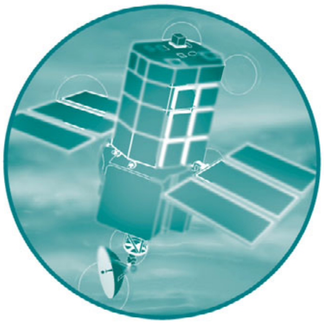
Defra/Environment Agency
Flood and Coastal Defence R&D Programme



Risk Assessment for Flood and Coastal Defence for Strategic Planning

R&D Technical Report W5B-030/TR

A Summary

Department for Environment Food and Rural Affairs

Environment Agency

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

Risk Assessment for Flood and Coastal Defence for Strategic Planning (RASP)

A Summary

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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.

Keywords
Flood risk assessment, strategic planning, flood warning, river and coastal defence, probabilistic assessment, national flood risk assessment, regional risk assessment, operations and maintenance.

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The work was 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. The work was lead by HR Wallingford Ltd in association with the University of Bristol, Halcrow and John Chatterton Associates. The Project Manager was Paul Sayers of HR Wallingford.

GLOSSARY

D_i	event: failure of defence section d_i
$D_{i,\mathrm{B}}$	event: failure of defence section d_i by breaching
$D_{i,\mathrm{OT}}$	event: failure of defence section d_i by overtopping
$D_1 \cap D_2$	event: failure of defence sections d_1 and d_2
$\overline{D_i}$	event: non-failure of defence section d_i
$d_1, d_2, \ldots, d_\mathrm{n}$	Defence sections 1, 2,…, n
$P(D_i)$	Probability of failure of defence section d_i
$P(D_i \mid x)$	Probability of failure of defence section d_i, given load x
$P(X \geq x)$	Probability that random variable X is greater than or equal to load x
P_k	the probability of defence system failure scenario k
$p(x)$	Probability density function of the load x
$z_1, z_2, \ldots, z_m$	Impact zones 1, 2,…, m

SUMMARY

It has long been recognised that flood risk cannot be eliminated completely and that understanding risk is key to improving risk management. In particular, this means deciding on 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.

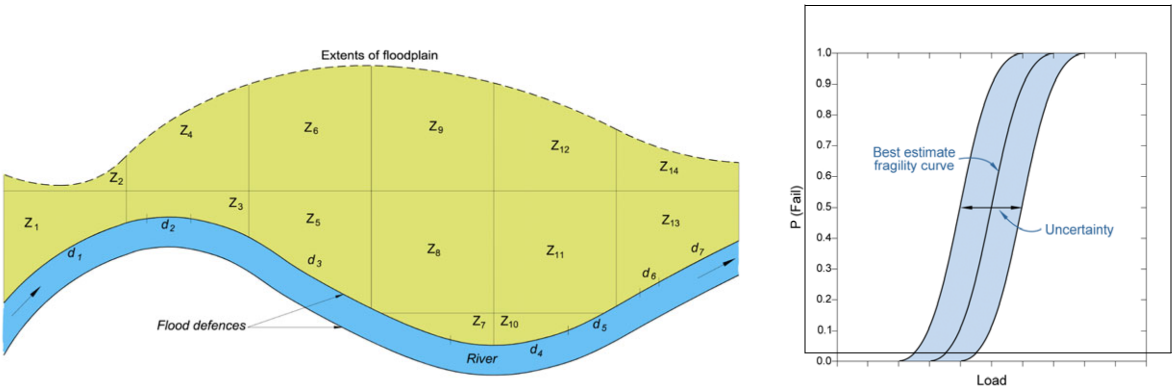
The need for improved risk assessment methodologies to support better flood risk management has therefore been the primary driver in support of the RASP project. The methods that have been developed through the RASP project will help the Environment Agency and Defra to understand more about how flood defences, and investment in flood management, influence flood risk. In particular, they provide a significantly improved ability to predict the spatial distribution of both the probability and consequences of flooding taking defence performance into account.

The RASP methods enact the basic cross-government framework for environmental risk assessment and risk management as well as addressing the specific needs presented by flood risk management. By enacting these frameworks within a generalised hierarchical methodology RASP enables *sources* (including a wide range of extreme wave and water level combinations), *pathways* (including the performance of multiple defences expressed in terms of a fragility curve) and *receptors* (including people and property) of risk to be combined. RASP therefore provides an important step towards an improved ability to manage flood risk in an integrated way.

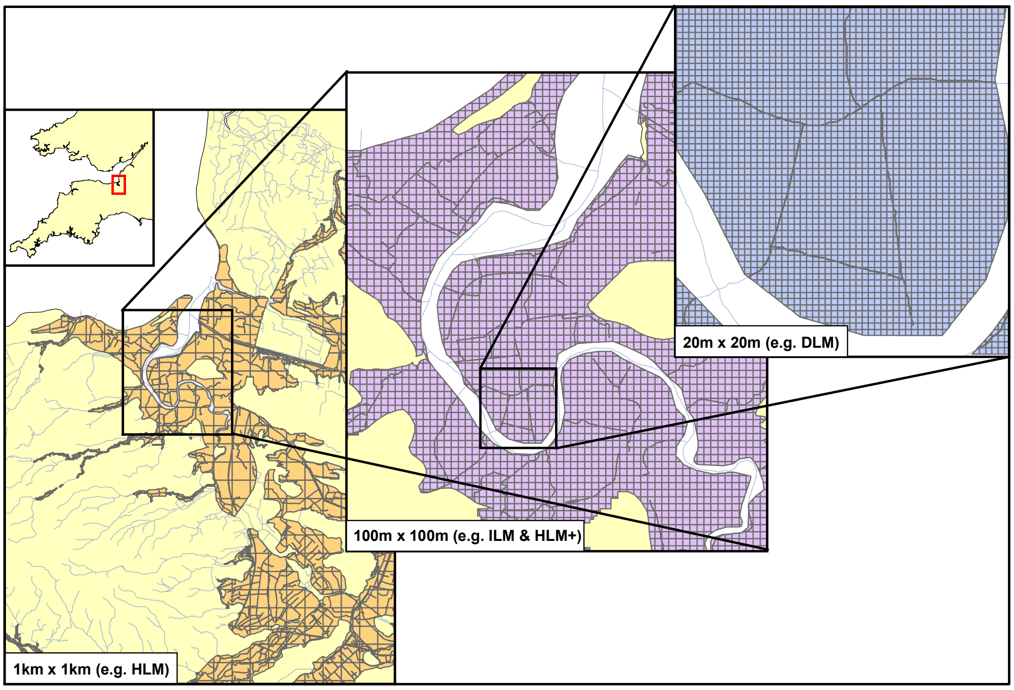
The RASP methods have been shown to provide a rational risk-based framework for the development of flood management policy, allocation of resources and monitoring the performance of flood mitigation activities at national regional and local scales; addressing strategic and overarching issues directly, such as:

- what is the probability and consequence of flooding, and how do they vary within the flood plain?
- 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?

In particular, RASP provides a hierarchy of methods to support the assessment of flood risk at a range of scales (national, regional, local) and levels of detail. At each scale the RASP methods are focused on understanding the probability of flooding at a particular location within the floodplain taking account of the protection afforded by defences. The notion of a system-based analysis (considering sources, pathways and receptors) is therefore fundamental to RASP. Equally important, and implicit within the RASP approach, is the concept of appropriateness; where the complexity of the analysis reflects the availability of data and the nature of the decision being made.



Fundamental building blocks of RASP – Defence systems, defence fragility and impact zones



Example of the spatial hierarchy of Impact Zones utilised in RASP

The utility of the RASP approach has been demonstrated through both case study and theoretical reasoning. To ensure the exploitation of these methods in the context of Integrated Flood Risk Management however, future work (research, development and operational) will be required and key recommendations are made.

Further information can be found in the accompanying Project Record (W5B-030/PR). Alternatively please contact Paul Sayers of HR Wallingford or Ian Meadowcroft of Environment Agency.

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1. RASP PROJECT OVERVIEW

1.1 Introduction

This report summarises the findings of the 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. In particular, RASP provides a hierarchy of methodologies to support the assessment of flood risk at a range of scales (national, regional, local) and levels of detail. At each scale the RASP methods are focused on understanding the probability of flooding at a particular location within the floodplain taking account of the protection afforded by defences.

The notion of a system-based analysis (considering sources, pathways and receptors) is fundamental to RASP. Equally important, and implicit within the RASP approach, is the concept of appropriateness; where the complexity of the analysis reflects the availability of data and the nature of the decision being made.

This report demonstrates the key features of the "tiered approach" to risk assessment developed in RASP and provides detailed guidance on their application through both case study and theoretical reasoning. In particular, the RASP methods support the development of common databases and consistent risk based data for use within Defra and the Environment Agency (and others). For example, the simplest of the RASP methods (demanding the least data inputs) has already been used to support a consistent assessment of the national flood risk.

The RASP R&D provides guidance to support risk assessment across a range of spatial and detail scales. Although RASP has significantly advanced the way in which risk assessments are undertaken, significant further work will be required to implement the methodologies. This report therefore concludes with a series of recommendations. The focus of these recommendations is to support the exploitation of RASP by both Defra and the Environment Agency, and to support integrated flood risk management in practice through the provision of consistent base data on flood risk.

More detailed discussion of the RASP methodologies can be found in the supporting reports (Environment Agency, 2004a and b).

1.2 Project aims

The RASP project aims to 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.

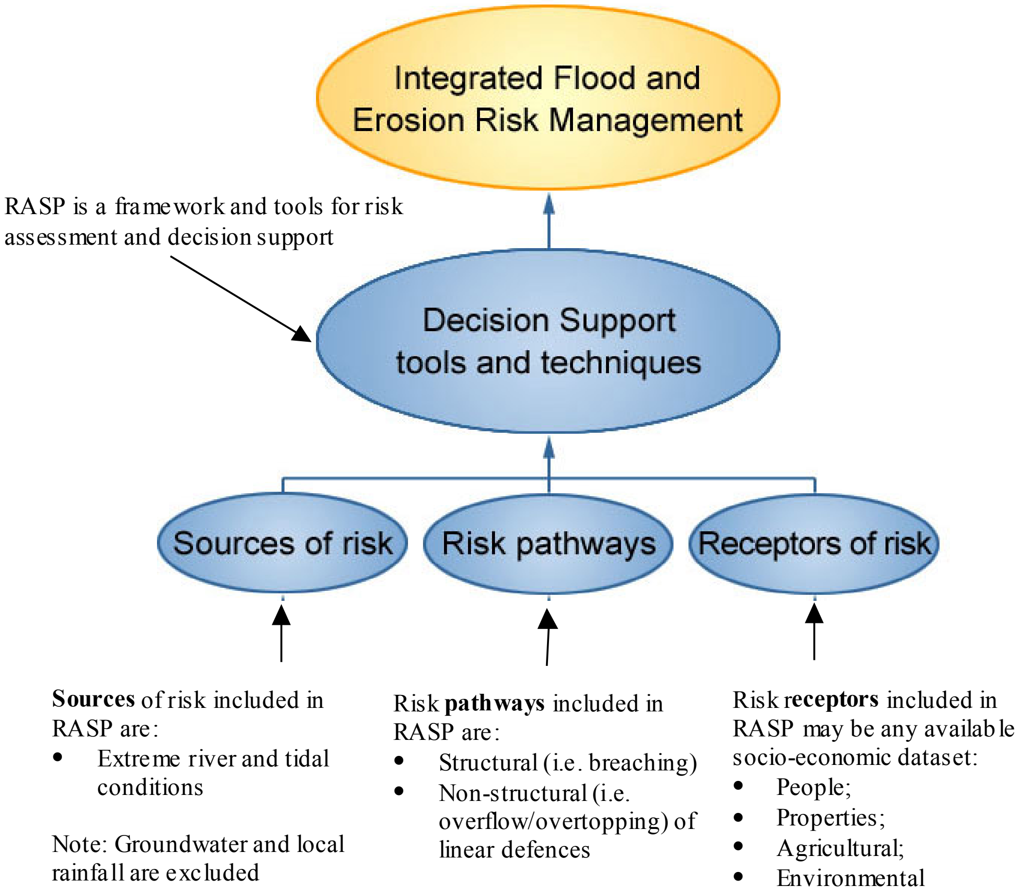


Figure 1 The role of RASP in supporting Integrated Flood Risk Management[1]

All RASP outputs are compatible with standard Geographical Information Systems to support simple user visualisation and integration with other spatial datasets. RASP has not delivered new software, but it has input into software development projects such as the Modelling Decision Support Framework and the NFCDD.

Throughout the development of RASP emphasis has also been placed on trialling and demonstrating the methodologies.

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

The RASP project has been undertaken (where possible) in parallel, and in co-ordination, with other national initiatives to help manage flood risk. The degree of linkage between the RASP project and the wide range of other initiatives confirms the high demand for risk assessment tools with the attributes of the RASP methodologies. Although future work is required, the RASP R&D has successfully delivered an approach that has gone a long way to meeting this demand.

1 For further discussion of the concept of an Integrated Risk Management Framework the reader is referred to Defra / Agency R&D Report FD2302/TR1 also known as HR Wallingford Report SR 587 Risk Performance and Uncertainty in Flood and Coastal Defence - A Review and the discussion in Hall, Meadowcroft, Sayers and Bramley (2003). Integrated flood risk management in England and Wales, Natural Hazards Review, ASCE, 4(3), 126-135.

It is therefore clear that the methodologies under development in RASP are likely to form significant elements of future R&D as well as software tools and databases developed to aid flood risk managers.

The key present and future links include:

- The *Modelling and Decision Support Framework* (MDSF). Originally MDSF (Environment Agency, 2003) 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 likely harm using property damages using standard depth average relationships and social vulnerability indices. RASP provides an analysis methodology to estimate the distribution of flood inundation probability and risk and is therefore complementary, not in competition with MDSF. On-going dialogue with users and the MDSF developers provides a clear indication that the link between RASP and MDSF should be strengthen and developed, in particular to integrate the RASP methods within the next generation MDSF tools. These recommendations for future development are outlined in more detail in Section 4.

