# CHAPTER 336

## ASSESSING COASTAL FLOOD RISKS

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Abstract

The English and Welsh coasts of the United Kingdom are protected from coastal flooding (as opposed to coastal erosion) by some 1300km of defences, containing about 2000 defence structures. Using data from the sea defence survey of these structures and over 20 years of joint probability data on sea levels and waves, Halcrow assessed the failure risks and coastal flood risks for all these defences. The risks were examined for three Bands or return periods, namely 50 years, 100 years and over 200 years. This analysis included 50 years of relative rise in sea level (isostatic and eustatic changes). The modes of defence failure examined were from overflow, overtopping and toe failure. The results were supplied to the insurance industry, as maps and on disc, as 1km map squares giving the risk band, flood depth and the postal codes in the areas.

Flood risks were shown to be significant and even though reduced when more recent flood defence projects were included, they remain high. The impact of individual storms was later examined and obviously, while the risks were limited to specific areas and coasts, they were still significant. The insurance industry have used these results in order to assess their financial exposure to individual events and to their reinsurers.

Introduction

Potential coastal flood risks areas represent only about 3% of the area of England and Wales, but the value of their insured assets is much higher. Two major storm events in October 1987 and January 1990 sharpened the insurance companies and the "reinsurers" (who insure the insurance companies) concern about their exposure to

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weather and coastal flooding risks. No one wished to see another 1953 type disaster. Consequently, in 1992 the Association of British Insurers (ABI) asked Halcrow to categorise the flood risk from coastal storm events for the benefit of their 450 members

The ABI membership between them account for over 90% of the UK business. ABI's key objectives are to help insurance companies by representing their interests to Government, particularly on public policy issues; providing them with technical services, in particular in respect of industry statistics, market and regulatory information and reducing the incidence of claims; and promoting insurance and insurance companies generally. It also helps its members at the pre-competitive stage, to improve their chance of success in achieving a balanced underwriting account.
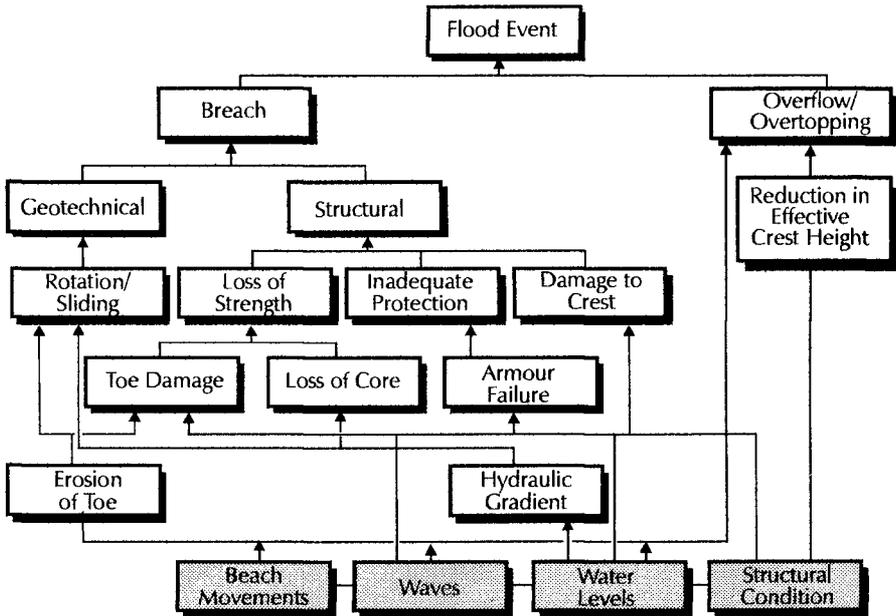
Naturally, ABI are the focus for presenting the industry's concerns on major issues to the Government, ministers and civil servants, MPs, European bodies, the media, consumer bodies and other opinion formers. This responsibility is taken very seriously and it is recognised that their value is diminished if based on inaccurate and illfounded information. Thus, ABI concentrates on resolving real live issues which will affect the industry, of which coastal flooding is particularly relevant.

