6. STEP 4: IDENTIFY IMPACT ZONES

6.1 Overview

RASP HLM identifies systems of defences associated with particular Impact Zones where impact zones are defined by a grid no greater than 1km x 1km. For each Impact Zone the defences that may contribute to flooding of that zone under a particular storm event and defence failure scenario are identified. Within RASP the Impact Zones are assigned a Land Use as identified through analysis of the CEH Land Cover Maps. The CEH Land Cover maps provide a classification of the British Isles into 27 different land use groups. This data is amalgamated into eight land bands for the purposes of RASP.

6.2 Inputs and outputs

Inputs: CEH Land Cover Map
Indicative Floodplain map
Land classification types

Outputs: Impact zones defined by land use with associated information that includes:

- Land use classification
- Nearest defence FDMS ID
- Distance to nearest defence
- Co-ordinates of centroid

Steps 4 through to 8 must be repeated for each flood event. This provides a total risk for the system identified within step 1.

6.3 Methodology

6.3.1 Identifying impact zones

The Impact Zones have been simply defined by gridding the IFM using a maximum grid size of 1km x 1km. The CEH Land Cover Map 2000 (product Version level 2/3 – Vector) can then be used to identify boundaries of common land use within discrete flood impact zones and, if required, risk could reported by land use banding.

Table 6.1 The RASP land use classification and, their CEH land band codes

RASP no.	RASP name	Description	Land Cover Class Code
1	Continuous Urban	Urban land, roads, railways, waste and derelict ground, including vegetated wasteland, gardens and urban trees. Areas of vegetation greater than 0.5 ha are identified by the appropriate cover class	17.2 (PAG 3 equivalent = A)
2	Suburban/Rural developed	As 1 but suburban and rural developed.	17.1 (PAG 3 equivalent = A/B
3	Arable cereals	Annual crops, recent leys, freshly ploughed land, rotational setaside, and perennial horticultural crops such as berries and orchards. Once setaside is substantially vegetated with weeds or rough grass, it is included in RASP land use Class 4.	4.1, 4.2, 4.3 (PAG 3 equivalent = B/C
4	Improved grassland	Acid, Neutral and calcareous semi-natural swards are generally not reseeded or fertiliser treated; they are dominated by lower productivity grasses.	5.1, 5.2 (PAG 3 equivalent = D
5	Neutral grassland	Acid, Neutral and calcareous semi-natural swards are generally not reseeded or fertiliser treated; they are dominated by lower productivity grasses.	6.1, 7.1, 8.1 (PAG 3 equivalent = E
6	Fen marsh and swamp	Vegetation, which is permanently, seasonally or periodically waterlogged for which agricultural potential is low to negligible.	11.1, 12.1, 21.2 (PAG 3 equivalent = E – or worse)
7	Rural woodland	Broad Leaved and coniferous woodland	1.1, 2.1 (PAG 3 equivalent = N/A)
8	Other	Remainder of sub-classes which have no economic loss potential through flooding but may have considerable environmental gain or loss.	Others (PAG 3 equivalent = N/A)

Example Impact Zones are shown in Figure 6.2 with an example of the CEH Land Cover data in Figure 6.3. A more detailed levels finer grid resolution could be used to replace the high level results.