- In 2002 the Environment Agency introduced a *National Flood and Coastal Defence Database* (NFCDD) which for the first time provides, in a digital database, an inventory of flood defence structures, their location, geometry and condition. Whilst the data held in NFCDD is by no means perfect, its existence is fundamental to the implementation of the concepts put forward in RASP. Information on defence type, location and condition is used by RASP at all levels of detail. RASP not only takes data from NFCDD put also passes results back. These include an estimate of the contribution that each defence makes to flood risk in terms of both its failure probability, expressed through a fragility curve, and in monetary terms. The experience of these applications provides clear indications that the link between RASP and NFCDD should be strengthened and developed, enabling NFCDD to be queried on a range of 'risks' (see Figure 2). These recommendations for future development are outlined in more detail in Section 4.

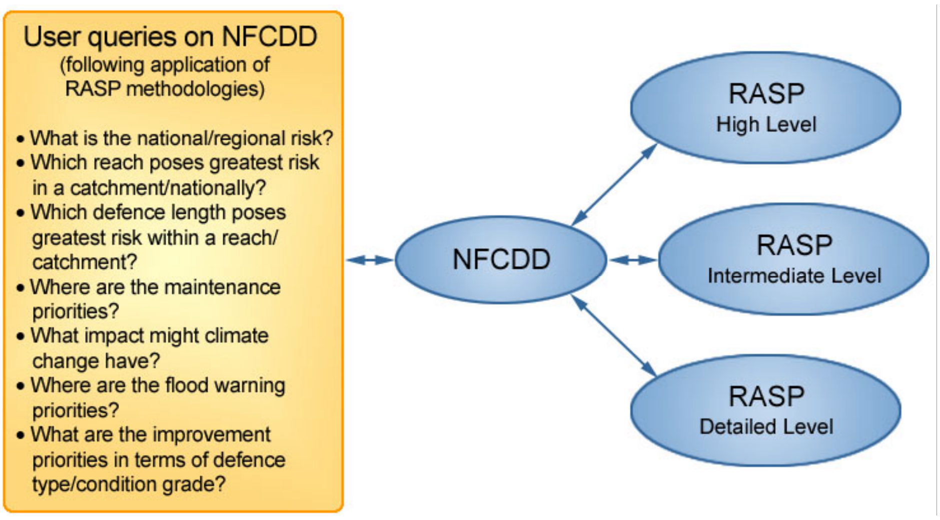


Figure 2 Envisaged interactions between the NFCDD and the RASP methodologies

- Research on performance and reliability of individual structures. For example, *reducing the risk of embankment failure under extreme conditions* (HR Wallingford, 2003) and *performance and reliability of flood and coastal defences* (HR Wallingford, 2004) led by HR Wallingford and *failure on demand of flood and coastal defence components* completed by RMC all provide information on individual defence failure mechanisms. These insights support the reliability analysis of defence performance and more dependable predictions of defence "fragility" within the RASP methods. The experience of these applications provides clear indications of further research and development (particularly the basic understanding of defence performance under load and its deterioration in time). These are outlined in more detail in Section 5.

- *Research into the development of a Performance-based Asset Management System* (PAMS). The Operations and Maintenance Concerted Action, Performance Evaluation Concerted Action, and the recommendations in the recently completed PAMS scoping study (Environment Agency, 2004c) have a close link with the RASP concepts of system analysis. In particular the improvements in the assessment of asset condition that all these projects support will improve the reliability of the system based risk assessment undertaken using the RASP techniques. Further research and development will, however, be required to embed all of these concepts within a decision specific tool to support Performance-based asset management. These are outlined in more detail in Section 4.

- *National flood risk assessment* – The RASP HLM has already been used to support the National Flood Risk Assessment (NaFRA and HR Wallingford 2002 and HR Wallingford, 2003) and is currently being further developed in support of the NaFRA 2004. The RASP HLM has also been used to support the National Assessment of Defence Needs and Costs – NADNAC (Halcrow and HR Wallingford, 2004). Together these projects and the RASP HLM (and its successors) are increasingly providing useful tools for consistently applied national assessment of risk to support more local decision making. The experience of these applications provides clear indications of further research and development. These are outlined in more detail in Section 5.

- *FORESIGHT* (Evans *et al*, 2004) – A major initiative by OST is to explore possible changes in flood risk in the future has been supported by the RASP HLM and proved itself extremely useful to inform long term policies. To further develop the techniques used in Foresight will require further research. Experience indicates that such a tool would provide a useful quantitative approach to support long term strategy and ongoing horizon scanning to explore the possible impact on flood risk of possible socio-economic, climate and flood management futures. Recommendations to support these developments are outlined in more detail in Section 5.

- The consistent framework offered by RASP forms part of the vision for flood risk management set out in the Risk, Uncertainty and Performance Review (Environment Agency, 2001, Sayers *et al*, 2002).

- *Flood Risk Management Research Consortium* – The FRMRC provides an opportunity to develop the systems approach initiated through RASP. A number of key links exist and a number of the Work Packages within FRMRC have been tailored to support integrated flood risk management. (see floodrisk.org.uk)

- Flood*Site* – Flood*site* is a significant European funded project co-ordinated by HR Wallingford that is programmed to run over the next five years. Flood*site* provides an excellent opportunity to develop risk-based management concepts and share approaches and concepts in detail at European level (see floodsite.net)

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

Defra's High Level Target 5A requires that the Environment Agency reports, nationally, on its assessment of the risk of flooding. The High Level Method in RASP has provided a methodology that directly supports this requirement and has been implemented through the NaFRA 2002 and is currently being updated for the NaFRA 2004. RASP also provides a basis for risk-based prioritisation and its potential use in establishing flood warning and maintenance priorities has been demonstrated through parallel projects undertaken in association with the Flooding Forecast and Warning and Operation and Improvement functions of the Agency (Environment Agency, 2004a and b).

2. UNDERPINNING CONCEPTS

2.1 Introduction

The chapter provides an overview of the underpinning concepts adopted in RASP. A more detailed discussion can be found in the Project Record (Environment Agency, 2004a).

2.2 Conceptual framework and the notation of a hierarchical assessment

Flood risk is conventionally defined as the product of the probability of flooding and the consequential damage (Environment Agency, 2001).

The availability of data and the resources available/considered appropriate to explore the components of probability and consequence will dictate the detail of the analysis. This has always been the case. However, within RASP the ability to vary the level of detail to reflect the decision in-hand has been for the first time formally recognised in a hierarchy of approach reliant on varying degrees of data input. It is not, however, the formal recognition of this hierarchy that is innovative within RASP but rather the progressive nature of analysis from one level of analysis to the next. For example, in determining flood risk, all levels of RASP consider the following terms and their interactions:

- ***Source terms*** – in the context of RASP *source* refers to loading conditions, for example the in-channel river water levels and coastal surges and wave conditions.

- ***Pathway terms*** – in the context of RASP *pathway* refers to the process by which a connection is established between a particular source (e.g. a marine storm) and a receptor (e.g. a property) that may be harmed. For example, the pathway within RASP consists of the primary flood defences (or high ground) and floodplain that may exist between the in-channel river flows and a housing development. Therefore two primary issues are considered at all levels:
  - Defence performance under load (expressed as a "fragility" function)
  - Floodplain inundation

- ***Receptor terms*** – in the context of RASP *receptor* refers to any entity that may be harmed by a flood and the material damage that may be suffered where a quantitative relationship between flood depth/velocity and the magnitude of the damage incurred exists.

2.2.1 Overview of the RASP hierarchy and decision-support

Table 1 provides an overview of a tiered assessment methodology developed in RASP. The principle is to provide consistent approaches at each level but with increasing detail of analysis and reducing uncertainties. For each tier of analysis the appropriate level of detail is based on consideration of the type of decision in hand and the availability of the required data and analysis, or its expected cost if it is not available. Thus, if high resolution data and analysis is available at little or no cost, then it is appropriate that it is used in the high level methodologies to reduce uncertainty. Insights into the uncertainty associated with a given level of analysis can then be obtained by comparing the results of the analysis from progressively more detailed levels.

This hierarchy reflects the importance to undertake an *appropriate* level of analysis that is justified by the importance of the decision, and its sensitivity to uncertainty, spatial resolution and data availability. The notion of appropriate analysis is fundamental to RASP and is reflected in the tiered methodology outlined in Table 1 and discussed below:

- The **High Level Method** – HLM (Environment Agency, 2004a, Sayers *et al*, 2002, Hall *et al*, 2003). National-scale flood risk assessment can provide consistent information to support flood management policy, allocation of resources and monitoring of the performance of flood risk mitigation activities. However, national-scale risk assessment presents particular challenges in terms of data acquisition and manipulation, numerical computation and presentation of results. The HLM (Environment Agency, 2004a) has been developed to address these difficulties through appropriate approximations. The methodology represents the processes of fluvial and coastal flooding over linear flood defences in sufficient detail to test alternative policy options for investment in flood management. Flood outlines and depths are generated in the absence of a consistent national topographical and water level datasets using a rapid parametric inundation routine. Potential economic and social impacts of flooding are assessed using national databases of floodplain properties and demography.

- The **High Level Methodology *plus*** (HLM+) provides an evolution of the HLM. The development of the RASP High Level Methodology was completed in early 2002 and applied through the National Flood Risk Assessment 2002 (HR Wallingford, 2002). The results of this analysis are already being used to support investment decisions and priorities for flood warning with significant interest in using the outputs across a wide range of Agency functions. However, the approach adopted in the RASP HLM was constrained by the availability of data at the time. Hence, the reliability of the NaFRA 2002 results (supported by the RASP HLM) reflect these constraints as well as the underlying reliability of the input datasets. For example, the HLM necessarily assumes no access to national topographic, defence crest level or water level datasets. However, since its development in 2001/2, significant advances have been made regarding the availability of data allowing these assumptions to be challenged. Hence, the HLM+ utilises these new data to deliver a national scale risk assessment methodology that is considerably more representative at a local scale. The HLM+ approach is currently being developed by HR Wallingford in a parallel project to the RASP research and is aimed at supporting the National Flood Risk Assessment 2004 being undertaken jointly by HR Wallingford and Halcrow. Details of the methodology are therefore not reported here.

- The **Intermediate Level Method** – The ILM (Environment Agency, 2004a, Sayers *et al*, 2003, Dawson *et al*, 2002, 2004) provides an approach to flood risk assessment appropriate for a reach or flood cell scale analysis. It is assumed that limited data may be gathered to support the approach and that detailed features of the floodplain are to be resolved. It is also designed to be used in conjunction with the HLM/HLM+ to support strategic decisions on flood risk management at catchment/shoreline process cell scales. In particular the ILM involves 1) statistical analysis of loads (including joint conditions for costs), 2) analysis of specified defence failure modes, 3) flood inundation modelling.

- The **Detailed Level Method** – The DLM (Buijs et al, 2003) provides the most detailed analysis and assumes access to detailed information about the composition of the defences in order to underpin an improved estimate of their probability of failure taking account of a number of different failure modes. It involves quantified descriptions of multiple defence failure modes. In conjunction with the higher level methods the DLM seeks to support scheme design as well as maintenance and improvement decisions.

Table 1 Hierarchy of RASP methodologies, decision support and data required

Level of assessment	Decisions to inform	Data sources	methodologies
High	National assessment of economic risk, risk to life of environmental risk Initial prioritisation of expenditure across all functions Regional Planning Flood Warning Planning	Defence type Condition grades Standard of Service Indicative flood plain maps Socio-economic data Land use mapping	Generic probabilities of defence failure based on condition assessment and SOP Assumed dependency between defence sections Empirical methods to determine likely flood extent
High Level Plus	*As above*	*Above plus:* Digital Terrain Maps Quantitative loading Floodplain depths in the absence of defences	*As above*, with improved estimate of flood depth using DTM
Intermediate	*Above plus:* Flood defence strategy planning Regulation of development Regional prioritisation of expenditure across all functions 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

Note: these levels of assessment do not uniquely support a single decision but rather elements of each can be used in combination.

The development of bespoke decision-support tools that utilise the RASP method is outside of the scope of the RASP Research Project. However, providing a hierarchy of methods to support the full range of Agency flood management activities is central to the RASP objectives. A conceptual framework for achieving this vision is represented in Figure 3. In Figure 3, data on the *source* terms supports a tiered analysis of *pathways* and *receptors* to provide common data in support of a range of flood management functions. This process is facilitated through a central interaction with NFCDD that provides a conduit for the flow of data from one tier to the next. A hypothetical example of how information can progressively be refined enabling flood risk maps to become progressively better resolved is shown Figure 4.