The areas covered in the Halcrow study were those protected by 1300km of coastal flood defence, the defences of only four main estuaries, namely, Tees, Humber, Thames (Upper and Lower) and Severn, but none of the other estuaries and channels. The pilot study in 1993 examined a detailed approach and one using the sea defence survey (SDS) data from the UK's Environmental Agency (EA). As the results in terms of flood risk were similar, the latter was chosen as it had the shortest completion time and was the most cost effective.

The first main study report was presented to the ABI membership in 1994 and was subsequently updated in 1995 to include for the new and improved defences built since the SDS was published in 1990. Additional studies include the prediction of flood risk from individual storms, using data supplied by the UK's Meteorological Office, examining and reporting on those defence lengths shown to be not performing or at greatest risk and the flood risks to London from combined tidal and high fresh water flows. The latter study is nearing completion.
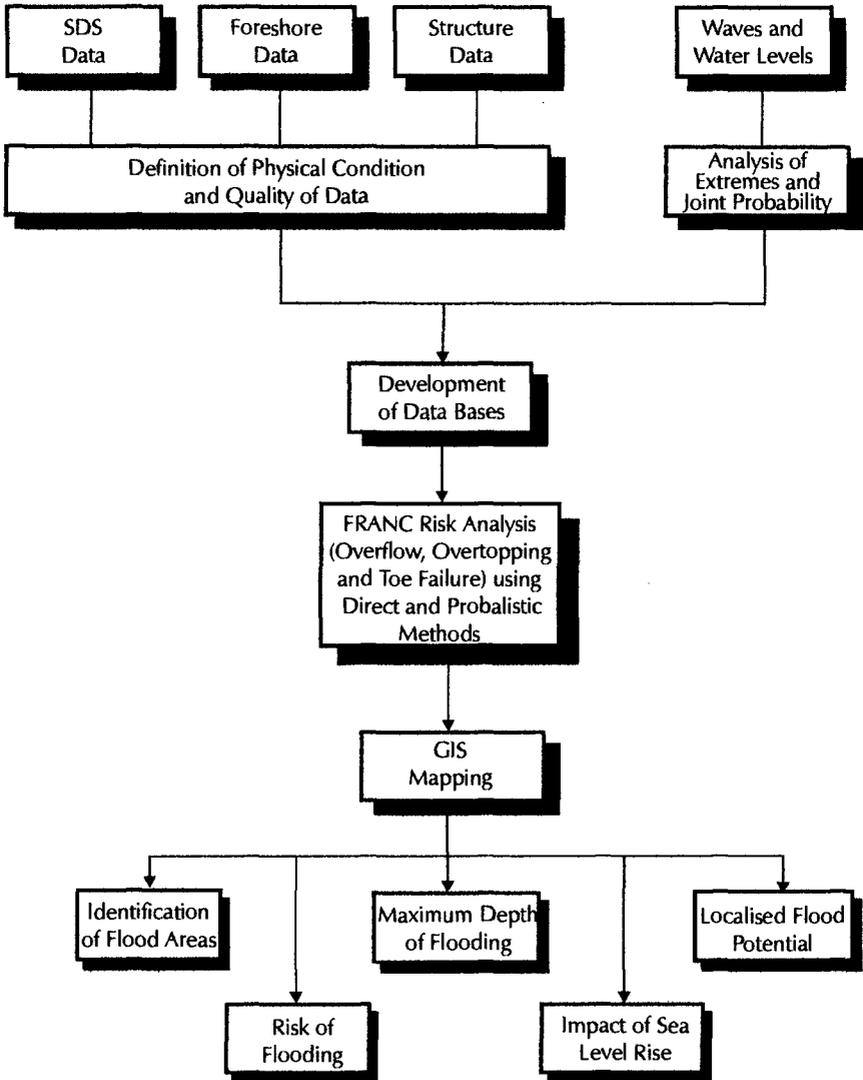
Study Methodology

The assessment of flood risk needs to examine the integrity of the existing sea defences and assess their likelihood of failure and the extent of the subsequent flood area. There are nearly 1300km of coastal flood defences in England and Wales, containing some 2000