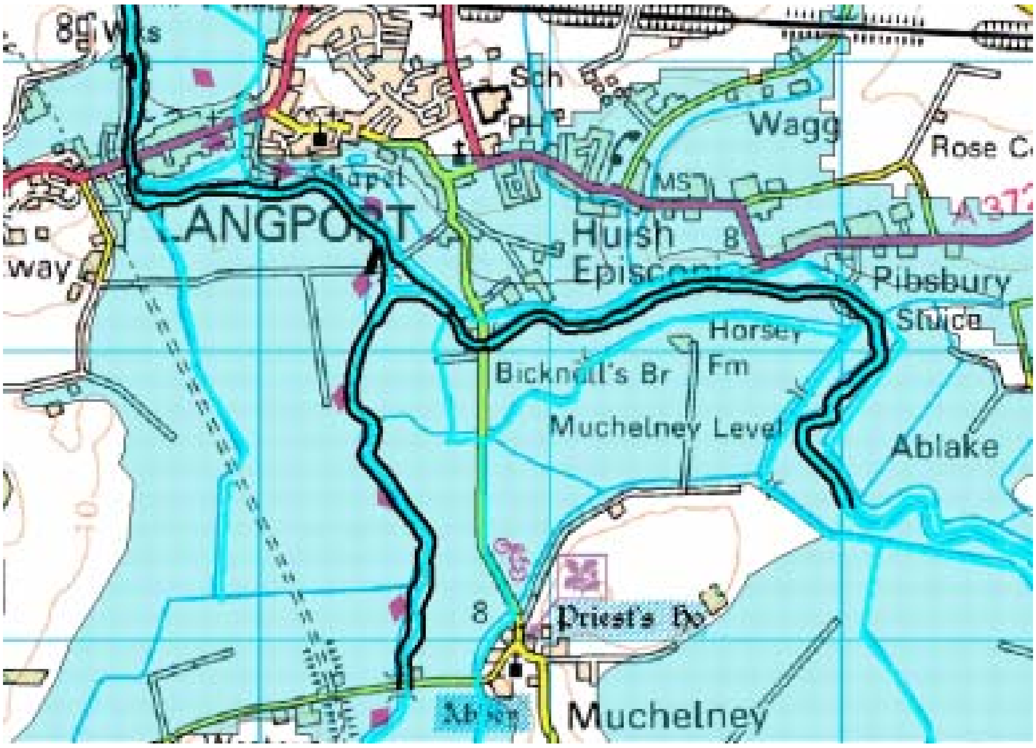


Figure 6.1 Stretch of river showing defences and the IFM

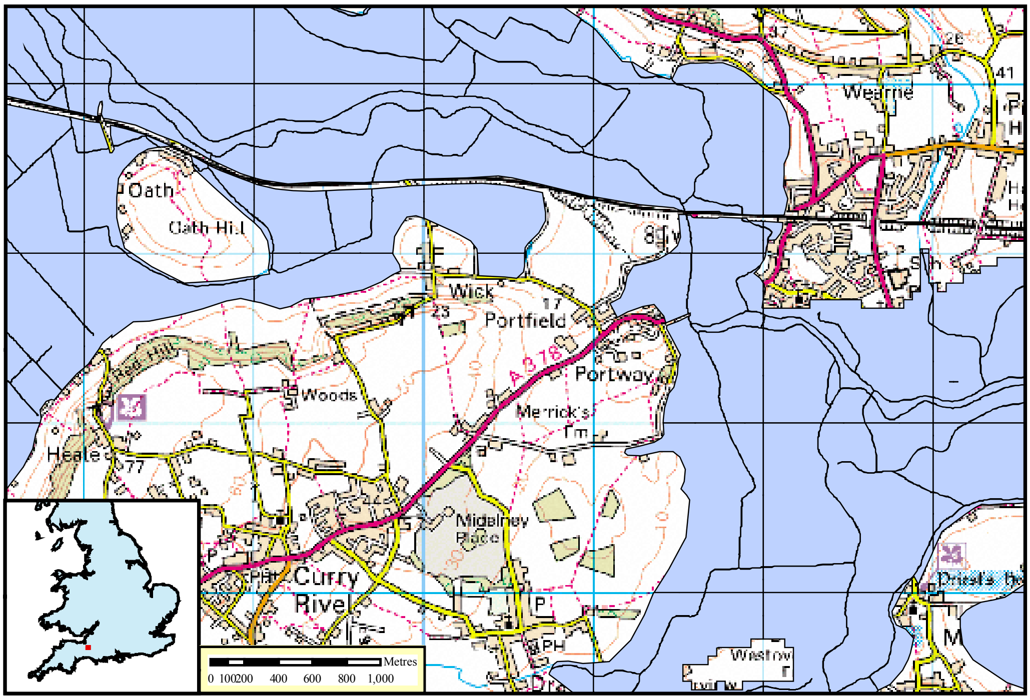


Figure 6.2 IFM split into impact zones

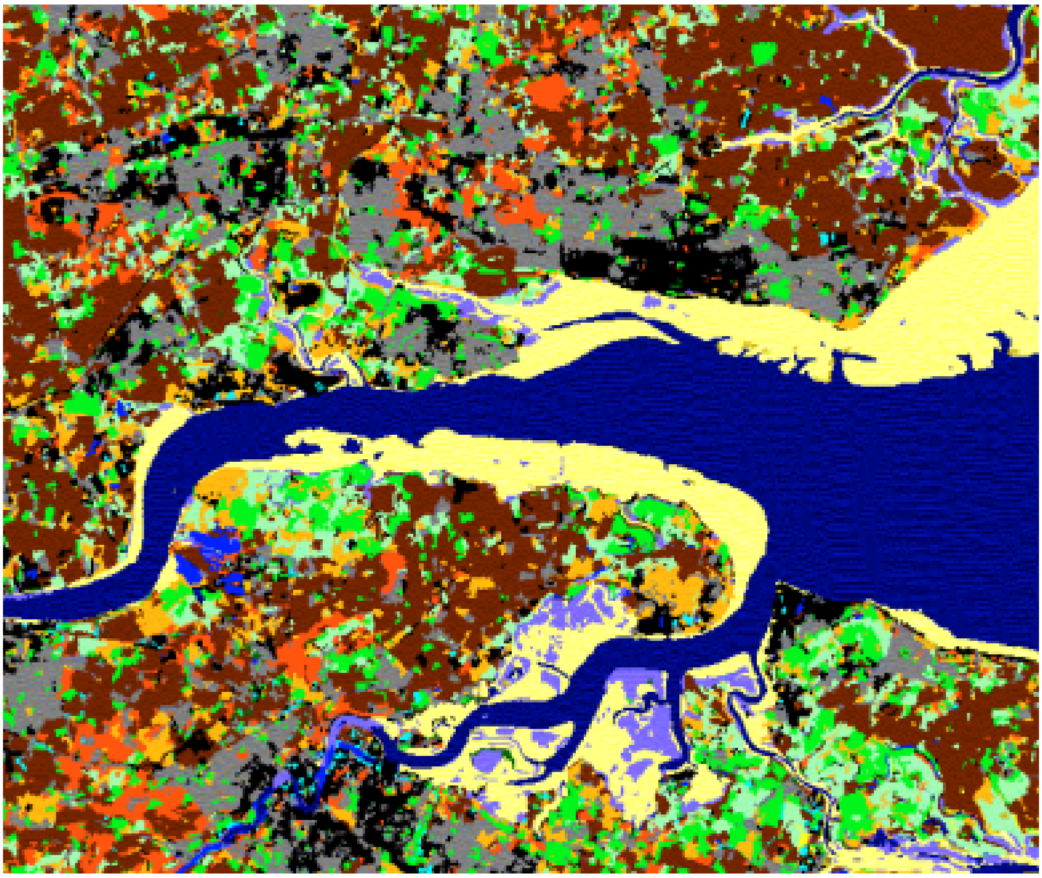


Figure 6.3 Example of data from the CEH Land Cover Map 2000

7. STEP 5: IDENTIFY FLOOD EXTENT FOR EACH DEFENCE FAILURE SCENARIO

7.1 Overview

Estimation of flood extent and depth in a given storm and defence failure scenario, such as overflow / overtopping (non-structural) or breaching (structural), is constrained by lack of quantitative load information (water levels, wave heights etc.), defence crest levels and topographic data. Moreover, the method for calculating the flood extent must be simple and quick so that it can be run for many thousands of breaching and overflow / overtopping scenarios. In view of this, a rapid parametric flood spreading routine has been developed for RASP that enables quick determination of flood extents for different scenarios. The methodology can be summarised as follows:

i. Identify floodplain type and hence the geometric shape adopted to calculate flood extents;
ii. Calculate the volume of water entering the floodplain over / through the flood defence;
iii. Determine flood extents along and across the floodplain.

The geometric shape behind a flood defence adopted to calculate flood extents (i) depends on the characteristics of the floodplain. This characterisation will be based on limited topographic data such as the OS PANAROMA dataset.

The volume of water entering a floodplain cell (ii) will depend on whether the flood defence has overtopped or breached and this will be determined by considering the defence type, failure type, load x, and evidence from past detailed analysis.

Flood extents (iii) are calculated by equating the volume of water calculated in part (ii) with the volume of water under the geometric shape determined in part (i). The key dimension that is required from this calculation is the length of flooding upstream and downstream of the overtopped or breached flood defence.

The calculated flood extents can be used to identify those defences that contribute to flooding in a particular impact zone. This information should then be used to update the findings in Step 2.

7.2 Inputs and outputs

Inputs:	Return period of water level for which a defence is overtopped / breached Standard of Protection (*SoP*) Valley type and slope
Output:	Upstream and downstream flood extent Defences within this extent

Steps 5 through to 8 must be repeated for each flood event. This provides a total risk within an impact zone. To calculate the total system risk, steps 4 to 8 are repeated for each impact zone.

7.3 Methodology

7.3.1 Identification of floodplain type and the geometric shape adopted to calculate flood extents

The method for calculating discharge entering floodplains and the subsequent geometric shape adopted to calculate flood extents is dependent on:

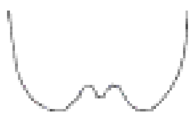
- Whether the floodplain is fluvial or coastal;
- The valley slope.

The Middlesex University Report, Flood Depth Model: Development and Specification[*] [7] subdivides the fluvial floodplains into three distinct, generalised typologies:

1. U-shaped;
2. V-shaped; and
3. W-shaped.

These typologies are described in greater detail in Table 7.1.

Table 7.1 Definitions of the floodplain types from Middlesex University Report, Flood Depth Model: Development and Specification [7]

Geomorphology	Floodplain width (m)		
	Less than 250m (narrow)	250-500m (intermediate)	500-1000m (wide)
Floodplain shape	**Floodplain characteristics**		
U-Shaped 	Flat flood profile: Sloping to floodplain boundary		
V-Shaped 	Steeper flood profile: Largely restricted to narrow floodplains		
W-Shaped 	Compound profile: Depths rising from river and then falling		
Coastal	Flat flood profile		

A valley type will be associated with each defence and will be derived from a topographical analysis within the GIS software.

The fluvial floodplains are further classified into three slope categories as follows:

- Shallow (gradients less than 1:5,000 and equivalent to a U shaped valley);

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[*] We wish to thank Professor Edmund C. Penning-Rowsell, Director of Flood Hazard Research Centre for permission to use data available in the unpublished report, Flood depth model: Development and Specification.

- Average (gradients ranging from 1:1,000 to 1:5,000, corresponding to a W shape valley); and
- Steep (gradients greater than 1:1,000 corresponding to a V shaped valley).

The geometric shape behind a defence adopted to calculate flood extents is given in Table 7.2.

Table 7.2 Geometric shape behind a defence adopted to calculate flood extents

Typology	Gradient	Failure scenario	Geometric shape
Coastal	Shallow	Overflow / Overtopping and Breaching	Semi-circular/rectangular
Fluvial	Shallow	Overflow and Breaching	Semi-circular/rectangular
Fluvial	Steep / Average	Overflow	Semi-circular/rectangular
Fluvial	Steep / Average	Breaching	Triangular

7.3.2 Calculating the volume of water passing into floodplains

To calculate the volume of water passing into floodplain storage it is necessary to integrate the area under a flow hydrograph. Two types of flow hydrographs are used in the analysis depending on whether the flooding takes place in a fluvial or coastal floodplain, and whether the defence is overflowed / overtopped or breached. The following sections give further information on how the flow hydrogaph for each case is developed.

Volume under the hydrographs for fluvial floodplains in case of overflow and breaching scenarios, and for coastal floodplains in case of breaching scenario

A triangular flow hydrograph is constructed as shown in Figure 7.1 The surface area of the flow hydrograph $Q(t)$ gives the volume of water entering a floodplain across flood defence(s) (see equation 7.1). The peak flow (Qp) and duration of flow (T) across the defence(s) will be predicted.

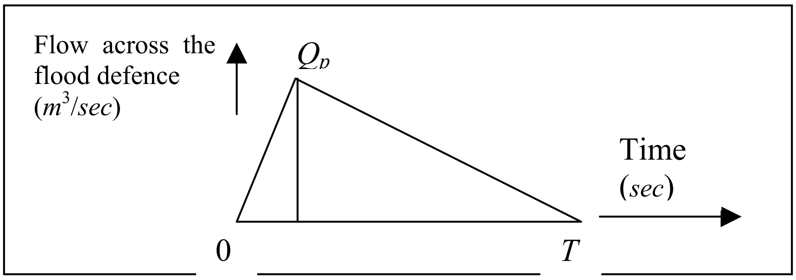

Figure 7.1 Triangular hydrograph

$$Vol = \frac{1}{2}\left(Q_p \times T\right) \tag{7.1}$$

where:

Vol = volume of water entering the floodplain across the flood defence (m^3)
Q_p = peak discharge across the defence (m^3/sec)
T = duration of flow across the defence (sec)

In case either overflow of fluvial defences or breaching of fluvial and coastal defences, the flow across the defence is similar to the flow over a rectangular, broad-crested weir and, therefore, the peak discharge is given by the following equation (French, 1994):

$$Q_p = 1.71 \times b \times h^{1.5} \tag{7.2}$$

where:
Q_p = peak discharge across the defence (m^3/sec)
b = length of the defence crest being overtopped or breach width (m), this is a function of the type of defence
h = maximum head on the crest or breach (m)
1.71 = coefficient, which has dimensions ($m^{0.5}$ / sec)

The method for determining the hydrograph duration is given below.

Volume under the hydrograph for coastal floodplains in case of overflow / overtopping scenario
Unlike for fluvial situations, coastal overflow / overtopping is a function of both waves and water levels. The flood volume depends on the flow per unit length of defence, the length of defence that is overtopped and the duration of flow across the defence (see equation 7.3).

$$Vol = q \times b \times T \tag{7.3}$$

where:
Vol = volume of water entering the floodplain over the crest of the defence (m^3)
q = flow per unit length of defence ((m^3/sec)/m)
T = duration of flow over the defence (sec)
b = length of the defence crest being overtopped (m), this is a function of the type of defence

Establish representative breach width, breach head and duration of flow across the defence(s)
In order to calculate the upstream and downstream length of the flooded area, it is necessary to estimate the following parameters for both the fluvial and coastal hydrographs:

- The length of the defence overtopped or the representative width of the breach, b;
- The maximum head across the flood defence, h, or specific flow over the crest, q;
- The duration of flow across the defence, T

Data available for the High Level Methodology consist of:

- An estimate return period of water level for which the defence will be overtopped / breached;
- Standard of Protection, *SoP*, for fluvial and coastal defences; and
- The assumed section length of a fluvial / coastal defence, L_{def}.

