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Dredging of Navigable Canal in the Venice Lagoon
Dragage du canal de navigation dans la Lagune de Venise
Ausbaggerung schiffbarer Kanal in der Lagune von Venedig

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SUMMARY

After a short description of the general design for the safeguard of Venice, an improvement is suggested, in order to reduce the impact of the newly-designed works on the ship traffic in the lagoon. In this context, a link of "barene" should be built along the existing channel Malamocco-Marghera, with two minor barrages across the Canale Rocchetta and the Canale Vittorio Emanuele. Computations show that it is possible to reduce substantially the closures of the Malamocco mouth, conserving practically, at the same time, the actual hydrodynamic situation.

Dragage du canal de navigation dans la Lagune de Venise

Résumé

Après une description du plan pour la protection de Venise, l'article présente une amélioration destinée à réduire les effets des nouveaux ouvrages sur la navigation dans la Lagune. La nouvelle idée consiste en la formation d'une chaîne de "barene" du côté du Canal Malamocco-Marghera avec la construction de deux barrages à travers le Canal Rocchetta et le Canal Vittorio Emanuele. Les calculs effectués indiquent qu'il est possible de réduire sensiblement les manoeuvres de fermeture de l'embouchure de Malamocco, tout en respectant la situation hydrodynamique actuelle.

Ausbaggerung schiffbarer Kanäle in der Lagune von Venedig

Zusammenfassung

Nach einer kurzen Beschreibung des allgemeinen Projektes für die Rettung von Venedig, präsentiert der Artikel einen Verbesserungsvorschlag, um die Auswirkung der neuen Bauten auf die Schiffahrt in der Lagune zu vermindern. Die neue Idee besteht in der Gestaltung einer "Barene"-Reihe entlang des Malamocco-Marghera Kanals mit dem Bau von zwei Sperrwerken durch den Rocchetta und den Vittorio Emanuele Kanal. Berechnungen zeigen, dass es so möglich ist, die Zeit, die für die Schliessung an der Mündung des Malamocco benötigt wird, substantiell zu verringern, dabei aber zugleich die aktuelle hydrodynamische Situation zu wahren.

1. INTRODUCTION

In november 1966 an extreme storm tide, whose peak at Punta della Salute, in the centre of Venice, reached the level of 1.94 m, flooded nearly completely the city. It was the first dramatic alarm of the "high-water" phenomenon, that in the following years occurred repeatedly, threatening public opinion, very sensitive to the safeguard of the historical and cultural heritage, represented by Venice for the whole world.

At present S. Marco Square, that is the heart of Venice, is inundated when the tide levels exceed 80 cm above the Punta della Salute tide gauge reference level, but a large part of the city is flooded with tide levels higher than 1.00÷1.10 m.

In the 1975-85 decade as much as 450 tide events exceeded 80 cm at Punta della Salute and, among them, about a hundred reached levels higher than 1.00 m.

The reasons of Venice submersion, that at the beginning of the century was a much less frequent phenomenon, are numerous and complex. Above all, the natural causes related to the joined effects of soil lowering and mean sea level raising, that can be estimated in total as 25 cm. have to be considered

Nevertheless, although with minor effects, the negative consequences of human intervention, that has deeply modified the lagune morphology, has also to be considered.

Among them the sea-entrances protection with jetties, the dredging of the navigable channels Vittorio Emanuele first and Malamocco-Marghera later, the extensive reclamation of shallow water areas for the formation of nine Industrial Zones of Marghera (Fig. 1).

During these years, many studies have been carried out in order to characterize the feasible interventions to defend the city of Venice and its lagune from the phenomenon of flooding.

However all the promoted proposal collide with the difficulty of conciliating the requirements of safeguard and protection of the peculiar environment where the city of Venice is located, with the not minor requirements, of not obstructing more than a certain limit the economical and productive activities that still concern Venice and its lagune. In such a context, it is especially felt the necessity of maintaining the port feasibility permitting even to the higher tonnage ships to enter the Porto Marghera Industrial Zone, along the navigable channel connecting this productive pole to Malamocco Entrance (Fig. 1).

2. THE ACTUAL PLAN FOR THE PROTECTION OF VENICE FROM FLOODING

The many studies, even those carried out with the aid of the most advanced and sophisticated tools of investigation, agree on the impossibility of obtaining a significant reduction of the "high-water" phenomenon within Venice lagune and in particular in the historic centre, without a drastic reduction of the cross section dimensions of the sea entrances.

However, if this action on one side could permit to solve the problem of the mean high water events, on the other side it would involve serious consequences either for the environmental aspects or for navigation and, therefore, for the port practicability.

A significant decrease of the maximum tide levels, obtained by means of a reduction of the sea entrances dimensions with fixed structures increases, as a matter of fact, considerably the current

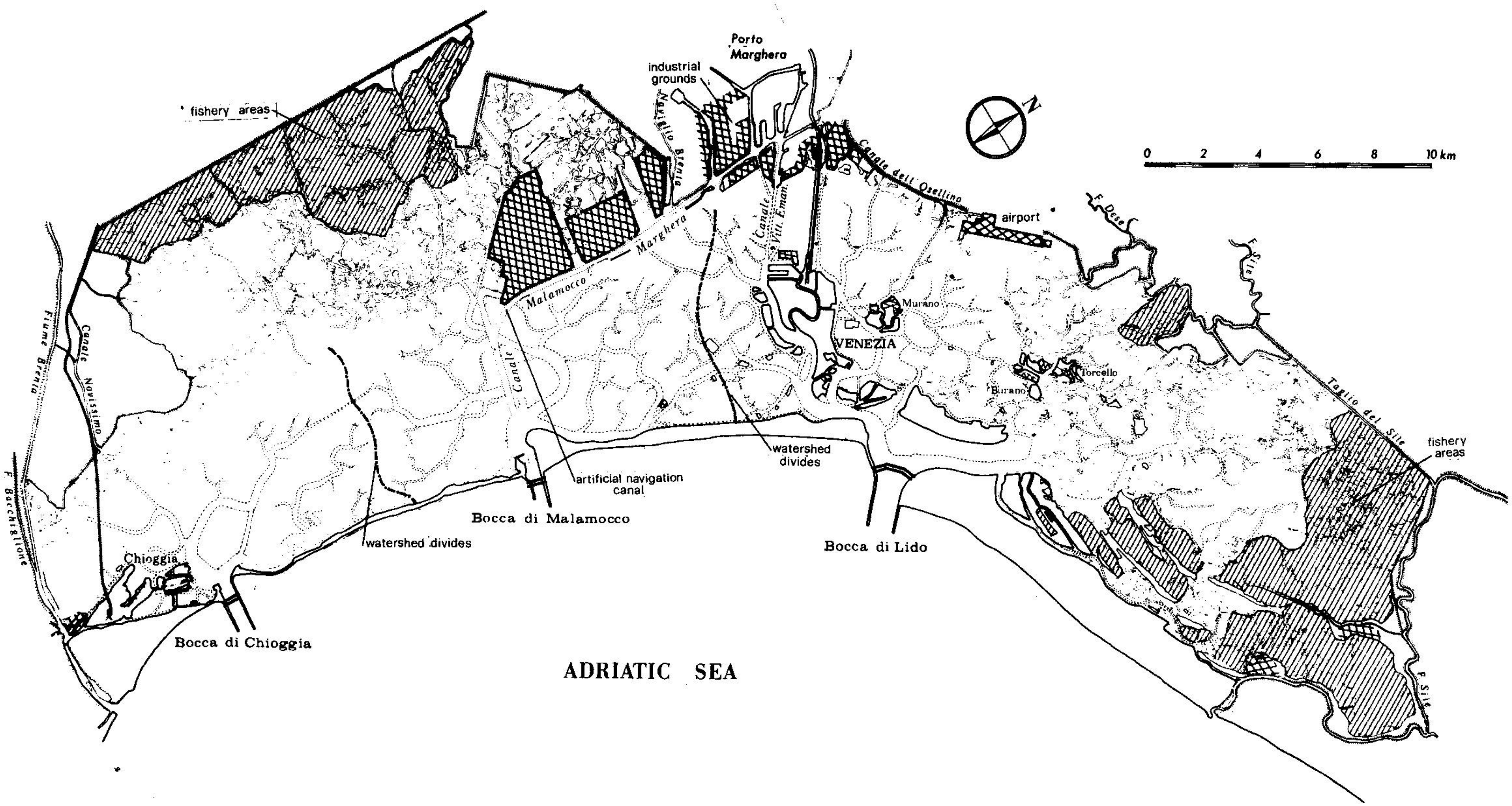

Fig. 1 A general map of the lagoon of Venice. The designed barrages in the mouths are also indicated.

velocities through the mouths even during the phases of maximum flux or ebb of the normal tides and it reduces noticeably the volumes of water exchanged between lagune and sea. While the first effect penalizes heavily the navigation, the second alters negatively the delicate balances,that already seem precarious, of the lagunar ecosystem, even though the water volumes exchanged with the sea during a normal spring tide is of the order of $300 \cdot 10^6$ m^3 and the sum of the maximum discharges exceed 20000 m^3/s.

The fear of modifying the tidal currents present capability to enliven even the most remote zones of the lagune from the mouths (in hydraulic sense), directed Consorzio Venezia Nuova, resposible for the project, toward a solution aimed, above all, to not alter, in any way, the water volumes exchanges between the lagune and the sea in normal tide conditions.

At this purpose it is foreseen the construction, at the three mouths of Lido, Malamocco and Chioggia, of three barriers consisting of a series of mobile gates, that lie on the bottom of the canals during the normal tidal conditions and are regulated until complete closure of the three entrances when the tidal level at Punta della Salute (Venice) exceeds 80 cm, in order to isolate completely the lagune from the sea.

Beyond the cost of the constructions, the principal negative aspect presented by this solution regards the obstacles to the navigation involved. It is sufficient to remind, referring to the decade 1975-85, that to avoid more or less extensive floodings of the city, the barriers at the mouths should have been operated nearly 450 times, avoiding the ships access to the lagune during the manoeuvres.

The negative inference due to the barriers presence on the harbour activity spreads, however, much beyond the time strictly necessary to the regulation manoeuvres.

The presence of the barriers and the relatively high frequence of the manoeuvres constitutes a psychological and not negligible deterrent.

Facing the possibility of not to be able to access the port, in fact, it is not improbable that a part of the traffic, once directed to Venice, chose as port of attrack another harbour in the Northern Adriatic Sea feasible with any tide condition.

3. THE PROPOSED DESIGN SOLUTION

The negative consequences on the navigation and on the harbour praticability involved by the proposed planned solution for defending Venice and its lagune from the phenomenon of flooding, leaded to examine the feasibility of an intervention complementary to the foreseen barriers at the sea entrances, in order to reduce significantly the number of manoeuvres of complete closure of the mouths, still maintaining the harbour feasibility. The proposal that herein is illustrated is based on the following observations:

- For the protection of the peculiar ecological system represented by the Lagune of Venice, are not possible interventions carring to a permanent or temporary partition of the lagunar basin;
- The Malamocco-Marghera and Vittorio Emanuele navigable channels constitute preferential ways of propagations along which the tide wave penetrates quickly from the sea into the lagune, exalting the inertial phenomenon, tending to raise the maximum levels, and reducing, on the contrary, the dissipative effects of the flow, tending to attenuate progressively the tide peaks. The presence of the two navigable channels and in particular of the Malamocco-

Marghera channel has noticeably modified the tide currents regime in the central part of the lagune, where the bottom depths have been subject during these years to a progressive deepening. Consequently it seems to be desirable whatever intervention orientated to reduce the effects due to the two channels existence and aimed to bring back the hydrodynamic behaviour of the central part of the lagune towards the once existing;

- Passing through the sea entrances, going from outside into the lagune, the maximum tide levels are reduced because of the significant flow resistances encountered by the tide wave in its propagation. The effect is the more emphasized the more, under the same conditions, is the dominated free surface extention;
- The most part of the events causing the flooding of Venice have maximum levels lower than 1.10 m, while the tide peaks exceeding such limit are relative rare (in average 4÷5/year).

Once taken into account all the above considerations, the design solution coming up is synthetically illustrated in Fig. 2. It substantially requires the realization of some interventions complementary to the sea mouth barrage works, already planned.

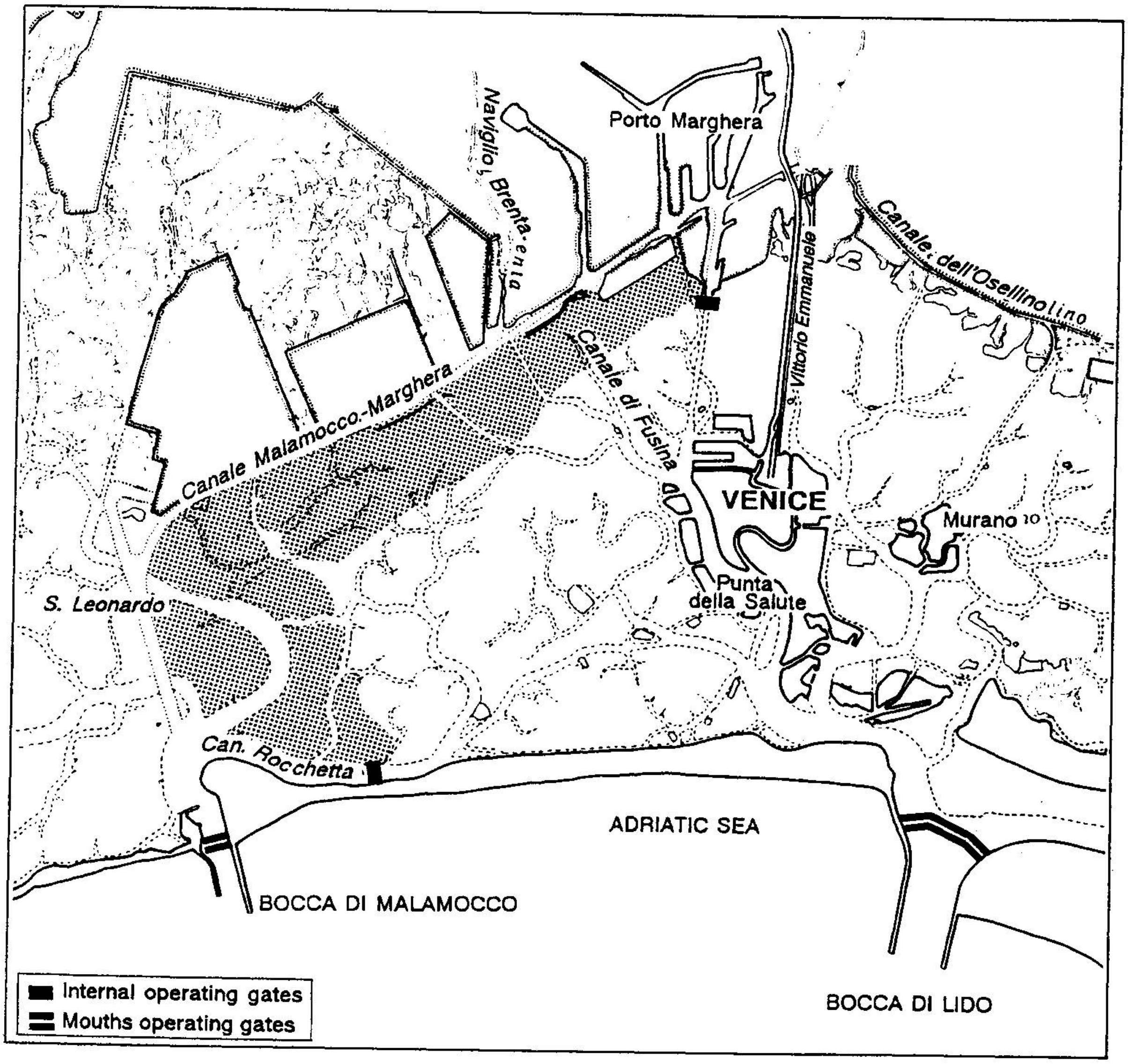

Fig. 2 A map of the central part of the lagoon showing the design solution.

In particular, the construction of a minor barrage, regulated by gates, is planned to limit the effects of the fast tide propagation along the Malamocco-Marghera navigable channel.

The same intervention is planned on the Rocchetta channel (Fig. 2), that links the Malamocco entrance to the basin dominated by the Lido mouth.

The realization, along the Malamocco navigable channel, of a strip of sandbanks (named "barene") nearly 1 km wide, obtainable raising the present bottom , deep 1÷1.5 m, to a level of 0.00÷0.10 m above the mean sea-level, is considered together with the two barrages.

This sandbanks strip, overflowed during the high tide phases, even if crossed by a series of minor canals, linking the Malamocco-Marghera channel to the central basin, reduces the direct influence of the channel itself on the tide currents regime in the whole central part of the lagune, promoting expecially in this zone the water feeding coming from Lido mouth.

The realization of these complementary works permit a different managent of the existing barriers at the three sea entrances.

For the tides with maximum heights up to 1.00÷1.10 m the limitation of the water levels in the the centre at Venice to values below 0.80 m could, in fact, happen with a regulation consisting of the complete closure of Lido mouth together with an analogous operation on the two internal barrages, but leaving completely open both Chioggia and Malamocco mouths. The barriers foreseen for these two mouths should be operated only when the provided regulation could not allow to limit the water levels in the centre of Venice below the specific value of 80 cm.

Operating in this way, for a wide range of events presently causing the flooding of a part of the city, it would be possible the limitation of the maximum water levels within the provided limits, maintaining the port feasibility and penalizing the navigation along the Malamocco-Marghera channel during only few days per year, that is at the occurence of the extreme storm tides, when it would be necessary to proceed to the complete closure of all the three barriers at the mouths.

4. EFFECTS OF THE DESIGN SOLUTION ON THE GENERAL AND LOCAL TIDE CURRENTS REGIME WITHIN THE LAGUNE

The effects due to the complementary works and the proposed regulation on the lagune regime, and in particular on the tide levels behaviour in Venice, were examined with the aid of two mathematical models set up on behalf of Consorzio Venezia Nuova by Ipros (Padova) and its consultants.

The first is a one-dimensional model [1], [2] simulating the non steady flow of the lagune by means of a net of multi-connected channels (Fig. 3).

From a physical point of view, it is based on the peculiar lagune morphology where the many actual channels, endowed with deeper dephts, constitute preferential propagation directions for the tide wave, while the contiguous water zones or sandbanks characterized by shallow dephts act prevalently as storage. In the model these shallow zones contribute at most to convey the flow in the sole direction of the feeding channel.

The structure of the one-dimensional model permit to describe the effects due to manoeuvres of the barriers at the mouths or of the internal barriers, on the basis of a connection between the flowing

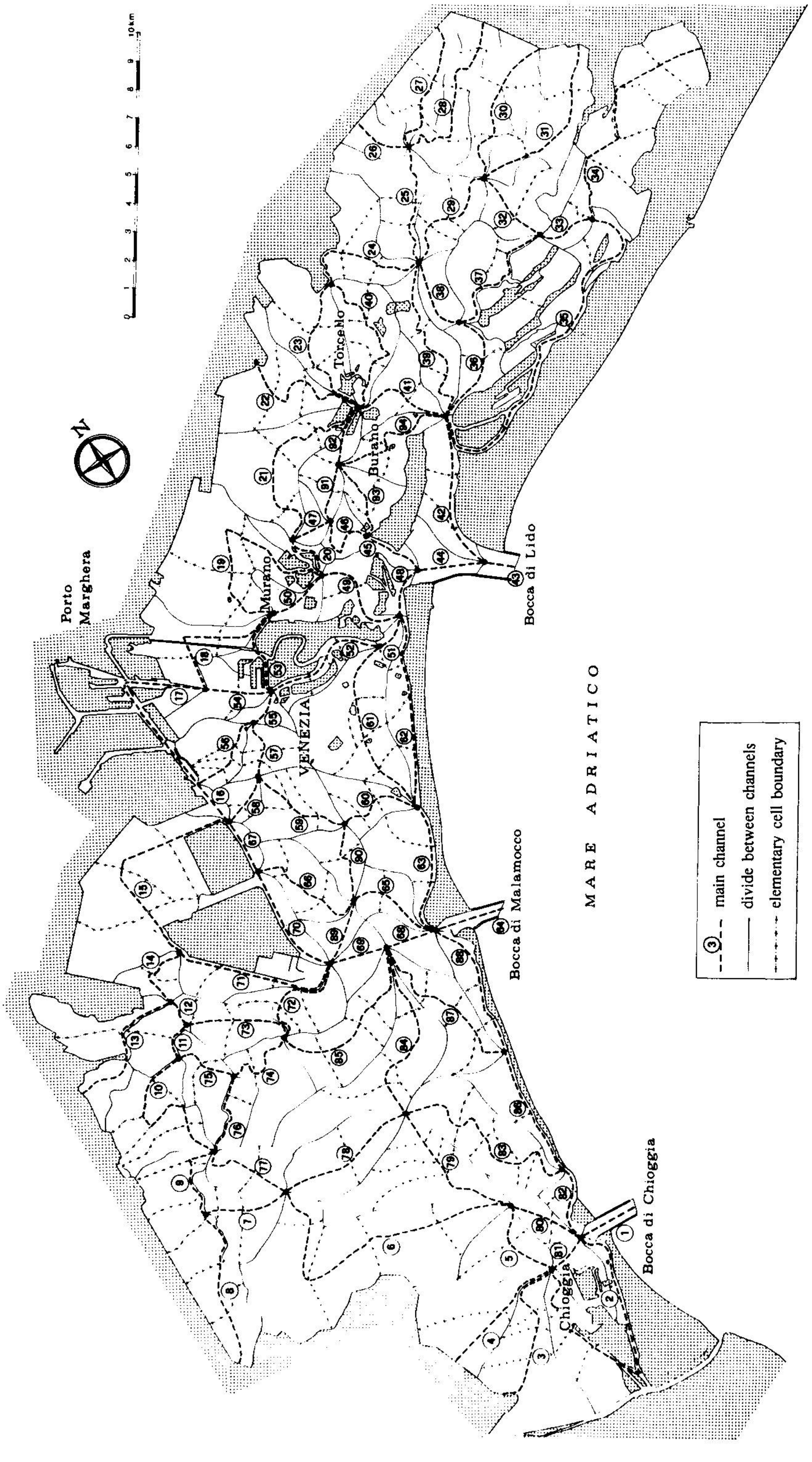

Fig. 3 The scheme of the one-dimensional mathematical model.

discharges and the instantaneous water level differences, coming out between upstream and downstream of each barrage, that depend on the particular geometry of the works.

