4.6 Flooding and climate change

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Coastal Flooding

Summary

- ❑ Climate change in the UK is likely to be associated with an increased risk of severe flooding in low-lying coastal areas and the return time of severe flooding events is likely to be significantly reduced.
- ❑ Emergency plans to mitigate the effects of such floods should be reviewed urgently.
- ❑ A detailed risk assessment of the likely effects on health of a major flood of low-lying areas is urgently needed.
- ❑ Further research into methods of coastal engineering leading to design guidelines for coastal defences is needed.

4.6.1 Introduction

On a world scale, global warming and a consequent significant rise in sea level would have severe impacts for some low-lying coasts and islands. The consequences for the UK are in general perceived as amenable to technological control, such as through the construction of more resilient sea defences. Perhaps the best example is the Thames Barrier, which was erected to protect London from severe floods with a design that allowed for a predicted sea level rise until the year 2030. This chapter is possibly one of the first attempts to address the issue of coastal floods, from the perspective of human risk and the health consequences as a result of rising sea levels and a potential increase in storminess. Our analysis presents a complex picture in which we find significant limitations in the current state of hazard and risk analysis of coastal floods and recommends that these need to be addressed before the impact of climate change on human health can be satisfactorily estimated.

4.6.2 Key questions for future risk scenario development

This chapter focuses on coastal flooding (sea defences) and omits discussion of coastal erosion (coastal defences). It assesses the human consequences of potential flooding events which could have impacts on a disaster scale. The reference event in this analysis is the East Coast Floods of 1953 in which 307 people died.

The following questions are to be addressed.

- ❑ If there were a recurrence of a major flood, as exemplified by the 1953 flood event, what hazards would it present today and in a future scenario of climate change?
- ❑ Can the current probabilities of major coastal flood events be estimated and how would these be affected by the future climatological estimates, both in terms of return periods and severity?
- ❑ What would be the loss of life and health implications for society of such a future event?

- ❏ Can increases in the risk of major coastal flooding be prevented by engineering measures (improved coastal defences) alone?
- ❏ What other mitigation measures may be needed to reduce vulnerability to such events?

The reactions of society to climate change also need to be considered. To answer these questions we have reviewed:

1. Flood disaster model: East Coast floods, 1953
2. The forcing factors: climate change scenarios
3. Flood characteristics
4. Sea defences and coastal management issues
5. Causes of vulnerability
6. Human health consequences of floods
7. Mitigation measures

4.6.3 East Coast floods 1953

This remarkable event was documented by Greave (1956)[1] and Summers (1978)[2], and is presented here as a model for future flood disaster events. On Saturday 31 January and Sunday 1 February 1953 a great storm surge, accompanied by gale force winds, swept over the north of the UK, causing widespread flooding of coastal areas. The waters of the North Sea, whipped by the northerly gales to huge tidal levels, smashed through the sea wall defences in hundreds of places from Spurnhead to Kent. The damage extended over 1000 miles of coastline, and involved breaches in the defences at some 1200 sites. In some places not a mile of sea wall remained intact. 307 people lost their lives and over 32 000 had to be evacuated from their homes. Whole communities were isolated. 24 000 houses were flooded and damaged – some beyond repair.

During the Saturday morning the winds reached force 10 with gusts up to 125 mph. In east Scotland the wind flattened thousands of acres of forest. The mean sea level rose by 0.6 m. Winds lashed the surface of the water with waves over 4.9 m height, the high waves being generated by the very long fetch, i.e. the sea track over which the winds were blowing. It seems probable that the surge had an elevation of about 2.6 m all along the Norfolk coast. Levels were particularly high at King's Lynn (3 m for comparison, a category 3 hurricane creates a surge of 3–4 m). Fortunately there had not been heavy rain or melting snow in the uplands and so rivers were not in flood or swollen at the time, if they had been the results would have been far greater in extent, widening the area and scope of the disaster. The East Coast defences and the authorities responsible for them were totally unprepared.

The sea attacked in two ways:

- ❏ wave action or scour against sea walls and dunes until they were breached (e.g. Lincolnshire, north Norfolk and parts of Kent); and
- ❏ sea surging up estuaries and overtopping and breaching river banks (e.g. Suffolk and Essex).

Some descriptions of deaths are given by Greave[1] (Appendix). The worse effects were in Canvey Island. A few people had been warned in time to take refuge in their house lofts. However, most were awakened at about 1.10am by a roar as the nearby sea wall was breached and the water thundered past their doors in an irresistible avalanche. Within 15 minutes the water was above window sill level. Much damage to walls, doors and windows was caused by floating debris being flung against houses. Many people were drowned in their beds. Others died of shock or exposure as they scrambled on to house roofs and waited in the dark and cold for help to come. Some people collapsed and slipped from places of refuge into the water and drowned. Especially vulnerable were the old, those living alone and those prone to respiratory or rheumatic illness. Fifty-eight people died that night on Canvey, but it was noted that the death rate climbed significantly during the two months following the disaster, as compared with the same two months the previous year[2].

This description illustrates some of the impacts of the flooding that need to be considered as far as human risk is concerned. The most devastating consequences were from the breach of the defences or banks by a wave of water carrying with it debris that smashed open houses, swept away people and caused drowning with little warning. Bungalows were at greatest risk for the occupants who had no upstairs for refuge. Since the flooding occurred in winter, many who survived the initial drowning subsequently died from exposure. Thus the elderly and small children would be the most vulnerable in such events, and the low temperature of the water would induce drowning on sudden immersion and also cause death in survivors by the subsequent development of hypothermia. The timing would be crucial, depending on whether the flooding occurred during a time of the day or at night when people would be least prepared. Other factors need to be considered. For example, at Tilbury the sewage works were submerged, creating additional problems and a nightwatchman was killed by coal gas escaping from a fractured main. Today, technological hazards would be substantially greater, for example, with the storage of chemicals and fertilisers in many places.

According to the Environment Agency (1999)[3] :

> *"The 1953 flood was the most devastating flood of recent times. Although the tide of 31 January 1953 was only a moderate spring tide, a large surge had been generated which was amplified by winds as it progressed southwards along the east coast. Sea levels in the North Sea rose over 2m higher than tidal predictions. The severity of the disaster was certainly increased because it all happened in darkness. There has been a series of less destructive floods since 1953."*
>
> *"After the flood defences failed in the 1953 storm, many of them were rebuilt and improved using 1953 levels as a maximum. The Thames Barrier was built as recommended in the Government's report on the 1953 flood, although not completed until 1982. The design recognised that sea level was rising by 0.8 cm per year and allows for the rise to continue until 2030. The barrier, which will cope with events up to a return frequency of 1 in 1000 years, was designed to protect London and upper parts of the Thames estuary from storm surges. As well as tidal defences, about 126 500 domestic and commercial properties rely on sea defences for their protection and some 366 000 people live in houses liable to flooding from the sea. For Wales, the figures are 33 000 properties and 84 000 people."*

However, these estimates of the numbers of people at risk may be open to question. Even in the 1953 East Coast floods it appears that adequate assessment of the extent of the flooding was not made, for example, records were based only on the areas where existing houses were impacted.

4.6.4 Forcing factors: climate change scenarios for the United Kingdom

Climatologists agree that there are two main issues involved in the assessment of future coastal flooding risk: the rate of sea level rise and whether storminess will increase as the result of climate change.

Sea level rise

The UK Climate Impacts Programme Technical Report No 1, 1998, describes four possible climate futures for the UK. Global mean sea level is set to rise in all four scenarios, the rate of increase ranging from 2.4 cm per decade to 10 cm per decade. The change in mean sea level around the UK coast closely follows that at a global scale and leads to a large reduction in the return periods for certain high tide levels around parts of the UK coast. Natural vertical land movements must also be considered. Thus the report concludes that the relative sea level rise by the 2050s under the Medium High scenario could be 41 cm in East Anglia and 21 cm in the west of Scotland. At the East Coast we can take 6 mm per year as the best estimate of sea level rise as a result of a fall in the land and rise in sea level. Thus the report concludes that for Harwich a high tide level of 5.6 m above datum that currently has a return period of 1 in 100 years (probability of 1% per annum) would have a 10 year return period (probability of 10% per annum) - an extreme example of the UK coastline for the 2050s. Furthermore, this return period and the resultant increased risk of flooding makes no allowance for a potential increase in storminess.

> *"A rising sea level puts low lying land at greater risk of inundation. This may happen simply by the sea covering the land if it has no defences, but also by storms acting together with higher sea levels to overtop sea defences if they are not adapted. The overtopping of sea defences, during storm surges, is likely to occur more frequently if mean sea levels rise. For example, floods which currently occur on the east coast of England once in 100 years could have a return period of 50 years by 2050, and on the west coast (for example at Avonmouth) the return period for a 100 year flood could reduce to 1.5 years."*[3]

Other experts talk about an increase in return rates of an order of magnitude so that the 1953 flood which is regarded as a 1 in 500 year event could become at least a 1 in 50 without including the increase in storminess. A trend of rising sea level is already discernible around the UK coastline (Section 1.2.2)

Storminess

The potential for changes in storminess are regarded as 'quite modest'. Summer gales could become a little more frequent, as could very severe winter gales. The average number of gales per year since 1881 is 12-15. By the 2080s, Scotland could see increases of severe gales up to 7%. Relatively little is known about modifications in the patterns of depressions that could lead, for example, to storms arising back-to-back with one weakening the sea defences and the other overtopping them. However, for trends that appear to show an increase in storminess in recent decades the records over the century show that this could also be explained as part of the normal variability. Wave heights have also been increasing in the North Atlantic, but this finding is also regarded by scientists as within normal variability.

