



# Coastal flooding, global warming and environmental management

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*A review of the difficulties associated with the definition of coastal flood frequencies and magnitudes leads to a recognition that there is considerable doubt in many parts of the world as to the precise nature of this particular hazard. Similarly, a review of the sea-level measurements that have been used to indicate a response to global warming shows that there is uncertainty about the amount of other controlling influences. What is clear, however, are that past management decisions about human endeavours in the coastal zone (including flood defences, occupance of flood-prone lands, extraction of ground water and natural gas) have had an impact on relative land and sea levels and have done more to increase the risk of coastal flooding than can be assigned so far to global warming. In addition, these changes induced by human activity may render inappropriate calculations of coastal-flood frequencies based on historical records since the latter relate to a period of time when the controls on flooding may have been very different.*

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## Introduction

Environmental management always includes two components: (1) an understanding of environment; and (2) the inclusion of that understanding into a management system. The definition of 'environment' and of 'management systems' varies from one profession to another, and what may be a matter of concern to some may not be so to many others. In the case of the coastal environment, however, there are many concerned professions including engineers, planners, conservationists, port managers, those concerned with coastal navigation, those in the fishing industry, offshore dredging operators, insurers, re-insurers, members of the holiday and tourist industries, owners of real estate and ultimately Governments (whose very survival may be prejudiced by inappropriate policies regarding the occupance of coastal zones). Amongst each of these groups there is a concern about those coastal hazards that most directly affect their responsibilities.

The range of coastal hazards that are of concern includes: coastal erosion (including unstable cliffs), coastal siltation, the movement of sediment within estuaries and the near-shore area, flooding and wind storms. Of all of these hazards the ones that have the most impact are wind storms and flooding. Dynamically the two often occur together, and an analysis of flood hazard must include reference to wind storms.

Relative changes in the elevations of land and sea are important to the occupants of the coastal zone, and those whose commercial activities are linked to it. This is especially the case if those changes are rapid and cause a significant change in processes such as flooding, siltation and erosion that materially affect human activity.

Over the last decade, debate concerning the potential for future changes in sea-level associated with global warming has been considerable. This has raised the general level of awareness in the dynamic nature of the coastal zone, and caused coastal-zone managers considerable concern. Increased awareness has also been accompanied by

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confusion. This paper is concerned to identify the key components of flooding in the coastal zone, under a global warming regime, which need to be considered by coastal-zone managers.

## Fundamentals of hazard assessment

The two fundamental components of any natural hazard (peril) are 'magnitude' and 'frequency' (with an assumption that the higher the magnitude the lower its frequency). The 'spatial component' of a hazard and its 'temporal variability' (including the changes in applicable frequencies that accompany shifts in the climate) also need to be understood.

This account will concentrate on magnitudes and frequencies in respect of coastal flooding. This demands a close look at the historical perspective and at present-day tendencies. Neither can be understood, however, outside their spatial context. Concerns about an increase in the flood hazard (and storminess) in the context of projected changes in climate are widespread in the management groups listed above. Such concerns have a stronger focus if viewed against a historical perspective and the related spatial contexts.

## Magnitudes

The magnitude of coastal flooding is usually measured in terms of elevation and inland extent. These two parameters are directly related to each other, and are controlled by the form and heights of the ground exposed to flooding.

Some of the greatest of the more recent floods include those of the North Sea in England and mainland Europe (e.g. 31st January–1st February, 1953). Storms of this magnitude are associated with specific atmosphere and storm conditions, especially if they coincide with exceptional high tides (e.g. Spring tides). A storm surge may also be involved [see Steers (1953) for an account of the 1953 flood]. In the North Sea such surges

**Table 1.** Return periods for water levels in the Tees and Middlesborough Docks, Tees Estuary, NE England (from Shennan and Sproxtton, 1990)

Return period (years)	Tees Dock (m. OD)	Middlesborough Dock (m. OD)
1:10	3.65	3.82
1:100	4.00	4.25
1:1000	4.35	4.68
1:10000	4.70	5.11

OD, ordnance datum.

are associated with deep atmospheric depressions. Nineteen surges per annum, on average, have a magnitude of more than 0.6 m above 'normal' each winter. Maxima approaching 3.5 m were recorded in the Thames Estuary in 1921 and 1953 (Lee *et al.*, 1995), though the theoretical maximum surge is close to 4 m (Dugdale, 1990). Damaging surge events in the North Sea area occurred in 1825, 1894, 1897, 1906, 1916, 1921, 1928, 1936, 1942, 1943, 1949, 1953, 1969, 1976 and 1978 (Lee *et al.*, 1995).

