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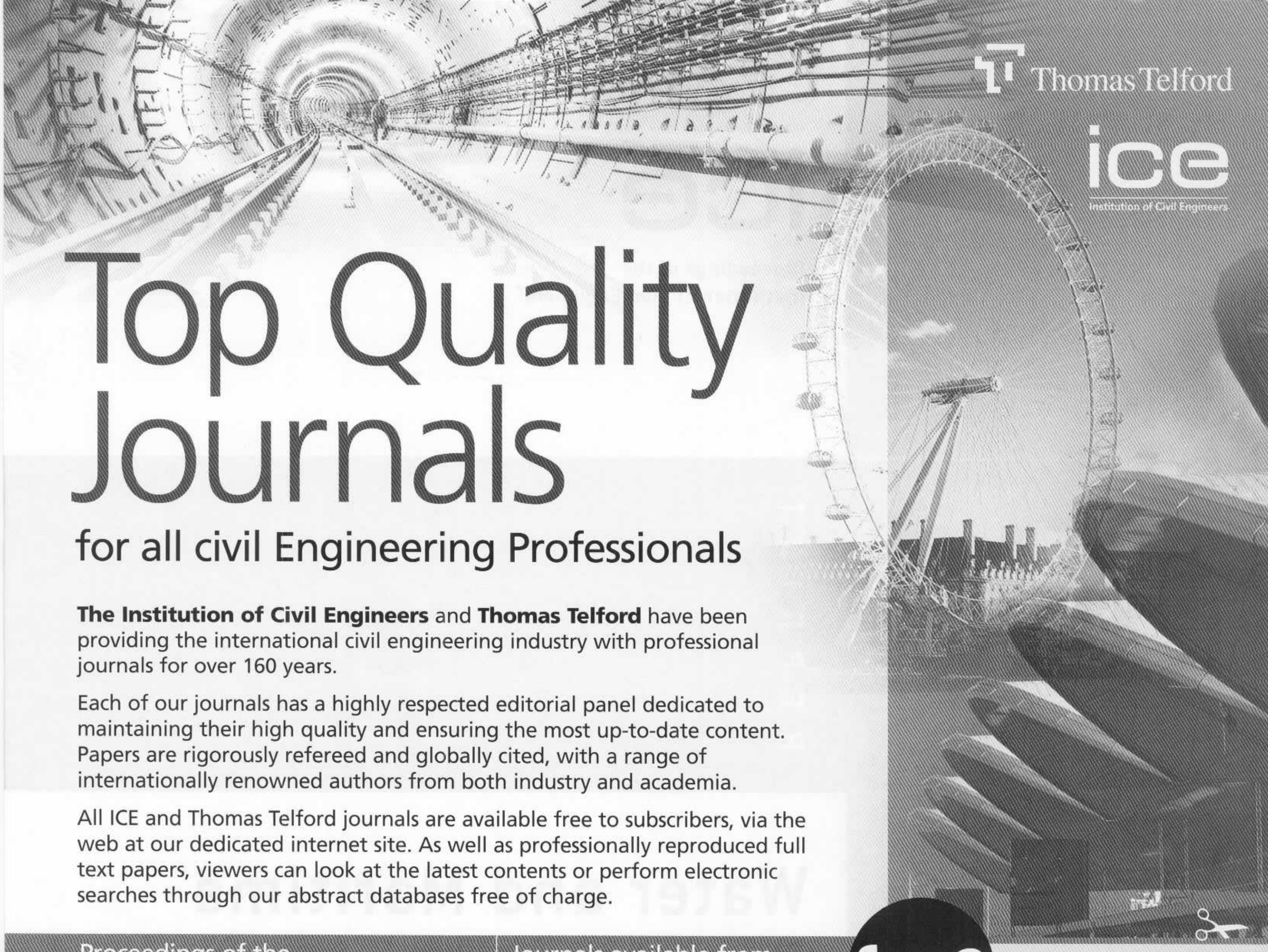Thomas Telford

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A methodology for national-scale flood risk assessment

J. W. Hall, R. J. Dawson, P. B. Sayers, C. Rosu, J. B. Chatterton and R. Deakin

Risk analysis provides a rational basis for flood management decision-making at a national scale, as well as regionally and locally. National-scale flood risk assessment can provide consistent information to support the development of flood management policy, allocation of resources and monitoring of the performance of flood mitigation activities. However, national-scale risk assessment presents particular challenges in terms of data acquisition and manipulation, numerical computation and presentation of results. A methodology that addresses these difficulties through appropriate approximations has been developed and applied in England and Wales. The methodology represents the processes of fluvial and coastal flooding over linear flood defence systems in sufficient detail to test alternative policy options for investment in flood management. Flood outlines and depths are generated, in the absence of a consistent national topographic and water level data set, using a rapid parametric inundation routine. Potential economic and social impacts of flooding are assessed using national databases of floodplain properties and demography. A case study of the river Parrett catchment and adjoining sea defences in Bridgwater Bay in England demonstrates the application of the method and presentation of results in a geographical information system.

NOTATION

A	catchment area
b	flow width
b_B	breach width
D_i	event: failure of defence section d_i
$D_{i,\mathrm{B}}$	event: failure of defence section d_i by breaching
$D_{i,\mathrm{OT}}$	event: failure of defence section d_i by overtopping
$D_1 \cap D_2$	event: failure of defence sections d_1 and d_2
$\overline{D_i}$	event: non-failure of defence section d_i
$d_1, d_2, \ldots, d_n$	defence sections $1, 2, \ldots, n$
E_t	error from neglecting scenarios with greater than t failures
$h_{\max}$	maximum head over the defence crest
IFM	indicative floodplain map
L	random variable for l
l	x.SOP
m	number of impact zones protected by a defence system
n	number of defence sections in a defence system
$P(D_i)$	probability of failure of defence section d_i
$P(D_i \vert x)$	probability of failure of defence section d_i, *given* load x
$P(X \geq x)$	probability that random variable X is greater than or equal to load x
P_k	the probability of defence system failure scenario k
$p(x)$	probability density function of the load x
q	overtopping discharge
q_p	peak overtopping discharge
R	expected annual damage
r	number of loading levels l considered
S_d	defence length
SFVI	social flood vulnerability index
SOP	standard of protection
$T_c(x)$	effective duration of the overtopping event
$T_f(x)$	duration of flow across the defence
T_s	typical effective duration of an overtopping event during a storm equal to the SOP
t	number of failure scenarios considered for a defence system
V_i	flood volume from failure of defence section i
X	random variable for load x
x	load proxy: multiple of the standard of protection
Y	random variable for flood depth
y	flood depth
y_k	flood depth in failure scenario k
$y_{\max}$	maximum flood depth
$z_1, z_2, \ldots, z_m$	impact zones $1, 2, \ldots, m$

1. INTRODUCTION

Over 5% of the UK population live in the 12 200 km^2 that is at risk from flooding by rivers and the sea.[1] These people and their property are protected by 34 000 km of flood defences. Serious flooding in 1998 and 2000 demonstrated the need for improved management of flood defences.[2–5] Recently the UK Government has allocated more resources for improving flood and coastal defence standards.[6] Flood risk assessment is required to support the appraisal of policy options, allocation of resources, and monitoring of the performance of substantial government investment in flood management.