It is therefore necessary to identify a simple relationship for determining the breach parameters and duration of flow across the defence based on this limited data.

Table 7.3 shows the equations used to define *b*, *h*, *q* and *T*. These equations consider the return period of water level for which a defence is overtopped / breached relative to the protection offered by a defence to factor a base value. For example, the duration of a 1 in 200 year flood event will be longer for a defence offering 1 in 50 year protection compared to a defence offering 1 in 100 year protection. Evidence in support of these equations and figures is shown in Appendix D.

Table 7.3 Summary of equations for calculating representative breach widths, maximum head and duration of flow across the defence

Failure mode	Defence Type	b	h or q	T
Overtopping	**Fluvial**	$b_{OT} = L_{def}$	$h = (Load\ x)^2 c_h$	$T = (Load\ x)^{0.5} A^{0.25}\ c_T$
	Coastal	$b_{OT} = L_{def}$	$q = (Load\ x)^{1.5} c_q$	$T = (Load\ x) c_T$
Breaching	**Fluvial**	$b_B = (Load\ x) c_b L_{def}$	$h = (Load\ x)^{0.5} c_h$	$T = (Load\ x)^{0.5} A^{0.25}\ c_T$
	Coastal	$b_B = (Load\ x) c_b L_{def}$	$h = (Load\ x)^{0.5} c_h$	$T = (Load\ x)\ c_T$

where:

L_{def} = Defence length (m)

Load x = Ratio between the return period of storm for which the defence is overtopped / breached and SOP of the defence (limited to a maximum value of 3)

T = Duration of flow across the defence(s) (hours)

h = Maximum head on breach or defence crest (m)

q = Flow per unit length of defence ((m^3/sec)/m)

b = Representative breach width or length of defence overtopped (m)

A = Catchment area (km^2).

c_b = Base value of *b*, determined when the Load is equal to the *SoP*, assumed to be 0.05 for fluvial coastal defences

c_h = Base value of *h*, determined when the Load is equal to the *SoP*, assumed to be 0.05m for overflow / overtopping scenario, and 0.5m for breach scenario

c_q Base value of *q*, determined when the Load is equal to the *SoP*, assumed to

= be 0.05 $(m^3/sec)/m$

c_T = constant, which has the following values

1.2 hours/km$^{0.5}$ for steep floodplains and Return Period of Storm > 50 years
0.6 hours/km$^{0.5}$ for steep floodplains and Return Period of Storm =< 50 years
1.2 hours/km$^{0.5}$ for shallow floodplains and Return Period of Storm > 50 years
0.6 hours/km$^{0.5}$ for shallow floodplains and Return Period of Storm =< 50 years
0.8 hours/km$^{0.5}$ for average floodplains and Return Period of Storm > 50 years
0.4 hours/km$^{0.5}$ for average floodplains and Return Period of Storm =< 50 years
3.0 hours for coastal floodplain

As discussed in Chapter 4, upstream storage facilities should be associated with the defences whose *SoP* they influence. This is achieved by using the actual *SoP* offered by the combined defence and storage. For example, a defence may be high enough to protect against the 1 in 20 year flood, but when considering upstream storage, the *SoP* is 1 in 100 years. Clearly, whilst the upstream storage is functioning a *SoP* of 1:100 should be used for the defence. However, the failure of the upstream storage should be considered meaning that the defences should have their *SoP* reduced to 1:20 years when considering failure scenarios involving the upstream storage.

7.3.3 Estimation of flood extents along and across the floodplain

Flood extents along and across the floodplain are estimated by equating the volume of water entering the floodplain (calculated in Section 7.3.2) and the volume of the flood outline within the floodplain.

The volume of the flood outline within the floodplain is calculated assuming a geometric shape that incorporates the flood extents, and a uniform depth of flooding, *d*, of 0.2m throughout.

The following sections illustrate the methodology for calculating flood extents for different floodplain types. Specifically:

CASE A	Fluvial floodplain with shallow slope
CASE B	Fluvial floodplain with steep average slope
CASE C	Coastal floodplain

Case A – Fluvial floodplain with shallow slope

If the floodplain is shallow (s => 1…5000) corresponds to a U shaped valley as described in Section 7.3.1. For both breaching and overflow / overtopping it is assumed that waters will be evenly spread upstream and downstream valley from the centre point of the defence (this assumes the breach occurs at the middle of the defence length). Consequently a semicircle is adopted to establish the flood extents (see Figure 7.2).

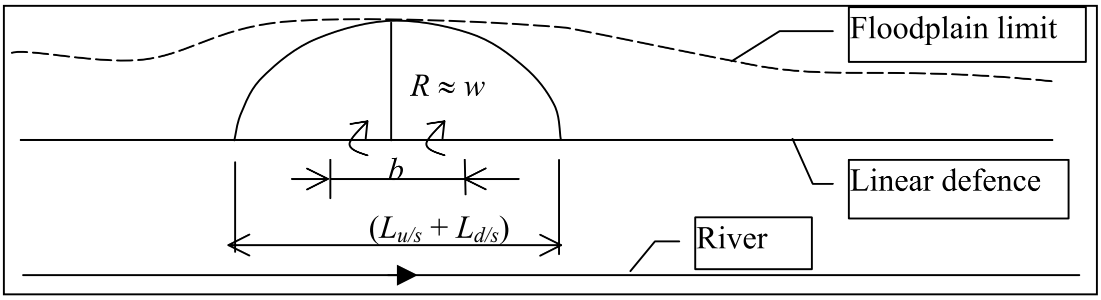

Figure 7.2 Flood extent for fluvial floodplain with shallow slope

Note: In the case of fluvial defence, type 4: culverts (see Figure 5.5 and Figure 5.9) it is assumed that flooding starts at the upstream end of the defence, and waters will be evenly spread upstream and downstream of the valley as shown in Figure 7.3.

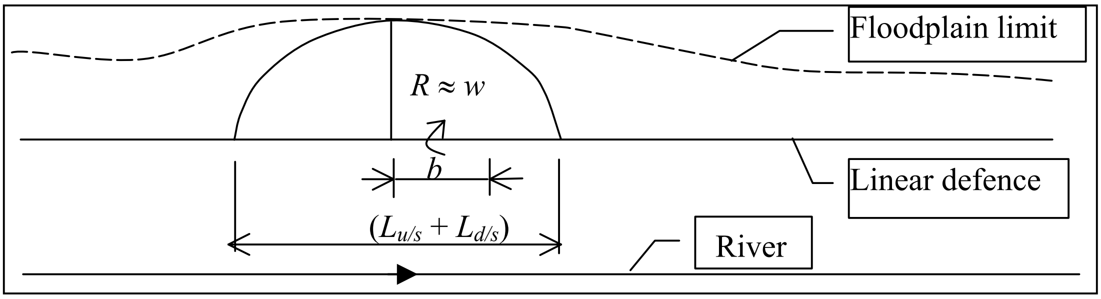

Figure 7.3 Flood extent for fluvial floodplain with shallow slope protected by culverts

Substituting equation 7.2 into 7.1, the radius of the semicircle is obtained (see equation 7.5) from equation 7.4.

$$\frac{1}{2}\left(1.71bh^{1.5}\right)T = \frac{1}{2}\left(\pi R^2\right)d \qquad (7.4)$$

where:
R = radius of the semicircle (m)
d = uniform depth of flooding of 0.2m

$$R = \left[\frac{\left(1.71bh^{1.5}\right)T}{\pi d}\right]^{\frac{1}{2}} \qquad (7.5)$$

If $R \leq w$

where: w = the width of the floodplain (m)

Note: w can be simply determined by dividing Floodplain Area (area within the defended area or reach polygon) by Reach Length (i.e. the polyline distance between the start of the upstream defence and the end of the downstream defence).

The maximum extent, along the defence, of the flooded area is two times radius (see equation 7.6):

$$(L_{u/s} + L_{d/s}) = 2 \times R \tag{7.6}$$

where: $(L_{u/s} + L_{d/s})$ = maximum extent, along the defence, of the flooded area (m)

If $R > w$ i.e. the flood waters reach the limit of the floodplain then the geometric shape adopted to calculate the flood extent is not a semicircle but a rectangle (see Figure 7.4), and the maximum extent along the defence (see equation 7.8) is given by the equation 7.7.

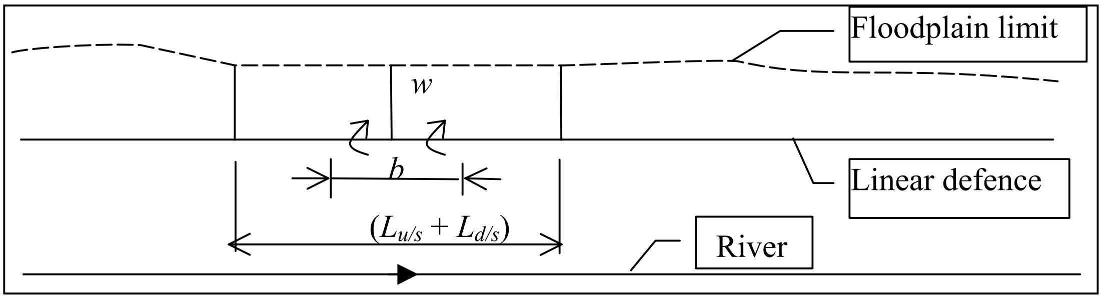

Figure 7.4 Flood extent for narrow fluvial floodplain with shallow slope

$$\frac{1}{2}\left(1.71bh^{1.5}\right)T = \left(L_{u/d} + L_{d/s}\right)wd \tag{7.7}$$

$$\left(L_{u/s} + L_{d/s}\right) = \frac{\left(1.71bh^{1.5}\right)T}{2wd} \tag{7.8}$$

The flood extents upstream and downstream of the breach are equal in case of a semicircle shape as well as a rectangular shape.