The bidimensional model used is, instead, a finite elements model [3], particularly suitable for describing the complex lagune geometry, considering, not only the presence of the principal channels but also of the minor (Fig. 4).

The equations of motion of a long wave is shallow water are integrated using, in the discretization of the time-depending terms, a two levels semi-implicit scheme [4] and discretizing the flow field by means of a series of triangular elements.

As a whole the lagunar basin, whose extension is nearly 450 km^2, is described by the finite elements model with about 5000 elements, introducing about 2900 computation points.

The two mathematical models have been previously calibrated utilizing both the results of some field campaigns for the discharges measure through the mouths and across the sections of the principal internal channels and the contemporary water levels recordings of about fifteen tide gauges installed within the lagune.

Water levels and discharges are reproduced by the two models with a good precision in the different locations within the lagune. It is obvious to notice that the bidimensional model, because of its own peculiarities, permit to investigate the flow field characteristics even punctually, in particular in the central zones of the lagune whose dephts are lower than in the channels but not negligible.

The efficiency of the proposed solution is demonstrated by the results obtained simulating, with the mathematical, models the propagation of a sinusoidal tidal wave with total amplitude of 1 m and period of 12 hours, oscillating around a mean value of 0.60 m.

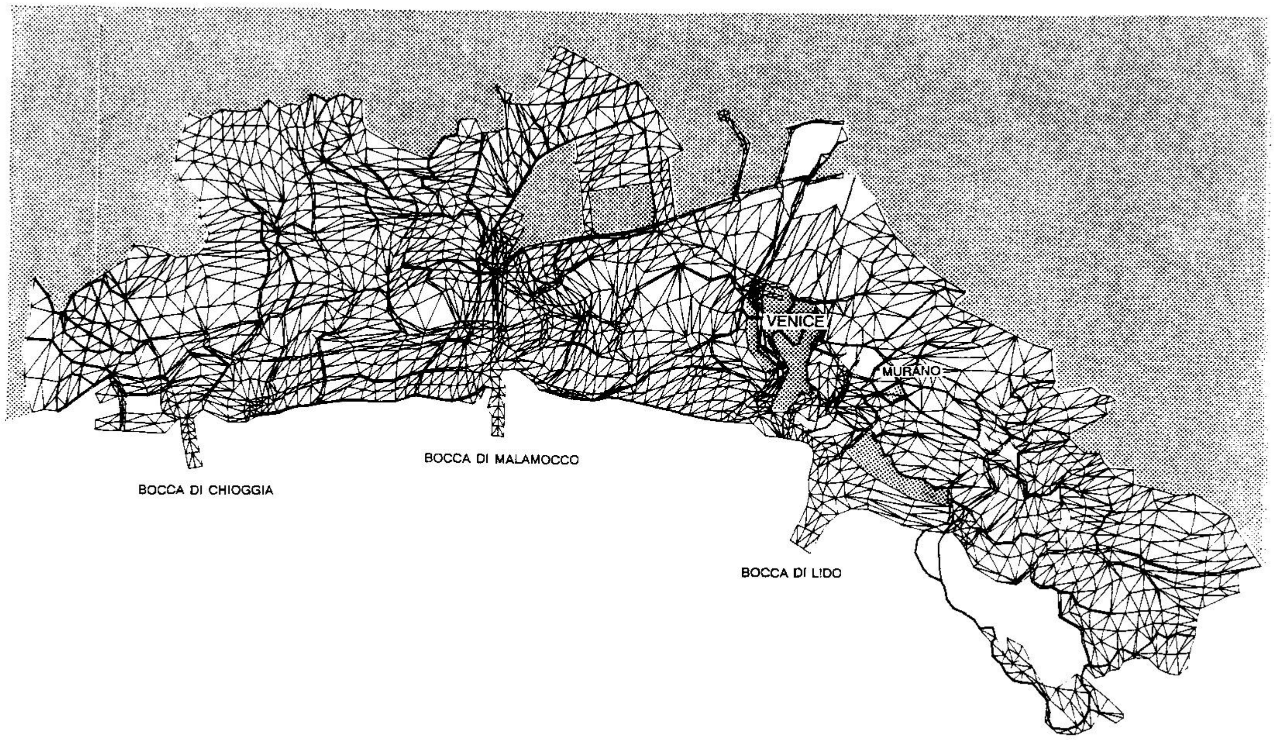

Fig. 4 The mesh of the two-dimensional finite element mathematical model.

Thinking of maintaining the Malamocco and Chioggia mouths completely open it has been simulated a 30 minutes closure manoeuvre of the barriers located at Lido mouth and in corrispondance of Vittorio Emanuele and Rocchetta channels, starting when the sea level reaches the value of 80 cm.

Afterwards the barriers have been maintained closed all the time, while the sea level exceeds the above mentioned limit and then reopened, still with a 30 minutes manoeuvre, in the descending tidal phase.

Along the Venezia (Punta Salute)-Marghera historic centre directrix, the maximum tidal water levels undergo a significant reduction, compared with the actual situation, and do not exceed 80 cm (Fig.5).

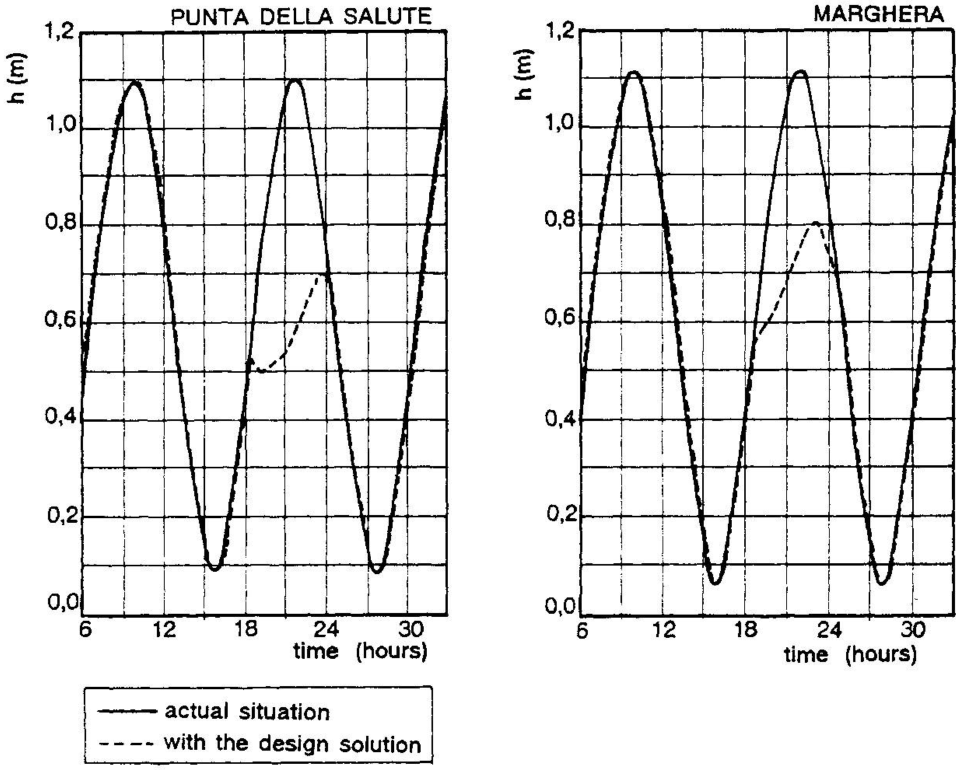

Fig. 5 Effects of the designed solution on tide level at Punta della Salute (Venice) and Marghera.

Significant reductions in the maximum water levels take place also in the whole central part of the lagune included between Vittorio Emanuele and Malamocco-Marghera channels and in the North-Eastern lagune where Murano, Burano and Torcello isles are located.

As a consequence of the manoeuvre, the tidal water levels behaviours in the basin dominated by the Chioggia mouth appear, instead, pratically uncharged.

Therefore the hypothesis on which the herein illustrated project is based, are confirmed by the results from computation. During the closure period of all barriers a considerable increase of the basin dominated by the Malamocco mouth takes palce , but, at the same time the direct feeding of the central part of the lagune from the Malamocco-Marghera navigable channel is obstructed.

Even with the Malamocco mouth completely open,the sandbanks strip planned close to the channel reduces the total tidal currents flow toward the central lagune,that is feeded prevalently by the minor

channels branching off the Malamocco-Marghera navigable channel, however characterized by a rather small scale discharges-curves.
The tidal water level behaviours in the different locations of the lagune agree with the variations, as compared to the actual situation, of the discharges through the sea-mouths, the Malamocco-Marghera channel and the minor channels branching off from it (Fig. 6).
The planned works and the above mentioned regulation manoeuvre allow, therefore, to limit below 80 cm the maximum tidal water level of the "normal high-tide events" up to nearly 1.10 m, without obstructing by no means the feasibility of the harbour, serving the Porto Marghera Industrial Zone, achievable in any case through the Malamocco-Marghera navigable channel.
Furthermore the manoeuvres frequence of complete closure of all the three sea-mouths is significantly reduced, changing from about fifty per year to only 4-5 times per year.

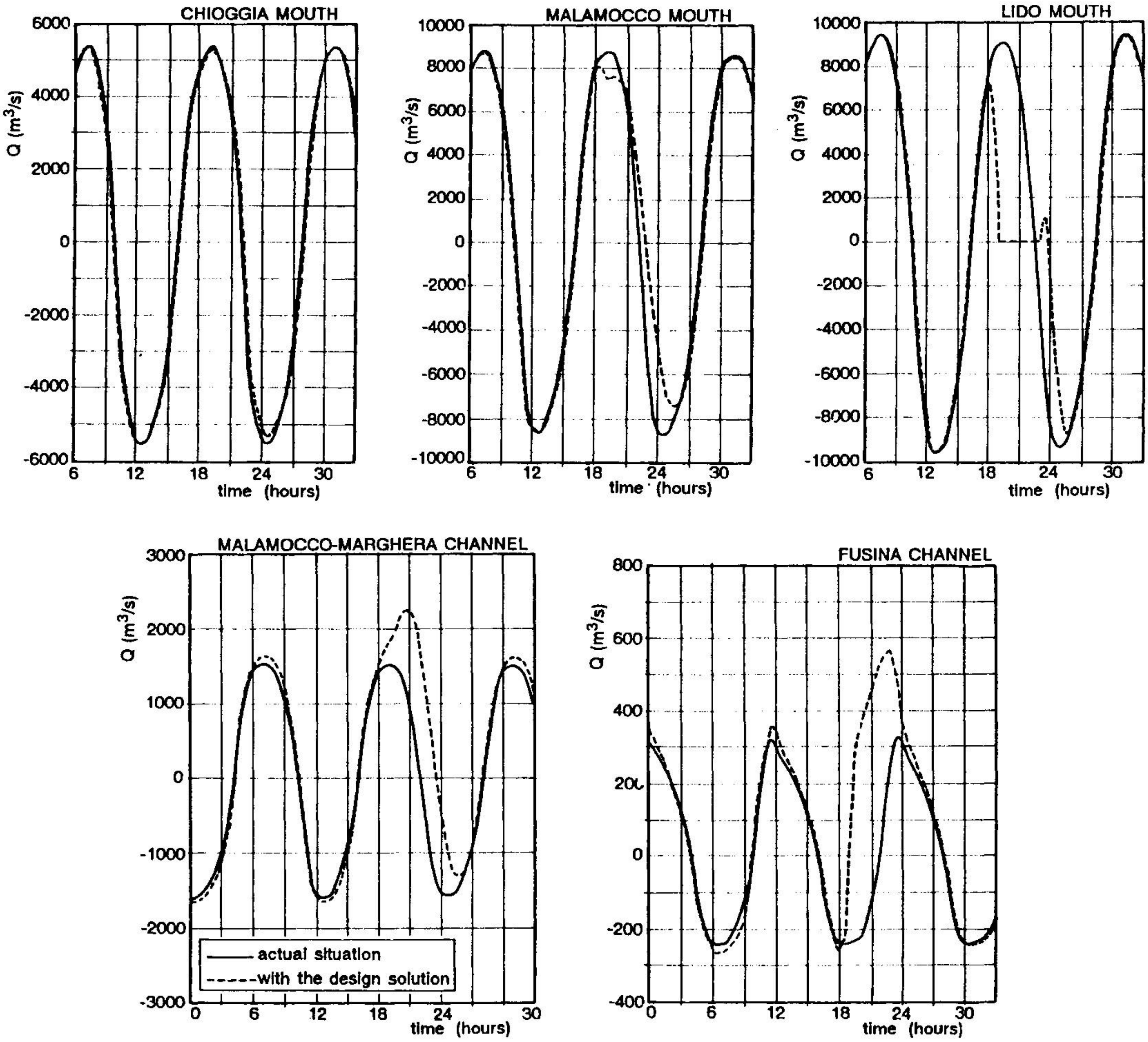

Fig. 6 Effects of the designed solution on the discharges through Chioggia, Malamocco and Lido mouths, and through Malamocco-Marghera and Fusina channels.

The manoeuvring only the Lido mouth barrier and the two internal minor barrages cannot guarantee the control of the extreme "high-tide" events.
Examining the effects of this operation on a real tide with a principal peak of 1.68 m and a secondary peak of 1.20 m, only for the last that would be reduced below 80 cm, it could be avoided the flooding of the city (Fig. 7).
For the principal peak this measure would not be sufficient and the complete closure of all the barriers planned at the three sea-entrances should be provided, avoiding, for a period of about twelve hours, the ship admittance to the lagune.
Finally, the permanent effects that the proposed works and in particular the realization of the sandbanks close to the navigable Malamocco-Marghera channel involves on the central lagune tidal currents, have been examined.

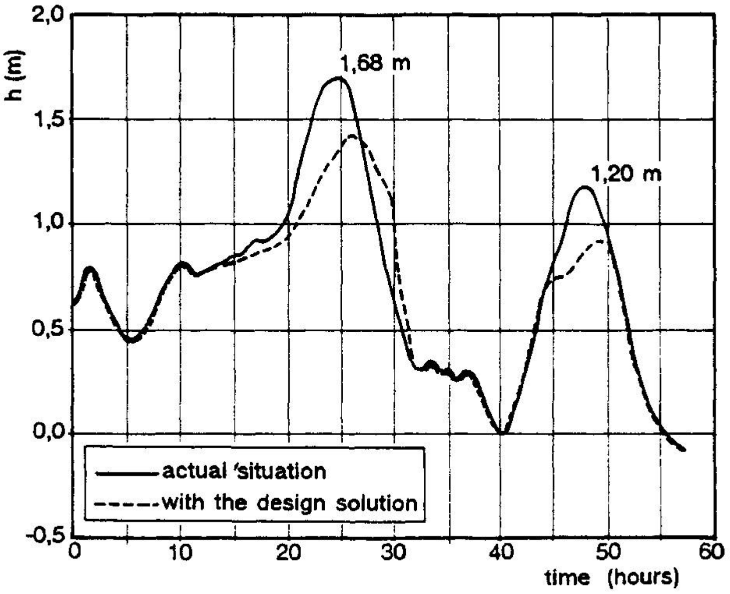

Fig. 7 Effects of the design solution on tide level at Punta della Salute for a real tide.

For the normal tides, for which no regulation at the barriers is required to limit the water levels in the historic centre, the effects are pratically negligible. This comes out from the comparison of the velocity fields relative to the actual (Fig. 8) and to the design (Fig. 9) situations, obtained with the bidimensional model and considering a sinusoidal tide with a 12 hours period and a total amplitude of 1 m oscillating around a mean value of 30 cm.
In the maximum ebb phase, negligible velocity increases are evident only in corrispondance of some of the minor channels crossing the planned sandbanks strip, but the general aspect of the field motion is substantially unchanged.

The presence of the sandbanks strip close to the channel turns also away from Venice the position of the watershed that tends to move towards the Malamocco mouth (Fig. 9), in a position closer to that previous to the dredging of the Malamocco-Marghera navigable channel.

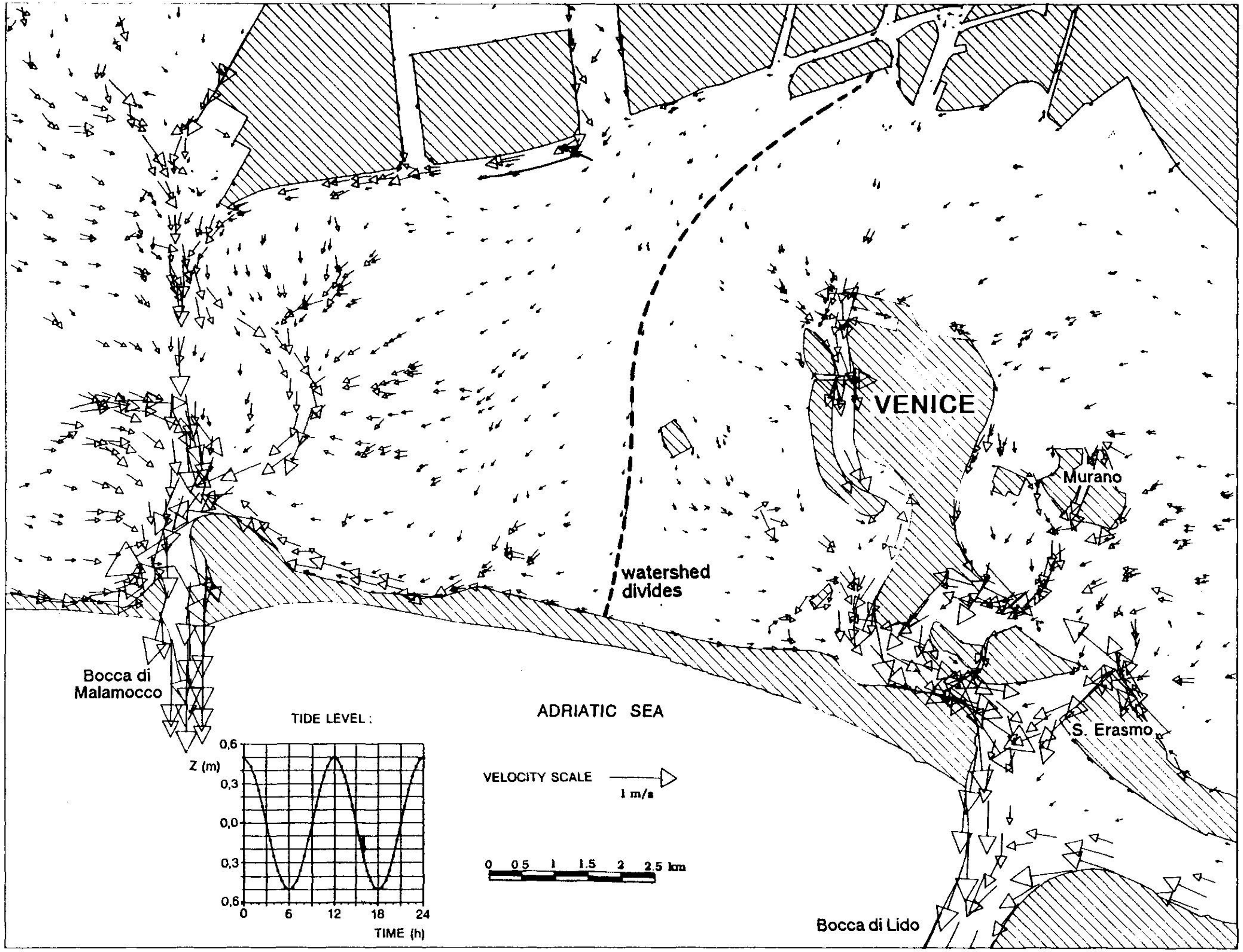

Fig. 8 Velocity field in the central part of the lagoon for the actual situation during the maximum outflow of a sinusoidal tidal wave.