A great problem in coastal flood-hazard management is that records of past magnitudes do not always exist. Obtaining historical records for some of the largest storms and associated floods is possible [as Lamb (1991) has done for a 500-year period, or so, for the North Sea area of Europe]. These may say very little about storms of lower magnitudes, which, nevertheless can be locally very damaging. A search through newspaper (which cover a shorter period of historical time) and other records may yield some information about flooding at lower magnitudes, but such information is unlikely ever to be complete.

The alternative, and usual, approach is to extrapolate extreme flood levels from measurements made over a shorter period. Shennan and Sproxtton (1990) provide a set of predictions, based on measured water levels, for Tees Dock and Middlesborough Dock (NE England) (Table 1), but recognize that there may be doubts over a linear extrapolation of the records in order to determine high-magnitude flood frequencies. In addition the period over which the records were taken (1921–1983) may or may not have been typical of a longer period.

Magnitude and frequency of flooding are inextricably linked in such analyses.

## Frequencies

Frequency analysis inevitably includes historical data where such are available. Such data may do more than just provide evidence of past flooding and the calculation (by linear extrapolation) of extreme flood events, they may also allow a statistical analysis that can also reveal other important aspects such as those shown by Eliasson (1996) for Reykjavik Harbour (Iceland). Eliasson showed that a probability integral could be defined which gives the expected tidal-surge level as a function of the return period when the latter falls in the range 30–100 years.

Two important constraints exist on the use of flood frequency analysis based on records. These are: (1) the assumption that even under natural conditions the climatic controls on flood frequencies and magnitudes have not changed over the centuries; and (2) that flood protection work will have changed the frequency of local flood experiences.

Indications exist that flood (and storm) frequency calculations cannot be applied to long-term records. The reason is that within one period of climatic conditions certain frequency–magnitude relationships will exist, while a change in the climatic conditions brings in a changed set of frequency–magnitude conditions. One indication is the discovery recorded by Lamb (1982) that the greatest number of storms, within the North Sea, occurs in the warmest centuries. Storm floods in the North Sea reached a maximum in the eleventh and thirteenth centuries, with severe floods in late Roman times and again in the twentieth century. The frequency of storm and flood events changes with climatic context. These may also change through time.

Engineering works have produced flood protection in respect of flooding of lower magnitudes. These works have removed many higher frequency (lower magnitude) floods from the system. What remains, therefore, is just two states: no flooding and catastrophic flooding (i.e. those flood levels capable of overtopping, breaching or bypassing flood defences). This has profound implications for coastal-zone management. The fundamental findings of Hewitt and

Burton (1971), which experience has borne out, include the crucial hazard-management observation that as flood protection is provided an increased occupation of flood-prone lands takes place. This increases the vulnerability of the area to extreme floods. When a high magnitude event does occur, far more damage is done than would have been the case before the flood defence system was constructed and the floodable lands occupied. What appears to be forgotten (or ignored) is that the engineering design parameters are based on a calculated flood frequency (which may be based on limited records taken during an untypical period) of perhaps the 1 in 500 year event. When an event of greater magnitude occurs, as it will, a far greater level of vulnerability exists than was the case before the flood defence system was constructed.

## Historical aspects

There has been a general rise in sea level since the last glacial maximum (and sea-level minimum) over at least the past 18 000 years, and perhaps even longer. This rise has not been uniform across the globe (Dugdale, 1990; Kidson, 1982). Indeed, on a larger scale, critical differences in the relative heights of land and sea may occur within one country. Thus, while, in general, the south of England is losing height relative to the sea, as is western France, parts of Scotland and Scandinavia are emerging (Jardine, 1982) (e.g. as a result of isostatic adjustment).

Coastal flooding has been documented over very different time-periods in different parts of the world. In some places it has been possible to use the geological record to extend the historical period farther back in time (e.g. Nio and Yang, 1991; Stanley and Warne, 1994). What emerges is that coastal flooding is a natural process by which adjustments occur (between land and sea, between water and sediments) and that human beings have invaded this dynamic space and, of necessity, have tried (by the introduction of rigid flood defences) to 'fix' a dynamic system whose natural tendency is to undergo continual change.

