DEFRA/Environment Agency
Flood and Coastal Defence R&D Programme

Risk Assessment for Flood & Coastal Defence for Strategic Planning

High Level Methodology
R&D Technical Report W5B-030/TR1

DEFRA
Department for
Environment,
Food & Rural Affairs

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High Level Methodology

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Statement of use
This document provides information for Defra and Environment Agency Staff about consistent standards for flood defence and constitutes an R&D output from the Joint Defra / Environment Agency Flood and Coastal Defence R&D Programme.

Contract Statement
This report describes work commissioned by the Environment Agency through the Risk Evaluation and Understanding of Uncertainty (REUU) Theme of the joint Defra/Environment Agency research programme. The REUU Theme Leader is Ian Meadowcroft of the Environment Agency. The appointed REUU Theme project representative was Mr Ishaq Tauqir, WS Atkins Consultants Limited. The HR Wallingford job number was CDS 0800/08. The work was carried out by members of the Project Team which was constructed from the following organisations: HR Wallingford Ltd (Engineering Systems and Management Group), University of Bristol (Department of Civil Engineering), Halcrow Maritime, and John Chatterton Associates. The Project Manager was Paul Sayers of HR Wallingford.

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GLOSSARY OF TERMS AND ACRONYMS

Term	Definition
CEH	Centre of Ecology and Hydrology
CG	Condition Grade, A visual assessment of the condition of a flood defence
EA	The Environment Agency of England and Wales
FDMM	Flood Defence Management Manual
FDMS	Flood Defence Management System (the software supporting the FDMM)
GIS	Geographical Information System
MDSF	Modelling and Decision Support Framework
NAAR	National Assets At Risk project
Pf	Probability of failure
$P(OT\|x)$	Conditional probability of overtopping given a loading x
$P(B\|x)$	Conditional probability of breaching given a loading x
$P(B\|x, CG=1\text{-}5)$	Conditional probability of breaching given a loading x and condition grade of 1-5
SoP	Standard of Protection
SVFI	Social Vulnerability Flood Index

EXECUTIVE SUMMARY

It has long been recognised that flood risk cannot be eliminated completely - but understanding the risks is key to improving risk management. In particular, this means deciding on risk management actions such as:

- Construction of new defences where they are most needed.
- Maintaining and operating defences and defence systems to minimise risk.
- Flood forecasting and warning to minimise the consequences in the event of flooding.
- Restricting development in flood and erosion-prone areas to control the impacts.

Risk assessment is rapidly becoming the basis for decision-making in all of these areas. It is also being used to support policy development to address strategic or overarching issues such as:

- What is the appropriate level of spending on flood and coastal defence to ensure risk is reduced, including the possible effects of climate change?
- What combination of risk management measures provides the best value?
- What is the 'residual risk' remaining after all risk management measures, and is this acceptable?

To better understand flood risks and improve the performance of flood defences it is necessary to consider the performance of *systems* of defences rather then merely considering single defences in isolation. If, for example, a town is protected by several different defences then it is necessary to consider how this flood defence system functions as a whole in order to assess and manage the flood risk to the inhabitants and assets in the town. With moves towards more integrated flood management, it is essential that risk managers have recourse to sound and practical tools and techniques for assessing the performance of whole systems in order to develop balanced, integrated risk management strategies.

This interim report describes the progress of an R&D project titled *Risk Assessment of flood and coastal defence for Strategic Planning* (RASP) funded through the Risk Evaluation Understanding of Uncertainty Theme of the joint EA/Defra research programme. The RASP Project aims to develop and demonstrate methods for supporting Integrated Flood Risk Management through the development and demonstration of methods for assessing the performance and risks associated with systems of linear flood defences (flooding arising from groundwater or local runoff is not included). The focus of this report is a high level methodology, which is designed for application on a national basis. More detailed methodologies will follow over the next two years.

In this report, the High Level Methodology is split into steps each described independently. The method is intended to meet Defra's High Level Target 5b (Defra, 1999), which requires the assessment of the risk of flooding using only the minimum, nationally available data, stored in the National Flood and Coastal Defence Database. The method involves:

- estimating defence resistance to overtopping by using the current Standard of Protection (*SoP*);
- estimating the probability of breach for each defence type in the Flood Defence Management Manual by using the *SoP* and numerical grade obtained from the Agency's condition assessment;
- considering all the linear defences and the areas of the floodplain they protect from inundation as a system;
- calculating depth of flooding by making appropriate assumptions about the amount of flooding behind the defences and neighbouring defences;
- estimating the consequences of flooding using nationally available socio-economic datasets.

Confirmation of the practicality of the High Level Methodology, and examples of the possible outputs, is provided through a case study application of the Parret Catchment. The results of this study demonstrate that the High Level Method has considerable utility that may be used for providing an estimate of flood risk that can be used for national resource allocation and prioritisation. However, it is also recommended that the High Level Methodology improved to include a topographic and extreme water level dataset once such datasets become nationally available.

For further information please contact Paul Sayers of HR Wallingford.

1. RASP PROJECT OVERVIEW

1.1 Introduction

It has long been recognised that flood risk cannot be eliminated completely - but understanding the risks is key to improving risk management. In particular, this means deciding on risk management actions such as:

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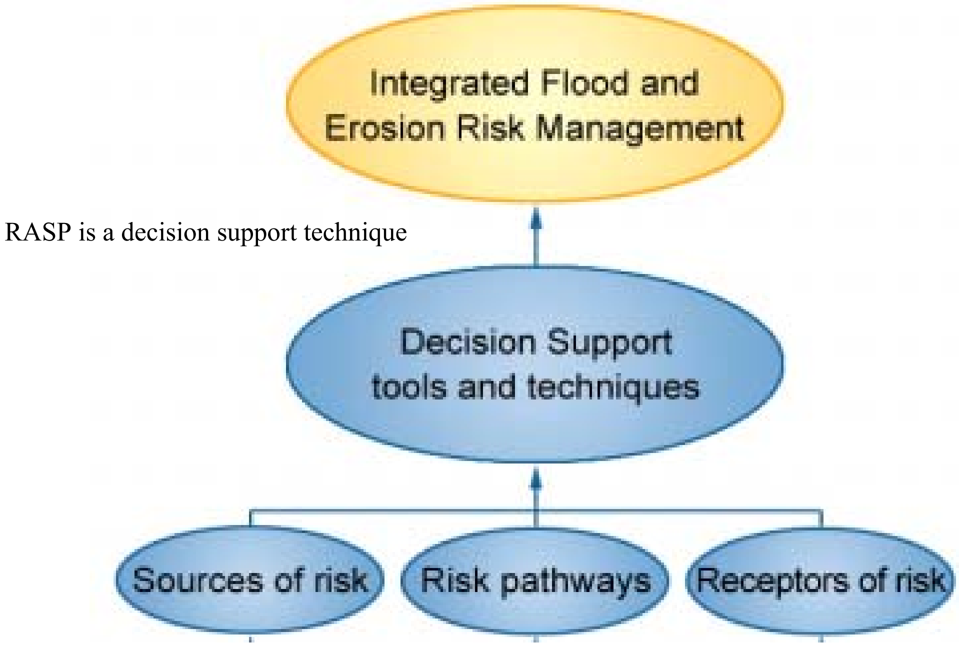
1.2 Overview of the RASP Project

The RASP project began in January 2002 and will be completed in Spring 2004 and will provide a flexible risk assessment methodology capable of supporting a range of decisions including, for example:

- National monitoring of risk from flooding.
- Strategic prioritisation of investment in defence improvements or other flood management options (e.g. increased storage or diversion).
- Targeting flood warning and emergency preparedness.
- Highlighting priorities for monitoring and maintenance and justification of maintenance decisions.
- Scheme design and optimisation.



Sources of risk included in RASP are:

- Extreme river and tidal conditions

Note: Groundwater and local rainfall are excluded

Risk **pathways** included in RASP are:

- Structural (i.e. breaching)
- Non-structural (i.e. overflow/overtopping) of linear defences

Risk **receptors** included in RASP may be any available socio-economic dataset:

- People;
- Properties;
- Agricultural;
- Environmental

Figure 1.1 The role of RASP in supporting Integrated Flood Risk Management[1]

1.2.1 A tiered methodology

In any decision-making situation however it is important to undertake an *appropriate* level of analysis, which is justified by the importance of the decision and its sensitivity to uncertainty. The notion of appropriate analysis is fundamental to RASP (Table 1.1) and is reflected in the tiered methodology that is currently under development:

- The **High Level Method (the subject of this report)** will be based on nationally available datasets on flood defences, flood plains and land use. It will provide a

1 For further discussion of the concept of an Integrated Risk Management Framework the reader is referred to HR Wallingford Report SR 587 Risk Performance and Uncertainty in Flood and Coastal Defence - A Review and the discussion in Meadowcroft, Sayers and Hall, Defra 2002

methodology for monitoring national flood risk (for example to support a more comprehensive assessment of national risk than the National Appraisal of Assets at Risk from flooding and erosion published by Defra in 2001, HR Wallingford, 2001).

- The **Intermediate Level Method** will use measurements or model estimates of flood water levels, flood defence levels and ground elevation to generate better estimates of flood risk. It will be used to inform strategic decisions on flood risk management.

- The **Detailed Level Method** will use detailed information about the composition of defences to generate an improved estimate of their probability of failure by a number of different failure modes. Simulation methods will be used to estimate risks in a large number of flooding scenarios.

Table 1.1 Hierarchy of RASP methodologies, decision support and data required

Level	Decisions to inform	Data sources	Methodologies
High	National assessment of economic risk, risk to life or environmental risk Prioritisation of expenditure Regional planning Flood warning planning	Defence type Condition grades Standard of Protection Indicative flood plain maps Socio-economic data Land use mapping	Generic probabilities of defence failure based on condition assessment and crest freeboard Assumed dependency between defence sections Empirical methods to determine likely flood extent
Intermediate	*Above plus:* Flood defence strategy planning Regulation of development Maintenance management Planning of flood warning	*Above plus:* Defence crest level and other dimensions where available Joint probability load distributions Flood plain topography Detailed socio-economic data	Probabilities of defence failure from reliability analysis 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	Simulation-based reliability analysis of system Simulation modelling of inundation

1.2.2 RASP outputs

Regardless of the *leve*l of detail of the analysis the RASP methodology will deliver consistent but progressively more dependable (i.e. more certain) results, including:

- an estimate of the flood risk associated with the failure of any single or combination of flood defences;
- an estimate of the total flood risk for identified impact zones in the flood plain;
- an indication of the contribution that each defence makes to the total risk in the floodplain.

RASP can therefore be used in support of a range of decisions:

- national monitoring of risk from flooding;
- strategic prioritisation of investment in defence improvements or other flood management options (e.g. increased storage or diversion);
- targeting flood warning and emergency preparedness;
- highlighting priorities for monitoring and maintenance and justification of maintenance decisions;
- scheme design and optimisation.

Appropriate guidance on how these outputs can be used to support specific decisions, for example the maintenance and operation of defences, will be provided through more development projects such as the planned Performance-based Asset Management System project. Equally, it is envisaged that future updates of the Catchment Management Planning Guidance, Shoreline Management Guidance and supporting Modelling Decision Support Tools will utilise the RASP methodologies.

All RASP outputs will be compatible with standard Geographical Information Systems to support simple user visualisation and integration with other spatial datasets. RASP will not be delivering new software, however, but it will be inputting into current software development projects such as the Modelling Decision Support Framework being developed in the Broad Scale Modelling Theme.