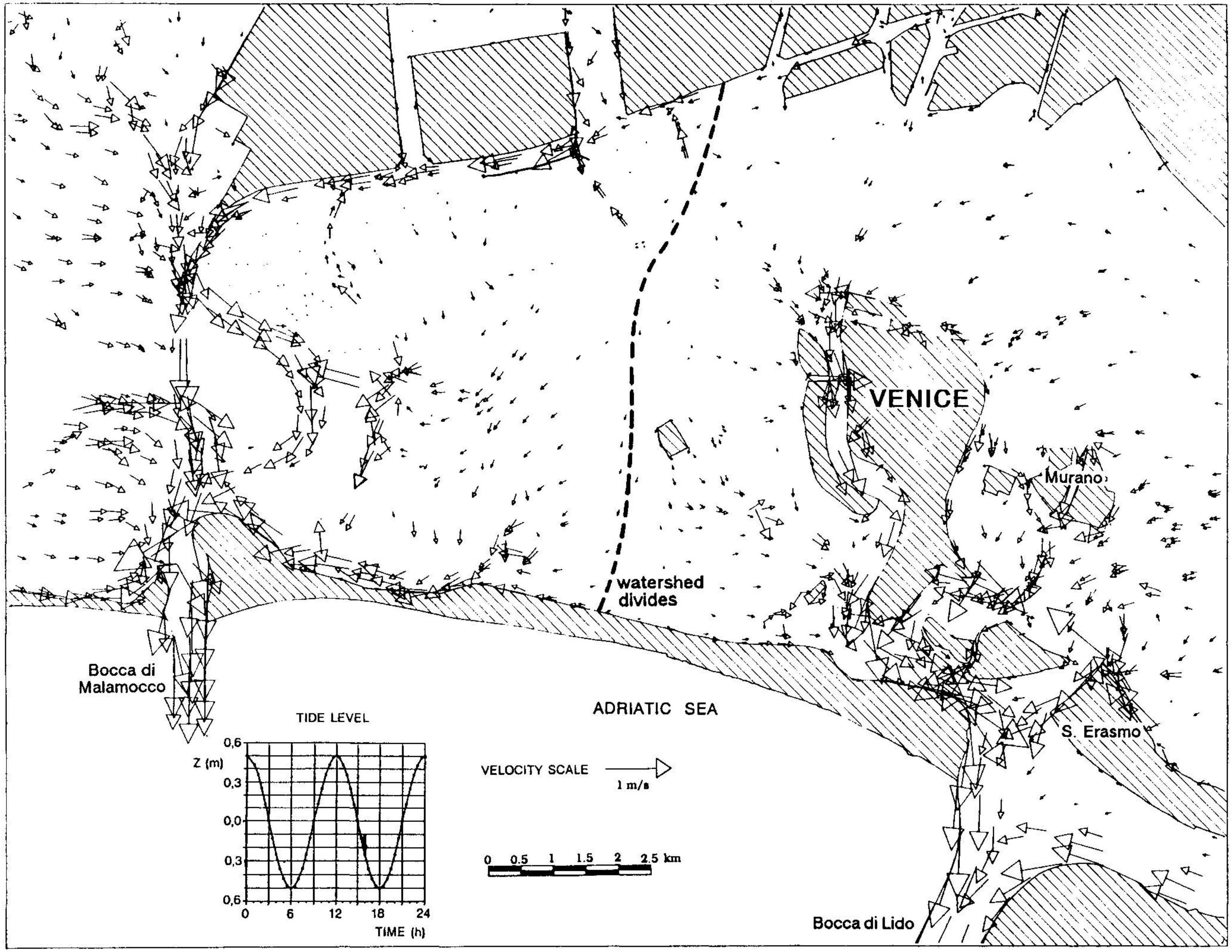

Fig. 9 Velocity field in the central part of the lagoon for the designed solution during the maximum outflow of a sinusoidal tidal wave.

5. CONCLUSIONS

To defend from flooding Venice and its lagune it is foreseen the realization of three mobile barriers at the sea-mouths of Lido, Malamocco and Chioggia. If the construction of two mobile barriers on the Vittorio Emanuele and Rocchetta channels and of a sandbanks strip along all the navigable Malamocco-Marghera channel are connected to the foreseen works, it will be possible to reduce significantly the number of tide events for which it is necessary to proceed to the complete barriers closure.

The normal high-tide events, up to maximum levels of 1.00+1.10 m, can be controlled with a combined manoeuvre of only the barriers placed at Lido mouth and in corrispondance to the internal channels (Vittorio Emanuele channel and Rocchetta channel). By means of these manoeuvres the tide levels in the lagune are reduced, avoiding the submersion of Venice that begins to be flooded when the water levels exceed 80 cm.

The proposed projectual solution involves remarkable benefits to be the navigation because the barrier regulations to be operated effectively during the normal high-tides do not concern the Malamocco and Chioggia mouths and allow the harbour praticability and the ships access towards the Porto Marghera Industrial Zone.

The formation of a strip of sandbanks on the eastward side of the navigable Malamocco-Marghera channel do not modify substantially the currents regime during the normal tides.

The simulations performed with the aid of the mathematical models show a minor influence of the Malamocco-Marghera channel on the central lagune feeding and point out a moving of the watershed between the mouths of Lido and Malamocco toward the second, in a position closer to that existing before the dredging of the navigable channel itself.

AKNOWLEDGMENTS

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Damming of Sea Arms: The Salt Water Lake Option
Construction de barrages sur des bras de mer: option du lac salé
Abdämmung der Meeresarme: die Salzwasserseeoption

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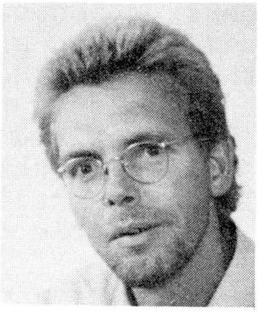

Wouter Iedeman, born 1955, obtained his biological degree at the Univ. of Groningen. For 3 years he was involved in the management of the international wetland "de Oostvaardersplassen". Presently he is jointly responsible for the integral water management of the Deltawaters of south-west Netherlands.

SUMMARY

Lake Veere and Lake Grevelingen are both former sea arms, dammed as a part of the Deltaplan. Though originally planned as freshwater lakes, they were maintained salt as a consequence of the decision to keep the Eastern Scheldt open. The infrastructure and the management was not originally aimed to meet the conditions necessary for the development of sound, well-functioning saltwater lakes. This article describes the conditions which have to be met and how the sustainable management of saltwater can be achieved.

Construction de barrages sur des bras de mer: option du lac salé

Résumé

Les lacs Veere et Grevelingen sont d'anciens bras de mer fermés à la suite de la réalisation du projet Deltaplan. Ils étaient prévus, à l'origine, comme lacs d'eau douce mais ont été maintenus en eau salée, suite à la décision de maintenir ouvert l'estuaire de l'Escaut. L'infrastructure et l'exploitation n'étaient pas, à l'origine, conçues pour un lac d'eau salée. L'article décrit les conditions à remplir et l'exploitation appropriée de l'eau salée.

Abdämmung der Meeresarme: die Salzwasserseeoption

Zusammenfassung

Die Seen "Veere" und "Grevelingen" sind beides frühere Meeresarme, eingedämmt als Teil des Deltaplans. Obwohl ursprünglich als Frischwasserseen geplant, enthalten sie weiterhin Salz infolge der Entscheidung, die Osterschelde offen zu halten. Die Infrastruktur und der Betrieb waren ursprünglich nicht für die Entwicklung gut funktionierender Salzwasserseen geeignet. Dieser Artikel beschreibt einzuhaltende Bedingungen und Massnahmen zur Wahrung des Salzgehaltes.

1. Introduction

The original Deltaplan for the south-west of the Netherlands intended to close all sea arms but one and to turn them into fresh water lakes. During the execution of the Deltaplan one became aware of the environmental and economic values of the estuaries. This has changed the Deltaplan considerably (fig 1). Well known is the construction of the storm surge barrier to combine safety against flooding and conservation of the estuarine character of the Eastern Scheldt. Less known are the consequences for the already closed sea arms Lake Grevelingen and Lake Veere which still contained seawater awaiting desalinisation. It was decided to keep these lakes salt. Now the management was challenged to utilise the full potential of these lakes and to make sustainable development possible.

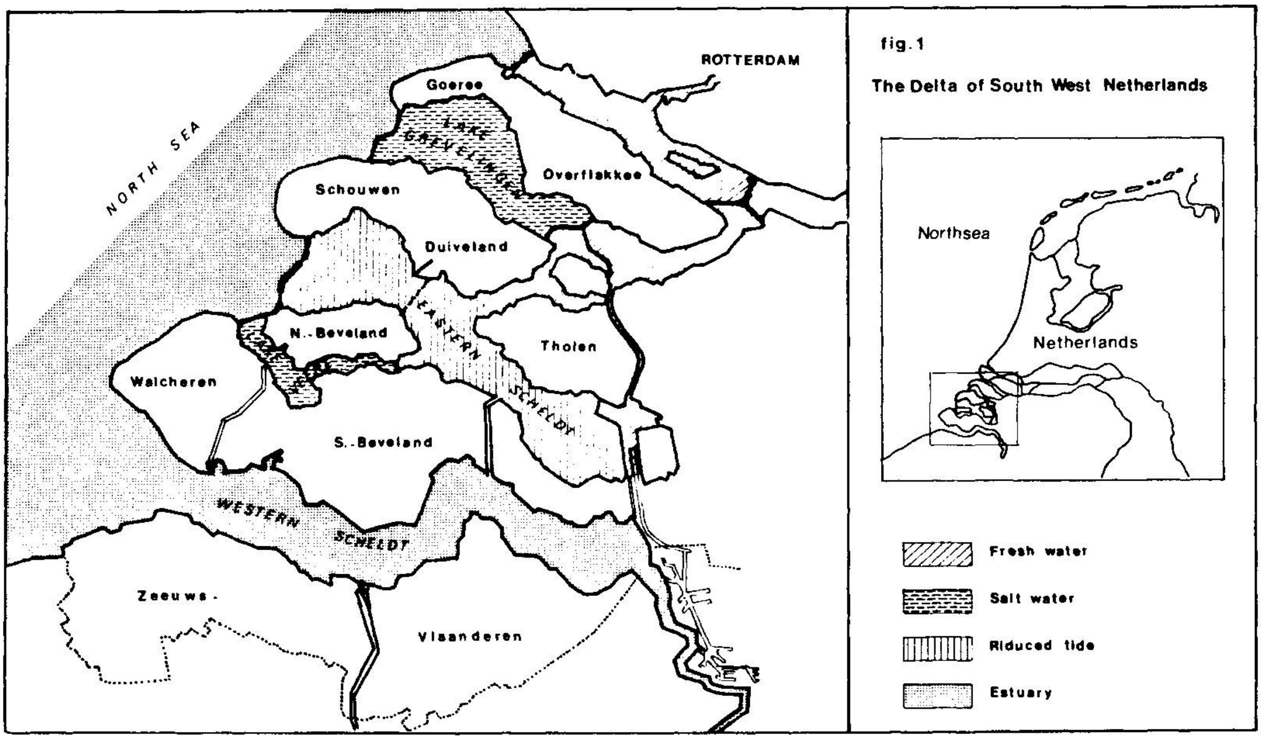
fig.1

The Delta of South West Netherlands

2. Lake Grevelingen and Lake Veere

2.1 history and characteristics

Lake Grevelingen and Lake Veere are both former seaarms. Lake Veere was dammed in 1961 and Lake Grevelingen in 1971. Since 1979 exchange with seawater is made possible in Lake Grevelingen by means of a sluice in the western dam with a capacity of 125 $m^3.s^{-1}$ averaged over a day. Lake Veere only has a lock in the eastern dam. In Lake Grevelingen the water level is maintained at MSL-0.20m. Lake Veere has a water level of MSL in summer and a lowered waterlevel of MSL-0.70m in winter for the benefit of the drainage of the surrounding polders. In table 1 the main characteristics are summarised.

table 1. morphometrics of Lake Grevelingen and Lake Veere

	lake Grevelingen	lake Veere
water surface (ha)	11000	2030 (MSL) 1742 (MSL-0.70m)
drainage area (ha)	13045	19335
mean depth (m)	5.3	5.0
max depth (m)	48	25
length (km)	23	24
width (km)	4-10	0.2-1.6

2.2 ecology

Lake Grevelingen is a good example of how valuable a saltwater lake can be. The water is extremely clear with a secchi depth of more than 5 m and the lake is characterised by the presence of typical aquatic and terrestrial animal and plant communities (2,9). Lake Veere on the other hand is bothered by problems of stratification and eutrophication. This becomes evident in high algae blooms in spring, excessive growth of sea lettuce and anoxia in deeper parts of the lake (1,4). Another problem is formed by the unstable conditions around the shoreline for benthic and plant communities, caused by the lowered water level in winter (5,10).

2.2.1 salinity and stratification

Though Lake Veere and Lake Grevelingen are cut off from the river influence, there is still a fresh water load from the surrounding polders. In Lake Veere the freshwater load equals the seawater load. This is the cause of the strongly fluctuating chlorosity (8-12 $g.Cl^{-}.l^{-1)}$ (7). In Lake Grevelingen the seawater load exceeds the freshwater load by about twentyfold. The chlorosity is constant and reflects the chlorosity of the coastal waters (15-17 $g.Cl^{-}.l^{-1}$)(2,12).

table 2. hydrology of Lake Veere and Lake Grevelingen

	lake Grevelingen	lake Veere
fresh waterload ($m^3.y^{-1}$)	$40-55.10^6$	$110-125.10^6$
salt waterload ($m^3.y^{-1}$)	10^9	100.10^6
volume (m^3)	575.10^6	102.10^6 (MSL) 89.10^6 (MSL-0.70m)
residence time (days)	200	180

A low, strongly fluctuating salinity is typical for the transition zone in estuaries. It is characterised by a low species diversity. This is true for Lake Veere, where the species diversity is rather low in comparison with Lake Grevelingen. For instance, the number of bottom fauna species in Lake Veere numbers around 40, in Lake Grevelingen on the other hand about 60 (5,8,10).

Another effect of the fresh water load on salt water lakes is the appearance of stratification. This is the phenomenon in which there is a sharp transition in the water column between layers of water with a different salinity or temperature (fig 2). In stagnant waters only wind can alleviate stratification.

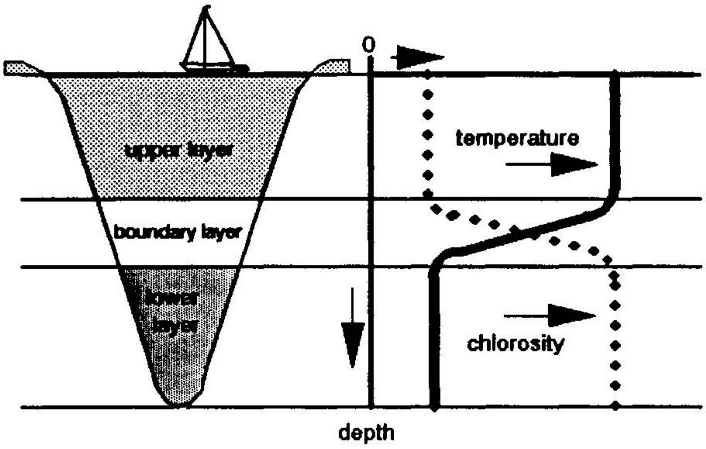

fig.2 Scheme of salt and temperature stratification

The boundary layer, which separates the upper and lower layer, forms a barrier for the exchange of oxygen and can lead to anoxia in the lower layer. The anaerobic surface depends strongly on the position of the boundary layer; the higher the position of the boundary layer, the greater the potential anaerobic surface. This is most striking in Lake Veere. In summer the boundary layer can rise to 4-6 m below water level and up to 25% of the lake can suffer from oxygen depletion (7). In Lake Grevelingen however stratification stays confined. Even in unfavourable years oxygen depletion rarely exceeds 5% of the lake surface (2,12) (fig 3 and 4).

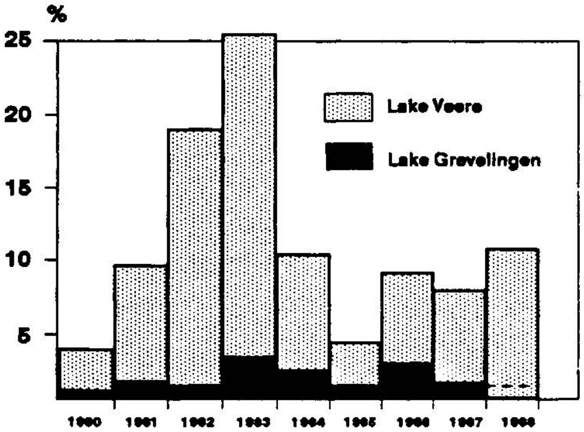

fig.3 Anaerobic surface in Lake Veere and Lake Grevelingen

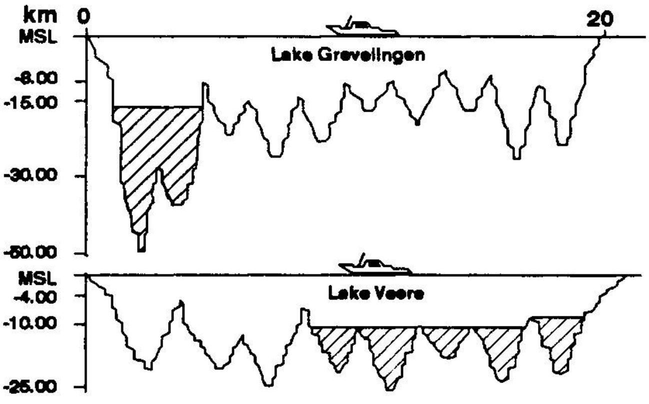

fig.4 Extension of anaerobic surface in Lake Veere and Lake Grevelingen

Anoxia is detrimental for life in the deeper parts. In Lake Veere little bottomfauna is found below 12m in the mid- and eastern section of the lake (5,10), whereas in Lake Grevelingen about 10% of the biomass lives below 14m (2,8). Also the surface of the feeding grounds for fish is reduced by anoxia.

2.2.2 eutrophication

Before damming nutrient cycles were dominated by external influences. The nutrient load originated mainly from rivers and sea. The residencetime of about a month reduced the importance of internal processes in the systems. By damming the influence of rivers and sea has been reduced a great deal. The nutrient load is now chiefly regional in origin. The surrounding polders form the main source for this nutrient load. Also hydrologic conditions have changed, through which the effect of internal processes in the lakes has increased. The overall effect is the increased susceptibility of the newly created salt water lakes to eutrophication.

This is most obvious in Lake Veere. In spring an excessive abundacy of algae and sealettuce (Ulva spec.) occurs and anoxia appears in deeper parts. Lake Grevelingen is not plagued by these problems. The cause of the problems of eutrophication in Lake Veere lies in the relation between nutrient load and carrying capacity of the system. The main nutrient is nitrogen, which is limiting for algae growth in the salt water lakes as well as in other shallow coastal waters. The nitrogen load on Lake Veere is 40 $gN/m^2.j^{-1}$. This is ten times as high as the load on Lake Grevelingen (table 3). Less than 50% of the nitrogen load disappears from Lake Veere by denitrification (14). In Lake Grevelingen the polder load is almost completely compensated by denitrification. This is caused by the high turnover rate of nitrogen in Lake Grevelingen. Each year the total amount of nitrogen goes through the cycle of uptake, transformation and regeneration at least five times (13). In Lake Veere this is about 2-3 times.

table 3. nitrogen fluxes in Lake Veere and Lake Grevelingen ($gN.m^{-2}.y^{-1}$) (13,14)

	Lake Veere	Lake Grevelingen
net load	35	3.5
exchange North Sea	-18	0.3
denitrification	15	3.0
bottom detritus	2	0.8

A very important link in this cycle is formed by the grazing bottom fauna like mussels (Mytilus edule) and cockels (Cerastoderma baltica). By grazing and excretion they accelerate the turnover rate (13,14). In parts of Lake Veere the bottom fauna is very poorly developed because of anoxia. As a result the grazing rate is rather low and algae concentrations are increased. This explains for the greater part the differences in chlorophyl concentrations between the western and eastern part of Lake Veere (25 $ug.l^{-1}$ against 150 $ug.l^{-1}$) (7). Due to the high turnover rate the primary production of 200 $gC.m^{-2}.y^{-1}$ in Lake Grevelingen is fairly high in comparison with the nutrientload (9). The primary production in Lake Veere amounts 380 $gC.m^{-2}.y^{-1}$ (11,14). This increased production leads to an increased sedimentation of organic material on the bottom and thus to an increased oxygen demand. In combination with stratification anoxia is likely to occur.

3. Ecological standards

Standards for sustainable, ecologically sound functioning saltwater systems do not exist. For natural waters like the North Sea a reference can be found in history or elsewhere. For artificially created lakes like Lake Veere and Lake Grevelingen this is not possible. A system orientated approach based on a fundamental understanding of the systems themselves and of other saltwatersystems therefore is necessary. The directorate of Zeeland and the Tidal Waters Division have in this manner tried to formulate conditions under which saltwater lakes can develop themselves into stable, sound systems (1,6). These conditions can be divided in those concerning chlorosity and stratification, eutrophication and water level management.

When species diversity is considered as an important natural value, a higher and more stable salinity is necessary. An analysis of the species diversity in estuaries has revealed that a salinity of >13 $g.Cl^{-}.l^{-1}$ can be considered as a minimum condition for the establishment of stable aquatic communities of a marine character. At the same time this forms a potential for shellfish-fisheries.

When the total anaerobic surface is restricted to <5% of the bottom surface, no significant problems seem to appear. To achieve this it is necessary to reduce the boundary layer in Lake Veere to a depth of >12-13m.

To prevent eutrophication the nutrient load should be in balance with the carrying capacity of the system. In this case accumulation of nutrients rarely appears and the primary production is mainly driven by internal nutrient regenaration. To judge this the total nutrient cycle should be considered. Nutrientconcentrations in winter are not only of importance, but also the effects on the system. A good indication is formed by the oxygen concentration in the deeper parts. This is influenced by the oxygen demand from the sedimentated algae and by the oxygen supply from the upper layer. The anaerobic bottom surface should therefore be restricted to maximal 5%. It is not possible to formulate a coherent set of standards for the other eutrophication parameters. They should be considered in relation to the standard for oxygen. Yet general directions can be provided: Lowered concentrations of chlorophyl in spring, lowered concentrations of nitrogen in winter and an adequate primary production (>200 $ug.l^{-1}$) with respect to carrying capacity for consumers. For a reduction of the amount of sea lettuce for recreational purposes nitrogen concentrations have to be reduced to less then 1.0 $mgN.l^{-1}$.

