Possible Defenses Against a Sea-Level Rise in the Venice Area, Italy[1]

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ABSTRACT ▮

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Already flooded several times a year by ordinary storm surges, the Venice area would be greatly endangered by even a very small, additional rise in sea level. In this paper, after a brief presentation of the geo-hydrologic context of the coastal plain of northeast Italy and of the lagoon of Venice, computation of the frequency and return periods of present-day extreme tide levels in the city of Venice and beyond the lagoon, at sea, is discussed. If a rise in sea-level occurs in the next century, as predicted by certain models, the construction of mobile gates at the lagoon passes could help maintain harbour and other activities in the lagoon and protect the historical city from flooding. This protection, even with navigable locks, would be adequate only if the sea-level rise is less than 0.3 m, however, and if at the same time the lagoon is completely cleared of existing water pollution. In order to avoid floodings during the periods when the lagoon has to be closed provisionally to the sea, fresh-water discharges from minor rivers and drains received in the lagoon, attaining up to 1000 m³/s at the time of extreme rainfall events, must be collected and pumped away. For a sea-level rise greater than 0.3 m, a system of powerful dykes, permanently separating the lagoon from the sea, will be necessary if the area is to remain inhabited. At present, whatever the climatic scenario may be, the most urgent priority is to reduce water pollution.

ADDITIONAL INDEX WORDS: *Sea-level rise, Venice, coastal protection, coastal land use, lagoon, coastal defenses, storm surge, extreme events, return periods.*

INTRODUCTION

A global climatic warming during the next century, which would cause a considerable sea-level rise, is considered probable by many authors. Predictions regarding the extent of the future sea-level rise diverge with different authors however, reflecting considerable uncertainty. This uncertainty is increased by a confusing mixture of assumptions made and of methods used by the various climate models, as well as by the fact that several kinds of feedback phenomena have not yet been taken into account. A compilation of these data (Table 1) shows that there is substantial disagreement about the overall magnitude of the change, with opinions ranging from an 8-cm sea-level drop (MEIER, 1990) to a rise in sea level of over 3.5 m (HOFFMAN *et al.*, 1986) by the end of next century. These estimations do not, of course, include effects of land movements and changes

in ocean dynamics, which one have to be added at each location to obtain the local relative sea-level changes. In this paper, after presenting the hydrologic context of the Venice area, the frequency and return periods of present-day extreme storm surge levels are updated in the city of Venice and computed for the first time beyond the lagoon, out at sea. Finally, some possible consequences of a sea-level rise for the depressed lands of the area and for the lagoon islands are considered, and counter-measures are suggested and discussed.

The Hydrologic Context

In Roman times, according to descriptions left by Vitruvius, Strabo, Livy and Pliny, the coast of northeast Italy was a continuous, almost impassable, sequence of lagoons, marshes and estuaries used by local populations mainly as a refuge in the case of barbarian invasions (Figure 1). Seven sea basins (*Septem Maria*) developed on the site of the present-day Po Delta, with the Lagoon of Venice at that time con-

Table 1. *Estimates of future global sea-level rise (cm)*

Authors	Year			
	2000	2025–2030	2050	2085–2100
Gornitz et al., 1982			40/60	
Revelle, 1983				70
Hoffman et al., 1983	4.8/17.1	13/55	23/117	56/345
US Department Energy, 1985				10/160
Hoffman et al., 1986	3.5/5.5	10/21	20/55	44/368
Thomas, 1986				64/230
Jaeger, 1988	-5/19	-4/52	-7/138	
Wigley, 1989		17/26	24/38	
Meier, 1990			-8/76	
Robin, 1986	25/165 (year unspecific)			

Figure 1. Anonymous 18th Century reconstruction of the coasts of northeast Italy in Roman times, based on the descriptions left by Pliny (from Miozzi, 1968).

nected with the Adriatic Sea through nine passes. Most of the marshy and lagoon areas were subsequently filled by sediments or dried up by man, and only a few lagoons remain today; Venice Lagoon, with three passes still open, is the largest one.

Preservation of the lagoon, essential to the State of Venice for strategic reasons, was made possible over the course of several centuries by diverting several rivers (a branch of the Po, the Adige, the Brenta, the Sile, the Piave, *etc.*), which threatened to fill the lagoon with sediments (Figure 2). This resulted in lengthening of the river courses, raising the water level in the river beds, and consequently, in more frequent flooding of the nearby land. To defend the country from flooding, river embankments were raised. In 1791 a new continuous dam (*Conterminazione lagunare*) was completed along the inner border of the Lagoon of Venice (Figure 3), in order to keep storm surges out of the cultivated land, and to delimit the lagoonal area where new land reclamation was forbidden.

The construction of all these embankments divided wide areas of land into compartments surrounded on all sides by dams, thus prevent-
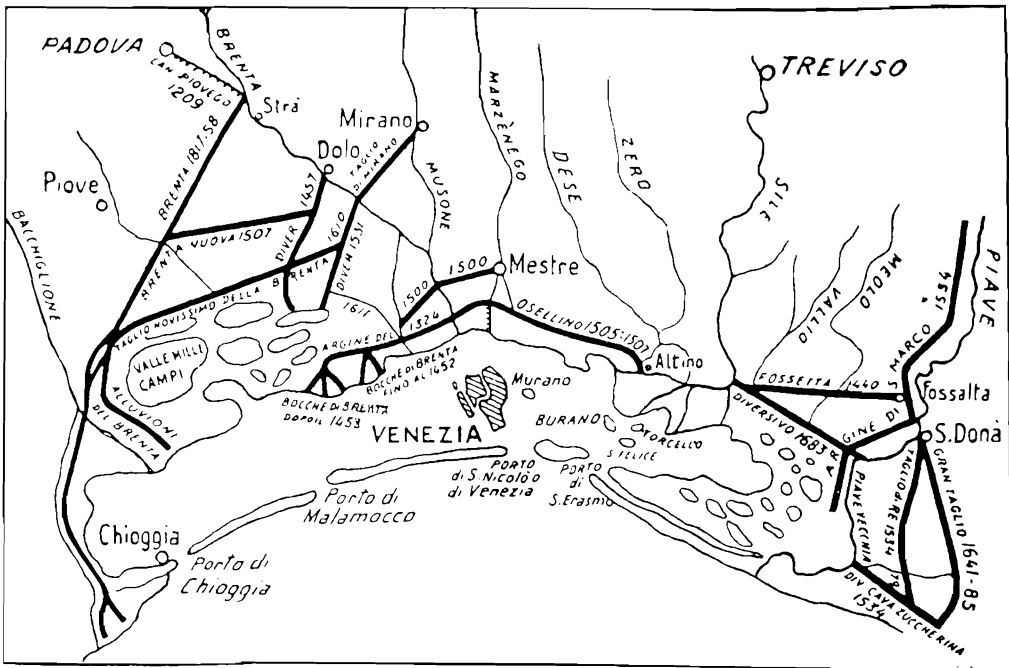
Figure 2. Diversions between the Piave and Brenta rivers [from Salvini *et al.* (1937), adapted].

