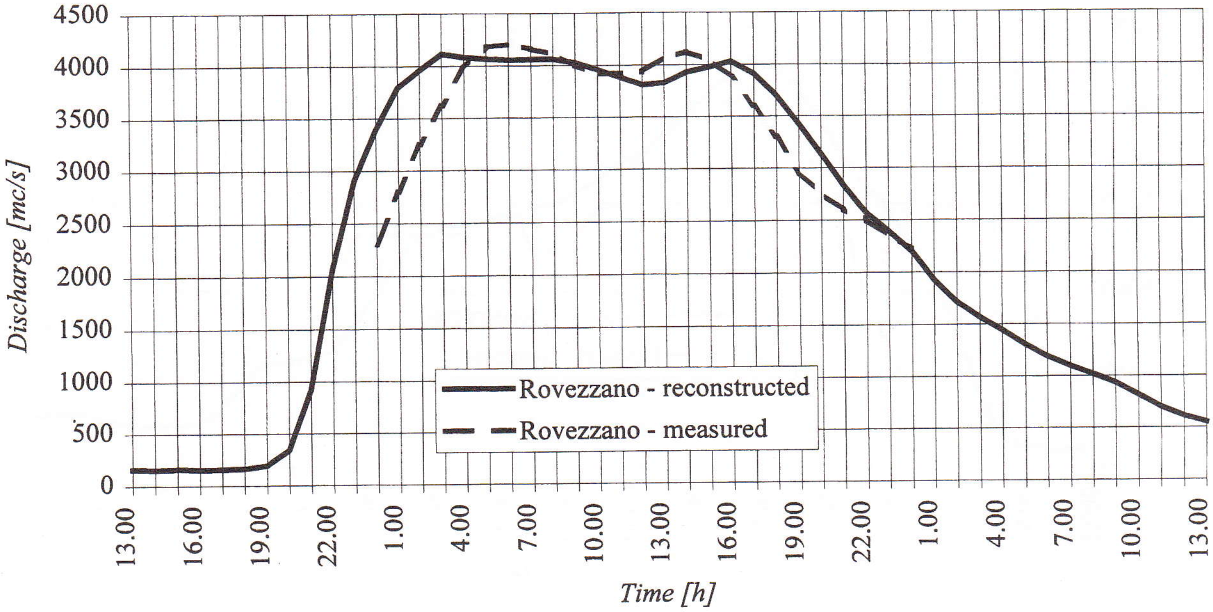

Figure 5 .Arno at Rovezzano - Estimated and simulated idrographs

Table 1. Comparison between measured and calculated hydrometric height

n. of river section	Name	Estimated level [m.s.l.m.]	Simulated level [m.s.l.m.]
1530	Campaldino	348.8	349.2
1450	Poppi	326	325.7
1320	Rassina	290	290.4
986	Ponte a Buriano (monte)	206.5	206.8
936	Laterina	175.5	175.8
933	Ponte del Romito (monte)	174.2	174.8
842	S. Giovanni	130.9	132.1

4. EFFECT OF PLANNED FLOOD CONTROL WORKS

The Basin Plan includes four different scenarios for reducing flood risk
For brevity, only one will be described in the following, according to the temporal phases of realization of the planned flood control works.

Phase 1 *Dams:* La Penna (dimension 209 m slm), Levane (dimension 172 m slm);
Arno Cases: Campaldino, Poppi, Figline, Incisa, Rignano, Argingrosso, Renai 1, Fibbiana, La Roffia, Santa Croce, Castelfranco, S. Donato, Campo-S. Jacopo, Musigliano;
Tributaries(*): Ambra 50%, Sieve 50%, Greve 25%, Pesa 25%, Elsa 25%, Era 25%, Bisenzio 25%, Ombrone 25%.

Phase 2 *Flood-ways:* Fucecchio, Bientina;
Tributaries: Ambra 50%, Sieve 50%, Greve 25%, Pesa 25%, Elsa 25%, Era 25%, Bisenzio 25%,

Ombrone 25%.