For the development of stable plant and animal communities along the shorelines a stagnant water level is necessary. Best conditions are found around the mid position of the former tides (MSL), because of the balance between shallows, transition and terrestrial zones. To protect the former intertidal areas against erosion outer bank defences should be built, as has been the case in Lake Veere and Lake Grevelingen.

table 4. standards for a ecologicaly sound functioning saltwater lake compared with the current values of Lake Veere and Lake Grevelingen

	standard	Veere	Grevelingen
chlorosity ($gCl^{-}.l^{-1}$)	>13	8-12	15-17
boundary layer (m)	>12	8-10	15-17
anaerobic surface (%)	<5	<25	<5
max.NO_3+NH_4 ($mgN.l^{-1}$)	1.0	3.0	0.5
max chlorofyl-a ($ug.l^{-1}$)	<<	150	25
primairy prod.($gC.m^{-2}.j^{-1}$)	>200	380	200
waterlevel	MSL	MSL/ MSL-0.70m	MSL-0.20m

4. Solutions

To create the required conditions for the development of a sustainable functioning salt water lake, two types of solutions can be chosen. The load can be adjusted to the carrying capacity of the system, or the carrying capacity of the system can be enlarged to handle the incoming load in a proper way. Also a combination of both solutions is possible (1,6).

Lake Grevelingen has, unintentionally, benefitted from both solutions. The polder load after damming was already low and the capacity of the sluice is large enough to take care of this load. All standards are met easily with the current management of waterexchange. Without exchange however chlorosity would drop to 11-12 $gCl^{-}.l^{-1}$ within 3 years (3).
Lake Veere has been harmed in two ways. The polderload has been concentrated on the lake and the capacity of the system to handle this load is restricted by the absence of exchange with coastal waters. The effect of different solutions is investigated with the help of computermodels for chlorosity and stratification (STRESS, Tidal Water Division) and for eutrophication (VEERWAQ, Delft Hydraulics) (7,14).
When the management of the existing lock is optimalised with respect to exchange, an exchange rate of 5-10 $m^3.s^{-1}$ is realizable. In addition to this a 75% reduction of the total polder load is necessary to meet the standards (table 5). Reduction of the polderload requires severe and expensive measures in the drainage area. Measures to enlarge the carrying capacity of the system are of preference. This can be done by increasing the exchange rate to 20 $m^3.s^{-1}$ or more. Doubling the exchange rate to 40 $m^3.s^{-1}$ provides an even more solid base to the system, so the standards can also be met under unfavourable conditions (1,6,7).

table 5. the effects of different management scenario's for Lake Veere

	A	B	C	D
chlorosity ($gCl^{-}.l^{-1}$)	8-12	13-14	13-14	14-16
boundary layer (m)	8-10	20	13	13
anaerobic surface (%)	<25	<5	5	5
max.NO_3 + NH_4 ($mgN.l^{-1}$)	3.0	2.3	2.2	1.5
max. chlorofyl-a ($ug.l^{-1}$)	150	55	65	35
primairy prod.($gC.m^{-2}.j^{-1}$)	380	250	285	210

A: current management
B: exchange rate of 5-10 $m^3.s^{-1}$ + reduction load of 75%
C: exchange rate of 20 $m^3.s^{-1}$
D: exchange rate of 40 $m^3.s^{-1}$

5. Conclusions

When the damming of sea arms is considered to be the only real solution to guarantee safety against flooding, the creation of a saltwater lake can be an attractive option with a high potential for nature, recreation and fisheries. In order to create the conditions necessary for the development of an ecological well functioning saltwater lake it is essential to make sufficient exchange with seawater possible and to adjust the freshwater and nutrient load to the carrying capacity of the system.

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Estuary Protection by Storm Surge Barriers

Protection d'un estuaire par un barrage contre les raz-de-marée

Flussmündungsschutz durch Sturmflutbarrieren

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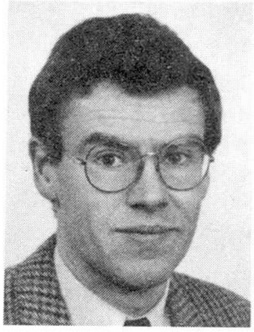

Philippe Rigo, born 1959, earned his Ph.D at the Univ. of Liège. Researcher in the laboratories of Hydraulic Constructions and Naval Architecture of this university, he was involved in the design of hydraulic steel structures. After one year of postdoctoral research at the Univ. of Kyoto in Japan, he has returned to Belgium and is now mainly occupied in the study of naval and floating structures.

SUMMARY

The storm surge barrier reduces flooding risks in the estuary. Design problems of barriers are analysed with respect to the effects of the sea level rise, with a rise of 1,5 meter, the probability in reaching a fixed water level which occurs once every 1000 years, will occur once every 10 years. Thus, structure safety coefficients are also affected.
The environmental impact of barriers on erosion or accretion is discussed relating to practical applications. Finally, several recommendations are made.

Protection d'un estuaire par un barrage contre les raz-de-marée

Résumé

Le barrage contre les raz-de-marée permet de maîtriser les risques d'inondations dans la région d'un estuaire. La conception d'un tel barrage est étudiée en tenant compte des effets de l'élévation du niveau de la mer. Avec une élévation du niveau de la mer de 1,5 m, la probabilité d'atteindre un niveau d'eau donné - qui se produisait tous les 1000 ans - se produit alors tous les 10 ans. Il s'ensuit que les coefficents de sécurité de la structure en sont affectés. L'influence des barrages sur l'érosion et la sédimentation est passée en revue sur la base d'expériences pratiques. Des recommandations sont proposées.

Flussmündungsschutz durch Sturmflutbarrieren

Zusammenfassung

Die Sturmflutbarrieren verringern das Ueberschwemmungsrisiko innerhalb einer Flussmündung. Analysiert werden Entwurfsprobleme dieser Barrieren unter Berücksichtigung des Anstiegs des Meeresspiegels. Ein Anstieg des Meeresspiegels um 1,5 Meter reduziert die Wiederkehrperiode des ursprünglich 1000 jährigen Hochwassers auf 10 Jahre. Aus diesem Grund sind Bauwerkssicher-heitskoeffizienten ebenfalls berührt. Der Einfluss der Barrieren auf Erosion oder Ablagerung wird diskutiert. Schliesslich werden Empfehlungen gegeben.

1. INTRODUCTION

In 1990, marine structures and rise in sea level of 0.5 to 1.5m in 2100 are still new considerations for the storm surge barrier design relating to the environment. It is with the knowledge of the past as well with new projects that these design problems have been studied. The increase of the frequency of exceptional storm surge is a new challenge for the marine structures and particularly for storm surge barriers. Presently, engineers and designers have to overcome obstacles to maintain safety in the future. Moreover. with this challenge they must consider a growing role of public opinion and its influence on the design.

In the following paper, I would like to present non exhaustive recommendations to help engineers in their further designs. These recommendations are based on my own experiences but above all on the experiences dealing with practical applications.

2. STORM SURGE BARRIERS PURPOSES.

Harbour facilities, including ship loading and unloading efficiency, can be maintained by closing a barrier when a storm occurs at high tide. Nevertheless, the main aim to build such structures is to reduce flooding risks in the estuary. Very often, in regard to tidal rivers, tide effects go tens of kilometers upstream of the coast. Thus, the flooding could reach a very large region affecting thousands of people. The storm surge barrier is well the easiest method to preserve the environment without having to replace natural beaches, banks and dunes by artificial dykes, sea walls and embankments.

The design of such devices is now recognized as protection technology and is used throughout the world, in Europe and more particularly in the North Sea. Examples of such are the Thames Barrier in London, the Hull lifting gate (G-B), the moveable weirs on the Elbe and the monstrous Oosterschelde barrier in the Netherlands. Today, there are new studies of city protection projects such as Rotterdam, Antwerp and Venice. Japan is also a country where such protection devices are often used. Usual tides are relatively small (about 1m). However, typhons or tsunamis, combined with hide tides have flooded several cities during this century (Osaka, Tokyo, Nagoya). Osaka Bay with its numerous ports and river mouths has many hide tide gates such as in Tokyo area.

2.1 The role of public opinion.

The decision to protect an estuary (including its upstream harbor and cities) must be taken into account by the national and regional political leaders as well as by harbor authorities. Public opinion has to play a fundamental role in the decision process. When flooding occurs, public opinion is suddently and poignantly focused on this problem. Thus, at this time political leaders become aware of the problem and then they quickly plan protection devices to satisfy the population. Usually such projects concerning large areas need intensive studies before starting. Above all they can become very costly. So, political leaders require several years of planning, sometimes two or three decades (the Delta plan in Netherlands was accepted in 1958 and projects were finished in 1986). Owing to influential public opinion, and leaders awareness which usually occurred just after flooding, the planned protection projects were often started hastily and as soon as possible. After several months or years the interest of public opinion decreased, the information about projects whether completed or not become less and less. The leaders had an option to continue, to reduced or to stop the planned works.

The Delta plan is good example of political leaders continously pressed by an interested public opinion. In this case government has carried the projects to a successfull conclusion. Upon completion, in 1987 the Dutch Ministry of Transport and Public Works continued to consult with contractors and engineers to develop designs related to the construction of a tidal surge barrier in the entrance of the channel of Rotterdam Harbour [1]. The foreseen construction was (after completion of the Oosterschelde dam [6]) the last link of the dutch shoreline shielding against exceptional tides. Currently, related to the rise in sea-water level, studies are made to see how their existing protection devices could be modified or changed [3].

In Belgium after the 1953 and 1976 hide tides from which floods occured, the Sigma plan (1977), divided in 3 phases, was established and had to be finished in 1987. The first phase was to raise the 450km banks of the Escaut estuary, as of today 250km have been raised. The second phase concerned with the construction of flooding bassins to reduce the hide tide effect, was never realize because of inapplicability. The last phase which dealt with a storm surge barrier was also abandoned after that some feasibility studies were made [2].

Of course, one can understand that according to the high cost of these works and some unexpected economical problems (such as pretroleum crisis), governments could modify and extend the scheduled time of the completion. But it is not acceptable to stop the project .... upon the next flooding public opinion will arise. Public opinion should be aware of the irresponsability of their political leaders. The public and their representatives must pay attention to the works in progress until completion.

Nowadays more and more engineers and political leaders take into account public opinion when they have to plan their projects. But it is not enough, after planning they also have to revise each step of the way according to the changing public opinion.

For instance, 30 years ago, just after that Isewan typhoon flooded Nagoya, a moveable weir on the Nagara river mouth in Nagoya had already been planned. At this time the goals were for flooding protection and water ressources. Environment protection was neglected. Presently, the water ressource problem has been solved and this estuary remains the biggest and one of the rarest natural river mouths in Japan. This project, which was started recently, has recently been quickly stopped owing to public reaction (in saving the existing river environment). Two mistakes occurred. After 30 years, a planned project had to be reconsidered regarding the aims of construction and the renewed interest of the people relating to the environment. To avoid such problems, it is highly recommended to work as close as possible with public opinion and its request for evolution.

The storm surge barrier on the Oosterschelde shows us another example of changing public opinion. Construction of a conventional fixed dam was under construction with completion scheduled for 1978. However, the rise of the environmentalist's concerns in the 1970s prompted a drastic re-thinking. Responding to public's concern for the fate of the region's rich natural habitat, the Government ordered a change of plans; which called for a moveable barrier rather than the fixed dam already under construction.

2.2. The North Sea.

In the past few decades, the flood menace in the coastal areas of the North sea has been increasing progessively. The North Sea water level is subject to large variations which have one's origins in 3 phenomenons.

The first one is related to the local climate behaviour. When an atmospheric depression arrives on the North Sea, the induced north winds create a rise of sea level which produce water storage along the coasts. The reduced water depth of North Sea as well as these estuary prompt an amplification of this phenomenon.

The second phenomenon concerns world climatic behaviour: "the Greenhouse effect". It is estimated on the basis of observed changes, that a global warming trend of 1.5°C to 4.5°C for the next century would lead to a sea level rise of 0.5 to 1.5m and maybe more [5].

The third concerns geological behaviour. It is now established that in reaction to the rising mouvement of elevation in the Alps area, North sea countries are now under the influence of a slow but huge movement of subsidence. So, it is estimated a subsidence of more then 50 cm in Hull before 2100.

Of capital importance for the North Sea countries is the sea level rise which will also seriously concern Bangladesh, Taiwan, Venice, most of the Atlantic coast from Mexico gulf to USA (Mississippi), the Nile delta as well as the deltas of the main Chinese rivers. A two meter rise would inundate 10 to 20 % of Bangladesh. The Maldives islands (670 km southwest of Sri Lanka) are generally less than two metres above sea level.

3. INTERACTION BETWEEN ENVIRONMENT AND COASTAL PROTECTION STRUCTURES.

The main elements related to marine environment are waves, winds, sea-water currents which change the motion of the bed material, the polution rate, the sea level rise, the earthquakes which induce tsunamis, ... and last but not least the flora and fauna of marine life. However, according to the author, aesthetic values must be considered by the designers as one of their formost worries.

Included among coastal protection structures are the fixed structures like dikes, jetties, piers, groynes, wharfs, etc. But in this study, we will be mostly interested in moveable gates and weirs called storm surge barriers or tidal surge barriers.

In analysing the interaction between marine structures and marine environment, the impact of marine structures will differentiate from the impact of sea level rise.

3.1 Impacts of the marine structures on the environment.

The barrier closure frequency must be limited to exceptional storm surge. For the other circumstances, the environment must be able to withstand the sea's attacks. The protection of the estuary by storm surge barrier must be considered only as a supplementary protection device, and only one of many. The barrier is the keystone of several coherent techniques of protection devices. Therefore, banks, beaches and coasts in the vicinity of the barriers must be able to resist at the same hide tides. Moreover, storm surge barriers remind us to not forget the protection role of river banks along which the tide acts. River banks must continue to hold out against usual high tide.

- Erosions and accretions : Sediment accretions or erosions (bank , river bed, etc.) can result from too long or too frequent closing times. The sea erosion power is, in fact, higher during storm surge. Therefore, it is important to analyse which can be the barrier closing effects on the sea-water currents (direction and velocity). Too large of a sediment accretion can induce navigational difficulties or increase dredging cost. On the other hand, erosion can produce crutial damage to the environment and compromise the stability of some marine structures (dikes, piers, jetties, etc.). For instance, to protect Niigata (city on the Japan Sea) against flooding, a derivation was built on the West side of the city (Fig. 1). Water level and discharge are regulated by moveable weirs. Main coastal currents act in an East to West direction. Therefore, the sandy beach which was usually accumulating from the high discharge from the upper part of the river, now arrives not at the natural mouth of the river but at least 10km away on the West side . So, the beach profile equilibrium was broken and the retreat of the beaches occurred changing the coastline. A large ground subsidence also amplifies this phenomenum. To restore old beach areas, zonal protective structures are now designed (Fig. 2)

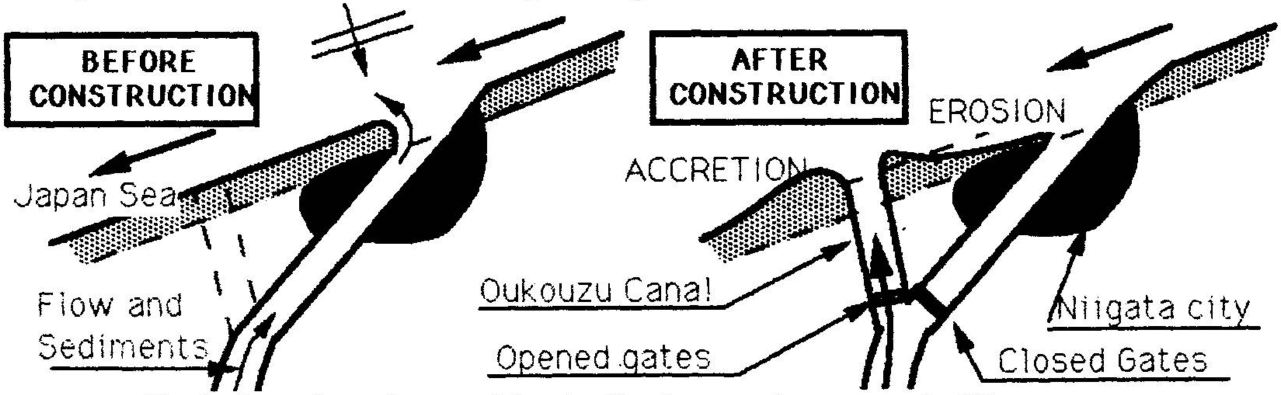

Fig. 1 : Coastal erosion resulting by flood protection system in Niigata.

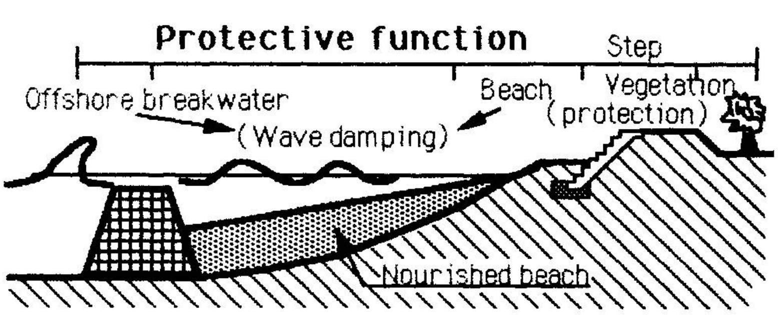

Fig. 2 : Conceptual Diagram of the Zonal Protective Method.

To meet the growing interest in the quality of the environment, Japan has promoted a new system of coastal protection [7] which combines environmentalism and safety. This system called "Zonal Protective Method " is shown in Fig. 2. This is a coastal improvement method, whereby multiple shoreline protection facilities are most appropriately arranged to provide disaster prevention to a given place in the vicinity of the shoreline. This method is benefical by encouraging comprehensive use of nearby on-shore areas. At the same time, these zonal protective structures have great resilence, functioning as a thick buffer against the threat of the sea.

- Aesthetic values : At the dawn of the 21th century, where ports and harbors are concerned, the estuary aesthetic values must be protected because they will be completely modified by the building of large structures such as storm surge barriers. As a result of this protection purpose and the small frequency of storm surge and the navigation needs, these barriers are not used during more than 99% of the time. So, whether they stay at a high suspended position as in Hull (Fig. 3a) or at Osaka (Fig. 3b), or whether they stay under the water level in the floor of the structure as the Tamise barrier in London or whether they stay along the river banks as the floating rotating barriers projected for the Antwerp (Fig. 4b) and the Rotterdam (Fig. 6) esturies protection, aesthetic appearance must be a consideration when structures are not in use. Lifting gates are not in keeping with site aesthetic values since their high frames which could sometimes reach 100m high as in an old project for Antwerp estuary (Fig.4a). On the other hand, barriers staying under water level or along the banks (Fig. 4b) are in keeping with the natural area and therefore, they are the most recommandable for further designs.

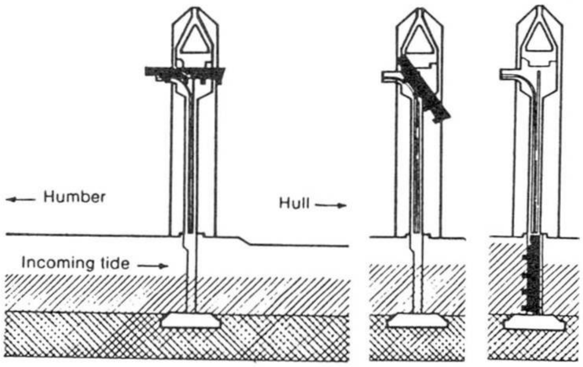

Fig. 3a : HULL lifting storm surge barrier.

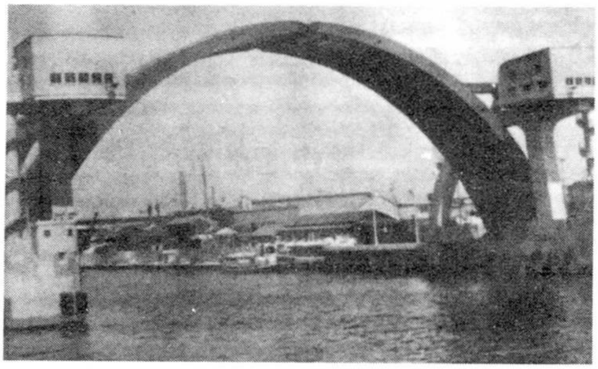

Fig. 3b : Osaka arch type gate.

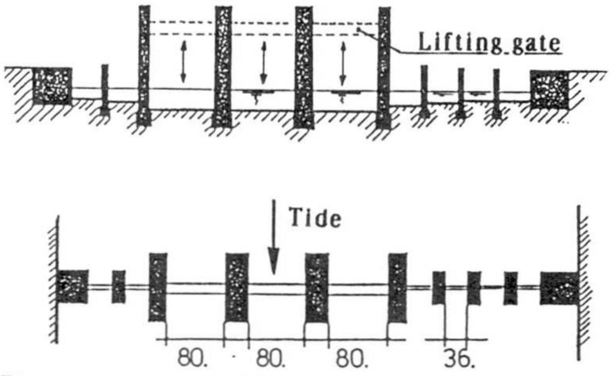

Fig. 4a: Antwerp lifting gates project.