The amount of resource, in terms of data acquisition and

Level of assessment	Decisions to inform	Data sources	Methodologies
High	Prioritisation of expenditure Regional planning Flood warning planning	Defence type Condition grades Standard of service Indicative floodplain maps Socio-economic data Land-use mapping	Generic assessment of defence resistance based on condition assessment and SOP Simple dependency assumptions Empirical methods to determine likely flood extent
Intermediate	*Above plus:* Flood defence strategy planning Regulation of development Maintenance management	*Above plus:* Defence crest level and other dimensions where available Joint probability load distributions Floodplain topography Detailed socio-economic data	Probabilities of defence failure from dominant failure mode Systems reliability analysis using joint loading conditions Modelling of limited number of inundation scenarios
Detailed	*Above plus:* Scheme appraisal and optimisation	*Above plus:* All parameters required describing defence strength Synthetic time series of loading conditions	Reliability analysis of multiple failure modes Continuous simulation of hydraulic loads

Table 1. Hierarchy of risk assessment methodologies[9]

analysis, that is committed to a risk assessment should reflect the nature of the decision(s) that the assessment seeks to inform. Flood management decisions take place at a number of levels, ranging from national policy decisions to planning decisions in catchments and coastal cells and local design and operational decisions. A hierarchy of flood risk assessment methods is therefore currently under development to support a range of flood management decisions (Table 1), building on previous tiered frameworks.[7–9]

This paper addresses the highest level in the hierarchy of flood management decisions, with the aim of supporting national-scale flood defence policy-making. National-scale risk assessment is by no means straightforward, because of the need to assemble national data sets and then carry out and verify very large numbers of calculations. The first assessment on this scale in the UK was published by HR Wallingford in 2000,[1] and provided an estimate of potential damage from flooding and coastal erosion in England and Wales. The 2000 study made use of nationally available flood outlines (the so-called indicative floodplain maps) and data sets on the domestic and industrial properties in floodplains. However, at the time, a national database of flood defences and their condition was not accessible, so the analysis necessarily made significant simplifications regarding the influence of defences on flood risk, taking no account of the standard of protection and condition of defences.

In 2002 the Environment Agency introduced a National Flood and Coastal Defence Database (NFCDD), which for the first time provides in a digital database an inventory of flood defence structures and their overall condition. Although the information held in NFCDD and other nationally available data sets is still limited, it has paved the way for the first national assessment of flood risk that incorporates probabilistic analysis of individual defence structures as well as the flood defence systems they create. This also means that possible changes in the performance of defence infrastructure under hydraulic loading (for example due to deterioration in condition, improvement in standard of protection or change in loading) can be evaluated. The risk assessment methodology therefore provides a tool for exploring the impact of future flood management policy and scenarios of climate change. Use of a national digital database is also attractive in that it enables changes in data to be automatically reflected within the assessment of flood risk. The objective of this paper is to describe this new national-scale flood risk assessment methodology.

2. OVERVIEW OF THE METHODOLOGY

Flood risk is conventionally defined as the product of the probability of flooding and the consequential damage, and is often quoted in terms of an expected annual damage, which is sometimes referred to as the *annual average damage.* For a national assessment of flood risk, expected annual damage must be aggregated over all floodplains in the country. An overview of the methodology by which this can be achieved is given in Fig. 1 and described in outline below.

The most significant constraint on a national-scale flood risk assessment methodology is the availability of data. The methodology presented here has been developed to make use of the following national GIS data sets and no other site-specific information.

(*a*) *Indicative floodplain maps* (*IFMs*). These represent the only nationally available information on the potential extent of flood inundation at the time of writing. The IFMs are outlines of the area that could potentially be flooded in the absence of defences in a 1:100-year return period flood for fluvial floodplains and a 1:200-year return period flood for coastal floodplains.

(*b*) *Ordnance Survey PANORAMA data set.* The methodology has been developed in the absence of a national topographic data set of reasonable accuracy. Topographic information at ±3 m vertical accuracy has only been used to classify floodplain types as it is not sufficiently accurate to estimate flood depths.

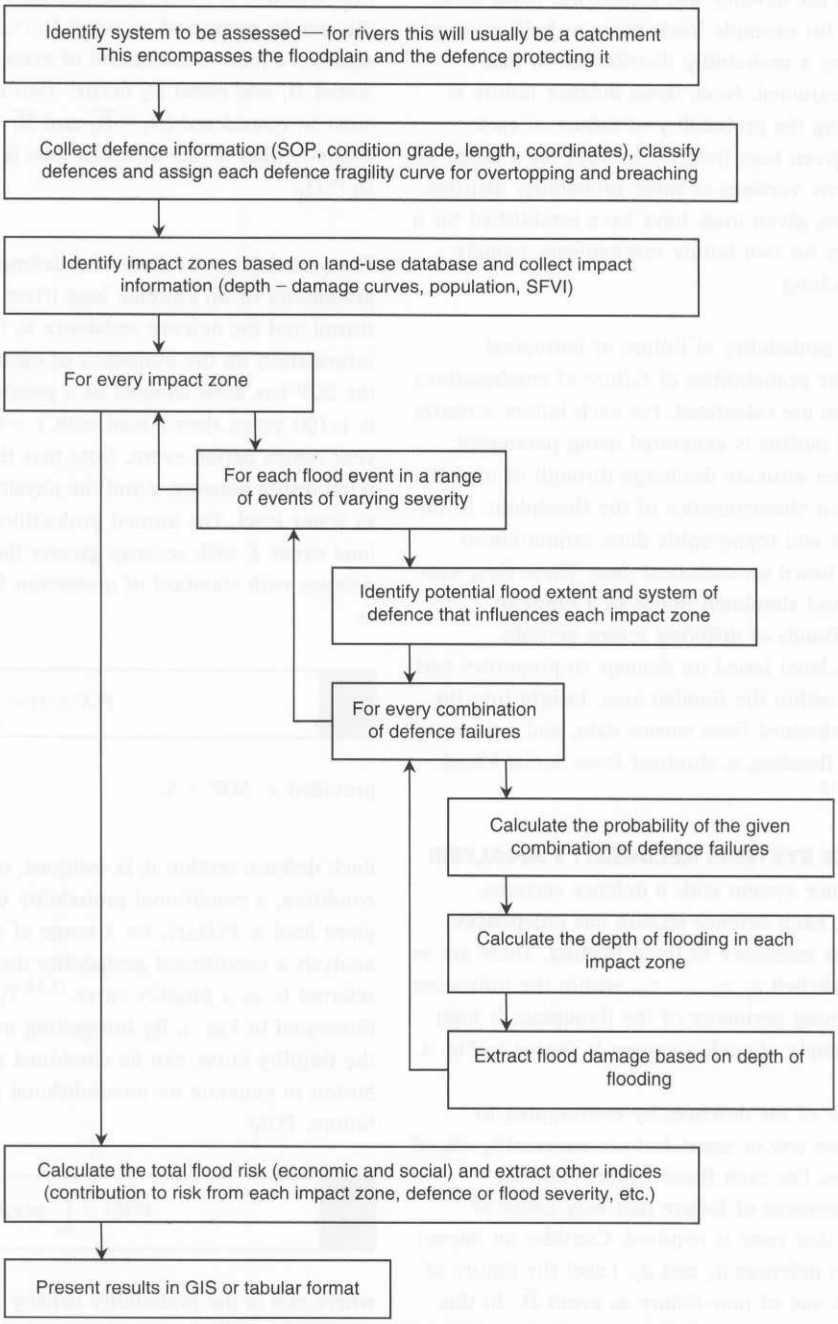

Fig. 1. Overview of the national flood risk assessment methodology

(c) *National map of the centreline of all watercourses.*

(d) *National Flood and Coastal Defence Database.* This provides a national data set of defence location, type and condition. Crucially, however, information on crest level and crest width is not mandatory and, therefore, is not available nationally. The methodology has been developed in the absence of quantitative information on the distribution of water levels and wave loads.

(e) *National database of locations of residential and business properties.*

In the absence of more detailed information on flood extent, in the current methodology the indicative floodplain is adopted as the maximum extent of flooding and is further subdivided into *impact zones,* not greater than 1 km × 1 km. Each flood impact zone is associated with a system of flood defences that, if one or more of them were to fail, would result in some inundation of that zone.

The probability of failure of a flood defence system can be estimated using the methods of structural reliability analysis.[10,11] However, to apply these methods requires (a) probability distributions for the hydraulic loads and the parameters describing defence response and (b) analytical or numerical expressions for each failure mode. Unfortunately the only available information on the relationship between flood water level and crest level, clearly crucial for flood risk analysis, is the so-called Standard of Protection (SOP), which is an assessment of the return period at which the defence will significantly be overtopped. In the current methodology the SOP is used to determine the frequency with which a defence is expected to be overtopped. It is also possible to estimate the frequency with which the defence will experience loads some factor times the SOP, for example loads twice or half as severe as the SOP. In this way a probability distribution of load relative to SOP is constructed. Next, flood defence failure is addressed by estimating the probability of failure of each defence section in a given load (relative to SOP) for a range of load conditions. Generic versions of these probability distributions of defence failure, given load, have been established for a range of defence types for two failure mechanisms, namely overtopping and breaching.

