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The Mediterranean: vulnerability to coastal implications of climate change

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ABSTRACT

The Mediterranean is experiencing a number of immediate coastal problems which are triggering efforts to improve short-term coastal management. This paper shows that coastal management also needs to address long-term problems and, in particular, the likelihood of climate change. Regional scale studies suggest that the Mediterranean is particularly vulnerable to increased flooding by storm surges as sea levels rise—a 1-m rise in sea level would cause at least a six-fold increase in the number of people experiencing such flooding in a typical year, without considering population growth. Protection is quite feasible, however, this would place a greater burden on those Mediterranean countries in the south than those in the north. All coastal wetlands appear threatened. Case studies of coastal cities (Venice and Alexandria), deltas (Nile, Po, Rhone and Ebro), and islands (Cyprus) support the need to consider climate change in coastal planning. However, the critical issues vary from site to site and from setting to setting. In deltaic areas and low-lying coastal plains climate change, particularly sea-level rise, is already considered as an important issue, but elsewhere this is not the case. Therefore, there is a need for coastal management plans to explicitly address long-term issues, including climate change, and integrate this planning with short-term issues. This is entirely consistent with existing guidelines.[1] *Given the large uncertainty concerning the future, planning for climate change will involve identifying and implementing low-cost proactive measures, such as appropriate land use planning or improved design standards incorporated within renewal cycles, as well as identifying sectors or activities which may be compromised by likely climate change. In the latter case, any necessary investment can be seen as a prudent 'insurance policy'.*

1. INTRODUCTION

Humanity is preferentially concentrated in the coastal zones of the world and these coastal populations are growing more rapidly than the global average.[2,3] This is causing significant changes to the coastal environment, placing increasing demands on coastal resources and increasing exposure to coastal hazards such as erosion, flooding and salinity intrusion. Global climate change will exacerbate all these ongoing problems and its potential implications are causing much concern around the world's coasts.[4,5] The Mediterranean is a good example of a coastal region where human stresses are already significant and continue to grow.[6] Increasing attention is being focused on more effective coastal management within the region, with the overall goal of sustainable development, e.g. the United Nations Environment Programme (UNEP).[1] In addition to the pressing short-term problems, these management activities need to address long-term issues such as global climate change.

This paper examines the vulnerability of the Mediterranean to the coastal implications of climate change, including accelerated sea-level rise. It also considers the range of proactive measures that coastal managers might apply to deal with these problems. A number of studies have already considered this problem, particularly for some of the deltas,[7–9] coastal cities such as Alexandria[10] and the region as a whole.[6] This paper builds on a recent top-down analysis of the possible problems of sea-level rise in the Mediterranean[11] and links this with case studies within the region to provide realistic examples of potential problems and possible approaches to their solution.

2. GLOBAL CLIMATE CHANGE AND ITS COASTAL IMPLICATIONS

The likely changes in most climate variables remain highly uncertain at the local scale relevant to impacts and possible responses (Table 1). However, for future sea levels at least the direction (a rise) and magnitude (faster than today) of change appears certain.

2.1. Sea-level rise

There is a widespread consensus that global sea levels have risen over the last century at a rate of 1–2.5 mm year^{-1}.[12] In addition to global changes local uplift or subsidence of the land surface must also be considered: their sum being termed relative sea-level change. This is by

TABLE 1
Some climate change factors relevant to coastal change and management (adapted from IPCC[12])

Factor	*Direction of change*	*Comments*	*Potential impacts*
Sea level	positive, accelerating	exacerbated by subsidence	numerous (see text)
Sea-water temperature	positive	—	increased algal blooms
Precipitation intensity	positive	—	increased flooding
Wave height	?	—	increased/decreased cross-shore erosion
Wave direction	?	—	increased/decreased longshore transport
Storm frequency	?	—	increased/decreased storm surge occurrence
Riverine sediment supply	?	also sensitive to catchment management	increased/decreased sediment supply to the coast

definition what an observer sees at any particular coastal site. As the sense and magnitude of vertical land movements vary from place to place, so relative rates of sea-level change show similar variability.

In the coming century accelerated global sea-level rise is expected, due to anthropogenic global warming. Given the uncertainties concerning global warming and ocean response, a global rise in sea level ranging from about 0.2–0.9 m by the year 2100 appears possible, with best estimates of a rise of about 0.5 m[12,13] or a two-and-a-half to five-fold acceleration. The large uncertainty concerning future sea levels must be taken into account when considering possible impacts and possible responses. The most serious impacts of sea-level rise are: (1) erosion; (2) inundation; (3) an increased risk of flooding and impeded drainage; (4) salinity intrusion into freshwater supplies; (5) higher water tables which may reduce the safety of foundations.[14] Erosion and inundation both result in land loss. It is important to note that these impacts of sea-level rise can be countered by other natural factors. For instance, a suitable sediment supply would counter beach erosion.

2.2. Other coastal implications of climate change

Many other climate change factors could have significant coastal implications (Table 1). However, the likely changes to most of these climate factors are less certain, with a possibility of both increase or decrease. This uncertainty hinders assessment of the implications of these possible changes and the development of appropriate proactive measures.