ing any natural drainage. These areas, already topographically depressed, became even more so (often below sea level) due to compaction phenomena and to lack of new sediment from floods. Where a natural drainage of rainfall was no longer possible, rapid development of marshy areas infested with malaria took place until the middle of the 19th Century, when the advent of electrification made their drainage and reclamation (*bonifica*) possible. The depressed land is situated mostly northeast and south of the lagoon and is in some cases over 2 m below sea level (Figure 4). In these areas two separate hydrologic systems exist. The lower depressed system depends for drainage on a number of pumps; the upper system, delimited by high embankments, includes river branches flowing directly into the sea.

Despite efforts to reduce inflow, about two dozen small watercourses still flow into the lagoon (VAZZOLER *et al.,* 1987), often through a complex system of covered drains, pumps, siphons, sluice gates, *etc.,* gradually set up over several centuries (Figure 5). The discharge of these waterways is usually small; however, in

the case of extremely heavy rainfall, their overall discharge may reach as much as 1000 m^3/s (CAVAZZONI, 1973). Thus, they could contribute to raising the water level in the lagoon at a rate of 1.5 cm/h, if the lagoon passes were closed (DAZZI *et al.,* 1987).

The Lagoon of Venice, according to measurements made in 1968–1971 (RUSCONI, 1987) has an area of 551 km^2, including 37 km^2 of islands, 88 km^2 of closed fish ponds (*valli*) and 11 km^2 of recent discharge areas. The remaining surface (415 km^2, *i.e.* 75% of the total lagoon) corresponds to salt marshes (*barene*) (47 km^2), lagoon basins (305 km^2) and canals (63 km^2). The water depth for 140 km^2 is between MSL and -0.75 m, for 147 km^2, between -0.75 and -1.5 m; and for 80 km^2 greater than 1.5 m. The average depth of all the water basins is 0.67 m.

Tides are of the mixed type. Mean tidal range is about 60 cm, with a mean spring tidal range of about 80 cm. Exceptional tidal ranges may reach over 160 cm, however (PIRAZZOLI, 1975, 1982). About 3×10^8 m^3 of water are exchanged between the sea and the lagoon at spring tides,

Figure 3. In A.D. 1791, six years before its fall, the Serenissima Republic delimited the landward boundaries of the lagoon by 99 cippi (boundary stones, one of which is visible in the foreground) and a continuous embankment along a perimeter of 157 km (the so-called *conterminazione lagunare*).

less than 0.8×10^8 m^3 at neap tides. The water surface is hardly ever horizontal in the lagoon. This is due to the characteristics of tidal propagation (which is delayed near the inner lagoon margins, in relation to the passes, and accompanied by a decrease in the tidal amplitude; on the other hand, the tidal amplitude often increases in the inner part of navigation channels, due to wave reflection phenomena) and to local wind set-up effects (the water level rising windward and dropping leeward) (PIRAZZOLI, 1987).

Regular tide gauge-measurements have been carried out in the city of Venice since 1871, first at St. Stefano, then, from 1906, also at Punta della Salute, first on the Grand Canal side, then since 1923 on the Canal of Giudecca side. Although the main tide gauge station has been displaced twice, contemporaneous records have shown that the tide levels were practically the

same at the old and the new station and accurate levellings enabled the records to be referred to the same datum (DORIGO, 1961). Composite mean sea level (MSL) changes have been computed from 1872 to 1987 (Figure 6). The values computed are in fact annual half-tide levels, but the difference between annual half-tide level and MSL is only of the order of 1 mm in the north Adriatic Sea (POLLI, 1970) and can therefore be ignored. A clear rising trend is evident until about 1960, followed by a period with a much slower rise, which is still ongoing. Since the establishment of the 1897 datum, average sea level has risen between 22 and 23 cm. This rise includes eustatic sea-level changes and local land movements.

Along the coast of Europe, when land movements are subtracted from the tide-gauge data, regional MSL changes show an average rise of about 4 cm from 1890 to 1950 and an almost sta-
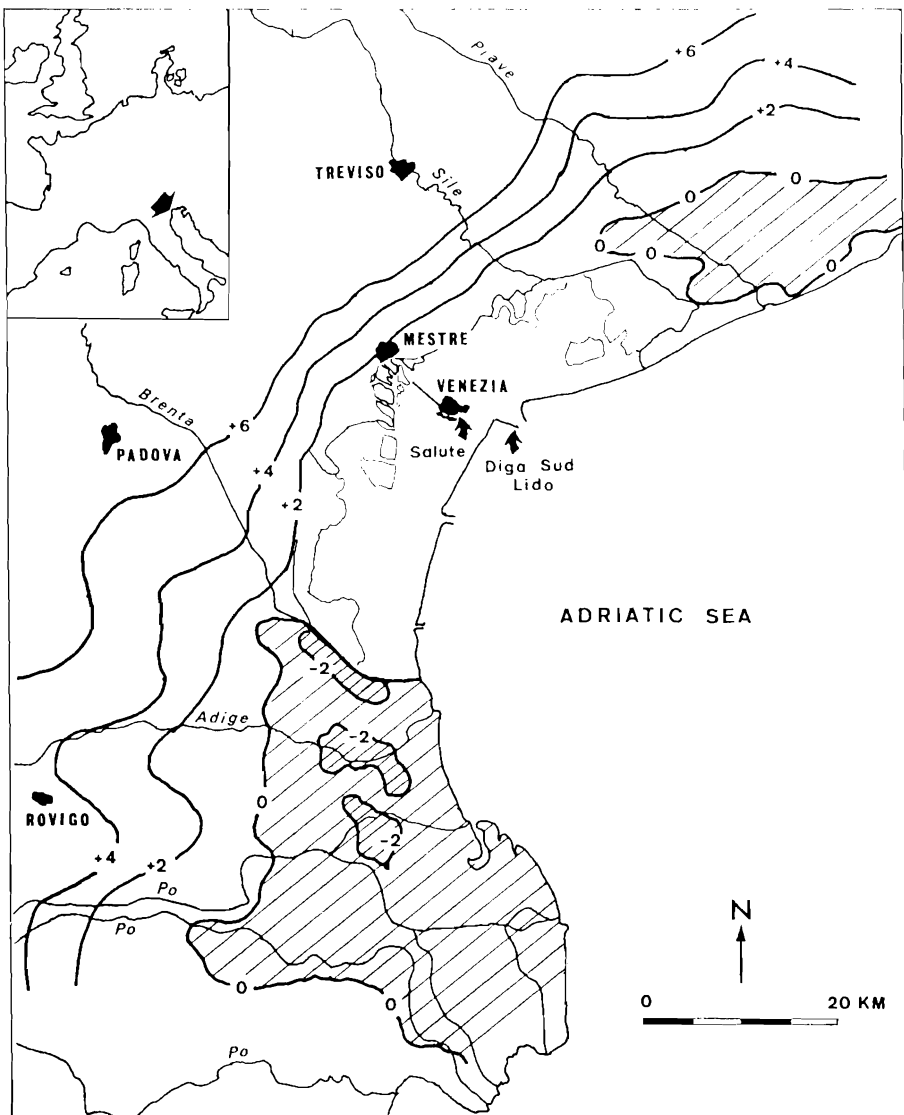
Figure 4.   Contour-lines in meters around the Lagoon of Venice. Wide areas below sea-level appear northeast and especially south of the lagoon. In three zones the land is below −2 m. Arrows locate tide-gauge stations mentioned in the text.