RASP will also involve demonstration studies at pilot sites and production of written guidance to enable widespread application. Through a linked study, the RASP High Level Methodology is currently being applied to all of England and Wales in order to update the National Appraisal of Assets at Risk (due for completion January 2003).

1.2.3 Links between RASP and other R&D and software projects

The RASP project is running in parallel, and being co-ordinated, with other national initiatives to help manage flood risk. The methodologies under developed in RASP are also likely to form significant elements of future R&D. These present and future links include:

- The *Modelling and Decision Support Framework* (MDSF). Originally MDSF was developed to support Catchment Flood Management Plans and provides a standardised GIS framework , and data structures, with a number of in-built functions to calculate property damages using standard Middlesex Guidance and social vulnerability under given scenarios of flooding. RASP provides an analysis methodology to estimate the distribution of flood inundation risk and economic damages and is therefore complimentary, not in competition with MDSF.

- The *National Flood and Coastal Defence Database* (NFCDD) provides key information on defence types and conditions used by RASP at all levels of detail. RASP will provide an estimate of the contribution that each defence makes to flood risk. It is recommended that this data is stored feedback to NFCDD, enabling NFCDD to be queried on a range of 'risks' (see Figure 1.2).

- Defra/EA funded research on performance and reliability of individual structures (for example *embankment failure under extreme conditions* led by HR Wallingford and *failure on demand of flood and coastal defence components* completed by RMC*)* will provide information on individual defence failure mechanisms in support of more detailed reliability analysis of defence performance and more dependable predictions of defence "fragility" within the framework of the RASP methodology.

- *Performance-based asset management* - Operations and maintenance Concerted Action, Performance Evaluation Concerted Action, and ESPRC funded work on condition monitoring and asset management (CMAM) led by the University of Bristol will be integrated with the RASP methods and MDSF within a specific tool aimed at better asset management. The project seeking to deliver this improvement is due to start January 2003 and is titled *Performance-based Asset Management (PAMS) – Phase 1*. The PAMS project will be led by HR Wallingford with inputs from University of Bristol, Posford Haskoning and RMC.

- The National Appraisal of Assets at Risk from flooding is currently being updated in 2002 using the RASP High Level Method outlined in this report.

- *FORESIGHT* – A major initiative by OST is to explore possible changes in flood risk in the future. The RASP High Level Methodlogy outlined in this report is likely to provide the tool for exploring the possible impact on flood risk of possible socio-economic, climate and flood management futures.

- The consistent framework offered by RASP also has significant links to many other flood defence initiatives, including
  - Risk, uncertainty and performance review (HR Wallingford, 2002) ,
  - Performance concerted action,
  - Operations and maintenance concerted action,
  - Condition monitoring and asset management,
  - Reducing uncertainty in river flood conveyance, and,
  - Reducing the risks of embankment failure under extreme conditions.

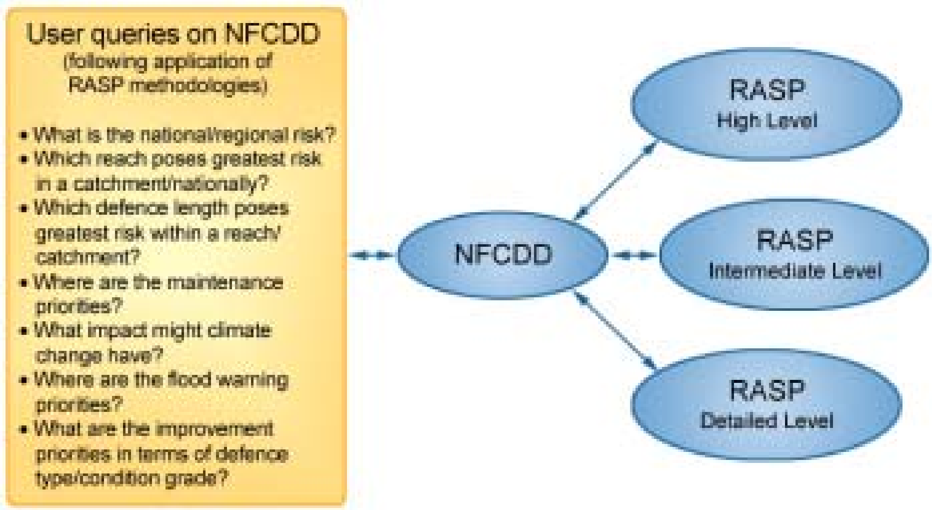


Figure 1.2 Envisaged interactions between the NFCDD and the RASP methodologies and results

1.3 RASP's contribution to achieving Defra's High Level Targets

Defra's High Level Target 5A (Defra, 1999) requires that the Environment Agency reports, nationally, on its assessment of the risk of flooding. The High Level Method in RASP will provide a methodology that directly supports this requirement. RASP will also provide a basis for risk-based prioritisation and culd provide useful insight to establishing national flood warning and maintenance priorities.

2. OVERVIEW OF HIGH LEVEL METHODOLOGY

The High Level Methodology is based on the analysis of impacts within the floodplain and is intended to meet Defra's High Level Target 5b (Defra, 1999) which requires an assessment of the risk of flooding. This chapter provides an overview of the high level methodology which is then described in more detail in the following chapters.

2.1 Data constraints

Perhaps the most important constraint that has shaped the RASP High Level Methodology is data. In understanding the methodology it is first important to understand the principal constraint placed upon it due to lack of data:

- **Flood plain extent:** At the time of writing, the only nationally available information on the potential extent of flood inundation are the Indicative Floodplain Maps (IFMs) published by the Environment Agency. These show outlines of the areas 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. In both cases the IFM has been based on evidence from topography mapping, flood modelling and/or records of past floods. Once available the methodology could be easily extended to include the Extreme Flood Outline as currently being developed by the Agency.

- **Quantitative wave and water level data** The methodology has been developed in the absence of quantitative information on extreme water levels and wave loadings. It is however noteworthy that in the future this assumption may be relaxed through access to the CEH-Flowgrid and POL datasets.

- **Flood plain topography** The methodology has been developed in the absence of a national topography dataset of reasonable accuracy. It is however, noteworthy that this assumption may be relaxed in the future with the purchase of the national dataset by the Environment Agency and the increasing availability of LiDAR data (although without information on flood water levels in itself access to a topographic dataset does not necessary improve the reliability of the method)

- **Information on linear defence infrastructure**. The recently created National Flood and Coastal Defence Database provides for the first time recourse to a national dataset of defence location, type and condition. Crucially however, information on crest level and crest width are not mandatory and therefore are not available national and can not be used here.

- **Economic and demography datasets**. National scale datasets exist for property locations, agricultural land classifications, transportation infrastructure and agreed methodologies for valuing their likely flood damage in the event of a flood to a given depth and of a given duration. Information of the distribution of social groupings and are also available nationally through datasets derived from census data. For example, a measure of the social harm of flooding may be obtained from Social Flood Vulnerability Indices.

2.2 Overview of the methodology

The method is broken into ten steps that are summarised in Figure 2.1 and described separately in the following Chapters.

The main criteria for the methodology are that it:

- is based on data in the NFCDD or readily available on a national basis;
- can be implemented routinely without expert input;
- is implemented in software, so fairly complex or numerous calculations are permitted.

A more detailed overview of the inputs and outputs of the methodology is shown in Appendix A, Figure 1A (at the end of the report). The remainder of this report describes and explains the methodology in detail.

In the current methodology, the Indicative Floodplain (as defined by the IFM) is therefore adopted as the maximum extent of flooding and is further sub-divided into impact zones, not greater than 1km × 1km. Each impact zone is associated with a system of flood defences which, if one or more of them were to fail, would result in some inundation of that zone.

The absence of a nationally available datasets of extreme flood levels and moreover, the lack of a complete dataset on defence crest level means that the probability of failure of a flood defence system can be estimated using standard methods of structural reliability analysis, as these methods require probability distributions for the hydraulic loads and the parameters describing defence response as well as analytical or numerical expressions for each failure mode. The only information on the relationship between flood water level and crest level, clearly crucial for any flood risk analysis, is the so-called Standard of Protection (SOP) afforded by the defence. The SOP provides an assessment of the return period at which the defence will significantly be overtopped or overflowed. Therefore within the current methodology the SOP is used as a proxy for load.

Under load each defence is considered as having two primary failure mechanisms; the defence can either be overtopped whilst remaining structurally intact or breached. A generic conditional probability distribution of defence failure for a given load defence type and condition, is used to estimate the probability of failure by these two separate mechanisms, overtopping and breaching, as well as a combined case of both breaching and overtopping. Combinations of defence failures are then considered where progressively increasing numbers of defences are considered to fail. For each scenario of defence failure(s) within a system of defences an estimate is made of the probability of that failure scenario occurring under a given load taking into account the dependency between defence sections. For each failure scenario an approximate flood outline is generated using parametric routines that estimate discharge through or over the defence and inundation characteristics of the floodplain. In the absence of topographic data the estimation of flood depth is based on statistical data from real and simulated floods in a range of floodplain types and floods of differing severity. 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 Social Flood Vulnerability Indices.

