INTEGRATING RELIABLE FLOOD MODELLING WITH PROBABILISTIC ANALYSIS IN PRACTICE

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ABSTRACT

In recent years there have been a number of advances in modelling flood events. This has been matched by simultaneous advances in probabilistic techniques to evaluate loading and response. The reliability of a flood risk assessment, however, remains constrained by the ability to determine the likelihood of defence failure and test multiple failure and load scenarios. In addition, conventional analysis has difficulty resolving flood risk resulting from multiple breach/failure locations and load combinations. Therefore, it often remains focused on the impact of a breach on discrete areas of the flood plain; rather than considering the potential damage resulting from a broader perspective of multiple failures arising in any given 'system' of defences. As a result, the improvements in flood inundation modelling and probabilistic analysis techniques have been largely incompatible in practice.

For 'simple' flood plains protected by a limited number of discrete defences subjective techniques based on expert judgement supported by limited modelling and sensitivity analysis offer robust and appropriate solutions to determining flood risk. However, in complex situations, a more advanced 'physically-based' approach is required. Therefore, to improve decision making in these complex situations and achieve reliable flood risk mapping, a probabilistic systems based approach that integrates flood inundation modelling with defence performance and economic analysis is presently under development. The methodology is being developed in tandem with a number of Coastal and Tidal Defence Strategy Studies and combines large quantities of synthetic data from joint probability analysis with 'system' thinking on defence performance, to enable economic damages to be directly and consistently assessed. The outline procedure presented in this paper is generic and could be applied to many situations to provide a consistent evaluation of different options. However, this level of analysis would not be appropriate in cases where the risk and investment levels are low or where decisions are clear cut.

INTRODUCTION

The preparation of strategies for the management of fluvial, tidal and coastal defences is becoming increasingly dependent on probabilistic analysis of flood defences. A problem central to the development of robust strategic options is to understand the way in which flood defence systems behave, the likelihood of failure and the resulting inundation and damage. Recent advances in probabilistic design provide the potential for a large number of defence and load realisations and hence a risk-based approach to the assessment of future defence management scenarios. This paper explores these techniques and present thinking in terms of combining loading and response using probabilistic techniques. The discussion included within the paper is evolving and is by no means complete. However, it seeks to demonstrate that probabilistic risk assessment can be applied in practice.

Outline of the Paper

This paper describes on-going research and its practical application in terms of reliably establishing flood risk. The techniques discussed have been developed through application and extension of techniques outlined in FCDPAG4 (MAFF, 2000) and in three strategy studies: Thames Tidal Embayments (Environment Agency, 2000, being undertaken by Arup); Folkestone to Rye (Environment Agency, 2001a, undertaken by HR Wallingford); and Thames Tidal Walls (West); (Environment Agency, 2001b, being undertaken by HR Wallingford).

The paper is structured in three sections:

- Defence performance and system failure
- Integrated flood inundation modelling
- Conclusions

DEFENCE PERFORMANCE AND SYSTEM FAILURE

Assessing the Likelihood of Defence Failure

Many authors have grappled with the thorny issue of assessing the likelihood of defence failure (Sayers and Simm, 1997; Hall *et al*, 2001). Typically, single deterministic values of residual life that represent a judged 'best' estimate have been, and are often still, used to provide a representation of the likelihood of failure. In more recent studies, defences have been categorised into bands that indicate their Estimated Useful Life (e.g less than 1 year, 1-5 years, etc). 'Mid value' estimates are then often used to inform decision making; at least with regard to assigning annual failure probability values. To move towards a probabilistic assessment of flood risk a better founded probabilistic description of the likelihood of failure is clearly required. However, this is extremely difficult given the complex interactions between load, hydraulic response and defence structural deterioration. To address this issue, a simplified probabilistic methodology has been developed for use in the Thames, west of Dartford, jointly by Arup and the Environment Agency (Environment Agency, 2000) that offers a practical way of determining annual failure probabilities for individual defences. The approach adopted utilises the 'Condition Grade' categories developed by the Environment Agency (Environment Agency, 1999) and is briefly outlined below in three steps.

Step 1 - Establish the 'Life Expectancy' for each generic defence type

Maximum life expectancies for various structures within the Thames Tidal Embayments Study[1] area (Teddington Weir to Dartford Creek/Mar Dyke) have been developed through consensus based on engineering judgement and experience. Typically, these range from 50 years for an embankment through to 75 years for steel sheet piling and up to 300 years for a masonry wall. In establishing these values it was assumed that the structure is subjected to *average* environmental and loading conditions throughout its life and never exposed to extremes. It was also assumed that the structure is 'unmaintained', i.e. no actions are undertaken (such as grass mowing, painiting, grouting, etc.) to prolong the life of the defence.

Step 2 - Establish an Age: Failure Probability relationship

For each generic defence type, a generic deterioration curve was then developed. These so-called 'Age: Failure Probability' relationships are shown in Figure 1 and based on an exponential function as given below.

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[1] An embayment is an area of the tidal Thames floodplain defined by the limit to which floodwater would extend in the event of a breach in the defences. Tributaries, high ground or artificial constraints extending to the River Thames separate embayments from each other. A total of 23 separate embayments have been identified between Teddington Weir and Mar Dyke/Dartford Creek.