ble pattern from 1950 to 1980 (PIRAZZOLI, 1989a). From 1890 to 1950 the relative sea-level rise in Venice has been about 15 cm, suggesting an approximate local subsidence rate of 1.8 mm/yr. From 1950 to 1970, when pumping of underground water for industrial use in the port of Marghera caused a marked decrease in the piezometric level in artesian wells (GAM-

BOLATI *et al.*, 1974) tide gauges indicated a local subsidence of almost 8 cm (*i.e.* at a rate of almost 4 mm/yr). Similar subsidence values (between 9 and 11 cm, from 1952 to 1969) have been measured from levellings at several benchmarks in the city of Venice. Since the late 1960s, when the piezometric levels rose with the great flood of November 1966, and espe-

Figure 5.   A small navigation lock between a freshwater course and the lagoon water (in the background) at a lower level.

cially since the early 1970s, when underground pumping ceased, local subsidence seems to have become almost negligible.

Water Pollution

In spite of important fishing and aquiculture activities, during the last decades the Lagoon of Venice has continued to receive heavy industrial, agricultural and urban wastes. Present-day average annual charges of nitrogen and phosphorus which enter the northern part of the lagoon (Lido basin) are summarized in Table 2. It can be noted that the amounts released into the lagoon waters by contaminated sediments on the lagoon floor (8540 t/yr of nitrogen, 650 t/yr of phosphorus) are of the same order of the sum of those estimated to originate from industrial, urban, agricultural and atmospheric sources (4760 and 1012 t/yr respectively). This causes concentrations which endanger aquatic life. ALBANI *et al.* (1987)

have identified lagoonal areas close to the city of Venice, the commercial port, the industrial zone and other zones where foraminiferal species show symptoms of stress, the highest ecological stress conditions being located near the Venice-Mestre causeway.

Most of the lagoon is polluted by heavy metals, mainly mercury, lead, cadmium, copper, zinc and iron. Only in a few small areas are these elements naturally present. Mercury concentrations above the legal limit (5 μg/l) are often measured in the northern part of the lagoon (VAZZOLER *et al.* (1987) report a maximum measured value of 58 μg/l), whereas lead concentrations exceeding the legal limit by a factor of two can be found in the south part of the lagoon.

The Frequency of Extreme Storm Surges

The highest annual tide levels recorded in the city of Venice since 1871 have been used, after
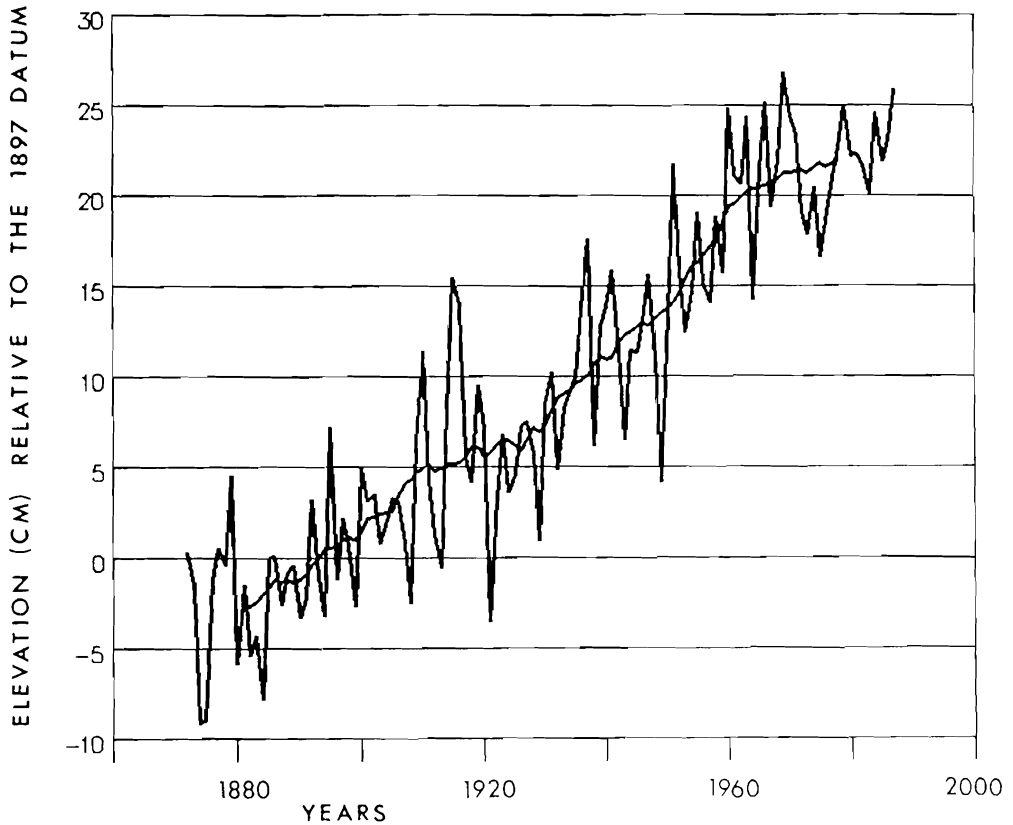
Figure 6.   Relative MSL changes in Venice from 1872 to 1987: the oscillating curve corresponds to yearly values and the more regular curve to 19-yr running means of the preceding values.