Flooding

According to the Environment Agency (1999)[3]:

"Areas which are less than 5m above ordnance datum are at greatest potential risk of flooding from the sea. Some 5% of the population and 1.5% of the land lie below this level, but sea defences have reduced the risk in many places. Furthermore, over 50% of all grade 1 agricultural land in England and Wales lies below this level. The east coast of England, particularly the area between the Humber and the Thames, is at the greatest risk of flooding from the sea. This is due to a range of factors:

- ❏ *much of the land along the east coast is flat and low lying;*
- ❏ *a history of land reclamation has resulted in a substantial proportion of the coastal strip and some inland areas lying below the high tide level and reclamation has interfered with the natural process of deposition;*
- ❏ *the relatively shallow waters of the North Sea result in the tide forming a special sort of wave which causes complex tidal patterns; and*
- ❏ *storm surges may coincide with high tides to cause abnormally high water levels in the North Sea.*

It is this interaction of the tide and storm surges that is the crucial factor in determining extreme water levels and the potential for flooding. Surges that occur at or near a neap tide are unlikely to cause dangerously high sea levels, but at or near a high spring tide even a modest surge can cause flooding. The greatest danger is when a large storm surge coincides with the time of high water during an abnormally high tide, although there is a tendency for the maximum surge to occur about four hours after high water. The east coast of England experiences an average of 19 storm surges over 0.6 m above 'normal' tide height each winter. The west coast has a similar frequency of surges and the south coast fewer. Severe wave action can add considerable height to water levels and can also contribute to the damage through battering. It can be a crucial factor in the breaching or overtopping of sea defences."

Tables 4.10 and 4.11 show the history of major floods before and after 1953.

Table 4.10 Major floods since the start of historical records

Year	Estimated effects of flooding
1362	Up to 30 000 people lost their lives across northern Europe and many parishes disappeared
1570	Up to 400 000 lost their lives across Europe
1634	Up to 6000 people lost their lives and land loss was similar to 1362
1703	About 8000 people died across Britain and the storm surge caused extensive flooding
1717	Up to 11 000 people lost their lives across Europe
1953	In eastern England 300 people drowned, 65 000 ha of farming land were flooded, 24 000 houses were flooded and 200 major industrial premises were inundated, cost about £900m
1990	In north Wales 2800 homes were inundated and 5000 people were evacuated

Table 4.11 Less destructive floods since 1953[3]

Date	Effects of flooding
January 1976	Port of Hull flooded, tides and waves breached sea defences at a number of points along the east coast of England, with large area of Norfolk under water
January 1978	Still water levels higher than in 1953, some areas suffered worse floods in 25 years
February 1983	Hull dry docks gates collapsed under weight of water. Walcott, Scarborough, Filey and Whitby suffered flooding
October 1996	Tide levels rose to the highest in a decade, the closing of the Thames Barrier prevented flooding in London

From Environment Agency, 1999

Range of East Coast Flood scenarios

The insurance industry has made some damage predictions for a flood disaster along the east and south coasts of England. The results of this research have not been made public, but five different scenarios were produced, at least one of which had worse implications than the 1953 event. A storm surge might occur when heavy rainfall had already swollen rivers, and be superimposed on spring tides with a higher predicted range and a peak coinciding more precisely with the predicted time of high water. Wind might have the effect of increasing the wave action on the open coast. Fiercer storms associated with climate change and higher surge levels could add extensively to the 1953 scenario in terms of the area affected. It is important to note that this type of coastal flood is not like a river in flood filling up a low lying area. Instead, a wall of water moving at speed in the form of a density current as in a dam break might occur and produce rapid inundation. The implications of this dam break analogue for the study of flood impacts will be discussed below under risk scenario development.

4.6.5 Flood characteristics

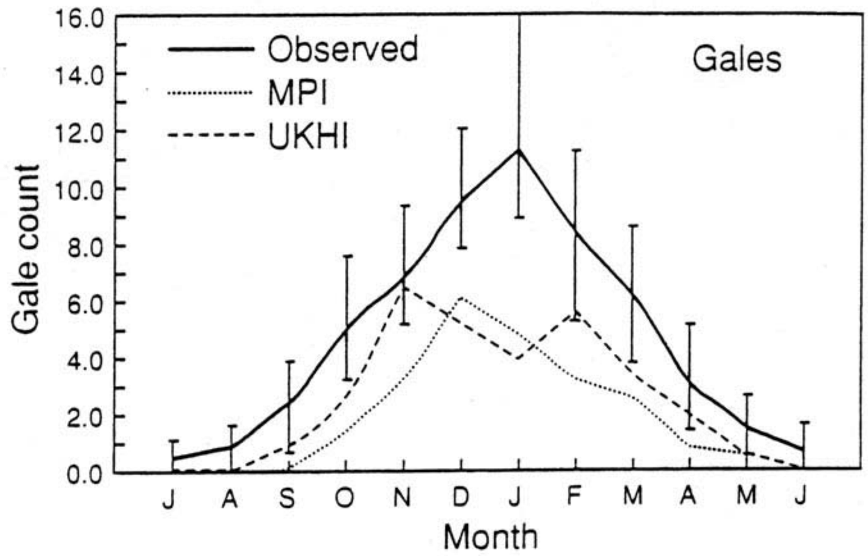
One element in the assessment of future coastal flooding risk, and its implications for human health, is to assess the likely 'goodness of fit' of the predictions outlined above to actual flooding events; to understand why there might be a mismatch between prediction and reality; and thus to identify future areas of research for the better understanding of coastal flooding. This requires both a) an identification of the additional factors involved beyond large-scale ocean-atmosphere modelling (and ultimately how these factors might be incorporated into improved numerical models) and b) a study of the historical archive on forcing factors and flood characteristics to give clues to the understanding of future events.

To simulate a reasonable global scale atmosphere or oceanic circulation, relatively coarse resolution numerical models are sufficient; good reproducibility between different models is apparent. However, at the regional scale of interest, the key forcing functions are found at sub grid-cell levels and these have proved difficult to model satisfactorily.

Where specific attempts have been made to evaluate the ability of models to reproduce realistic weather patterns the results have not been encouraging. Thus, for example, Hulme *et al.*,[4] have shown that two General Circulation Model experiments (UKHI and ECHAM/MPI) underestimate the number of gales over the British Isles by approximately 50%. Furthermore, while the ECHAM model simulates the correct form of the annual cycle, the UKHI model greatly underestimates December-January frequencies and thus produces a bimodal distribution (Figure 4.17). Spatial impacts have been similarly difficult to assess satisfactorily. The majority of large-scale models fail to specify even crude presence/absence coastal configurations. Operational storm surge models, such as those operated through the Proudman Oceanographic Laboratory, take account of shallow water bathymetry to some degree and have been used to model specific events (e.g. Flather's, 1984 modelling of the 1953 storm surge[5]). However, there is a need to further evaluate the effect of different coastal configurations (estuaries, barrier islands, open coasts) on flooding levels. Coupled wave-tide-surge models are beginning to be developed but these also need to be evaluated across a range of estuarine configurations. One aspect of such interactions is the potential interaction of wave-tide-surge effects with enhanced river flows under the severe cyclonic conditions associated with surge events[6].

Figure 4.17

Observed and model-simulated mean monthly frequencies of gales over the British Isles (range bars = range in 10 year averages from 100 year observed record)[4]



There has been considerable interest over the last decade in trying to prove or disprove a perceived increase in the long-term storminess in the North Atlantic Ocean and the possibility that such an increase might be linked to global warming changes due to atmospheric carbon dioxide concentrations. Much of this work has focused on using records of wave climate to infer changing storm frequencies. Unfortunately, however, most of these records are short (of less than 30 years' duration) which makes confirmation of long-term changes difficult and, at one further step removed, assessments of whether or not storm forcing is changing under greenhouse gas-induced atmospheric warming next to impossible. Nevertheless, several studies have indicated linear trends in significant wave height in the North Atlantic[7], although individual analyses are not always in agreement[8,9,10]. Evaluations of longer-term marine climate change are generally based on windspeed records from coastal and/or weather ship stations. These records tend to be of longer but still limited duration (40-50 years); furthermore such records vary greatly in quality over time. Thus, for example, the analysis of historical weather maps for severe storms (core pressure <990 hPa) suggested a substantial increase in the number of such storms in the North Atlantic 1930-1990[11]. However, analyses of windspeed records from coastal stations in the German Bight 1870-1990 have revealed no such increase (Figures 4.18a&b[12]), suggesting that differences may be more apparent than real and represent the increasing quality of environmental monitoring. This example also illustrates the point that trends in meteorological variables tend to average closer to zero given a longer averaging period[13]. More recent analyses for the whole of the NE Atlantic suggest a small increase in storminess over the last two to three decades, albeit tempered by the overwhelming signal of inter-annual and decadal variability[14] and the finding that different analytical methods give different results[15]. A better alternative methodology to both the wave height and station windspeed approaches, however, is to use longer tide gauge records (e.g. Newlyn, Cornwall: >80 years) to reveal, when de-trended for long-term sea level change, storm surge characteristics over time[16].