Probability of defence failure = pf = $e^{a + b\ln L}$

Where pf = probability of failure of a single defence length independent of its neighbours' performance, ***L*** is the **remaining life** of the defence element and ***a*** and ***b*** are constants which depend on the maximum life expectancy of the generic defence type. It was of course recognised that the deterioration of flood defence structures may not follow an exponential curve. For example, large earth embankments may experience early rapid deterioration to a relatively stable condition before experiencing further rapid deterioration to failure. However, in the absence of empirical evidence on which to base alternative deterioration profiles, more realistic decay functions cannot at present be defined.

Step 3 – Establish the 'defence specific' Annual Failure Probability and Condition Grade
The Condition Grade (from 1 to 5) provided by the Environment Agency Flood Defence Management System (FDMS) is then utilised to establish an equivalent failure probability range for each defence as given below and shown in Figure 1.

Condition Grade	CG1	CG2	CG3	CG4	CG5
pf	0.001 – 0.0029	0.003 – 0.0069	0.007 – 0.0149	0.015 – 0.0249	0.025 – 0.99

Thus, a frontage designated CG1 would be assigned an annual failure probability (pf) of between 0.001 and 0.0029. It should be noted that these probability intervals are essentially arbitrary and are not supported by empirical data but, through extensive debate, are considered an appropriate translation of the Condition Grade, assigned on inspection, to an 'annual failure probability'. To determined a precise 'annual failure probability' in any given year the Condition Grade is then combined with knowledge on the age of the defence as discussed below.

Step 4 – Establish the Annual Failure Probability in any year
For the purposes of decision making it is not sufficient to simply determine the present day conditions of a defence, but an estimate of how a particular defence may perform in the future is required. Therefore, the *annual failure probability* assigned to any defence element in any particular year depends on the age of the element *and* on the condition of the element under consideration at the time of inspection as described by the Condition Grade. These two criteria (Steps 2 and 3) are combined to give an 'effective age' of the defence to enable future changes in annual failure probability to be determined.

For example, a concrete defence element may be expected to have a useful life of 100 years. If constructed sixty years ago it might be expected to have a remaining life of 40 years. This would lead to an anticipated *annual failure probability* of 0.005 (using the exponential deterioration curve for a concrete defence given in Figure 1) and hence be expected to receive a Condition Grade of 2 in a present day inspection (see Table above). However, if the Condition Grade assigned by an experienced inspector was CG4 (and hence the defence was in worse condition than may have been expected based on the generic *age:failure probability* relationship) its effective age would be 82 leaving a **remaining life** of only 18 years (equivalent to an annual failure probability of 0.015 in Year 0; the lower limit of the CG4 equivalent failure probability). This approach provides some practical first steps towards determining a probabilistic description of a varying future annual failure probability. However, it attempts only to deal with intrinsic uncertainties in defence performance based on condition of structural elements; uncertainties in future load sequences and severity are ignored. This is an issue that will need to be addressed in order to relate the likelihood of failure to the drivers of failure; i.e. the extreme wave, water level and flow conditions. It will also be important to refine the assumed deterioration curves as empirical evidence becomes available.

Defence 'System' Failure

The above is focused towards establishing an annual failure probability within any year for one defence length. Within FCDPAG3 (1999) the appraisal of breach failure is also based on an individual, self-contained, defence for which annual failure probabilities can be interpolated. In reality this assumption is often fundamentally flawed. Flood plains are typically protected by a myriad of defences of varying condition and residual structural strength (see Figure 2). In this case, failure of any one or more defences may lead to inundation of some or all of the flood plain. Therefore, a particularly difficult issue in any flood risk assessment is to determine the likelihood of failure of any particular defence length (as discussed above) and, based on these individual assessments, the likelihood of a failure occurring somewhere within the 'system' of defences. Within FCDPAG4 (MAFF, 2000) two scenarios are presented for assessing the probability of system failure (P_{system}) where defences are similar in length:

Assume defences are fully independent

In this case it is assumed that a particular defence length will behave in accordance with its own intrinsic qualities such as construction material and residual structural strength. Under this assumption the probability of system failure is easily described as:

$\mathbf{P}_{system} = 1-((1-pf_1). (1-pf_{2)} ... (1-pf_{n-1}), (1- pf_n))$ (e.g from Figure 2, where n=6, $\mathbf{P}_{system} = 0.32$)

where n = the number of discrete defence lengths

Assume defences are fully dependent

In this case it is assumed that there is a tendency for defences exposed to similar loading to behave in a similar way. For example, for each defence length, failure is most likely to occur during a major storm. Under this assumption the probability of system failure is easily described as:

$\mathbf{P}_{system} = \text{Maximum } pf_i$ $i=1$ to n (e.g. from Figure 2 $\mathbf{P}_{system} = 0.10$)

In reality it is likely that $\mathbf{P}_{system}$ will lie somewhere between 0.32 and 0.10 and the degree of correlation between defences will depend on their proximity, structural form and failure mechanisms, as well as their exposure to extreme loads that may lead to failure. The most complex part of this process is to determine the correlation between these components and hence the 'system' failure probability. To determine the value of P_{system} a number of possible methodologies are available to achieve a more realistic representation of partial dependence between defences. These are discussed below.