Case B - Fluvial floodplain with steep and average floodplain slopes
Steep and average floodplain slopes correspond to V and W shaped valleys, as described in Section 7.3.1.

For overflow / overtopping scenario, Case A is applicable.

In the case of breaching, it is assumed that water will be unevenly spread upstream and downstream valley with regard to the centre point of the defence. Hence, the geometric shape adopted to calculate the flood extent is a triangle (see Figure 7.5).

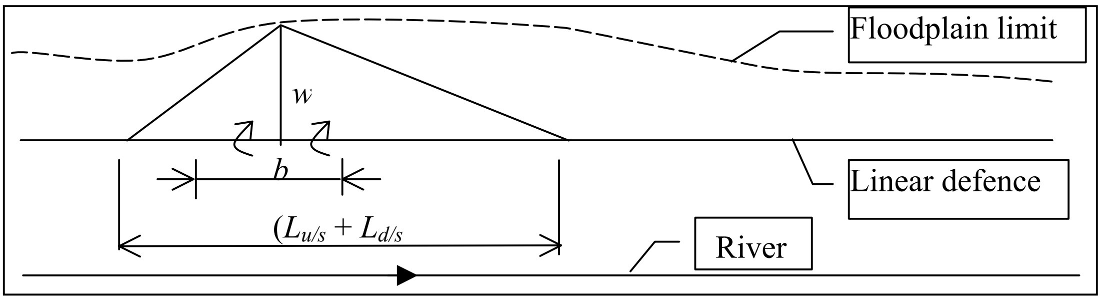

Figure 7.5 Flood extent for fluvial floodplain with steep and average slopes

Note: In the case of fluvial defence, type 4: culverts (see Figure 5.5 and Figure 5.9) it is assumed that flooding starts at the upstream end of the defence, and waters will be unevenly spread upstream and downstream of the valley as shown in Figure 7.6.

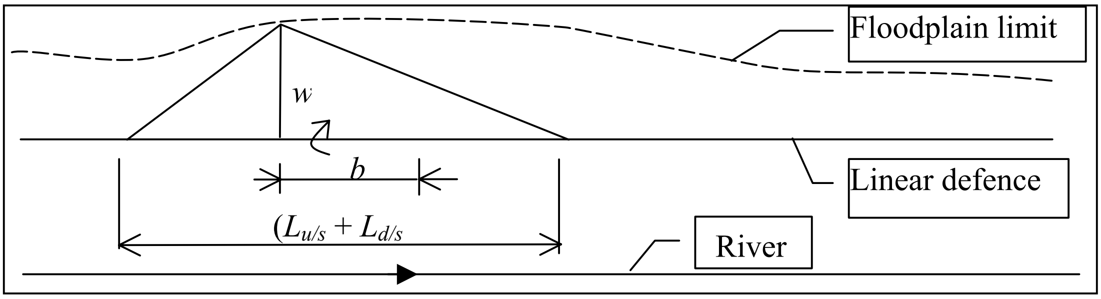

Figure 7.6 Flood extent for fluvial floodplain with steep and average slopes protected by culverts

The maximum extent, along the defence, of the flooded area (see equation 7.10) is deduced from the equation 7.9.

$$\frac{1}{2}\left(1.71bh^{1.5}\right)T = \frac{1}{2}\left(L_{u/d} + L_{d/s}\right)wd \tag{7.9}$$

$$\left(L_{u/s} + L_{d/s}\right) = \frac{\left(1.71bh^{1.5}\right)T}{wd} \tag{7.10}$$

In order to divide the maximum extent of flooding in two segments placed upstream and downstream breach, an approximation is to assume that the average slope across the floodplain and the average longitudinal slope are in the same range (see equation 7.11).

Thus

$$L_{u/s} = w \tag{7.11}$$

In the case of overtopping only, waters will be evenly spread from the centre point of the defence and the geometric shape adopted to calculate the flood extents is either a semicircle or a rectangle (Case A).

Case C - Coastal Floodplain

The flood extent within a coastal floodplain is approached in the same manner as for the *shallow* fluvial floodplain.

For overflow / overtopping scenario it is assumed the radius of the semicircle shape is obtained from equation 7.12:

$$R = \left(\frac{2qbT}{\pi d}\right)^{\frac{1}{2}} \tag{7.12}$$

The maximum extent, along the defence, of the flooded area given by equation 7.13:

$$\left(L_{u/s} + L_{d/s}\right) = 2R \tag{7.13}$$

Flood extents within a coastal floodplain following breaching of a defence are determined as in Case A.

Methods for estimating these parameters are given in Section 7.3.2.

For numerical examples of the flood extent calculations see Appendix E.

7.4 Identification of the defence system protecting the impact zone

Identification of the nearest defence (from step 2) to the impact zone being analysed provides a starting point for identifying the system of defences associated with the impact zone. Defences upstream and downstream of this defence can be analysed to check whether they cause flooding within the impact zone. Defences may cause flooding in more than one impact zone and therefore be part of more than one defence sub-system.

8. STEP 6: ESTIMATE FLOOD DEPTH WITHIN THE FLOOD AREA FOR EACH FAILURE SCENARIO

8.1 Overview

The flood depth adjacent to a failed defence is based on evidence from a review of approximately 70 flood scenarios (real and simulated) held by Middlesex University [7], which was used to establish a relationship between flood depth at a particular point in the floodplain on a line perpendicular to the failure location, and return period of water level. A depth factor, *e*, is applied to this depth to account for distance upstream and downstream of the failed defence.

8.2 Inputs and outputs

Inputs: Impact zones (as defined in step 4)
Middlesex University floodplain depth tables
e-values

Outputs: Average flood depth for impact zone

8.3 Methodology

8.3.1 Calculating the depth factor *e*

The Middlesex University Report [7] mentioned above provides the flood depth at specific locations on the typical floodplains for different return periods during *natural flood*. Those values represent the maximum depth within the flooded area (Appendix F).

It is assumed that maximum depths will be recorded along the line that is perpendicular to the river. The depth factor, *e*, reaches maximum and is equal to 1.0 in the centre of the defence section that has failed (i.e. overflown / overtopped or breached). Moving upstream or downstream from that location, the depth reported by Middlesex University is reduced by the factor *e*, which is zero at the upstream and downstream ends of the flooded area.

As a linear correlation between the depth factor, *e*, and the maximum extent, along the defence, of the flooded area, ($L_{u/s} + L_{d/s}$) is assumed. The value of the depth factor, *e*, at any location within the flooded area is therefore calculated using the equation 8.1 (see Figure 8.1).

$$e = 1 - \frac{x_{u/s\,(d/s)}}{L_{u/s\,(d/s)}} \tag{8.1}$$

where:

e = value of depth factor
$x_{u/s\,(d/s)}$ = distance *u/s* or *d/s* from the centre of the failed defence (m)
$L_{u/s\,(d/s)}$ = maximum extent *u/s* or *d/s* from the centre of the failed defence (m)

A summary of depth factor equations is given in Table 8.1.

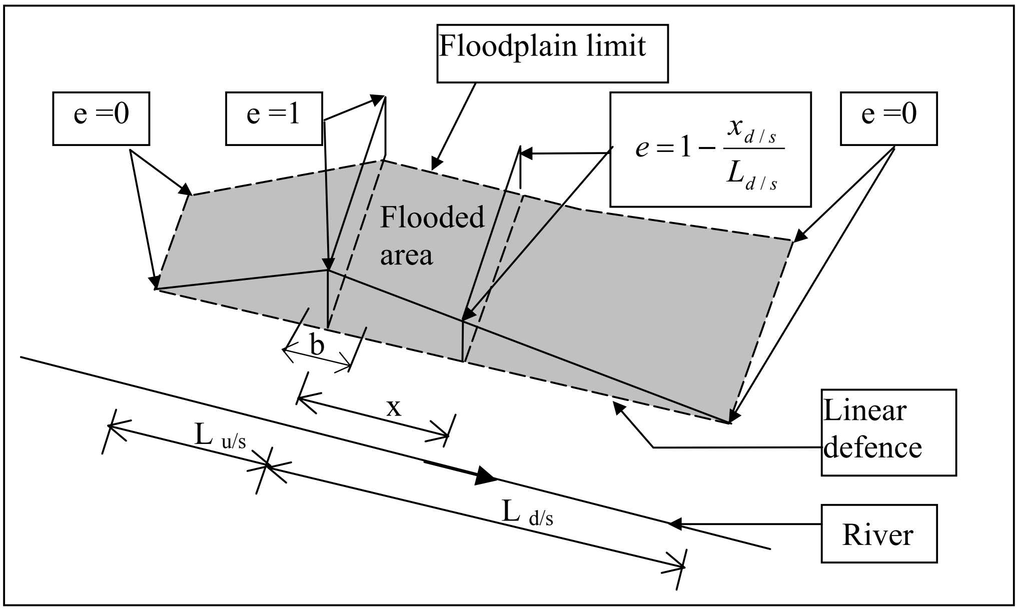

Figure 8.1 How the depth of flooding varies along distance from defence failure

Table 8.1 Summary of depth factor equations

	Slope *s*	**Failure mode**	**Flood radius *R***	**Depth factor *e***
Fluvial	Shallow (1:5000)	Breach and Overtopping	$R<=w$	$e = 1 - \frac{x}{\left[\frac{(1.71 \times b \times h^{1.5}) \times T}{\pi \times d}\right]^{\frac{1}{2}}}$
			$R>w$	$e = 1 - \frac{x}{\frac{(1.71 \times b \times h^{1.5}) \times T}{4 \times w \times d}}$
	Steep (s=1:500), and, Average (s=1:1000)	Breach	-	$e_{u/s} = 1 - \frac{x}{w}$ & $e_{d/s} = 1 - \frac{x}{\left[\frac{(1.71 \times b \times h^{1.5}) \times T}{w \times d} - w\right]}$
		Overtopping	$R<=w$	$e = 1 - \frac{x}{\left[\frac{(1.71 \times b \times h^{1.5}) \times T}{\pi \times d}\right]^{\frac{1}{2}}}$
			$R>w$	$e = 1 - \frac{x}{\frac{(1.71 \times b \times h^{1.5}) \times T}{4 \times w \times d}}$