Having estimated the probability of failure of individual sections of defence, the probabilities of failure of combinations of defences in a system are calculated. For each failure scenario an approximate flood outline is generated using parametric routines. These routines estimate discharge through or over the defence and inundation characteristics of the floodplain. In the absence of water level and topographic data, estimation of flood depth has been based on statistical data. These data were assembled from real and simulated floods in a range of floodplain types and floods of differing return periods. Economic risk is calculated based on damage to properties and agricultural land use within the flooded area. Insight into the population at risk is obtained from census data, and a measure of the social harm of flooding is obtained from Social Flood Vulnerability Indices.[12]

3. FLOOD DEFENCE SYSTEMS RELIABILITY ANALYSIS

Consider a flood defence system with n defence sections, labelled $d_1, d_2, \ldots, d_n$. Each defence section has independent and usually a different resistance to flood loading. There are m flood impact zones, labelled $z_1, z_2, \ldots, z_m$, within the indicative floodplain. The remaining perimeter of the floodplain is high ground. A simple example of such a system is shown in Fig. 2.

Failure of one or more of the defences by overtopping or breaching will inundate one or more, but not necessarily all, of the flood impact zones. For each flood impact zone the probability of every scenario of failure that may cause or influence flooding in that zone is required. Consider an impact zone protected by two defences d_1 and d_2. Label the failure of defence d_i as event D_i and of non-failure as event $\overline{D_i}$. In this case there are three scenarios of defence system failure. The first scenario is where both defences fail. In more formal terms this can be expressed as event $D_1 \cap D_2$, where the symbol $\cap$ signifies a joint combination of events: that is, $D_1 \cap D_2$ signifies 'Event D_1 *and* event D_2 occur'. Two more failure scenarios must be considered ($D_1 \cap \overline{D_2}$ and $\overline{D_1} \cap D_2$), and a scenario where neither of the defences fails (a non-failure scenario), $\overline{D_1} \cap \overline{D_2}$.

The probability of failure of a defence is a function of the probability of an extreme load (river water level or marine storm) and the defence resistance to that load. In the absence of information on the frequency of extreme loads, a factor x times the SOP has been adopted as a proxy for load. Thus if the SOP is 1:100 years, then a load with $x = 0{\cdot}5$ corresponds to a 1:50-year return period event. Note that there is not a linear relationship between x and the physical loading variable(s) such as water level. The annual probability $P(X \geq x)$ of at least one load event X with severity greater than or equal to x at a defence with standard of protection SOP can be approximated as

$$P(X \geq x) = \frac{1}{x \cdot \mathrm{SOP}} \tag{1}$$

provided $x \cdot \mathrm{SOP} > 5$.

Each defence section d_i is assigned, on the basis of its type and condition, a conditional probability of failure event D_i for a *given* load x, $P(D_i|x)$, for a range of values of x. In reliability analysis a conditional probability distribution of this type is referred to as a *fragility curve*.[13,14] Typical fragility curves are illustrated in Fig. 3. By integrating over all loading conditions the fragility curve can be combined with the loading distribution to generate an unconditional probability of defence failure, $P(D_i)$

$$P(D_i) = \int_0^\infty p(x)P(D_i \mid x)\,\mathrm{d}x \tag{2}$$

where $p(x)$ is the probability density function of the load x, which is derived from equation (1) as explained below. The

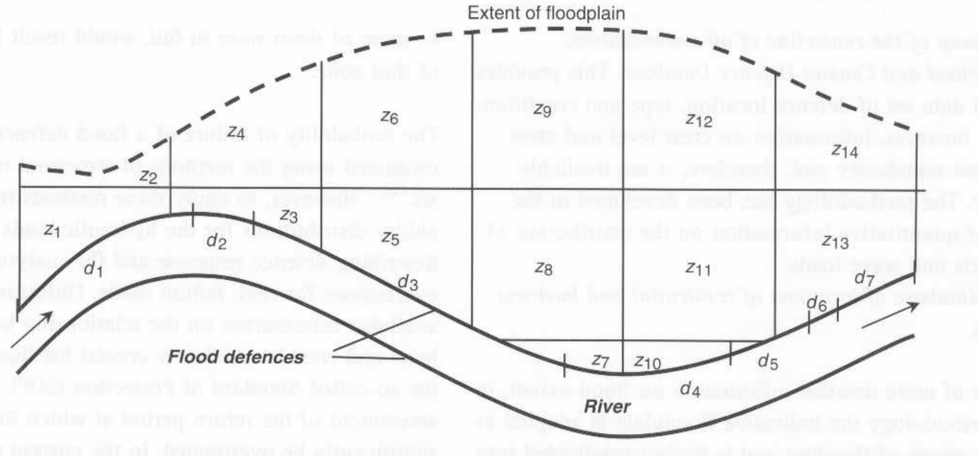

Fig. 2. Notation used to describe a flood defence system and flood impact zones

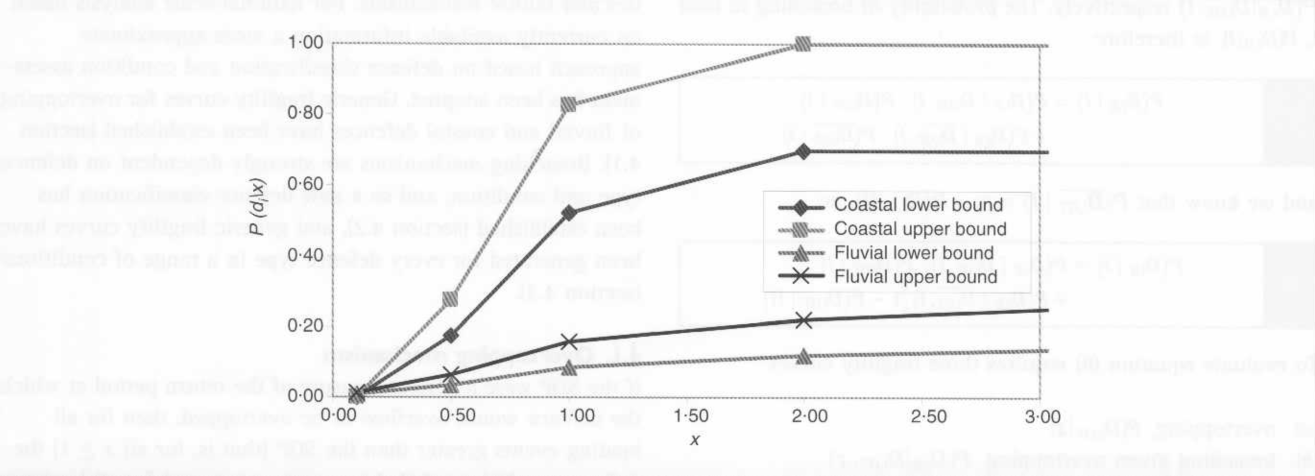

Fig. 3. Overtopping fragility curve used in national flood risk assessment (fluvial and sea defence)

product $x \cdot \mathrm{SOP}$ is a measure of the severity of the hydraulic load, so it is replaced by the symbol l, in which case

$$P(D_i) = \int_0^{\infty} p(l)P(D_i \mid l)\,\mathrm{d}l \tag{3}$$

and $P(D_i|l)$ can be obtained from the fragility curve by reading off at $x = l/\mathrm{SOP}$. If equation (1) is to be used to estimate $p(l)$ then $P(D_i|l)$ should be close to zero where l is outside the range of applicability of equation (1). For the purpose of the current analysis the fragility curve is defined in discrete terms at q levels of l: $l_1, \ldots, l_q$, enabling equation (3) to be rewritten as

$$P(D_i) = \sum_{j=2}^{q-1}\left[P\left(L \geq \frac{l_j + l_{j+1}}{2}\right) - P\left(L > \frac{l_j + l_{j-1}}{2}\right)\right]P(D_i \mid l_j) \tag{4}$$

where L is a random variable representing the hydraulic load. Unlike the commonly used first-order reliability method[11] this discrete approach allows arbitrarily shaped distributions of load and structural response. From a computational point of view, the discrete approach is attractive because it generates exact bounds on the probability of failure, illustrating numerical errors in the same format as the other uncertainties in the analysis (see section 7).