However, some climate change factors are more certain. Global climate model simulations indicate that the return period for heavy rainfall events may decrease in many parts of the world, given global warming.[15] This would intensify flooding, particularly in low-lying coastal areas where the base level will be simultaneously increasing due to sea-level rise. It suggests the need for an increased drainage capacity given global warming, particularly in coastal areas.[5] Sea water temperature is also expected to rise. Although adverse coastal implications are not well understood, it can be speculated that many existing problems will be enhanced, such as excessive algal growth. It is worth noting that it has been reported that the deep circulation of part of the eastern Mediterranean has been observed to change recently, although the precise cause remains uncertain.[16]

Climate change may also lead to a change in the frequency and intensity of storms.[17,18] In addition to wind damage coastal storms cause storm surges which flood low-lying coastal areas and allow destructive wave action to penetrate inland. However, it is difficult to construct plausible scenarios and the few studies that have considered this factor have conducted sensitivity analyses.[19] The possibility of an increase in storm frequency causes considerable concern, but a decrease in storm frequency and intensity is also possible with widespread benefits. The development of plausible regional scenarios of future storm characteristics remains an urgent requirement for coastal vulnerability assessment.

2.3. Vulnerability to climate change

To help to provide a better understanding of societal vulnerability to these changes the Intergovernmental Panel on Climate Change (IPCC) Common Methodology (CM) was developed.[20,21,3] The concept of vulnerability embraces: (1) the physical and socio-economic susceptibility to global climate change and (2) the ability to cope with these consequences (i.e. susceptible countries or areas may not be vulnerable). The CM has been applied in a number of countries around the world, including Egypt.[22]

Aggregation of the national results show that the likely impacts of sea-level rise vary from country to country and setting to setting.[5] Certain geomorphic settings are more vulnerable than others, particularly deltas and small islands, most particularly low-lying coral atolls. Coastal wetlands appear to be threatened with loss or significant change in most locations as their present location is intimately linked with present sea level, although their ability to respond dynamically to such changes by sedimentation and biomass production needs to be carefully considered.[23] Developed sandy coasts may also be vulnerable if development is concentrated too close to the shoreline, primarily due to the high costs of maintaining a sandy beach for both recreation and protective purposes.[24] These costs are often highly uncertain.

The CM has also been applied to a few limited factors at a global level—the Global Vulnerability Analysis (GVA)—with the objective of obtaining regional and global results.[25,26] The factors considered include flooding due to storm surge, wetland loss and potential protection costs against flooding. The GVA is a first-order analysis and the global datasets which were available were somewhat limited and a number of assumptions were necessary. Therefore, while national results are provided in appendices only aggregated regional or global scale results are expected to be valid. Overall, considering the world as 20 regions, four appear most vulnerable: the southern Mediterranean, Southeast Asia, Asia Indian Ocean Coast and Africa Indian Ocean coast.[25]

3. THE MEDITERRANEAN

The Mediterranean (Fig. 1) is an enclosed sea characterised by a limited tidal range (often less than 30 cm). It has a long coastline of over 46 000 km, with 75% located in four countries—Greece, former Yugoslavia, Italy and Turkey—and 40% of the coastline located on islands,

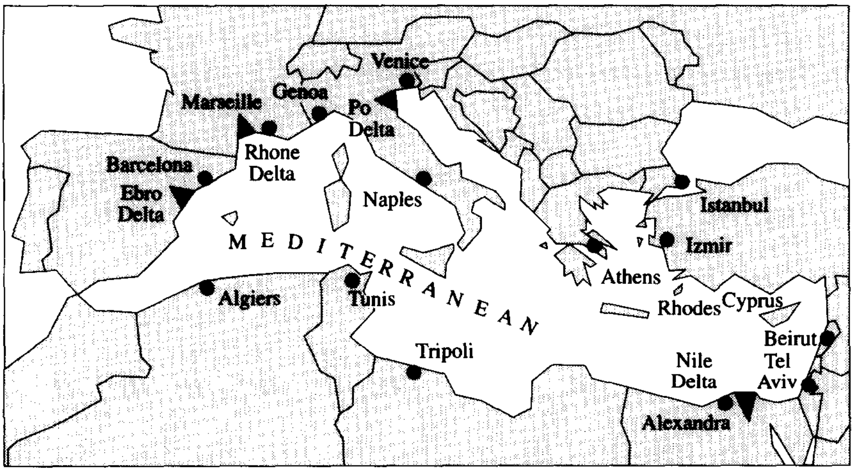

Fig. 1. The Mediterranean, including coastal cities with a population exceeding one million people in 1990, Venice and the major deltas.

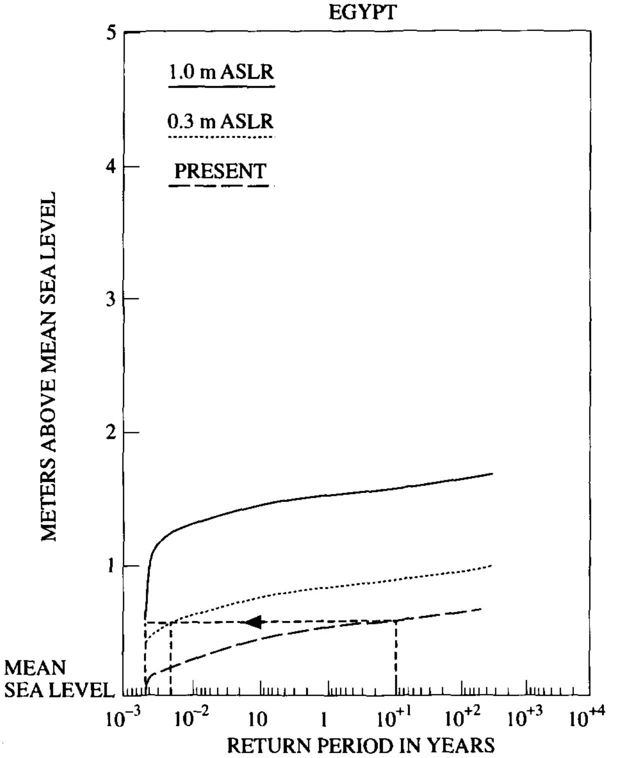

Fig. 2. The flood exceedance curve for the Nile delta, which typifies such curves for the Mediterranean.