Phase 3 *Arno Cases:* Pratovecchio, Bibbiena, Corsalone, Rassina, Castelluccio, Renai 2, S. Colombano;
Tributaries (*): Solano 100%, Coralone 100%, Chiana 100%, Greve 50%, Pesa 50%, Elsa 50%, Era 50%, Bisenzio 50%, Ombrone 50%.

(*): the percentage refers to the portion of the total works planned on the tributaries.

Some results obtained by considering the planned works are shown in figures 6-7, where flood hydrographs in two sections, one upstream Florence (Rovezzano) and one upstream Pisa (S.Giovanni alla Vena), are compared.
Hydrographs refer to the actual conditions and to the planned conditions in order to show the effects induced by th eplanned works.
The 1992 event has been simulated only for the Phase 1, while the 1966 event for Phase 1, 2 and 3.

Phase I
Event type 1992. Flood discharges are generally contained in the main channel. Reduction of water level upstream Florence is due to the effects produced by Levane and La Penna dams. Downstream Florence the main effect on peak flow mitigation is substantially due to the storage areas of Renai and La Roffia.
Event type 1966. Flood control works planned in Phase 1 allow a significative reduction of peak flows consequent to events similar to 1966 one. For example, at Incisa site the simulated maximum discharge is about 2.280 m^3/s (in 1996 it was 3.300 m^3/s), whereas at Nave di Rovezzano is 3.400 m^3/s (4000 mc/s in 1966)
Downstream Florence, hydraulic conditions remain generally critical, with many areas subjected to inundation.

Phase II
Event type 1966: flood discharge at Nave di Rovezzano is 3100 m^3/s. Downstream Florence the maximum flood peak is about 4200 m^3/s in Marcignana. The storage areas are all saturated (included Fucecchio and Bientina areas) , but still estensive inundation occurs.
Peak flow at S. Giovanni alla Vena is about than 2400 m^3/s.

Phase III
Event type 1966. Maximum discharge at Nave to Rovezzano reduces to 3000 m^3/s. Downstream Florence discharges are everywhere less than 3700 mc/s.
The maximum flow at S. Giovanni alla Vena is about 2200 m^3/s.