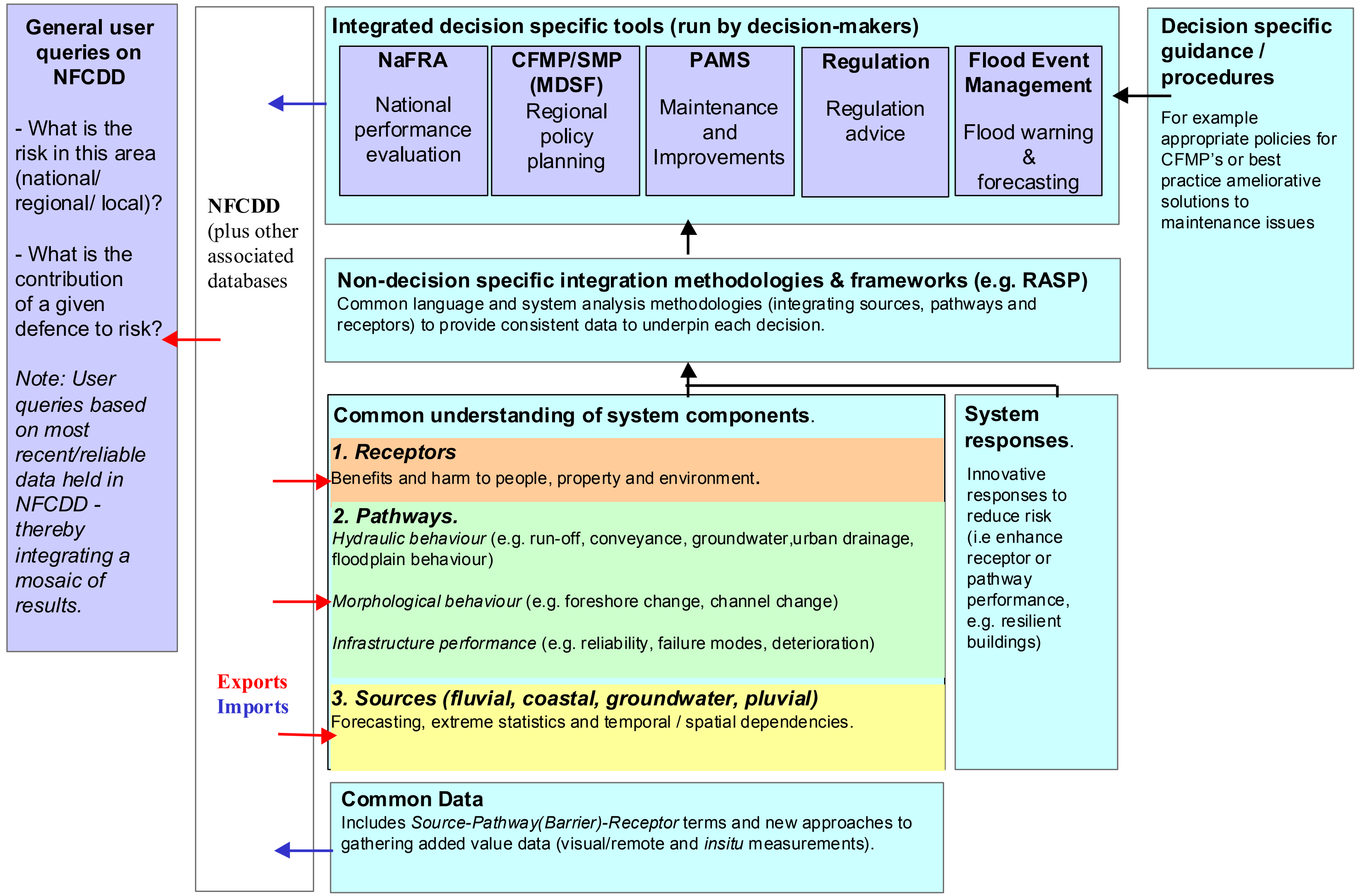
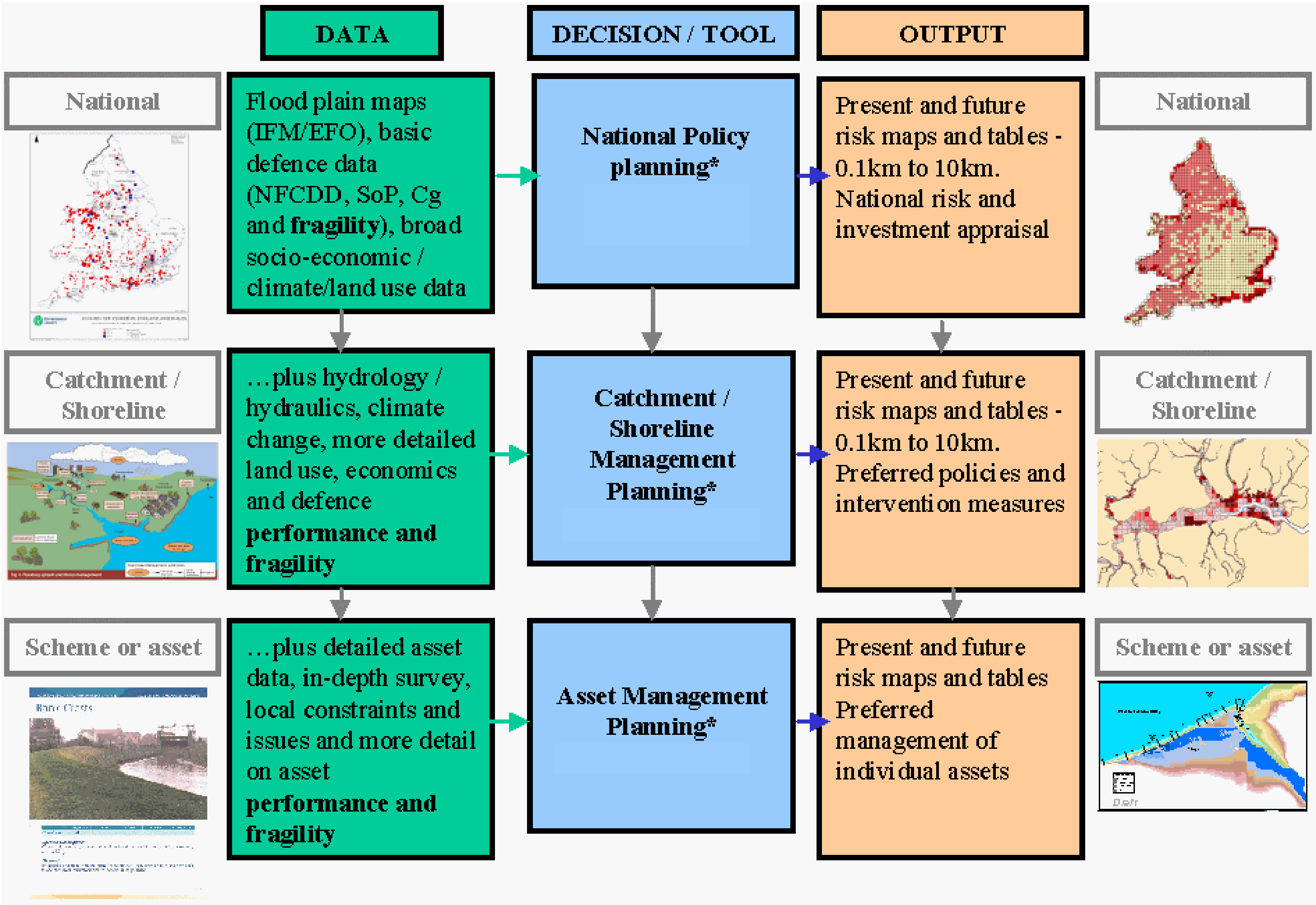


Figure 3 Use of consistent data to support a range of flood management decisions



*Plus other decisions and tools used for flood forecasting and warning, regulation etc

Figure 4 **A simplified view of how the progressively more detailed analysis refines flood risk data**

2.3 Spatial building blocks

All tiers of the RASP hierarchy divide the river/coast and its associated natural floodplain (i.e. the hinterland that could be flooded in the absence of defences) into:

- Flood systems
- Impact Zones.

Flood systems and Impact Zones therefore form the basic building blocks of the RASP analysis described in more detail below.

2.3.1 Definition of a flooding system

Systems risk analysis starts with the identification of self-contained flooding systems. These are floodplain areas that are distinct and separate from each other. A flooding system is defined as a continuous area of the floodplain with an uninterrupted boundary with the river, coast or high ground (Figures 5 and 6).

A flooding system may be influenced by either fluvial flows or coastal tides and waves or both. The size of a flooding system varies with the demands of the physical setting. A flooding system within RASP is therefore defined by the limits of the natural flood plain and the defences that protect it. All of the RASP methodologies assess flood risk within the context of a flooding system.

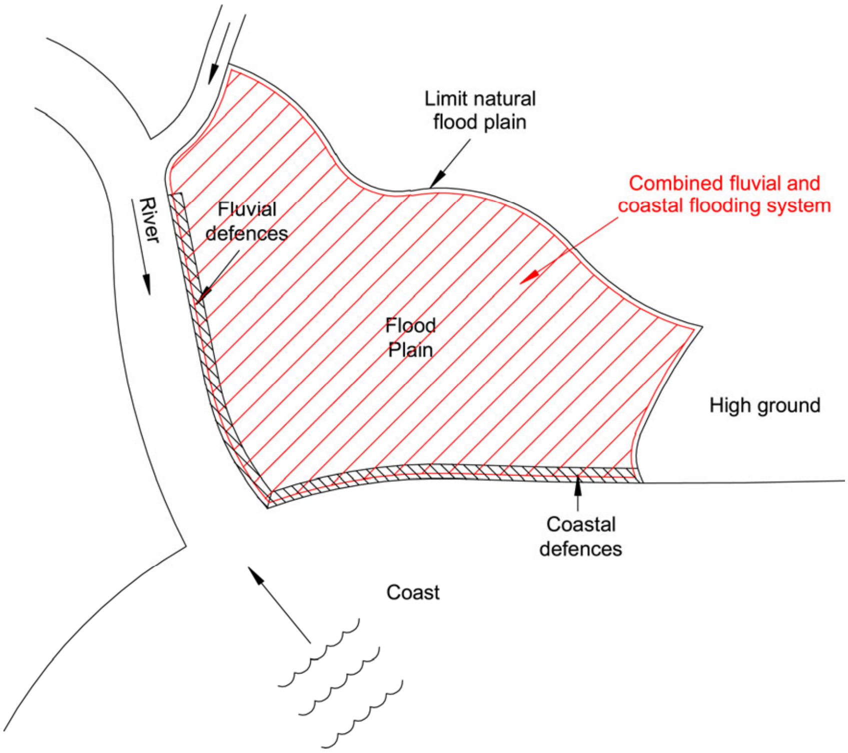


Figure 5 A combined fluvial and coastal flooding system

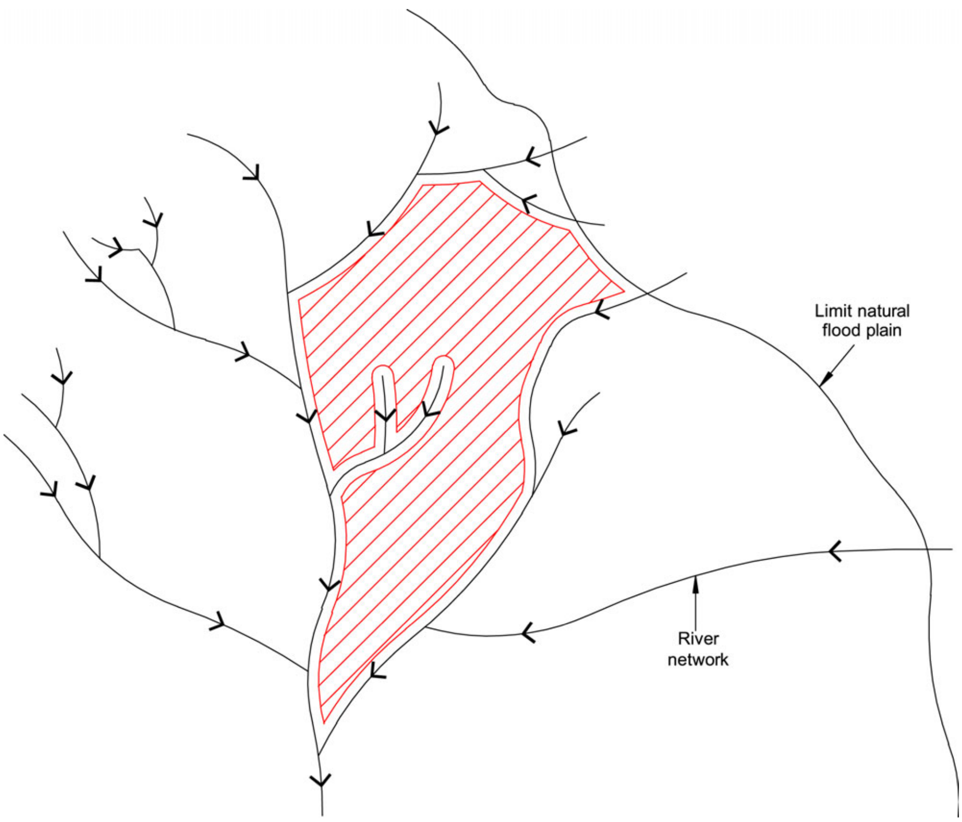


Figure 6 A fluvial flooding system

2.3.2 Definition of an Impact Zone

The RASP methods are focused on understanding the probability of flooding at a particular location within the floodplain taking account of the protection afforded by defences. An Impact Zone is therefore a defined area of the natural floodplain. In theory an Impact Zone could be of any shape or size. However, for convenience and to provide the similar transfer of information from one analysis level to the next, RASP adopts a simple grid based approach with indicative grid sizes, with each grid representing an Impact Zone, as follows:

- HLM – 1km x 1km grid
- HLM*plus* – *upwards of* 100m x 100m
- ILM – *approx.* 10-50m x 10-50m
- DLM – approx. 10-50m x 10-50m.

All grids are square (except where bounded by the river/coast and/or the edge of the defined flood plain) with a national grid origin. This facilitates simple overlays of results of one method with another and promotes simple transfer of results to and from NFCDD. An example of the grid approach to the definition of Impact Zones is shown in Figure 7.