mainly in Greece, former Yugoslavia and Italy.[27] About 54% of the coast is rocky and 46% sedimentary: the latter areas are most vulnerable to climate change. Extratropical storms occur in the autumn, winter and spring, and these can cause significant waves and surges given appropriate conditions. Due to the limited tidal range the flood exceedance curves have a low gradient, so a small rise in sea level significantly reduces the return period of a given elevation flood (e.g. Fig. 2). There is a large population located in the coastal zone, exceeding 130 million in 1985, with a number of large cities such as Barcelona, Athens, Istanbul and Tripoli.[27] Many of the cities are growing rapidly. The coastline is also intensively utilized for coastal tourism, with 100 million tourists in 1984 rising to a projected 173–341 million tourists in 2025. This means that significant amounts of tourist infrastructure already exist, or will be built, immediately adjacent to the coast.

The Mediterranean occupies an active geological plate boundary, therefore land uplift or subsidence can be expected to be widespread. Flemming[28] found, using archaeological evidence, that uplift appears to

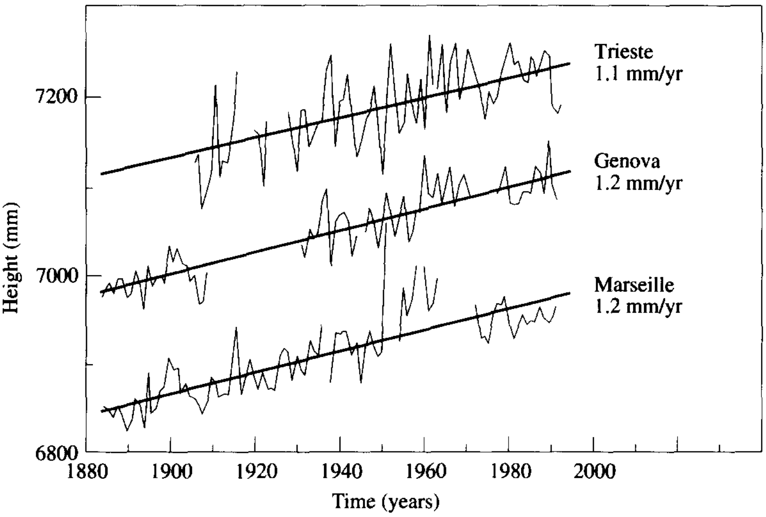

Fig. 3. Relative sea-level rise data from the Mediterranean for stations exceeding a 50 year duration, including the linear trend. Height is arbitrary. Data provided by the Permanent Service for Mean Sea Level, Bidston.

dominate in the region and hence relative sea-level rise is typically less than global trends, with important exceptions such as subsiding deltaic areas. Tide gauge records longer than 50 years are required to produce robust statistics on rates of sea-level change,[29] which makes some earlier analyses of sea-level trends around the Mediterranean suspect.[30,31] Three suitable records are available from the northwest Mediterranean and show a rise of 1.1–1.2 mm year^{-1} (Fig. 3). This trend in sea-level rise is consistent with IPCC[12] and demonstrates that slow rates of sea-level rise are already a problem within the Mediterranean.

A number of studies suggest that the coastal Mediterranean is vulnerable to a number of aspects of projected climate change, particularly accelerated sea-level rise.[6] The results from the global aggregation provide further insight into the likely magnitude of these problems. While the Mediterranean has no coral atolls, it contains numerous islands and is fringed by a number of deltaic plains, including the Rhone, Po, Ebro and, most particularly, the Nile delta. However, there are few national studies of the vulnerability of this coastline to different scenarios of sea-level rise and climate change in general. The main exception is the Nile delta and environs which has attracted considerable interest given its large size, existing environmental problems, high vulnerability to sea-level rise and its strategic importance to Egypt.[6,7,10,32–36] Similarly, little quantitative regional data is available, except for the GVA. The following discussion includes new calculations using the GVA model, including some impacts for a 0.5 m sea-level rise scenario.

The GVA divides the Mediterranean into a northern (including the Black Sea) and southern region, with a boundary at Istanbul.[1] Therefore, these regions correspond to the European Mediterranean and the western Asian/North African Mediterranean, respectively. Some results are summarized in Table 2. The population living beneath the 1 in 1000 year storm surge level totalled nearly 10 million people in 1990, although many of these people are already protected from flooding by structural measures. Given scenarios of a 0.5-m and a 1-m rise in sea level and no other changes, this population will increase by about 35% and 70% respectively, on both sides of the Mediterranean (i.e. a rise imposed on today's situation). Population growth in the northern Mediterranean is not expected to be significant. In contrast, the southern Mediterranean is expected to experience substantial population growth, increasing the population within the flood zone without any rise in sea level. Taking population projections for 2020 with no rise and a 1-m rise in sea level would produce a cumulative increase of about 65% and 175%, respectively, in the population living beneath the 1,000 year surge compared to 1990. Continued population growth beyond 2020 is expected to further increase the population living in the potential flood zone for the southern Mediterranean, but this has not been quantitatively evaluated.