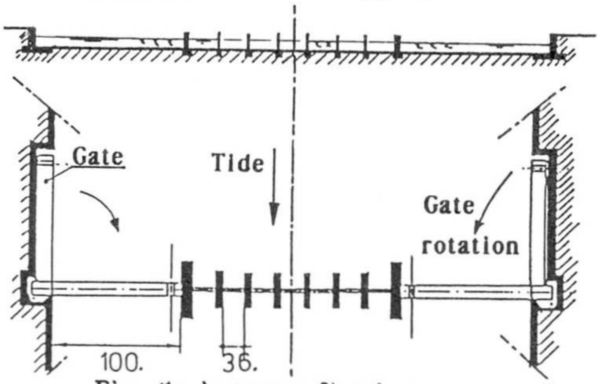

Fig. 4b: Antwerp floating gates project.

3.2 Impacts of sea level rise on the marine structures and the environment.

The recurrence period of a storm surge (mainly characterized by the highest water-level reached) will strongly be affected by the future rise in sea level. The relationship between frequency of overtopping and sea level is assumed to be log-linear, and is expressed by a coefficient which indicates the inclination of the curve (Fig. 5). In the North Sea this coefficient is about 1.5. Therefore, the impact on safety in low coastal area is considerable. The chance of a catastrophic event along coastal areas increases a hundred-fold by a sea level rise of 1.5m.

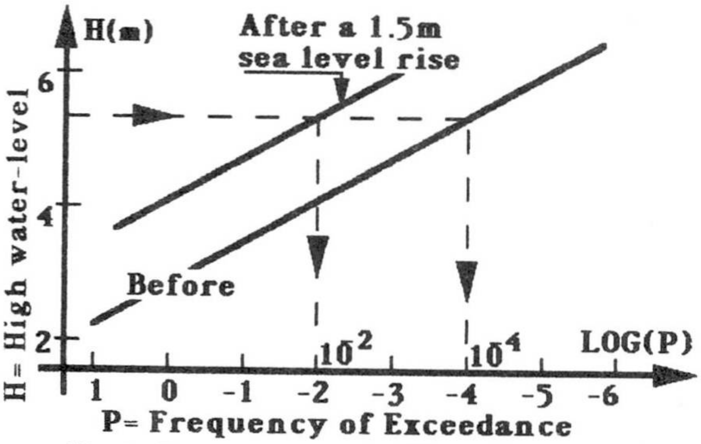

Fig. 5 : Recurrence probability of sea-water level.

The recurrence period of events such as in the case of the 1953 storm surge, would become a 3 years recurrence instead of 300 years. It means that in the future, a storm surge which was considered before only in disastrous scenarios, must be now considered as highly probable.

3.2.1 Structures :

The impact of sea level rise automatically has a direct relevance to coastal lowlands. Increased storm surge creates an impact on damage to the dikes, dams and coastal structures including the storm surge barriers.

The modification of the frequency of exceedance of water levels has serious consequences on the safety coefficients of the marine structures. These safety coefficients were choosen when the barriers were designed. Up to now, as in the Delta plan, a sea level rise of only 20cm per century has been taken into account.

With respect to the existing structures, the impacts of sea level rise are not easily estimated. Reduced safety coefficient taken in the past for exceptional water levels must be strongly reconsidered. Without modifications,"young structures" (10 to 20 years) can often withstand small sea level rise but will have to be reinforced in case of 1 or 1.5m rise. "Old structures" (more than 50 years) are sometimes more economical to rebuild than to modify. With respect to the Delta plan's structures [3] , studies show that it needs 2,500 - 12,500 millions US$ to adapt protection devices in case of a sea level rise, respectively 0.5 and 1.5m . As a comparaison, these amounts are respectively 15% and 80% of the total amount of the Delta Plan's projects.

Related to the design of new structures, it may seem that their design is easy to consider. Such is not the case. Theoreticaly, it is sufficient to consider the expected sea level rise at the end of the structure's life span. In reality, the predicted sea level rise and the technical life could not be obtained with a high accuracy. Predictable of sea level rise for the next century varies on a large range (0.2m to more than 2m) according to the scientist [5]. Although the technical live span of usual marine structures is normally 50 to 100 years, in the case of storm surge barriers considering their high costs, 100 years or more can be acceptable (200 years for the Eastern Scheldt storm surge barrier in Rotterdam). Moreover it is not possible to anticipate what engineers will decide tomorrow. It is not uncommon to see structures still in use after their life span has elapsed, yet structures are often replaced before their life span has elapsed. Therefore, it is one of the most difficult decision to determine the characteritic storm surges (recurrence of 1/10000, 1/100 and 1/10) for later consideration in barrier design.

From an economic point of view and related to sea level rise, it might be interesting to make step by step adaptations to the structures, in order to prevent the necessity of investing money, required after 50 or 100 years. So, it is recommended to combine the larger maintenance works (which are necessary owing to life span of about 100 years) with an adaptation of the structures.

3.2.2 Environment :

On the other hand, sea level rise causes effects to the environment which result in larger and sometimes irreversible damage. Loss of land of river deltas will occur as a result of erosion inundation flooding of coastal areas. As well changes in morphology and ecology increased saltwater intrusion into rivers and into saline seepage, will also occurs. It will also affect fresh water intake for irrigation and domestic water supplies.

Geological records indicate that the natural environment has a great capacity to adapt to very slow changing conditions without the extinction of any species or organisms. Nevertheless in the case of protected coasts, the consequences of inland migration of wetlands being obstructed by dikes or sea walls, may result in certain types of natural environment being reduced in size or disappearing altogether.

Allowing nature to run it course, (in narrow coastal protected areas) will not be a better solution as natural sandy coasts will be subject to erosion and the indertidal areas will radically change. As the equilibrium beach profile will follow rising water levels, the shoreline will ultimately retreat inversely proportional to the submerged slope. Beach retreat is usually about 1 m for 1cm level rise. Therefore a sea rise of 1m would mean about 100m of beach erosion. In the places where such retreat can not be permitted, protection devices such as the "Zonal Protective Method" as in Japan will have to be used. Sand depletions can also prevent beach and dune from retreating

3.2.3 Public opinion.

As explained, such a sea level rise will have many effects on society but in terms of daily problems, the effects may appear to be irrelevant. The same can not be said for structural engineering investments as the estuary protection which could take decades. Moreover, there are many other problems which compete against sea level rise, for the attention of decision makers and public opinion. Experience shows that only a sudden event or disaster will trigger countermeasures (for example : the Sigma plan was planned after the great flood in 1953). Therefore, to ensure an effective and timely response, scientists and engineers must join forces to consider consequences on today's and tomorrow's structures, even if public opinion and decision makers seem unconcerned.

The public opinion related to sea level rise is slow or nonexistant due to the length of time period, of cause and effect (at least in the near future). Nevertheless engineers must be courageous in taking into account such parameters which increase the investments. They must not wait for nature to show what it can do.

4. STORM SURGE BARRIER OF ROTTERDAM AND ANTWERP.

With Rotterdam's storm surge barrier project resulting in closing of the New Waterway, the Netherlands has started a protection project for their last unprotected estuary. Several construction consortiums submitted their designs to the Dutch authorities [1, 4]. With regards to the marine environment, it is interesting to show one innovative design which remarkably protects the site aestheticism (Fig. 6).

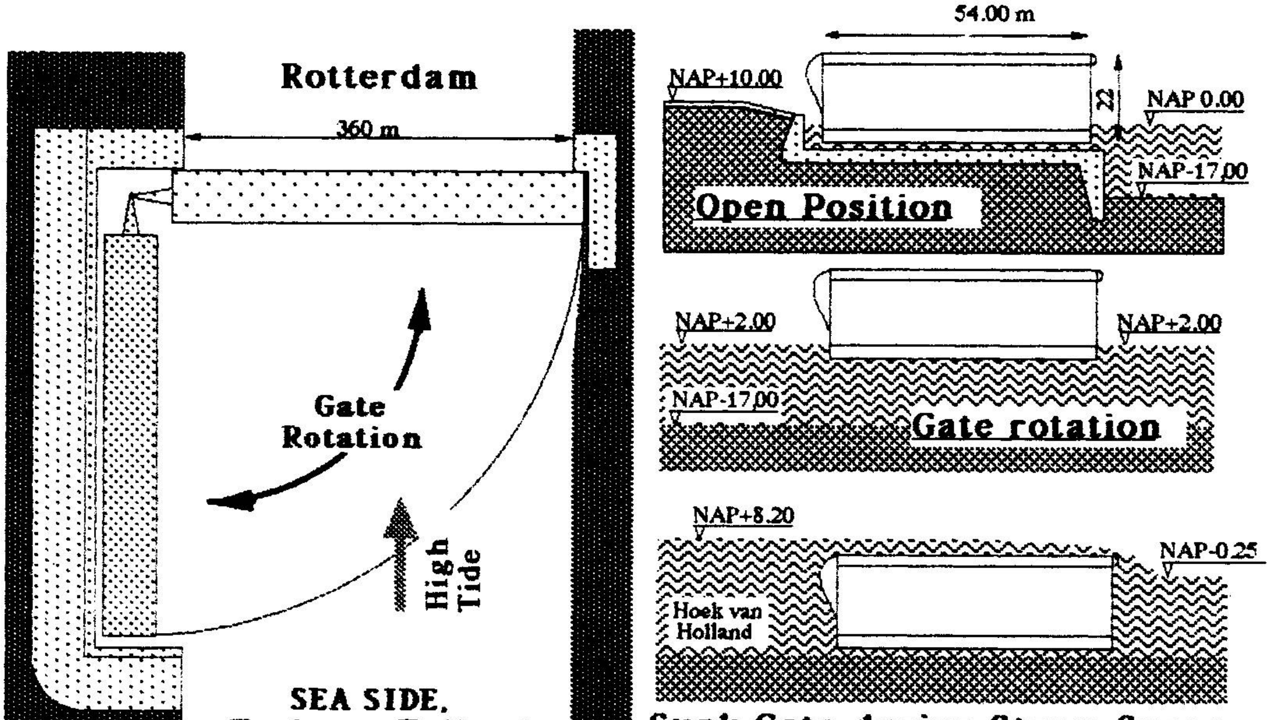

Fig. 6 : The floating storm surge barrier projected for the Rotterdam New Waterway.

In Belgium, the aim of the Sigma plan (1977) was to reduce the flooding risk to a probability of 1/10000. Completioned was planned for 10 years in the future. The main protection device was a storm surge barrier in the Oosterweel. The Antwerp's barrier had to keep two channels for the navigation of at least 60m width and 9.7m deep. In 1980, the proposed design (Fig. 4.a) was composed of 3 lift gates of 80m span and 6 radial gates of 35m span. As the requirements meant an unlimited air clearance, the projected gates had to be lifted 80m above the river water level from four towers 125m high. The excessive cost, the huge head rooms including lifting powers, and the negative effect on the environment, especially related to the site aestheticism, have caused the project to be abandoned.

Since the first step of this project, another one has been suggested which provides lower cost and higher aestheticism [6]. This design (Fig. 4.b) is composed of two 100m span floating gates, one on each side, allowing for the two directions of navigation. During the closing the floating gates have the minimum draft, thereafter they can be ballasted. The central part is composed of usual moveable weirs. This idea although not accepted at this time seems to be in 1990, the optimum one. Nevertheless, it is hoped that for the safety of this area and its population, the Belgian decision makers would at this time agree that, *an ounce of prevention is worth a pound of cure*. Thus, it is now hoped that a deep reconsideration of the Antwerp protection devices should be started soon.

5. CONCLUSIONS

With the dawing of the year 2000, interaction between the marine environment, estuary protection by storm surge barriers and sea level rise should not continue to be neglected. Therefore, the followings recommandations are made :

- Estuary protection by storm surge barrier must be considered only as a supplementary protection device for several coherent protection techniques. Dikes, banks, etc. as well as the natural environment must be able to withstand the usual sea's attacks. Moreover marine current modifications may create erosion or accretion.

- With respect to the estuary aestheticism, it is strongly recommended to plan structures as compatible to the environment as much possible, as in the case of floating tidal surge barrier.

- The most important problem of the sea level rise is the increase of the frequency of exceedance of water levels. With a rise of 1.5 meter, the probability of reaching a fixed water level which arrives once every 1000 years, will become once every 10 years. From an economic viewpoint, it is recommended to combine the overall maintenance of the structure with a step by step structural adaptation in relation to the rise in sea level.

- The natural environment has a great capacity to adapt to very slow changing conditions without the extinction of any species or organisms. Nevertheless, sandy coasts being subject to erosion, loss of land will occur by inundation and the indertidal area will drastically change. Moreover increased saltwater intrusion will happen. Therefore, from today, methods such as the "Zonal Protective Method " or sand depletion where beach retreat is expected, must be used.

- Because of the high risk of environment perturbation, and taking into account public opinion about estuary protection projects, high tide is particularly sensitive. Since these works have been planned for decades, an evolution of the public's opinion can occur. Then engineers are strongly advised to review periodically the uncompleted or not yet started works. On the other hand, in 1990 the sea level rise appeared to be irrelevant to public opinion. Therefore, it is also the job of the designers to anticipate such phenomenon in order for it not be necessary (for one time) for a sudden event to happen triggering countermeasures.

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Safeguarding of Venice
Sauvegarde de Venise
Rettung von Venedig

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SUMMARY

The present paper partly describes reasons for the increasing need, through the last century, for safeguarding Venice, and the political discussions and decisions which have taken place in the period from the last sixties when public realized the risk of flooding. It recalls the comprehensive plan for safeguarding and restoration of the Lagoon. Further a brief presentation of parts of the studies carried out to secure an optimal design of the new works is given. This part focuses on the effects on the evolution of the famous beaches of Venice and the morphology around the three inlets which connect the Lagoon and the Adriatic.

Sauvegarde de Venise

Résumé

L'article décrit les raisons du besoin accru, au cours des cent dernières années, pour la sauvegarde de Venise et l'établissement d'un plan général pour le sauvetage et la restauration de la Lagune. Il rappelle les discussions et décisions politiques qui ont eu lieu dès la fin des années soixante, lorsque le public a réalisé le risque d'inondations. Quelques études sont présentées. Elles permettent d'assurer le projet optimal des nouvelles constructions. L'article traite des effets du développement régional sur les fameuses plages de Venise et la morphologie autour des trois bras de mer qui relient la Lagune et l'Adriatique.

Rettung von Venedig

Zusammenfassung

Der vorliegende Artikel beschreibt die Gründe für die während des letzten Jahrhunderts gestiegene Notwendigkeit von Schutzmassnahmen für Venedig und den umfangreichen Plan zur Rettung und Wiederherstellung der Lagune. Er nimmt die politischen Diskussionen und Entscheidungen der Zeit seit den späten sechziger Jahren wieder auf, als die Oeffentlichkeit das Risiko einer Ueberflutung erkannte. Einige Studien werden vorgestellt, die ausgeführt wurden, um den Entwurf der neuen Kunstbauten zu optimieren. Behandelt werden die Auswirkungen auf die berühmten Strände von Venedig und die Morphologie um die drei Wasserarme herum, die die Lagune mit der Adria verbinden.

1. INTRODUCTION

In connection with the safeguarding of Venice against flooding, a consortium of Italian engineering companies, the Consorzio Venezia Nuova (CVN), has been given concession by the Italian government to develop a comprehensive plan for saving Venice. The CVN has chosen DHI to assist them in many of the hydraulic and environmental aspects of the project.

The project involves the construction of combined storm surge barriers, locks, and refuge ports at the three inlets, additional jetties and breakwaters for the protection of the barriers as well as coast protection and beach nourishment works along the barrier islands.

DHI has during the period 1988-1990 undertaken the First Phase of the Study: Venice Lagoon - Inlet Stability and Impact of New Works.

- Morphological Study.

  The main purpose of this is to establish a general understanding of the morphological processes of the area insuring that the mathematical modelling is covering all important processes. Furthermore a detailed programme was established for the two other elements of the study: The Mathematical Modelling and the Field Campaign.

- Field Campaign.

  The purpose of the field campaign is to establish a detailed description of all relevant data, such as: wind, waves, currents, tides, bottom conditions and suspended sediments serving as input and detailed calibration basis for the mathematical modelling. The field campaign has covered two winter seasons of 4 months duration each during the winters 1988/89 and 1989/90.

- Mathematical Modelling.

  The main purpose of the phase I modelling has been to demonstrate the capability of the modelling setup and to establish a sound basis for the detailed planning of the final second phase, which is planned to be executed in 1991.

  The mathematical phase II modelling includes 2-dimensional modelling of waves, currents and sediment transport patterns as well as bed level changes in the areas close to the inlets. Furthermore the littoral transport conditions along the littorals will be modelled. Finally special study programmes of siltation in refuge ports and locks as well as scour/sedimentation investigations for the gate structures will be performed.

This paper describes the historical development of regulatory works, the effects on the morphology, the plans for future protection works and presents the mathematical tools used for investigation of the effects of the new works on the morphology around the inlets and along the littorals.

2. DESCRIPTION OF THE MORPHOLOGY OF VENICE LAGOON AND THE HISTORIC DEVELOPMENT OF REGULATORY WORKS

The Venice Lagoon is located in the NW-ern part of the Adriatic. The Lagoon is separated from the Adriatic by sand spits, tidal inlets and barrier islands as follows: Cavallino Beach, the NE-ern sand spit, Lido Inlet, the N-ern tidal inlet, Lido Island, the N-ern barrier island, Malamocco Inlet, the middle tidal inlet, Pellestrina Island, the S-ern barrier island, Chioggia Inlet, the S-ern tidal inlet, Sottomarina Beach, the S-ern sand spit.

Before men started to regulate the inlets and to protect the barrier islands, the system of sand spits, tidal inlets and barrier islands was quasi stable, due to the general sediment transport pattern of the area, which is SW-ward littoral drift Northeast of the lagoon and N-ward drift South of the lagoon. However, from the human point of view the natural system caused severe problems to habitation and navigation as follows:

- The tidal inlets were wide, shallow and constantly changing causing difficulties to the navigation
- The low barrier islands were often breached during storm surges causing damages and loss of property and lives.

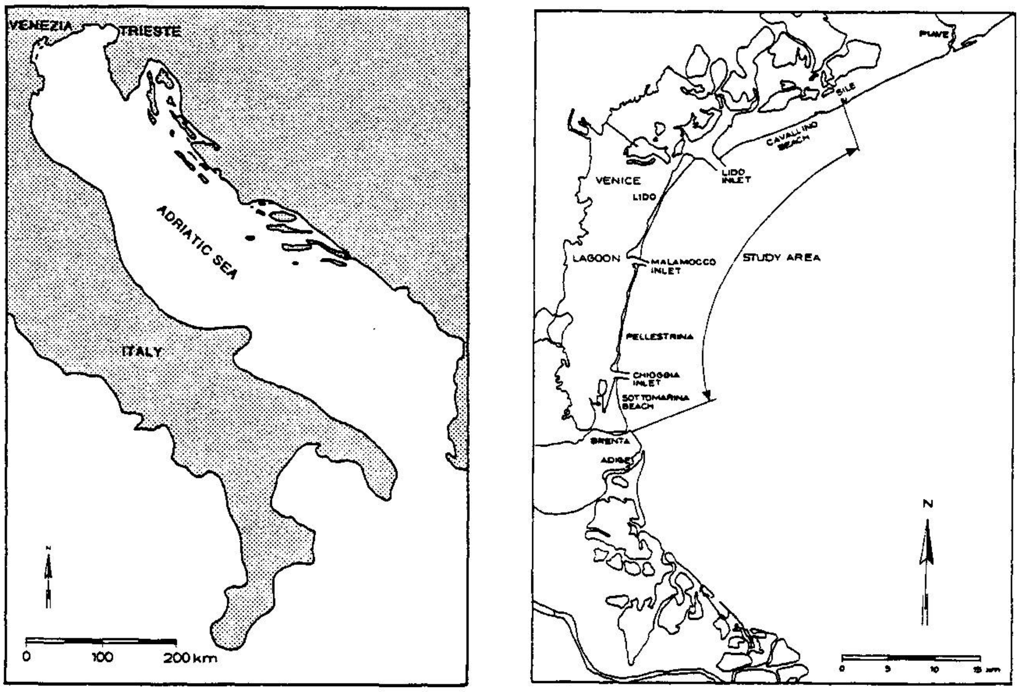

Fig. 1. Location maps: Adriatic Sea and Venice Lagoon with adjacent coasts

- The Lagoon suffered from sedimentation due to rivers discharging sediments into the lagoon.

As early as from the 14th to the 17th century the rivers were diverted around the lagoon to discharge direct into the sea.

Flooding of Venice has been documented since the 16th century. At that time a flood was an extraordinary event. The protection of the Lido and Pellestrina Islands as well as Sottomarina Beach by seawalls, the so-called Murazzi, started already at that time. From the middle of the 19th century of the following very large mitigating measures were initiated:

- Very large inlet jetties were constructed in all three tidal inlets.
- Navigation channels were dredged.
- The old seawalls at the barries islands were reinforced.

Most of these works were finished at the beginning of the 20th century.