Table 2.   *Average charges of nitrogen and phosphorus released into the waters of the northern part of the Lagoon of Venice, according to Orio and Donazzolo (1987).*

Origin	Nitrogen t/yr	%	Phosphorus t/yr	%
Urban	854	6.4	355	21.4
Industrial	2015	15.2	150	9.0
Agricultural	1331	10.0	422	25.4
Atmospheric sources	560	4.2	85	5.1
Lagoon floor sediments	8540	64.2	650	39.1
TOTAL	13 300	100.0	1662	100.0

deduction of the changes in MSL, to estimate the frequency of extreme events, according to the method defined by GUMBEL (1958). Thus the probability, F, of an extreme storm surge of height x (in cm) is related to the return period, T (in years), of the event by the equations

$$F(x) = e^{-e^{-y}} \qquad [1]$$

$$T(x) = \frac{1}{1 - F} \qquad [2]$$

where y is a reduced variate linear function of x.

For the extreme high-tide levels recorded in Venice during the period 1872–1987, the best fitting frequency line is

x = 91.879 + 14.135 y   (Figure 7)

The band around the straight line corresponds to the control interval of 0.67 probability. All the extremes with return periods longer than 1.3 years observed are situated within the control curves.

The whole series of extreme data available however, may not be statistically homogeneous, since the morphology and hydrodynamics of the lagoon have been modified by human activities on several occasions. It would be advisable, therefore, to separate the data into several intervals of time and calculate the probability of extreme events for each interval.

A sea-level rise would require the construction of mobile or permanent gates at the lagoon passes in order to protect the city of Venice and other inhabited islands of the lagoon from storm surges. This would of course make obsolete the Venice tide-gauge stations, which would become isolated from the sea. In addition, storm surges enter the lagoon from the sea. It seems logical, therefore, to estimate the frequency of extreme events from data collected outside the lagoon, yet today predictions of storm surge levels in Venice are still mainly based by local observers on the records of Venice stations.

More complete tide-gauge records available outside the lagoon are provided by the station at Diga Sud Lido. They are almost continuous from 1924 to 1963 and since 1968, but unfortunately, do not include the first extreme event recorded on 4 November 1966. Estimations of the frequency of extreme storm surges outside the lagoon and comparisons with the situation in Venice are limited therefore, to the periods
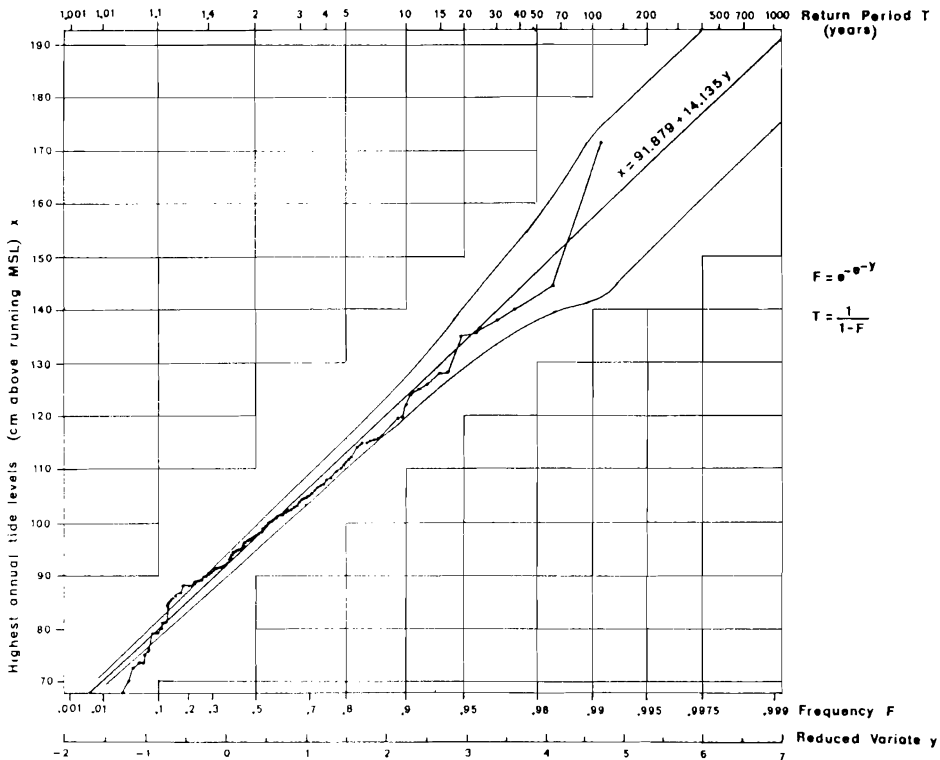

Figure 7. Frequency of the annual highest tides in Venice and control band of 67% probability (period 1872–1987). The scales x, y, F(x) and T(x) have been plotted on a probability diagram, where the maximum annual tide heights x are traced along the ordinate and the probability F along the abscissa.

1924–1963 and 1968–1987. The results are summarized in Tables 3 and 4 and in Figure 8, which update extreme storm surge estimations previously published by PIRAZZOLI (1970). Two main phenomena appear.

(1) The frequency of flooding increased from 1924–1963 to 1968–1987, both in Venice and at sea, though MSL changes are deducted from the data. The origin of this recent increase in flood frequency is unknown, but is possibly climatic.

(2) The height reached by extreme storm surges is systematically greater at Diga Sud Lido than in Venice. For the period 1968–87 however, this is true only for return periods longer than 3 years, (i.e. for high tide levels more than 1.1. m above the running MSL) which are the most dangerous. For extreme high-tide levels lower than 1.1 m above the running MSL, on the other hand, (i.e. for events with return periods shorter than 3 years) the levels reached in Venice are slightly higher than at sea.

The differences in level between the highest annual tide levels recorded at Diga Sud Lido and the ones in Venice are plotted in Figure 9, together with their 7-yr and 11-yr running means. The two series of extreme events are compiled separately and are therefore statistically independent, though in many cases they correspond to the same events. It can be seen that until c. 1950 the highest levels were on average about 7 cm lower in Venice than outside the lagoon. This difference was gradually cancelled in the 1950's, due to the deepening of navigation channels. Today, most of the highest annual tide levels are slightly higher in Venice than outside the lagoon. Only a few values, corresponding to extreme events with longer return periods, are still higher at sea.