Based on an estimate of the probability of flooding, one million people presently experience flooding around the Mediterranean in a typical year, nearly all of them living in the southern Mediterranean. People around the northern Mediterranean are generally well protected from flooding with structural measures. However, as sea level rises, so these defences will become less effective and the risk of flooding will increase (Fig. 2). Making first-order estimates of the decline in the level of protection as sea levels rise and the expansion of the hazard zone suggests that the number of people experiencing flooding in a typical year will more than double given a 0.5-m rise and increase more than six times given a 1-m rise, without considering population growth. Globally the corresponding increases are two- and three-fold, respectively,[26] illustrating that the Mediterranean is particularly vulnerable to such changes. The biggest changes would be in the northern Mediterranean, where the increase given a 1-m rise would be more than 100 times present values.

These results suggest that even small rises in sea level cannot be ignored around the Mediterranean and coastal populations in low-lying areas will face a choice between coastal abandonment and

TABLE 2

Some regional consequences of sea-level rise for the Mediterranean region (SLR—global sea-level rise scenario). Risk zone is the area beneath the 1000 year storm surge (see also Hoozemans *et al.*[25])

	Risk zone population (millions) by year and SLR						*Protection costs against a 1-m SLR (see text)*		*Wetlands at loss given a 1-m SLR (see text)*	
Time (years)	1990	2020	1990	2020	1990	2020	*US $ (billions)*	*% GNP* (1990)	*km²*	*% Total*
SLR (m)	0	0	0.5	0.5	1.0	1.0				
Northern Mediterranean	4.1	4.1	5.7	5.6	7.2	7.1	25.5	2	200	100
Southern Mediterranean	5.6	9.1	7.5	12.2	9.4	15.4	18.1	7	2 600	100
Total	9.7	13.2	13.2	17.8	16.6	22.5	43.6	—	2 800	—

building/upgrading coastal defences. The cost of protection can be evaluated to see how this compares with regional wealth. Assuming that all areas with a present population exceeding 10 people km^{-2} are protected against a 1-m rise in sea level using standard coastal engineering techniques, the absolute costs are higher for the northern Mediterranean, but the costs relative to 1990 Gross National Product (GNP) are significantly higher for the southern Mediterranean. This response would reduce the population which experiences flooding in a typical year below present levels to about 300 000 people (based on 1990 population).

Lastly, the coastal wetlands in the Mediterranean appear highly vulnerable to loss, largely due to the negligible tidal range which restricts their vertical range and ability to accrete vertically in response to sea-level rise.[8,37] Total loss as shown in Table 2 is unlikely, but near total losses should be expected assuming business as usual and a 1-m rise in sea level, with a number of adverse consequences such as a decline in fisheries and coastal biodiversity. Improved management of existing wetlands and allowance for sea-level rise in coastal policy could help to conserve some of these threatened wetlands—improved deltaic management is one area which is being evaluated (see Section 5).[9]

In conclusion, the GVA shows that a rise in sea level could cause some important and often adverse changes to the coast of the Mediterranean. Overall, the southern Mediterranean coast appears more vulnerable to sea-level rise than the northern Mediterranean coast. Some more detailed case studies which consider cities, deltas and islands in the Mediterranean are now examined to better understand these problems.

4. COASTAL CITIES

The protection of cities is expected to be a major cost of accelerated sea-level rise.[38] It would also appear to be one of the more likely responses given the high value of many city areas, although many uncertainties exist.[39] There are a number of historic cities around the Mediterranean such as Venice and 13 coastal cities had a population exceeding one million people in 1990 (shown in Fig. 1), collectively containing over 35 million people.[40] The population of the cities in Europe is growing slowly, with projected rates of increase in the range 3–12% from 1990 to 2010. However, substantial and continuing investment in new and upgraded infrastructure is expected. The cities of western Asia (including Istanbul) and North Africa are growing more rapidly, with projected rates of increase in the range 43%–106% from 1990 to 2010. This means that tremendous investment is required just to stand still.[41] Istanbul is projected to become the first megacity (population >8 million) in the Mediterranean before 2010, with other likely coastal megacities by 2050 being Alexandria, Tripoli and Algiers. Therefore, urban centres around the Mediterranean are likely to place rapidly increasing demands on coastal resources. This is already apparent around many cities in terms of declining water quality and pollution, which are often triggers for improved coastal management efforts, e.g. Izmir.[42]

The likely rate of climate change is much slower than many of the changes occurring in coastal cities, although if poorly managed the impacts of climate change could be serious.[43] Therefore, it is more obvious than in most other settings that climate change will be interacting with a changing landscape. This makes assessment of likely impacts somewhat difficult, but also presents opportunities. When considering proactive response measures for climate change it will be vital to manage other long-term changes to the urban landscape such that vulnerability to climate change is not enhanced and ideally is reduced.

4.1. Venice

One of the most famous and historic cities in the Mediterranean, Venice has always been intimately linked to the sea, being located close to sea level on islands in the Venice lagoon. Therefore, flooding by storm surges has always been a problem. The occurrence of flooding has been exacerbated this century by a relative rise in sea level of about 28 cm:[44] flood frequency in San Marco Square increased from 7 times per year to 40 times per year from 1900 to 1990.[45] These repetitive floods are destroying the fabric of the city, as well as being one contributing factor to population decline in the city. The relative sea-level rise occured due to a combination of subsidence due to groundwater withdrawal[46,47] and global sea-level rise. Given that global sea-level rise has been in the range 10–25 cm century^{-1},[12] global sea-level rise rather than subsidence may be the major contribution to the observed increases in flood frequency this century.