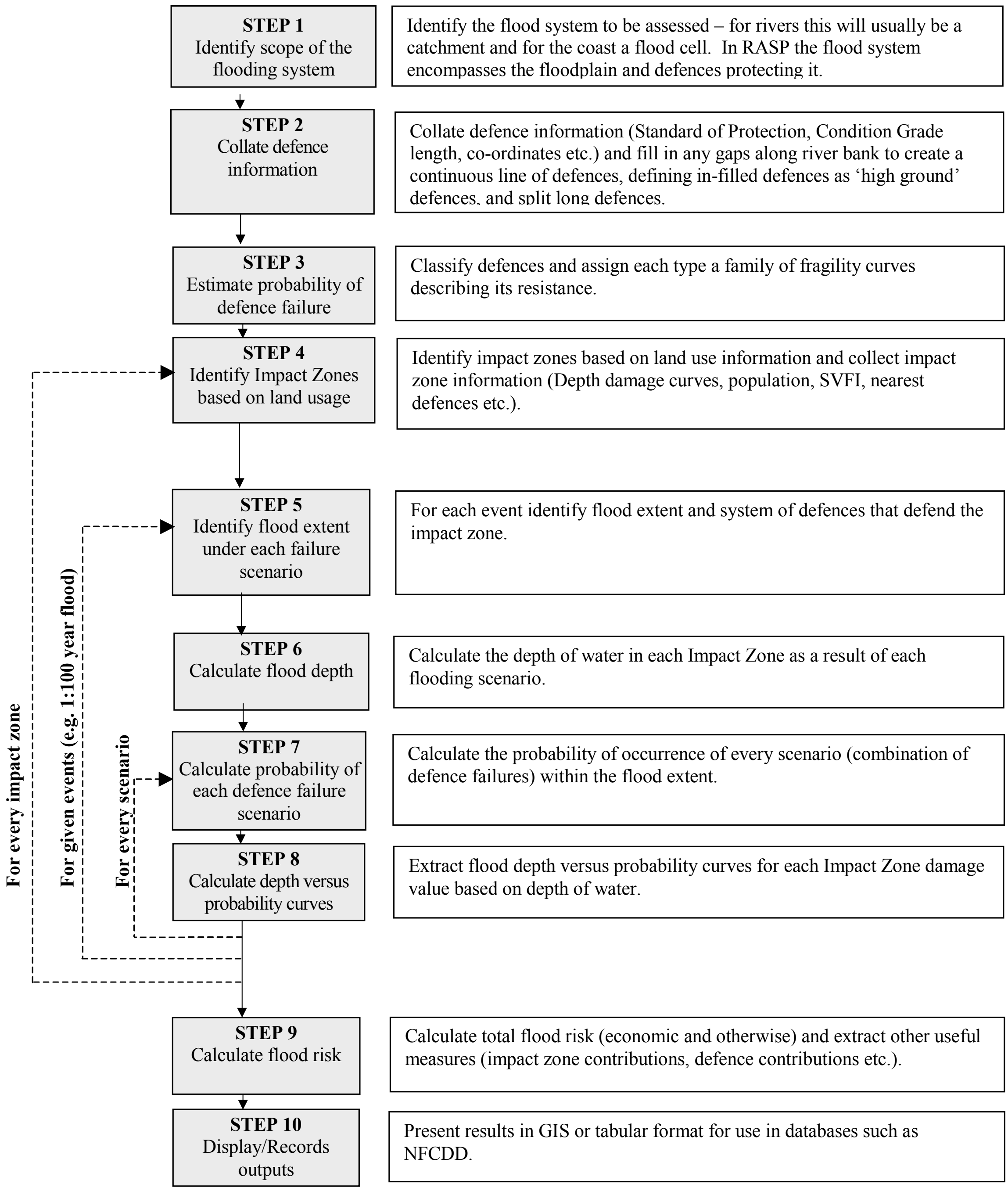


Figure 2.1 Ten steps to a high level risk output

3. STEP 1: IDENTIFY THE SCOPE OF THE SYSTEM

3.1 Overview

Systems risk analysis starts with the identification of self-contained flooding systems. These are floodplain areas that are distinct and separate from each other and have been defined on the basis of the Agency's Indicative Flood Maps. The flooding system is defined as continuous areas of the floodplain that have an uninterrupted boundary with the river or coast. Consequently, the system will often be large, for a river, this will frequently be an entire catchment and will include the fluvial, tidal and coastal defences.

3.2 Inputs and outputs

Inputs: The Indicative Floodplain Map
River centreline data from CEH
Shoreline

Outputs: Flood systems, based on watercourses, and coastal and fluvial floodplains

3.3 Methodology

Figure 3.1 shows the river Parrett and the fluvial (blue) and tidal (green) elements of the Indicative Floodplain.

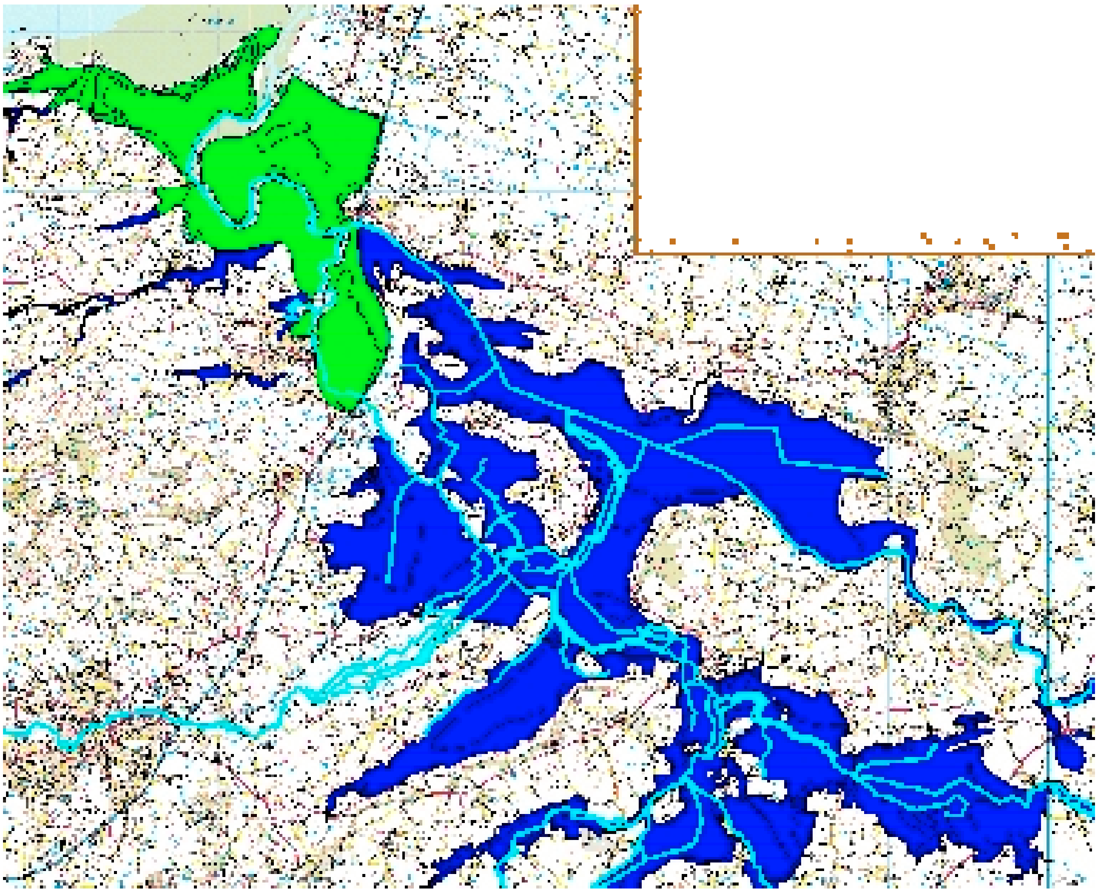


Figure 3.1 Indicative Floodplain of the river Parret's catchment in North Somerset

4. STEP 2: COLLATE INFORMATION ON THE LINEAR DEFENCE SYSTEM

4.1 Overview

There are three parts to step 2:

- collecting all necessary defence data,
- filling gaps in the defence line with defences classified as '*High Ground*' or having no raised defence, and,
- splitting long defences into short defences for the purposes of analysis

4.2 Inputs and outputs

Inputs: Floodplain system (as defined in step 1)
Start and End National Grid Reference for each defence
Defence Length
Defence type, sub-type, material (and revetment type if applicable)
Standard of Protection (*SoP*)
Condition Grade (*CG*)
Nominal floodplain width
Valley classification

Outputs: Continuous defence line along both sides of river and along the shoreline (terminating only at river sources or the limit of the coastal flood plain) where gaps are filled in with '*High Ground*'
Classification of defences based on FDMM codes
Defence properties associated to each defence
Long defences split into lengths of approximately 300-500m

4.3 Methodology

4.3.1 Information needed for each defence

Associated with each defence, the minimum information required is:

- Upstream and downstream defence co-ordinates, used for GIS purposes
- Defence length is used in the defence splitting routine described in section 4.3.3.
- Defence type, defence sub-type and material codes (and revetment type if applicable), which are used to classify the defence into generic defence types, described in step 3.
- Standard of Protection (*SoP*) and Condition Grade are used to assess the structure's proneness to failure, described in step 3.

4.3.2 Defence tramlines

Frequently the defence line is incomplete and stretches of the river/coast appear to be undefended as shown in Figure 4.1. This is because it is often only the defences that are identified in an asset survey and natural river banks/coastal dunes which also retain the river or protect the coast up to a given load are not always included. The defence system must be complete for analysis to work and so it is necessary to create complete defence tramlines along the river and along the coast. The missing lengths of defence are therefore assumed to have no raised defence with an NFCDD defence type code of *HG* which denotes *High Ground*. The Standard of Protection assigned is the *SoP* of the reach. Figure 4.2 and Table 4.1 show filled in data for a stretch of river.

4.3.3 Defence splitting

Research (CUR/TAW, 1990) has suggested that defences show reduced dependency along their length. Parts of a defence greater than about 500m apart show almost independent properties. To account for this, defences over the length of 600m are split into sections of between 300-500m for the purpose of analysis.

4.3.4 Upstream storage

Upstream storage facilities can be considered as long as they are correctly associated with the downstream defence system whose *SoP* they influence. The impact zones within which they mitigate flooding will therefore be correctly identified also.

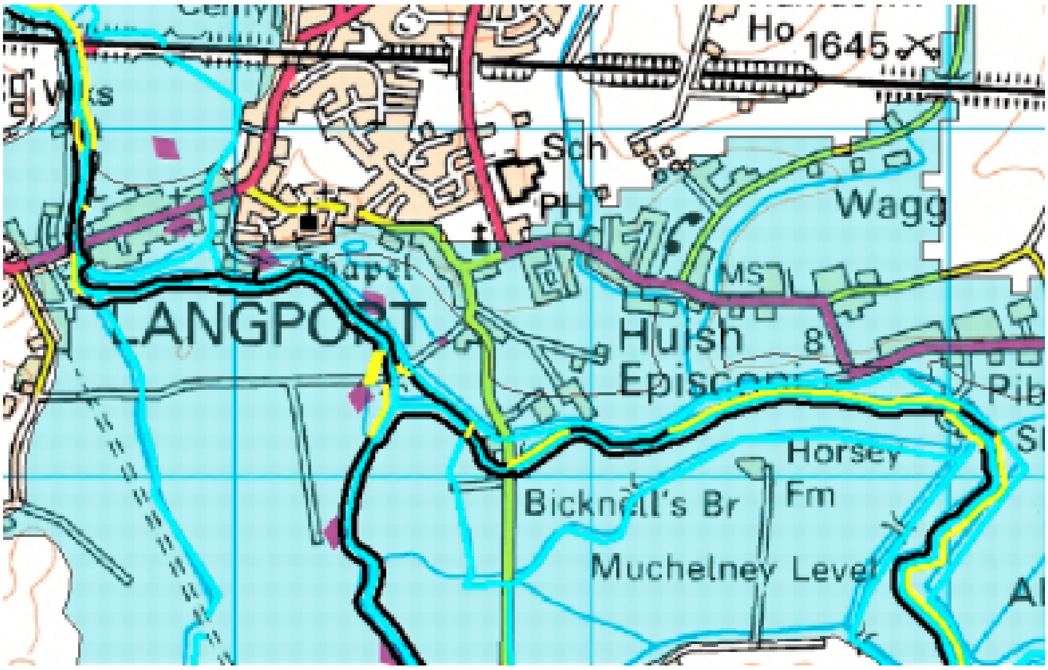


Figure 4.1 Defences along the river Parrett showing incomplete defence line

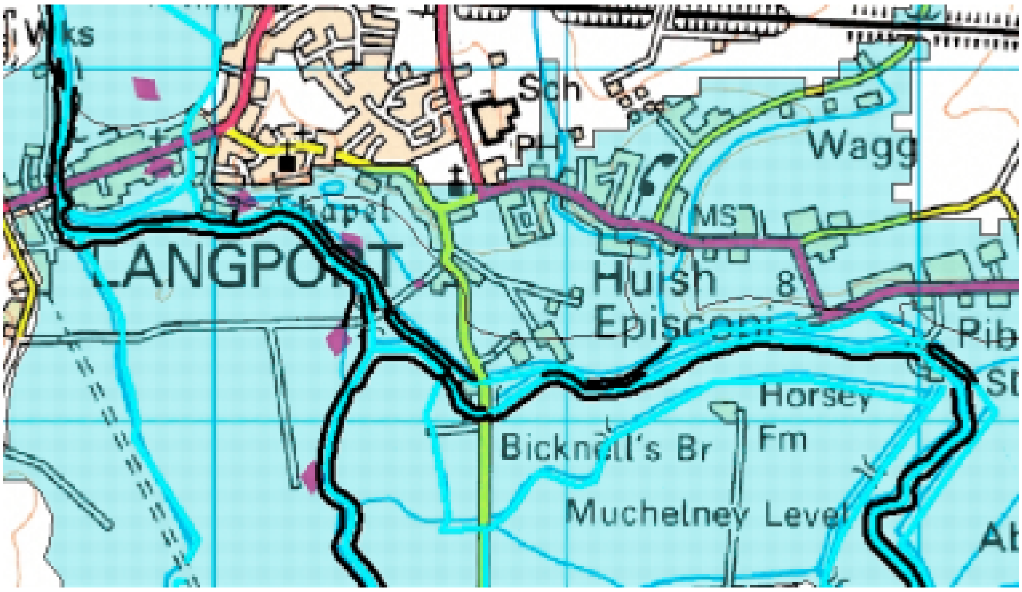


Figure 4.2 **The yellow defence lines (which are the gaps in Figure 3) have been filled in and classified as 'High Ground'**