The Altimetric Situation in Venice

The present-day relationship between the high-tide levels and the altimetry in Venice has been represented in Figure 10 by three curves. Curve V, expressed as a percentage of the total surface of the historical city, summarizes the distribution of elevations at street level in relation to the 1897 datum, according to FRASSETTO (1976). The lowest point of the city, at + 0.67 m (i.e. 0.45 m above present MSL), is observed in St. Mark's Square (Figure 11), just outside the basilica (SBAVAGLIA, 1977). At + 1.0 m, 3.6% of the street level in the urban area (14 ha) is underwater. At + 1.2 m, 35% is submerged; at + 1.4 m, 90% is submerged. In 57% of the city, the street level is situated at elevations between + 1.1 and + 1.3 m above the 1897 datum (Figure 12).

Curve H represents the distribution of the high tide levels, expressed as a percentage of all the high tides in one year (c. 700). It can be seen from curves V and H that the lowest point in the city is only 13 cm above the mean high tide level (which is the value of H corresponding to 50%) and is reached by about 15% of high tides. The level + 1.0 m, on the other hand, is not reached by the normal tide in normal meteorological conditions.

Curve T, deduced from the tide tables for the year 1989 and expressed as a percentage of a one-year period, represents the residence time of the tide above each elevation. Curve T is necessarily below curve H; for example, the elevation + 0.4 m is equal or lower than 75% of high-tide levels (curve H), but is submerged only during 27% of the time (curve T). In the same manner, the elevation + 0.7 m is reached by 13% of the high tides, but submergence occurs only during 1% of the time (87 hours per year) in the absence of unfavorable meteorological events.

Table 3. *Characteristic parameters of the extreme annual tide levels recorded in Venice and at Diga Sud Lido, in relation to the running MSL.*

Tide gauge	Venice (Salute, St. Stefano)			Diga Sud Lido	
Time interval	1872–1987	1924–1963	1968–1987	1924–1963	1968–1987
Sample size	116	40	20	40	20
Slope $1/\alpha$ of the frequency line	14.135	13.873	14.123	13.660	16.927
Standard deviation (cm)	17.16	15.833	15.01	15.59	17.99
Mode (cm)	91.88	91.18	100.00	95.68	98.19
Mean (cm)	99.82	98.7	107.4	103.1	107.5

Table 4. *Expected return periods of extreme tide levels at Punta della Salute and at Diga Sud Lido for certain time intervals.*

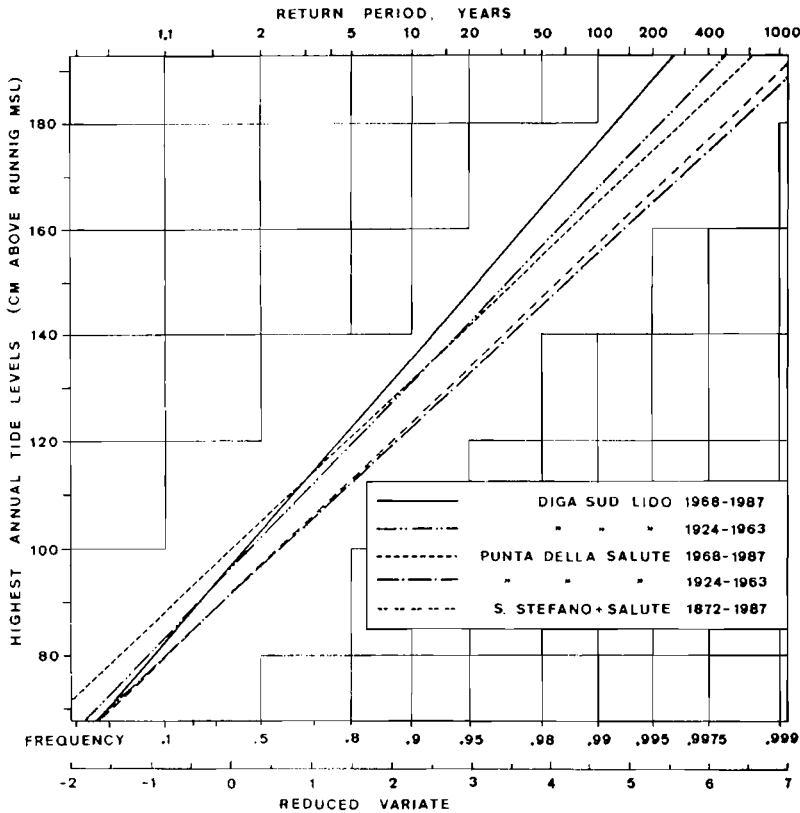| Tide heights (cm) above		Return periods (years)				
		Punta della Salute			Diga Sud Lido	
The 1897 datum	Running MSL	1924–1963	1872–1987	1968–1987	1924–1963	1968–1987
194	172	339	288	165	267	79
160	138	30	27	15	23	11
140	118	7.4	6.9	4.1	5.6	3.7
120	98	2.2	2.1	1.5	1.8	1.6

Figure 8. Comparison between the frequencies of the annual highest tides at Venice and at Diga Sud Lido, for various periods of time.

Consequences of a Sea-Level Rise

For the depressed land in the continental area around the lagoon, a gradual rise in sea level would imply an increase in management costs: drainage pumps would have to work longer over larger surfaces and displace water at a higher level; dams would have to be strengthened and heightened. The various river courses discharging into the lagoon would have to be diverted (or pumped) into the nearest river (Piave, Sile or Brenta) opening directly into the sea. The only flows allowed down to the lagoon would consist of small quantities of non-polluted water, in order to compensate for seasonal differences between rainfall and evaporation.

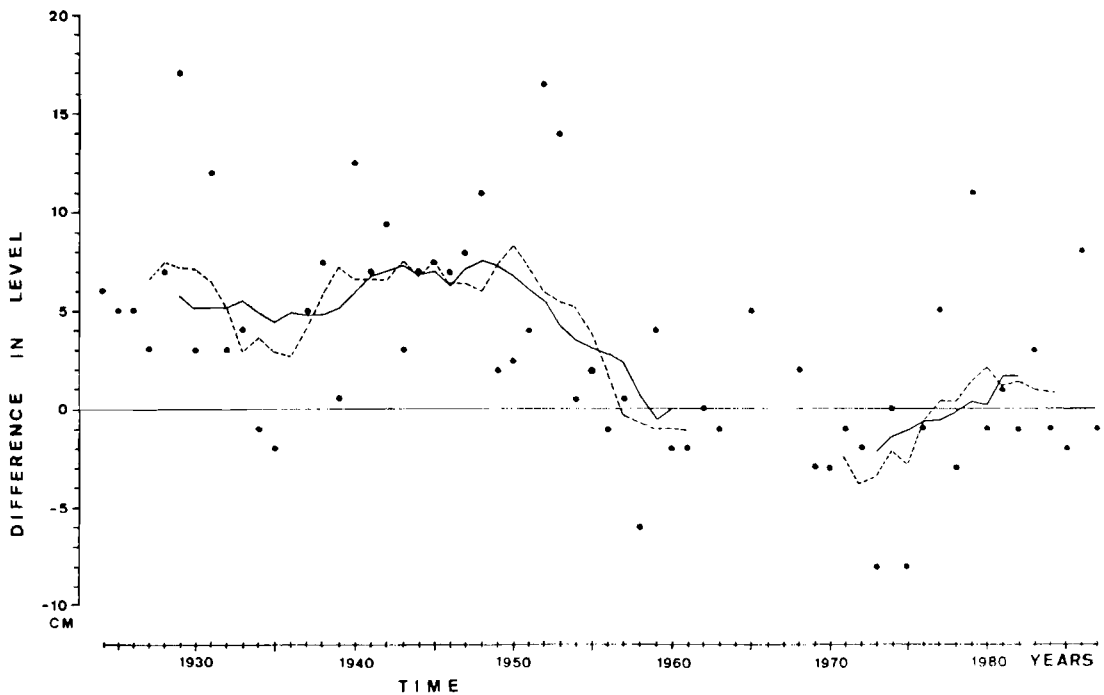These actions are technically possible even