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                        └──────────────┘
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            │  Breach  │              │  Overflow/   │
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  │ Geotechnical │    │  Structural  │  │ Reduction in │
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  │ Rotation/│ │  Loss of │ │ Inadequate │ │ Damage to│
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    │  Beach   │ │  Waves  │ │  Water  │ │ Structural │
    │ Movements│ │         │ │  Levels │ │ Condition  │
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**Figure 1.     Key failure modes**

structures and the integrity of each defence had to be examined. Flood risk can be approached in a number of ways, from highly subjective visual assessments, through to detailed probabilistic analyses based on comprehensive structural data. Whilst detailed probabilistic analyses, including all failure modes, can be applied in specific cases, the pilot study showed it was not economically viable for application on a nationwide basis.

Two methods were examined in the pilot study, which explored the relative costs and the quality of results from each approach. The first method offered a detailed approach, analysing a number of key failure modes (see Figure 1) to provide a quantified assessment of failure risks. This method also incorporated a set of screening tests to reduce the number of defences to be analysed, with the remainder requiring detailed structural information. The major disadvantage of this approach was not the amount of calculation required, which could be automated, but the high costs of acquiring detailed data which could only be acquired through structural inspections (Burgess and Reeve, 1994).

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  │  SDS     │  │ Foreshore│  │ Structure│        │  Waves and   │
  │  Data    │  │  Data    │  │  Data    │        │ Water Levels │
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  ┌────┴─────────────┴─────────────┴────┐        ┌────────┴─────────┐
  │    Definition of Physical Condition │        │   Analysis of    │
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                            │   Development    │
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                            │ FRANC Risk Analysis │
                            │(Overflow, Overtopping│
                            │ and Toe Failure) using│
                            │ Direct and Probalistic│
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Figure representing methodology flow chart with boxes: Identification of Flood Areas, Maximum Depth of Flooding, Localised Flood Potential, Risk of Flooding, Impact of Sea Level Rise.

## Figure 2.    Methodology

The alternative second method made use of information in the UK's Environmental Agency's (EA) sea defence survey (SDS) to estimate risk of failure, supplemented with environmental data. This methodology (see Figure 2) concentrated three primary failure modes namely:

- Overflow        -        when the still water level exceeds the crest of the defence;

- Overtopping      -      when the combined effect of waves and water levels results in waves running up and breaking over the defence;
- Toe Failure      -      when the toe of the structure fails due to low beach levels at the base of the defence (erosion being one of the most common causes of damage to sea defences).

For open coasts, normally overtopping and toe failure and to a certain extent, overflow were critical, but for the estuaries the modes were overflow and toe failure with overtopping being less critical.

The starting point of the study was the 1990 SDS which was a major undertaking and a considerable step forward in flood defence management by updating the original 1980 Herlihy study. An analysis for each defence required a site specific knowledge of waves and water levels. Therefore, inshore study points were defined on the open coast and in the estuaries. Future relative sea level changes were also established. Water level time series covering a period of 30 years were combined with 20 years of offshore wave data, transformed inshore through modelling, to produce marginal and joint probability extremes together with a statistical description of the conditions.

The quality of available structure and beach data was, unfortunately, extremely variable and thus two types of risk assessment were developed for each defence; "direct" and "probabilistic" approaches. In general terms the "direct" approach involved determining the specific conditions and calculating to see whether a particular structure could withstand or would be likely to be at risk of failure under these conditions. The risk of failure and hence flood risk was described by risk bands, with Band 1 defined as a defence potentially vulnerable to a 1 in 50 year event ie with an annual probability of failure greater than 0.02, Band 3 as a defence withstanding conditions with a return period of 200 years, and Band 2 falling between these two limits. The "probabilistic" approach was a first order risk method to calculate the annual probability of failure and defined the risk as Bands 1, 2 or 3, depending on the annual probabilities of failure comparable with the return periods above.