Figure 4.18a

Windspeed records from coastal stations in the German Bight[11]

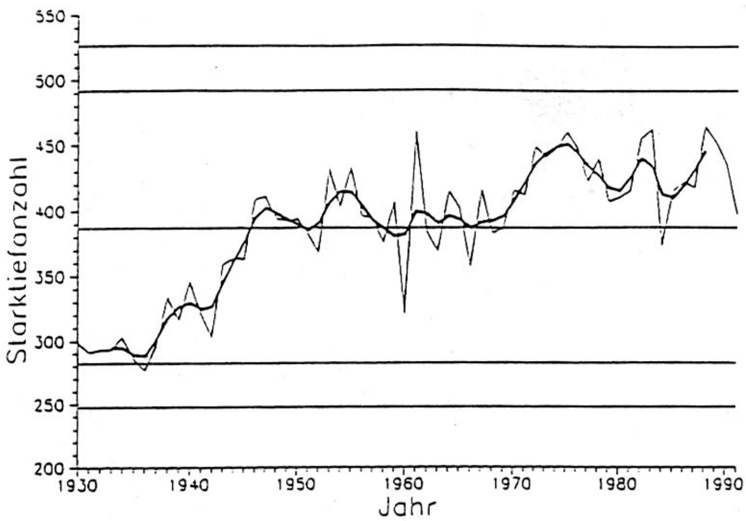
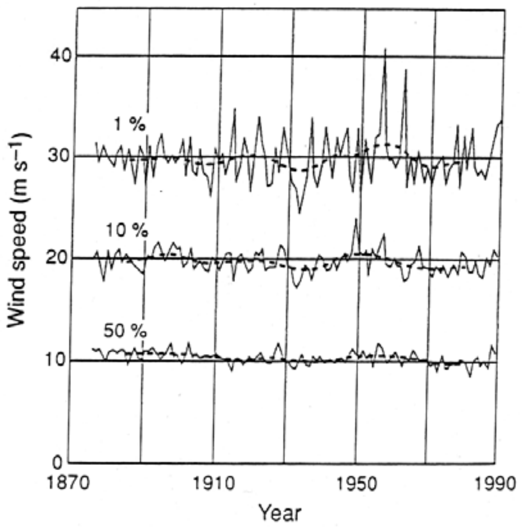


Figure 4.18b

Time series of 1, 10 and 50% exceedence percentiles derived from annual distributions of daily geostrophic windspeeds in the German Bight[12]



Astronomically predicted tidal water levels around the UK coastline differ from recorded water levels as a result of meteorological influences. The suction created by low atmospheric pressure and the effect of long duration, unidirectional high wind stress causes actual water levels to exceed predicted levels during storm surge events. Such events can therefore be seen as residuals from expected tidal heights on a tide-by-tide basis. Distributions of surge elevations in what might be termed 'fairweather' conditions are normally distributed, whereas years of extreme surge activity are typically positively-skewed (Figure 4.19).

Extreme surge activity - the number of days in a year in which at least one hourly surge value exceeded the highest 1% value of all surges on the record - is shown for Newlyn, Cornwall, in Figure 4.20. These statistics, when allied to extreme tide elevations, can be used to identify variations in the annual frequency of extreme flooding events (Figure 4.21). Particularly interesting is the Orford *et al.* (1996)[16] construction of the temporal variability of surge generation (Figure 4.22). The five-year moving average identifies reduced surge activity in the mid-1930s and the late 1950s. Turning positions are identified as 1931 and 1970, suggesting the possibility of a decreasing surge potential in the 1980s and 1990s.

Figure 4.19

Surge distribution in fairweather and cyclone active years[16]

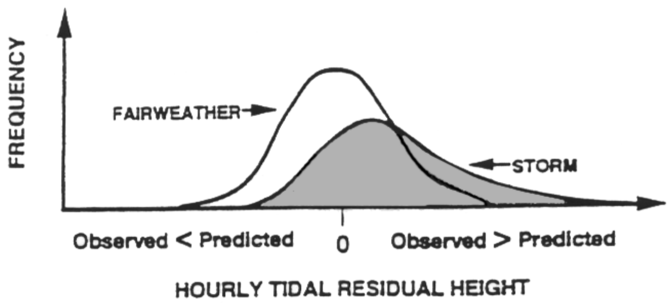


Figure 4.20

Variation in annual frequency of extreme surges (<1%) at Newlyn, Cornwall, 1912-1992. Includes a 5-year running mean[16]

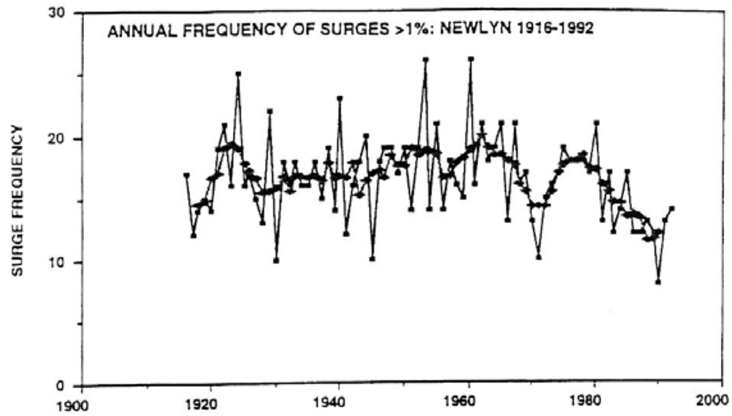


Figure 4.21

Variation in annual joint occurrence of extreme tidal elevation surge levels at Newlyn, Cornwall, 1912-1992. Includes 5-year running mean[16]

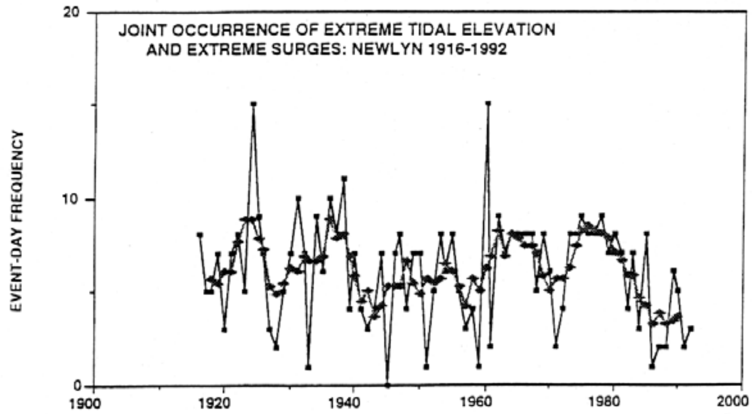
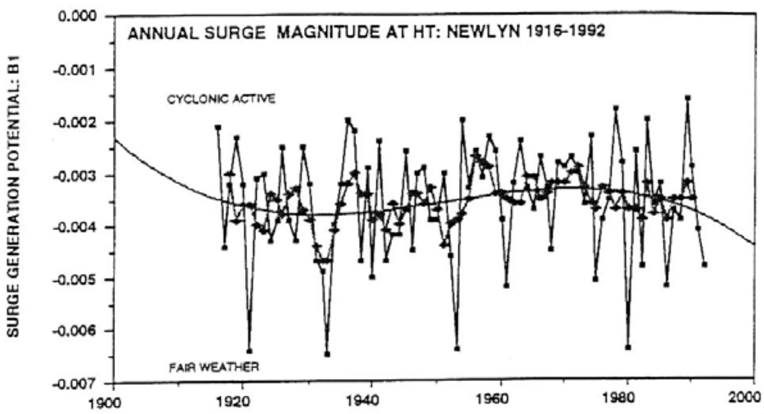


Figure 4.22

Variation in annual surge generation at high tide, Newlyn, Cornwall, 1916-1992. Includes 5-year running mean[16]



As the effect of wind stress is inversely proportional to water depth, these effects are particularly pronounced on the margins of shallow shelf seas like the North Sea. Thus standard deviations of non-meteorological residuals are high at southern North Sea stations (e.g. Southend, Essex: 0.23 m) compared to Atlantic coasts stations (e.g. Newlyn, Cornwall: 0.15 m). As long time series of water level data are available from North Shields (77 complete years), Southend (44 years) and Sheerness (51 years)[17], this form of analysis might be profitably applied to tide gauge datasets from the southern North Sea.

In the North Sea, storm surges are either forced by the passage of extratropical storms across the northern entrance ('external surges') or result from the passage of strong cyclonic systems across the North Sea itself ('internal surges'). Surge elevations with 50-year return periods range from +0.7 m in the northern North Sea to +4.0 m in the German Bight[5,18]. In January 1953, January 1978 and January 1995, water levels typically exceeded predicted tidal levels by 2.4 m, 1.6 m and 1.4 m respectively. Analysis of observed tidal records shows that surge events are common during the winter months in the southern North Sea. Thus, for example over a 4.5 month period during the 1994/1995 winter 18 surge events of 0.5 m or more were recorded at Thornham, North Norfolk. It is, however, the large events which exceed the level of the Highest Astronomical Tide (e.g. 4.0m O.D. at Brancaster, North Norfolk) and which threaten coastal defence lines which attract attention. Suthons (1963)[19] lists the occurrence of 15 storm surges on the east and south coasts since 1883. There is also some suggestion that the frequency of surges has been increasing. Thus at King's Lynn, R. Jenkins (in Steers *et al.*,[20]) has shown from an analysis of annual tidal maxima since 1860 that there were five years in which tides exceeded 4.98 m O.D. in the period 1860-1948 (89 years) and six in the period 1949-1978 (30 years). By way of illustration, Table 4.12 gives a selective record of storm surge heights for which detailed height information is known on the North Norfolk coast between 1897 and 1996. In addition, major North Sea surges are known to have occurred in July 1817 and on 8 January 1949, 20-21 March 1961, 15-17 February 1962 and 19 February 1969.