Table 4.1 Example defence data, the filled in defence sections are highlighted

Fdms_ID	Length	Type	Sub Type	Material	CG	SoP	Length	Midpoint_x	Midpoint_y	Startx_coord	Starty_coord	Endx_coord	Endy_coord
1122587610103L01	819	FC	B	E	2	100	818.56	343915.30000	125775.40000	343994.37462	125460.59347	344096.16146	126085.13342
1122587500402L01	429	CB	N	E	3	100	429.21	341521.30000	127219.30000	341539.91280	127007.00539	341365.67701	127339.32208
1122587610101L02	35	FI	W	M	2	100	34.63	342780.00000	126012.00000	342768.31738	126004.51613	342785.22099	126000.00827
1122587500405R98	11	HG			2	100	11.15	341578.90000	126774.90000	341573.52955	126776.43318	341584.28729	126773.49408
1122587610106R03	860	HG			2	100	859.84	343986.20000	125766.50000	344037.99682	125460.47692	344136.15448	126116.36633
1122587610102R99	193	HG			2	100	193.33	342850.60000	126079.80000	342766.80041	126032.01138	342932.46601	126129.63809
1122587500502R99	111	HG			2	100	111.11	342395.80000	126307.30000	342367.75663	126268.24269	342418.03878	126356.44886
1122587500504L01	1418	FI	N	E	3	100	1418.21	342449.10000	125485.30000	342475.92777	124831.87667	342374.74366	126109.81258
1122587500506R01	1417	CB	N	E	3	100	1416.73	342505.90000	125488.60000	342522.36282	124833.43573	342419.09932	126099.54915

5. STEP 3: ESTIMATE THE PROBABILITY DEFENCE FAILURE

5.1 Overview

By considering the conditional probability of defence failure for a multiple, x, of a defence's current SoP over a range of x, a distribution of conditional failure probabilities for overtopping and breaching (for condition grades 1-5) can be plotted as a fragility curve. A fragility curve is a plot of the conditional probabilities of failure of a defence over a range of loadings, an example of this is shown in Figure 5.1. These nationally generic, defence specific fragility curves will be used to assess probabilities of failure with respect to overtopping and breaching and will be defence type specific. These curves are to be derived at a later date from frequency analysis of previous failures and rigorous probabilistic analysis of different defence types.

5.2 Inputs and outputs

Inputs: Defence information, including SoP, condition grade, element type, element sub-type, material and revetment type (from step 2)

Primary Output: Fragility curves showing conditional probabilities of failure for each flood defence section in the system (for use in later stages of the methodology) by mechanisms of overtopping and breaching.

Step 3 is performed for every defence within the system only once. The defences, their fragility curves and other attributes will be referenced at many other stages within the methodology.

5.3 Probabilistic assessment of strength

5.3.1 Introducing fragility

The fragility (Casciati, 1991) of a structure is the probability of failure, conditional on a specific loading, L. If the failure of a structure is described by a limit state function Z such that $Z \leq 0$ represents system failure and $Z > 0$ represents the not failed condition, then the fragility function $F_R(L) = P(Z \leq 0 \mid L)$. A *fragility curve* is a plot of the conditional probability of failure of the structure given varying loadings.

In a detailed risk analysis, an understanding of the overtopping and breaching mechanisms of a defence 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 and breaching of fluvial and coastal defences have been established (see below).

5.3.2 Considering overtopping

The *SoP* gives a measure of the severity of the event which is expected to overtop an individual defence. Unfortunately, for high level analysis there is no information about the probability of loading (*e.g.* national datasets of the probability distribution of the water level) and no information about the crest level. All that is known is an estimate of the return period at which the defence will be overtopped.

It is not certain that the defence will in fact be overtopped in an event that coincides with the *SoP*, since the *SoP* is merely an estimate. If an event much higher than the *SoP* occurs we will be fairly confident that the defence will overtop. Similarly if an event much lower than the *SoP* occurs, we can be fairly confident that it will not overtop. This reasoning is represented by considering events that are some multiple, *x*, times the *SoP* and then estimating the conditional probability of the defence overtopping, given *x*. This is illustrated in Table 5.1 and the fragility curve is shown in Figure 5.1.

Table 5.1 Load and conditional failure probabilities (where OT denotes failure by overtopping) which are plotted in Figure 5.1

Load (*x*)	P(*OT*|*x*)
0.1	0
0.5	0.25
1.0	0.75
2.0	1
5.0	1

In Figure 5.1 the load under consideration is the water level, *x*, relative to the Standard of Protection, *SoP*. The fragility curve therefore provides a complete probabilistic description of the structure's proneness to overtopping under the full range of loading conditions.

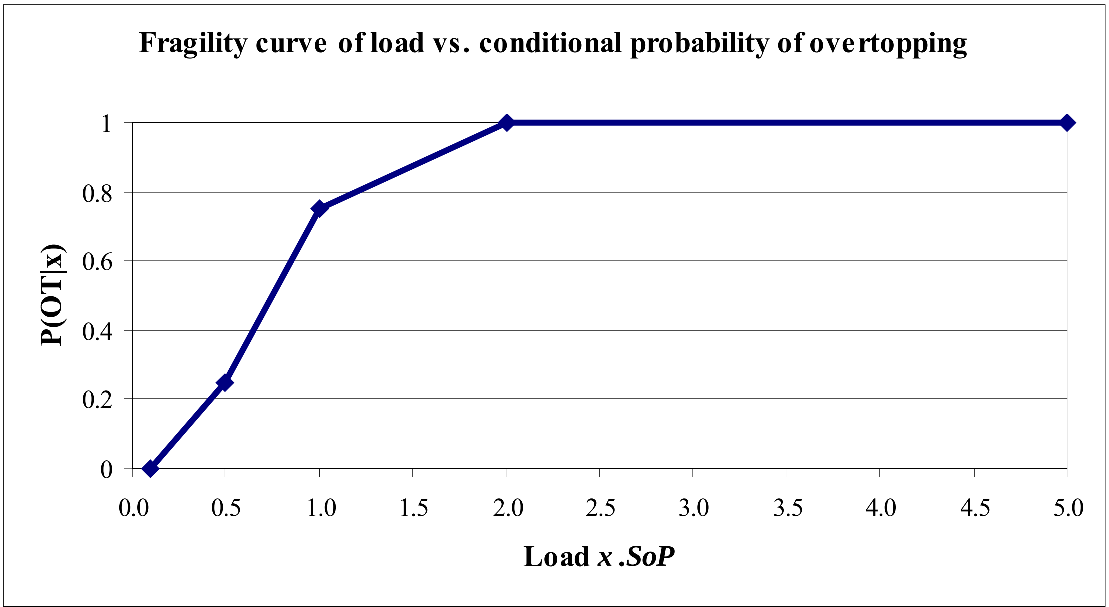


Figure 5.1 Fragility curve plotting conditional probability of overtopping for river water levels relative to a defence's Standard of Protection

A defence specific fragility curve is generated by multiplying the x-axis by the Standard of Protection.

5.3.3 Considering breaching

In the case of breaching, the conditional probability is not governed by just the severity of the event, but also by the condition grade of the defence. There will therefore be a family of five curves corresponding to each of the Agencys Condition Grades as shown in Figure 5.2.

There is a degree of dependency between failure by overtopping and failure by breaching.

Whilst it is possible for a defence to breach without overtopping, a breach is much more likely to occur once a defence has been overtopped. Two fragility curves are therefore used to calculate the conditional probabilities of breaching; these are the probability of breaching given that overtopping has not occurred and the probability of breaching given that it has occurred (see Table 5.2). The conditional breach probability given in Table 5.3 is calculated using equation 5.1.

$$P(B) = P(OT) \times P(B \mid OT) + P(\overline{OT}) \times P(B \mid \overline{OT}) \quad (5.1)$$

where:

$P(B)$ = conditional breaching probability

$P(OT)$ = conditional probability of overtopping

$P(B \mid OT)$ = conditional probability of breaching given that overtopping has occurred

$P(\overline{OT})$ = conditional probability of no overtopping

$P(B \mid \overline{OT})$ = conditional probability of breaching given that overtopping has not occurred

Table 5.2 Conditional probabilities of breaching given overtopping or no overtopping of a vertical concrete coastal defence used to calculate the breaching probabilities shown Table 5.3

Load x.SoP	P(B|$\overline{OT}$, CG=1)	P(B|$\overline{OT}$, CG=2)	P(B|$\overline{OT}$, CG=3)	P(B|$\overline{OT}$, CG=4)	P(B|$\overline{OT}$, CG=5)
0.10	0.00	0.00	0.00	0.00	0.01
0.50	0.00	0.00	0.01	0.04	0.04
1.00	0.01	0.01	0.04	0.08	0.12
2.00	0.04	0.04	0.08	0.20	0.32
5.00	0.16	0.20	0.32	0.48	0.72
Load x.SoP	P(B|OT, CG=1)	P(B|OT, CG=2)	P(B|OT, CG=3)	P(B|OT, CG=4)	P(B|OT, CG=5)
0.10	0.00	0.00	0.00	0.01	0.01
0.50	0.01	0.01	0.01	0.02	0.05
1.00	0.05	0.05	0.10	0.15	0.20
2.00	0.30	0.40	0.50	0.50	0.50
5.00	0.50	0.60	0.70	0.80	1.00

Table 5.3 Conditional breaching probabilities which are plotted in Figure 5.2

Load x.SoP	$P(B\|CG=1)$	$P(B\|CG=2)$	$P(B\|CG=3)$	$P(B\|CG=4)$	$P(B\|CG=5)$
0.10	0.00	0.00	0.00	0.00	0.01

0.50	0.00	0.00	0.01	0.04	0.04
1.00	0.04	0.04	0.09	0.13	0.18
2.00	0.30	0.40	0.50	0.50	0.50
5.00	0.50	0.60	0.70	0.80	1.00

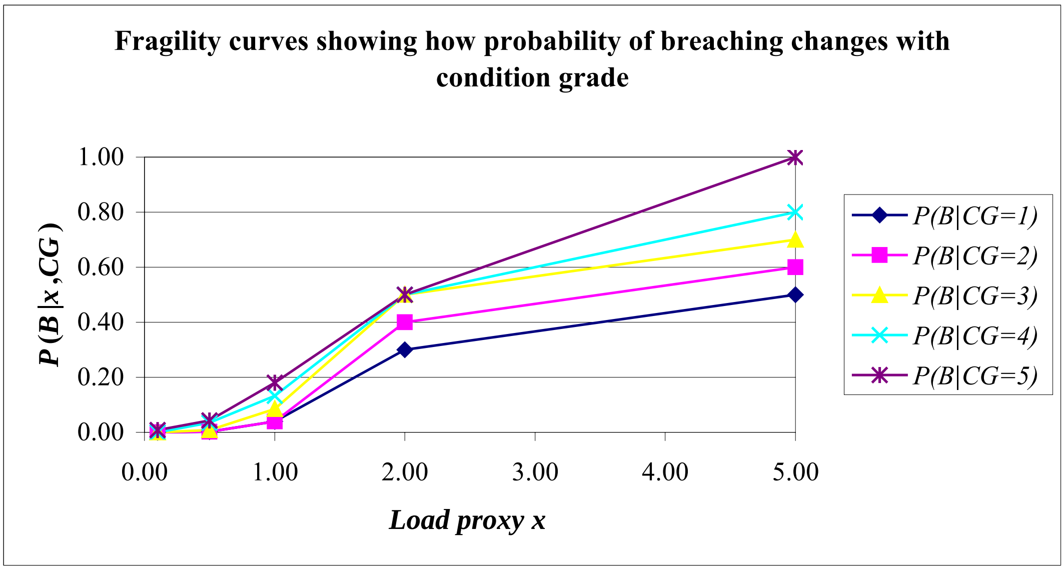


Figure 5.2 Conditional probabilities of breaching for water levels relative to a defence's Standard of Protection and its Condition Grade

For each defence type, conditional probabilities of overtopping, *P(OT)*, as well as conditional probabilities of breaching given overtopping, *P(B|OT)*, and no overtopping, $P(B\,|\,\overline{OT})$, for water levels relative to a defence's SoP and its Condition Grade are shown in Appendix C.