Figure 9.   Differences in level between the highest annual tide levels recorded at Diga Sud Lido and the ones at Venice from 1924 to 1987. Dots: annual values; full line: 11-yr running mean; dashed line: 7-yr running mean.

for a considerable rise in sea level, but probably not economically realistic in the long run. The limit not to be overstepped will be decided by the social acceptability of increasing costs and hazard risks. Beyond this limit, social adaptation and changes in land use are preferable, moving industrial plants inland and reverting depressed lands to their previous state of marshy lagoon areas.

In the Lagoon of Venice, on the other hand, the problem will be completely different, since even a very small rise in sea level will be sufficient to endanger an inhabited center of great historical, artistic, cultural and monumental value.

The effects of a rise in sea level on the frequency of storm surge events is easily estimated from Figure 8, by moving the ordinate scale, or from Table 3. Assuming the period 1968–1987 as a reference basis and disregarding the possible influence of near-future changes in storm surge probability and in tidal range, a MSL rise of 20 cm would make the most dangerous storm surge levels three times more

frequent; for a MSL rise of 34 cm, the return period of a flood equivalent to that of 4 November 1966 (1.94 m above the 1897 datum) would decrease from 165 to 15 years in the city of Venice, and from 79 to 11 years outside the lagoon, at Diga Sud Lido.

The effects of a gradual rise of the normal high tide levels on the city of Venice can easily be estimated from the graphs of Figure 10, by displacing upwards the H and T curves and keeping V fixed.

For a 20-cm sea-level rise, sea water will be brought into St. Mark's Square by 55% of high tides (*i.e.* each day on average) and will stagnate for 1283 hours per year (15% of the time). The elevation +1.0 m (above the 1897 datum), though still slightly above the astronomical tide, will be reached by 6% of high tides, each time the meteorological situation is unfavorable.

For a 30-cm sea-level rise (Figure 13A), sea water will appear in St. Mark's Square with 75% of high tides and remain there during 2323 hours per year (27% of the time). The elevation
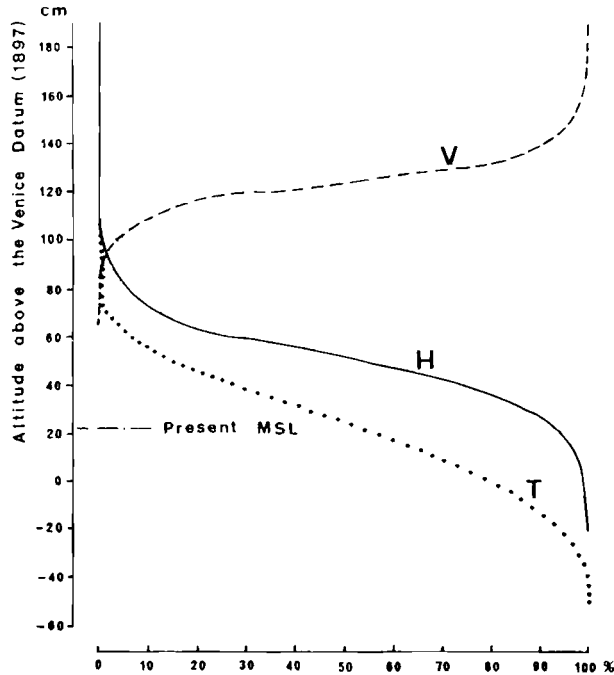
Figure 10. Altimetric distribution of the street level in the city of Venice in relation to the present-day high tide levels. V: distribution of altitudes at street level in Venice; H: distribution of high tide levels at Punta della Salute; T: distribution of residence times of the water above given elevations.

+ 1.0 m will be reached or overpassed by 13% of high tides and the level will remain submerged during 87 hours per year, from the effect of the astronomical tide alone. All unfavorable meteorological events will result in an increase in the frequency and duration of floods.

For a 40-cm sea-level rise, St. Mark's Square will be flooded partly or totally by 87% of high tides, for 3583 hours per year (41% of the time). The elevation + 1.0 m will be reached or overpassed by 30% of high tides and will remain underwater for 502 hours per year (6% of the time).

For a 50-cm sea-level rise, St. Mark's Square will be flooded by 95% of high tides with submergence for 4902 hours per year (56% of the time). The elevation + 1.0 m will be reached by 55% of high tides and overpassed for 1283 hours per year.

For a 100-cm sea-level rise (Figure 13B), the physical survival of what was once the maritime State of Venice would be possible only with a protective system of solid dykes perma-

nently separating the lagoon from the sea. The lowest points of St. Mark's Square would be over half a meter below the outer MSL, 40% of the street level in the city would also be below MSL and 99% below the mean high tide level. Totally isolated from the sea, the lagoon (or what would remain of it) will become a depressed, closed, brackish basin.

Possible Defense Strategy in the Lagoon of Venice

Three stages of defense are possible. At the first stage, a system of mobile gates constructed at the lagoon passes could contribute to defending the lagoon from storm surges, prevent "normal" flooding, and permit normal lagoonal activities. Navigation locks would enable the maritime traffic to continue to circulate without penalizing delays.