In order to estimate the probability of combinations of defence failures in a system it is important to consider the dependence between loads at different points in the system as well as possible dependence between defence response to loading. In this national-scale analysis three simple assumptions are made.

(*a*) Loading of all defences in a defence system is considered to be fully dependent: that is, all defences are subject to the same load at the same time. The relief of load on downstream defences due to failure of an upstream defence, for example, is not considered.

(*b*) The resistance of different defences to extreme loading is independent: that is, the strength of each defence is assessed independently and does not depend upon the strength of its neighbours. The assumption of independence means that if defence d_1 and d_2 are both subject to load l, then the probability of them both failing is given by

$$P(D_1 \cap D_2|l) = P(D_1|l) \cdot P(D_2|l) \tag{5}$$

(c) The resistance within a given defence section is fully dependent: that is, the whole section responds to loads in the same way.

For very long defences the third assumption becomes difficult to sustain. Whereas the parameters describing defence resistance, for example crest height or geotechnical properties, will show strong dependence nearby, CUR/TAW[10] suggest that over a distance greater than about 500 m these parameters are more or less independent. Therefore defences over 600 m in length are split into sections 300–500 m long.

Having accepted the assumptions outlined above, the probability of a typical failure scenario in which defences $d_1, \ldots, d_r$ fail and defences $d_{r+1}, \ldots, d_n$ do not fail, labelled event $D_1 \cap \ldots \cap D_r \cap \overline{D_{r+1}} \cap \ldots \cap \overline{D_n}$ is calculated as follows

$$\begin{aligned} &P(D_1 \cap \ldots \cap D_r \cap \overline{D_{r+1}} \cap \ldots \cap \overline{D_n}) \\ &\quad = \sum_{j=2}^{q-1}\left[P\left(L \geq \frac{l_j + l_{j+1}}{2}\right) - P\left(L \geq \frac{l_j + l_{j-1}}{2}\right)\right] \\ &\quad \times P(D_1 \mid l_j) \ldots P(D_r \mid l_j) \cdot P(\overline{D_{r+1}}|l_j) \ldots P(\overline{D_n} \mid l_j) \end{aligned} \tag{6}$$

To understand the impact of defence failure it is also important to establish the mode of failure, be it breach or overtopping. The impacts of overtopping and breaching failure modes can be quite different, so denote failure of defence d_i by overtopping as $D_{i,\mathrm{OT}}$ and its failure by breaching as $D_{i,\mathrm{B}}$. Non-failures are labelled $\overline{D_{i,\mathrm{OT}}}$ and $\overline{D_{i,\mathrm{B}}}$ respectively. Breaching and overtopping are not independent failure mechanisms. Indeed overtopping is one of the common initiating mechanisms of a breach. This dependence is accounted for by first considering the probability of failure by overtopping given a particular load l, $P(D_{i,\mathrm{OT}} \mid l)$ and then the probability of breaching, with or without overtopping, again in load l, labelled $P(D_{i,\mathrm{B}} D_{i,\mathrm{OT}}, l)$ and

$P(D_{i,\mathrm{B}}|\overline{D_{i,\mathrm{OT}}}, l)$ respectively. The probability of breaching in load l, $P(D_{i,\mathrm{B}}|l)$, is therefore

$$\begin{aligned} P(D_{i,\mathrm{B}} \mid l) = {} & P(D_{i,\mathrm{B}} \mid D_{i,\mathrm{OT}}, l) \cdot P(D_{i,\mathrm{OT}} \mid l) \\ & + P(D_{i,\mathrm{B}} \mid \overline{D_{i,\mathrm{OT}}}, l) \cdot P(\overline{D_{i,\mathrm{OT}}} \mid l) \end{aligned} \tag{7}$$

and we know that $P(\overline{D_{i,\mathrm{OT}}} \mid l) = 1 - P(D_{i,\mathrm{OT}}|l)$, so

$$\begin{aligned} P(D_{i,\mathrm{B}} \mid l) = {} & P(D_{i,\mathrm{B}} \mid D_{i,\mathrm{OT}}, l) \cdot P(D_{i,\mathrm{OT}} \mid l) \\ & + P(D_{i,\mathrm{B}} \mid \overline{D_{i,\mathrm{OT}}}, l)\left[1 - P(D_{i,\mathrm{OT}} \mid l)\right] \end{aligned} \tag{8}$$

To evaluate equation (8) requires three fragility curves

(*a*) overtopping, $P(D_{i,\mathrm{OT}}|x)$
(*b*) breaching given overtopping, $P(D_{i,\mathrm{B}}|D_{i,\mathrm{OT}}, x)$
(*c*) breaching given no overtopping, $P(D_{i,\mathrm{B}} \mid \overline{D_{i,\mathrm{OT}}}, x)$

Considering one typical scenario, where the first defence is overtopped, the second defence is breached, and the remaining defences, $d_3, \ldots, d_n$, do not fail—that is, $D_{1,\mathrm{OT}} \cap D_{2,\mathrm{B}} \cap \overline{D_3} \cap \ldots \cap \overline{D_n}$, equation (6) (setting $r = 2$) becomes

$$\begin{aligned} & P(D_{1,\mathrm{OT}} \cap D_{2,\mathrm{B}} \cap \overline{D_{r+1}} \cap \ldots \cap \overline{D_n}) \\ & \quad = \sum_{j=2}^{r-1} \left[P\left(L \geq \frac{l_j + l_{j+1}}{2}\right) - P\left(L \geq \frac{l_j + l_{j-1}}{2}\right)\right] \\ & \quad \times P(D_{1,\mathrm{OT}} \mid l_j) \cdot P(D_{2,\mathrm{B}} \mid l_j) \cdot P(\overline{D_3} \mid l_j) \ldots P(\overline{D_n} \mid l_j) \end{aligned} \tag{9}$$

where $P(D_{2,\mathrm{B}} \mid l_j)$ is obtained from equation (8).

For each defence there are three states that are of interest: overtopped, breached and not failed. For an impact zone protected by n defences there are therefore 3^n system states whose probabilities are to be estimated. For a large system, the analysis of such a large number of scenarios may require an excessive amount of computer processing time. However, provided the defence resistance is not fully dependent high-order scenarios—that is, scenarios in which a large number of defences in a system fail—make a small contribution to the total probability of failure and so can be neglected. The error due to this approximation can be calculated exactly provided the probability of non-failure for the whole system, $P(\overline{D_1} \cap \overline{D_2} \cap \ldots \cap \overline{D_n})$, is also calculated. Suppose that in a system with n defence sections, the probabilities of all scenarios with between zero and five failures have been calculated. There will be

$$t = \sum_{i=0}^{5} \frac{n!}{i!(n-i)!} \tag{10}$$

such scenarios, the probability of each of which is labelled P_k, $k = 1, \ldots, t$. The error, E_t, from neglecting scenarios with greater than t failures, is given by

$$E_t = 1 - \sum_{k=1}^{t} P_k \tag{11}$$

4. CONSTRUCTING FRAGILITY CURVES

In a detailed risk analysis, fragility curves for overtopping and breaching mechanisms would be constructed on a site-specific basis by consideration of defence dimensions, material properties and failure mechanisms. For national-scale analysis based on currently available information a more approximate approach based on defence classification and condition assessment has been adopted. Generic fragility curves for overtopping of fluvial and coastal defences have been established (section 4.1). Breaching mechanisms are strongly dependent on defence type and condition, and so a new defence classification has been established (section 4.2), and generic fragility curves have been generated for every defence type in a range of conditions (section 4.3).

4.1. Overtopping mechanism

If the SOP were a perfect measure of the return period at which the defence would overflow or be overtopped, then for all loading events greater than the SOP (that is, for all $x \geq 1$) the defence would have failed by overtopping, and for all loading events less than the SOP (that is, for all $x < 1$) it would be safe. However, flood defences typically include some allowance for freeboard, and in wave conditions coastal flood defences may overtop in conditions significantly below their SOP. There is also uncertainty in the crest levels and extreme loads themselves, as well as in the SOP allocated in the assessment process. Freeboard allowance cannot be assumed to be nationally uniform, because of different local conventions and assumed rates of settlement. The fragility curves shown in Fig. 3 have therefore been adopted. The curve shows a significant chance of overtopping at $x < 1$, especially for coastal defences, but the defence is not guaranteed to overtop at $x > 1$. Uncertainty is reflected through the use of upper and lower bounds on the conditional failure probability for a given load, x, as described in section 7. Evidence from floods of known severity overtopping defences of known SOP, primarily from records of the autumn/winter floods of 2000,[3] has been used to verify points on this curve.