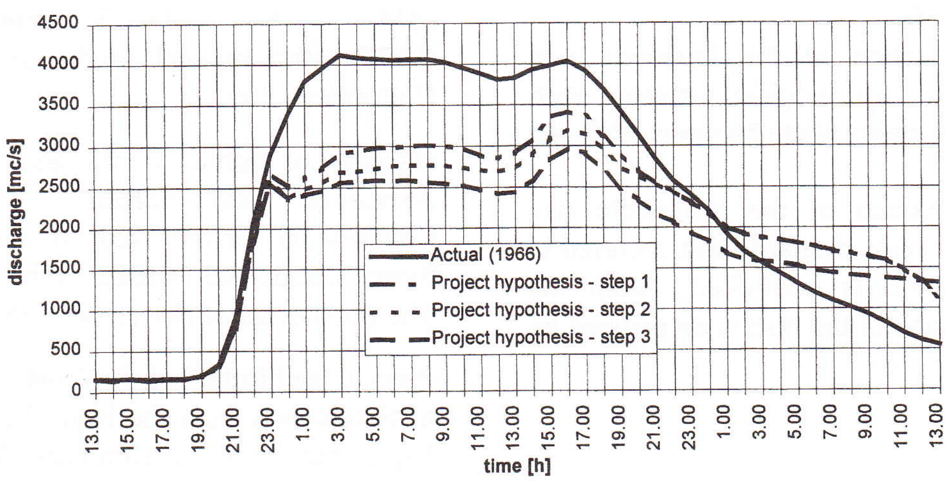

Figure 6. Hydrograph of event 1966 - Arno at Rovezzano

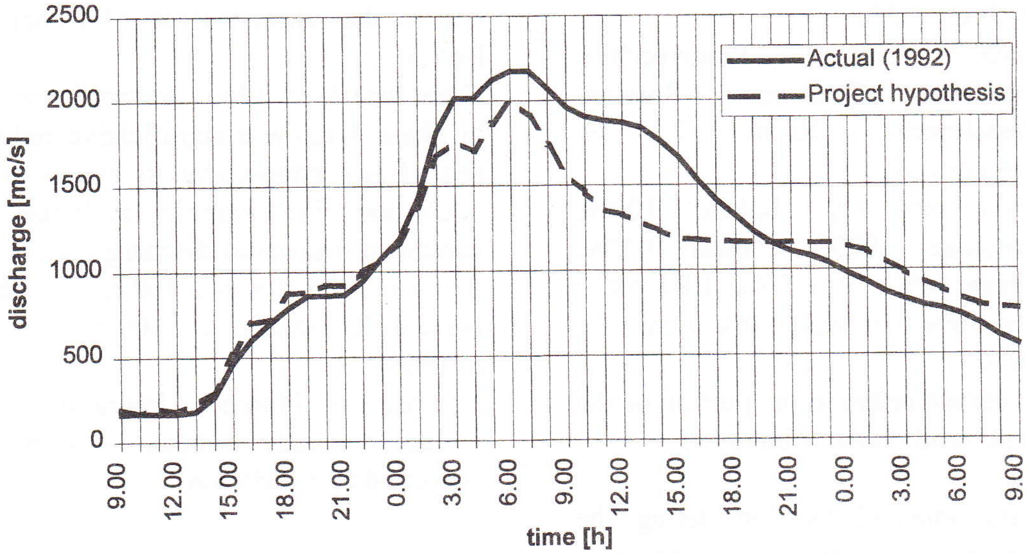

Figure 7. Hydrograph of event 1992 - Arno at Rovezzano

CONCLUSIONS

The dynamic of flood flows in the Arno River has been studied by a hydrological-hydraulic model able to simulate the generation and propagation of flood along the main course of the river.

After calibration, the model has been used to evaluate the effetcs induced by the flood control works palnned in the Basin Plan.

Results show a significative mitigation of peak flows if flood control works are taken in account in the simulation. Particularly, in the three phases of the Basin Plan we note:

Phase 1: reduction of the hydraulic risk associated to hydrologic events similar to that occurred in 1992;

Phase 2: reduction of the hydraulic risk associated to hydrological events with characteristics intermediate between 1992 and 1966 events;

Phase 3: reduction of the hyadraulic risk associated to events similar to that occurred in 1966: inundation is controlled within the storage areas and in the reservoirs planned by the Basin Plan.

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ENVIRONMENTAL IMPACT AND POSSIBLE DEVELOPMENTS IN THE BASIN OF THE RIVER ARNO, IN RELATION TO THE PROPOSED INTERVENTIONS FOR THE REDUCTION OF THE FLOOD HAZARD

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The project for the Basin of the river Arno forsees the realization of hydraulic interventions along the course of the entire river for the reduction of flooding risks.
These intervention, in semi-urbanized or agricultural areas, must be planned in context with a systematic re-modelling of the fluvial territory, compatible with the ecosystem and social economic resource.

The hydrographic basin of the river Arno, is almost entirely situated within the administrative boundaries of the Tuscan Region and concerns eight provinces out of nine, even though some, only marginally.
The population of the Arno basin amounts to roughly 2.500.000 inhabitants. They are concentrated within the urban areas, (conurbations) along the major valleys: in order of importance we firstly have the conurbation Florence, Prato and Pistoia, in the major central valley in Tuscany, the conurbation Pisa and Livorno, then those of the lower Arno valley from Empoli to Pontedera; subsequently those of the higher Arno valley with Figline and San Giovanni. It is in these conurbations that the largest number of industries of Central Italy, are situated with a special stress on textiles (Prato) and leather (Empoli - Pontedera).
The Arno also crosses two major art cities, celebrated world over, such as Florence and Pisa, and many other smaller centres of great historical importance and interest.
The Arno basin territory is thus articulated:
- total surface measures
9116 sq.k.
- farmland
47,35%
- woodland
38,40%
- the remaining urban or semi urbanized surface 14,25%