## Spatial aspects

The potential for coastal flooding has a strong spatial component at a variety of scales. On the global scale such flooding is associated with large low-lying areas such as the largest deltas (e.g. the Brahmaputra, Bangladesh), the major river inlets (e.g. the Amazon), areas of dominant coastal wetlands (e.g. Everglades of Florida) and areas experiencing subsidence on a large scale (e.g. Venice, see Bandarin, 1994).

On a continental scale, such as within Europe, coastal flooding is associated with low-lying areas (e.g. the Rhone delta, the Rhine delta) and with areas that experience flooding because of on shore storms (e.g. the coastal towns of southern England). On a national scale one part of the coastline is unlikely to experience catastrophic flooding at the same time as another [e.g. major floods in East Anglia (on the east coast of England) have never been recorded at the same time as a catastrophic flood anywhere on the west coast].

There exists a flood hazard in all low-lying coastal areas. Sometimes, where the area is stable in geological terms, the historical frequency–magnitude relationships may continue to be applicable. In other areas, where geological subsidence is a part of the dynamic development of the area, the frequency of flooding at any (and every) magnitude may be increasing. In coastal Louisiana, for instance, the rise of sea-level relative to a subsiding land level is not only increasing the amount of flooding, it is also causing saline intrusion into the groundwater, an increase in the volume of sediment in estuaries and bays, as well as affecting the tidal range, changing the detailed position of the shoreline and creating new or extended wetlands.

Dugdale (1990) reports a consensus view that sea-level rise has an average rate of between 1.1 and 3.0 mm yr<sup>-1</sup> though different rates apply in different oceanic regions. In addition, there appears to have been a tendency for rates to rise in more recent years (Barnett, 1984; Gornitz, 1995).

In some areas it is recognized that human activity has caused land subsidence relative to sea level (Belperio, 1993) and where this is in coastal areas, such as the Po Delta

in Italy (Bondesan *et al.*, 1995), this will continue to lead to greater risks from coastal flooding than would otherwise have been the case. Such subsidence may be related to the extraction of underground water-resources, as in Venice (Bandarin, 1994), or as a result of port development, land reclamation and/or industrialization as in Port Adelaide (Belperio, 1993) and Manilla (Spencer and Woodworth, 1993).

## The future

Future changes in flooding are usually discussed in terms of the potential for climate change. The predictions endorsed by the Inter-governmental Panel on Climate Change (IPCC) and published in May 1996 can be found in Houghton *et al.* (1996). Their implications for coastal flooding and storminess vary around the globe. It is accepted that it is the coastal zone which may suffer most, mainly through sea-level rise (Turner *et al.*, 1995; Turner *et al.*, 1996). However, conditions may become more temperamental with excited variations around the mean (Leinfelder and Seyfried, 1993) and this implies a greater frequency (in the short to medium term) of both coastal storms and associated floods. Increased intensity of atmospheric processes will tend to increase the magnitude and the frequency of high-magnitude floods and storms in many parts of the world (Berz, 1993).

Concern has also been expressed about the effect that predicted changes in climate and sea level will have on near-shore sedimentation (Healy, 1996). Along sand-dune coasts there is an increased threat of the erosion of coastal dunes with the potential for increased sedimentary deposition (of these eroded sands) in the near shore. This may have the secondary effect of extending embayments further inland and causing the additional flooding of wetlands.

Most of the realistic estimates of climate change accept an element of uncertainty (Bodansky, 1995; Chao, 1995; Leinfelder and Seyfried, 1993; Ungar, 1995) and some authors define this as 'considerable uncertainty'. This uncertainty also extends into any economic predictions concerning both the effects of climatic change and the impact

of human management reactions on the nature of climate change (Turner *et al.*, 1996).