Maximum levels of inundation have increased over the last 190 years as a result of the long-term geological subsidence of S.E. England (Figure 4.23)[21]. Over the last 8750 years, the rate of submergence has been 0.76 +/- 0.16mm per year, with mean rates in the Thames estuary varying between 0.83 and 1.42mm a-1 over the last 7500 years[22]. Records of sea level rise during this century are reported in Table 4.13. Global warming is expected to add an additional eustatic sea level rise term to these long-term trends and it has been argued that this increase might be particularly significant in the North Atlantic. However, a composite 'relative sea level index' has shown no century-scale acceleration in Mean Sea Level (Figure 4.24). This is in line with earlier predictions that a sea level acceleration might not be detected until 2010 (Figure 4.25)[23]. As sea level rise estimates have been revised downwards in recent years (Figure 4.26), then this 'early warning' might not be detected until even further into the twenty first century.

Figure 4.23

Storm surge levels at London Bridge 1780-1970 and defence levels prior to construction of the Thames Barrier[21]

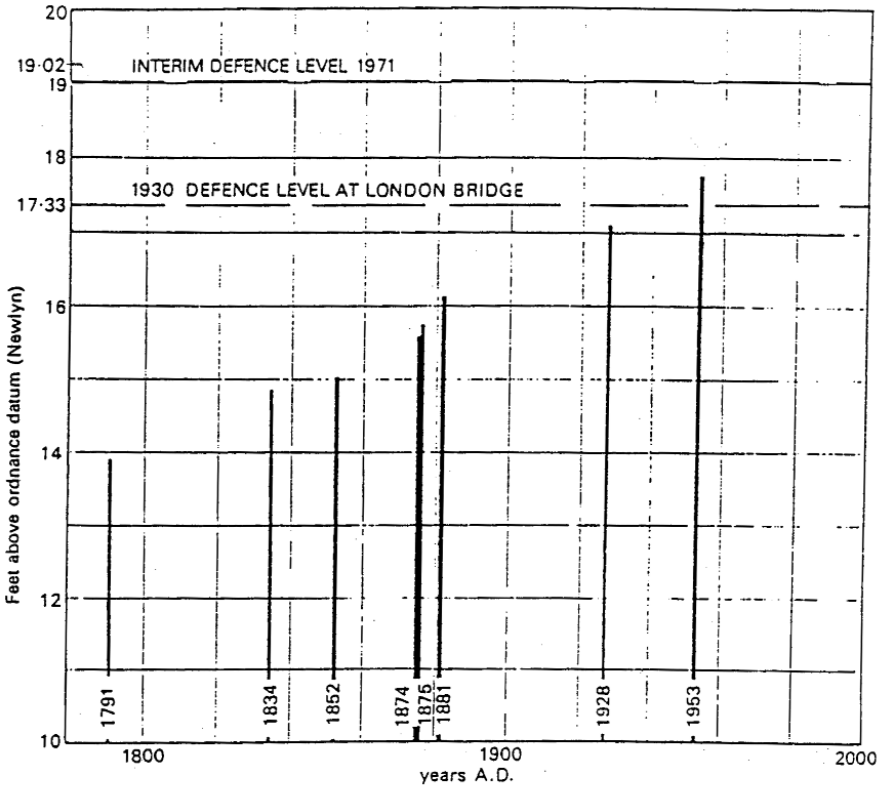


Figure 4.24

Detrended, composite sea level index for the twentieth century computed from Mean Sea Level data from 5 stations (Aberdeen, North Shields, Sheerness, Newlyn and Liverpool)[23]

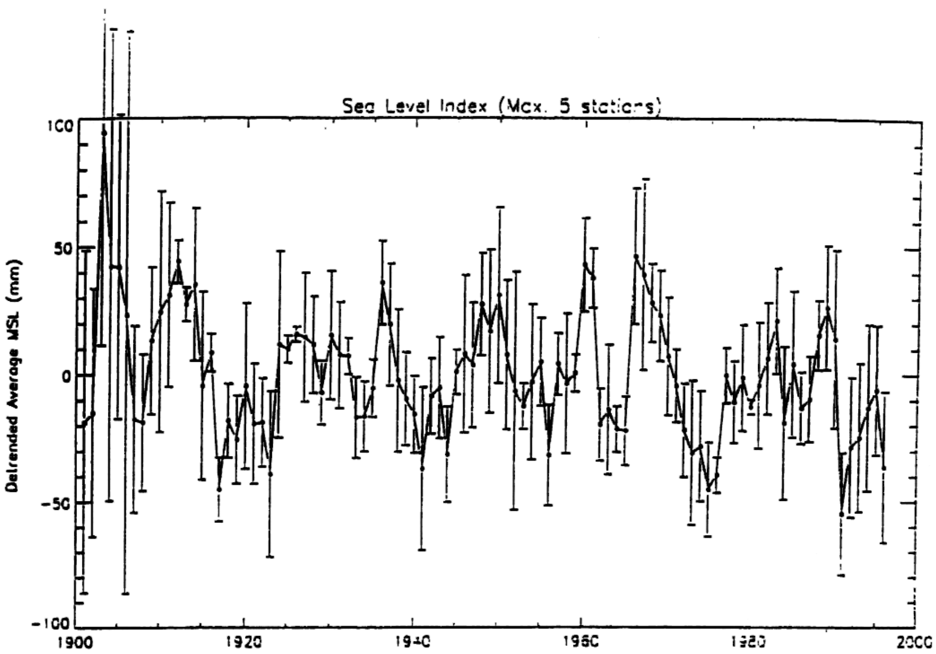


Figure 4.25

Simulated mean sea level time series based on perceived rates of near-future sea-level rise in the second half of the 1980s. Dotted line describes linear trend of 1.72 mm a^{-1} [23]

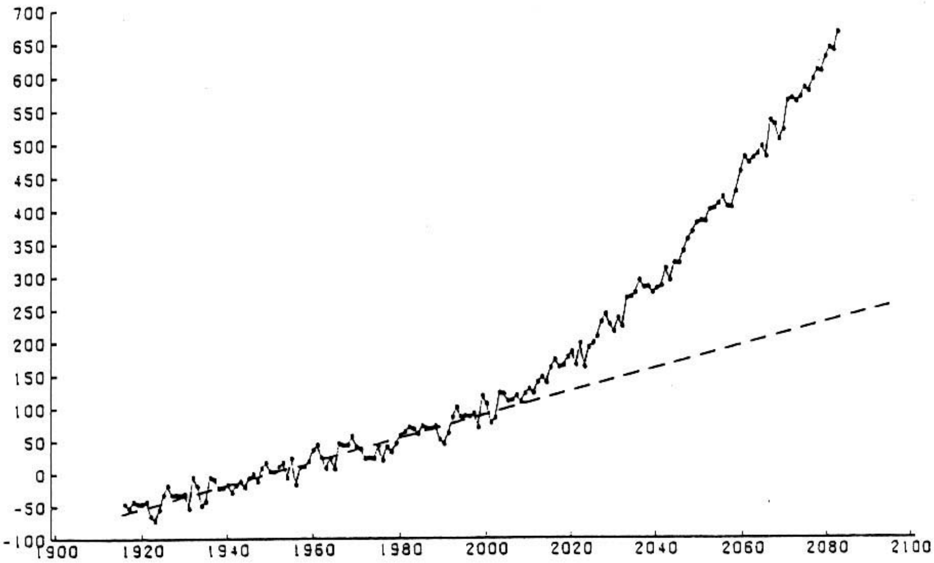


Figure 4.26

A history of sea level change predictions[38]