Approximate methods to introduce a degree of dependence

A simplification made within the Thames Tidal Embayments Studies was to separate the defences into two classes: 'strong' defences with a 'low' probability of failure; and 'weak' defences with a 'high' probability of failure. If the 'strong' sub-system fails then it is assumed that the 'weaker' sub-system also fails. To determine the overall 'system' failure probability a mixed correlation approach is then adopted. First for each sub-system (i.e 'strong' and 'weak' defences) the statistical independence assumption is made, i.e. $\mathbf{P}_{sub\text{-}system} =$

$1-((1-pf_1).(1-pf_2)....(1-pf_n))$. Then, the two sub-system failure probabilities are combined assuming statistical dependence, enabling the system failure probability to be defined as $\mathbf{P}_{system}$ = maximum of $P_{'weak'}$ sub-system and $P_{'strong'}$ sub-system. Within this above approach, however, the failure probability assigned to a defence length remains uninfluenced by the condition of its immediate neighbours or the sequence and severity of the loading.

Develop correlation matrices that describe relationships between defences
The *approximate methods* can be improved to enable the condition of the immediate neighbours to a defence to influence the likelihood of its failure by using a Conditional Probability Relationship as discussed in PAG4. This involves the establishment of a *correlation matrix* to describe conditional failure probability relationships (i.e information on the change in the likelihood of failure of a particular defence assuming its neighbouring defence fails or a severe storm is encountered). However, although this is relatively simple in theory, application of this approach in practice is constrained due to the limited understanding of the interaction of defences and their structural performance under extreme loads. Therefore, although a promising approach, it will require further thinking and research to develop *evidence* based correlation matrices. As with the approximate methods, this approach would continue to rely on deterioration curves based on average loading to determine future annual failure probabilities and therefore would take no account of the sequence or severity of future loading.

Develop full simulation based approaches of defence performance
The most powerful approach is one of full simulation that seeks to combine evidence on defence performance, loading and response. These techniques are starting to be explored through the use of simulation tools that consider the reliability of defence system as a whole with 'built-in' correlation between defence elements and loading. This type of approach is currently being developed by the Dutch for managing dyke rings (PC Ring Project) that includes correlation between loading and condition assessments (Vrijling and van Gelder, 2000). Similar approaches are presently being considered for application in the UK where the defence system and flood plain is complex, although it will require considerable research effort to develop useable and scaleable methodologies.

INTEGRATED FLOOD INUNDATION AND ECONOMIC DAMAGE MODELLING

Establishing defence performance is difficult but, unfortunately, only one part of the equation. The flood forcing functions are also often complex and include hydraulic loading (waves, surges, fluvial flows), defence failure (i.e. overtopping and overflow) and flood propagation across the flood plain. In the past it has been convenient to consider flood risk in terms of single hazards, i.e extreme water levels, wave induced overtopping or fluvial flows. Then use discrete return periods of these hazards (i.e. the 1:100 year water level) and assume these relate well to discrete flood inundation return periods, or even, incorrectly, economic losses of the same return period. Over the past few years this view has been challenged and recent work by HR Wallingford as part of the Thames Tidal Walls Strategy development (Environment Agency, 2000) has adapted and extended the joint probability methodologies that are traditionally used to derive hydraulic load conditions, to the broader question of economic damage that recognises waves, surges, fluvial flows and various defence failure scenarios as potentially important contributors to flood risk (see Figure 3).

Although the Thames Tidal Walls (West) Strategy Study study (Environment Agency, 2000) is on-going, and the methodology continues to be developed through associated research at

HR Wallingford, the key elements of the approach are outlined in Figures 4 and 5 and are discussed below in nine steps.

Steps 1 to 3 – Establishing the hydraulic loading conditions (see Figure 5)
Joint probability methods have been developed over many years and are now common place in most assessments of hydraulic loads (HR Wallingford, 1994). More recently these methodologies have been extended to directly consider the response of defences to those loads, for example in terms of wave run-up or overtopping and, where suitable relationships are known, structural response such as rock stability. HR Wallingford 1998, demonstrates a discrepancy between the joint exceedance return period of the load and the return period of the response derived from it. Comparisons suggest that if the target response return period is used to select the joint exceedance load, then the response return period could be underestimated by a return period factor of up to 2 to 3 times. Therefore, the need to adopt a joint probability method to establish the extremes of a response of interest is clear.

In seeking to select the preferred flood defence option, the primary driver used in England and Wales is one of comparing potential costs and damages associated with each option. However, to determine potential economic loss, spatial changes in both loading and defence response (i.e overtopping) are important intermediate steps that need to be understood and represented within the flood model if it is to reproduce well the flood inundation characteristics of the flood plain; a feature of particular significance in determining flood risk in the Thames estuary where the flood plain is extensively interconnected.

For example, exposure of defences to hydraulic loading along the Thames varies significantly at any one time depending on the wind direction and surge. Also fluvial flows are important in raising water levels west of Dartford Creek Barrier. To account for all these influences on defence loading and to understand their spatial variation, within the Thames Tidal Walls (West) Strategy it is proposed to extend an existing iSIS model of the Thames estuary (developed by the Thames Region, Environment Agency) to include the southern bank flood plain east of Dartford Creek. The hydraulic boundary conditions for this integrated model of the estuary and flood plain will then be provided by a simulated datatset of approximately 700,000 high tide events (i.e. equivalent to 10,000 years) of simultaneous water level and wind speeds predicted at Southend-on-Sea (assuming a continuation of the present day climate) using the JOIN-SEA software (HR Wallingford, 1998), see Figure 6. It is noteworthy that fluvial flows were shown to have little influence on extreme water levels east of Dartford Creek and are therefore excluded from the JOIN-SEA analysis. It is also noteworthy that wind speeds at Southend-on-Sea are used as a ‘proxy’ for wave conditions through the study area. The use of wind speed as the second variable in the joint probability analysis at Southend-on-Sea, instead of wave conditions, enables simultaneous wave conditions to be predicted at any location within the estuary, with the correct joint relationship with predicted water levels at Southend-on-Sea. This relationship can then be used determine simultaneous, but varying, combinations of wave and water levels throughout the study area as discussed below.