The software package "SANDS" already existed, which could be used for data storage, retrieval and analysis. However, to perform the risk analysis computational software had to be developed for the project, acronym "FRANC", which enabled all three failure modes to be analysed by both the "direct" and "probabilistic" approaches. This was essential given the volume of data and the need to analyse 3 modes of failure for nearly 2000 defences. "FRANC" read the relevant data

direct from the "SANDS" database, performed the calculations, combined the results and assigned the defence classification. The software was designed to establish either an overall probability of failure risk based upon the results of all three mechanisms or to establish the worst case, ie the most likely mode of failure. The results were generated in a format that could be directly linked into the flood area mapping.

To perform the analysis of overflow and overtopping, both wave and water levels were needed. A 30 year water level time series for nearshore locations was obtained from the Proudman Oceanographic Laboratory's (POL) tide and surge model for the United Kingdom. Additional data, including annual maximum levels, were obtained for the Severn, Thames, Tees and Humber estuaries, supplemented by information gathered from the relevant Port Authorities.

Wave data at offshore locations were obtained in the form of a time series output for the North European Storms Study (NESS), which gave wave height and direction for some 32 offshore locations and covered a period of just over 20 years. For the outer areas of the estuaries, wave time series were hindcast from wind measurements covering a period in excess of 14 years for each estuary. Extreme wave heights in the upper estuaries were calculated from monthly maxima wind speeds using shallow water wind-wave hindcasting techniques.

The site specific information on waves and water levels was derived from inshore study points using wave refraction models. This required the digital reproduction of the nearshore bathymetry around the entire English and Welsh coastlines and resulted in the generation of sets of time series wave conditions at each of these locations. Shallow water effects were accounted for by spectral saturation, Bouws et al (1985), whilst wave breaking at each structure related to the beach condition and water level.

In interpolating the water level data to the study points, extreme values were adjusted to reflect the natural variation in Mean High Water Spring (MHWS). Future relative sea level changes in 50 years time for each location required the IPCC's (1990) prediction of global sea level increase due to global warming and isostatic changes described by Shennan (1989).

Extreme values of water levels, wave heights and periods were defined in terms of a return period with the marginal distribution functions determined by fitting a distribution to the data. In this case, the Generalised Extreme Value (GEV) was used to estimate extreme values from the annual maxima of each variable (Carter et al, 1986). Joint extreme values were established empirically from frequencies of occurrence (see Owen, 1980 and Hawkes, 1990), for assessing the risk

of overtopping, where the combination of water levels and waves is important. The results of these data processing exercises were incorporated into the database, for use in the risk assessment.

The results of the risk analysis were transferred to a Geographic Information System (GIS) to relate the risk classification of each defence to its associated flood area. The flood areas were defined by establishing the intersect between predicted extreme water levels and the terrain. Flood depths were established from the interrogation of the Ordnance Surveys (OS) base data and any available drawings to derive ground level estimates. Maps were produced on OS backgrounds using the GIS for 10km by 10km coastal flood areas, showing the risk bands and predicted maximum depth of flooding within each 1km grid square. This size grid was chosen mainly because of the large area that had to be covered in the short time available and the lack of detailed survey data below the 5m contour.

Two characteristics of the sea defences were of relevance to the flood risk mapping; the location of a defence and its risk classification. The location of each defence length was defined by start and end co-ordinates in the SDS database. An automated routine was used to interrogate this information and plot the defences within the GIS. The risk classification output from the defence analysis software was loaded into the GIS database and related to the plotted graphic elements using a unique defence length code identifier. When more than one defence structure existed within a defence length, the highest risk probability amongst those structures was assigned to that length.

The risk assigned to a defence length was then transferred to the area being defended. Again, the rationale of assigning the highest risk was applied so that in cases where a single flood area was bordered by a number of defence lengths of differing risk values, the highest risk value amongst those was transferred to the defended area. The seaward extent of the defended area was taken as being the line of defence and the landward extent that line at which the water level, associated with a given event, intersected the land surface ie the same methodology as that used in the SDS. The accuracy with this line could be determined was largely reliant on the availability of ground level information, some of which was poor.

The variation found in the water levels associated with the 50 and 200 year event typically ranged between 0.1m and 0.5m. This made the differentiation of discrete flood boundaries associated with the 50, 100 and 200 year events problematical, given the quality and quantity of ground level data available from OS sheets.