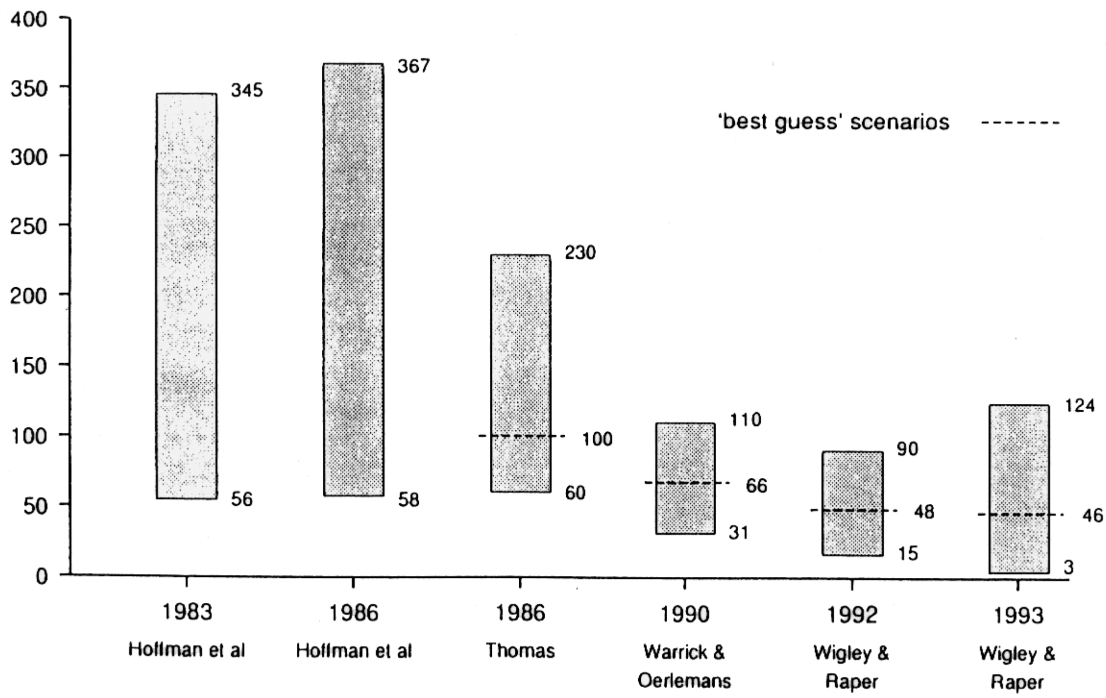


Table 4.12 Storm surges on the North Norfolk coast from published records and field surveys (compliled by the Cambridge Coastal Research Unit)

Location	Recorded water levels (m above Ordnance Datum)								
	1897	1912	1953	1969	1976	1978	1990	1993	1995
Blakeney	4.96		4.88–4.27						
Blakeney Quay			6.07			4.90			4.66
Stiffkey		4.66	4.57			5.55			4.45
Wells			5.13	4.27	4.55–4.66	4.91			
Burnham Overy			5.49			5.51	4.67–4.10		4.54
Burnham Deepdale				4.43	4.35	4.62	4.55–4.37		4.55
Scolt Head Island			5.37			5.22–4.71		4.45	4.61

Table 4.13 Historical trends in Mean Sea Level (MSL) in the British Isles[17]

PSMSL country station code	GLOSS code	No. of complete years of RLR data	First-last year in RLR data-span	Measured trend and standard error on the trend (mm yr $^{-1}$)	Standard deviation of the annual mean values about the fitted linear trend (mm)	Station name
170/001	236	35	1957–1996	-1.09 ± 0.40	27.9	Lerwick
170/005		25	1965–1994	0.76 ± 0.75	33.3	Wick
170/011		48	1932–1996	0.67 ± 0.20	25.9	Aberdeen I
170/012		64	1901–1965	0.93 ± 0.18	27.4	Aberdeen II
170/027		27	1964–1993	1.99 ± 0.92	41.1	Rosyth
170/041		37	1914–1950	0.47 ± 0.31	20.5	Dunbar
170/053		77	1901–1996	1.86 ± 0.15	33.5	North Shields
170/061		33	1960–1995	1.11 ± 0.52	31.2	Immingham
170/068		36	1956–1995	1.81 ± 0.48	32.5	Lowestoft
170/081		44	1933–1983	1.22 ± 0.24	24.1	Southend
170/083		22	1961–1983	1.58 ± 0.91	28.5	Tilbury
170/101		51	1901–1996	2.14 ± 0.15	34.5	Sheerness
170/111		27	1961–1993	1.94 ± 0.50	25.3	Dover
170/131		28	1962–1996	1.45 ± 0.60	32.0	Portsmouth
170/157		30	1962–1996	3.04 ± 1.01	57.1	Devonport
170/161	241	80	1916–1996	1.69 ± 0.12	25.6	Newlyn
170/191		42	1938–1996	2.12 ± 0.45	45.1	Holyhead
170/211		19	1959–1983	2.58 ± 0.88	28.8	Liverpool Princes Pier
170/225		24	1962–1996	1.04 ± 0.62	33.5	Heysham
170/231		31	1938–1977	0.26 ± 0.70	39.6	Douglas
170/236		25	1968–1995	0.91 ± 0.61	24.7	Portpatrick
170/272		45	1918–1963	-0.25 ± 0.34	30.5	Belfast 2
175/011	239	26	1959–1994	-0.58 ± 0.68	34.8	Malin Head
175/071		58	1938–1996	0.23 ± 0.30	38.3	Dublin

4.6.6 Coastal management issues

Current responsibility for the maintenance of sea defences

In England, the responsibility for flood and coastal defence policy lies with the Ministry of Agriculture, Fisheries and Food (MAFF). This includes the administration of legislation, which enables flood and coastal defence works to be carried out. The legislative framework is based on the Coast Protection Act of 1949, the Land Drainage Acts of 1991 and 1994, and the Environment Act of 1995. The Coast Protection Act was created for the protection of the coastline against erosion from the sea, whilst the Lane Drainage Acts, the Water Resources Act and the Environment Act provide the political framework for flood defence. MAFF provides national strategic guidance and specialist help supported by a comprehensive research and development programme[24]. A variety of authorities have powers for the implementation of flood and coastal defence policy and the construction of defence works. These include local authorities, Internal Drainage Boards, private landowners, and the Environment Agency. The Environment Agency has a supervisory role for all aspects of flood defence in England and Wales, including flooding from the sea. The Agency also has permissive powers for establishing and maintaining sea defence works and flood defence works on watercourses designated as main rivers. The work of the Agency is discharged through a national network of Regional and Local Flood Defence Committees. Over 240 organisations have been involved in the administration, financing and delivery in the coastal zone[24]. Whilst individual flood and coastal defence works are designed, constructed and maintained by local operating authorities, MAFF may provide a substantial contribution to the funding of capital defence works undertaken by the Environment Agency, local authorities or drainage boards.

According to the Agricultural Select Committee report on Flood and Coastal Defence[25], there are significant gaps in the delivery of national policy priorities at the local level. This is due to the disparate legislative framework for flood and coastal defence activities, and the patchy and inadequate coordination between operating authorities. This problem is now being addressed through coastal groups and the development of shoreline management plans. Such changes in the organisation of responsibilities will need to be taken into account in future coastal flooding risk analyses.

The nature and the current state of the sea defences

Due to the varied nature of the East Anglian coastline and the division of coastal protection and flood defence responsibilities, there exists a wide range of sea defence solutions. Over one-fifth of the region between the Humber and the Thames is below flood risk level[26]. Approximately 1500 km of defences protect the region from tidal flooding. In agricultural and sparsely populated areas of South Humberside, Lincolnshire and parts of Norfolk and Suffolk, flood protection is generally provided by earth and stone banks, some of which have some form of seaward slope protection[27]. In low-lying, more populated areas with appreciable wave action, the sea defences include concrete stepwork or concrete slabs on the seaward side of the bank, topped by a splash wall, which, by wave reflection, reduces overtopping of the structure. The Wash defences consist of banks fronted by extensive saltings, which under most conditions act to break the waves long before they reach the structure. Reinforced concrete sea walls and associated groyne systems protect urban areas. Most cliffed sections of the coast where there is development are protected with sea walls and revetments. In some cases flood protection is provided by the maintenance or enhancement of natural features, such as the profiling of the shingle bank at Blakeney in Norfolk. Beach nourishment has also been done in several places along the East Coast. Most recently, shore-parallel breakwaters have been constructed near Sea Palling and Caister in Norfolk.

The risk of flood damage to property, infrastructure, and human health will depend to a large extent on the state of the sea defence systems in any given location. While major reinforcement and extension of the sea defence infrastructure was undertaken along the East Coast after the devastating floods of 1953[26], many of these defences are reaching the end of their design life. In many parts of the East Coast, the defences are becoming increasingly vulnerable to wave damage due to a lowering of fronting beaches. Estuarine embankments have often been built of indigenous materials not suitable for sea walls, such a peat, silt and weakly structured clays[27]. A further problem with the construction of banks is the unconsolidated strata underlying the structures. Settlement is another common problem, leading to fissuring and attrition on the side facing the water[27]. The national Sea Defence 1995 Survey Update, dealing with the condition of sea defences, [24] revealed that in the Anglian Region, 36.3% (Phase 1; NRA maintained defences); 41.9% (Phase 2); Local Authority maintained defences); and just 3.4% (Phase 3); privately owned defence) sea defences were in good condition. The survey also showed that 12.2% (Phase 1) and 64.9% (Phase 3) sea defences in the Anglian region were in poor condition (i.e. that moderate work and maintenance is required to return the defences to a good condition as originally built). A flood risk assessment that takes into account the state of the sea defences is now urgently needed and is necessary if the health risk from future storm surges is to be determined.

Present and likely future shoreline management planning approaches

Flood defence works carried out by the Environment Agency are funded by central taxation revenues through a combination of Capital Grants and Revenue Support Grants (through local councils). All coastal defence schemes have to be justified by cost-benefit analysis. Due to ever increasing demands from local authorities for grant-in-aid, a priority scoring system for sea defence schemes was introduced in April 1998[25]. Every project proposal is screened against national criteria to determine the order of priority in which eligible projects will be funded by MAFF. The scoring procedure is made on the basis of the priority, urgency and economics of the scheme proposed. In keeping with MAFF's national strategic aim, projects based on flood warning, the provision of urban coastal defences, and urban flood defences are given greatest priority. This system has been heavily criticised because it is extremely difficult for any rural scheme to qualify for funding. Sites of international environmental significance were given added weight under the revised priority scoring system in 1999. The Select Committee[25] found that at present there seems to be a shortage of finance for all but the most urgent of works and that operating authorities could maintain vital local flood and coastal defence programmes only with major difficulty. The Environment Agency has estimated that £1.3 billion will need to be spent on renovating sea and flood defence capital works over the next 10 years - this equates approximately to the current rate of spending. As a consequence of the downward movement of the East Anglian region relative to the UK land mass as a whole and the sea level rise caused by global warming, a relative sea level rise of 6mm per year is taken into account in the crest heights of flood defences when they are renewed or replaced.