5.3.4 Estimating failure probability of a defence

Whilst the RASP methodology uses conditional failure probabilities instead of the more traditional discrete approach, it can be useful to provide an output of defence failure bounds based on the generic fragility curves. This is achieved by integrating the conditional failure probabilities over the expected probability of encountering a given event. The fragility function can subsequently be combined with the loading distribution to generate a probability of defence failure, $P(Z \leq 0)$.

$$P(Z \leq 0) = \int_0^{\infty} F_R(L)dl \qquad (5.2)$$

The loading distribution is based on a probability of encountering an event (equation 5.3) provides a load distribution which can be integrated over the fragility curve to obtain an expected failure probability for a defence.

$$P_{encounter\,n\,to\,m} = P_{exceed\,m} - P_{exceed\,n} \qquad (5.3)$$

where P_{exceed} in a particular year is defined in equation 5.4.

$$P_{exceed} = \left(1 - \left(n \times Return\,Period\right)^{-1}\right)^{n} \qquad (5.4)$$

where *n* is the number of events in a year.

Using the overtopping and breaching probabilities from Table 5.1 and Table 5.3, and an assumed Standard of Protection of 1:100 years and a condition grade of 3, Table 5.4 shows that the probability of the defence being overtopped or breached as being 0.036 and 0.007.

Table 5.4 Example calculation of defence failure probability given Standard of Protection, Condition Grade and fragility

Event(x)	$P_{encounter}$	P(OT|x)	$P(B\|x,CG=3)$
1:10	0.905	0.00	0.00
1:50	0.075	0.25	0.01
1:100	0.010	0.75	0.09
1:200	0.005	1.00	0.50
1:500	0.003	1.00	0.70
>1:500	0.002	1.00	1.00
	ΣP_{enc}xP_f=	0.036	0.007

5.3.5 Handling uncertainty

There are many uncertainties associated with this step:

- the accuracy of the defence's *SoP*
- the subjective nature of the condition grade, and,
- the process of converting this data into generic fragility curves.

These need to be accounted for and demonstrated in the final output, it is therefore proposed that interval curves be used instead of precise curves. Table 5.5 and Figure 5.3 show upper and lower bounds on the conditional probabilities shown in Table 5.4.

Table 5.5 Conditional probability bounds for overtopping, OT, given loads that are various proportions, x, of the Current SoP

Load *x.SoP*	*P(OT|x)* - Upper	*P(OT|x)* - Lower
0.1	0.00	0.00
0.5	0.20	0.30
1.0	0.60	0.90
2.0	0.80	1.00
5.0	0.95	1.00

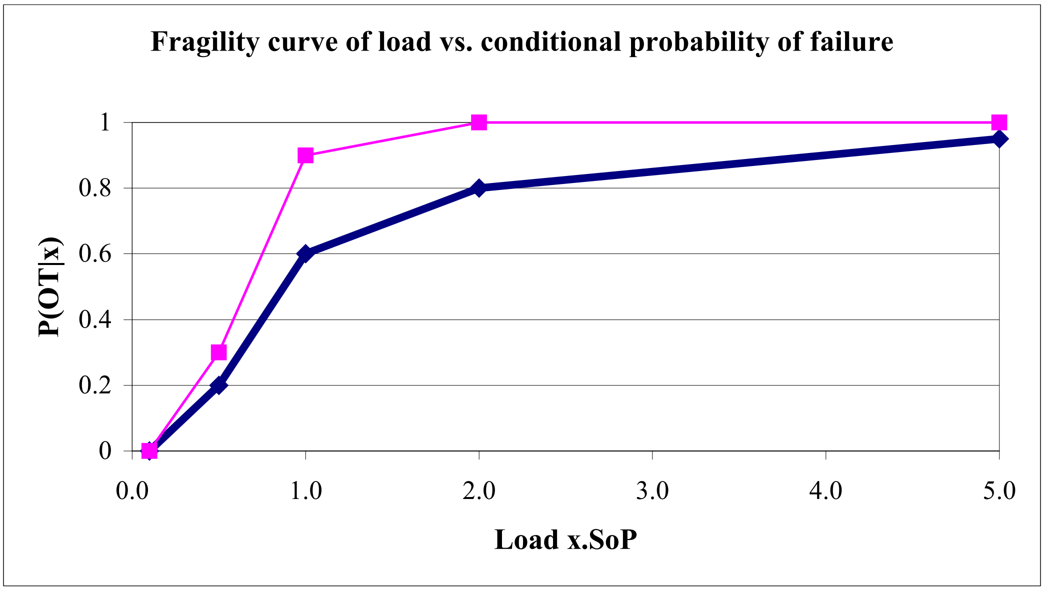


Figure 5.3 Conditional probability bounds for overtopping, OT, given loads that are various proportion, x, of the Current SoP

5.3.6 Special cases

A culverted watercourse

In both cases of failure, by overtopping and breaching, the conditional probability is governed by the severity of the event as well as by the condition grade.

High ground

Breaching of defences defined as "high ground" is not possible. The overtopping probability is also reduced by half to reflect the likelihood of high ground being considerably higher than raised defences of a similar SOP.

5.3.7 Updating fragility curves

Fragility curves will continue to be updated to reflect the latest research (i.e. CLASH, IMPACT, Embankment studies etc.), further expert consultation, and studies from the more detailed stages of RASP.

5.4 Defence classification

There are many types of defence employed by the Agency, each of these displays different behaviour under loading and varying failure mechanisms. Each defence type must therefore be assigned a family of fragility curves that reflect the appropriate defence behaviour. A classification methodology using the available data has been implemented.

5.4.1 The problem with the available data

Within the FDMS and NFCDD there is no field that provides a classification of defence types according to fixed categories (a "*picklist*"). There is a freehand description and a list of asset elements. These elements are the structural elements of the assets. For example, an embankment could have a CHANNEL SIDE, BERM, FRONT SLOPE, CREST and REAR SLOPE. These can be further classified into sub-types and the material from which they are constructed. Many of the possible element types in the classification are not relevant to linear flood defence systems. A list of the types and codes used are in Appendix B. These types do not lend themselves to classification of defences according to their failure mode and so do not form a useful basis for flood risk assessment. A similar problem was encountered using NSDS data for the NRA R459 report "Risk assessment for sea and tidal defences".

5.4.2 Outline of methodology

The method by which the problem has been approached is to:

- eliminate asset element and sub-element types not relevant to the defence system, such as bridges (see Appendix B),
- establish a logical hierarchical classification of flood defences that forms the basis for outline reliability analysis,
- allocate asset types and sub-types to each of the defence types in the hierarchical classification, and,
- create an algorithm that can be fully automated, as such a task is infeasible manually.

The main aim for identifying each defence type is to associate it with a fragility curve that describes in probabilistic terms the defence response to loading. At high levels in the hierarchical classification this fragility curve there will be greater uncertainty. Where more detailed classification (i.e. lower in the hierarchy) is possible and as more information becomes available the bounds of the fragility curve will narrow as shown in Figure 5.7. See also Appendix C.

5.4.3 Previous classification methodologies

When studying previous classifications it is important to remember the reason for their implementation which was not necessarily the same as required by RASP.

DoE Coast Protection Survey (1980)

The aim of this survey was to mark out existing sea defences, beach types and areas of erosion and accretion. The classification use was:

- Embankment
  - Clay
  - Concrete
- Gabions
- Revetment
  - Timber
  - Concrete blocks
  - Rock
- Sea Walls
- Groynes
- Dunes
- Beaches
- Cliffs

CIRIA Technical Note 125 (1986)
This study focused exclusively on sea walls, classifying them primarily based on whether they were vertical or sloping, then on their porosity and finally their structural aspects and the form of their construction.
CIRIA Protection of river and canal banks (1989)
This study focussed on fluvial defence empolyed throughout the UK and classified them as follows:

- Natural bank protection
  - Grass
  - Grass reinforced with synthetic materials
  - Reeds
  - Willows and other trees
  - Timberwork
  - Brushwood
  - Temporary protection
- Vertial bank protection
  - Steel sheet piling
  - Steel and asbestos trench sheeting
  - Gabion structures
  - Concrete, brick and masonry gravity walls
  - Precast units
  - Reinforced earth structures
  - Miscellaneous low-cost structures
- Revetments
  - Stone
    - Rip-rap
    - Pitching
    - Masonry
    - Gabion mattresses
    - Forms of grouting
  - Concrete
    - Blocks
    - In-situ slabs
    - Fabric mattresses
  - Geotextiles and geomembranes
    - Grassed composites
    - Mats and grids
    - Two-dimensional fabrics
  - Open or dense stone asphalt

National Sea Defence Survey (1990)
This survey was to establish the extent, condition and liability for the maintenance of sea defence structures. The survey records types of structures, their properties and condition. The classifications used were:

apron	breastwork	groynes	stop-log
armour	cliffs	piling	tetrapod

bastion	dune fence	revetment	valve
bank	embankment	shingle ridge	wall
breakwater	gabions	splash wall	wave return wall

An individual defence can have more than one structure associated with it.

Flood Defence Management System (1996)

This is the system currently in use by the EA and is in the process of being transferred to the NFCDD in a similar format. The classification methodology follows the morphology of the structure identifying individual components (for example inward face or crest), their sub-types (for example whether they are part of a wall or embankment), their material of construction and revetment material (if appropriate). An example of this (for a fluvial defence) is shown in Figure 5.4.