A continued and more rapid rise in global sea levels, as projected, will progressively increase the flood frequency; a 30-cm rise in relative sea level will lead to flooding in San Marco Square 360 times per year (i.e. daily) without other changes.[45] If Venice is to survive some action is essential. Various proposals exist, with flood barrages to separate the lagoon from the sea being most favoured.[44] Other approaches have been suggested, although there appears to be no perfect solution with a clear conflict between the needs of navigation within the lagoon versus flood prevention for Venice.[47–49] Whatever is ultimately decided, it needs to be a long-term solution which mandates considering future rates of sea-level rise as one of the key factors in design.

While no other city on the Mediterranean is as vulnerable to small changes in sea level as Venice, it illustrates that small relative increases in sea level (≤30 cm) can have serious consequences in terms of flood frequency (cf. Fig. 2).

4.2. Alexandria

Alexandria is another historical city on the western edge of the Nile delta. It has a rapidly growing population and stressed environment.[41] The original city developed on a series of shore-parallel ridges up to 12 m above sea level. Human influence on the region has increased and the lagoon south of Alexandria has been largely reclaimed for agriculture, leaving Lake Maiout.[50,51] Lake Maiout is maintained at 2.8 m beneath sea level by continuous pumping to stop these areas being inundated. The prospect of sea-level rise suggested the inundation of this low-lying land leaving Alexandria to the north as a peninsula or an island.[52]

Subsidence in this area appears to be minimal and global sea-level rise scenarios can be applied directly as relative sea-level rise scenarios.[10] Based on a Geographic Information System (GIS) analysis of Alexandria Governorate (the geopolitical unit in which Alexandria is situated), El-Raey *et al.*[10] estimate that 700 km^2 of land (35%) is below sea level, with a resident population of 1.2 million (or 37% of the Governorate population) and 50% of industry (by area occupied). Based on the existing population, a 0.5-m rise in sea level would place a further 400 000 people beneath sea level, increasing to 800 000 people given a 1.0-m rise. The low-lying areas are also under development pressure given the lack of alternative sites, so future population and economic growth may tend to occur in the more vulnerable lower-lying locations, substantially increasing the vulnerable population.

Alexandria has a series of pocket beaches which are threatened with near total loss given a 0.5-m rise in sea level.[10] These beaches have a high recreational value and six beaches are already nourished (with land-based sand sources). Therefore, it seems likely that nourishment would be an effective response against sea-level rise, although other factors such as water quality and pollution also need to be considered.

Therefore, proactive responses appear prudent for Alexandria as even small rises in sea level could adversely affect the city. Lake Maiout does not have a direct link to the sea and initially higher sea levels will only increase seepage and decrease drainage capacity. Anecdotal reports of increased waterlogging in low-lying areas may be a manifestation of the existing slow rise in sea level at Alexandria.[10] Failure of the seawall, which allowed the lagoons to be reclaimed, would allow catastrophic flooding of significant areas in Alexandria Governorate and neighbouring areas. Therefore, it would be prudent to evaluate the existing levels of safety for both the drainage system and seawall, and how they would decline with rising sea levels. The possibility of land use planning should also be considered to encourage growth away from the most low-lying (i.e. vulnerable) areas. However, given the present development pressures and rapid increase in population this goal is probably difficult to achieve. All efforts to combat climate change need to be integrated with solutions to existing problems (see Hazma[41]).

4.3. Istanbul

Unlike Alexandria and Venice, Istanbul is not a low-lying city and land loss/increased flooding given sea-level rise are unlikely to be major problems.[53] However, sea-level rise does have implications for water supply and the proper functioning of sewage supply systems. It would be prudent to consider the implications of sea-level rise over the design life of any new systems or upgrades.

4.4. Discussion

These examples demonstrate that global sea-level rise is a concern in coastal cities. While immediate problems require urgent action, their solution should be consistent with longer-term policies to reduce vulnerability to climate change (e.g. UNEP[1]). Land use planning to direct development away from hazardous zones offers significant benefits in rapidly growing cities, but it is these settings where such planning can be most difficult to implement. Further discussion concerning coastal cities and climate change will be found in Nicholls.[43]

5. DELTAS

Deltaic areas are inherently susceptible to sea-level rise, being low-lying plains formed by the deposition of alluvial sediments.[5] Further, deltas naturally subside to varying degrees and hence experience relative sea-level rise without any global rise. Only sedimentation and local biomass production can compensate and hence maintain the deltaic area, but human management of many deltas and their catchments are often reducing this capacity by reducing the availability of sediment and modifying wetland hydrology. This is well-illustrated by the Mississippi delta.[54]

There are at least 31 alluvial–deltaic areas around the Mediterranean[49,55] including the Nile, Po, Rhone and Ebro deltas. These four deltas are experiencing similar problems to the Mississippi delta[8,9,33] and more widely most alluvial–deltaic areas are experiencing a decline in sediment input.[55] Therefore, any global rise in sea level is exacerbating a range of existing problems within deltaic areas which can be related to human management.

5.1. Egypt and the Nile delta

The Nile delta is by far the largest delta within the Mediterranean occupying over 20 000 km^2. Since ancient times the fortunes of Egypt has been linked to the Nile floods and the crops which this allowed to be grown on the delta. However, during this century increasing regulation of Nile, culminating in the construction of the Aswan high dam in 1964, has completely decoupled the delta from the river system which formed it.[33] Significant shoreline recession has been occurring throughout this century,[32] although this recession is not universal. Based on geological evidence high rates of subsidence of up to 5 mm $year^{-1}$ are occurring in the northwestern part of the delta.[56]

Together with the Ganges–Brahmaputra delta in Bagladesh, the Nile delta was recognised as highly susceptible to sea-level rise in one of the first vulnerability assessments.[7,32] Given a 1-m rise in sea level these early studies estimated that 8 million people would be displaced from their homes (1985 population). Compounding factors included population growth and socioeconomic developments, which are relocating away from the Nile valley towards the coast,[57] and the possibility of excessive groundwater withdrawals raising the rates of subsidence. These early studies drew attention to the fundamental coastal management problems of deltas and recognised the human role in enhancing or reducing the magnitude of the problems. More recent studies all confirm that planning for sea-level rise must form an important element of coastal management in the Nile delta.