Step 4, 5 and 6 Establish flood inundation and resulting economic damage (see Figure 5)
The JOIN-SEA simulation is equivalent to more than 10,000 years of high tide data. It is therefore impractical to run a hydraulic model and determine the flood inundation and resulting economic damage for a range of defence failure scenarios in all of these events. Instead, it is proposed to adopt a representative sub-set of the full population of joint hydraulic loading conditions to drive the integrated iSIS model of estuary and flood plain.

For a range of defence failure scenarios, economic damages can then easily be assessed using the iSIS results for the sub-set of hydraulic conditions. It is also interesting to note that the predicted flood inundation automatically includes the variations in hydraulic loading during any single storm event (or combination of events if required) along the estuary. Variations in wave conditions can be derived independently from iSIS based on wind speeds at Southend-on-Sea provided by the JOIN-SEA simulation, and the resulting wave conditions included explicitly within the iSIS model. Variations in water levels are predicted within the iSIS hydraulic model directly from the water level boundary condition provided at Southend-on-Sea.

Steps 7 and 8 Derive directly extremes of economic loss (see Figure 5)
Within FCDPAG 3 it is assumed that the practitioner has a number of discrete results of economic damage (1:1 year, 1:10 year etc) taken from a small set of flood inundation results. Using the approach discussed above in Steps 4 to 6, the full population of wind speed and water level conditions may be represented by a selected sub-set of conditions. For each of these conditions the economic damage can be established based on the predicted inundation. Using contouring methods developed at HR Wallingford (HR Wallingford, 2001) it is possible to extend this relatively small number of realisations of economic damage to the full population of joint probability conditions of wind speed and water levels predicted at Southend-on-Sea (see Figure 7). The extended dataset provides a 10,000 year population of economic damage from which extremes may be directly extracted; including an Annual Average Damage or any other statistical parameter.

Step 9 Repeat various scenarios of defence 'system' failure and climate change (Figure 5)
A key innovation of the methodology proposed for the Thames Tidal Walls (West) Strategy is its ability to be run for many combinations of defence failure realisations and future climate scenarios. For example, a change in mean sea level can easily be incorporated within the joint distribution of waves and water levels by simply re-scaling the marginal extremes for future water levels and re-contouring the economic loss results to establish future marginal extremes of economic damage without the need for further inundation modelling. Equally, more subtle changes in wind/wave climate can be incorporated and their significance tested in a similar manner.

CONCLUSIONS

A new approach to flood risk assessment is presently under development for making better decisions where the loading, defence system and flood plain is complex and the decisions to be made are difficult to determine. The methodology described in outline in this paper:

- Enables the changing annual failure probability of a defence due to deterioration to be incorporated in a simple way. More advanced methodologies to enable defence deterioration to be linked to possible realisations of future loading are now required.

- Recognises that flood plains are defended by a 'system' of defences. Present practical methodologies in both the UK and overseas are immature in this area. However, key advances towards a more realistic representation of the defence systems and the 'risks' they pose are emerging.

- Implicitly recognises that defences and interconnected flood plains are exposed to a combination of extreme water levels (fluvial and surge) and wave conditions.

- Avoids the assumption that links extremes of economic damage to particular events. Instead, it enables a full distribution, and hence direct extraction of extremes and other statistical descriptions, of economic damage to be calculated using well tried and tested joint probability methodologies.

There is considerable development work still required to enable a consistent and objective risk assessment methodologies to be developed for use when decision making complex. However, many of the foundation stones are now in place.

ACKNOWLEDGEMENTS

The authors wish to thank members of the Embayments Methodology Steering Group, especially Arup (Duncan Hay), Environment Agency, MAFF and Andrew Pepper (ATPEC Ltd), who have contributed considerably to the conceptual development of the Thames Region's Tidal Embayment Studies. Also the advice provided by Dr Peter Hawkes and Robert Cheetham of HR Wallingford and Mike Turville of Environment Agency (Southern Region) in developing the approach proposed for use in the Thames Tidal Walls (West) Strategy Study is gratefully acknowledged.