The protected areas were overlaid with 1km grid squares. Each 1km grid square took on the highest risk classification of any defended areas which it wholly or partially covered. Post code sector

data was provided by the UK's Post Office and the risk was related to the post code sectors.

In addition to the risk classification assigned to each grid square, an attempt was made to assess the depth of flooding using the very limited ground level data available. The approach was generally simple, making a direct interpolation of the depth of flood water calculated at available data points behind the defence and at the inland boundary of the flood water. Where possible, the influence of features such as inland embankments was included.

This method of interpolation obviously created discrepancies when assigning a single flood value across 1km grid squares, which might contain areas of higher relief. Similarly, where the level of the ground was below that defined by drawings or spot heights, underestimation of the depth of flooding occurred.

Results

Each analysis was rigorously checked for its approach and the correctness of numerical results and a further check was carried out to verify the overall output. Direct verification was restricted due to the lack of recorded instances of defence failures, despite obtaining newspaper reports. The "Effective Level of Service" recorded in the SDS provided an alternative measure against which the analysis results could be compared, details of which are given in Table 1.

| Classification | SDS (%) | Halcrows' Study (%) |
|---|---|---|
| Band 1, 50 year | 33 | 28 |
| Band 2, 50 to 200 years | 15 | 5 |
| Band 3, > 200 years | 52 | 67 |

**Table 1.    Overflow classification results, percentages of defences at risk**

The results from the original study showed a good agreement for overflow with those in the SDS (only overflow was examined in the SDS) with 64% of all structures analysed having the same risk classification. Of the remaining 36%, the majority had a lower classification than that given by the SDS. However, notwithstanding the differences in analysis and classification techniques, a slightly lower result is expected as the Halcrow study used probabilistic calculation where possible, in preference to a direct method of determination.

**Figure 3.     Coastline of England and Wales, outlined by Band 1
               risk areas**

 Consequently, the overall result was considered satisfactory and was
confirmed by major coastal flood events. Consequently, the overall
results was considered satisfactory and was confirmed by recent major
coastal flood events such as those at Towyn in North Wales, which
were shown to be in Band 1.

Toe failure results were spread between the risk bands although 22% of them fell within Band 1. Given the widespread erosion of many of the UK's beaches, this was perhaps not too surprising. Of possibly greater significance was the high percentage of defences apparently at risk from overtopping. Whilst the risk criteria were based upon well established and universally accepted overtopping thresholds (see Owen, 1980 and Hawkes, 1990), the question of whether critical damage would only result from sustained overtopping over a reasonable duration, was examined. To take account of this, the risk thresholds were therefore set an order of magnitude higher, ie assuming the defence could withstand ten times the established criteria before failure could occur. All the areas falling into Band 1 are shown on Figure 3.

It should also be noted that, with the Band 3 risk threshold as a 1 in 200 year event, the total number of potentially defences at risk falling within Band 2, was only 12%. This percentage could only be increased if the upper and lower thresholds for Band 2 were an order of magnitude apart ie taking Band 1 as a 20 year event.

The initial study was based upon the structural data in the SDS and did not include new defences or remedial works carried out since 1990. However, minor updating of the SDS information was undertaken where possible, and Halcrows recently completed an updated study for the ABI following liaison and co-operation from the EA Regions. The results, which included the most recent defence improvements, showed a reduction of 7% in the structures vulnerable to Band 1 events.

The maps produced for ABI only indicate the flood areas associated with the defined sea defences and the named estuaries. Other potential risk areas, eg the Fens inland of the Wash and other estuaries were not within the defined scope of this study and were therefore not included on the maps. In addition, the available OS maps were not up to date and recent urban developments may have been missed.

Whilst many defences and thus coastal areas were given a Band 1 classification, this did not mean that all defences protecting such areas had an equivalent risk as, in reality, the failure of only a relatively short length of defence could lead to widespread flooding. As described earlier, the weakest link in any flood area frontage was taken to represent the risk associated with that area, although the majority of the defences might have had a much greater integrity and a relatively minor amount of remedial works could be sufficient to move the areas into Bands 2 or 3.