This will be possible, however, only if all sources of water pollution, whether of industrial, agricultural or urban origin, are elimi-

Figure 11. In St. Mark's Square, during this flood, the water is already about 60 cm deep just outside the basilica. People can still walk on a higher path, quickly built with trestles and planks, but the water is even reaching the level of the planks, which will soon be washed away, stopping even this emergency pedestrian movement.

nated before starting to reduce the exchanges between the lagoon and the sea. Contaminated sediments of the lagoon floor should also be removed. This seems to be the most urgent priority given the present-day critical situation, clearly apparent to any occasional visitor. It should be remembered that since its foundation the city of Venice has had no sewage system and that heavy pollution is brought by almost all the water courses discharging into the lagoon. Throughout its long history, Venice has relied on tidal currents for the evacuation of its waste water. However, the sources of pollution have increased sharply during the last decades, due primarily to chemical pollution from industries, the recent heavy use of fertilizers and pesticides on cultivated lands, and accelerated urbanization around the lagoon. The situation is already critical at certain periods of the year, with the occurrence of devastating algal blooms; it could rapidly become

unbearable if the exchanges with the sea had to be reduced.

When sea level has risen 30 cm, the exchanges between the lagoon and the sea would have to be interrupted occasionally for long periods. Even limited water pollution would, therefore, compromise the habitability of lagoon islands.

With a MSL at +40 cm, mobile gates at the lagoon passes could be opened less and less frequently and often only for short periods, given the time needed for the opening and closing operations.

At +50 cm, the construction of a permanent barrier separating the lagoon from the sea could no longer be deferred. However, as the construction of this barrier will take some time, it will be necessary, once it is confirmed that the MSL is rising rapidly, to start work earlier, when the MSL is still slightly lower (e.g. at about +30 cm).

Figure 12.   During floods, when no emergency higher path is available, the city appears deserted.
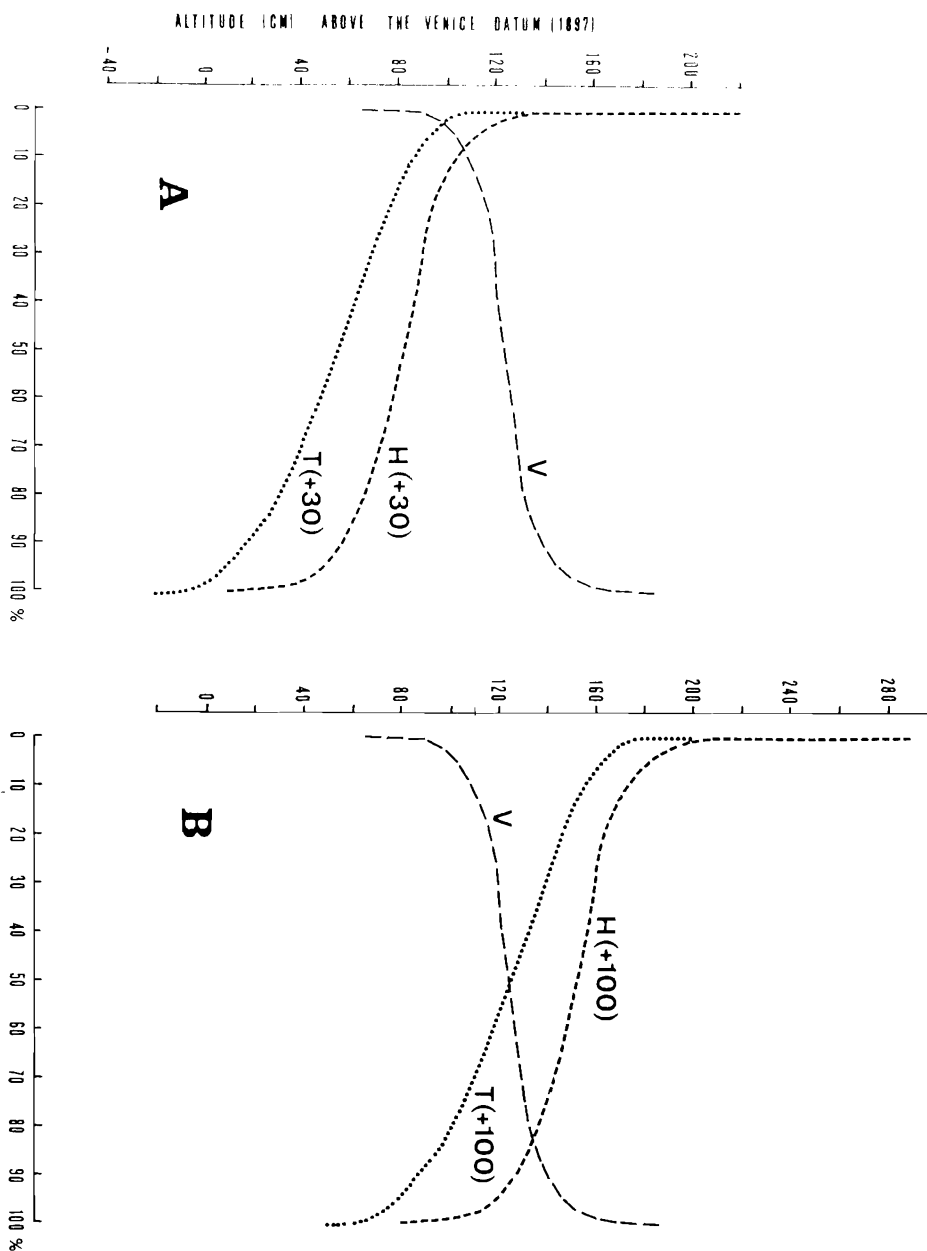
Figure 13. Altimetric distribution of the street level in the city of Venice in relation to the high tides corresponding to a MSL at 30 cm (A) and at 100 cm (B) above the present one. H: levels reached by the high tide; T: residence time of the water above given elevations.

CONCLUDING REMARKS

According to the predictions summarized in Table 1, a global sea-level rise of 30 cm may occur within a few decades and a rise of at least 50 cm is expected by most authors by the end of next century, if not earlier. In spite of many uncertainties inherent in this kind of predic-

tion (PIRAZZOLI, 1989b), the possibility that an atmospheric increase in CO_2 and other gases could finally lead to a "greenhouse" increase in temperature, and consequently to a rapid sea-level rise, is ominous enough in many coastal areas and cannot be disregarded.

Engineering projects for the defense of the Lagoon of Venice, such as those studied at present by the Italian Government, should take into account the possibility that mobile gates at the lagoon passes may become an insufficient remedy within a few decades, and therefore, that a rapid transformation into a permanent barrier is needed.

Whatever the scenario may be, the most urgent priority is a strict control of the water quality in the lagoon, which should be achieved before any construction works involving a decrease in the exchanges with the sea.

Even if the assumptions of climate models are wrong and the climate of next century will be the same as today, this control of the water quality would not be in vain since the reduction of water pollution is today a pressing need. The Lagoon of Venice remains a geologically subsiding area and any reduction of the effects of storm surges will imply decreased exchanges between the lagoon and the sea.