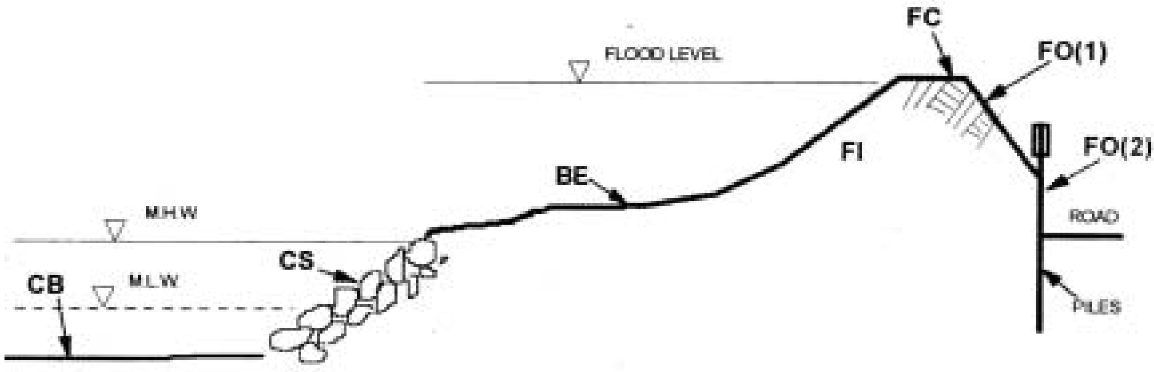


Figure 5.4 An example of the FDMM element coding system. CB and CS represent the Channel Bed and Side. BE, FI, FC and FO represent the Berm, Inward Face, Crest and Outward Face (taken from the Flood Defence Management Manual, 1996)

Association of British Insurers (Halcrow, 1992)

The methodology used here is similar to that used in NRA SR459 'Risk Assessment for Sea and Tidal Schemes'.

MAFF Coast Protection Survey (1994)

The classification methodology was similar to the NSDS, but asset types were identified:

sea wall	groyne	others
embankment	gabion	
revetment	shore	

and these were then further classified according to their structural components:

armour	breastwork	toe piling
apron	cliff/scarp	pitching
bastion	beach ridge	recharge
bank	groynes	revetment
breakwater	piling	wall

Risk Assessment for Sea and Tidal Schemes, NRA SR459 (HR Wallingford, 1996)
This study was undertaken to discuss development and use of risk assessment for analysis and design of sea defences. As these objectives are not dissimilar to those of RASP, the classification will be of particular relevance. The methodology classified structures by considering:

- Structure width (vulnerability of rear slope to damage): w/h<7m is classified as 'narrow' consequently w/h>7m is 'wide'
- Wall slope (sloping or vertical – if composite, judgement should be made to establish which is the dominant wave energy dissipator)
- Degree of protection behind and on top of structure (e.g. revetted rear slope or crest)
- Crest walls (additional wall of at least 25% freeboard to be considered as such)

5.4.4 RASP classification
The classification builds on and in many respects is similar to the classifications outlined above. It is explicitly hierarchical, illustrating how, as more information is acquired, it is possible to define defence performance more precisely. Initially defences are classified into seven major types as shown by the third layer of the hierarchy in Figure 5.5.

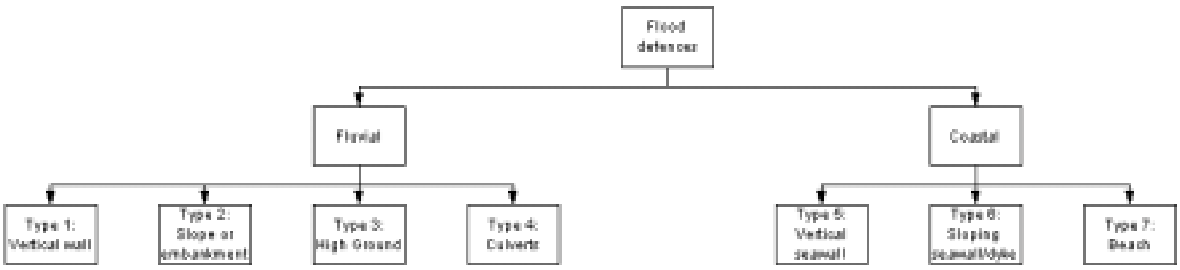


Figure 5.5 Major classification groups of flood defences

The lower levels of the classification hierarchy for each of the defence types are shown in Figure 5.7, 5.8, 5.9, 5.10, 5.11, 5.12 to the associated NFCDD codes are given in Table 5.6, 5.7, 5.8, 5.9, 5.10, 5.11. The algorithm is a carefully constructed series of '*if*' statements and is shown in Appendix H.

A defence is usually composed of several components. For example a sea defence may have a foreshore, a frontslope, a crest and a backslope. All of these will have an influence on the proneness to failure of the defence. However, the primary criterion for classification should be the aspect with the most influence on proneness to failure.

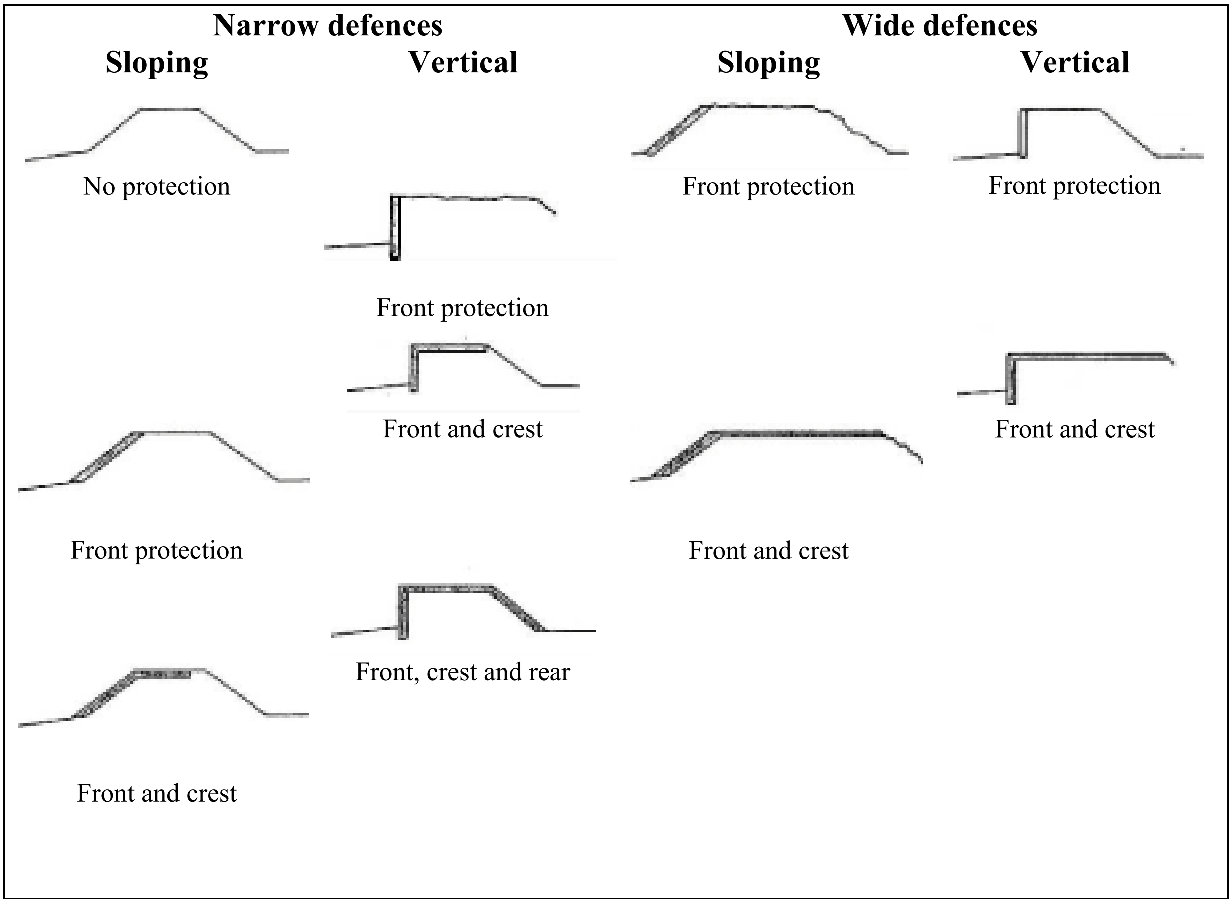
The generic classification steps are as follows:

1. Identify whether defence is coastal (including estuarial defences) or fluvial by checking the assets tidal flag in the NFCDD.
2. Sub-divide into the seven major classes of defence as shown in Figure 5.5.
3. Identify whether defence is 'wide' or 'narrow'. Until width values are available a 'wide' defence is classified as not having a rear slope (i.e. no NFCDD element code of FO).

4. (a) Ascertain degree of protection of defence based on whether they are protected on the front face, crest and rear face. Protection is assumed if the revetment material of the asset element is not turf or trees. Examples of defences classified by width and by degree of protection are shown in Figure 5.6.
   Note: For the purposes of implementing the algorithm, it is necessary to know whether there is an outward slope to perform step 3, but the width classification is at a higher level than the degree of protection classification.
4. (b) Sub-classify depending on material of front face protection (no classification based on crest or rear slope material).
5. Identify any structures (e.g. outfalls) within defence as this will effect the defence's fragility.
6. Finally, further classification can be made based on whether the channel (in the case of fluvial defences) is lined or unlined or (in the case of sea defences) whether the defence is tidal or coastal.

It should be mention that steps 5 and 6 are not being implemented in the NAAR update. Step 6 is not implemented because there is no evidence to differentiate between structures that have the additional channel lining and those that do not.

Initially, it may only be possible to construct fragility curves at relatively high levels of the classification. As more information becomes available, the fragility curves at lower levels can start to be populated. This increase in data will also allow the bounds on the fragility curves to be narrowed as demonstrated in Figure 5.7. Further refinement will be possible in more detailed analysis when the dimensions of the defence become available.



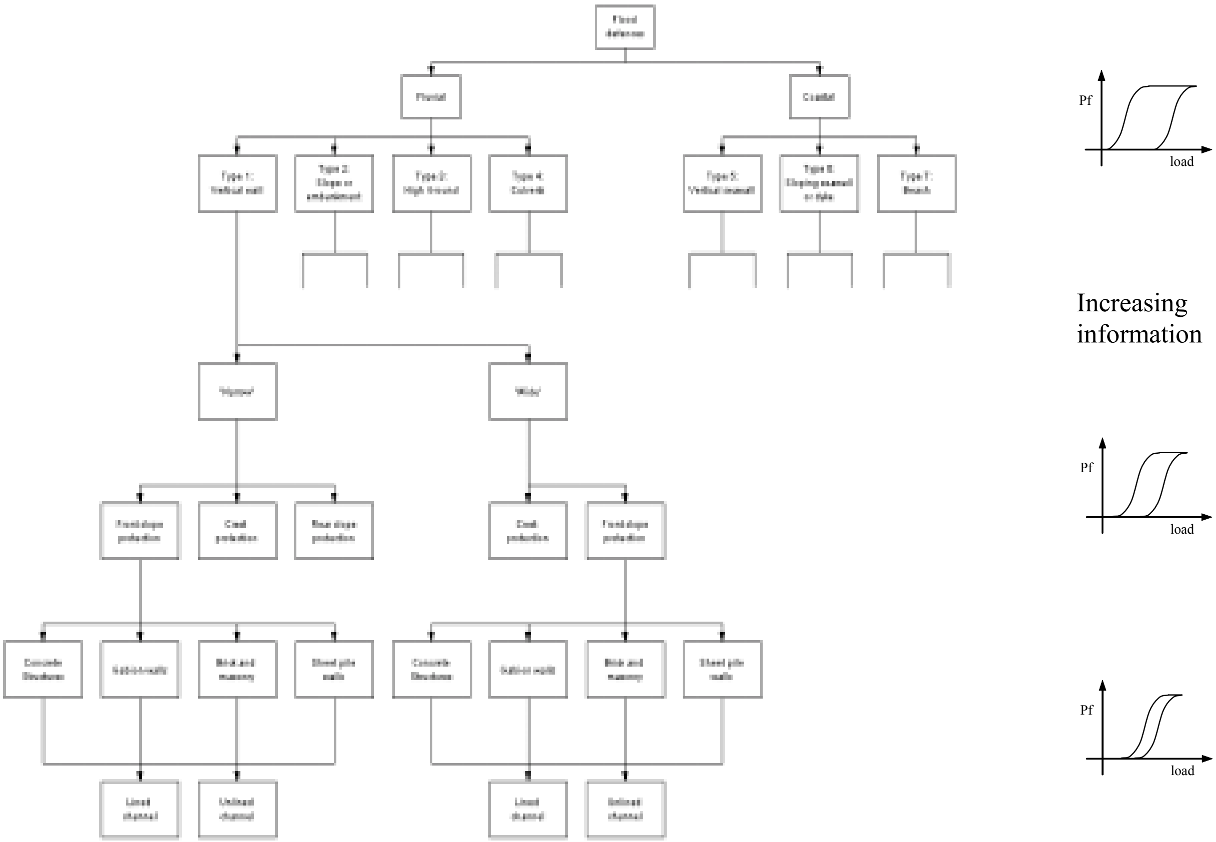
Front, crest and rear

Figure 5.6 Example of classification based on defence width and crest and rear slope protection

5.4.5 Linking NFCDD codes to the RASP classification

This section links the suggested classification with the codes used to populate the NFCDD.