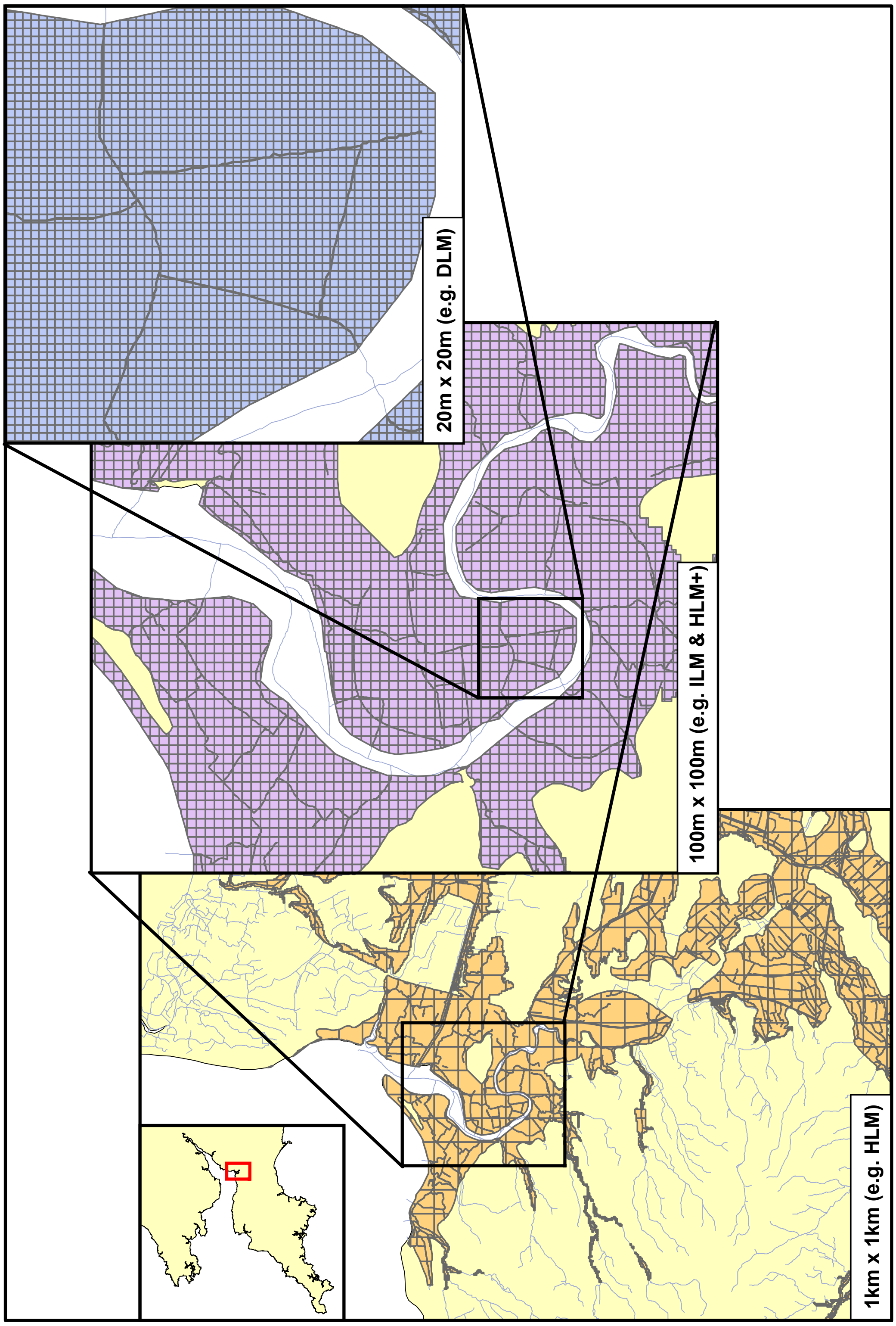


Figure 7 Impact Zones – Increasing resolution with increasing detail of analysis

2.4 Definition of the defence system and use of NFCDD

2.4.1 Creating a continuous line of defence information

RASP demands that information is provided on the nature and form of the boundary behind the natural floodplain and the river or coast. This is sometimes a raised or man-made "defence" but is often simply a function of natural topographic features forming the river bank or coastal bank – often referred to as *high ground*. Although high ground, by definition, cannot be breached it can be overtopped and forms a legitimate part of the defence system. A key underpinning concept of RASP is therefore to have a complete knowledge of the form and nature of the boundary behind the river or coastline – a so-called tramline of "defence" information.

In support of developing this tramline of defence information the Environment Agency records the location of every raised flood defence within NFCDD. Although the quality of this data remains questionable, it is improving. In addition to the support for continual improvement of the data within NFCDD, a key recommendation from the RASP project is to extend NFCDD to include the non-raised defences to support the concept of a continuous tramline of information. Without such a complete picture of how the boundary between the floodplain and river/coast is formed, a reliable assessment of flood risk and effective management becomes, at best, difficult.

Note: Secondary defences are excluded from the concept of a continuous defence line at present. Experience gained through the project suggests that the methods should be developed to include the influences of secondary defences set-back from the primary defence line.

2.4.2 Defining a defence system

In the absence of a defined topographical boundary (for example as seen along some linear watercourses) flooding systems, as defined above, can become large. In such large natural systems it is clear that the defences no longer act in concert to protect a given area of the floodplain (e.g. an Impact Zone). Therefore it is often not necessary to consider such long lengths as single defence systems, but rather to define defence systems separately for each Impact Zone as a subset of the defences within the larger flooding system. (This reflects a similar concept to the *Asset Group* field within NFCDD.)

Within the HLM unique defence systems have been defined for each Impact Zone using an automated procedure. First, those defences that could, if breached during a 1000 year return period storm event, lead to flooding within a given Impact Zone are identified. From this list of defences the most upstream and downstream defences are identified and used determine the upstream and downstream limits of the flooding system appropriate to that Impact Zone.

Within the ILM and DLM a similar approach could be adopted but using more detailed models. Alternatively, at the ILM and DLM, less automated definitions of the flooding system are possible and are to be encouraged.

2.4.3 Reliability based defence classification

NFCDD classifies every raised flood defence based on the individual defence components (for example inward slope, crest and outward slope) and their composition (for example turf or concrete). This leads to a classification in which sub-divisions have little bearing on the proneness to failure, whilst important characteristics such as crest width and level can go unrecorded.

For the purpose of the RASP HLM a simple (but complete in terms of linear defences) classification has been developed. The classification focuses on those salient characteristics of a defence cross-section that influence its resistance to extreme loads. An algorithm has been established that gives a direct mapping from the classification used by the Environment Agency to the new reliability-based classification.

The generic classification steps are as follows:

1. Identify whether defence is coastal (including estuarial defences) or fluvial.
2. Identify which of the seven major classes of RASP defence (see Figure 4). (*Note* – At present NFCDD fails to include a simple descriptor of the defence type).
4. Consider the nature of the fluvial channel - is it lined or unlined – that may influence the conveyance and loading on the structure.
3. Consider the nature of the loading of coastal defences – primarily a combination of tidal/fluvial or tidal/wave loading.
4. Consider the width of the defence and hence the exposure of the rear face to potential damage.
5. Consider the degree of protection afforded to the front face, crest and rear face in the form of surface cover (rock, asphalt, grass etc.).
5. Consider the presence and influence of any structures within a defence (e.g. cross drainage structures) that may influence the performance of the defence under load.

At the high level in the classification are seven defence types that show significantly different behaviour (Figure 8).

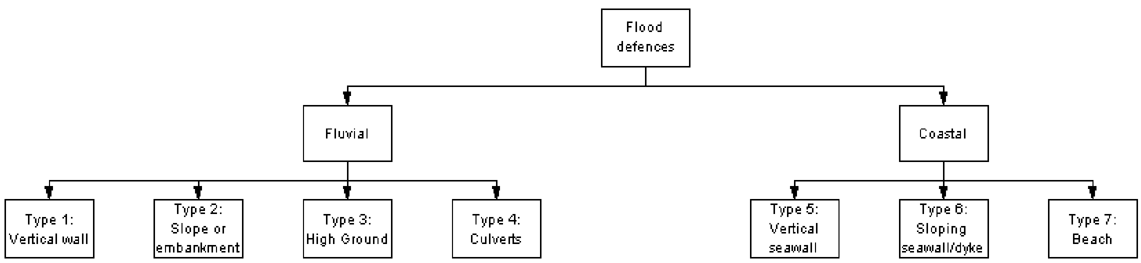


Figure 8 Major classification groups of flood defences

The next levels within the hierarchy consider the degree of protection offered by the defence. A wider defence has been assumed to provide more protection than a narrower defence, as has a defence that is protected on its front slope, crest and rear slope compared to one without protection. The next level of classification considers the properties of individual components. Examples of these next level definitions are shown in Figures 9 and 10.

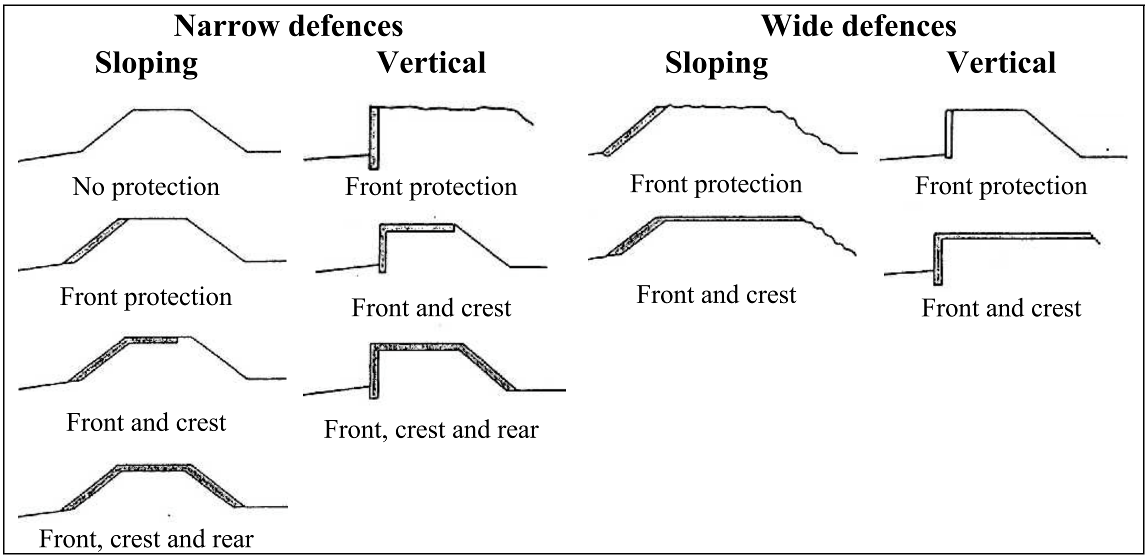
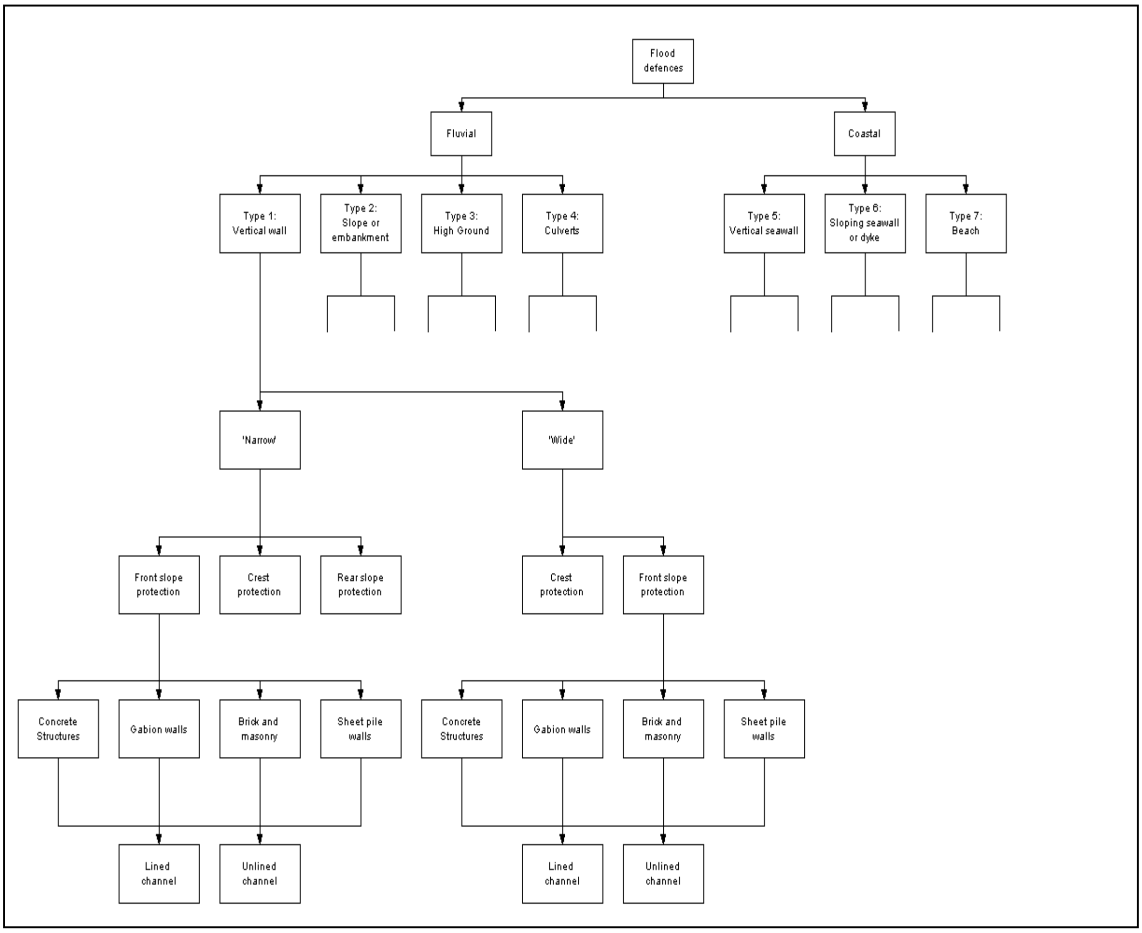


Figure 9 Example of classification based on defence width and crest and rear slope protection (Environment Agency, 1997)

Type 1: Vertical river walls



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

Figure 10 Detailed classification of vertical fluvial defences

Although specific to the RASP HLM, this structured approach to classification provides a useful starting point for more detailed classification systems (such as those that may be developed to support operation and maintenance activities).

2.4.4 Defence performance and the concept of 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 $F_R(L) = P(Z \leq 0 \mid L)$ where the symbol "|" denotes "given". A *fragility curve* is a plot of load against probability of failure. In reliability analysis a conditional probability distribution of this type – in this case relating the conditional probability of failure of the structure given varying loadings - is referred to as a 'fragility curve'. A typical fragility curve is illustrated in Figure 11.

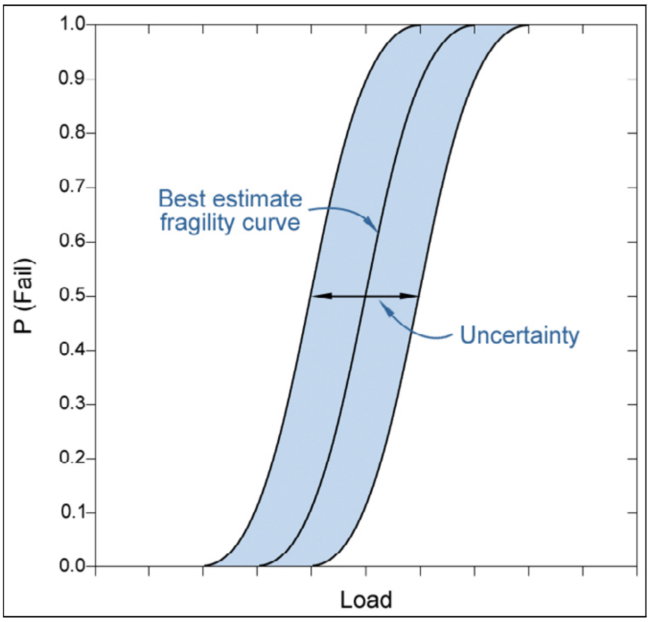


Figure 11 A typical fragility curve

The probability of a defence breaching in a storm of given severity is influenced by the type of defence and its condition. At a national scale the only information on defence condition is a visual assessment that grades each defence and its components from Grade 1 ("very good") to Grade 5 ("very poor"). The Environment Agency's Condition Assessment Manual provides benchmark photographs of the main types of defence in all five conditions. Grade 5 nominally represents a defence in an effectively failed condition. However, the photographs in the Condition Assessment Manual indicate that some of these defences would afford some resistance against breaching, at least in less severe loading conditions. The RASP methodologies therefore attempt to reflect this residual resistance.