Table 8.1 Summary of depth factor equations (continued)

	Slope *s*	Failure mode	Flood radius *R*	Depth factor *e*
Coastal		Breach	-	$e = 1 - \dfrac{x}{\left[\dfrac{\left(1.71 \times b \times h^{1.5}\right) \times T}{\pi \times d}\right]^{\frac{1}{2}}}$
		Overtopping	$R<=w$	$e = 1 - \dfrac{x}{\left[\dfrac{(q \times b) \times T}{\pi \times d}\right]^{\frac{1}{2}}}$
			$R>w$	$e = 1 - \dfrac{x}{\dfrac{(q \times b) \times T}{4 \times w \times d}}$

where,
s = Floodplain slope
R = Radius of flooded area when assumed to be a semicircle (m)
b = Representative breach width or assumed length of overtopping (m)
h = Maximum head over crest or breach (m)
q = Flow per unit length of defence ((m^3/sec)/m)
d = Uniform depth of flooding of 0.2m
x = Distance along river from the centre point of the breach (m)
w = Nominal floodplain width (shortest distance from breach to edge of IFM), (m)

The depth of water at any location within the flooded area, D', is the product of depth of water across the floodplain, D, (see Appendix F for depth values) and value of damage factor, e (see Figure 8.2).

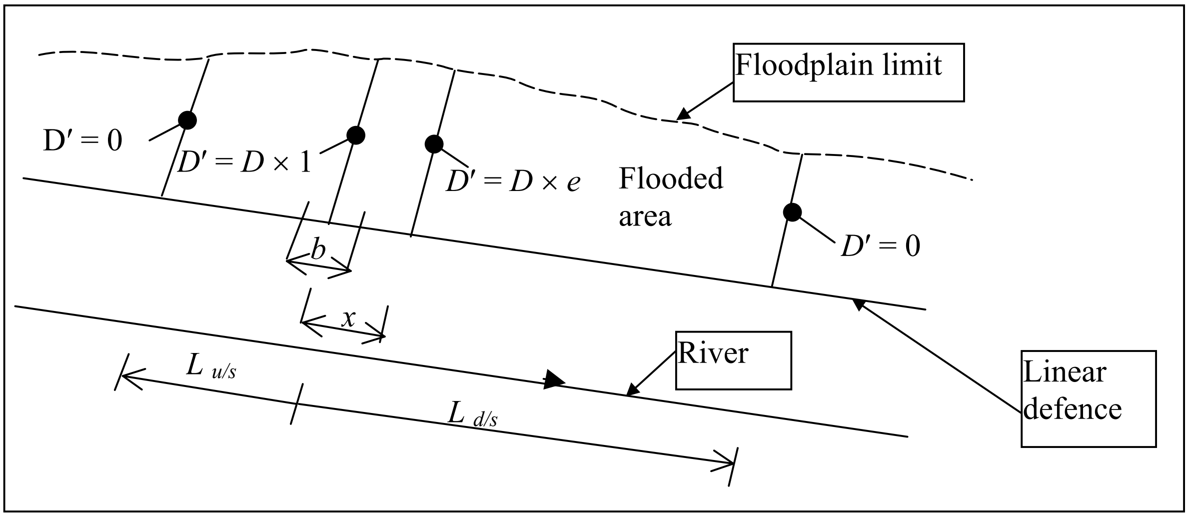

Figure 8.2 Showing how the flood depth varies along distance from defence failure

8.3.2 Multiple defence failure scenarios

If one of the two scenarios or both occur at more than one location, the depth factors are calculated at each location.

Independent flooded areas

There is no need for any further calculation, as the two failures do not influence each other (see Figure 8.3).

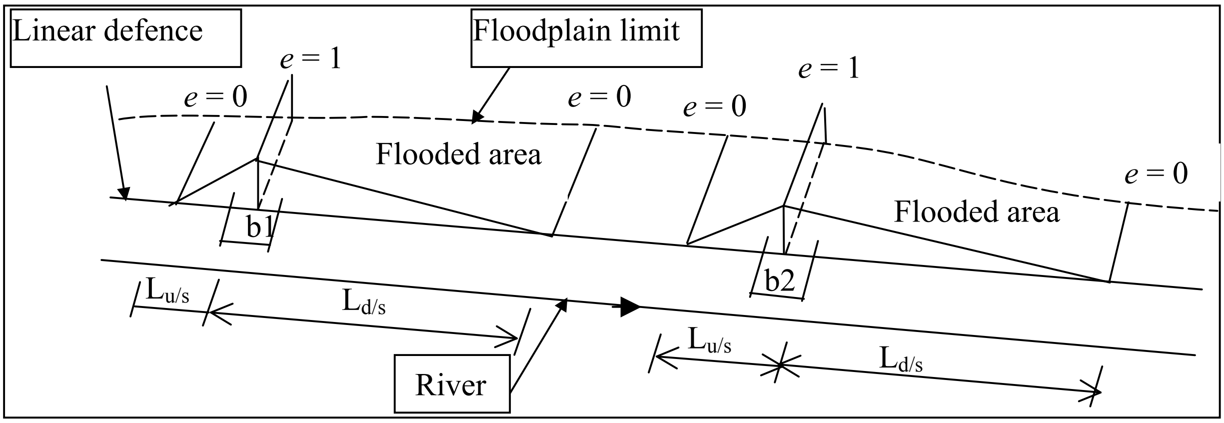

Figure 8.3 Independent flood areas from multiple defence failure

Overlapping flooded areas

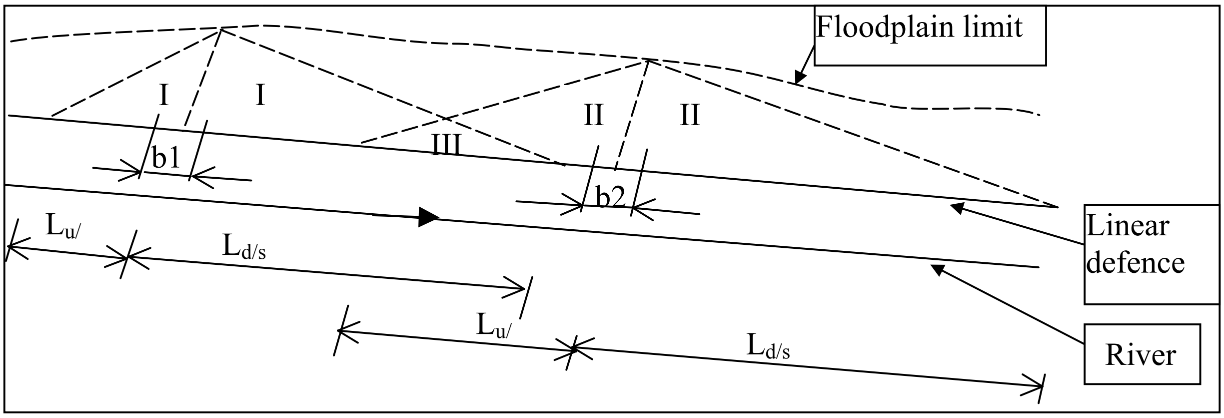

Figure 8.4 Overlapping flood areas from multiple defence failure

The value of depth factor, *e*, within the flooded areas I and II depends upon the characteristics of the flood events 1 and 2, respectively (see Figure 8.4).

The highest depths from the flood events 1 and 2 are recorded at the same time within the overlapping area III.

The value of the depth factor, *e*, within the overlapping area, III is given by equation 8.2:

$$e_{III} = \begin{cases} e_I + e_{II} & if \quad (e_I + e_{II}) \leq 1 \\ 1 & if \quad (e_I + e_{II}) > 1 \end{cases} \qquad (8.2)$$

As a conclusion, the value of depth factor, e, within the overlapping area III, has the following bounds (see equation 8.3):

$$e_{III} = \min[(e_I + e_{II}), 1] \tag{8.3}$$

9. STEP 7: ESTIMATE THE PROBABLITY OF COMBINATIONS OF DEFENCE FAILURE

9.1 Overview

Step 5 determined the flood extent, Step 6 calculated the flood depth and this step results in, for every impact zone in the flood plain, an estimate of the probability of flooding within the impact zone for a given defence failure scenario. A defence failure scenario is defined as a possible combination of defence failure (either by overtopping or breaching) that leads to flooding. For a system containing more than one defence, there are many possible failure scenarios that can lead to inundation and the total probability of inundation of the floodplain is calculated by considering the probability of all defence failure scenarios. A system with n defences will have 2^n possible combinations of failure (including the non-failure scenario). Each of these scenarios could involve failure by breaching or failure by overtopping. If the mode by which the defence has failed (breaching or overtopping) is to be specified, the number of scenarios increases further.