Type 1: Vertical river walls



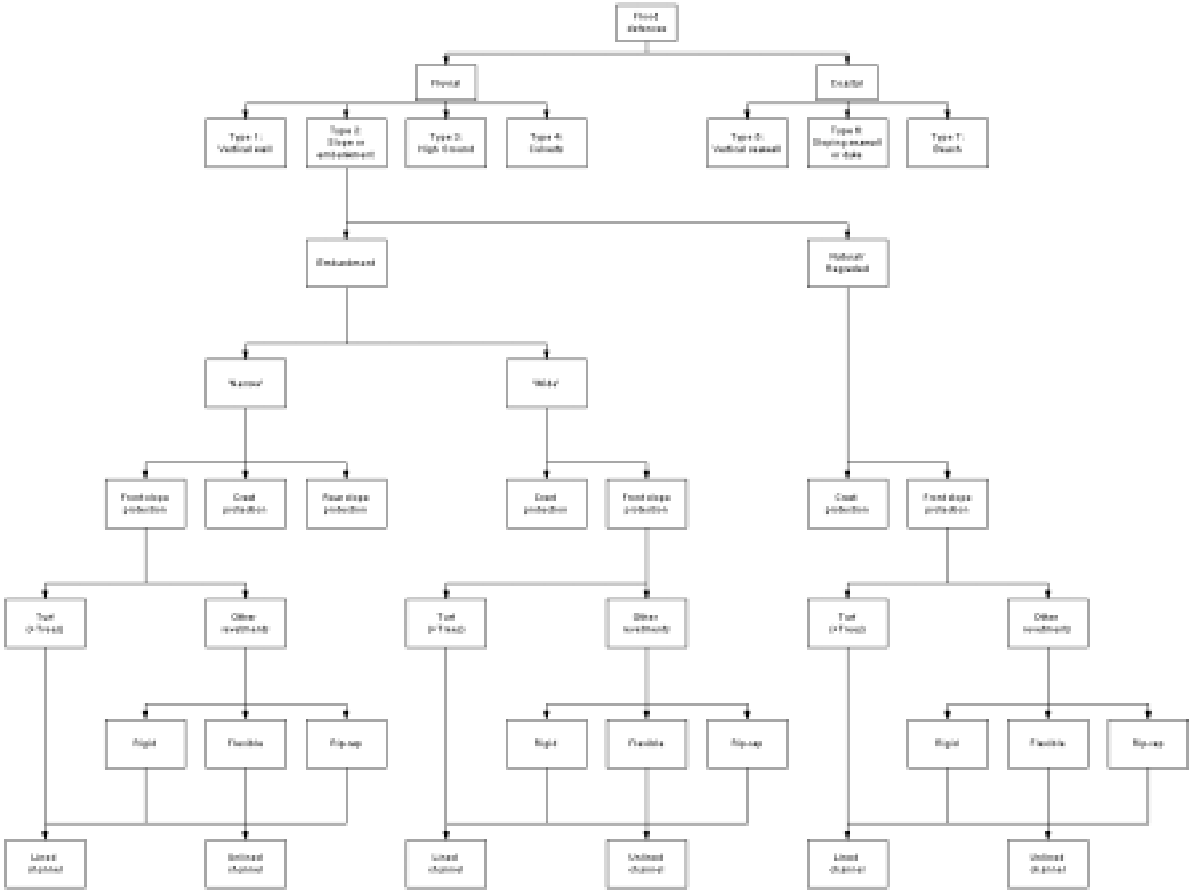
Note: Only front protection is classified further by material type.

Figure 5.7 Detailed classification of vertical fluvial defences showing how more sophisticated classification enables the bounds of the associated fragility curve to be narrowed

Table 5.6 RASP classification description and associated NFCDD codes for vertical fluvial defences

RASP Classification	Relevant NFCDD codes			
	Type	**Sub-type**	**Material**	**Revetment**
1. Fluvial defences				
1.1. Vertical wall				
1.1.1. Concrete structures (reinforced or gravity)	Channel: CB Defence: CS/FI/BE/FC/FO	L/N/R H/W	C/D/F/G/H/M/O/R/S C/D/Q/R	- -
1.1.2. Gabion walls	Channel: CB Defence: CS/FI/BE/FC/FO	L/N/R H/W	C/D/F/G/H/M/O/R/S G	- -
1.1.3. Brick and masonry structures	Channel: CB Defence: CS/FI/BE/FC/FO	L/N/R H/W	C/D/F/G/H/M/O/R/S M	- -
1.1.4. Sheet pile walls	Channel: CB Defence: CS/FI/BE/FC/FO	L/N/R H/W	C/D/F/G/H/M/O/R/S P	- -

Type 2: Slopes or embankments



Note: Natural and regarded banks are assumed to be 'wide'
Note: Rigid revetments include concrete slabs and flexible revetments include asphalt, concrete blockwork and pitched stone.
Note: No further classification of Type 3 (High Ground) is necessary.

Figure 5.8 Detailed classification of fluvial slopes or embankments

Type 4: Culverts

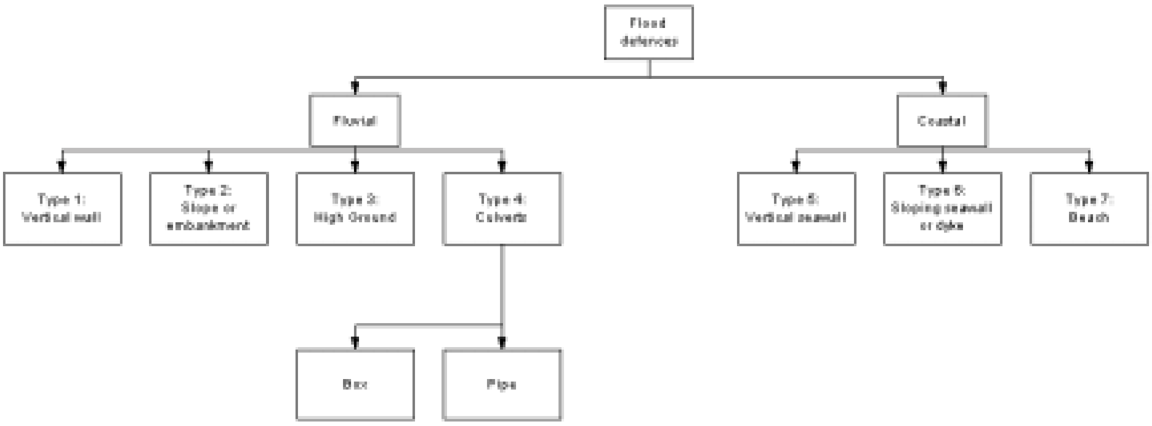


Figure 5.9 Detailed classification of culverts

Table 5.7 RASP classification description and associated NFCDD codes for sloping fluvial defences, high ground and culverts

1.2. Slope or embankment	**Type**	**Sub-type**	**Material**	**Revetment**
1.2.1. Embankment	Channel: CB/CS Defence: FI/BE/FC/FO/(DO)	L/N/R/W B (VE/GE)	 C/D/F/G/H/K/M/N/O/R/S/ W (K/N/W/Z) E/V/ (K/N/W/Z)	- Flexible: A/B/F/S Rigid: H/J/Y Rip-rap: U/W Flex/Rigid: O Other: Z
1.2.2. Regraded	Channel: CB/CS Defence: FI/BE/FC/FO/(DO)	L/N/R/W R (VE/GE)	 C/D/F/G/H/K/M/N/O/R/S/ W (K/N/W/Z) E/V/ (K/N/W/Z)	- Flexible: A/B/F/S Rigid: H/J/Y Rip-rap: U/W Flex/Rigid: O Other: Z
1.2.3. Natural	Channel: CB/CS Defence: FI/BE/FC/FO/(DO)	L/N/R/W N (VE)	 C/D/F/G/H/K/M/N/O/R/S/ W (K/N/W/Z) E/V/ (K/N/W/Z)	- Flexible: A/B/F/S Rigid: H/J/Y Rip-rap: U/W Flex/Rigid: O Other: Z
1.3. High ground				
	HG	-	-	-
1.4. Culvert				
1.4.1. Box	CU	BC	A/B/C/D/F/L/M/O/P/Q/S/X	-
1.4.2. Pipe	CU	PI	A/B/C/D/F/L/M/O/P/Q/S/X	-

Note: VE and GE (vegetation and geotextile) are bracketed to demonstrate that they can be associated with element types, but not important in the classification process.
Note: CU (culvert) may have many associated elements (such as protection to the entrance and exit), but these are not relevant to the classification process.

Defences with cross-section structures

River defences frequently have outfalls, flap valves, penstocks and sluice gates placed within them. These structures are often the point of failure for many such defences and as a result of this need to be taken into account when calculating defence fragility and therefore considered in the classification.

A methodology for representing the weakening of the structure could be accounted for by a change in the structure's fragility, as described in section 5.4.6. This would be done by cross referencing NFCDD asset ID codes to identify the number of cross-sectional structures within an asset. This step is not being implemented within the NARR update. The NFCDD codes associated with these additional structures are shown in Appendix B, but for the purposes of the classification, it is not necessary to differentiate between different structure types.