A special case in the context of "linear" defence systems is where a watercourse is culverted. Here the overflow of flood waters into the floodplain is governed by the severity of the event as well as by the condition grade of the culvert. Simple rules have been developed to deal with this situation within the HLM. Although not explicitly addressed at the more detailed levels, similar rules could be developed without modifying the general approach.

Given the lack of field evidence of defence breaching in loads of known severity for defences in known pre-storm condition, and the simplistic condition grading system currently used within the Agency, the development of a reliable description of defence fragility is at present very difficult.

Improvement in the approach to condition assessment and inspection will be a pre-requisite to improving the risk assessment. This will be a major component of the research being undertaken under the PAMS programme, and will necessarily need to continue to be updated to reflect the latest research (including both national and international research, e.g. HR Wallingford, 2004 and Environment Agency, 2004d).

2.5 A risk-based analysis framework

Consider a flood defence system with n defence sections, labelled $d_1, d_2, \ldots, d_n$. Each defence section has an independent, and usually a different, resistance to flood loading. There are m Impact Zones, labelled $z_1, z_2, \ldots, z_m$, within the natural floodplain. The remaining perimeter of the floodplain is high ground. A simple example of such a system is shown in Figure 12.

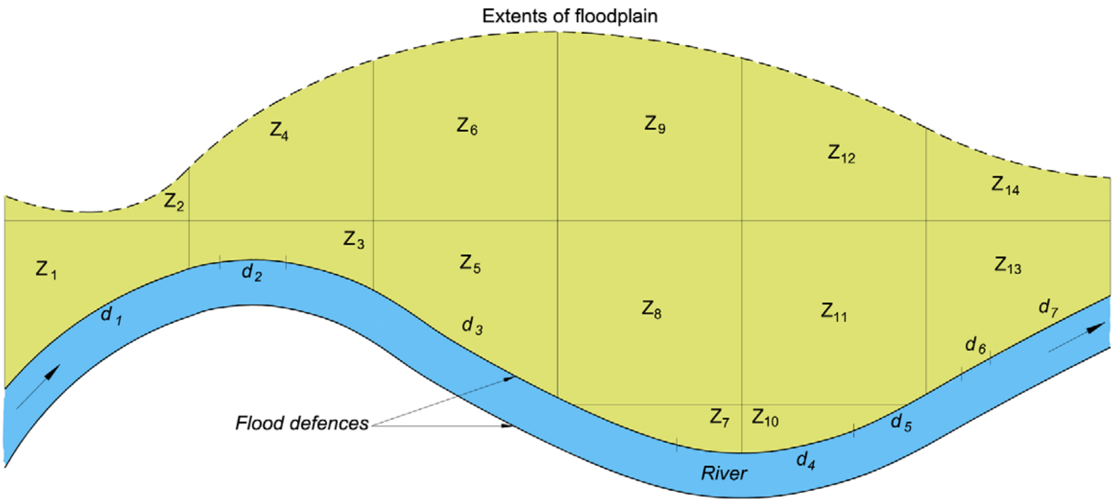


Figure 12 Example flooding system and Impact Zones and the notation used to describe them

Failure of one or more of the defences by overtopping or breaching will inundate one or more, but not necessarily all, of the Impact Zones. For each Impact Zone, the probability of every scenario of failure that may cause or influence flooding in that zone is required.

For example, consider an Impact Zone protected by two defences, d_1, d_2, and label the failure (i.e. breaching) of defence d_i as D_i and non-failure as $\overline{D_i}$. In this case there are three scenarios of defence system failure. The first scenario is where both defences fail. In more formal terms this can be expressed as $D_1 \cap D_2$ where the symbol $\cap$ signifies a joint combination of events *e.g.* $D_1 \cap D_2$ signifies "Event D_1 *and* event D_2 occur". Two more failed scenarios must be considered, $D_1 \cap \overline{D_2}$, $\overline{D_1} \cap D_2$, and one scenario where neither defence fails (a non failed scenario), $\overline{D_1} \cap \overline{D_2}$.

Each defence section d_i is assigned, based on knowledge of its type and condition, a conditional probability of failure (D) for a *given* load x, $P(D_i|x)$, for a range of values of x – the so-called defence fragility as described above in Section 2.4.4. By integration over all loading conditions an unconditional probability of defence failure, or expected annual breach failure probability, can be obtained:

$$P(D_i) = \int_0^\infty p(x)P(D_i \mid x)dx \tag{1}$$

where $p(x)$ is the probability density function of the load x.

The fragility curve is defined in discrete terms at q levels of x: $x_1,\ldots, x_q$, enabling Equation (1) to be re-written as:

$$P(D_i) = \sum_{j=1}^{q}\left[P\left(L \geq \frac{x_j + x_{j+1}}{2}\right) - P\left(L > \frac{x_j + x_{j-1}}{2}\right)\right]P(D_i \mid x_j)\,. \tag{2}$$

where L is a random variable representing the hydraulic load.

To estimate the probability of occurrence of a scenario in which a given number of defences in a system breach requires information about the dependency between the variables describing system behaviour, including loading and response.

Of course, flood inundation is not only a function of a defence breaching; a defence maybe simply be overtopped. Therefore, for each defence there are three states that are of interest: not breached but overtopped, not breached and not overtopped, breached and overtopped. To explore all possible combinations for a large system, the analysis of such a large number of scenarios would require an excessive amount of computer processing time. However, high order scenarios (*i.e.* scenarios in which a large number of defences in a system all breach) make a small contribution to the total probability of failure and therefore can be neglected. The error due to this approximation can be calculated exactly and therefore controlled.

Suppose that in a system with n defence sections, the probabilities of all scenarios with between zero and five breaches have been calculated. There will be:

$$r = \sum_{i=0}^{5} \frac{n!}{i!(n-i)!} \tag{3}$$

such scenarios, the probability of each of which is labelled P_j, $j = 1,\ldots, r$. The error E from neglecting higher order scenarios is given by:

$$E = 1 - \sum_{j=1}^{r} P_j \tag{4}$$

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

$$P(Y \geq y) = \sum_{y_j \geq y} P_j \tag{5}$$

The probability distribution of flood depth (Equation (5)) is calculated at the centroid of each Impact Zone and assumed to apply to the whole of the Impact Zone. For a given Impact Zone the expected annual damage R is then given by:

$$R = \int_0^{y_{\max}} p(y)D(y)dy \tag{6}$$

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 given area of interest is then obtained by summing the expected annual damages for each Impact Zone within that area.

3. RASP - METHODS AND OUTPUTS

3.1 Introduction

This chapter provides an overview of the tiered methodologies developed in the RASP project. The key differences between tiers are highlighted and the various outputs from the methods illustrated by example.

Following an introduction to the common generic steps that underpin each analysis level, the discussion is structured in terms of sources, pathways and receptors and the way in which each tier in the analysis deals with them.

A more detailed discussion can be found in the Project Record (Environment Agency, 2004a).

3.2 Common framework of analysis

Each tier in the RASP hierarchy follows the same general analysis steps. Although this overall framework of analysis is common (involving nine primary steps as shown in Figure 13) the methods employed at each step vary.

The following section provides a discussion of the methods and their key differences. Where possible, use is made of the results from a series of case/pilot study applications (see Box 1) to illustrate particular issues and demonstrate the increasing resolution and information that is gained through more detailed analysis.

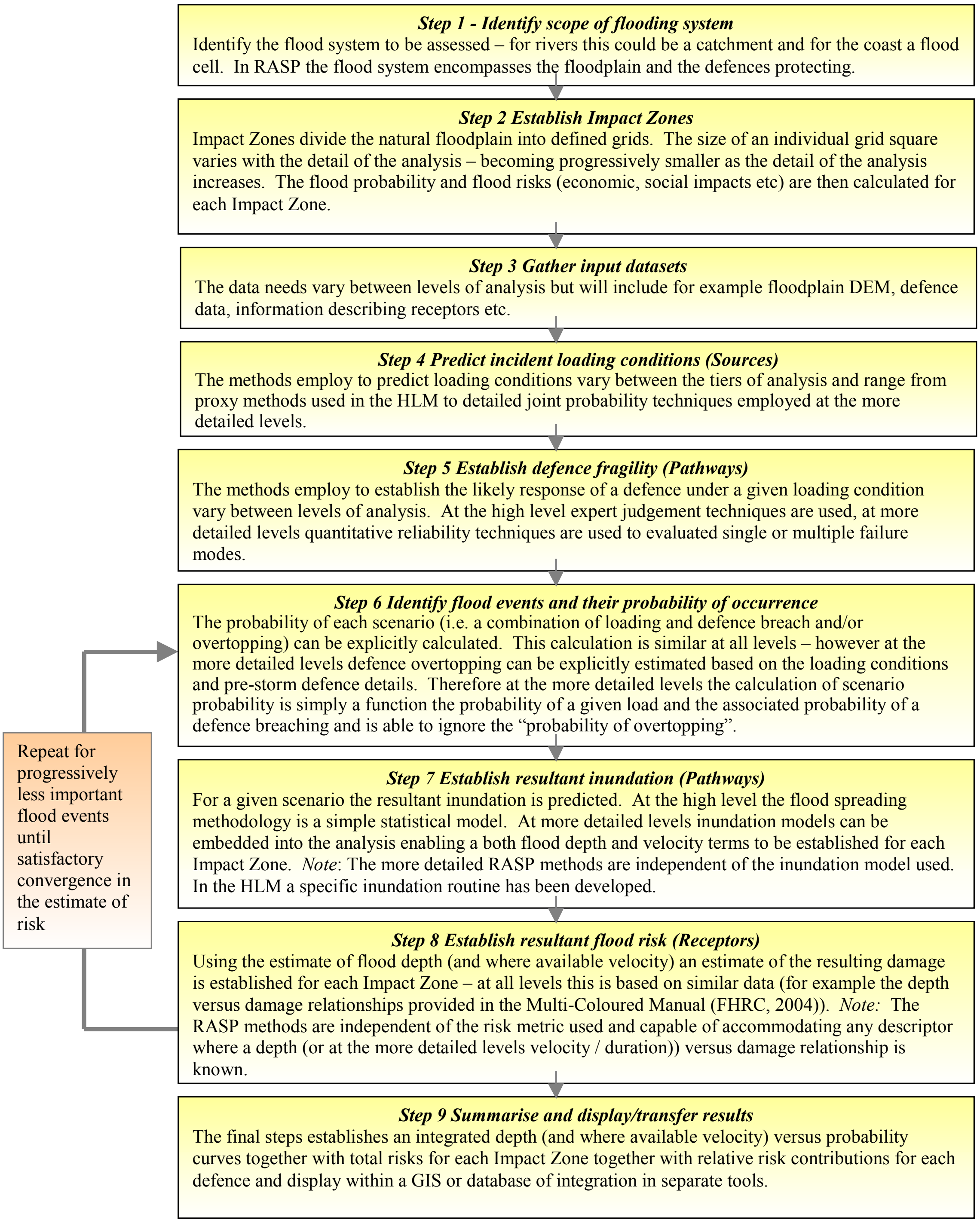


Figure 13 A generic analysis process common to all tiers of the RASP hierarchy

Box 1 Use of case / pilot studies to underpin the development of the RASP methods

Where possible the utility of the RASP methods have been explored through case/pilot study application. In particular, the RASP techniques have been trialed at the following locations and supported the following projects:

National Flood Risk Assessment 2002 – supported by the HLM, this project was completed in parallel with the RASP Research Project and provided for the first time a national assessment of both flood probability and flood risk within the Indicative Flood Plain. This project was completed in partnership with the Environment Agency operations and Defra. (*Note*: The RASP HLM+ is currently under development to support the NaFRA 2004)

Pensarn to Kinmel Bay Coastal Floodplain – North Wales – supported by the ILM. This project was completed in parallel with the RASP Research Project and provided an assessment of flood risk for the Pensarn to Kinmel Bay floodplain taking into account the likely performance of a range of coastal and fluvial defences. Detailed topographic data was utilised based on a combination of ISAR and *insitu* measurements. Coupled with detailed wave and surge analysis this study provided an exemplar in terms of providing flood risk assessment appropriate for use in maintenance and improvement planning as well as regulation and planning decisions. This study was completed in partnership with Conwy Borough Council, the Environment Agency Welsh Region and the Welsh Development Agency together with a local developer. All parties supported the transparency of the analysis provided by the RASP methods and as a result were able to support the results as a common and agreed "best" picture of present day flood probabilities – an important step in delivering more effective regulation of floodplain development.

Burton-on-Trent Fluvial Floodplain, Midlands Region – support by the ILM. Although a number of attempts were made to link with a CFMP pilot study this proved too complex in terms of project programme and funding. Therefore, as the RASP project had easy access to data and base models for Burton-on-Trent in Midlands Region, this area was selected as the fluvial case study for the RASP ILM.

Caldicot Levels estuarial floodplain – supported by RASP DLM/PC-Ring. The DLM of RASP aims to provide the most intensive assessment of flood probability and hence has a high data demand. In concept, the DLM in RASP reflects more closely the approach adopted in the Netherlands to support their analysis of structural failure of defences protecting individual polders. Therefore, the opportunity was taken to explore the applicability of the Dutch methodology, enshrined in the software PC-Ring, to a UK floodplain. The Caldicot Levels were selected early in the RASP research as having sufficient data to support such a detailed analysis.

3.2.1 Source terms – Predicting incident loading conditions

In the context of RASP sources refers to loading on the defences in terms of water levels and wave conditions.

Through each tier the methodologies employed to predict the incident loads on the defences vary considerably from one level to the next. These differences are summarised in Figure 14.