ACKNOWLEDGEMENTS

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□ RÉSUMÉ □

Déjà inondée plusieurs fois par an par des ondes de tempête ordinaires, la région de Venise serait très menacée par une ultérieure montée, même très faible, du niveau de la mer. Dans cet article, après une brève présentation du contexte géo-hydrologique de la plaine littorale du nord-est de l'Italie et de la lagune de Venise, sont calculés et discutés les temps de retour et la fréquence des niveaux extrêmes de marée actuels, dans la ville de Venise et en mer, à l'extérieur de la lagune. Si une montée du niveau marin doit se produire au cours du prochain siècle, comme le prévoient certains modèles, la construction d'écluses mobiles aux passes lagunaires peut contribuer au maintien d'activités portuaires et autres en lagune et à la protection du Centre historique contre les inondations. Mais cette protection ne serait adéquate que si la montée ne dépasse pas 0,3 m et si, en même temps, l'actuelle pollution des eaux est entièrement éliminée. Afin d'éviter les inondations pendant les périodes de fermeture temporaire des passes, les débits des cours d'eau qui se déchargent en lagune, et qui peuvent atteindre jusqu'à 1000 m³/s en cas de précipitations extrêmes, doivent êtres collectés et pompés ailleurs. Si la montée du niveau de la mer dépasse 0,3 m, un système de digues fixes, séparant définitivement la lagune de la mer, deviendrait nécessaire. Pour l'instant, quel que soit le scénario climatique prévu, la priorité la plus urgente reste celle d'éliminer la pollution des eaux.

□ RIASSUNTO □

Già allagata varie volte all'anno dall'ordinaria "acqua alta," la regione di Venezia sarebbe gravemente minacciata da ogni ulteriore rialzo, anche se limitato, del livello marino. In questo lavoro, dopo una breve descrizione del contesto geo-idrologico della fascia litorale padana e della laguna di Venezia, vengono calcolati e discussi i tempi di ritorno e la frequenza degli attuali livelli estremi di marea a Venezia ed in mare, all'esterno della lagune. Se nel prossimo secolo dovesse prodursi un innalzamento del livello marino, come previsto da certi modelli climatici, la costruzione di dighe mobili alle bocche di porto potrebbe contribuire al mantenimento di attività portuali e diverse in laguna ed alla protezione del Centro storico contro l'"acqua alta." Tale protezione sarebbe però insufficiente, anche con adeguate conche di navigazione, se il rialzo del livello marino dovesse superare 0,3 m e se non venisse operato un preliminare totale disinquinamento delle acque lagunari. Per evitare allagamenti durante i periodi di temporanea chiusura delle bocche di porto, le portate dei corsi d'acqua che attualmente si immettono in laguna, e che possono raggiungere 1000 m³/s durante eventi meteorologici estremi, dovranno essere raccolte e pompate altrove. Se l' innalzamento del livello marino dovesse superare 0,3 m, un sistema di possenti dighe permanenti di separazione tra la laguna ed il mare sarebbe indispensabile al mantenimento dell'abitabilità nella regione lagunare. Qualunque sia lo scenario climatico considerato, la più urgente priorità attuale resta il disinquinamento. *Una versione in italiano di questo lavoro è pubblicata dalla rivista Ateneo Veneto (1990)*.

□ RESUMEN □

Inundada varias veces al año por mareas meteorológicas, el área de Venecia ser vería grandemente dañada por un, incluso muy pequeño, aumento del nivel medio del mar. En este artículo, tras una breve presentación del contexto geohidrológico de la costa Noreste italiana y de la Bahía de Venecia, se analiza las frecuencias y períodos de retorno de niveles del mar extremos actuales en la ciudad de Venecia y fuera de la Bahía, en el mar. Si ocurriera un aumento del nivel del mar en el próximo siglo, como predicen ciertos modelos, la construcción de puertas móviles en la desembocadura de la Bahía podría ayudar al mantenimiento del puerto y otras actividades de la misma y, asímismo, protegería la ciudad histórica de una ubybdaculaaib, Esta protección, sin embargo, sería adecuada solamente si el ascenso es menor que 0.3 m y si la Bahía es limpiada completamente de la polución existente. Con objeto de evitar inundaciones durante los períodos en los que las puertas hayan de estas cerrascas, las descargas de los ríos menores, hasta 1000 m³/sg en avenida, deben canalizarse y desguarse. Para un incremento del nivel mayor que 0.3 m, sería necessario un sistema de diques que separase permanentemente el mar de la Bahía, si se desea que el área permanezca habitable. Por el momento, independientemente del escenario climático que se produzca, la prioridad más urgente es reducir la polución marina.—*Department of Water Sciences, University of Cantabria, Santander, Spain.*

□ ZUSAMMENFASSUNG □

Weil Venedig bereits durch normale Sturmfluten mehrfach im Jahr überflutet wird, ist es stark gefährdet durch einen nur sehr geringen zusätzlichen Meeresspiegelanstieg. Einer kurzen Darstellung der hydrogeologischen Zusammenhänge zwischen der nordostitalienischen Küstenebene und der Lagune von Venedig folgen Berechnungen über Frequenzen und Wiederkehrintervalle derzeitiger extremer Tidewasserstände im Stadtgebiet von Venedig und dem Seegebiet jenseits der Lagune. Wenn der Meeresspiegelanstieg so stattfindet wie in verschiedenen Modellen vorhergesagt, können mobile Verschlüsse in der Lagunenöffnung dazu beitragen, den Hafen und andere Unternehmensbereiche in der Lagune sowie die historische Stadt vor Überflutungen schützen. Dieser Schutz, evtl. auch durch Schleusen, ist aber nur sinnvoll bei einem Meeresspiegelanstieg von weniger als 0,3 m bei glei-

chzeitiger völliger Beseitigung der derzeit existierenden Wasserverschmutzung. Um Überflutungen in den Zeiten zu vermeiden, in denen die Lagune zur See hin geschlossen ist, müssen die Abflüsse aus dem Binnenland in die Lagune (bis zu 1000 m^3/s während extremer Regenereignisse) gefaßt und abgepumpt werden. Für einen Meeresspiegelanstieg von mehr als 0,3 m ist ein System von Deichen notwendig, damit das gesamte Lagunengebiet bewohnbar bleibt. Wie auch immer sich das Klima und Wasserstände entwickeln werden, am vordringlichsten ist die Reduzierung der Wasserverschmutzung.—*Reinhard Dieckmann, WSA Bremerhaven, FRG.*