While such upgrading of sea defences will have to be carried out in urban areas, alternative approaches are being sought for agricultural coastal areas. Greater priority has recently been given to so-called soft engineering approaches to flood and coastal defence. The mitigation of erosion and flooding is achieved through increased reliance on natural features, such as beaches, mudflats and flood plains. It has been recognised that the traditional hard engineering approach, based on substantial human intervention in the natural processes, often had adverse effects on the adjoining coastline, or on the site intended for protection itself, due to lack of understanding of the sediment transport mechanisms prevailing in the area. Soft engineering can replace reliance on the existing ageing system of hard defences, but in most cases it is used to provide protection to the defences already in place. For example, on the Lincolnshire coast MAFF is investing approximately £120 million over a 40-year period in the UK's largest beach nourishment project[25]. One of the most significant changes in coastal engineering in the last few years has been the introduction of offshore breakwaters. The use of offshore breakwaters is considered a soft engineering approach because the structures influence the wave-induced circulation near the coastline and encourage the accumulation of beach material. Whilst breakwaters have been successfully used in shoreline stabilisation efforts, particularly in the USA, Japan and the Middle East, the work at Bognor Regis[28] and Sea Palling[29] indicates that the effect of these structures on the beach morphology is not currently fully understood for locations with the large tidal range and strong long-store drift typical of much of the UK coastline. Further research is being carried out to establish design guidelines for UK schemes.

Since 1995, shoreline management practices in England and Wales have been guided by Shoreline Management Plans (SMPs) to provide a more comprehensive and integrated approach to managing the cost[24]. The primary aim of the SMP is to provide the framework for the development of sustainable coastal defence policy for a particular stretch of coastline. SMPs are currently non-statutory and are the product of collaboration in coastal groups between maritime local authorities, statutory agencies and other organisations with coastal responsibilities. SMPs have been produced for the entire English and Welsh coastlines and include environmental and other non-market considerations in order to achieve environmentally sustainable solutions. As well as taking account of local economic and development planning needs, the guidance offered in SMPs is based on processes occurring in coastal cells along the relevant section of coast. A recent review of the East Anglian SMPs[30], however, has revealed that there is still a substantial lack of knowledge regarding these processes and the way in which they interact with sea defence measures. Although the coastal cells on which these plans are based are assumed to be discrete natural units within which sand and shingle-sized sediment is retained, detailed information on sediment transport pathways, particularly of fine sediments, within or between the cells, is often lacking. To provide an adequate assessment of the risk of coastal flooding, and thus the risk of flooding to human health, it is necessary to qualify and, if possible, quantify the uncertainty introduced by this lack of information.

The three main options for shoreline management identified in the SMPs, are 'managed retreat', 'accommodation', and 'hold the line'. These options are currently being reassessed for the second round of plans.

Assessment of past, present, and possible future adaptation strategies

As mentioned above, coastal defence and management policy and responsibilities are changing and such changes need to be incorporated in any coastal flood risk assessment. O'Riordan and Ward[6] presented arguments in favour of a more participatory and mediated approach to consultation and decision-making. In their opinion, a more integrated approach to shoreline management will facilitate a workable consensus amongst the stakeholders and create an outcome which will be continually reassessed.

Traditionally, there was a widespread perception that we have a duty to prevent land loss. This perception is slowly changing because of increased agricultural productivity per hectare and a lessened need for domestic agricultural self-sufficiency[24]. These factors might in future be acknowledged in the implementation of local responses to flood defence and coastal protection of agricultural land, including the managed realignment of the coastline. Such changes in perception would, in turn, have important effects on the risk of coastal flooding. At present the managed abandonment of coastal areas, which are untenable in the long-term, is controversial because there is no financial mechanism for the reimbursement of property holders and landowners whose assets are sacrificed for the wider benefit of the community. Long-term adaptive policies that encourage managed retreat will have to be formulated. The Select Committee recommended that, in future, The Environment Agency should have powers to deter inappropriate development in flood plain land or require developers to set aside sufficient funds for the provision of flood defence works before planning permission is granted.

4.6.7 Vulnerability

Population at risk

The popularity of coastal districts has resulted in the steady increase in their populations at a time when the population of the country as a whole is relatively static. In 1995 the population of England and Wales was 51.8 million and it is projected to grow by 5% over the 40 year period to 2031. The number of people living within 10 km of the coast in England and Wales is about 16.9 million, or about a third of the population. Roughly 11.5 million people are estimated to live within 1 km of an estuary in Great Britain. East Anglia as a whole, and its coastal districts in particular, have been growing in population continuously since the 1951 census at a rate much faster than the national population. Table 4.14 shows the population changes between 1951 and 1991 in the seven most populous coastal districts in East Anglia (excluding the one manufacturing city, Ipswich), and the UK as a whole, confirming this trend over most of the coastal region.

Table 4.14 Population changes 1951 to 1991: UK and coastal districts

District	1951	1961	1971	1981	1991	% increase 1951-1991
UK ($\times 10^6$)	48.9	51.3	54.0	54.1	54.8	12
Great Yarmouth ($\times 10^3$)	68.9	72.6	75.7	80.8	87.7	27.2
North Norfolk	77.3	73.8	74.2	82.0	90.4	16.9
Broadland	55.3	65.9	86.5	98.3	106.2	92
Suffolk coastal	74.5	82.9	89.1	95.2	107.8	44.7
Waveney	74.6	77.8	90.6	99.2	106.6	42.8
Colchester	85.5	93.8	118.1	133.7	142.4	66.5
Maldon	28.6	31.0	40.5	47.7	52.7	84.2

It can be seen that in many parts of East Anglia the increase in population in coastal areas has been substantial. It is not evident that this has been strongly guided by considerations of flood risk and the insurance industry (D Crichton, *pers comm*) has observed, for example, that development goes ahead in about a third of cases where the Environment Agency has objected.

Building vulnerability

The vulnerability of buildings and their occupants to flood depends primarily on the height of the flood water in relation to the floor level of the house. Flood damage is worse if the water is fast flowing and if the flood water is sea water. Vulnerability estimates have been made for the UK building stock[31].

An important consideration affecting the likely number of casualties is that occupants of single-storey houses and mobile homes are much more likely to suffer loss and injury or death because they cannot escape or move their property to upper floors. Buildings built on piers to elevate them above expected flood water would be safer for the expected flood, but may be more vulnerable than conventionally founded buildings if higher flood waters occur. Census data unfortunately provide little information on building types. Estimates have been made by Cambridge Architectural Research Ltd based on regional data available on the distribution of building types in an English house condition survey (1991). This suggests that a proportion of more vulnerable building types - namely bungalows and mobile homes - in these coastal districts may be substantially greater than the average in the population as a whole. Regionally, East Anglia has 16.6% of bungalows in its urban dwelling stock compared with 6.9% for the south-east. It is not clear whether this proportion is changing with time or how far it applies to rural buildings also. In the East Coast floods in 1953, 65 deaths occurred when most of the bungalows between Hunstanton and King's Lynn were swept away[2].

Sea coast defences

Although sea defences have been improved since 1953, sea-level rise and the expected greater frequency and severity of wind storms resulting from climate change will ensure that a high risk of catastrophic flooding remains in the coastal zone. In addition, many of the sea defences established after 1953 are now reaching the end of their design lives. Concern about the present flood and coastal defence infrastructure has been expressed by the House of Commons Select Committee on Agriculture in its Sixth Report (1998), which states[25]:

> *"… Flood and coastal defence policy cannot be sustained in the long-term if it continues to be founded on the practice of substantial human intervention in the natural processes of flooding and erosion. Indeed, it is of great concern to us that the legacy of flooding and erosional problems arising from this practice - and the likely increase in future of climatological and other environmental pressures on the UK's ageing flood and coastal defence infrastructure - might combine to present flood and coastal defence authorities with insuperable difficulties."*

Many of the ageing defences are being replace using alternative, 'soft', engineering schemes (for example, beach re-charge or managed re-alignment). Very little is known about how these changes in coastal management affect natural processes in the coastal zone and thus how they affect the characteristics of possible future extreme flooding events.

The Environment Agency[3] designs coastal defences to protect against a storm with a specified risk of recurrence, which is cost-effective and commensurate with current land use. Generally, there is greater protection for urban areas than rural areas (Table 4.15).