Although there are reports of a global sea-level rise within the past 100 years, there is considerable doubt about the reliability of some records, and no certain link to global warming as the cause. Reported rates of sea-level rise at various locations around the world lie in the range 0.3–3 mm yr<sup>-1</sup>. This is a greater range than the consensus view of the global average (Dugdale, 1990). Local causes such as vertical earth movements and influences on specific water-level gauges are recognized as influencing many readings (Gornitz, 1995). However, for management purposes changes in sea level, whatever the reason, are an important consideration. The very rapid rates of change along the coast of Louisiana, which are about 10 times the global rate (Gornitz, 1995), are a cause for management concern. Delta areas are known to experience a more rapid sea-level rise than adjacent areas that are not a part of the deltaic system. This is because the earth's crust under deltas tends to subside more rapidly than that in adjacent areas (Day *et al.*, 1995). Under natural conditions the supply of sediment during flooding, within the river systems, allows the delta surface to build up at a rate which keeps pace with this rise in sea level. As flood control schemes have been established along many of the river systems leading into deltaic areas (e.g. Mississippi, Rhine) this natural supply of sediment has been withheld from the delta and its surface has been unable to adjust to higher sea levels. This inevitably leads to an increased flood risk in such deltaic areas.

Uncertainty in the climatic change context has been looked at by Shlyakhter *et al.* (1995) in terms of the risk management issues of sequential decision strategies, value of information and the problems of interregional and intergenerational equity. Permitted development of very low-lying ground now leads to the observation that some of these are under a greater risk from flooding than was previously the case (Hughes and Brundrit, 1995). The problem is that there are now so many such locations of increased flood risk around the world.

## Flood risk management

In essence, flood risk management, like any other form of risk management faces dilemmas posed by uncertainty, ambiguity and a lack of consensus as to the 'best' course of action. The manager will attempt to establish the best available factual background (in this case information about the existing and predicted coastal flood hazard) and then consider the policy alternatives, with conclusions reached by consensus.

This review has identified some of the more significant aspects of the coastal flood hazard. It has identified the fact that the hazard is not going to go away, and in many cases is going to provide a greater threat in the future. This is partly because underlying controls, such as the geological subsidence of parts of the earth's crust and the encouragement of subsidence by human extraction of underground resources, and the increased occupation of flood-prone lands will make greater flooding and flood damage inevitable.

## Conclusions

Those many professions concerned with the coastal zone and its occupants recognize the hazard posed by flooding. Their problem often lies in an inability to grasp the true scale at which flooding can occur, and the ways in which environmental change can increase either the magnitude or the frequency of the flood hazard.

This review has drawn on studies around the globe that show that changes in sea level will lead to changes in flood characteristics. It is also clear from these studies that the cause of such changes is not exclusively that of a response by sea level to global warming. It seems much more likely that present flood-related difficulties have more to do with natural geological subsidence (which has a variety of causes), man-induced subsidence, the control of inland flooding that leads to a reduction in the necessary supply of silt to depositional coastal areas (and thereby preventing them from maintaining a balance with changes in sea level) and above all with the fact that occupation of potentially

floodable land has taken place leading to an increase in the people and properties vulnerable in the event of a catastrophic flood.

A presumption has been made that insurance is the route to coping with flood risks (Berz, 1993), but this may turn out not to be the case, and in any event avoids the moral dimension. The potential exists for a catastrophic event, or a sequence of catastrophic flood events such that insurers and their re-insurers may be rendered incapable of meeting the financial cost of claims. However, even to presume that insurance is a management option is to avoid the fact that the lives of people are involved, and in this insurance is an irrelevance.

When it is recognized that some of the causes of increasing catastrophic flood risk lie in the hands of those who manage the coastal zone it is inevitable that the agenda of management concerns as well as the policies of central Government should be re-examined. For example, should further occupation of areas liable to extreme floods be prohibited? Should a free flow of river sediment into deltaic washlands be restored? Should man-induced subsidence (e.g. through the extraction of natural gas, or the extraction of water, as has been done in Venice and Tokyo) cease? Should there be an attempt (as in California) to restore ground levels by pumping back into the ground? There are no easy answers to such questions, but it is clear that management issues may be as important in determining future coastal flooding as any changes that global warming may cause.

What needs to be decided is the nature of the flood hazard along the coastline of concern, and to identify the management decisions that need to be made. In this context a decision to do nothing becomes a positive decision. In each case it is worth asking four basic questions (see Hewitt and Burton, 1971):

- (1) is there a technically feasible solution?
- (2) is the solution economically justified?
- (3) is the solution socially acceptable?
- (4) is the solution environmentally sound?

The problem of coastal flooding is not going to go away. Management strategies are required to cope with this inevitability.

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