Table 5.8 The NFCDD codes associated with outfalls, flap valves, penstocks and sluice gates

Outfalls	Type	Sub-type	Material	Revetment
Flap Valves	OI/OO/OM/OP	F	B/L/S	-
Penstocks	OI/OO/OM/OP	P	B/L/S	-
Gates	OI/OO/OM/OP	O/G	B/L/S	-
Screens	OI/OO/OM/OP	K	L/S	-

Type 5: Vertical seawalls

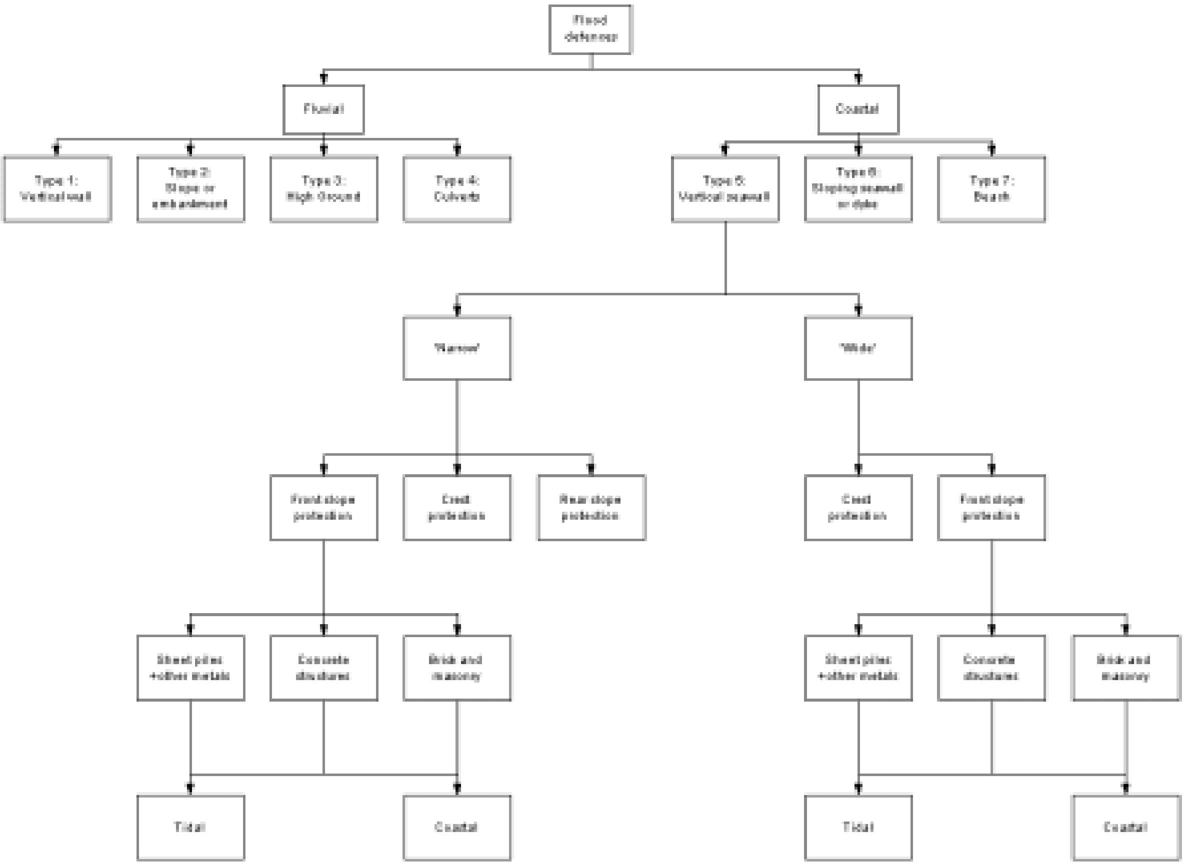


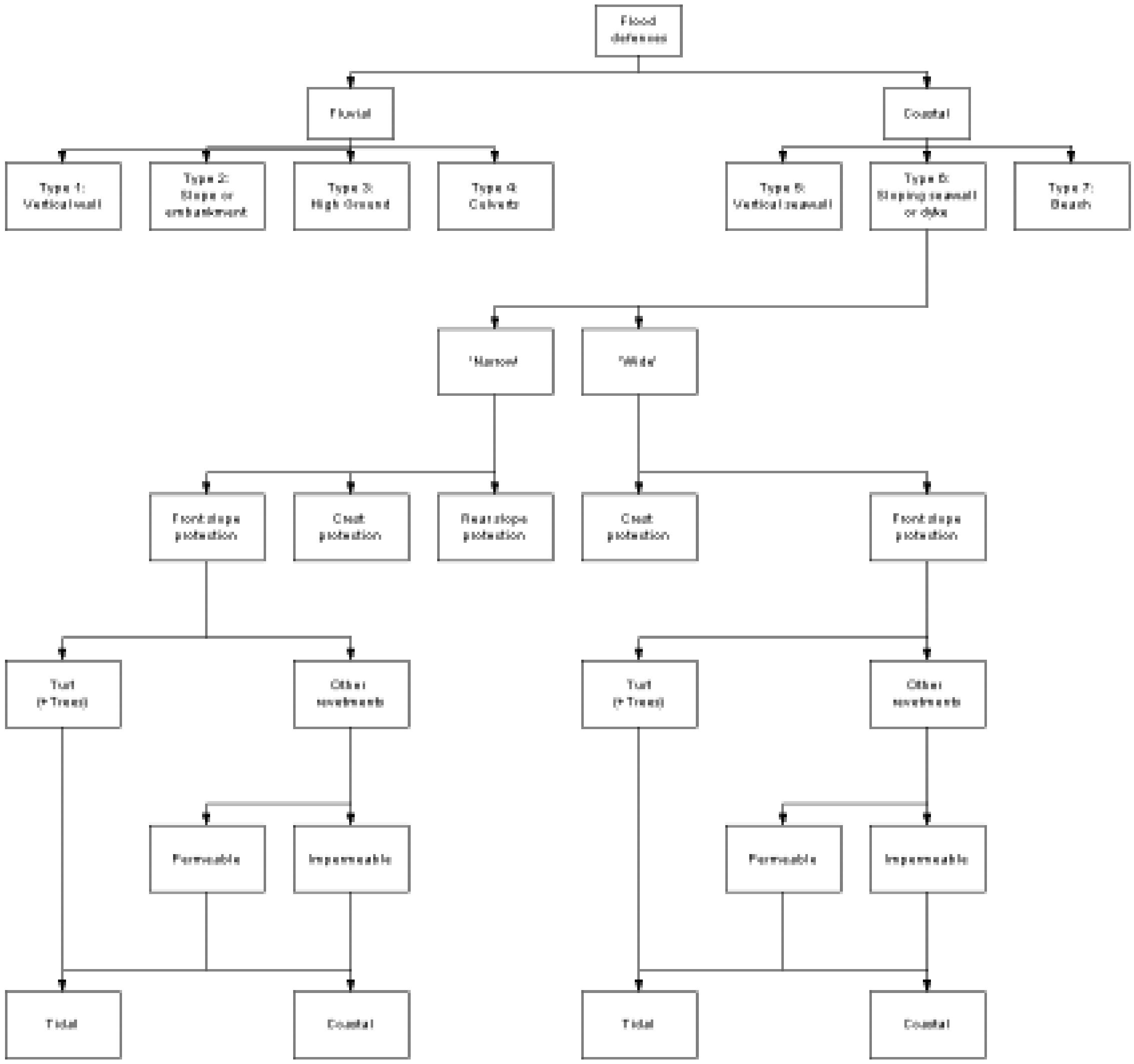
Figure 5.10 Detailed classification of vertical coastal defences

Table 5.9 RASP classification description and associated NFCDD codes for vertical coastal defences

RASP Classification	**Relevant NFCDD codes**			
	Type	**Sub-type**	**Material**	**Revetment**
2. Coastal defences				
2.1. Vertical sea wall				
2.1.1. Sheet piles and other metals	Seabed/ Foreshore: CB/FS Defence: CS/FI/FC/FO/(DO)	 W	I/J P/L/S	- -
2.1.2. Concrete structures	Seabed/ Foreshore: CB/FS Defence: CS/FI/FC/FO/(DO)	 W	I/J C/D/Q	- -
2.1.3. Brick and masonry	Seabed/ Foreshore: CB/FS Defence: CS/FI/FC/FO/(DO)	 W	I/J M	- -

Note: The use of the element code SW is unclear. The FDMM (Environment Agency, 1996) does not contain this code and seawalls are usually classified in the same manner as fluvial walls. In the NFCDD the easiest way to differentiate between the fluvial and tidal defences is the use of the Tidal Marker field.

Type 6: Sloping seawalls or dykes



Note: Permeable revetments include rock armour, impermeable revetments include asphalt.

Figure 5.11 Detailed classification of sloping coastal defences

Table 5.10 RASP classification description and associated NFCDD codes for sloping coastal defences

2.2. Sloping seawall or dyke	Type	Sub-type	Material	Revetment
2.2.1.	Seabed/ Foreshore: CB/FS Defence: CS/FI/FC/FO/(DO)	B	I/J A/B/C/D/E/L	- Permeable: F/H/J/K/T Impermeable: U/W/Y Either: A/B/O/Z

Note: The use of the element code SW is unclear. Whilst the FDMM and previous users of the code system have used the same methodology for coastal defences as for fluvial defences, its use as a code requires clarification.

Note: The difference between the revetments Asphalt(A) and Bitumen Aggregate(B) and the meaning of Found Slag (F) need to be confirmed.

Type 7: Beaches

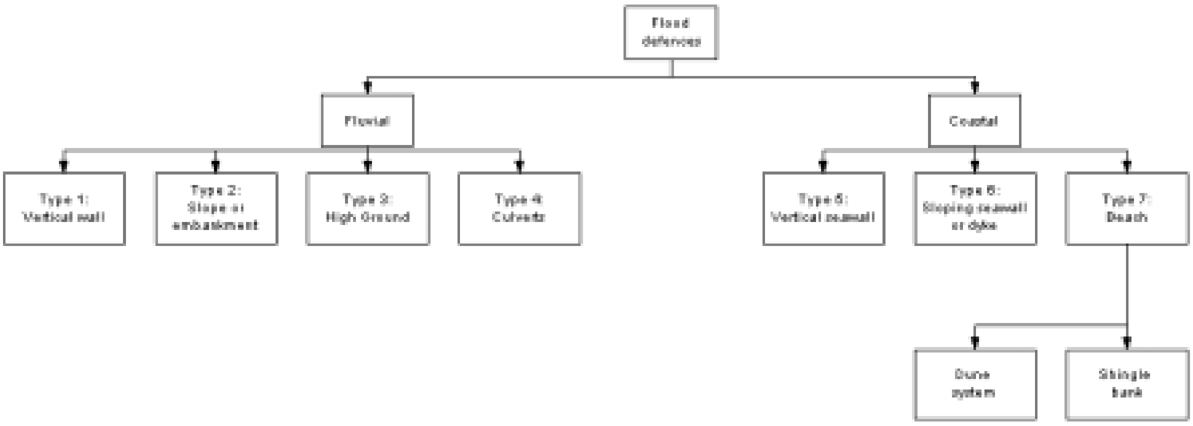


Figure 5.12 Detailed classification of beaches

Table 5.11 RASP classification description and associated NFCDD codes for beaches

2.3. Beach	**Type**	**Sub-type**	**Material**	**Revetment**
2.3.1. Sand / dune system	FS/DU	B	I	-
2.3.2. Shingle bank	FS/FI/FC/FO	B	J	-

Note: The use of the code FS is unclear. The FDMM suggests the use of CB to represent the foreshore. There is also associated with each asset fields used to describe the foreshore dependency, type and condition.

5.4.6 Cross-section defences and their influence on fragility

Where appropriate data is available, cross-section defence structures, such as culverts and outfalls should be identified. A strength reduction factor is applied to account for the weakening of defences at these points. The factor, *F*, increases with the number of intersecting structures as shown in equation 5.5.

$$F = 2 \times No\,of\ structures \qquad (5.5)$$

The strength reduction factor increases the probability of failure (*Pf*) of a defence:

$$Pf_{defence+structures} = Pf_{defence} \times \left(1 + {}^{F}\!/_{100}\right) \qquad (5.6)$$

5.4.7 Defence classification and uncertainty

As shown in Figures 5.7, 5.8, 5.9, 5.10, 5.11 and 5.12, the defences should be classified to the lowest level within the hierarchy to decrease the uncertainty associated with the fragility curves. The lowest level of classification is not implemented, as there is no evidence to differentiate between lined and unlined channels or tidal and coastal defences.

If the only classification available is one of the generic seven types, the bounds are defined by the lowest and highest bounds of the structures from the level below to reflect the greater uncertainty.