The aforesaid territory is protected from an environmental and landscape point of view, in the entity of 33% of the total surface via a series of ties and restrictions of these one must consider a 9,40% of strictly controlled land and a 23,60% of less rigoronsly controlled land.
These restrictions mostly concern woodland areas.
During the last major flooding episode, in 1966, the percentage of flooded area was 3,50% of the total surface. The florentine flood, considered exceptional as far as entity and damages were concerned, was one episode besides which there have been other 8 similar ones over the last nine centuries (from the XIIth century to the present day). However, contemporarily there have been a further 56 floods of minor entity in the city's historic centre.
More or less the same has happened in Pisa.
The worst damage concerns the artistic heritage on perishable support (such as paintings on canvas, pictures on wood, manuscripts and prints on paper or similar materials), as also happened during the 1966 flood.

With the progressive impermeabilization of the valleys along the rivers, due to the ever growing urbanization which has been taking place over the last 40 years, there has been an increase in flooding risks especially in the more vulnerable parts of the territory.

This rise in the risk factor is due to several elements such as the diminishing of the number of farmers in hilly and mountainous areas, with the subsequent decrease in the control of the waters in uncultivated areas.

Another central factor which increases the risk of flooding, is the deep change in the agricultural production - systems, that often ruin the small infrastructures for the interception of water and interfere with the land structure in such a way that they contribute to the quick flowing of surface waters towards torrents and rivers.

Therefore the most fragile surface of the basin is that 14,25% that is where there is a larger concentration of population, industry and a consistent percentage of historic, artistic and architectural patrimony.

An approximate calculation allows us to asses that a 12-15% of this "fragile surface", was interested by the 1966 flood.

On the contrary, only the 3-4% of the total farmland of the Basin was affected by that same flood.

Basing ourselves on this element we can come to the conclusion that the safeguard and the re-balancing of the more fragile territory cannot take place within that surface but only by involving external areas.

The Project for the Basin which has now been adopted, now concerns areas for the diminushing of the flood hazard, which total circa 200 Sq.K. equal to 2,20% of the total surface of the basin and therefore below the 3,51% of the territories flooded in 1966.

The Project includes the installment along the course of the Arno, of 22 accumulation tanks, for excess water, varying from a minimum capacity of 1 cubic metre to a maximum of 18. It also includes the use of the already existing reservoirs of Levane and La Penna for the containing of the flood and the realization of further infrastructures such as for the use of the Fucecchio and Bientina marshes.

This series of interventions, has given way to a parallel study on environmental impact, based on the analysis of a certain quantity of characteristic environmental situations, from which to draw general operational strategies.

The study of the environmental impact may appear minimal if one compares the punctual projected remedies to the general lowering of the flood hazard in the large urban areas round Florence and Pisa.

In the present case it appears to be more of a study for the support and the handling of the on sites operational phase.

This appears even more clearly in the goals set by the Project:

1) Reduction of the flood hazard, stability of the riverbed and the planeland crossed by rivers.
2) Reduction of the hydrogeological risk, planning of the forest hydric arrangement, stabilily of the slopes.
3) Reclaiming of the degraded areas characterized by the presence of rivers, and polluted soil and distinguished by landscape and environmental alterations.
4) Reduction of pollution in rivers and streams, re-adjustment of the water purification systems, safeguarding of aquatic life.
5) Availabilily and quality of underground hydric resources.
6) Utilization of the hydric resources of industrial, agricultural and energy production purposes as well as for human consumption
7) Re-organization of the open quarries and their limiting, via a readjustment of the environment
8) Rubbish disposal
9) Subsidence

10) Protection of historically and archaeologically important sights and creation of special protected areas with parks and nature reserves.

It becomes evident from these goals, that the Project for the Basin is effectively an integrated plan for the re-claiming of the entire territory along the river Arno. As such, the principal aim is that of the restoration of the ecosystem and its conservation and improvement via financial investments compatible with the social economic and cultural needs.

The balance between the entity of the spendable budget and the quality of the results is at present being evaluated by a modern society via a series of instruments in its possession, amougst which the study of environmental impact.