The introduction of the jetties blocked the littoral drift completely, causing accumulation Northeast of the Lido Inlet north jetty at Cavallino beach and South of the Chioggia Inlet south jetty at Sottomarina beach. This trapping of sand increased the general erosion along the barrier islands. Furthermore sand was accumulated in the northern and southern ends of the barrier islands in the lee areas of the long jetties, which further added to the general erosion. This erosion raised the demands for reinforcement of the seawalls and groyne fields especially along the central part of Lido and Pellestrina. However, as no sand was supplied to the suffering beaches, and as the transport of sand away from the central parts of the islands continued, the beaches have been completely eroded away in these areas exposing the sea walls directly to the wave attack.

By the construction of the inlet jetties, the cross-section area of the inlets was drastically decreased, which caused an increase in the tidal currents in the inlets, which again resulted in erosion in the inlets and nearby lagoon shoals. This erosion started in the late part of the 19th century and ceased around 1950, when the equilibrium cross section were reestablish. During this period the inlet erosion amounted averagely approx. 700.000 m^3/year. Most of the eroded sand was jetted with the ebb currents out into the Adriatic, from where some of it was transported towards the littoral zone. By this mechanism, the starvation of the barrier island beaches was to some extent mitigated up to around 1950.

Around 1925 the development of the industrial suburb, Mestre, located at the mainland opposite Venice, accelerated, which did also the demand for groundwater. The groundwater was extracted from layers of sand and clay extending to the underground of Venice. This caused the whole area to subside. Adding to this man-induced subsidence the natural subsidence and the eustatic sea level rise results in a total subsidence of Venice of approx. 25 cm since the turn of the century. The continuous development in the lagoon area involved other large changes during this century, of which the most important are:

- Large reclamation works, mainly in the Mestre area.
- The construction of closed fish ponds.
- Dredging works in the industrial zone and in the canals amounting to $19 \cdot 10^6$ m^3 during the years 1952-60.
- Dredging of the large Canale dei Petroli from Malamocco inlet to Mestre, $31 \cdot 10^6$ m^3 during the years 1961-69.
- Increasing pollution of the lagoon.

This very drastic development within the fairly small and vulnerable lagoon area caused a series of problems to be more and more evident during the 1950'ties. The most important problems faced by the Venice community at present are:

- The frequent flooding of Venice.
- The deterioration of the lagoon morphology and ecology.
- The erosion of the barrier islands.
- The decreasing socio-economic conditions in Venice.

The requirements by the public for the solving of the above problems have gradually developed. This process will be described in the following.

3. THE MATURING OF THE SAFEGUARDING PROJECTS

Public opinion started to be well aware of the risk of flooding after the terrible storm surge in November 1966 with 1.2 m of water in San Marco Square and, more recently, in 1986 with almost one meter. Since the beginning of the century the yearly frequency of flooding has increased of around 6 times, reaching a value of 40 times a year.

The flooding of November 1966, which lasted about 24 hours, gave the evidence of the vulnerability of the city, and contributed to increase the on-going inland migration of the young population in search for better job opportunities. After the 1966 flooding the scientific community started an intense process for finding solutions along a line deeply influenced by the well accepted idea that the increased frequency of flooding and the higher water levels had been produced by human interventions such as: the extraction of groundwater, the reclamation works, the dredging of navigation channels and the construction of closed fish ponds.

A law was passed to stop the extraction of groundwater and in the following years the antropic contribution to subsidence disappeared. Further, a full set of drastic morphological interventions were proposed in order to reduce the propagation of the tide inside the lagoon with very little attention to the beneficial effects of the permanent tide flushing on water quality. These interventions included permanent restriction of the inlets and their complete closure, permanent reopening of fish ponds and removal of reclaimed areas and separation of Venice from the artificial navigation channel of Canal dei Petroli by means of a dike. Other proposals were related to the local defence of the city, such as artificial lifting of the ground level including buildings etc., confinement of the small city islands which constitute Venice.

The "period of proposal" lasted seven years till 1973 and produced no other practical intervention apart from the very important one of stopping groundwater extractions. During the evaluation process of the various drastic solutions the need of more information on the hydraulics and morphology of the lagoon was well recognised both by the decision makers and the public. In 1973 the government tried to address the problems for the safeguard of Venice with the first special law for Venice and, in 1975, with the guidelines for the application of the law.

The defence against flooding had first priority, the ecosystem and the port were considered secondary resources not to be damaged in an irreversible way.

The idea of floating gates at the three inlets originated from the 1970 call for proposals issued by the national Research Council. In 1975 the Minister for Public Works issued another call for proposals and in 1981 the feasibility project for the defence of the lagoon against flooding was completed by a group of leading experts. The proposed barriers consisted of permanent structures reducing the areas of the inlets coupled with a row of floating gates.

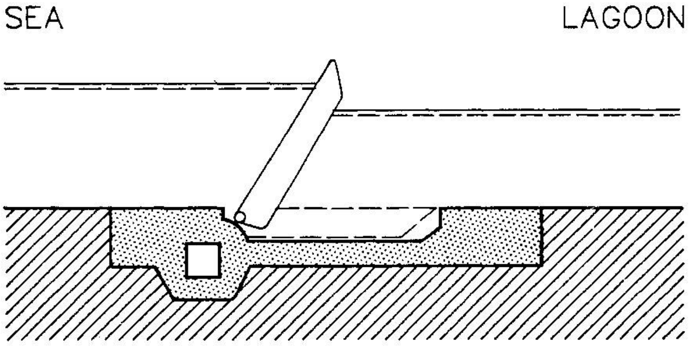

Fig. 2. Sketch of the proposed floating gates.

The feasibility project of 1981 was approved by the Greater Council of Public Works with a list of requests for further investigation, particularly on the impact of the permanent structures on tidal flushing. Only in 1984, with the second Special Law for Venice, the defence against flooding was associated with the need of intervention for environment restoration of the lagoon. The Law suggested that the ecosystem should be studied as a whole and the various interventions should be coordinated by the State through a private technical organization, the Consorzio Venezia Nuova, under the control of Magistrato alle Acque, a 500 year old Venetian institution responsible for the government of the lagoon system. Together with the protection against high water the law defined other objectives, including the protection of the littorals, the restoration of the ecosystem, the morphological re-equilibrium of the lagoon, the check on the feasibility of excluding oil tankers from the lagoon.

During the first 5 years of life Consorzio Venezia Nuova has developed a comprehensive plan of studies. A result of these studies has been the completion of the preliminary project for the new works at the inlets, the so-called REA project. The project has been developed taking into account a vast series of specific provisions that emerged from the long political and scientific work which led to the Special Act of 1984.

The institutional decisions and ruling can be divided into two main groups.

The first group contains the more general provisions requested by the public opinion according to which the work ought to maintain characteristics of an experimental nature, of reversibility, phasing and flexibility, search for the most suitable means to protect and strengthen commercial port activities and the local fishing industry, bear in mind the possibility of gradually replacing oil tanker traffic in the lagoon with oil pipelines and respect the natural, artistic and monumental heritage of the areas (no superstructures or intermediate piers).

The second group contains specific provisions which are conservative criteria in order to avoid all the potential negative impacts of the work on the lagoon morphology and water quality: No significant change in the volume of water exchanged between sea and lagoon, no significant change in the distribution of the flow rates between the three inlets and their relative canals, no appreciable alteration in sediments transported along the littorals, no significant change in the cross section area of the inlets, guaranteed access to the lagoon ports through the openings for commercial boat, fishing boats, passenger ships and pleasure crafts.

During 1990 the REA project has been discussed by the City Council, the region and the State and, at the end of the process, Consorzio Venezia Nuova has been asked to proceed with the completion of the project.

The attitude of public opinion towards the project has been influenced by a four year period without relevant high water and with noxious algal blooms. The scientific evidence of the risk of high water such as the one of 1966 and the need of protection barriers took second place, after the emerging need of interventions for pollution control. The requirement was put forward by the politicians that the gate operation must not increase the content of nutrient from the inland watershed in the lagoon.

The 1989 REA project is a great improvement completely different from the ideas of 1974 and from the proposal of 1981. Part of the merits goes to the public opinion who promoted the integration of the restoration of the lagoon environment in the project, but the price paid is very high because Venice is still under the offence of flooding, and it will remain in this situation during the next ten years which will be necessary for the completion of the works.

4. HYDROGRAPHIC CONDITIONS IN THE NWern PART OF THE ADRIATIC

In the north western part of the Adriatic Sea there are two dominant wind systems - the Bora coming from east north east and the Scirocco coming from south east. The coastal areas off Venice Lagoon are strongly influenced by the waves and currents induced by these two wind systems. The fine sand ($d_{50\%}$ = 100-200μ) which constitute the beaches and coastal areas are transported along the adjacent beaches towards the area of interest - and trapped by the large jetties at Lido and Chioggia inlets. Apart from the extreme storm events, where the transport rates in the coastal zone are very high, the strong currents though the inlets due to the tide influence the development of the bathymetry - especially close to the inlets. The tide in this area is semidual (i.e. two cycles per day) with a typical range of 1 m at spring tide, and typical currents speeds in the inlets up to 2-3 knots.

5. MATHEMATICAL MODELS

A setup of mathematical models must include the relevant phenomena which determines the development of the morphology in the areas. These are wave conditions along the coasts, currents driven by tide, wind and, in the nearshore zone, waves, and the corresponding sediment transport capacity.

Two types of model complexes have been applied during the first phase of mathematical modelling:

· MIKE,	two-dimensional wave-, current and sediment transport models, S10, MIKE21.HD, MIKE21.ST
· LITPACK	littoral drift and coast line evolution models.

All the models in the two dimensional model complex operate in a rectangular grid with constant grid spacing. The wave model S10 is a refraction model for monochromatic unidirectional waves. MIKE21.HD is a dynamic depth integrated current model in which currents driven by wind, tide, breaking waves can be modelled. In MIKE21.ST the wave and current fields found by S10 and MIKE21.HD are utilised to calculate a sediment transport field averaged over the tidal cycle and the corresponding initial bed level changes. In MIKE21.ST the sediment transport as function of the local wave, current and bed material parameters are calculated by a detailed intra wave period model, see Fredsøe et al. (1985) and Deigaard et al. (1986). An overview of the model complex applied for calculation of the initial bed level changes are shown in Fig. 3.

LITPACK is a model complex for investigations of coastal processes of sandy beaches. LITPACK consists of a hydrodynamic module which calculates waves and longshore currents in the surf zone, a sediment transport module which calculate the longshore sediment transport by use of the same detailed sediment transport module as applied in MIKE 21.ST, and finally a one line model for calculation of coast line evolution.

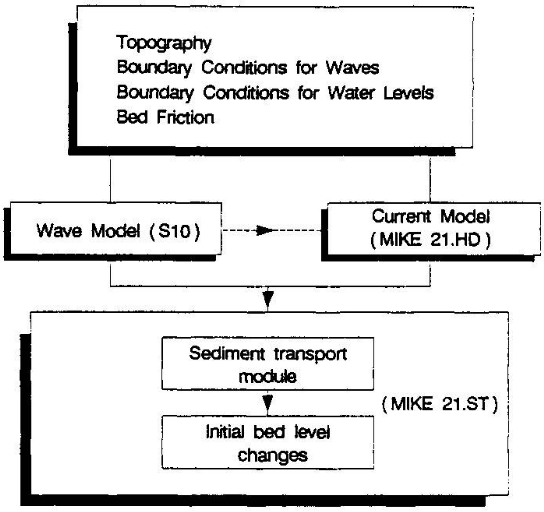

Fig. 3. Overview of the parts of the MIKE model complex used for calculation of initial bed level changes.

6. FIELD INVESTIGATIONS

There are 3 major purposes of field investigations in the area: 1) to collect general information of the local conditions, wind, waves, currents, bathymetry, bed material etc., 2) to collect data for calibration and verification of models which can then be applied for a larger range of conditions, 3) monitoring of a number of relevant parameters for documentation of the effect of the new works.

The field measurements include both long term recording of a number of parameters in fixed stations and intensive investigations of currents and suspended sediment.

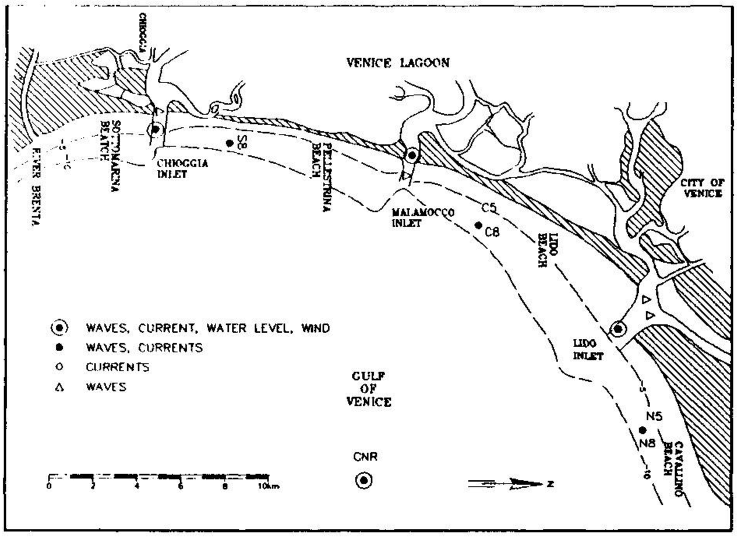

Fig. 4. Overview of fixed stations and recorded parameters.

The long term recording programme consists of 22 self-recording instruments in fixed locations in and off the three inlets. These locations and the measured parameters are shown in Fig. 4. The instruments used both for current and wave recording are electromagnetic meters while the pure wave meters use acoustic signals. All instruments are mounted 1-1.5 m above the bed. The sample rate varies between 1 and 3 hours.

For calibration and verification of the hydrodynamic models very precise information on water levels is needed. For this purpose the measurements mentioned above are supplemented by registrations carried out by Comune di Venezia of water levels in the three inlets every 5 min.

The above described long term recordings cover the period Dec. 1988 to April 1990. Apart from this, some of the instruments were deployed already in the period Sept. 1987 to April 1988 and some instruments are still maintained for monitoring purposes. The long term recordings are carried out by ECOMAR, Milan, Italy.

The intensive measurements concentrated on detailed investigations of current patterns around the inlets both under ebb and flood flow and calm and rough conditions and collection of data for calibration and verification of the sediment transport model, i.e. simultaneous measurements of suspended sediment, current profile, wave conditions, characteristics of bed material and suspended material.

The current investigations were carried out by float tracking and current profiling by an electromagnetic meter. A laser system, normally used for land surveying supplemented by a GPS system in large distances from shore (more than 2 km), was applied for positioning. The registration of suspended sediment was carried out by analysis of half litre water samples sucked from 0.05, 0.10, 0.30, 1.0 m above the bed. The grain size distributions of the sediment were determined by analysis of 25 litre samples sucked 0.1 m above the bed and of grab samples of bed material.

Examples of results

The data material is very comprehensive. As an example is shown an extract of collected data during two days with rough weather, mainly the 26th and 27th of March 1990. Fig. 5.A, B, C and D show measured significant wave heights and current speeds in the 3 offshore stations N8, C8, S8 and wind speed and direction at the CNR measuring platform.

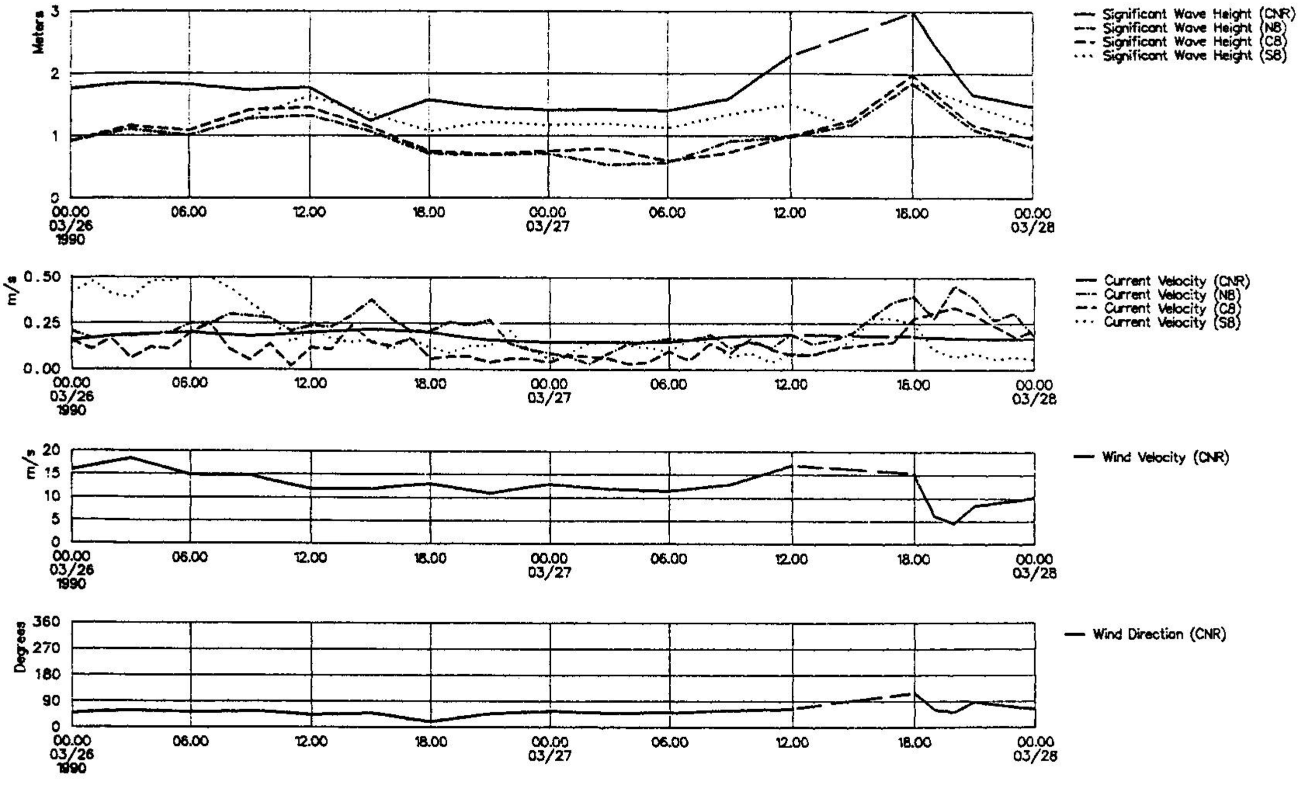

Fig. 5. Example of timeseries of measured waves, currents and winds.

The utility of these simultaneous measurements are obvious: verification of wave and current models, all kinds of statistic analysis and correlations between waves, winds and currents.

Fig. 6.A and B show two series of float tracks carried out on the 27th of March under ebb and flood flow and the water level registration from the inlets and the CNR platform. These detailed measurements supplement the long term measurements and are very useful for model verification. Note for instance the strong bending of the ebb flow jet due to the relatively strong wind driven southgoing current along the coast.

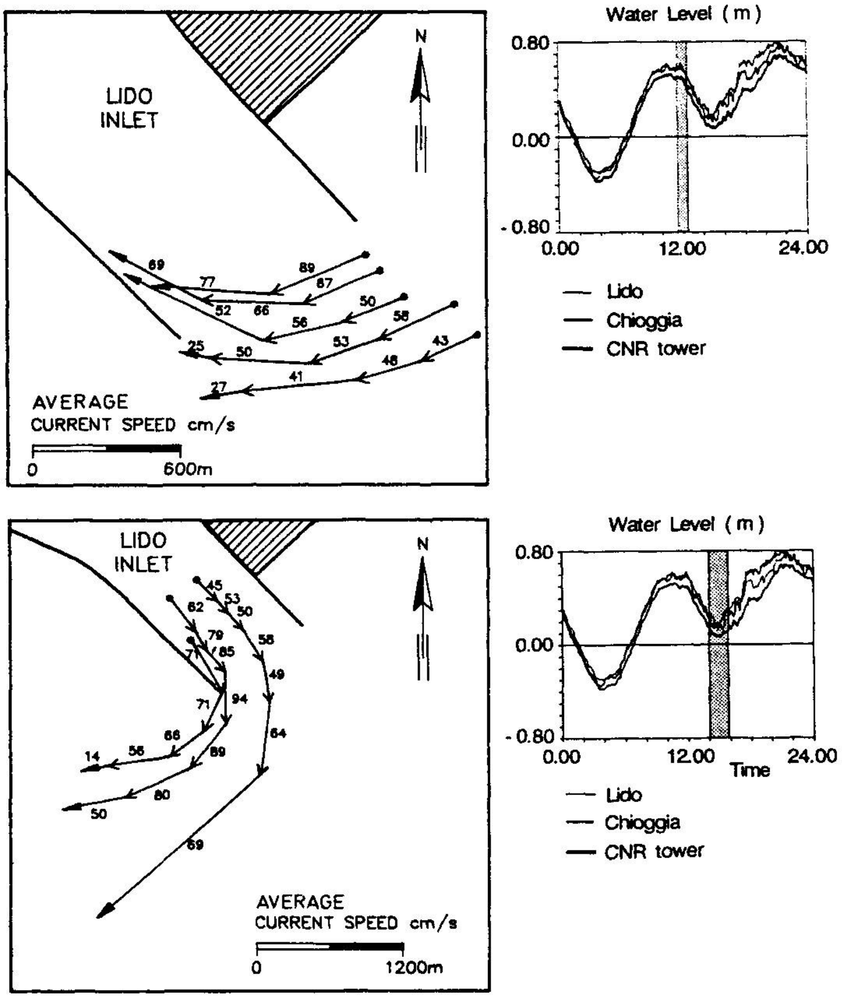

Fig. 6. Detailed investigation of current patterns around Lido Inlet.