Stanley and Warne[33] analyzed geological/geomorphological changes of the delta evolution over the last few millennia and projected them until 2050. The influence of human activity on the evolution of the delta has been increasing throughout the study period and this trend is expected to continue. Erosion and reshaping of the sandy delta fringe will continue, but with localised accretion. The area of the four remaining lagoons will continue to decline in area due to shoreline recession to the north and reclamation on the inland shores. Combined with increasing levels of pollution, this will lead to loss of fisheries and wildlife areas. The agricultural lower delta plain will also be impacted by relative sea-level rise, with falling crop yields and other adverse impacts.

Delft Hydraulics *et al.*[34] present a rather different analysis based on the IPCC Common Methodology. While this was a national study most results pertain to the Nile delta, including Alexandria (see Section 4.2). Assuming a 1-m rise in sea level by 2100 they came to a number of important conclusions. Firstly, assuming no responses:

- enormous capital values could be lost due to shoreline retreat and, more particularly, increased flooding, while much coastal infrastructure would cease to function as designed;
- about 4.7 million people (1990 population) would be displaced from their homes;
- salt water intrusion and reduced drainage capacity present significant additional problems.

Secondly, assuming appropriate responses are implemented:

- to protect the capital values and people identified above, a national response strategy is necessary, as distinct from a series of local response strategies;
- the problems caused by salt water intrusion are generally insensitive to the possible response measures. The impacts might be alleviated by agricultural responses and this requires further evaluation.
- the costs of measures are large in relation to Egypt's present earning capacity;
- there is a need for institutional and technical capacity building to facilitate planning for climate change and effective and integrated coastal management in general.

Strzepek *et al.*[35] made an integrated study of Egypt using an agricultural economic model to examine the combined effects of changes in crop yields, water supply and arable land on Egypt's agricultural economy. General Circulation Model results were used to develop scenarios for temperature and flow in the Nile river, while a 1-m rise in global sea level was assumed for 2100. Under one scenario the availability of water from the Nile falls significantly and the loss of agricultural areas in the delta due to sea-level rise is of less relevance, as no water would be available for irrigation. This analysis reinforces the importance of the conclusion of Delft Hydraulics *et al.*[34] concerning saltwater intrusion.

Therefore, the Nile delta is highly vulnerable to sea-level rise. Some form of structural solution appears to be the only feasible long-term response. This will require long-term planning. One planning issue that needs to be raised at a strategic level is the continued construction of new development on the coastal fringe and progressive and piecemeal lagoon reclamation.[57]

5.2. Ebro, Rhone and Po deltas

These three deltas are in the northwestern Mediterranean and are being studied as part of the European Union-funded MEDDELT (Impact of Climate Change on Northwestern Mediterranean Deltas) project[9] (see also pp. 737–910 in Ozhan[58]). All three deltas are two orders of magnitude smaller than the Nile delta,[6,58] although both the Po and the Rhone are part of larger areas of coastal lowlands.[51,59] All the deltas have been extensively modified for agricultural and other purposes, and at the same time they are all receiving greatly diminished sediment supplies due to human-induced changes within the catchment. The greatest reduction is in the Ebro delta, which only receives 4% of its former sediment supply.[9] In the Po delta reclamation and fluid withdrawal has lead to significant subsidence in excess of 2 m in some areas and, more broadly, in the northeastern Italian coastal plain over 2300 km^2 of land is already below sea level and protected from inundation by dikes.[47] In the Ebro delta rice cultivation is important and some of the rice fields are already at or slightly below sea level. In the Rhone delta significant areas of wetland appear vulnerable to inundation.[3] Therefore, continuation with present policies combined with sea-level rise will cause progressive changes and ultimate loss of land, or alternatively require polderisation similar to that already common in the Po delta.

The losses that would result from coastal abandonment are less quantified than in the case of the Nile, but comprise mainly agricultural and aquacultural areas, as well as natural areas of importance to wildlife. Given that some sediment transport is still occurring to these deltas, it is possible to take a natural systems engineering approach. Simply put, it should be possible to maintain some, or possibly all of the existing delta area by managing natural processes.[9,60] Using the selfregulation of natural systems many of the functions of the delta might be maintained into the foreseeable future at minimal cost. Changing catchment management to release more sediment to the deltas, where possible, would further enhance this capability. However, this type of management requires a fundamental change in philosophy, as natural processes must be allowed to occur rather than be excluded or tamed; also, it requires more scientific knowledge of the deltaic processes. In this area the MEDDELT project will provide important new information and management tools.[61] Similar management approaches are being investigated in the context of preserving the Mississippi delta,[54,62] and such approaches might find wide application in response to climate change.

5.3. Discussion

There is some awareness of the possible impacts of climate change in deltaic settings, based largely on the rapid present changes which are already occurring. The possibility of 'working with nature' to counter the impacts of sea-level rise exists in many deltaic settings, including the Ebro, Po and Rhone deltas. However, in the Nile delta the lack of sediment makes this possibility appear unrealistic and diking of the delta appears more likely.