To estimate the probability of a particular failure scenario in a defence *system* requires understanding of the dependency between loads and defence resistance within the system. At the High Level, RASP makes the following assumptions:

- Loads are *fully dependent*, i.e. all defences experience loads of the same severity at the same time; and
- defence resistance is *independent*, i.e. the strength of each defence is assessed independently and its response in a given load is the same irrespective of the response of neighbouring defences.

These assumptions lead to the following equation (9.1) for determining the probability of defence failure:

$$P(A \cap B \mid L) = P(A \mid L) \cdot P(B \mid L) \tag{9.1}$$

where A and B represent two independent defence sections failing under the dependent load (related to the flood event) L.

The probability of occurrence of a given failure scenario under a given loading condition is calculated using the fragility curve for that defence type as defined in step 4, which in turn is based on the defence classification detailed in step 2.

Steps 6 through to 8 must be repeated for each flood defence failure scenario and from these results, the total risk within an impact zone for a given event can be calculated. To calculate the total probability of impact zone inundation, steps 5 to 8 must be repeated for every flood event.

9.2 Inputs and outputs

Inputs: Defence classification (from step 2)
Defence fragility curves: $P(OT)$, $P(B|OT)$ and $P(B|OT')$ (from step 3)

Outputs: Bounds for the probability of occurrence for a failure scenario for multiple flood events

9.3 Methodology

There are two steps in the process of calculating the probability of defence failure:

- Defining failure scenarios; and
- Calculating probability of each failure scenario.

The following sections describe in greater detail the methodology for Step 7.

9.3.1 Definition of failure scenarios

As discussed in the overview, a system with n defences will have 2^n possible combinations of failure (including the non-failure scenario). Considering a simple three defence system (numbered from 1 to 3), there are eight possible failure scenarios, as shown in Table 9.1. Each defence can fail (indicated by a line over the defence number) either by overtopping or breaching meaning that there are 3^n scenarios that need to be analysed.

Table 9.1 Defence failure scenarios

Scenario No.	Order of failure	Failed defences
1		no failure
2	1st Order	$1 \cap \bar{2} \cap \bar{3}$
3		$\bar{1} \cap 2 \cap \bar{3}$
4		$\bar{1} \cap \bar{2} \cap 3$
5	2nd Order	$1 \cap 2 \cap \bar{3}$
6		$1 \cap \bar{2} \cap 3$
7		$\bar{1} \cap 2 \cap 3$
8	3rd Order	$1 \cap 2 \cap 3$

Note: 1, 2, 3 = section of failed defences
$\bar{1}$, $\bar{2}$, $\bar{3}$ = section with NO failure

The number of scenarios and associated calculations rapidly exceeds reasonable computer processing time. The number of scenarios to be analysed is kept to a minimum by considering only those that can flood a given impact zone. When this is not sufficient, high order failure scenarios (for example those where more than five defences fail simultaneously) with a low probability of occurrence can be eliminated from the calculation (some analysis of this is provided in the High Level Case Study Report in Appendix I). The inaccuracy due to this approximation can be calculated exactly and, provided it is not significant, the probabilities of the remaining scenarios are often factored so that the total probability sums to unity.

9.3.2 Calculation of probabilities

The probability of failure of each individual flood defence (Scenarios 2,3 and 4) is determined by making reference to the fragility curves defined in Section 4. For those scenarios with multiple defence failures the fragility curve for that scenario is calculated by considering the specific fragility curves for individual defence sections. For example the conditional overtopping probabilities of sections 1 and 2 (scenario 4) would be calculated using equation 9.2. This should be applied to both lower and upper bounds of the fragility curves.

$$P(\mathit{OT\ sections\ 1\&2}|x) = P(\mathit{no\ OT\ section}\ 1|x)^*\ P(\mathit{no\ OT\ section\ 2}|x)^*P(\mathit{OT\ section\ 3}|x) \tag{9.2}$$

where x is the load proxy and OT represents failure by overtopping.

Every defence that can inundate a given impact zone is part of the defence sub-system identified in step 5. Each possible failure scenario for these defences should be analysed. The probability of each scenario occurring can be calculated and tabulated, as shown in table 9.2. The sum of the probabilities is unity.

Table 9.2 An example calculation for a three defence system of different scenario failure probabilities. Note the sum is unity

Scenario No.	Failed defences	Upper bound probability of scenario	Probability of scenario	Lower bound probability of scenario
1	no failure	0.750	0.716	0.684
2	$1\cap\bar{2}\cap\bar{3}$	0.065	0.071	0.076
3	$\bar{1}\cap 2\cap\bar{3}$	0.143	0.157	0.171
4	$\bar{1}\cap\bar{2}\cap 3$	0.023	0.030	0.036
5	$1\cap 2\cap\bar{3}$	0.012	0.016	0.019
6	$1\cap\bar{2}\cap 3$	0.004	0.007	0.009
7	$\bar{1}\cap 2\cap 3$	0.002	0.003	0.004
8	$1\cap 2\cap 3$	0.000	0.001	0.001
	Σ	**1.000**	**1.000**	**1.000**

This is discussed in more detail in the High Level Case Study report (Appendix I).

10. STEP 8: ESTABLISH FLOOD DEPTH VERSUS PROBABILITY CURVES FOR EACH IMPACT ZONE

10.1 Overview

Within each Impact Zone potential socio-economic impacts have been identified using standard databases (see Appendix H). To calculate the flood risk (either economic, people at risk etc) the damages associated with a particular flood depth occurring are multiplied by the probability of the depth being equalled or exceeded, (i.e. the results from Step 8 are combined with the socio-economic data damage curves). The economic flood risk is measured as the average annual damage (AAD) associated with a combination of failure and overtopping defence failure scenarios. The damage value for each defence failure scenario is calculated based on the expected flood depth in an impact zone for a given event.

10.2 Inputs and outputs

Inputs: Impact zones (as defined in step 4)
Economic damage for given flood depths for different property types
Flood depth (as calculated in step 6)
Floodplain maps
Land use information (Focus database, Address Point)
FHRC Depth damage curves
Other impacts (SVFI, population numbers)

Outputs: Damage value based on flood depth for a given failure scenario within an impact zone

The output of this step of the RASP methodology is a flood damage value for a given flood event, for a given defence failure scenario, within a given impact zone. The output from step 6 is a probability of this failure scenario occurring. An average annual damage value can therefore be calculated. As shown in Figure 2.1, steps 6-8 must be repeated for every failure scenario to give a total average annual damage value for a given event. Steps 5-8 are repeated for each event to give a total average annual damage value for the impact zone. A total average annual damage value is calculated by performing the analysis for each impact zone, this value represents the total system economic flood risk.

10.3 Methodology

10.3.1 Impact zone depth-damage curve

Each property will have an associated depth-damage curve, but each area of agricultural land will have a flood damage cost in pounds per hectare per year according to the Agricultural land classification (ALC) within the impact zone (see Figure 10.1). These are summed within each impact zone to provide total damage for given flood events. Agricultural damage is not depth related. These depth-damage curves are based on generic property and land-used descriptors from the Address Point, Focus and the Agricultural Land databases (see Appendix G).

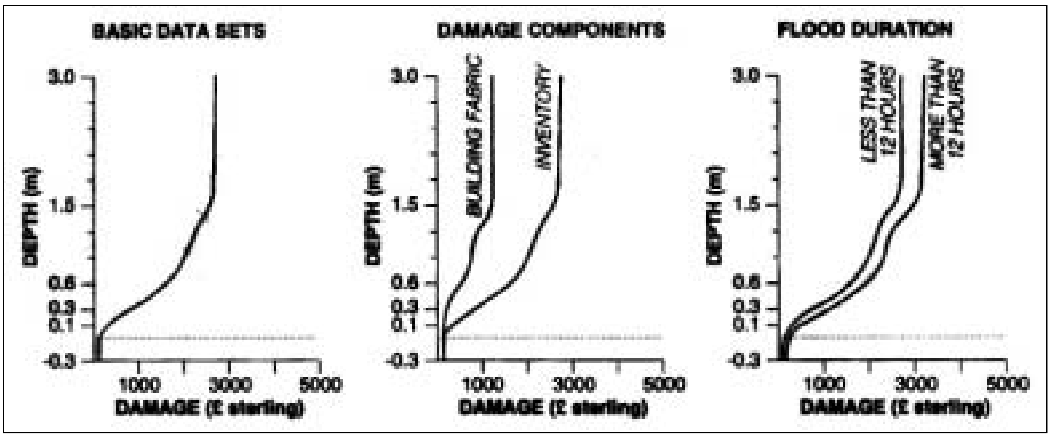

Figure 10.1 Example of depth-damage curves (Penning-Rowsell and Chatterton, 1977)

10.3.2 Total economic damage for a flood event

The flood depth within the impact zone is an output from Step 6, the expected damage within the impact zone for a given event can then be read off the impact zone's depth-damage curve.