4.2. Defence classification

In England and Wales the Environment Agency classifies every flood defence based on the individual defence components (for example inward slope, crest and outward slope) and their composition (for example turf or concrete).[15] This leads to a classification in which subdivisions have little bearing on the proneness to failure, whereas important characteristics such as crest width and level can go unrecorded.

For the purpose of national-scale risk analysis a simple new classification has been developed, focusing on those salient characteristics of a defence cross-section that influence its resistance to extreme loads. An algorithm has been established that gives a direct mapping from the classification used by the Environment Agency to the new classification introduced here.

At the high level in the classification are seven defence types that show significantly different behaviour (Fig. 4). The next level within the hierarchy considers the degree of protection offered by the defence. A wider defence will provide more protection than a narrow defence, as will a defence that is protected on its front slope, crest and rear slope, compared with one without protection.[8] The next level of classification considers the properties of individual components.

4.3. Breaching mechanism

The probability of breaching in a storm of given severity is influenced by the type of defence and its condition. As suggested in section 3, it is also strongly influenced by the presence or absence of defence overtopping. Therefore a family of fragility curves has been developed including each defence classification, condition grade and overtopping/non-overtopping cases. The fragility curves were developed using a similar technique to that proposed by the US Army Corps of Engineers (USACE),[16] in which critical points on the curve are fixed by a combination of expert judgement and analysis, with a straight line between them.

The only nationally available information on defence condition is a visual assessment that grades each defence from grade 1 ('very good') to grade 5 ('very poor'). The Environment Agency's Condition Assessment Manual[17] provides benchmark photographs of the main types of defence in all five conditions. Grade 5 nominally represents a defence in an effectively failed condition. However, the photographs in the Condition Assessment Manual indicate that some of these defences would afford some resistance against breaching, at least in loads where $x < 1$, so a fragility curve has been established based on assessment of this residual resistance. Unfortunately, field evidence of defence breaching in loads of known severity for defences in known pre-storm condition is very scarce indeed. Verification of the fragility curves has therefore been based primarily on published values of the resistance of defence materials to overtopping.[8,10,18]

5. FLOOD INUNDATION

Having estimated the probability of every scenario of defence system failure, the consequences of flooding are established by first estimating flood depths (this section) and then estimating damage (section 6). Flood depth estimation is based on volumetric analysis that employs a series of simple approximations. Further justification for these approximations is provided in HR Wallingford Report SR603.[19] The inundation calculations outlined below are conducted for every failure scenario of breaching and/or overtopping and at every discrete level of loading. The purpose of the inundation method is to estimate the flood depth in a specified scenario, irrespective of the probability of that scenario occurring. The depth estimates are then weighted according to the probability of each failure scenario (section 5.5).

5.1. Overtopping flood volumes: fluvial floodplains

In the case of overtopping of a fluvial defence, the flow of water over or through the defence is similar to the flow over a rectangular, broad-crested weir, and therefore the peak discharge q_p (m^3/s.m) is given by[20]

$$q_p = 1{\cdot}71 b h_{max}^{1{\cdot}5} \tag{12}$$

where b is flow width (in metres), which is taken as equal to the defence length, and h_{max} is the maximum head (in metres) over the defence crest, which is approximated by[19]

$$h_{max} = 0{\cdot}05 x^2 \tag{13}$$

As previously, x is the ratio of the return period of the event under consideration to the SOP of the defence, and is allowed to take any value between 0 and 3. An upper limit to the ratio x has been imposed to reflect the natural limit to h_{max} over any single defence. Above this limit, overtopping of upstream defences, a process that is not explicitly represented in the methodology, is likely to limit the continued increase in h_{max} with increasing load. The flood volume (m^3) from failure of defence section i, V_i, is estimated as

$$V_i = 0{\cdot}5 q_p T_f(x) \tag{14}$$

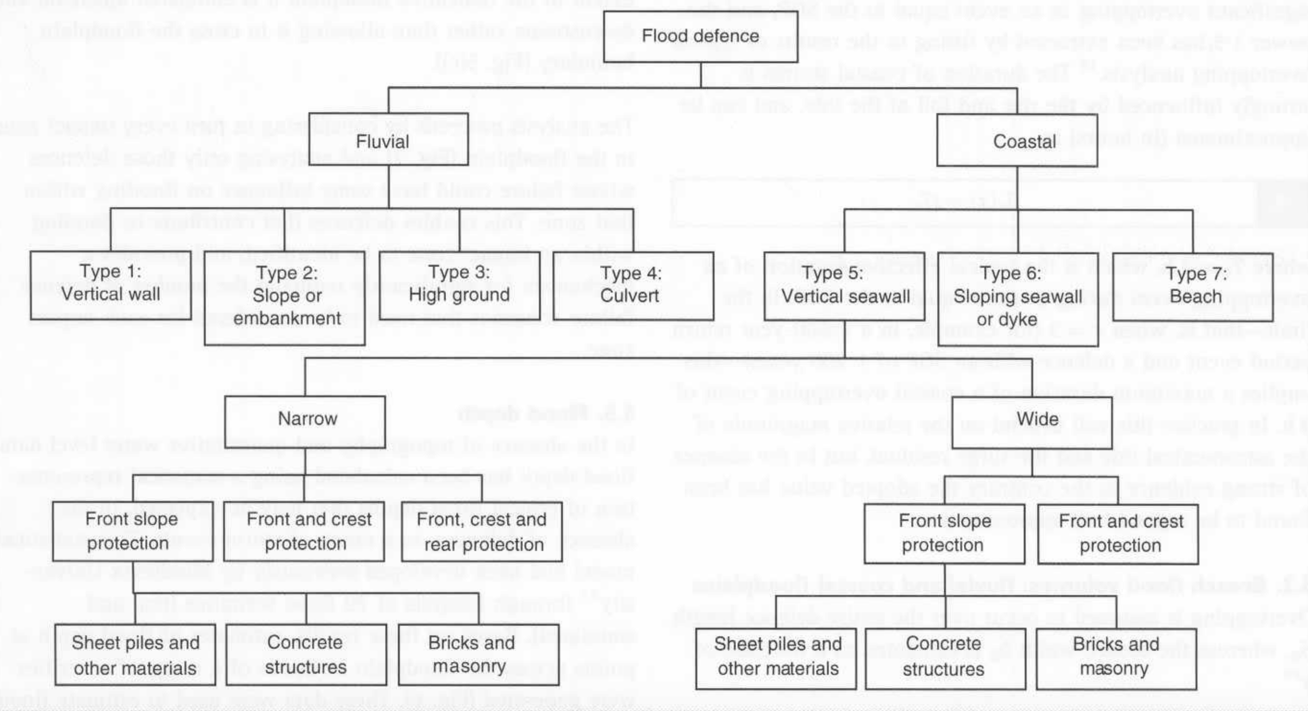

Fig. 4. Main classes of flood defence with details of vertical seawall classification

Floodplain type	Event return period: years	B: h/km$^{0{\cdot}5}$
Steep	>50	1·2
Steep	≤ 50	0·6
Average	>50	0·8
Average	≤ 50	0·4
Shallow	>50	1·2
Shallow	≤ 50	0·6

Table 2. Values of parameter B

where $T_f(x)$ is duration of flow across the defence (in seconds), given as a function of the form[19]

$$T_f(x) = A^{0{\cdot}25}Bx^{0{\cdot}5} \tag{15}$$

where A is the catchment area (km^2) and the coefficient B is obtained from Table 2, yielding T_f in hours. In equation (14) both the duration, T_f, of the flow across the defence and the maximum depth, h_{max}, of flow over the defence depend on the ratio x. Therefore both duration and water depth will increase as the ratio x increases.