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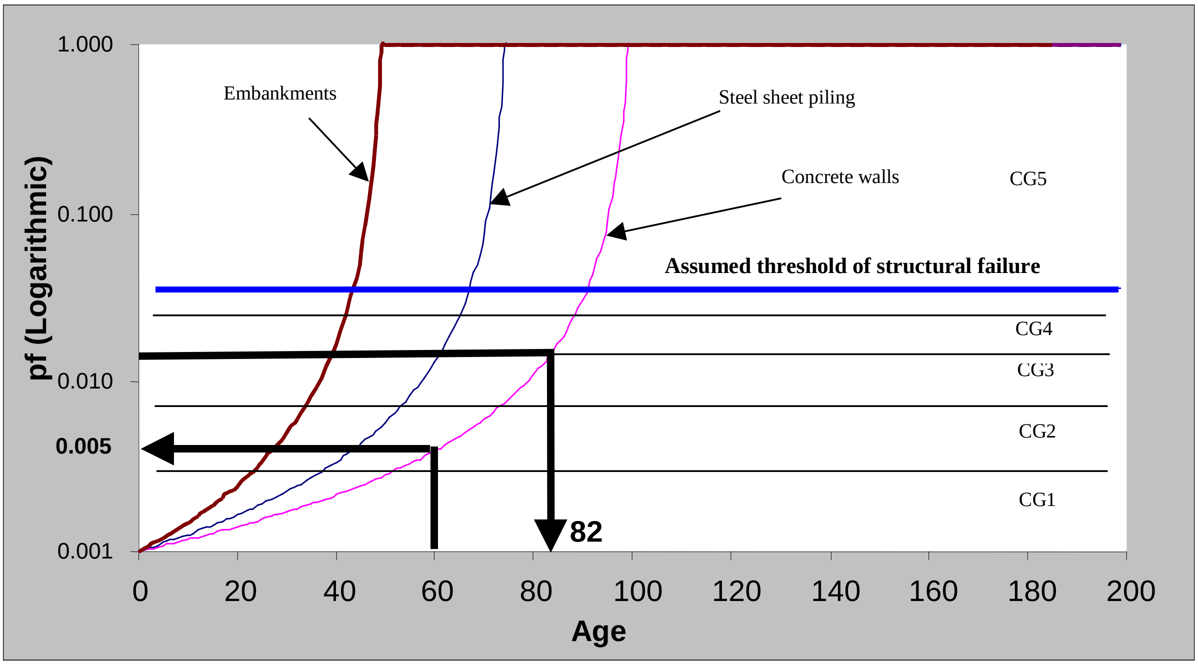