Note: At present the RASP methods are restricted to considering coastal and fluvial loading (i.e. water overtopping/overflowing into the floodplain and spreading across the surface of the floodplain). A series of demanding extensions would be to include first pluvial and then groundwater sources within the same conceptual framework. Both of these issues are recommended as priority actions to move further towards a system-based analysis of flooding and support true integrated flood management.

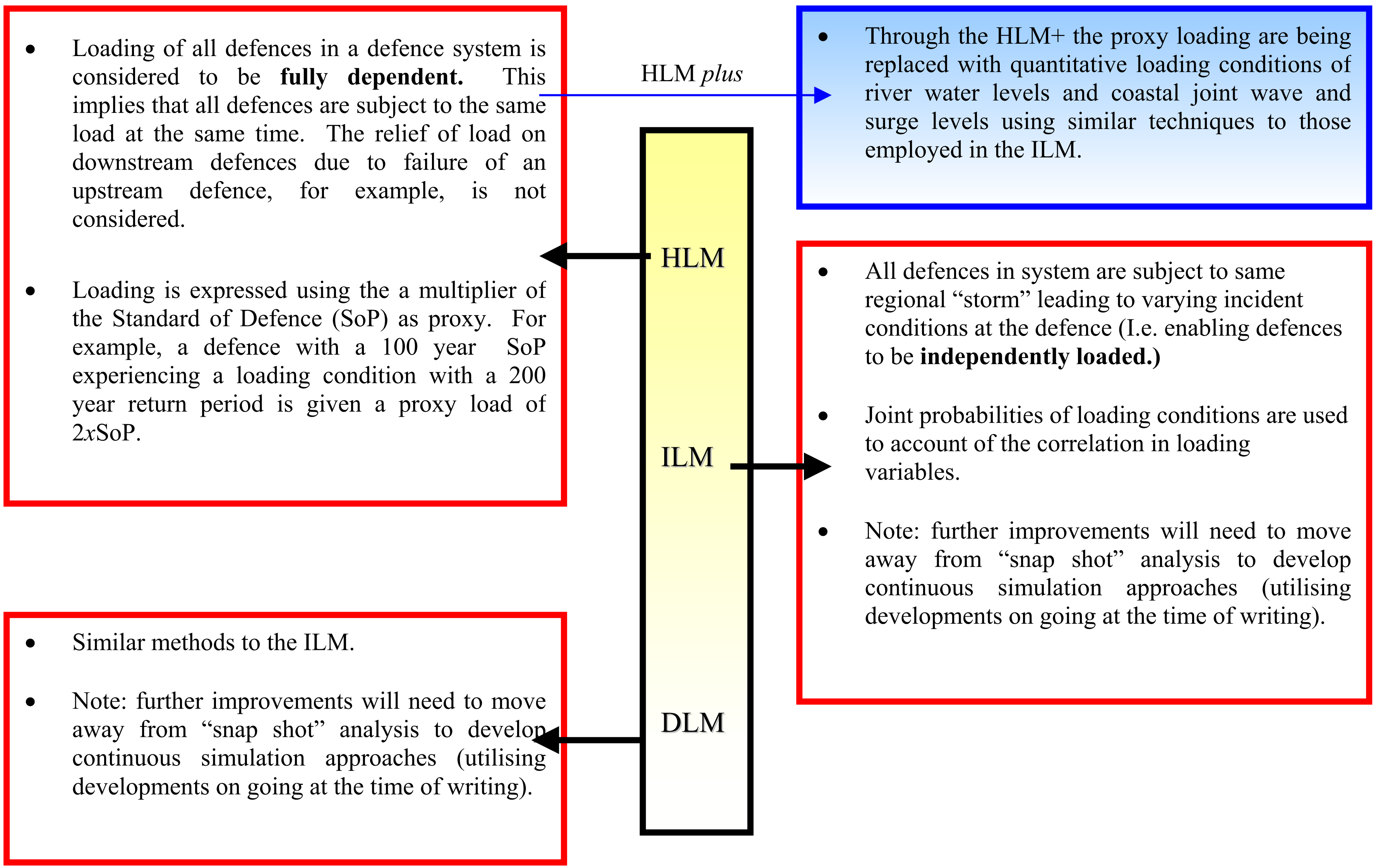


Figure 14 Loading conditions - Key differences between the analysis tiers

3.2.2 Pathway terms – Infrastructure performance

Perhaps the most important feature of the RASP analysis is its ability to include the performance of defences within the analysis of flood risk. As discussed in Chapter 2 this is done through the application of the concepts of defence fragility that describe the likelihood of a defence failing under a given load. Within a detailed risk analysis, an understanding of the overtopping and breaching mechanisms of a defence can be constructed on a site-specific basis by consideration of defence dimensions, material properties and failure mechanisms. For national-scale analysis a more approximate approach based on defence classification and condition assessment has to be adopted. A summary of the differences in the approaches to determining defence fragility at each tier is provided in Figure 15.

The increasing detail of analysis affords an increasing understanding of the defence response to loading and an increasingly reliable estimate of likely defence performance. This concept of increasing knowledge is illustrated in Figure 16.

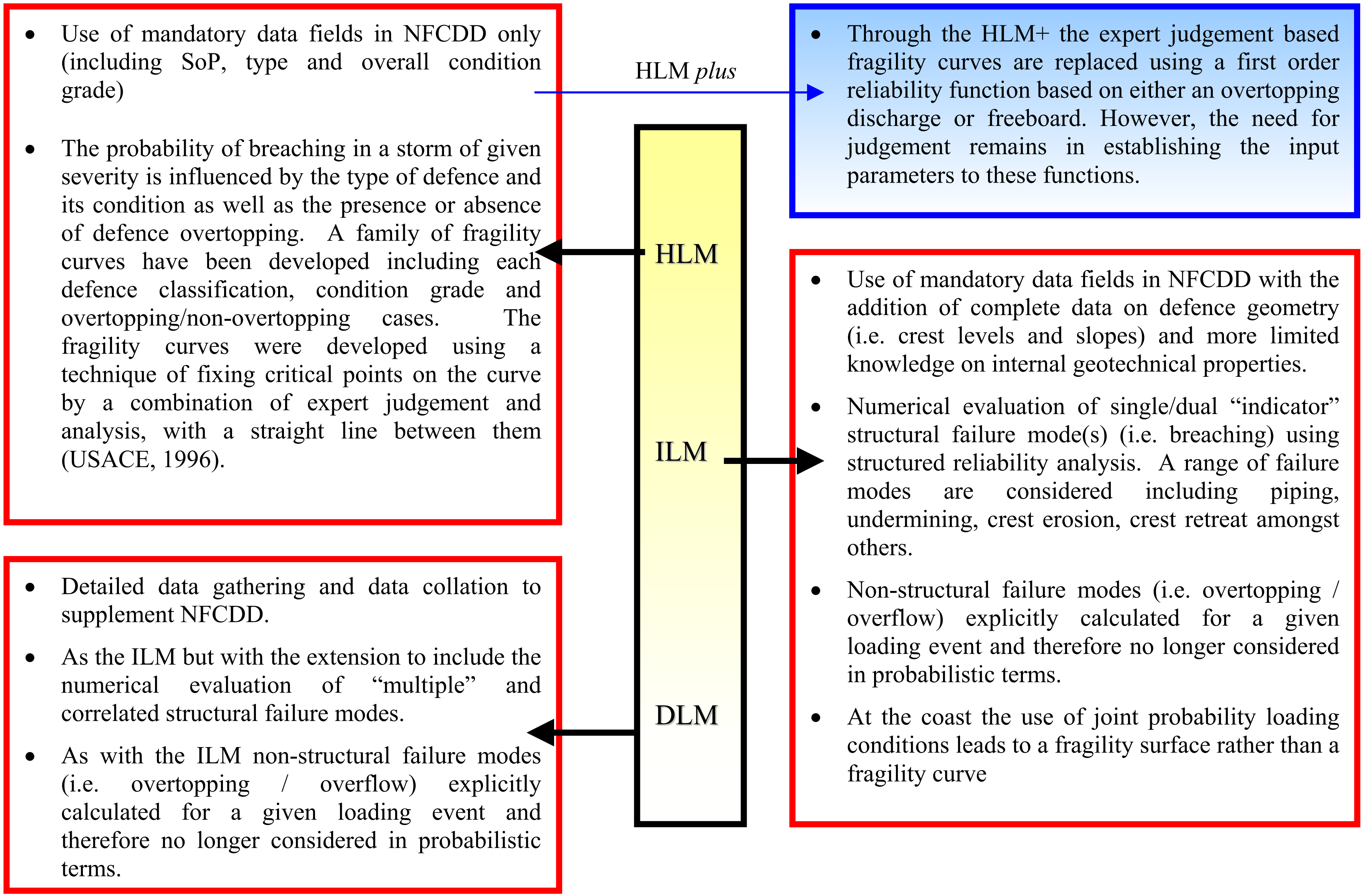


Figure 15 Defence performance – Key differences between the analysis tiers

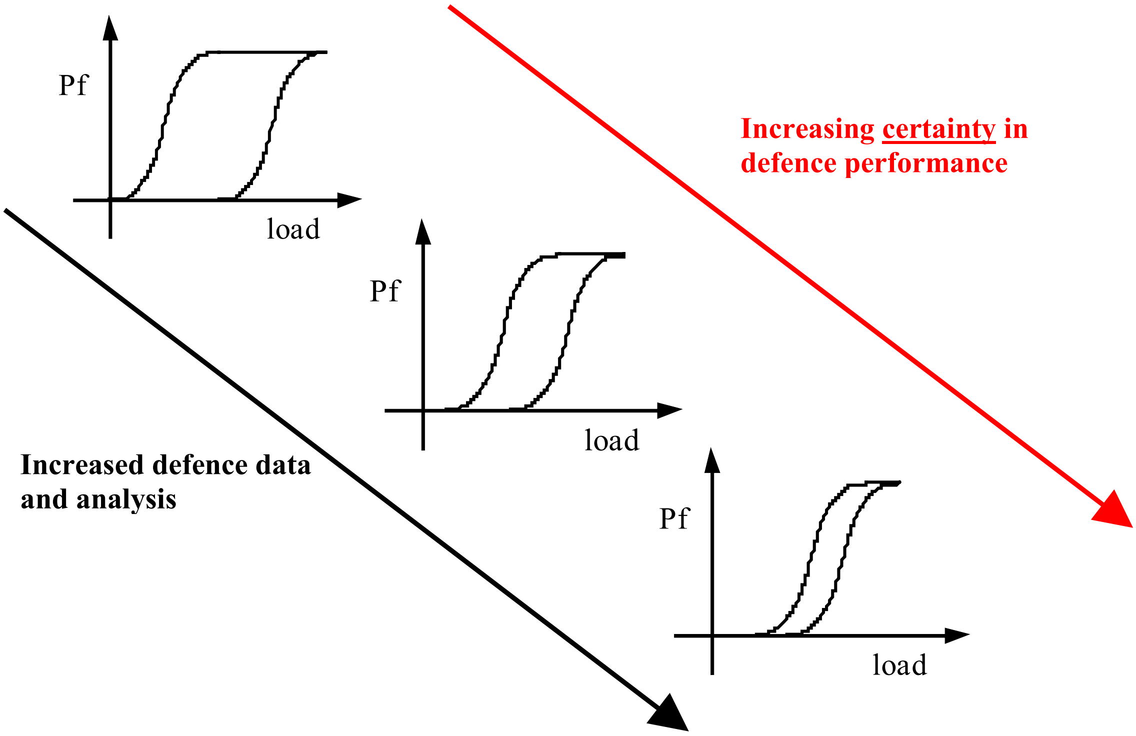


Figure 16 Increasing detail of analysis delivers an increasingly reliable understanding of defence fragility

Examples of the defence fragility calculated from each tier of the analysis are shown in Figures 17a, b and c. Figure 17a shows an example taken from the HLM approach and is based on a process of expert elicitation without recourse to quantitative analysis. The process of expert judgement was undertaken in the absence of quantified loading data, and hence the severity of the load on the defence was described in relative terms as a function of the Standard of Protection of the defence. Figure 17b presents the results from the HLM+ analysis where a single failure mode is analysed using quantitative descriptors of the loading and the defence geometry (crest level, height, width etc) and a first approximation to a limited state function. General comparison of the HLM and HLM+ suggests that expert judgement often (but not uniformly) over-estimates the likelihood of failure of a defence at low return period events and under-estimates the increase in failure probability with increasing load (hence underestimates the probability of failure at higher loading). An understanding of the defence performance under load is fundamental to understanding risk and further research on the detail of the failure mechanisms will be needed.

Figure 17c describes a fragility *surface* rather than a fragility *curve*. This simply reflects the description of the loading conditions in terms of a joint population of wave and water level condition available at the more detailed levels.

By integrating across all defences a “system” fragility surface can be obtained. As shown in Figure 18, this simply, but usefully, provides the flood risk manager with an understanding of which combination of events is most likely to cause structural failure somewhere in the defence system. (Of course, this information must be allied with inundation and damage models to understand risk – as discussed in the following sections).

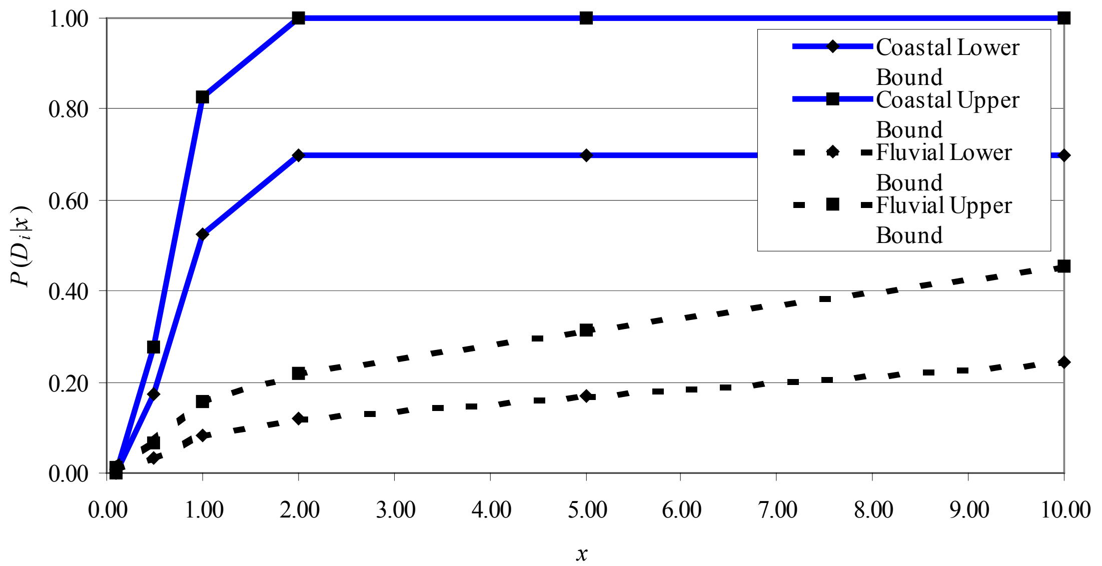


Figure 17a Typical fragility curves adopted in the HLM
(Note: the x axis shows loading in terms of a multiplier of the SoP of the defence.)