5.2. Overtopping flood volumes: coastal floodplains

Coastal overtopping is estimated from

$$V_i = qbT_c(x) \tag{16}$$

where b is the length of the defence overtopped (in metres), $T_c(x)$ is the effective duration of the overtopping event converted into seconds, and the overtopping q (m^3/m.s) is approximated from[19]

$$q = 0{\cdot}05x^{1{\cdot}5} \tag{17}$$

The rate $q = 0{\cdot}05$ m^3/m.s at $x = 1$ is taken as the definition of significant overtopping in an event equal to the SOP, and the power 1·5 has been extracted by fitting to the results of typical overtopping analysis.[18] The duration of coastal storms is strongly influenced by the rise and fall of the tide, and can be approximated (in hours) as

$$T_c(x) = xT_s \tag{18}$$

where $T_s = 3$ h, which is the typical effective duration of an overtopping event during a storm equal to the SOP. In the limit—that is, when $x = 3$ (for example, in a 1:600-year return period event and a defence with an SOP of 1:200 years)—this implies a maximum duration of a coastal overtopping event of 9 h. In practice this will depend on the relative magnitude of the astronomical tide and the surge residual, but in the absence of strong evidence to the contrary the adopted value has been found to be a good first approximation.

5.3. Breach flood volumes: fluvial and coastal floodplains

Overtopping is assumed to occur over the entire defence length S_d, whereas the breach width b_B is estimated as a function of x[19]

$$b_B = 0{\cdot}05xS_d, b_B \leq S_d \tag{19}$$

There is little information on the breaching process, but observational evidence from the autumn 2000 flood records (for example in Lewes, where river walls with an SOP of 30–50 years breached along 33 m in three sections during a 70–100-year return period event) has been used to support equation (19). The flood volume is then estimated from equation (14), using $T_f(x)$ values from equation (15) for fluvial defences, and substituting $T_c(x)$ (equation (18)) for $T_f(x)$ in the case of coastal defences. It is assumed that the duration of flow through a breach will be the same as the overtopping duration for a storm of given severity. In both cases the maximum head, h_{max}, over the breach is assumed to be given by[19]

$$h_{max} = 0{\cdot}5x^{0{\cdot}5} \tag{20}$$

That is, the depth of flow is taken as 0·5 m when $x = 1$.

5.4. Flood extent

The flood extent is obtained by spreading the flood volume assuming an average flood depth and outline shape. First a uniform flood depth of 0·2 m is assumed, together with either a semicircular or trapezoidal outline shape constrained by the indicative floodplain to establish the limits of flooding for a given volume. Note that this depth is used only to estimate the flood outline and is not directly used in the damage assessment.

To determine the outline shape, the floodplain is classified using a 1:50 000 digital terrain model and the indicative floodplain maps (IFMs) as U-shaped for flat floodplains, V-shaped for steeply sloping narrow floodplains, and W-shaped for compound floodplains in which flood depths increase from the river and then reduce.[21] U-shaped and coastal floodplains are assumed to have a semicircular flood outline centred at the point of failure, with equal upstream and downstream flooding (Fig. 5(a)). V-shaped floodplains are assigned an asymmetrical triangular outline, with a greater downstream flooding (Fig. 5(b)). For all floodplains, when the flood outline reaches the extent of the indicative floodplain it is elongated upstream and downstream rather than allowing it to cross the floodplain boundary (Fig. 5(c)).

The analysis proceeds by considering in turn every impact zone in the floodplain (Fig. 2) and analysing only those defences whose failure could have some influence on flooding within that zone. This enables defences that contribute to flooding within an impact zone to be identified, and provides a mechanism for significantly reducing the number of defence failure scenarios that need to be considered for each impact zone.

5.5. Flood depth

In the absence of topography and quantitative water level data, flood depth has been calculated using a statistical representation of typical flood depths that may be expected, in the absence of defences, in a range of storm events. This statistical model had been developed previously by Middlesex University[21] through analysis of 70 flood scenarios (real and simulated). Based on these results, estimates of flood depth at points across the floodplain in floods of a range of severities were generated (Fig. 6). These data were used to estimate flood depth at points between a failed defence and the floodplain boundary, in events of a given severity. The Middlesex data

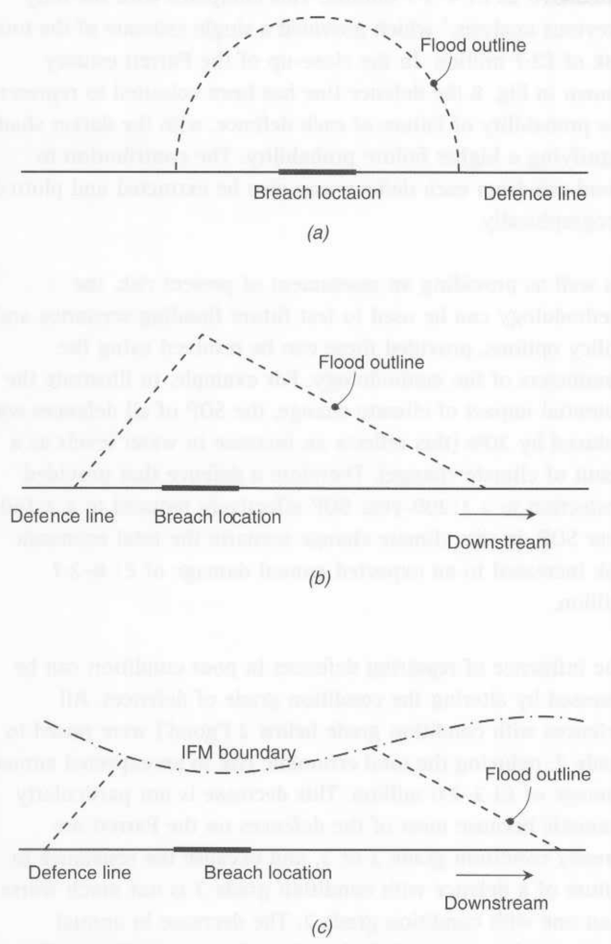

Fig. 5. Assumed flood outlines and depths: (a) U-shaped floodplains; (b) V-shaped floodplains; (c) V-shaped floodplains where flood outline meets boundary of IFM

related to flood depths immediately behind the failed defence, and so were further modified to estimate flood depths upstream and downstream (or along the coast) from the failure. The depth is assumed to decrease linearly, by a factor e, with distance upstream and downstream of the failure location, where $e = 1$ at the failed defence and $e = 0$ at the predicted limit of the flood outline. In the case of multiple defence failures resulting in the flood outlines overlapping, the factor e is aggregated to a maximum of 1.

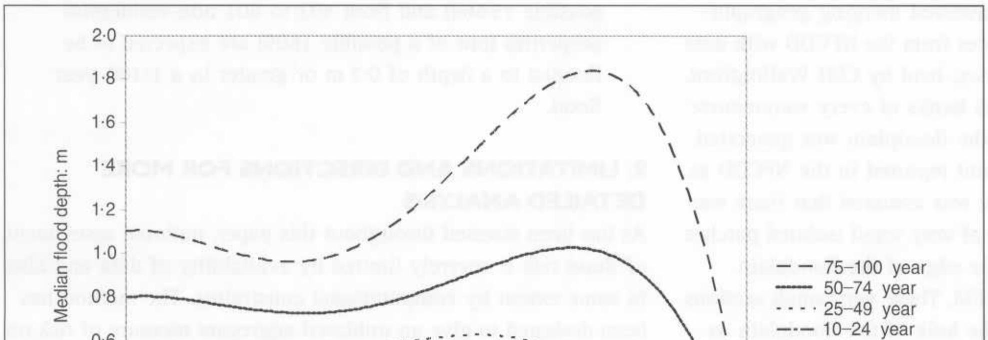

Fig. 6. Smoothed median results of statistical data on flood depths across the floodplain for floods of varying return period (years)[21]

If a given point in the floodplain is predicted to be inundated in t different defence failure scenarios, each of which results in a flood depth y_k, $k = 1, \ldots, t$ with corresponding probability P_k, then the probability of the flood depth Y exceeding some value y is given by

$$P(Y \geq y) = \sum_{y_j \geq y} P_j \tag{21}$$

6. ANALYSIS FOR FLOOD DAMAGE

The probability distribution of flood depth (equation (21)) was calculated at the centroid of each impact zone and assumed to apply to the whole of the impact zone.