Figure 1 Deterioration of different generic defence types in the tidal Thames

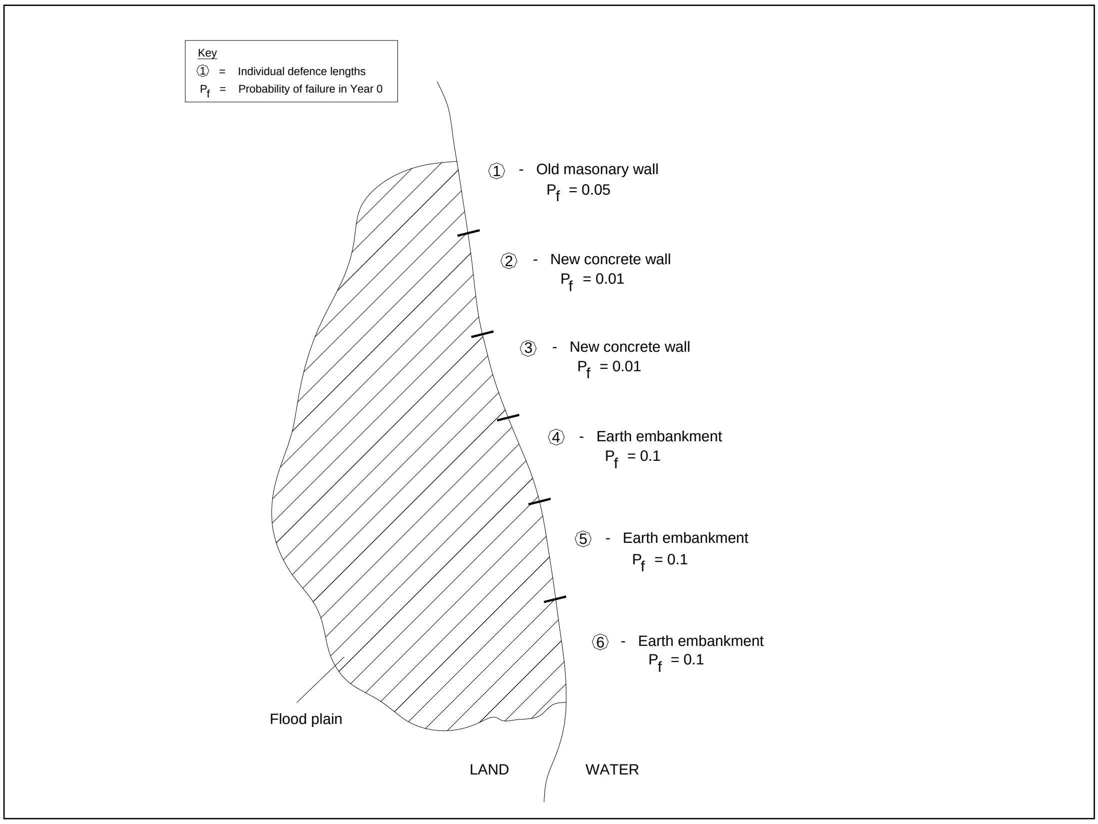

Figure 2 Schematic of defence lengths protecting a single flood plain

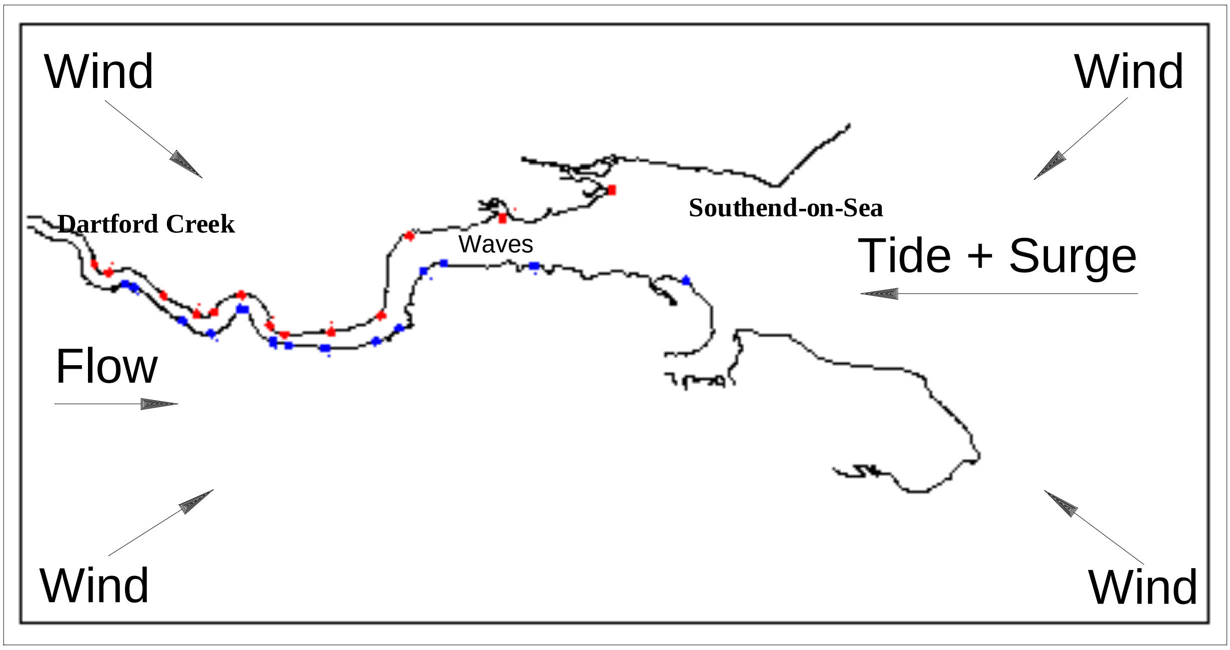

Figure 3 Thames Tidal Walls Study Area – Dartford Creek to Southend-on-Sea: Complex loading and an interconnected flood plain

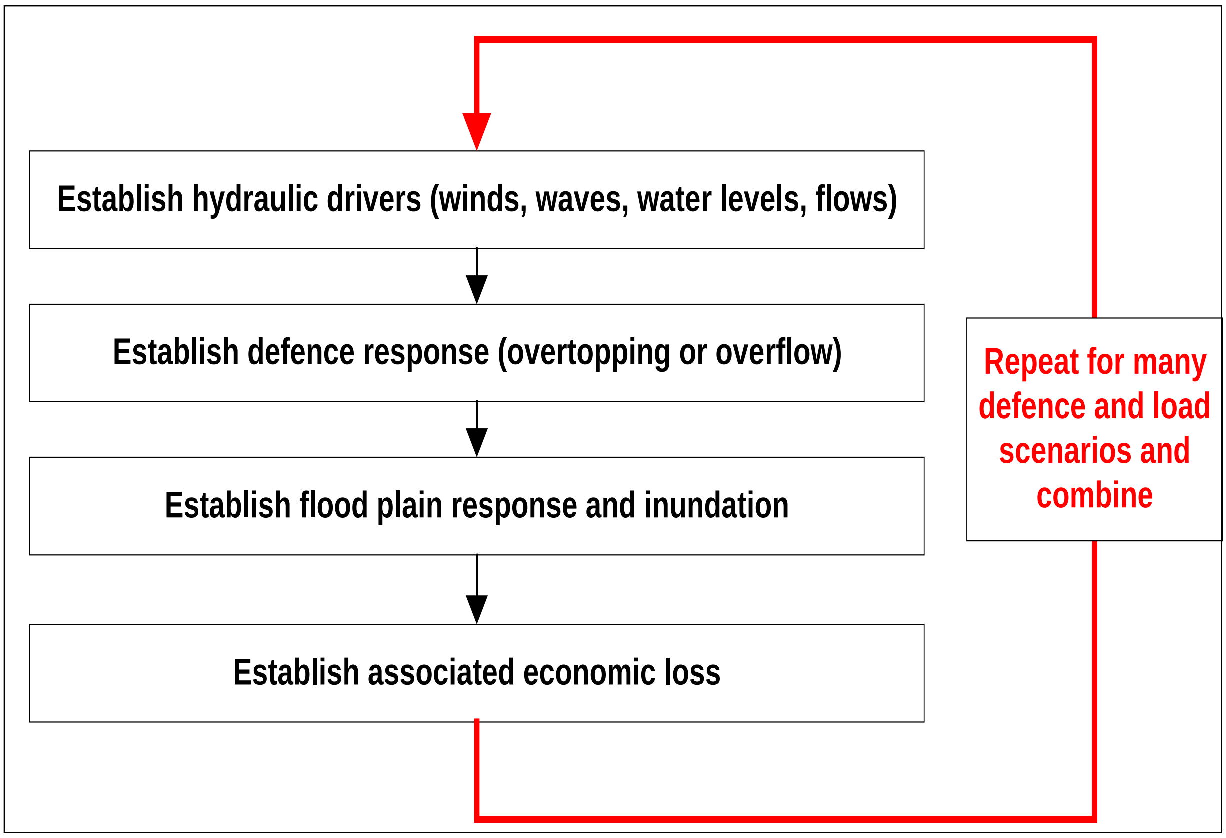

Figure 4 Overview of approach to the integrated flood inundation and economic modelling