11. STEP 9: CALCULATE FLOOD RISK BOUNDS AND OTHER OUTPUTS

11.1 Overview

The economic risk which is measured in terms of average annual damage for each event and each scenario within an impact zone is calculated by multiplying the economic damages from step 8 with the scenario probabilities from step 7. These are then summed over all flood events and scenarios to give bounds of total economic risk for a given impact zone. The average annual damage contribution from each defence is also extracted.

11.2 Inputs and outputs

Inputs: Probability bounds of failure scenarios (as defined in step 7)
Depth damage curves for impact zone (as defined in step 8)

Outputs: Bounds for the total economic risk of the system
Bounds for the total economic risk of each impact zone
Bounds for the risk contribution of each defence in the system

11.3 Calculating system risk

To calculate total bounds of economic flood risk for the system, equation 11.1 is used. This is essentially a loss probability equation for each impact zone. The economic damages are the output from step 7 and the scenario probabilities are the output from step 6.

$$\sum_{all\ impact\ zones}\left(\sum_{all\ events}\left(\sum_{all\ scenarios}(financial\ damage\ from\ scenario \times probability\ of\ scenario)\right)\right) \tag{11.1}$$

The total risk bounds of each impact zone are a useful output, but total risk bounds for the system (as identified in step 1) are calculated by summing the risk bounds for each zone (as shown in equation 11.1).

Another useful output is the contribution to the risk from each defence. This is calculated by aggregating the risks for each defence in each of its failure scenarios. Defences that protect more high risk impact zones will therefore have a higher associated risk contribution.

11.3.1 Risk outputs

Many queries on the flood risk can be viewed. These are:

Economic damage

The number of domestic and commercial properties in each Impact Zone can be easily extracted from nationally available databases, such as OS Address Point. For a given Impact Zone the expected annual damage *R* is given by

$$R = \int_0^{y_{max}} p(y)D(y)dy \quad (21)$$

where y_{max} is the greatest flood depth from all failure scenarios, $p(y)$ is the probability density function for flood depth and $D(y)$ is the damage at depth y. The total expected annual damage for a catchment or nationally is obtained by summing the expected annual damages for each Impact Zone within the required area. The contribution each defence has to the risk can also be established enabling a range of economic risk measures to be determined, for example:

1. Total system flood risk;
2. Flood risk for each impact zone;
3. Flood risk contribution from each defence;
4. Risk by condition grade;
5. Risk by SoP;
6. Risk by flood event;
7. Risk by defence type.

11.3.2 Additional risk output

1. Failure probabilities of each defence;
2. Houses flooded to a given depth with probability p;
3. People at risk;
4. Measure of social vulnerability.

12. STEP 10: PRESENT THE RESULTS

12.1 Overview

Present the useful outputs in tabular and graphical form.

12.2 Inputs and outputs

Inputs:	Total flood risk bounds for floodplain (from step 9) Risk bounds for impact zones (from step 9) Failure probability bounds for each of the defences (from step 3) Bounds for the risk contribution of each defence in the system (from step 9)
Outputs:	Tabular and Graphical summaries

12.3 Example

RASP results will be presented as GIS outputs (see Figures 12.1, 12.2 and 12.3) and may be exported to NFCDD in order to support the decisions outlined in the Introduction to this Report. Figure 12.1 shows the estuary of the river Parrett in North Somerset. The floodplain has been shaded according to the economic risk, darker shades representing a higher risk.

It is also noteworthy that the RASP methodology can also be used to assess intervention strategies (such as increasing the maintenance programme) or test scenarios (for example climate change or increased floodplain development). Two such tests are demonstrated in Figures 12.2 and 12.3. Figure 12.2 shows the same area as Figure 12.1, but an increased maintenance programme has resulted in all defences of Condition Grades 3-5 improved to Grade 2. Whilst there is an obvious reduction in risk (captured by the lightening of the floodplain), the result is not especially dramatic as many of the defences were already in good condition. Figure 12.3 shows the result of a climate change scenario in which the *SoP* of each defence has been decreased by 20% (to reflect the increased loading from water levels). The obvious darkening of the floodplain demonstrates that there is a significant increase in risk as a result of such a change.

See also Appendix I – Case Study – The Parrett Catchment.

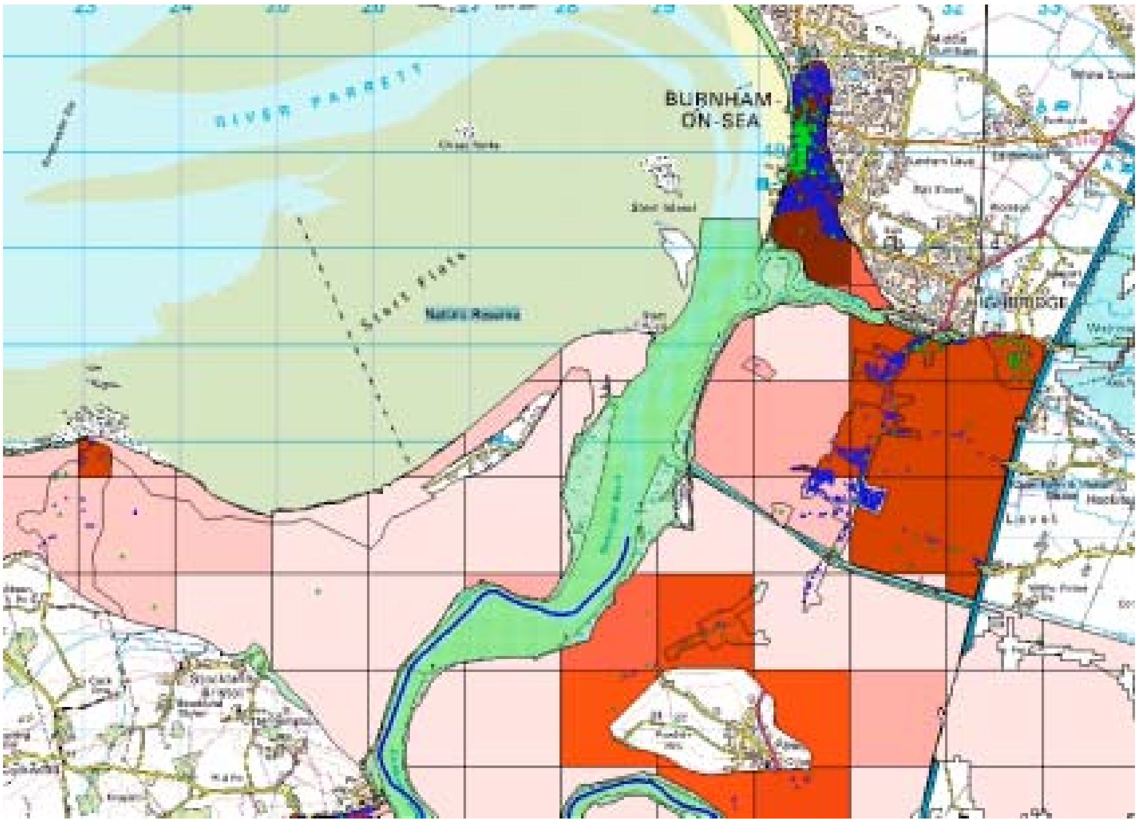

Figure 12.1 Typical GIS output from the RASP High Level Methodology showing the estuary of the river Parrett. Darker shades represent a higher risk. The dots represents Residential and non-residential properties

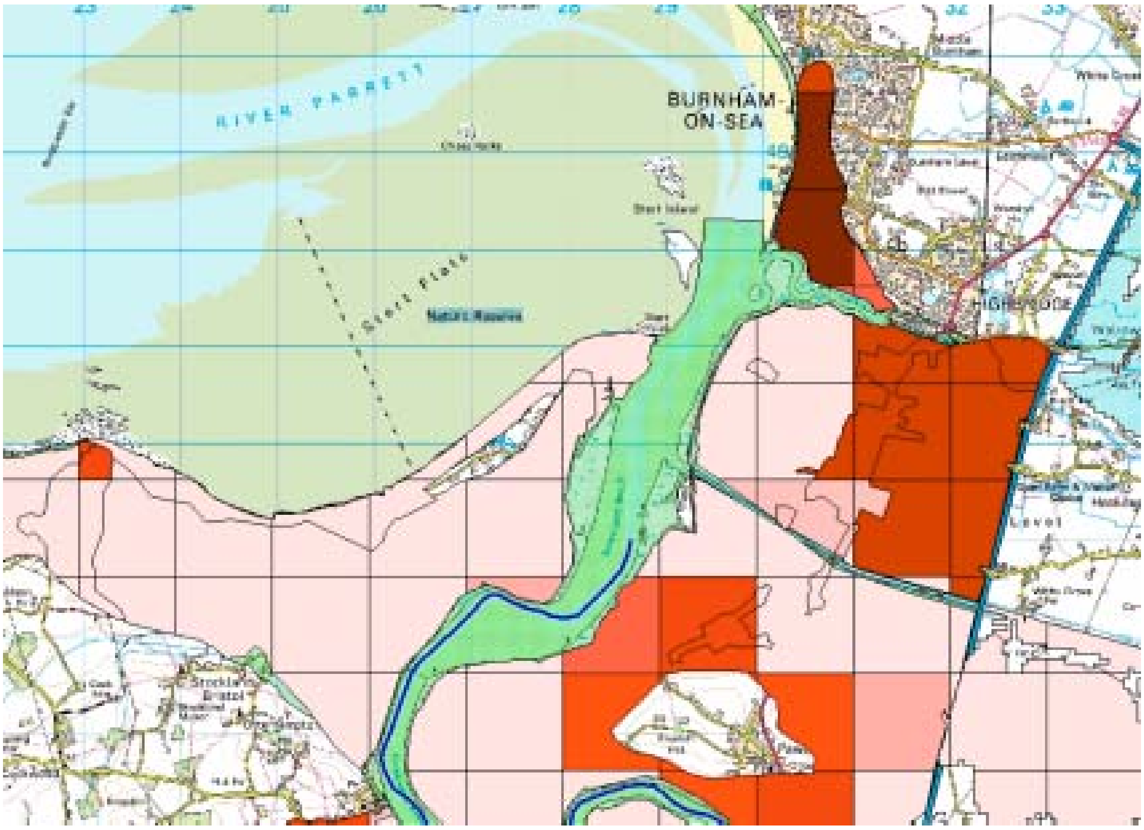

Figure 12.2 RASP output for the Parrett estuary after maintenance of the defences is increased