6.1. Economic damage

The numbers of domestic and commercial properties in each impact zone were extracted from nationally available databases of economic damage values at given flood depths. For a given impact zone the expected annual damage, R, is given by

$$R = \int_0^{y_{\max}} p(y) D(y) \, \mathrm{d}y \tag{22}$$

where $y_{\max}$ is the greatest flood depth from all failure scenarios, $p(y)$ is the probability density function for flood depth, which can be obtained from equation (21), and $D(y)$ is the damage in the impact zone in a flood of depth y metres. The total expected annual damage for a catchment or nationally is obtained by summing the expected annual damage for each impact zone within the required area.

6.2. Social impacts

The population at risk was estimated from the number of inhabitants within an impact zone using 2001 census data. The Social Flood Vulnerability Indices (SFVI)[12] were used to identify communities vulnerable to the impacts of flooding.

Social vulnerability is ranked from 'very low' to 'very high' and is based on a weighting of the number of lone parents, the population over 75 years old, the long-term sick, non-homeowners, unemployed, non-car-owners and overcrowding, obtained from census returns. The risk of social impact is obtained as a product of probability of flooding to a given depth and the SFVI, providing a comparative measure for use in policy analysis.

7. HANDLING UNCERTAINTY

Each of the stages in the methodology outlined above is prone to uncertainty because of the approximations in the methodology and the great variability in the quality of data available for national-scale analysis. At a national scale many local errors will cancel each other out. However, it has been necessary to estimate risk at a fairly detailed local scale before aggregating risk nationally. These local assessments provide a useful starting point or cross-check for more detailed analysis, but are rather approximate so have the potential to be quite misleading, particularly if quoted to an inappropriate precision.

A simple but explicit method of representing uncertainty has been adopted at each stage in the analysis and carried through to all results. Uncertainty is represented by dealing with lower and upper bounds on each of the most uncertain quantities. For example, the uncertainty in the fragility curves is addressed by representing these curves as upper and lower bounds on the curves shown in Fig. 3. Thus risk estimates are presented as upper and lower bounds. These bounds have been elicited from experts as the credible limits between which they expect the actual value to lie. No calibration of expert judgement has been applied, but the judgement of several experts has been pooled in the analysis in order to address bias and overconfidence in expert judgements. No assumption about the distribution of risk between these bounds is implied, though in the absence of further information the best estimate will lie at the midpoint. This best estimate should be quoted only on a whole catchment or national basis. At a more local scale the wide bounds on risk estimates will provide a motive for further data collection and analysis.

8. EXAMPLE IMPLEMENTATION

The flood risk assessment methodology was first tested on the Parrett catchment in the south-west of England, a system of sufficient complexity to evaluate the robustness of the methodology, before proceeding to the full national assessment. The lower reaches of the Parrett include a network of drainage channels, whereas the upper reaches are quite steep. The fluvial defences adjoin short sections of sea defence in Bridgwater Bay. To enable comparison with a previous study,[1] inflation-adjusted depth-damage data from 1990[22] rather than the most recent data[23] were used in the test implementation.

Establishing the defence system involved merging geographically indexed data on flood defences from the NFCDD with data on the centreline of all watercourses, held by CEH Wallingford. A continuous defence line on both banks of every watercourse and along all coastlines fronting the floodplain was generated. Significant lengths of river were not reported in the NFCDD as having a defence, in which case it was assumed that there was no raised defence. Large numbers of very small isolated patches of floodplain were located near the edge of the floodplain owing to the rasterisation of the IFM. These very small sections of floodplain were merged with the bulk of the floodplain as they contributed insignificantly to the overall risk but added substantial computational burden.

The two main outputs for the analysis,[19] which were geographically indexed in a geographical information system (GIS), were the risk in each impact zone and the average contribution to this risk from each defence in the flood defence system. Fig. 7 shows the output from the economic risk assessment. The total expected annual damage for the Parrett catchment was calculated as £1·4–2·1 million. This compares with the only previous analysis,[1] which provided a single estimate of the total risk of £2·7 million. In the close-up of the Parrett estuary shown in Fig. 8 the defence line has been coloured to represent the probability of failure of each defence, with the darker shade signifying a higher failure probability. The contribution to flood risk from each defence can also be extracted and plotted geographically.

As well as providing an assessment of present risk, the methodology can be used to test future flooding scenarios and policy options, provided these can be resolved using the parameters of the methodology. For example, to illustrate the potential impact of climate change, the SOP of all defences was reduced by 20% (this reflects an increase in water levels as a result of climate change). Therefore a defence that provided protection to a 1:200-year SOP effectively reduced to a 1:160-year SOP. In this climate change scenario the total economic risk increased to an expected annual damage of £1·8–2·7 million.

The influence of repairing defences in poor condition can be assessed by altering the condition grade of defences. All defences with condition grade below 2 ('good') were raised to grade 2, reducing the total economic risk to an expected annual damage of £1·3–2·0 million. This decrease is not particularly dramatic because most of the defences on the Parrett are already condition grade 2 or 3, and because the resistance to failure of a defence with condition grade 3 is not much worse than one with condition grade 2. The decrease in annual average risk can be weighed against the estimated cost of repairing the defences.

Other queries that can be made on the output data include

(*a*) risk contribution from defences aggregated by condition grade
(*b*) risk contribution from defences aggregated by SOP
(*c*) risk contribution from floods of varying severity
(*d*) number of houses at risk of flooding to a given depth with a given probability. For example, in the Parrett catchment, between 2335 and 2704 residential properties (out of a possible 15 668) and from 492 to 601 non-residential properties (out of a possible 1605) are expected to be flooded to a depth of 0·2 m or greater in a 1:100-year flood.

9. LIMITATIONS AND DIRECTIONS FOR MORE DETAILED ANALYSIS

As has been stressed throughout this paper, national assessment of flood risk is severely limited by availability of data and also to some extent by computational constraints. The method has been designed to give an unbiased aggregate measure of risk on a national basis, and cannot be expected to be consistently accurate for every locality. Key limitations are as follows.

(*a*) The frequency of extreme fluvial flows or marine storms has not been assessed directly. The factor x times SOP has been used as a proxy for load.
(*b*) Probabilistic analysis of defence resistance using fragility curves is based on a simple defence classification and generic fragility curves that do not take explicit account of