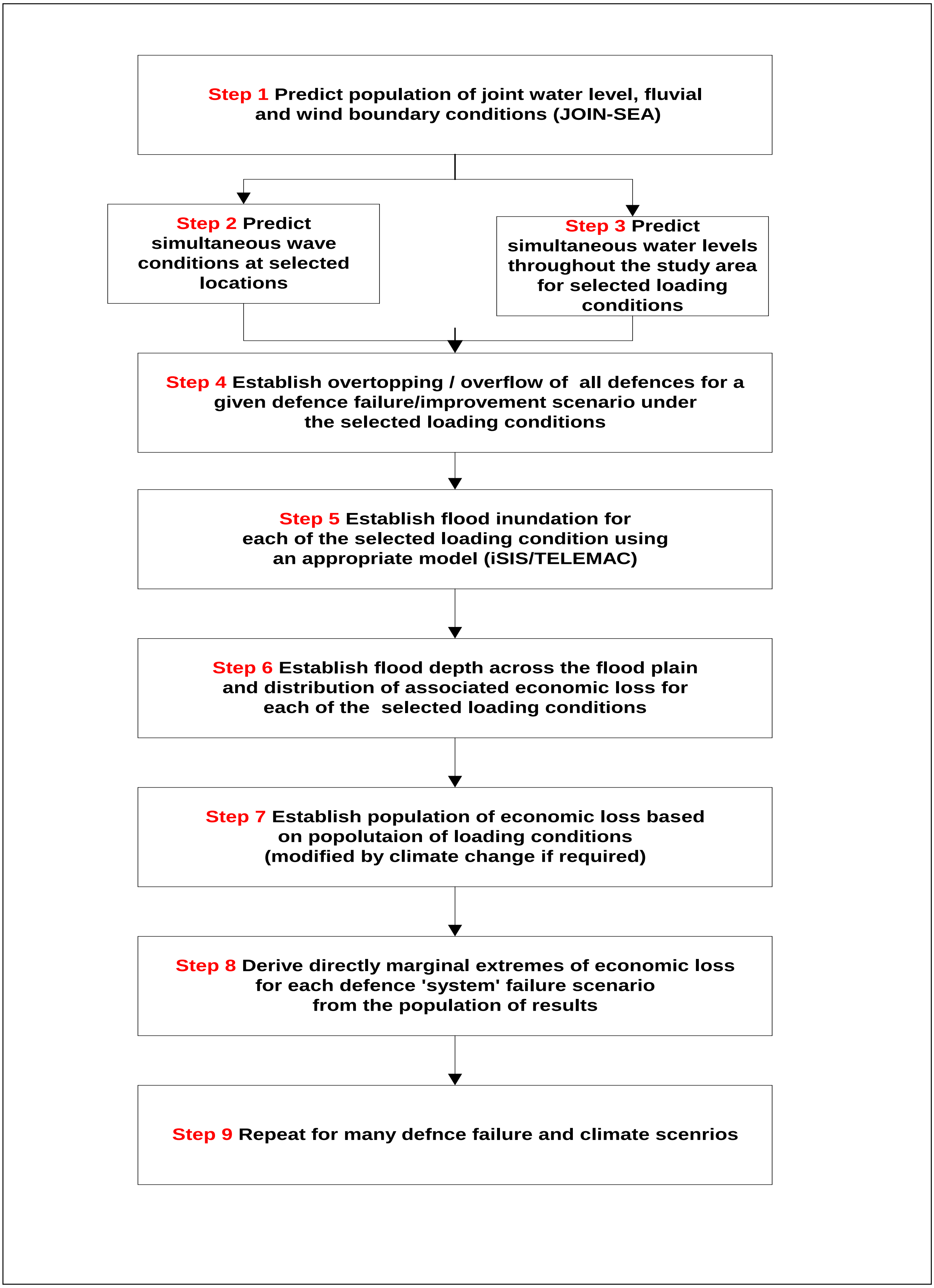

Figure 5 Flow chart showing the probabilistic economic damage assessment methodology