The result of this choice will be a Program of Sustainable Development so as to meet the goals of the Project, with reference to the urban environmental set-up of the territories involved.

The analysis of the fluvial landscape gives us a picture of a degraded river: where if flows alongside agricultural areas, it presents continuous erosions of the banks. The flood-plains are subject to excavations or plantations of unappropriate shrubs or trees. There are trees grown on gravel deposits along the margins of the riverbed. There are numerous sand excavations in the areas adjacent to the banks or in the alluvial areas nearby, or in old inlets of the river filled with sediments. Close to the built up areas, the banks are often used as rubbish dumps or scrap deposits. Here one can easily come across some old industrial plants no longer in use and abandoned quarries. In the urban centres the river is canalized, in the planes it is embanked. In short, great part of the river course is denaturated.

The areas analyzed territorially for the placing of the accumulation tanks are grouped into 4 types:

1 - Uncultivated or degraded areas (usually with illegal rubbish dumps)

2 - Para-agricultural areas close to urban zones, with sporadic infrastructures

3 - Agricultural areas intermingled with unusual elements such as open quarries for inert materials

4 - Agricultural areas with herbaceous, extensive or cultivated plantations.

The most past of the controlled areas in the Project for the Basin, belong to type 1 and 2; there are several areas of type 3; type 4 essentially covers those areas which are cultivated with herbaceous plantations.

In a few of these areas there is the further problem concerning the safeguard of the buildings of historic-architectural value.

The areas on which a particular attention is concentrated are those which present a higher environmental relative sensitivity: within a plan for the active handling of a flood hazard, infact, one could hypothesize that in single segments of the river (higher, medium and lower course of the stream), in case of flood the tanks to be filled first are those with less environmental quality preserving the better ones with a lower flooding frequency.

However the more consistent part of the interventions will be concentrated on the requalification of the environment, especially in those areas closest to the urban centres.

This theme is today being strongly developed. It is no longer sufficient simply to plan the re-arrangement of an area, but the latter, must also integrate itself fully in an ecosystem where the purely hydraulic elements of the problem, match territorial, landscape and naturalistic features.

We therefore can find examples of fluvial re-modelling where the concrete embankments are removed and replaced by embankments constructed with natural materials: it is the case in Gelsenkirchen in Germany.

In many areas, the problem one is faced with, is the compatibility of these remedies with the hydraulic functions, which after all, will be the major one,

because the minimum flooding frequency is forseen in the measure of twenty years and the permanence of the water, only in the measure of a few days.
It is obvions that the remedies chosen, include a re-modelling of the territory with a subsequent appropriate choice of shubbery and trees to be planted. A purely technical hydraulic project could turn out to be a bad environmental product.
Due to the series of environmental and landscape ties on the territory treated, one might envisage a series of Regional Fluvial Parks, such as those which can be found in northen Italy along all the major rivers in Lombardy totalling 1400 Sq.K.
This might also lead to new forms of local economy connected to leisure time.
All the projects for the hydraulic re-arrangement of the territory, must be interpreted as programs for the "re-naturalization", and re-vitalization of the water courses, starting from the present situations, even though they may be degraded, and working towards a compatibility with the territorial structure: one cannot reclaim territory via artificial means, disregarding a "historic fluvial layout", but one must try on the contrary to establish a new development process ecologically oriented.
It is along these lines that a series of "fluvial revitilizing" projects have been carried out in Germany: a project on the river ISE, 42 K long, in lower Saxony, with a basin of 420 Sq.K.; a much larger one, in the Ruhr basin: this includes the rivers Ruhr, Emsher and Lippe, with 53 municipalities, 4400 Sq.K. of territory, a population of over 5.000.000 inhabitants. In other words it is half the size of the Arno Basin and counts double the population in a region where the industrial pollution is at very high levels.
The re-modelling of the fluvial environment and the planning of the ecosystems are the projectual answer for the re-balancing of territorial system such as the Arno Basin.
The Project for the Basin is the guiding reference point for the next fundamental operational and handling phase.