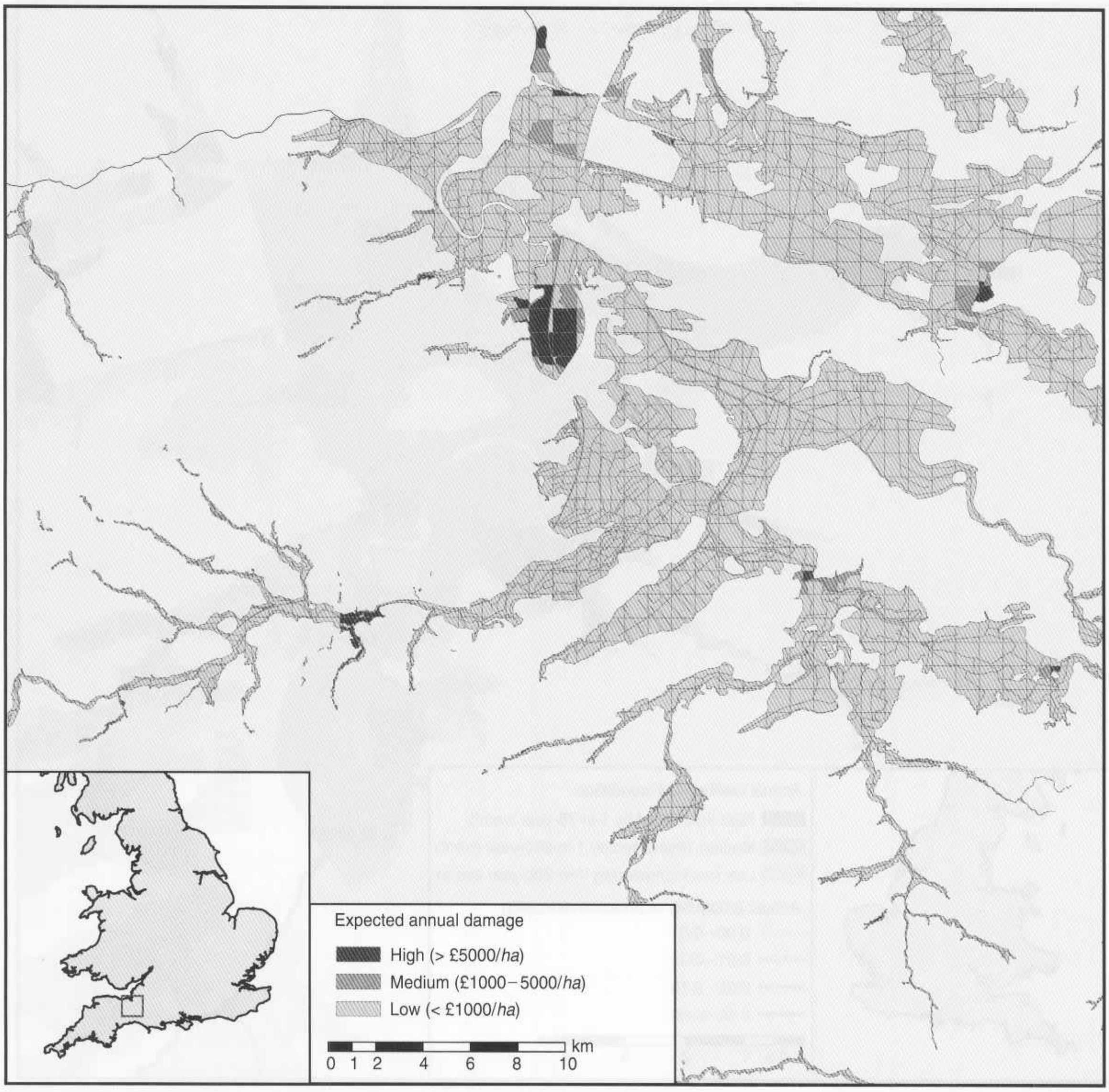

Fig. 7. GIS representation of flood risk for the Parrett catchment

defence geometry, and other key parameters that determine defence resistance.

(*c*) The current quality of information relating to defence location, condition and SOP within the NFCDD is highly variable.

(*d*) The flood spreading routine is based on volumetric concepts but does not include any hydrodynamic modelling and is based on a simple characterisation of floodplain morphology and approximate flood outlines in the IFM.

(*e*) Flood depths are based on statistical analysis of real and simulated data, and do not take account of local topography.

These approximations are appropriate for national-scale risk assessment, but site-specific decision-making, for example for catchment flood management planning or scheme design, will require more detailed data collection and analysis. The following aspects must be given more attention in a more detailed analysis

(*a*) statistical analysis of hydrology, and joint probability loading conditions for sea defences, including spatial dependence and antecedent conditions in both cases

(*b*) quantified analysis of multiple defence failure modes making use of site-specific measurements

(*c*) analysis of the dependence between defence strength parameters within defence sections and between neighbouring sections

(*d*) hydrodynamic modelling for flood depth and extent using high-resolution topographic information

(*e*) consideration of the influence on flooding of groundwater and local runoff

(*f*) more detailed analysis of the tangible and intangible impacts of flooding, including disruption to transportation systems

(*g*) analysis of the influence of non-structural flood mitigation measures such as flood warning.

Furthermore, when more detailed information is available in an appropriate format this can also contribute to national-scale analysis. More detailed analysis will also contribute to verification of the national-scale method.

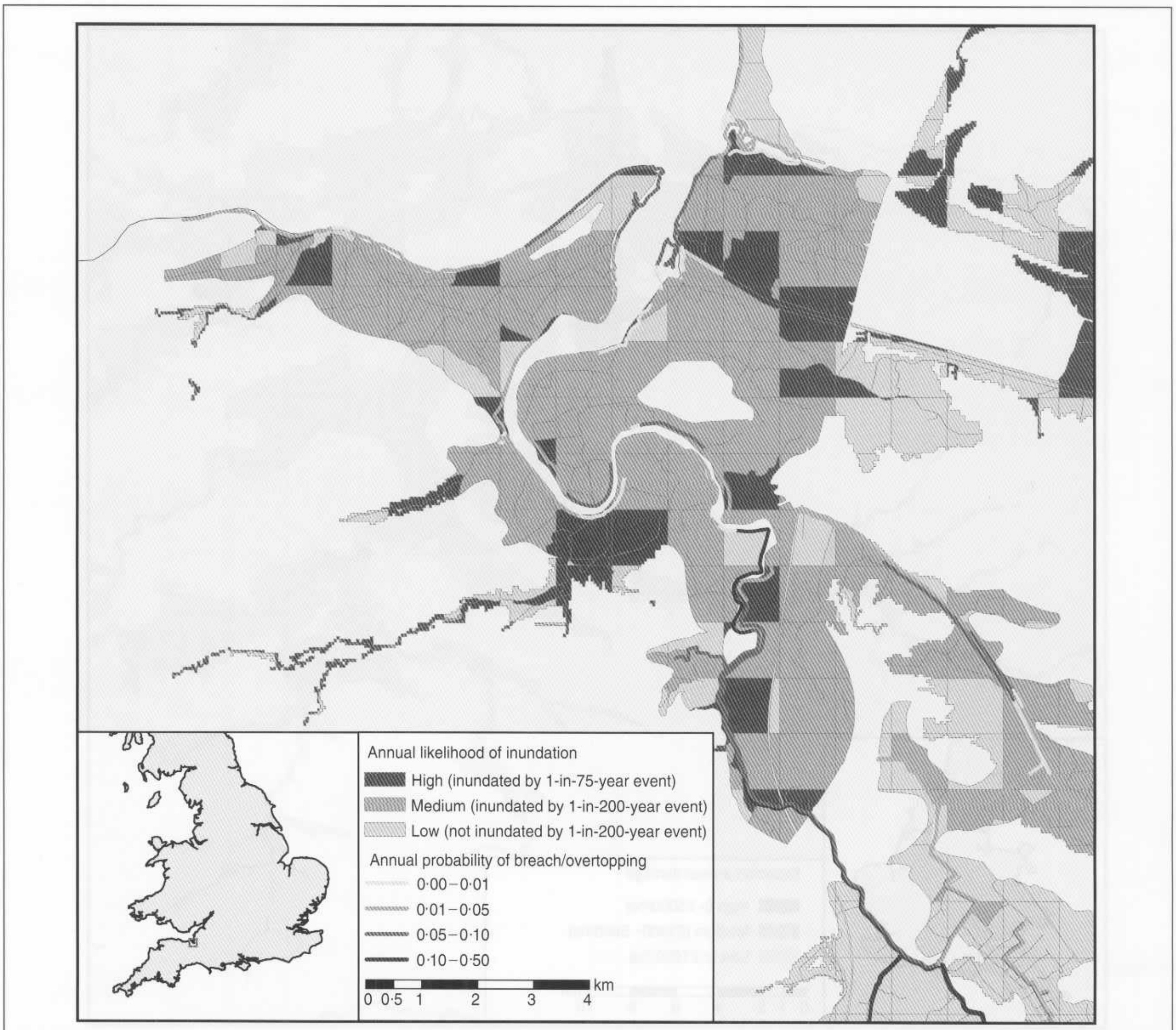

Fig. 8. GIS close-up, showing relative likelihood of flooding and probability of failure of individual defences

10. CONCLUSIONS

The methodology outlined in this paper represents a significant advance on the only previous national appraisal of flood risk, and is a step towards fully probabilistic, process-based assessment of national flood risk from fluvial and coastal sources. The methodology uses only nationally available data sets in England and Wales. It has been tested on the Parrett catchment in south-west England and has now been applied to all of England and Wales. The risk assessment methodology is based on analysis of systems of linear flood defences, taking into account the defence Standard of Protection, type and condition grade.

The methodology provides an estimate of economic risk for zones within the floodplain, which can be aggregated to a regional and national scale. Use of Social Flood Vulnerability Indices gives a measure of the potential social impact of flooding. The methodology also identifies the contribution to risk of individual defence sections. It can be used in national policy analysis by testing scenarios of changed flood frequency, investment in flood defences or floodplain occupancy. It can also form the starting point for more detailed catchment and local-scale analysis.

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