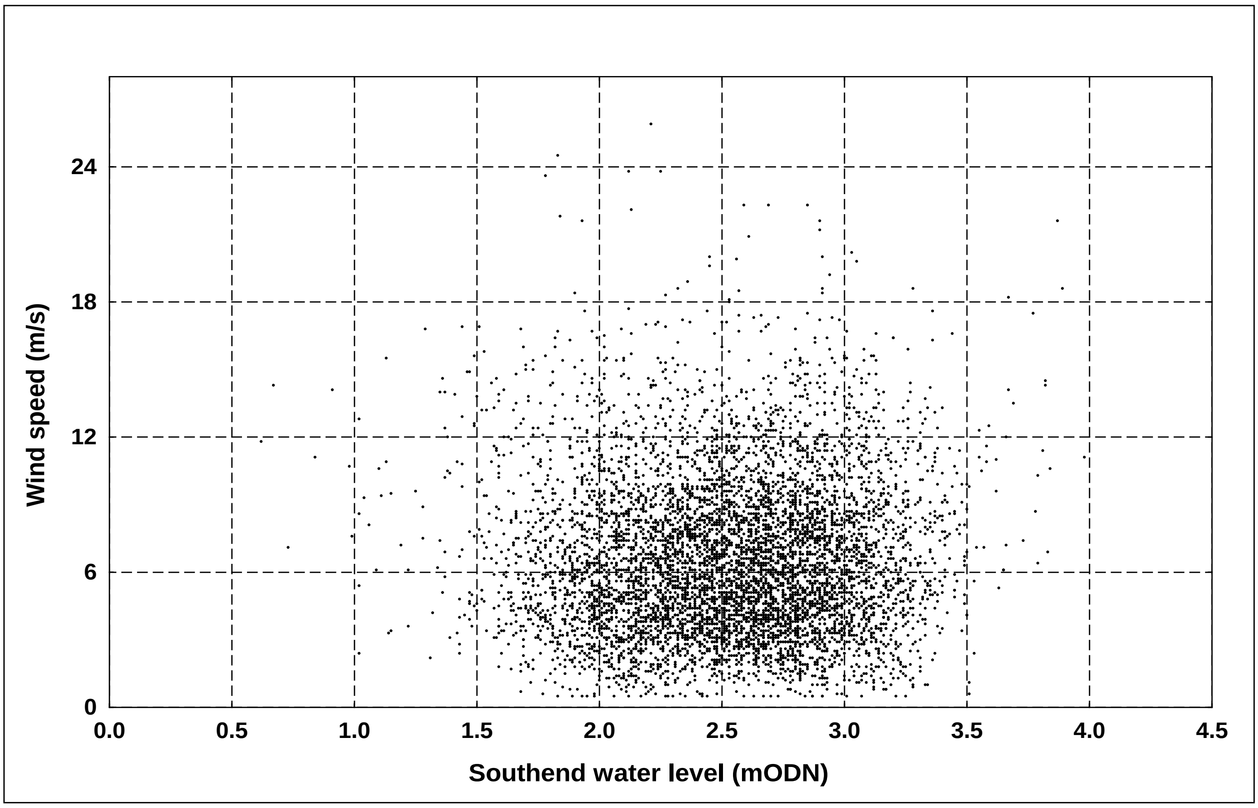

Figure 6 Population of joint wind and water levels at Southend-on-Sea

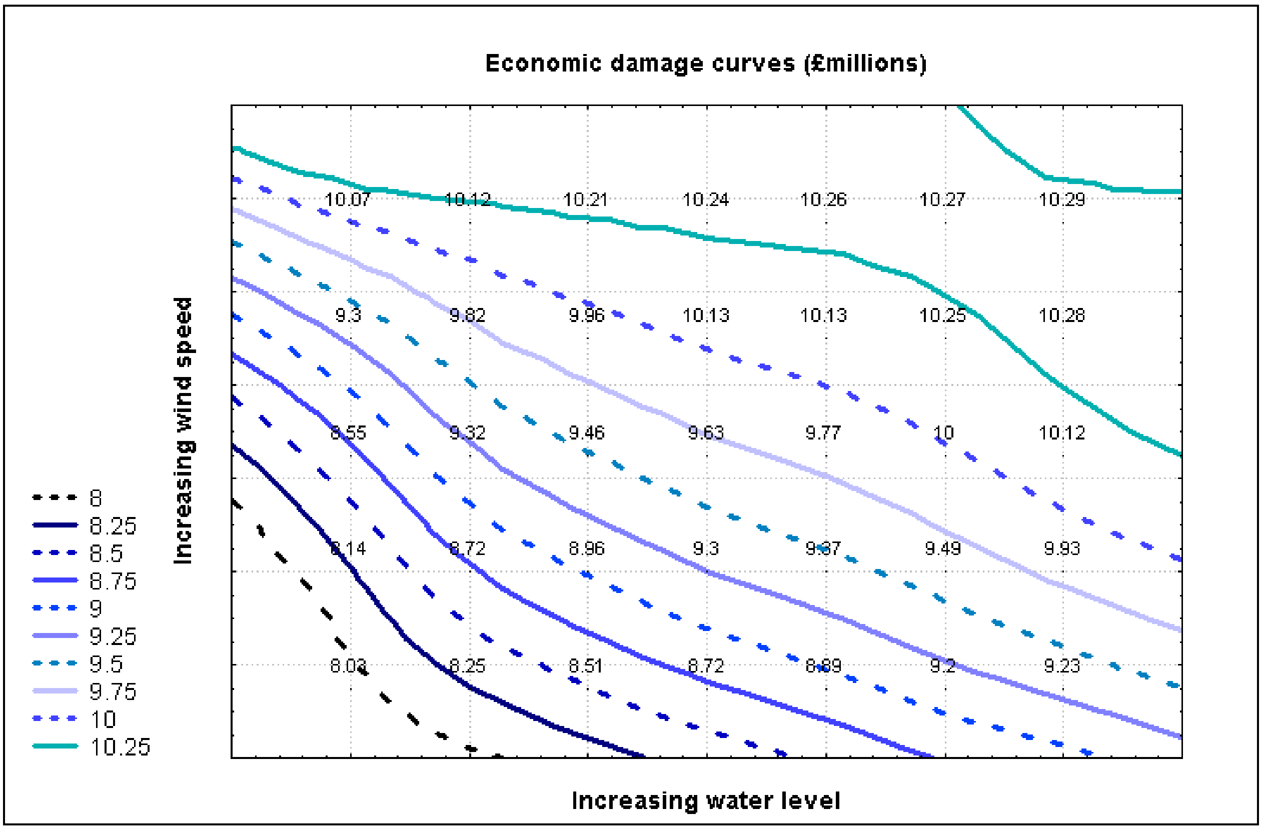

Figure 7 Indicative contours of economic damage based on results from selected full model runs