6. ISLANDS

There are 162 islands in the Mediterranean exceeding 10 km^2, with a further 4000 smaller islands, found particularly in the eastern Mediterranean. These areas have a low resource base and have often welcomed significant tourist development.[63] However, this can lead to serious problems and trigger coastal management initiatives.[1] Therefore, the potential problems of climate change have received less attention than deltas. However, they could be serious in a number of ways, including beach erosion (undermining the tourist industry) and more speculatively, a potential decline in rainfall[64] which could cause serious problems for water supply in settings where water shortages already occur.

6.1. Cyprus

Cyprus is the third largest island in the Mediterranean, with a total coastal length of some 735 km, of which about 365 km has been under Turkish occupation since 1974. The 1990 population was about 700 000.

Like many of the islands in the Mediterranean the Cypriot economy increasingly depends on coastal tourism and as a result there is considerable and growing pressure to utilize and exploit the coastal zone.[65] Six main coastal management problems can be recognized: (1) coastal erosion; (2) sea grass and other debris on the beach; (3) growth of algae close to the beach; (4) tourist pressure on the coastal environment; (5) degradation of marine ecosystems; and (6) water pollution.

The shortage of sandy beaches suitable for tourism, together with the widespread occurence of erosion, has led to the construction of many small scale groynes and breakwaters, especially along the popular south coast. However, it is now more widely questioned if the growing number of shore-parallel (detached) breakwaters along many of the newly developed tourist beaches are always an ideal solution to these problems.

6.1.1. *Climate change as a coastal management issue*

Climate change is not presently perceived as a coastal management problem in Cyprus. As a considerable length of the Cypriot coastline is already subject to erosion, and this problem is likely to be exacerbated by climate change, future erosional trends will be considered here to focus on the relative importance of climate change. The major causes of the existing erosion problems are believed to be: (1) the construction of river dams, removing the supply of sediment and (2) extensive beach mining, although other factors may also contribute. Three impacts of climate change (Table 1) might change erosion rates: (1) accelerated sea-level rise; (2) changes in wave characteristics (e.g. increase in storm frequency); and (3) changes in river discharges.

Based on archaeological data,[28] Cyprus appears to be experiencing long-term uplift of between 0 and 1 mm year^{-1}. This uplift will counteract global sea-level rise and given a global rise in sea level of 0.5 m by 2100, relative sea-level rise in Cyprus will be in the range 0.4–0.5 m. This is a significant change which needs to be taken into account when planning sustainable solutions for coastal zone problems. Any rise in sea level is expected to cause beach erosion, unless a supply of sediment is available. Based on a rule of thumb developed from the Bruun Rule, a first-order estimate of the recession is 100–200 times the rise in sea level,[66] or 40–100 m in this case. This estimate takes no account of longshore sediment transport, or other sediment inputs or losses. Therefore, areas which are already eroding will probably erode substantially more than these estimates.

Coastal erosion is also conditioned by wave processes. Given increasing storm frequencies, greater cross-shore sediment transport will occur, generally removing sediment from the upper beach or dunes to the shoreface (>4–5-m depths).[67] This would exacerbate the problems of beach erosion. Conversely, reduced storm frequencies would help to counter the likely erosion due to sea-level rise.

Changes in the amounts and pattern of river run-off are difficult to predict. However, in the case of Cyprus changes in run-off are of little relevance as most rivers (and their sediment yield) have already been separated from the coast by reservoir construction. The net result is a pervasive problem of coastal erosion which is already well apparent.

Therefore, continued erosion is to be expected without any changes in climate. It will be exacerbated by a rise in sea level and this will be conditioned by the uncertain changes in wave climate.

6.1.2. *Possible responses*

Based on these preliminary estimates continued and more rapid beach erosion appears likely, which would have important implications for the long-term sustainability of the tourist industry. A key policy goal would seem to be to maintain the limited beach area and hence to sustain the vital tourist industry. This can be accomplished in a number of distinct ways. On wide sedimentary coastal plains erosion will not lead to beach loss unless a hard structure is built, fixing the position of the shoreline. Therefore, building setbacks for new construction which allow natural dynamics to occur seaward may be appropriate in suitable locations. The precise size of the setback would require more evaluation. In areas of pocket beaches, or locations where existing development is close to the shoreline, protection will probably be appropriate, including beach nourishment. The availability of suitable sand resources may be problematic, but given the large benefits of maintaining the beaches, sources external to Cyprus could be considered if this was necessary. Therefore, with regard to the three potential strategies available to coastal societies (planned retreat, accommodation, or protection[5]), a strategy of protection combined with planned retreat (via setbacks) seems most appropriate. It is likely that the issues raised here will be generic to many of the islands in the Mediterranean.

When considering possible responses institutional considerations are also critical. In Cyprus interest in integrated coastal zone management (ICZM) has been triggered as a process to solve present and near future problems and it is receiving widespread support in this regard.[65,68] Therefore, bringing longer-term issues such as climate change into the Cypriot ICZM process requires reappraisal, including answering the key question: 'What do the Cypriots want to do with their coast in the long-term?' There are many different users (tourism, wetlands, industry, military) with different intentions, with different temporal and spatial claims, with different responsibilities, and hence the potential for a range of conflicts. To facilitate the answering of this central question in an orderly and practical way, two essential requirements should be met:

- the user groups and their representatives should be identified;
- the requirements of each user group should be identified.