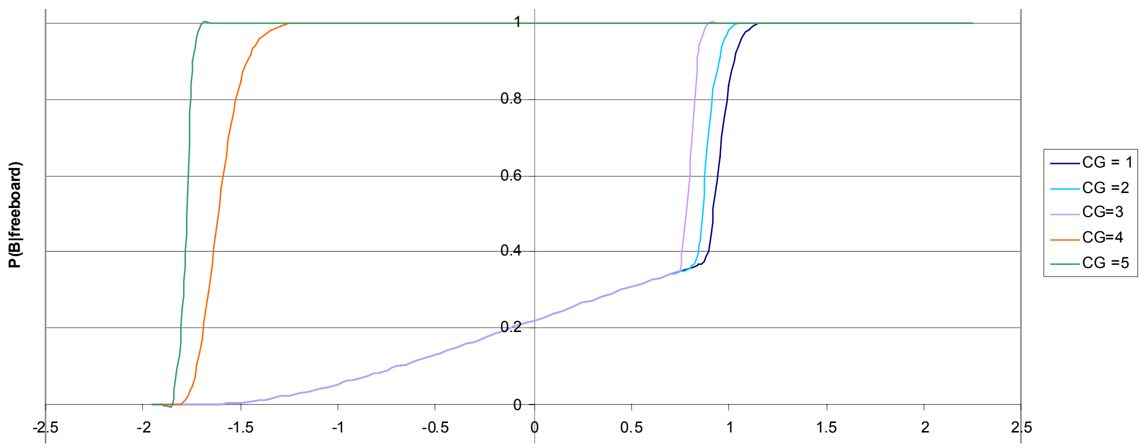


Figure 17b Typical fragility curve under development in the HLM+ for a fluvial embankment
(Note: the x axis shows loading expressed through a quantitative descriptor – in this case freeboard in metres.)

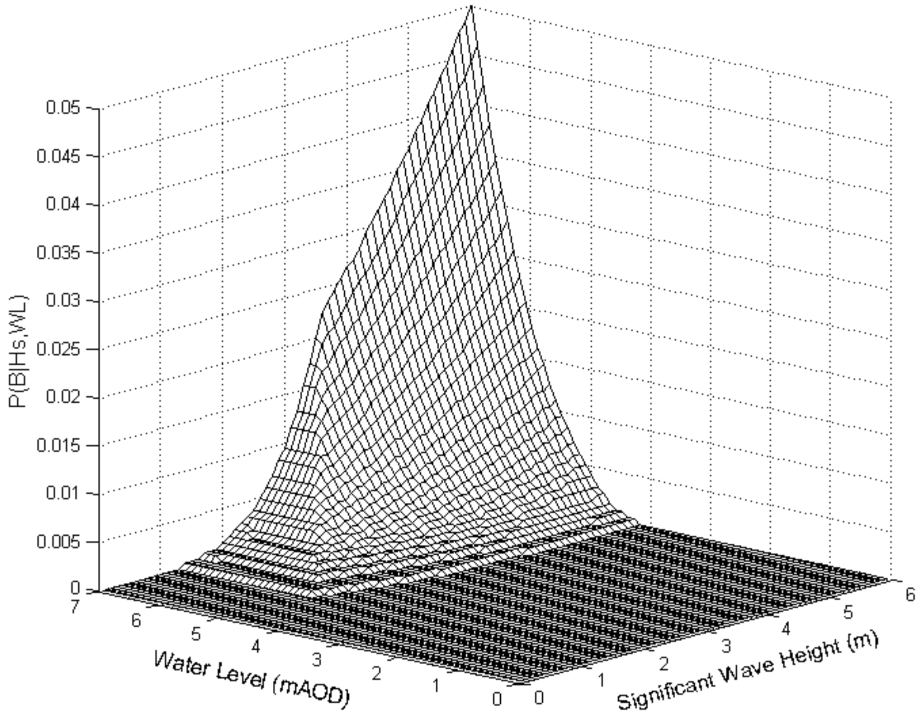


Figure 17c Typical coastal fragility surface generated at the ILM
(Note: the loading conditions have been expressed as a joint density function and therefore the expression of the defence fragility as a surface reflects this.)

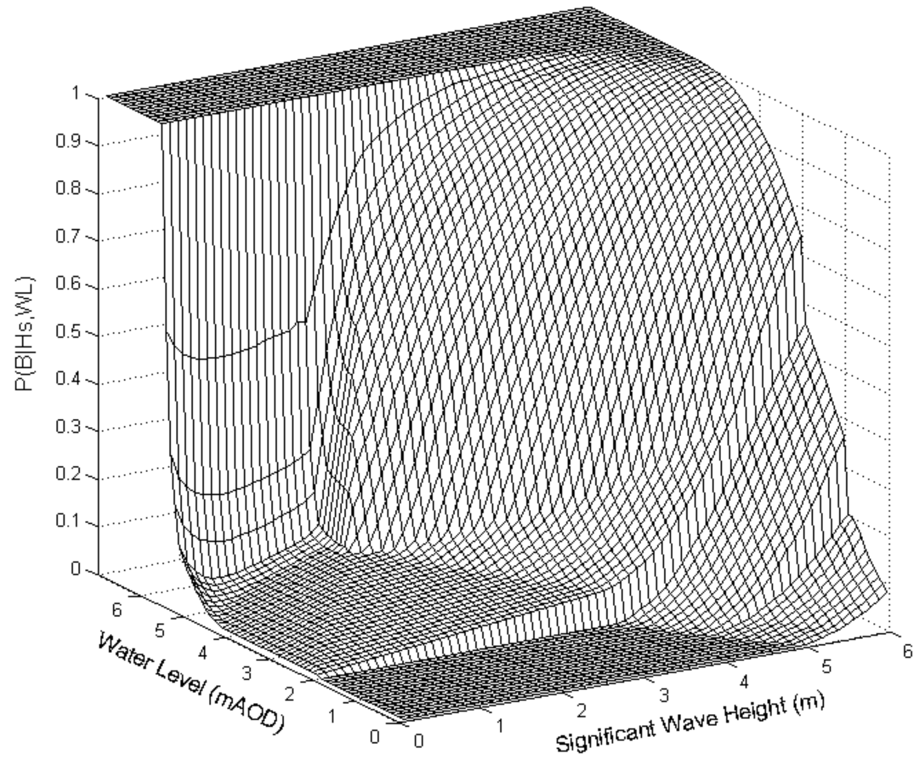


Figure 18 Defence system fragility surface – An integration of the fragility of all defences within the defence system

By multiplying the systems failure probability distribution and the loading distribution, insight is gained into the critical storm conditions for a given defence system. This surface is plotted in Figure 19 as a series of contours; the darker contours represent higher density values. The points marked with circles on Figure 19 represent the peaks of the distributions and the wave height water level combinations that are most likely to cause defence failure.

Figure 20 – taken from the North Wales example –provides useful feedback to the decision-maker. In particular it suggests that the fragility of the defences has been under-estimated during low return period storm events. In a more formal application the fragility of the defences would be revisited and the analysis repeated – a simple process within established models.

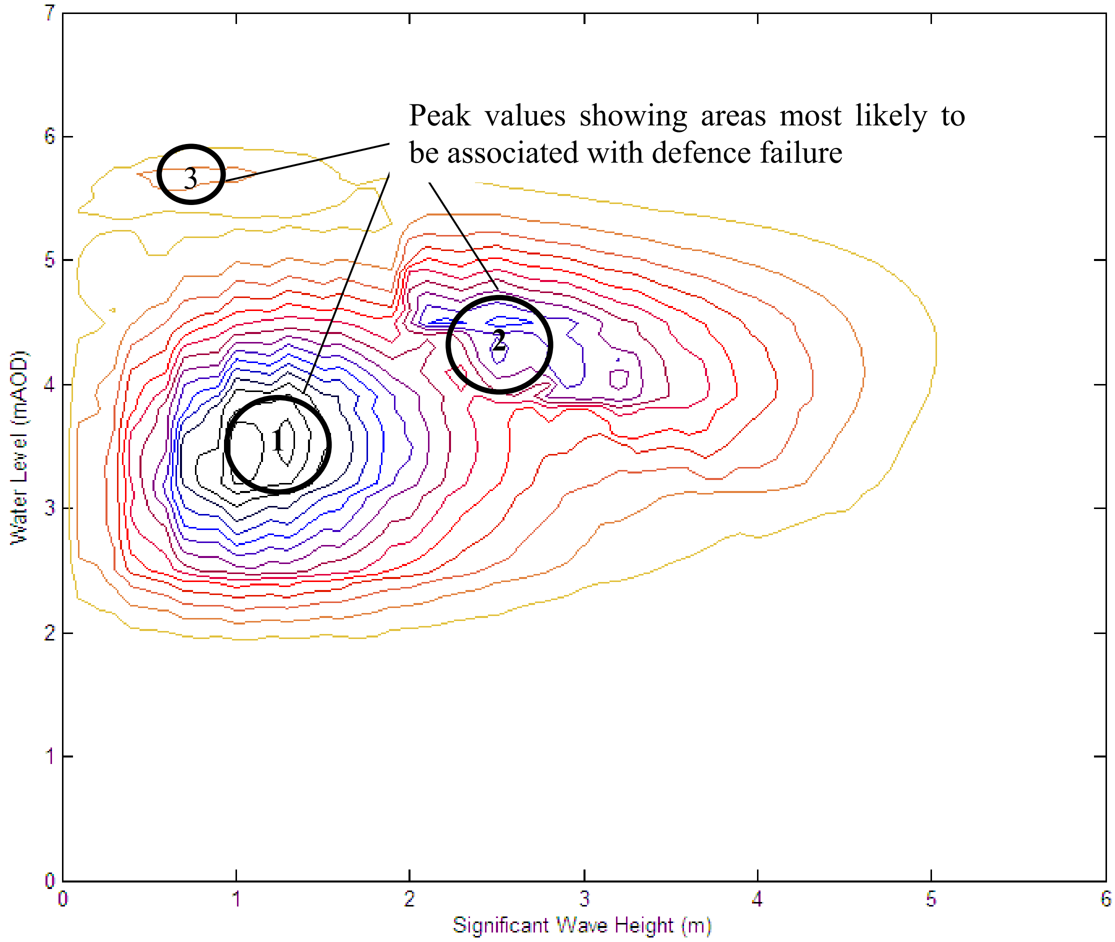


Figure 19 A contour plot of $P(D_s|H_s, WL).f(H_s, WL)$ where darker contours represent higher values. The circles mark the approximate locations of peak values

Where multiple failure modes are included it is also possible to identify the principal factors that contribute to the likelihood of failure. An example of this type of output is shown in Figure 20, where contributing failure modes are ranked in terms of importance.

This information has been restructured in Figure 21 to show how it may be used to provide information to a flood manager as to the key components of a defence (or the lack of data regarding the details of the defence) that contribute to risk and/or uncertainty. Such detailed information can provide valuable information when determining the most cost efficient maintenance or improvement intervention strategy. This has been further developed in the PAMS scoping study. Similar information also enables designers to understand the key structural elements that contribute most to failure and enable efficient design modifications to be explored.

Note: At present the RASP methods are restricted to considering linear defences. At the more detailed levels a simple extension would be to include the performance of pumps and gates within the systems based analysis. A more demanding extension would be to include the performance of sub-surface infrastructure associated with urban drainage within the same framework. Both of these issues are recommended as priority actions to move further towards a system-based analysis of flooding and support true integrated flood management.

It is also noteworthy that at present the RASP methodologies consider only present condition and exclude temporal issues such as deterioration. An important extension of the RASP methodologies will be to include time dependent issues such as the interaction between morphology response and infrastructure behaviour as well as on-going deterioration or improvement of defences. The inclusion of these time dependent processes is recommended as a priority action in support of more timely interventions and improved whole life option analysis.