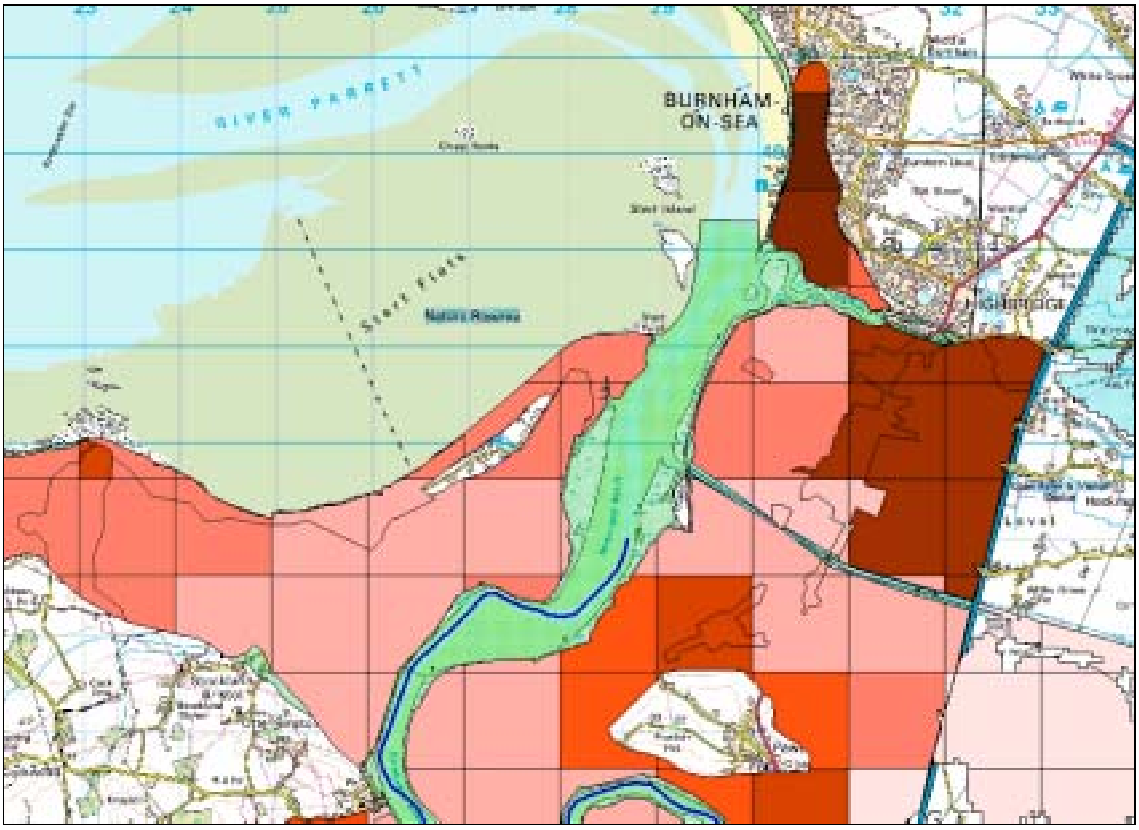

Figure 12.3 RASP output after a <u>climate change scenario</u> that increases water levels

13. CONCLUSIONS

The first twelve months of the RASP project have provided a number of useful insights and techniques for assessment the flood risk associated with systems of linear defences. The methodology outlined in this report is a significant first step towards a consistent measure of national flood risk from fluvial and coastal sources. The report demonstrates a methodology for national-scale flood risk assessment that uses only nationally available datasets in England and Wales, has been developed, 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 (excluding groundwater and local runoff), taking into account the defence Standard of Protection (the return period at which the defence is expected to be overtopped), 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. 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/coastal cell and local-scale analysis.

Over the coming few years these High Level Methodologies will be applied to support specific decisions and extended to provided increasing levels of detail. These next steps include:

- Development of more detailed levels of systems analysis through the Intermediate and Detailed levels of RASP
- Application of the RASP High Level Methodology to establish the national assets at risk from flooding
- Development of a specific application through the demonstration of the RASP techniques as part of performance-based asset management systems.

14. RECOMMENDATIONS

14.1 Future improvements to the High Level Methodology

The High Level Methodology outlined in this report 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 that the reader should note and that should be addressed through further develop are as follows:

1. **Lack of topography and quantitative load information** - A key constraint placed on the RASP high level methodology (the approach that underpins the National Flood Risk Assessment 2002) is the lack of a national topographic and quantitative water level dataset. With regard to topographic data this is likely to change by April next year (2003) with the purchase by the Agency of a national dataset (it is interesting to note that it may be possible to extract crest level from the dataset too). Equally, a national dataset on extreme river flows is available and could be used in conjunction with data from Proudman to generate a national dataset of extreme riverine and coastal water levels. Availability of these datasets would significantly improve the reliability of the methodology and enable the frequency of extreme fluvial flows or marine storms to be assessed directly without the need to rely on factor *x* times SOP a proxy for load. It would also remove the need to adopt flood depths based on statistical analysis of real and simulated data, enabling local topography to be considered.

2. **Reliance on generic fragility curves** - 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 defence geometry and other key parameters that determine defence resistance.

3. **The need for better defence data** - The RASP methodology relies upon knowledge of the interface between the river/coast and the hinterland. Therefore a continuos tramline of defences has been developed as part of the NFRA 2002 around the main river network and shoreline. This has been assigned a link to the data within NFCDD to provide details on defence type, condition and SoP. In many areas this has been difficult due to geo-spatial referencing errors within NFCDD as well as missing data. This has resulted in significant, yet unquantified, uncertainty in the results (some of which is captured in the upper and lower bounds on the fragility curves – but not all).

4. **Improved flood spreading routines** - 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.

5. **Exclusion** of other sources of flood risk – Groudwater and local runoff are excluded from the RASP framework at present that deals only with flooding arising from flow over linear defences. Equally the failure of pumps and gates are excluded.

14.1.1 Recommendation 1 – Development of a High Level Plus Methodology

The methodology outlined in this paper is a significant first step towards a consistent measure of national flood risk from fluvial and coastal sources. However, the limitations described in 1 and 4 above could be relatively easily removed. These amendments will alter the detail of the high level methodology outlined in this report in a number of areas, for example enabling an improved inundation model to be incorporated and remove the reliance on a statistical model of flood depth. However, they will not alter the concept of the methodology. The resulting methodology will be considerably more robust and locally representative. It will also provide the framework for evolution of our understanding of national risk as improved data becomes available without step changes in methodology.

14.1.2 Recommendation 2 – Improvement in NFCDD structure to reflect input needs of RASP and its outputs

An opportunity exists to integrate the concept of "defence tramlines" into NFCDD and EA/LA asset management as well as undertaking a review of the data assigned to the tramlines as part of on-going NFRA 2002. This review and quality assurance process would add considerable confidence to the results, and provide a basis for future National Risk Assessments and NFCDD updates. At present, in the absence of a direct link between NFCDD and the RASP methodology, further updates will be expensive and introduce random errors rather than evolving to an ever-improving understanding of the location, type and condition of defences.

To make advances in this area will demand significant resource effort – for both contractor, EA /LA and NFCDD staff over say a 6-8 month period at least.

14.1.3 Recommendation 3 - Extent the concept a systems framework to include groundwater and local run-off – Whole system analysis frameworks

Although the flooding processes associated with groundwater and pluvial events (i.e. local runoff) are different from those of fluvial and coastal, there would be significant merit in exploring and developing a conceptual framework within which these could be considered in the whole system assessment of flood risk.

14.2 Directions for more detailed analysis

Whilst these approximations outlined in this paper are appropriate for national-scale risk assessment, 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 more detailed analysis:

1. Statistical analysis of hydrology, and joint probability loading conditions for sea defences, including spatial dependency in both cases.
2. Quantified analysis of multiple defence failure modes making use of site-specific measurements.
3. Analysis of the dependency between defence strength parameters within defence sections and between neighbouring sections.
4. Hydrodynamic modelling for flood depth and extent using high resolution topographic information.

More detailed analysis of tangible and intangible impacts of flooding, including disruption to transportation systems. 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. This more detailed analysis will contribute to verification of the national-scale method.

15. REFERENCES

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