These user requirements need to be checked with respect to internal conflicts, national policies and environmental impacts (as triggered by climate change). Then, the necessary institutional and technical infrastructure associated with the users' requirements needs to be defined in a conceptual stage to roughly assess feasibility, cost, performance and side-effects in a preliminary stage. The implications of the inherent uncertainties concerning climate change need to be carefully evaluated. In general, it seems prudent to only implement low-cost strategies at present, such as setbacks in appropriate locations. Other low-cost strategies include allowing for likely rates of sea-level rise when designing breakwaters etc. Most fundamentally the ICZM process should expect the coast to change and be prepared for likely changes in whatever form they might take.

7. DISCUSSION

While this review is not exhaustive, it illustrates that apart from deltaic areas, there is little active concern about sea-level rise and climate change around the Mediterranean. In terms of coastal management immediate problems such as declining water quality and tourist development have been the triggers for coastal management. Within deltaic areas and coastal lowlands generally, interest in sea level and climate change can also be related to existing problems of failing sediment supply and subsidence.

Tide gauge measurements show that relative sea-level rise is already occurring in the Mediterranean (Fig. 3) and in the next century this rise is expected to accelerate. Global rise in sea level by 2100 has a large uncertainty, with a 1-m rise being the likely maximum. Any rise in sea level will have adverse impacts: those impacts being a function of the magnitude of the rise and the human response to that rise. A well-planned response will tend to minimize impacts and *vice versa*. Other implications of climate change are less certain, but many adverse impacts could occur. It is also apparent that climate change will generally exacerbate existing problems, rather than create fundamentally new ones.[6] Therefore, solving existing problems generally increases flexibility in the face of climate change. However, there is also a need for an explicit long-term (50+ years) perspective as part of coastal management and to be most effective, coastal planning will have to simultaneously address the full range of short-term, medium-term and long-term coastal problems. An appropriate institutional mechanism for such planning is integrated coastal zone management. All signatures to Agenda 21 have endorsed this institutional mechanism. Existing regional guidelines for coastal management also address climate change.[1]

An important first step towards incorporating climate change in ICZM would be further local to national scale studies to better evaluate likely impacts and the full range of possible adaptation options. These studies will need to be more comprehensive than many earlier studies and include all pertinent climate change factors, combined with other scenarios, such as population and socio-economic changes. The Common Methodology has formed the basis of many vulnerability assessments, but experience has raised a number of problems and deficiencies when it is applied.[3,5,18] Rather than continue with the Common Methodology this suggests the need for further development of methodologies for vulnerability assessment which are more tailored to local needs. For instance, a methodology designed to assess the vulnerability of Mediterranean deltas is being developed.[9,8,61] The general IPCC guidelines for assessing climate change impacts and adaptations[69] may be useful in guiding such developments.

In the context of the Mediterranean particular attention should be focused on the most vulnerable sectors and areas such as the deltas, developed sandy beaches and coastal wetlands. In addition, a more proactive approach to coastal planning which recognises the possibility of climate change and sea-level rise needs to be fostered. This could take advantage of the opportunity to influence new developments, as well as renewals and redevelopments, such that they are more resilient in the face of climate change. Given the large degree of uncertainty these measures need to be low-cost and/or flexible, such that they will be effective for the full range of likely scenarios. Suitable adaptation options are often limited and have long lead times, so they should be identified and evaluated without delay.[5] In cases where climate change could have serious consequences, additional investment can be seen as a prudent 'insurance' policy. Public consultation and a shared view of the desirable and permitted coastal uses is also important, otherwise technically sound approaches may fail due to the lack of public support. The institutional management structure needs to be considered such that it can evolve and adapt (e.g. National Research Council[70]). Being able to learn from experience is important, as any management plan is inevitably based on incomplete knowledge and can be objectively viewed as an educated experiment. Therefore, constant evaluation and possible tuning and/or redesign of the management efforts are required. This institutional arrangement can also take account of changing user requirements for the coastal zone as they inevitably occur.

Tourist developments on sandy beaches provide one simple example, as already discussed in the context of Cyprus. New tourist resorts could locate all long-life infrastructure a short distance (say 100 m) inland from the coast and only place easily moved structures near the beach. This would maintain a choice between protection (often beach nourishment) and a planned retreat if the beach erodes less than the setback. Tourist reaction to such a policy is poorly understood, but critical to its acceptance to resort operators. In pocket beach settings, which are common in the Mediterranean, erosion may lead to unacceptable beach decline or loss.[10] Therefore, the effectiveness of other measures such as engineering structures and the availability of sand for beach nourishment needs to be assessed. Given the widespread shortage of sand in many parts of the Mediterranean importing external sources of sand may be necessary.

Actual response costs to climate change remain highly uncertain, even for a defined set of climate scenarios, and the determination of optimal responses at sub-national to national levels remains a key research question. The best available analysis is for the Netherlands,[19,71] a country where protection is the only possible response. In most countries national responses to climate change will be more variable and comprise some combination of planned retreat, accommodation and protection.[72,73]

8. CONCLUSIONS

While there is awareness of climate change around the Mediterranean, it is receiving little practical concern except in deltaic areas, where failing sediment supply and subsidence are already problems. While these areas are some of the most threatened given climate change, all coastal activities could be adversely affected. Existing efforts at ICZM are targeted at more immediate problems. These existing management efforts need to be expanded to include longer-term issues, including the implications of climate change. A first step would be more comprehensive vulnerability assessments of some of the more vulnerable settings (deltas, small islands, wetlands, etc.). Given the large uncertainties any measures should be low-cost and highly flexible, such that they are effective for the full range of likely scenarios. In some cases where climate change could cause serious problems aditional investment to counter possible climate change can be seen as a prudent 'insurance policy'. Institutionally the ICZM process needs to be adaptive in nature, so that experience and changing user requirements can be addressed in an evolutionary manner.

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