The results provide a relative measure of flood area risks and the risk of failure does not necessarily imply that a total functional failure of a defence and subsequent flooding would definitely occur. It

simply indicates potential risks and vulnerability under particular conditions. No account could be taken of remedial or emergency action, which might occur prior to or after an event. Because of constraints in time, the impact of successive tides could not taken into account, nor the likely time for breach repair or flood duration.

The 1:10,000 maps and Figure 3 show very large areas of the coast and specified estuaries as Risk Band 1, ie being at risk to inundation from a 50 year storm event, it does not mean that all these areas are susceptible to any one single event, simply that they have a greater probability of being affected. Thus, while a major storm event could affect large areas of the East, South and West coastal areas of England and Wales, it will not affect all coastal areas as its impact will be limited to relatively short lengths of coastline, particularly on the South and West coasts. On the East coast a major event could affect larger areas, as experienced during the disastrous 1953 event.

The impact of individual storms was therefore examined following on after the two earlier studies. As described above, the coasts of England and Wales were divided into three coastal areas: West, South and East. Meteorological records going back to the last century were analysed by the UK's Meteorological Office in order to determine generic storm types. In all, the two storms likely to have the most significant impact on each of the coasts and their associated wave and surge conditions were defined for each section of coast. Significant storms affecting more than one section of coast were also defined. While it is possible to define wave and surge levels in terms of their probability of occurrence, it is not possible with storms. This is because they are made up of many different elements eg air pressure, density and spacing of isobars, storm track direction etc, each of which can influence the other. The impact of the conditions produced (wave and surge) also varies along the coast, say being 1 in 50 year near its centre decreasing to 1 in 1 year towards its edge.

The storms produced varying conditions along the coastline and thus assigning a particular return period to an individual storm is problematical. A prime example is the 1953 East coast storm, where shoreline conditions experienced in Yorkshire were estimated to be in the order of 1 in 50 years, whilst by the time the storm surge had been driven south to Lincolnshire and East Anglia, it represented a 1 in 500 year condition.

The analysis defined the impact of potentially different storm types for each coastal area rather than specific storms. Detailed comparison of the analysis against past events was not possible, but a qualitative comparison of results and newspaper reports of flooding was made.
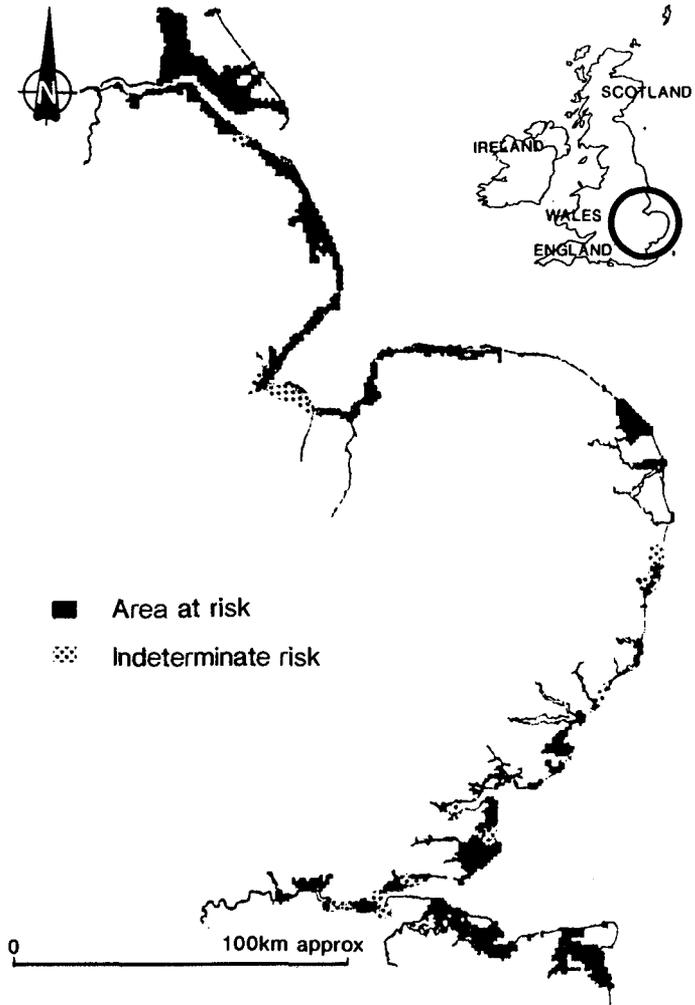
**Figure 4.     Flood risk areas resulting from a major East coast storm**