Table 4.15 Indicative standards of protection against tidal flooding for grant-aided schemes[32]

Current land use	Return period (years)	Annual probability of failure
High density urban containing significant amount of both residential and non-residential property	100–300	0.3%–1%
Medium-density urban. Lower density than above, may also include some agricultural land	50–200	0.5%–2%
Low-density or rural communities with limited number of properties at risk. Highly productive agricultural land	10–100	1%–10%
General arable farming with isolated properties. Medium productivity agricultural land	2.5–20	5%–40%
Predominantly extensive grass with very few properties at risk. Low productivity agricultural land	<5	>20%

It can be seen from Table 4.15 that maximum protection is afforded by defences anticipated to resist a flood with a return period of 300 years although provision is made for the consideration of higher standards where appropriate. The 1953 flood was estimated to be a 1 in 500 year event (as can be best determined) and it would be important to ascertain what would happen to these defences in a return 1953 event. In 1976 very similar sea levels recurred but there was no flood. The defences held, confirming the engineers' belief in the security provided by the defences. Decision-making processes, including cost-benefit analysis, may lead to the establishment of standards that may be more or less demanding than the indicative standards of protection shown in Table 4.5. Risks to life are not routinely included in the assessment on the grounds that flood warning systems should provide protection. In the Netherlands, where 60% of the national wealth depends on defences against inundation, risks to life are taken into account.

A special example in the UK is the Thames Barrier, owned and maintained by the Environment Agency, which was completed in 1982 at a cost of £600 million. It costs £4 million a year to operate and protects over a million housing equivalents. It was designed to contain a 1 in 1000-year flood event. The barrier has been closed 30 times in the 15 years from 1982 to 1997. The barrier is closed whenever sea levels are forecast to rise to within 450 mm of defences in central London. With current projections of sea-level rise, forecasts show that there will be ten barrier closures per year by the early part of this century and with current operating rules this could increase to 325 barrier closures per year by 2100[3] . Estimated probabilities of flooding in east London from a failure of the Thames Barrier are regarded as 'tolerable' when the risks of between 100 and 1000 casualties is less than 1 in 1000[33]. Individual risk for people living in the likely area of inundation is less than 1 in a million. The consequences to human health of a 1 in 1000-year flood overwhelming coastal defences do not appear to have been calculated.

Infrastructure

Studies of flood and storm surge casualties in other countries indicate that the failure of power, the performance of the transportation infrastructure, and the maintenance of relief and rescue facilities are critical to minimising casualties and dealing with injuries. For the most at-risk coastal locations, detailed studies are needed of the infrastructure (roads, railways, airports, power transmission, telecommunications) and its propensity to be damaged, of the risk to emergency services (fire brigade, ambulance, A & E departments in hospitals, police) and their location and viability, and the existence of places of safety within each local community. It is not generally appreciated that the east coast floods in 1953 occurred against a backdrop of post-war Britain, when there were 500,000 servicemen available for rescue work, together with military logistic tools such as landing craft, which were immediately put into the disaster response and would have undoubtedly made a large impact on the rescue capability of that time. None of this would be available in the present day and it is not evident that the emergency services have drawn up emergency plans for responding to a catastrophic coastal flood. Current initiatives by the Environment Agency are encouraging the development of such emergency plans by all potentially affected local authorities.

Forecasts and warnings

Coastal high water levels are predicted by a model used by the Met Office in Bracknell, which has been constantly updated since it was first devised following the floods in 1953. The predictions for East Anglia are normally very good and well validated to within 10-20 mm. The model was devised and is updated by the Proudman Oceanographic Laboratory. The Environment Agency has for the last three years been the central government body responsible for issuing warnings based upon its use. The Agency goes into flood warning mode from September to May, when wide-scale forecasting is performed every 6 hours. The model can also be used to model synthetic sea levels for exceedence levels for sea coast defences. The model does not take into account changes in sea level and increases in storminess caused by climate change. Local models exist, for example for the Thames Barrier, which include river flows. Commensurate with developments in forecasts and warnings would be the designation of risk zones for populations depending upon their susceptibility to flooding - the hazard maps on which such zones could be drawn by the Environment Agency will soon be available to the public.

Community preparedness

The extent to which most communities at risk are aware of the flooding hazard (through for example, warning sources such as radio or TV), and are knowledgeable about evacuation measures is limited. The Environment Agency launched a new awareness campaign in October 1999. A special study would be needed for the risk assessment on the details of operation of the warning system, including lead times and criteria for evacuation of areas at risk. Details of flood warning plans for each area are available from the Environment Agency.

4.6.8 Human health consequences of floods

Floods and health

The impact of a coastal flooding event will depend upon the behaviour of the flow of water, its velocity and depth. In addition, wintry weather will greatly increase the risk of deaths from exposure. After the East Coast floods there was a reported increase in mortality in the flooded community in the three months and the year after the flood[1,2]. In the Netherlands flood of 1 February 1953, resulting from the breach of a polder, extensive areas of the country were affected and 1795 people died, mainly by drowning. Six medical problems were identified after the flood:

- ❏ identifying and recovering corpses;
- ❏ evacuating the sick and old;
- ❏ providing physicians with routine supplies;
- ❏ setting up emergency hospitals to take care of the evacuated;
- ❏ restoring hygienic services (food, water, sanitation); and
- ❏ taking measures to fight epidemics.

It was explicitly stated that the injured, as a group, did not represent a medical problem. The age and sex specific mortality of those killed in the flood was estimated and a three- to four-fold greater risk of death in the elderly was found[34,35].

In the Bristol, England, flood on 10/11 July 1968, 13 cm of rain fell on the city of Bristol between 5 am and 5 pm. About 3000 houses, shops and other buildings were flooded. The peak of the rainfall coincided with a high spring tide, which blocked the outflow into the river Avon. The water level reached no higher than the ceilings of the ground floor and subsided in most cases after about 10 hours. One man was drowned in the flood. Of great interest is the effect this event appears to have had on subsequent mortality and morbidity[34,35]. In the 12-month period after the flood the surgery attendance of the flooded population for whom records were available increased by 53% (males 81%, females 25%), although the total number of people attending did not change substantially - the non-flooded group showed a slight fall in attendance. The difference between the attendance of flooded and non-flooded men was statistically significant, as was the difference in attendance within the flooded group for the period before and after the flood. The increase in attendance by women was not significant. Hospital referrals from the flooded group more than doubled during the year after the flood. This was again accounted for mainly by men. Hospital admissions showed the same trend. The reasons for illness were non-specific and no diagnosis suggested any direct physical relationship with the flood.

Mortality rates were also calculated for all homes in the city and in the county of Bristol which had been flooded, as well as those which had not been flooded. Surprisingly, mortality in the flooded group increased by 50%, mainly in the three-month period after the flood. The most pronounced rise was in the age group 45-64, for both male and female deaths, otherwise the increases were predominantly amongst those over 65, especially women over age 75. For the rest of non-flooded Bristol deaths fell by 1%. Again no specific cause of death could be linked to the flooding and the increase was provisionally explained in terms of the psychological effects of the flooding. A similar pattern to mortality was observed in Canvey Island after the floods in 1953[2,3]. Remarkably, this type of analysis does not appear to have been repeated in subsequent flood events.

On a world scale, floods present a major natural hazard[34,36]. For example, in flood-prone Bangladesh, approximately 15 000 people are killed each year on average due to flood disasters. Among all natural disasters in the USA, floods are the main cause of death. Two thirds of the 6000 disastrous events on record in the 1990s relate to floods and flood-generating storms. In the USA, with more than 20 000 cities and communities subject to flash flooding alone, the average annual loss of life due to floods has been estimated at between 48 and 146 deaths. Notable floods occur in the People's Republic of China where more than 40 million inhabitants are estimated to be affected yearly by flood. Malilay[37] has reviewed the literature, which shows continuing differential levels of mortality associated with individual flood events in various areas of the world, and more investigation is needed of the factors that contribute to flood-related deaths, illnesses and injuries. Surprisingly little information has been gathered that provides the level of insight given by the studies of the East Coast flood in 1953 and the Bristol flood in 1968. In most events, however, the spectre of major epidemics of infectious diseases due to disruption of water purification and waste-water disposal systems does not appear to be realised through increases in endemic diseases such as malaria and cholera in tropical areas. Large numbers of casualties with multiple injuries also do not seem to be a major problem. Releases of toxic substances in floods from hazardous chemical sites is a potential hazard. The mental health effects of flood disasters have been studied, but more work on the long-term impacts on morbidity and mortality are warranted.

In summary, the main anticipated impact on humans of an East Coast flood would be deaths by drowning, followed by deaths from exposure, which would occur in the phase of the disaster striking. Some deaths would arise subsequently from delays in search and rescue, which would be inevitable with a large part of the country under water. Large numbers of injured requiring rapid transfer do not appear to be an issue for the emergency services, though this may be a false impression created by the delays in rescue in severe flooding events when access to survivors in the first few hours after the event is impossible (so trauma victims die from lack of urgent attention). Clearly, the time of day would be very important in terms of both the size of impact and access to survivors (flooding at night is much more hazardous). Further increases in mortality and morbidity amongst survivors would occur in those who require regular primary care treatment, such as access to insulin in diabetes sufferers, and other key maintenance medication in the chronic sick. For this sub-group of the population, including the elderly, expeditious removal from flooded areas to safe havens would be important. Provision of food and potable water and first aid to those large numbers of people trapped in the flooded area, but otherwise unharmed, would be an immediate need in the post-impact phase. Acute and longer-term mental health issues amongst survivors would need to be addressed, as after other major disasters. The long-term impacts on morbidity and mortality as revealed by the Bristol flood study and the reporting after the East Coast floods in 1953 show that illness and deaths may rise in non-specific ways. A 'culling' effect may be happening here, i.e. a hastening of death in those predisposed to die by underlying illness.