Fig. 7. shows an example of measured suspended concentrations and current profiles in the position C5, see Fig. 4. on the 26th of March. These measurements are used for verification of the sediment transport model and for general establishment of a correlation between background concentrations of fines and wave and current conditions. For comparison Fig. 7. includes a distribution of suspended sediment calculated by the sediment transport model with the relevant parameters.

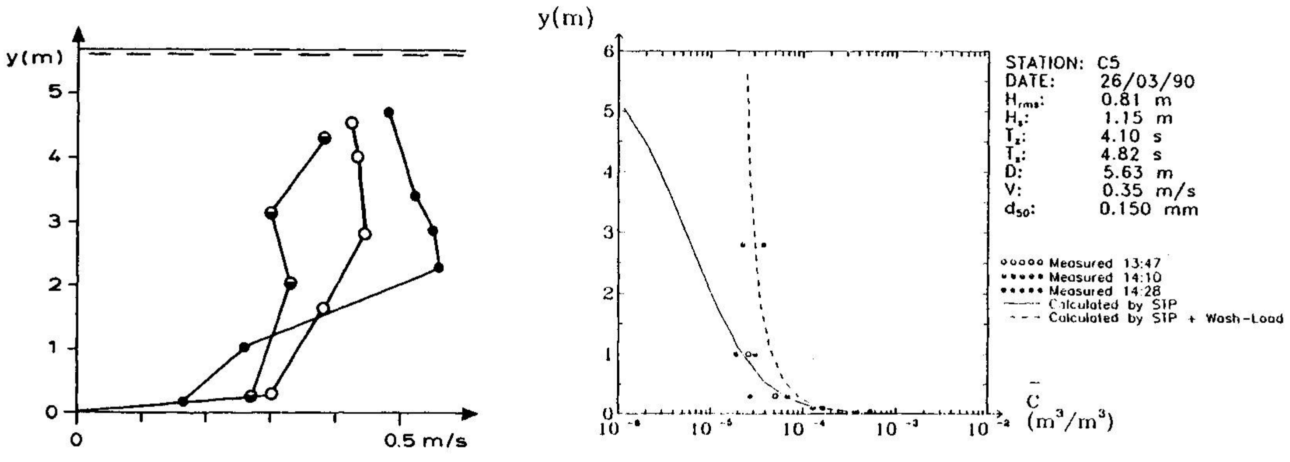

Fig. 7. Measured current profiles and measured and calculated suspended sediment profiles. C is volume of suspended sediment per volume of sediment and water.

7. PRELIMINARY RESULTS FROM MATHEMATICAL MODELS

The first phase of mathematical modelling included calculations of initial bed level changes in the two dimensional model complex MIKE and a first verification of the sediment transport and littoral drift model by simulation of the previous evolution of a stretch of the relevant coastline by LITPACK.

Coastline Development by LITPACK

The most direct way of verification of the basic sediment transport model is comparisons as shown in Fig. 7 between measured and calculated suspended sediment profiles. Another very valuable verification of the sediment transport model are comparison of the coastline evolutions found by LITPACK and observations. Fig. 8 shows the observed and simulated coastline evolution north of Lido inlet during the period 1933-83. This comparison shows that the size of the calculated net littoral drift is reasonable.

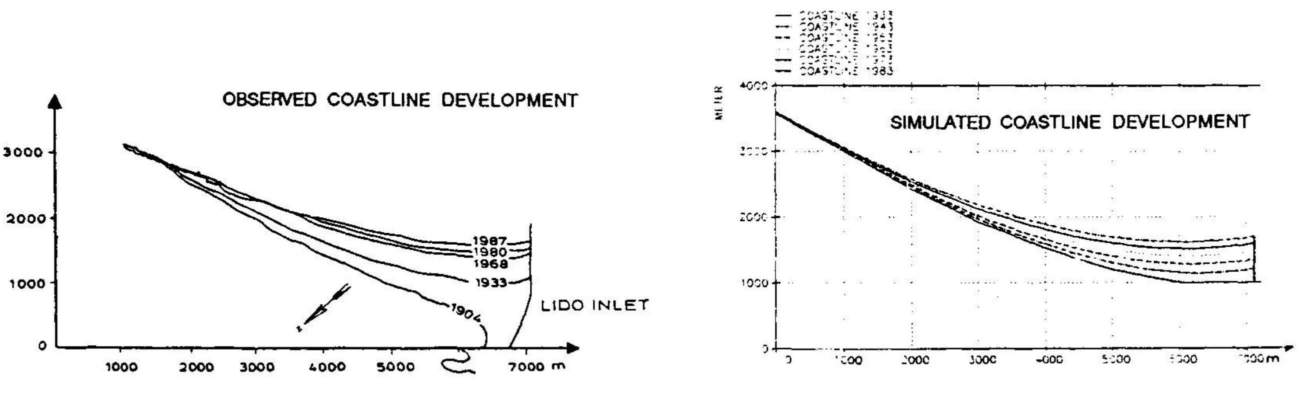

Fig. 8. Comparison of observed and simulated coastline evolution. Cavallino Beach.

2-dimensional modelling

Wave, current and sediment transport fields for a typical Bora and a typical Scirocco storm combined with a typical tide have been modelled. The simulations have been carried out for the actual layouts of the structures around the inlets and two proposals for future layouts. Further, the effects of closing the gates during the Scirocco storm have been investigated. The areas covered by the models are sketched in Fig. 9. In the so-called Regional Area wave, current and sediment transport fields are investigated in a 300 m grid. In the local model areas at Lido, Malamocco and Chioggia inlets, the sediment transport phenomena are studied in more detail. In these models the grid spacing is only 50 m.

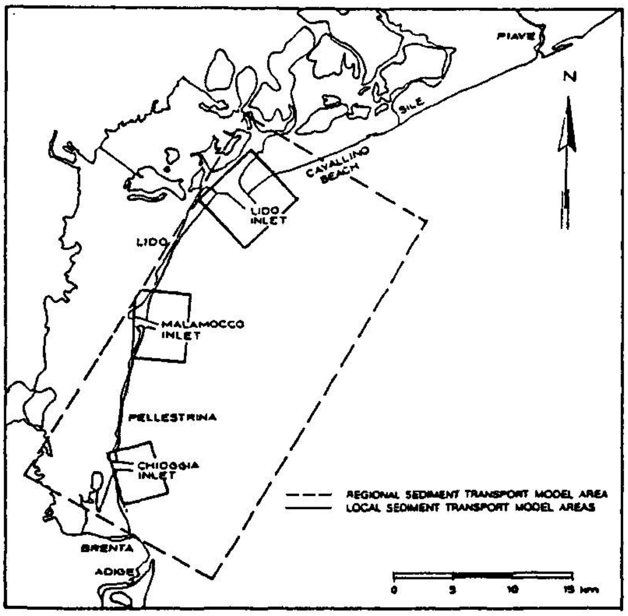

Fig. 9. Overview of Model Areas.

An example of results produced by the model complex is illustrated in the Fig. 10.A - D. This example treats the local area around Chioggia inlet for the existing constructions and strong Scirocco wind conditions, $H_s \simeq 2.8$ m, tidal range 0.8 m.

Fig. 10.A shows the bathymetry of the area. The grain size of the bed material is a very important parameter for the sediment transport calculations and is digitized in a similar way and used as input to model complex.

By the wave model S10 the wave field is calculated. The results are illustrated in Fig. 10.B, in which isolines for significant wave heights are shown. The time varying current field is calculated by the hydrodynamic model MIKE21.HD. The driving forces included in this simulation are wind, tide and variation in the radiation stresses (wave driven currents). As an example the current field at maximum flood flow is shown in Fig. 10.C.

The sediment transport field averaged over the tidal cycle has been calculated based on the wave field, the current fields and the grain size distribution. The calculated average transport field is shown in Fig. 10.D.

It appears that the wave driven currents along Sottomarina carry large amounts of sediment. This so-called littoral drift is responsible for the evolution of Sottomarina Beach, which advances ~ 6 m/year. Close to the southern jetty a large counter clockwise current vortex appears. This wave-driven current pattern occurs because the wave fronts are refracted around the shoal SE of the inlet. The sediment transport rates along the jetty increase strongly from outside to inside the surf zone. Because the breaking waves are able to carry more sediment in suspension than the non breaking waves. The net transport in the inlet appears to be close to zero in this case. This is because the current speeds during ebb and flood flow are found from the current simulations to be nearly identical.

The duration per year of the conditions simulated in this example is estimated at 1.8 day/year - assuming that this condition represents all strong Scirocco wind cases. From the above described sediment transport field the initial bed level changes per year corresponding to Scirocco wind are determined. These calculated bed level changes are illustrated in Fig. 11. The bed level changes reflect the variations in the transport capacities. Along Sottomarina Beach the decrease in littoral drift leads to large deposition areas. The counter clockwise current and sediment transport pattern south of the jetty leads to erosion where the transport capacity is increased due to the increase from outside to inside the surf zone in the amount of suspended sediment. Inside the inlet no net erosion is seen because the transport capacity is identical during ebb and flood. The erosion NE of the inlet takes place during ebb flow where the ebb flow jet passes this area. The pattern SE of the inlet occurs due to the shoal. Erosion takes place where the water depth decreases in the current direction and deposition takes place where the current has passed the shoal and the water depth increases (north of the shoal).

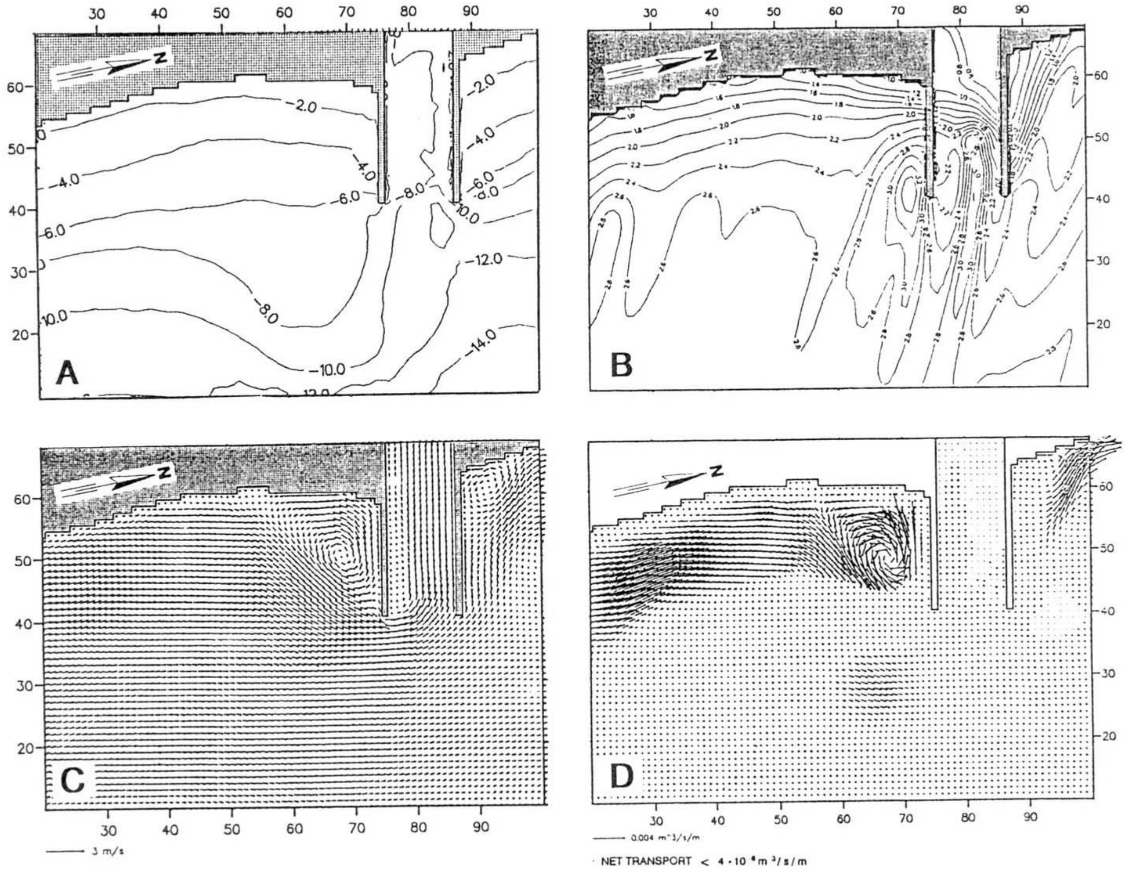

Fig. 10.A Bathymetry
10.B Wave heights
10.C Current pattern at maximum flood flow
10.D Sediment transport field averaged over the tidal cycle

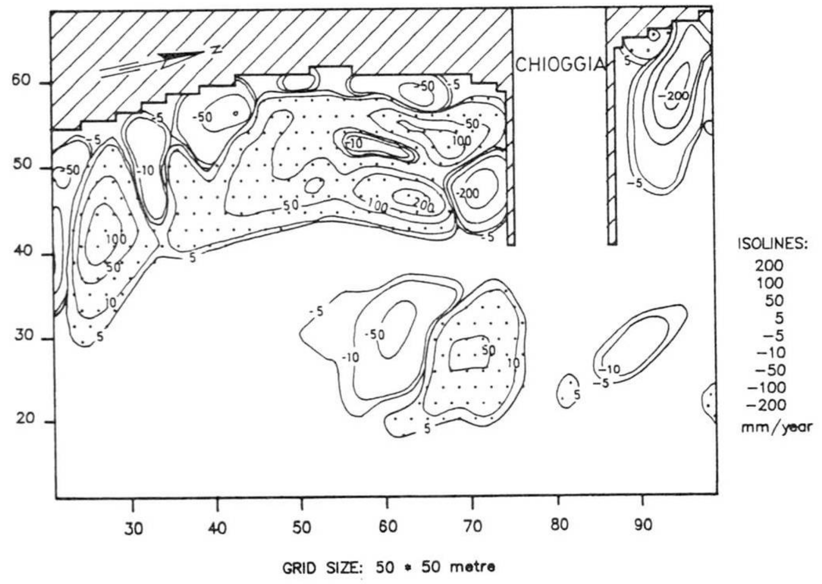

Fig. 11. Calculated Initial Bed Level Changes per Year corresponding to Strong Scirocco Wind.

Preliminary estimates of the impact of the new works

From the first phase of mathematical modelling it seems that the effects of the new works are concentrated relatively close to the inlets. The most important changes are found in cases where the future layouts include offshore breakwaters. In these cases sedimentation will take place in the sheltered areas between the inlet mouth and the breakwater. Further a proposed offshore breakwater at Chioggia seems to increase the area along the Sottomarina beach with shelter for the north easterly waves. This means some increase in the accreation immidiately south of the southern jetty.

In Malamocco and Chioggia inlets the simulations of the present layout show an ongoing erosion in the inlet mouth and a corresponding deposition far away where the current speeds decrease. This so-called 'flushing effect' disappears when the gates are closed. The closing of the gates during all rough Scirocco wind conditions therefore reduces the natural erosion in the inlet mouth. Furthermore, the preliminary simulations draw attention to the ongoing deposition near the inlet mouth of Lido due to littoral drift along Cavallino Beach.

Future investigations

The first phase of mathematical studies has shown that the very large jetties constructed during the last century to secure the navigation has changed radically the sediment transport pattern in the area and has caused the ongoing erosion along the Lido and Pellestrina beaches. The preliminary calculations have shown that the new works only influence the overall morphology of the littorals slightly compared to the existing man made interference in nature. However, there is, evidently, a need for restoration of the beaches and of cause the local areas around the new barriers will be influenced both by the structures themselves and by the closures of the gates. Further, it is very difficult to build refuge ports and locks in areas with strong currents and large amounts of suspended material without facing siltation problems.

The second phase of studies therefore focuses on these problems. It is planned to investigate the effects on the bathymetry of gate closure in a number of different wave and current conditions in the local model areas around the three inlets. The very delicate exchange of sediment through the inlets will be studied by use of both numerical models and collected field data in an attempt to estimate the net erosion or deposition in the lagoon. Based on measured and calculated amounts of suspended sediment and currents at the entrances to the planned refuge ports and locks, the siltation in these basins will be estimated and the optimal design will be chosen.

Further, the future investigations include study of design of an artificial, wide beach along the Lido, which suffers from lack of sand and which could be an even more attractive place to go for the many tourists who visit Venice. Along the Pellestrina the problems are more serious because the foreshore has been totally eroded and in long stretches the only protection of the lagoon is a seawall. In the nearest future different protection schemes for the Pellestrina will be investigated.

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Tidal Power and the Environment on the River Mersey

Energie marémotrice et environnement de la rivière Mersey

Gezeitenkraft und die Umwelt des Mersey-Flusses

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SUMMARY

A large tidal power resource exists in the UK and the Mersey Barrage is a promising proposal to exploit this for electricity generation. This massive engineering project would produce a clean predictable and renewable source of energy with a long life. Against the environmental benefits must be offset the costs to shipping and the local estuary environment which arise from the changed tidal regime, although scope does exist for mitigation of these costs. Consultations are essential to establish a publicly acceptable balance between the contrasting engineering, economic and environmental demands.

Energie marémotrice et environnement de la rivière Mersey

Résumé

Un site potentiel considérable d'énergie marémotrice existe au Royaume Uni et le barrage de Mersey est une proposition intéressante de production d'énergie électrique. Ce projet d'ingénierie important produirait une source d'énergie à long terme, sûre et renouvable. En opposition aux avantages pour l'environnement, il faut mettre les coûts de transport maritime et les conditions d'exploitation dans l'estuaire, qui résulteraient d'un changement de régime des marées. Une solution semble exister pour compenser ces coûts. La consultation est essentielle pour accorder les besoins divergents de l'ingénierie, de l'économie et de l'environnement.

Gezeitenkraft und die Umwelt des Mersey-Flusses

Zusammenfassung

Eine grosse Gezeitenkraftresource existiert im Vereinigten Königreich, und die Mersey-Sperre ist ein vielversprechender Vorschlag, um sie für Elektrizitätsgewinnung zu nutzen. Dieses massive Ingenieurprojekt würde eine klar voraussagbare und erneuerbare Energiequelle mit langer Lebensdauer produzieren. Gegen die Umweltvorteile müssen Nachteile für die Schiffahrt und die Oekologie der Flussmündung infolge der Gezeitenänderung aufgerechnet werden, obwohl für die Herabsetzung dieser Kosten ein Spielraum existiert. Beratungen sind notwendig, um ein öffentlich akzeptiertes Gleichgewicht zwischen den gegensätzlichen Ingenieur-, ökonomischen und Umweltanforderungen zu erreichen.

1. INTRODUCTION

1.1 Tidal Power in the UK

Renewable energy sources can reduce pollution by displacing thermal generation of electricity. In the UK, tidal power represents one of the largest available renewable energy resources and is estimated to be capable of replacing 17% of annual electricity demand [1].

Despite its beneficial effect at the macro-environmental scale each tidal power scheme must demonstrate that it does not produce environmental disbenefits at the local scale. By its nature tidal power generation produces radical changes in the estuarial environment. The most important of these are associated with a rise in the water level and modifications to tidal currents.

1.2 The Mersey Barrage

The proposed Mersey Barrage is sited in the northwest of England (Fig 1) and is currently leading in the race for large scale development of tidal power in the U.K. With industry backing, the scheme is currently being prepared for a Parliamentary Bill. As well as generating electricity the scheme will bring additional social and financial benefits to the area and it enjoys considerable local support. Navigation, business and environmental interests which would be affected are being consulted through working parties [2].

The Mersey estuary possesses characteristics which make it an attractive location for a tidal power barrage;

- the tidal range is favourable with a mean spring tide range of 8.4 metres.
- the broad upper estuary provides an upstream basin of large area.
- the basin discharges to Liverpool Bay through a narrow channel which could be closed with a barrage of economical length.

Large gated sluices in the barrage allow the flood tide to flow into the basin. During the ebb tide water is released through the turbines to generate electricity.

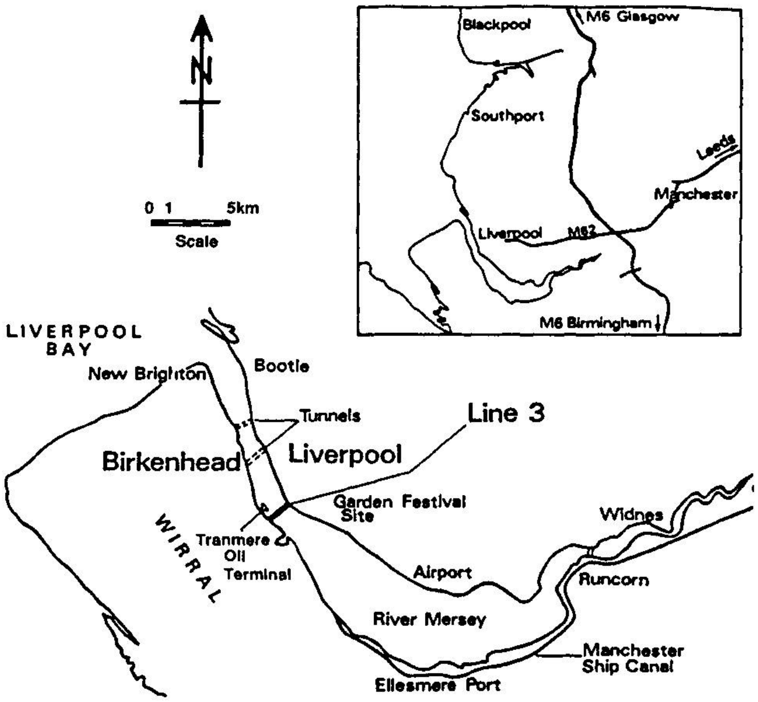

Figure 1 - Mersey Barrage Location

On normal tides it is found to be economic to pump water into the basin for a short period at the top of the tide after the sluice gates have been closed, thus increasing the volume of stored water to be released later at a greater differential head.