Two storms affecting individual coasts were examined, together with one affecting both the East and South coasts, one affecting both the West and South coasts and one hypothetical storm for each coast. The hypothetical storms represent small changes of previous storms to modify the timing of the storm surge to coincide with high water. These were then compared as a way of establishing the storm scenarios with the greatest impacts.

Typical variations in the wave and water level conditions adopted for the single storms and the two earlier studies were examined, including the probabilistic wave heights and water levels for return periods of 50, 100 and 200 years. The comparison showed variation in wave height for the East coast locations were markedly different and other differences along the remaining coasts were also apparent. The variations were smaller for water levels.

The results produced by "FRANC" for these storms showed that one of the East coast storm produced the highest number of defences at risk ie 36.5% (see Figure 4) The percentages at risk from the other two East coast storms were very similar, although their distribution was different.

The South coast storms indicate that a high percentage of defences were at risk (approximately 70%). Both have an eastbound surge associated with waves of between 9m and 13m, generated by gale force winds sweeping in from the Atlantic. On the West coast, the hypothetical storm produced the worst conditions with 383 defences at risk (48.1%). Had it been coincident with high tide, the results would have been more severe.

## The Insurance Industry's Application of the Results

The information from the studies was applied by the Insurance Industry in two basic ways, namely;

- the practical application of the project output data in overall portfolio exposure and in underwriting individual property risks on a geographic basis according to flood risk; and
- strategic use of the valuable data (which supplements and refines the existing knowledge base) to assist Government, through its agencies (MAFF and the EA), to target resources to exposed locations, always recognising the need for cost/benefit analyses.

The individual insurers try to obtain sufficient premium to cover their potential exposure and to do this they need to understand the underlying risk. The output of the project was therefore applied to this end by analysing the areas at risk against the locations and post codes of the insured properties to establish their aggregate portfolio exposure.

Insurers usually also have to operate with the support of reinsurers (who are also subject to the same regulatory approach) to give them added capacity or to reduce the financial consequences of a catastrophic loss eg 1987/90 storms or coastal flood. These reinsurers need to be satisfied that the insurers they are backing are

not themselves overexposed and also require some technical evidence these studies provided in order to take on these risks.

The data analyses from the study were therefore able to assist the insurers to:

- assess their overall exposure;
- determine whether correct rates are being charged; and
- provide information to reinsurers to gain their "capacity" and "catastrophe" support.

It also allows them to put pressure on the relevant Government Departments and to consider their exposure globally.

References

Bouws E, Gunther H, Rosenthal W and Vincent C, 1985. Similarity of the wind wave spectrum in finite depth water. J Geophys Res 90 (CI).

Carter, D J T et al, 1986. Estimating wave climate parameters for engineering applications, Department of Energy Offshore Technology Report OTH 86 228, HMSO.

Diment R P and Deakin R, 1994. The role of GIS in risk assessment, European Geographic Information Systems Conference '94, Paris.

Hawkes P J, 1990. Joint probability of waves and water levels on the north Wales coast, Hydraulics Research Limited, Report EX 2133.

IPCC (Intergovernmental Panel for Climatic Change), 1990. Climate Change, Cambridge University Press.

Herbert D M, 1993. Wave overtopping of vertical walls, Hydraulics Research Wallingford, Report SR316.

Maddrell R J, Burgess K A and Mounsey C, 1995. Coastal flooding: assessing the risks for the insurance industry, ICE Conference, Bournemouth, p167 - 184.

Owen M W, 1980. Design of seawalls allowing for wave overtopping, Hydraulics Research Station Wallingford, Report EX 924.

Shennan I, 1989. Holocene crustal movements and sea level change in Great Britain, Journal of Quaternary Science.