Risk scenarios

Hazard maps for coastal flooding are being used to produce risk maps delineating the population at risk. Refined versions of risks maps should utilise the hazard areas of flood impact, and should include zones of graduated risk of death and injury.

$$\text{Risk} = \text{hazard (probability of event)} \times \text{value} \times \text{vulnerability}$$

'Value' in this equation could be the number of people at risk, with 'vulnerability' as the proportion of the population at risk, or most exposed, for a variety of reasons, to the flood impact (Section 4.6.7). Establishing risk requires first of all an understanding of the most foreseeable flood scenarios. Some work on this is now in progress in the Environment Agency, with the aim of providing a standardised approach across the country. The worst scenario would be a flood in the absence of any coastal defences and the Agency has performed a mapping exercise based on how far the water would travel until the sea level equated with the land level. These so-called Indicative Flood Plain Maps have now been generally released. The maps will be essential for estimating the total population at risk for disaster planning purposes. For assessing the risk in a reasonably foreseeable flooding event a study of a dam break analogue with modelling of the consequent gravity current of water would be needed.

A reasonably foreseeable scenario for East Coast floods would be the breach of a section of the coastal defences, or possibly a small number of breaches, during a storm/tide event comparable to 1953. A breach could be for example, 50 m or 100 m wide, taking three days or 10 days respectively to repair. From the Humber to the Wash and around the Norfolk and Suffolk coasts the population is dependent upon a wall of sea defences of variable strength: a failure in an extreme weather event could lead to even a small breach which could have devastating consequences. The development of a flood scenario under these circumstances is possibly politically difficult for the Environment Agency and here research by independent workers would be invaluable in order to increase our understanding of the impacts such an event would have on settlements and human health.

4.6.9 Mitigation measures

A key factor in any analysis of risk is the extent to which society may take steps to protect itself against the impact of climate change. The implications of these for risk also need to be studied in depth. Specific areas for mitigation strategies are described below.

Forecasts and warnings

Forecasts and warnings of flood hazard to the population have been the responsibility of the Environment Agency for the last three years. The Storm Tide Forecasting Service (Met Office) predicts height of tides, taking account of surge activity, and the Environment Agency determines, in accordance with pre-set criteria, the threshold of a combination of tide, wind speed and wind direction which if exceeded would trigger a six-hour warning before high water. Warnings go out through various routes and emergency services are put on alert. Flood wardens alert those in the areas they are designated to cover. The warning service is tailored to particular circumstances and the degree of risk - warning systems range from individual telephone alerts to general radio announcements. Only certain high-risk areas with relatively frequent flooding have siren warning systems. Many thousands of other people live in areas where they are probably quite unaware that they could be impacted by a major coastal flood. The current indicative flood plan areas are based on combinations of historical records, computer modelling and expert judgement.

The decision to evacuate settlements would be taken by the Police Technical Group, responsible for major incident planning in conjunction with county and borough councils. The understanding of the population for disaster planning, and the feasibility of the measures to evacuate people from areas of risk, needs to be further evaluated.

Engineering measures

The sea defences are a combination of hard (concrete) and soft (e.g. sand dunes) 'barriers' (see above). The Environment Agency has compiled a directory of sea defences and it is possible that some parts may fall short of the indicative criteria laid down for them. Strengthening of the weakened parts of the defences is an ongoing process. Predicting sudden failure does not appear easy and so predictions may not be routinely performed. Repairs of the sea defences do take into account sea-level rise. The engineering issues involved in raising defences to combat rising sea levels needs to be further explored in terms of overall safety and risk, as well as cost. DEFRA provides funds for approved capital works which, nevertheless, are a local responsibility.

Further work is needed on whether hardening of houses in some way in those areas most at risk would be beneficial. Bungalows and trailers or caravans would be most at risk in a flood, as mentioned above.

Land use planning

Already, local planning departments give consent to about a third of the developments against the advice of the Environment Agency. The population increase in coastal districts over the last five decades has been between 50-100% and the trend seems likely to continue. This demographic change would be a key factor in any risk assessment. In the future the insurance industry might play a key part by refusing to provide cover to developments not recommended by the Environment Agency.

Community preparedness

Providing adequate public information on the flood risk is overdue. The Environment Agency ran a public awareness campaign in October 1999 and this was repeated in 2000 and may help to improve matters, but to date planning for flood emergency has been low key. For example, the health sector has not been drawn into a comprehensive disaster planning process. Emergency planning needs to be at the national, regional and local level with agreement on the worst reasonably foreseeable scenarios, as well as others which can be prepared for. The Environment Agency is required to operate a programme of flooding incident exercises with other operating authorities. Undoubtedly much more work on the vulnerability of housing and the delineation of flood risk areas has been undertaken in the private sector, e.g. by insurance companies, than is available to researchers outside the industry.

Probabilities of extreme flooding events

Natural hazards such as sea surges are subject to non-linear behaviour, but a recent study of extreme event statistics has concluded that the forecasting is still best done by a combination of probability statistics and numerical modelling based on the monitoring of past events (Julian Hunt, *pers comm*). The Health and Safety Executive has used the Thames Barrier example in its publications on quantified risk assessment and tolerability of risk[33]. Individual and societal risks have been estimated using the annual probability of it being overcome by a tidal surge (1:1000), as defined by its designed failure rate, and the population at risk of inundation should it fail. We may use the indicative criterion for the sea defences in the same way, but they are not, for probability purposes, a single structure. Thus, the probability of inundation *anywhere* along the sea defences will depend upon how well-correlated the impacts of a single surge event will be (i.e., whether all or only parts of the coast will be affected by the same event), and so it is likely that the annual risk of a group of people being drowned as a result of a breach somewhere along the defences will be potentially higher than 1:200. An important additional consideration is the weakened state of the present defences as described above, which may add to the risk. A key question in any discussion of probability is what would happen in a very large event (greater than 1:1000 for the Thames Barrier, or the 1:1000 event breaching the sea defences), when the loss of life could possibly be very large indeed. An increase in storminess would make failure more likely, especially if the types of storms change, by increasing wave and surge heights and damage to defences in an extreme event. The 1 in 200 criterion (at best) seems inadequate, especially when the Thames Barrier is engineered to a 1 in 1000 year event, and further review of this figure and its basis is needed for risk assessment purposes. These considerations do not appear to have been well debated in the public domain, but are essential for exploring the human consequences of floods.

The potential for mitigation in such a flooding event is high through further development of the warning system and community preparedness. Timely evacuation would be the key measure to reduce risk, but it is not evident that a detailed risk assessment and an analysis of risk reduction measures has been undertaken. The Environment Agency is doing important work on disaster planning, but this is not yet in the public domain.

4.6.10 Risk assessment: Summary of the direct and indirect impacts on human health to be considered

A risk assessment would need to be based on a 1953-type flood model. It would need to incorporate mitigation measures and use scenario modelling of a sea surge and a flow of water following a sudden breach of the sea defences. One or more study areas could be chosen to evaluate the impact of flooding in different types of urban areas. The probability of such an extreme event along the East Coast is stated to be 1 in 100 to 1 in 200 years, but this return period could decrease by an order of magnitude with the prospect of rising sea level and increased storminess. The following impacts would need to be evaluated further.

❏ Impact phase. Death by drowning and exposure. Potentially hundreds to several thousands of people in the event of a breach, or several breaches, of the sea defence wall.

❏ Immediate post impact phase. Deaths of injured or sick and aged individuals unable to obtain first aid, or primary care or treatment in hospital during the 'golden hours'. Perhaps as many as 10% of the overall mortality figure.

❏ Recovery phase. Subsequent increase in morbidity (hospital referrals and hospital admissions) and non-specific mortality in the flooded group in the months after.

❏ Recovery phase and subsequent mental health sequelae. Mental health problems are likely to be significant in survivors of a major event, but only a small proportion are likely to be severely affected by post-traumatic stress disorder or anxiety/depression as a result of the incident. Non-specific psychological syndromes may appear, but are unpredictable.

❏ Other causes of ill health. The risk of infections arising from floods in the UK appears to be quite low. Other hazards include the threat of toxic substances entering the flood water and adding to the health impact. Multiple disasters, e.g. floods causing train derailment, plane crashes at airports, chemical releases from factories in the line of the flood, will need to be considered as part of an overall risk assessment.

4.6.11 Conclusions and recommendations

Coastal and river flooding present some of the most serious natural hazards that the UK faces. This chapter has focused on East Coast flooding risk, which is undoubtedly the most hazardous extreme type of flooding event. The effects of global warming are likely to make the return time of such an event shorter and its impact more destructive.

Any estimate of the impact of an extreme East Coast event on human health will depend upon a risk assessment being performed which will take into account the hazard (sea surge, waves and tide), the probability of forcing events and their return times, the vulnerability of sea defences and the efficacy of mitigation measures, as discussed above. The Environment Agency and the insurance industry have already done much work on these issues, but this does not appear to be in the public domain.

The social, structural, infrastructural, economic and human vulnerability to a catastrophic East Coast flood needs to be evaluated by an interdisciplinary modelling study of a sea defence failure and the flow of flood water into one or more representative urban areas, work which is still at the research stage.

This preliminary work on human consequences of coastal flooding has highlighted a serious natural hazard to a substantial proportion of the UK population, even in the absence of climate change effects. There is a need to review urgently the adequacy of the existing disaster reduction measures and bring the risk issues involved into the public domain.

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