The preferred scheme is on a line some 2km upstream of a large and busy oil terminal at Tranmere. The barrage is some 1.7km long and 35m high in the deepest channel with an installed generation capacity of up to 700MW. Ships locking into the upriver docks and the Manchester Ship Canal have to pass the barrage.

This paper outlines the decision processes that have determined the siting of the proposed barrage, the layout of the structures and the operational constraints. The role of physical, economic and environmental factors in the design process is discussed.

2. BARRAGE DESCRIPTION

2.1 Line

Initially three possible lines were considered, line one near the mouth of the estuary, line two in the narrows between Liverpool and Birkenhead and line three upstream of the narrows. The line across the narrows was quickly rejected because there was insufficient width of river to accommodate all the necessary structures and because of the difficulty of construction access and the fast tidal currents. The downstream line was initially preferred but, being exposed, needed protection by a large breakwater to allow vessels to enter the locks.

The leisure benefits would be maximised by a downstream barrage which would provide the largest potential for water recreation and the development of disused dock areas. However Liverpool is still a busy port and the downstream line was eventually rejected primarily because of the cost of providing a sufficiently large lock to accommodate VLCCs berthing at Tranmere Oil Terminal and the uncertain environmental consequences of constructing a large breakwater. Therefore the upstream (line 3) location was selected for further development.

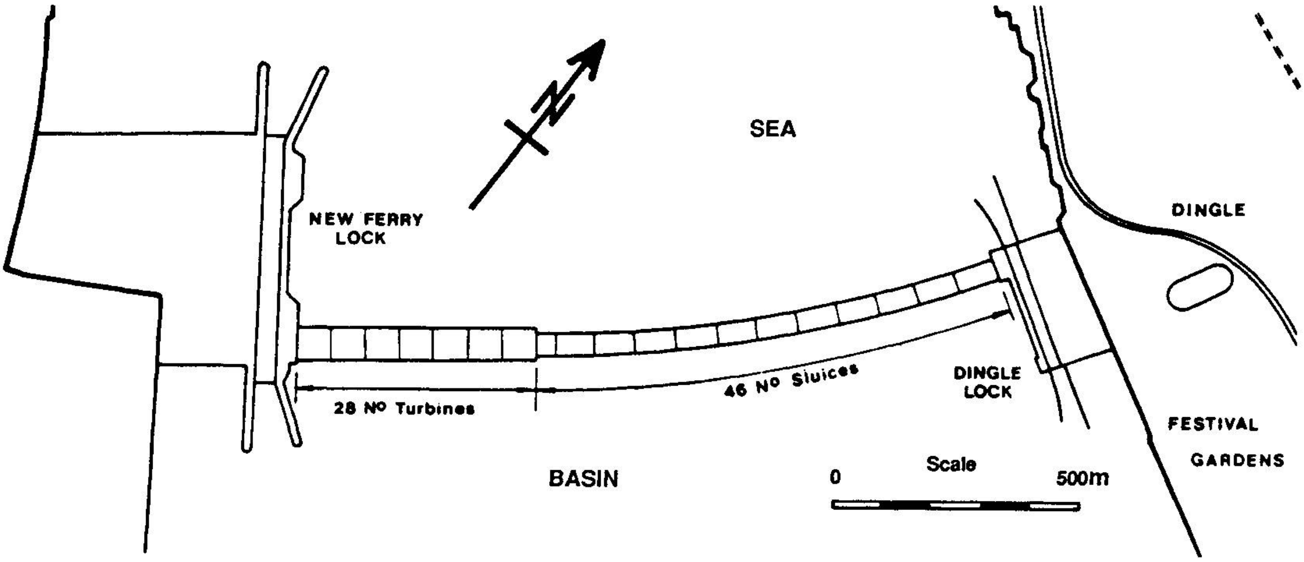

Figure 2 - Barrage Layout - Line 3

2.2 Layout

The base scheme comprises twenty eight 8m diameter turbines, forty six channel sluices and two locks (Figure 2). Twenty turbines are installed in five large concrete caissons, each containing four water passages (Figure 3). The remaining eight turbine water passages are constructed in-situ within the construction pit. All the sluices are constructed as floating caissons. Most of the sluice caissons contain four gated water passages (Figure 4). Between the sluices and the turbine generators there is a transition structure containing only two sluice passages. The sluices are founded at -9m OD whereas the turbine generator caissons have to be founded at -21.5m OD to provide sufficient submergence for the turbines. Variations to this layout are under consideration as noted in Section 4.4.

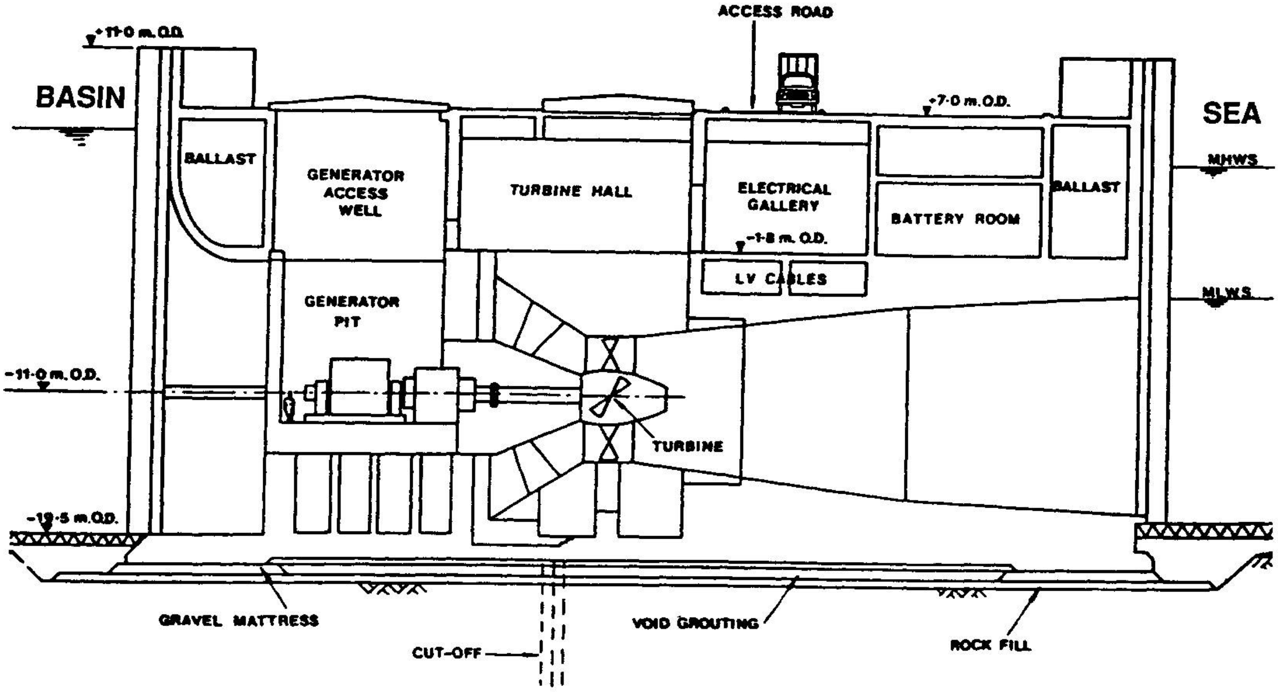

Figure 3 - Turbine-generator caisson

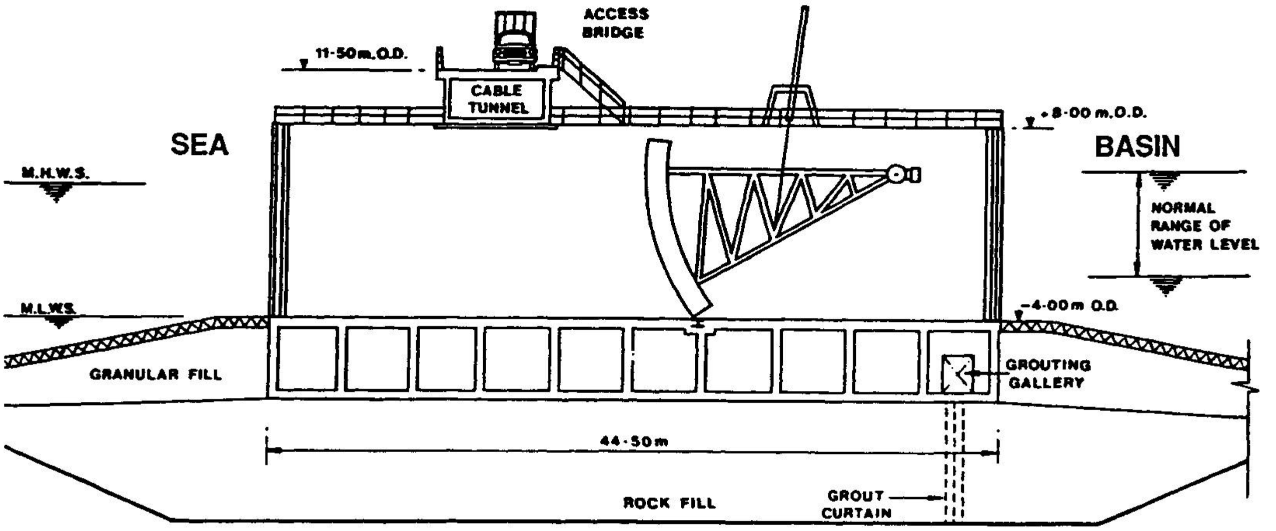

Figure 4 - Sluice caisson

2.3 Foundations

The chosen layout was designed to take maximum advantage of the limited amount of firm rock foundation available, and was identified after a seismographic survey extending some 1km upstream and downstream from the chosen line. Although sandstone outcrops on both banks the rockhead drops gently from the

West bank until at a depth of about 25m below OD, approaching mid river, it dips sharply forming a deep buried channel. The subdrift level on the eastern half of the river is very irregular with many deep holes consistent with subglacial erosion. One borehole failed to reach rock at -60m OD. The alluvial deposits are variable weak to stiff boulder clays and sands. Various schemes for founding turbine-generator caissons and deep sluices over the buried valley were investigated [3]. These included piles of various types and soil replacement but all were rejected on economic grounds. However, it was determined that shallow channel sluice structures could be founded at about -9m OD directly on the firm boulder clay and the possibility of founding smaller turbine units there is also being examined.

The foundation conditions at the chosen line threrefore effectively restricted the larger turbines to the western half of the river and the sluices, and possible smaller turbines, to the eastern half.

3. ESTUARY CLOSURE

3.1 Closure Sequence

The closure sequence of any estuary barrage is an environmentally sensitive operation and early studies concluded that the complete cutting off of tidal flows would be ecologically unacceptable. However, by installing the sluices first and the judicious use of dredging it is possible, in the case of a tidal power barrage, to maintain the existing tidal prism well into the construction phase. The aim thereafter should be that the tidal prism is never reduced below that of the operational barrage. A further restraint is that shipping access to upriver ports must be maintained at all times.

A number of schemes have been developed for staged in-situ construction of the Mersey Barrage [4] and these were compared with caisson methods. The studies concluded that in-situ construction gave a similar cost to caisson construction but with an extended programme. Caisson construction was therefore selected as the preferred method for a combination of environmental and economic considerations.

3.2 Caisson Construction Method

In the preferred method of construction all the major structures except Dingle Lock are constructed within dewatered cofferdams constructed close to the western bank. The cofferdams will enclose the New Ferry Lock and a section of adjacent barrage together with all the remaining barrage structures which are constructed as floating caissons. The cofferdam is divided to allow staged installation of the sluices, starting at the east bank. Dingle Lock has been planned to be constructed either in an existing dry dock within the estuary or in-situ as a double wall sheet pile cofferdam.

4. BARRAGE OPERATION

4.1 Operating Cycle

The proposed barrage will operate as an ebb generation barrage with flood pumping. Water levels, currents and power are predicted using a 2D hydraulic model of the estuary extending into Liverpool Bay and reducing to a 25 m grid at the barrage line. This model allows rapid evaluation of the effects of changes to the operational regime and design as well as investigation of the construction stages. A physical model at Hydraulic Research, Wallingford, has also been used.

Water levels upstream and downstream of the barrage are shown during a typical operating cycle in Figure 5 for a mean spring tide. High water downstream is almost unchanged as compared to existing conditions but low water downstream of the barrage is slightly raised. The upstream water levels exhibit a reduced tidal range with low tide at about present mid tide level and an increase in the high water stand period.

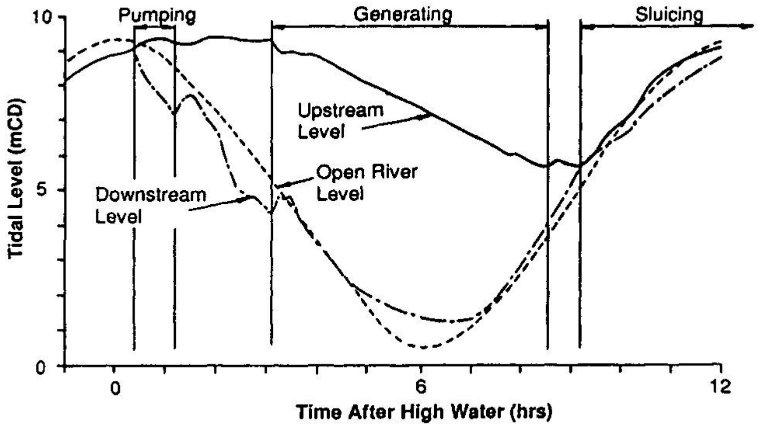

Figure 5 - Operating Water Levels - Spring Tide

4.2 Effects of Barrage Operation

4.2.1 Water Levels

The increased durations of higher upstream water levels has a direct beneficial effect on navigation, in that restrictions on access to upriver ports caused by Bromborough Bar are reduced.

The higher water levels cause some problems with land drainage and accommodation works to alleviate these effects are being studied.
The barrage could also be used to control upstream water levels and act as a storm surge barrier. This may be required as the mean sea level rises. Use of the barrage as a storm surge barrier would have a minor effect on the structural design.

4.2.2 Tidal Range

The reduction in tidal range upriver reduces the tidal prism and therefore increases retention times for effluent as well as reducing the areas of exposed intertidal mudflats which are internationally important as roosting and feeding grounds for wintering wild fowl. Those areas which are exposed only below mid tide at present would be completely submerged with the barrage operating. Figure 6 shows the effect of the barrage on the areas exposed by a mean spring tide. Figure 7 shows the relative importance of the various exposed areas to bird life. It is notable that the intertidal areas lost by barrage operation are generally of little importance. The tidal prism and the duration of exposure of the mudflats can be modified by adopting different numbers of sluices and turbines and by different operating regimes.

4.2.3 Tidal Currents

Tidal currents will generally be reduced because of the lower total flow. However, around low water, currents downstream of the turbines will be higher than at present. Not only tidal current rates but also the current directions will be modified. Figs 8 and 9 show the effect of the operating barrage on currents during a mean spring tide. The output from the 2D hydraulic model will be transferred to a ship handling simulation model to determine time windows during which access to the barrage locks is possible taking account of both draft and cross-current limitations.

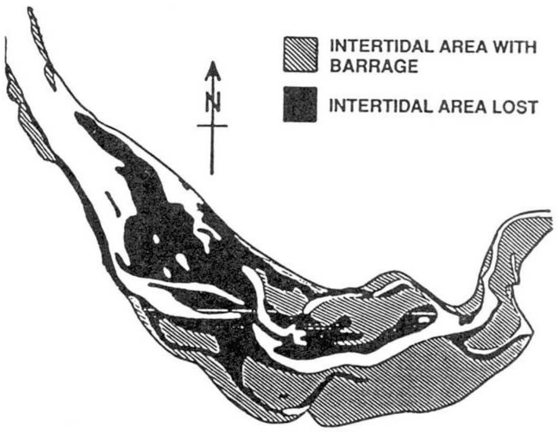

Figure 6 Intertidal Areas

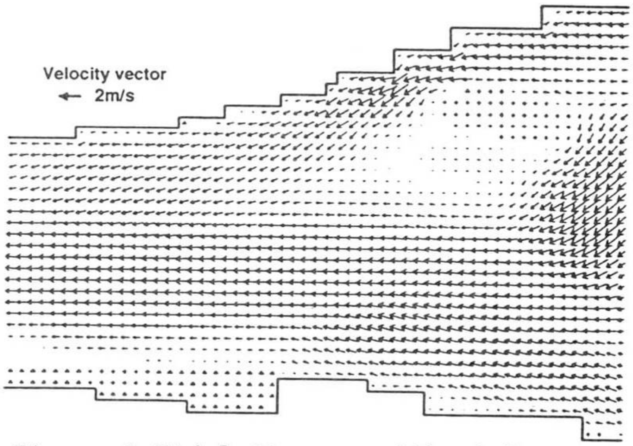

Figure 8 Tidal Streams without Barrage (HW+4 hrs)

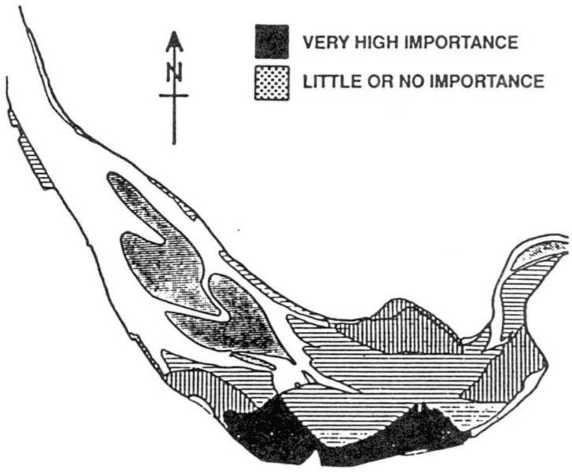

Figure 7 Relative Importance of Intertidal Areas to Birds

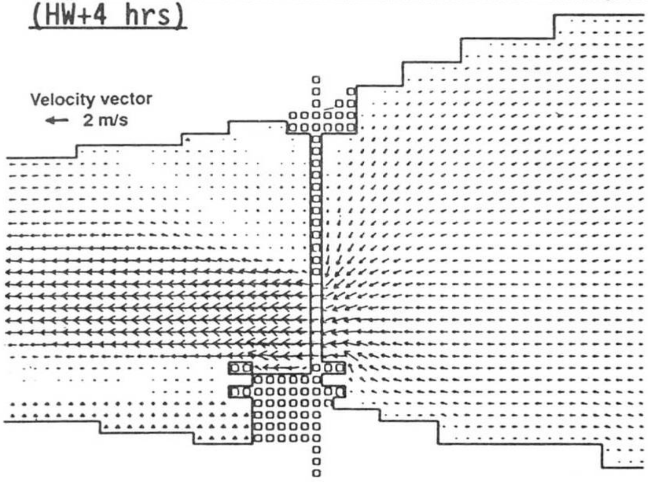

Figure 9 Tidal Streams with Barrage (HW+ 4hrs)

4.2.4 Sedimentation

Taking the complete morphological system which includes Liverpool Bay and the Mersey Estuary the barrage is expected to increase the rate of accretion of sand downstream from the barrage but reduce the accretion upstream which will become more silty. The net effect on dredging for shipping is not likely to be great. However, modelling of this complex phenomenon is at an early stage and it is too early to draw definitive conclusions.

4.3 Environmental Assessment

A preliminary stage in the Environmental Assessment process has been completed [5], [6] and further work is underway. The estuary currently has poor water quality with low oxygen concentrations although a clean up campaign has been started. The increased pollutant retention time caused by the barrage would be largely offset by the greater basin surface area and volume. The possibility of algal blooms leading to "red tides" must also be considered. There is a low fish population and a poor or impoverished invertebrate fauna. However the Mersey contains about 660 ha of saltmarsh which is important for bird roosting and feeding. Preliminary estimates [6] predict a reduction in availability of feeding grounds due to reduction in areas of exposed mudflats of 20% - 40% depending on species. However there is scope to ameliorate the effects by designing the barrage to maximise the tidal prism and hence area of intertidal mudflats by incorporating post-generation ebb sluicing and flood tide pumping into the operating cycle [7].

The environmental benefits of constructing the Mersey Barrage are considerable and must also be assessed. By displacing the generation of 1.5 TWh per annum of electricity from thermal power stations the quantity of CO_2 released into the atmosphere will be reduced by over 1 million tonnes per annum. Over the operating life of the project, which is expected to be 120 years the consumption of 50 million tonnes of coal or its equivalent may be saved.

4.4 Influence of Environmental Effects on Design

The environmental effects in the broad sense of the term, including effects on currents and water levels which affect shipping rather than the ecology will, along with certain overriding physical and economic constraints, determine the layout of the barrage.

Features currently under consideration to improve hydraulic performance and reduce environmental effects include:

- smaller diameter turbines
- lower sill levels for some sluices
- training walls
- rearranging a limited number of sluices and turbines.

5. CONCLUSIONS

Besides the more usual engineering and economic considerations many significant environmental aspects require study and consultation with the appropriate authorities when determining the feasibility of a tidal power barrage. By the use of a caisson construction method and the inclusion of flood pumping environmental impact of a Mersey Barrage may be minimised but not eliminated. Consultation is required to determine a publicly acceptable balance between the contrasting demands.

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