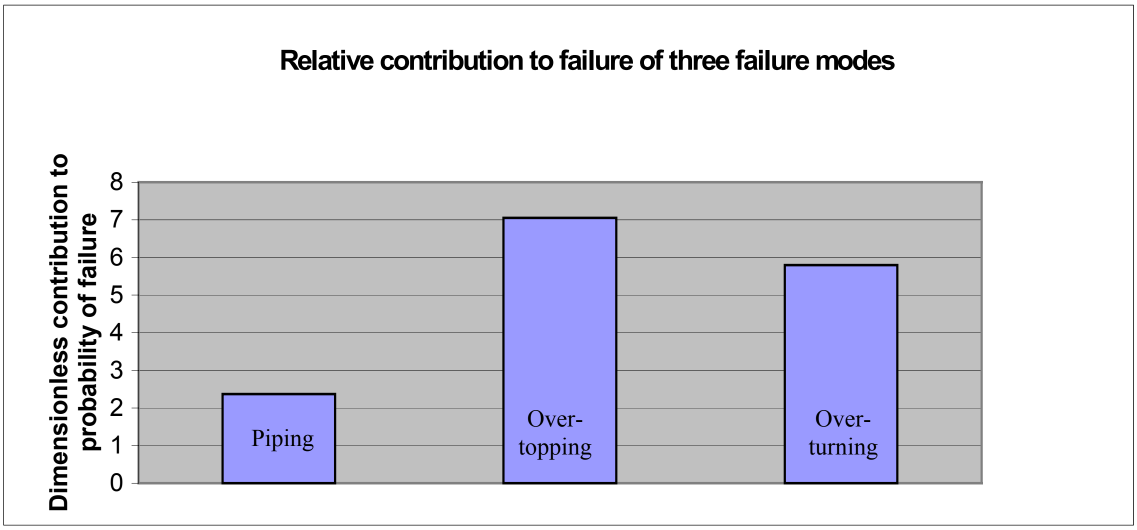


Figure 20 Example output from a multi-failure mode reliability analysis showing the relative importance of each failure modes to the overall probability of structural failure
Note: The figure above shows overtopping as the critical failure mode

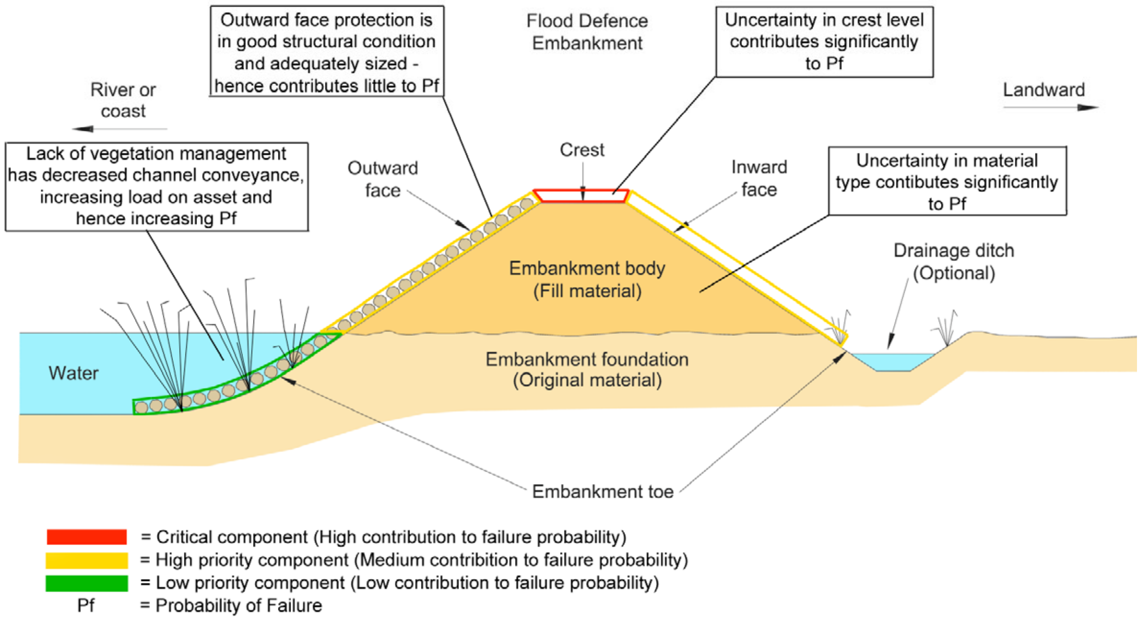


Figure 21 Using the information from RASP DLM to target maintenance and improvement interventions – An example output

3.2.3 Pathway terms – Estimating flood spreading inundation

Resolving the inundation extent, depth and, increasingly, velocity for given storm and defence response event is crucial to understanding the chance of a particular Impact Zone being flooded in a particular scenario. As previously noted, RASP does not aim to develop new spreading models *per se* but rather utilise spreading models in an efficient way to enable an integrated system-based analysis of flood probability to be established.

As shown in Figure 22, at the high level, a specific flood spreading tool has had to be developed. This reflects the tradition of flood spreading developments focused at more local scale analysis where both time and data are less constrained. At the IL and DL RASP uses off-the-shelf models and is independent of the selected approach providing it is capable of realising multiple (in the order of 2000) simulations of load and defence response in an acceptable time.

Note: An important challenge for the uptake of the RASP methodologies at a more detailed level is the development of an efficient IT system architecture capable of integrating efficiently with an inundation model. This is just one of the issues recommended as part of a priority action to develop the system architecture of RASP methods and its interface with users inside and outside of the Environment Agency.

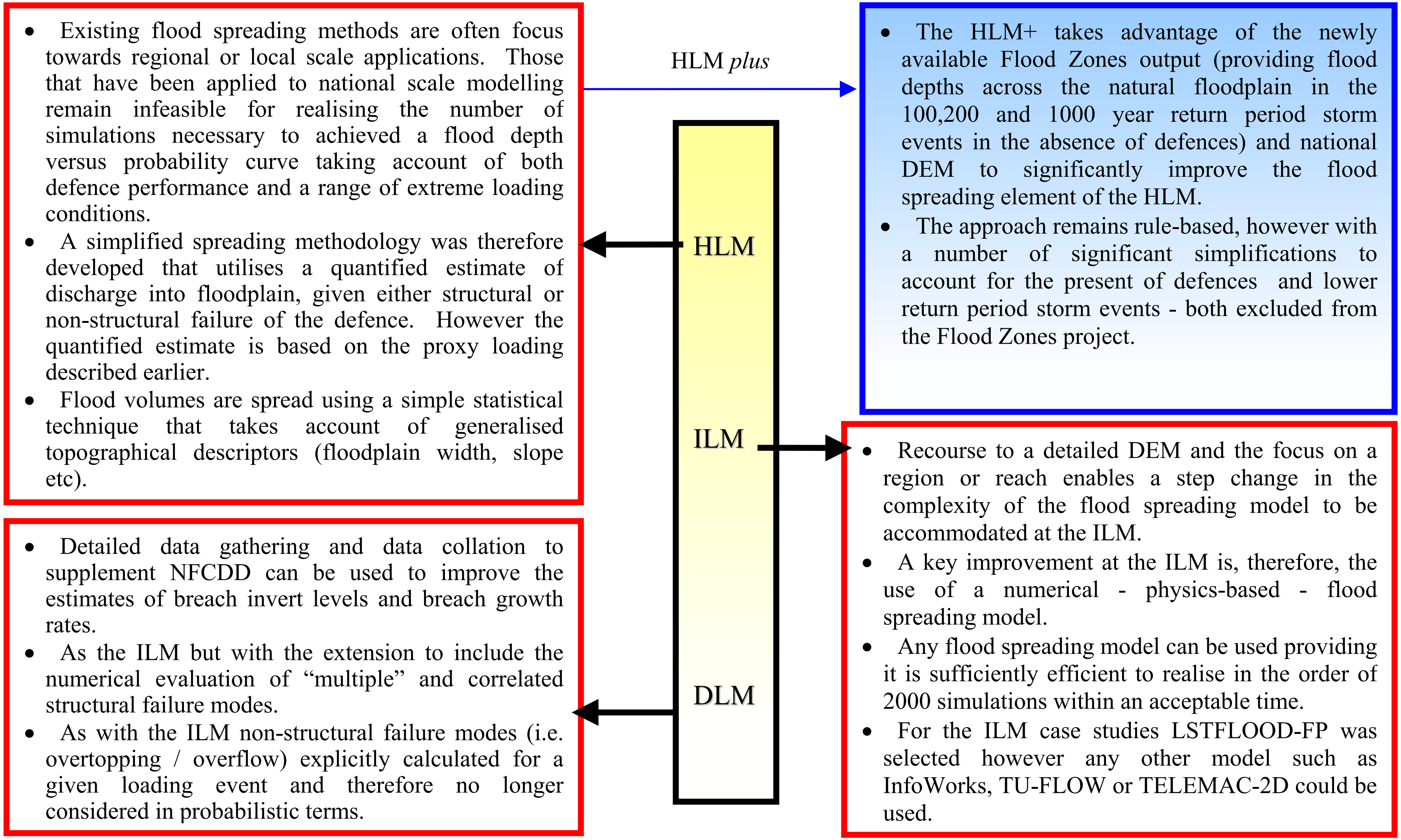


Figure 22 Flood spreading – Key differences between the analysis tiers

3.2.4 Integrating sources and pathways – establishing flood inundation probability

An intermediate output available from all of the tiers of RASP is an integrated map showing the spatial variation in flood probability (Figure 23). At each tier of analysis the output is provided in the same format and consists of, as a minimum, a flood depth versus probability relationship for each Impact Zone in the floodplain as shown in Figure 24.

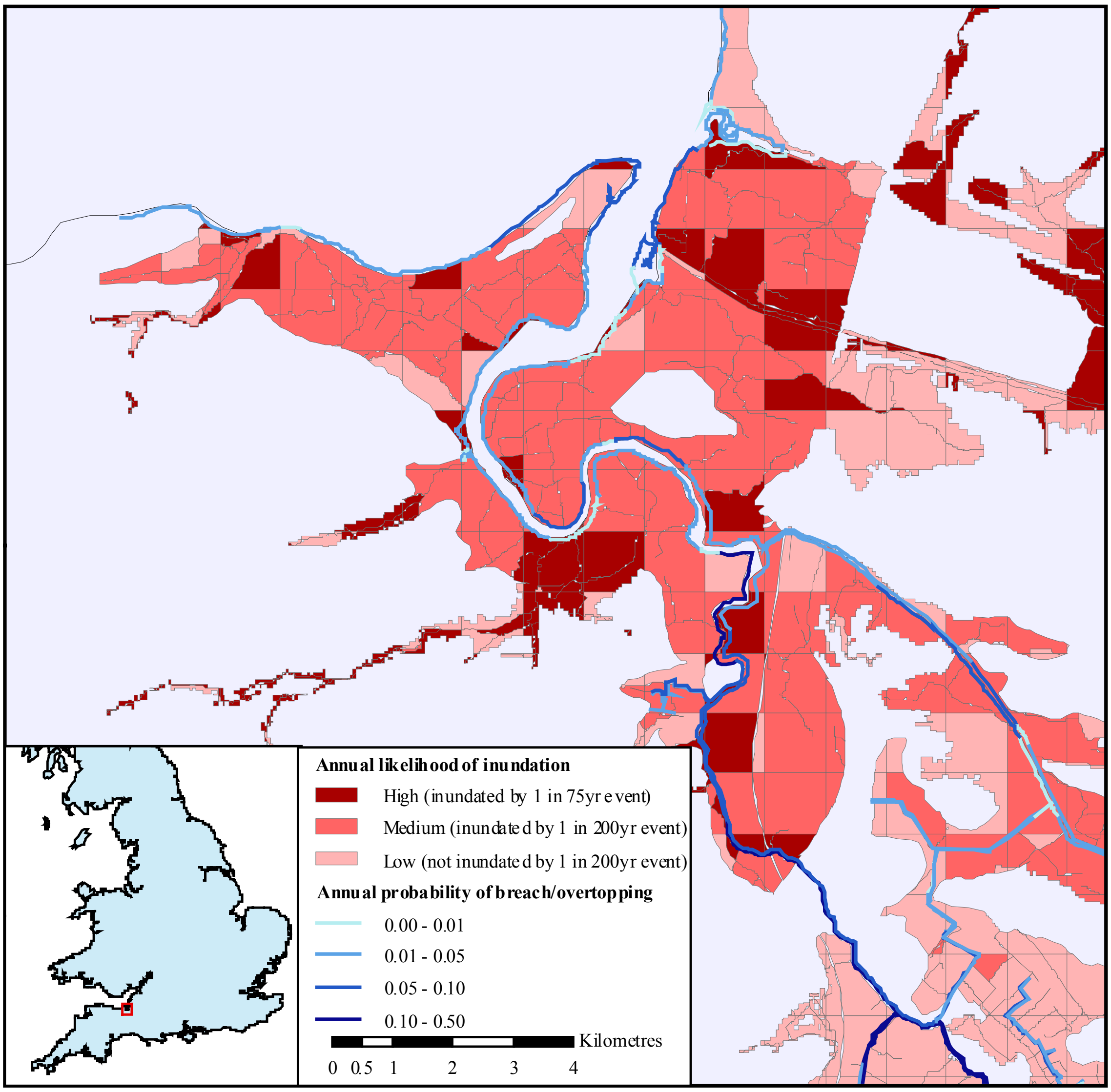


Figure 23 Typical results from the RASP analysis showing the spatial variation in flood inundation probability

(Note: example taken from the RASP HLM analysis of the Parret Catchment undertaken in support of the NaFRA 2002. At more detailed levels the grid resolution of the Impact Zones significantly improves but the format remains the same)

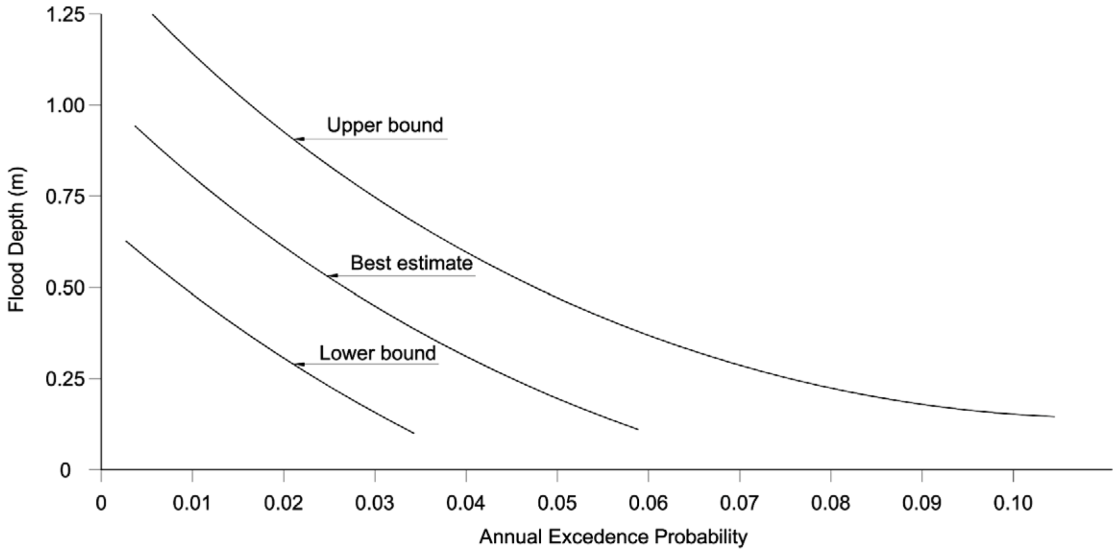


Figure 24 Typical results from the RASP analysis showing flood depth versus probability relationships
(*Note: example taken from the RASP HLM analysis of the Parret Catchment undertaken in support of the NaFRA 2002. At more detailed levels the uncertainty on the results reduces and the additional terms of velocity and rate of rise become available.)*

The key differences between the results from progressively more detailed analysis is the level of resolution and reliability of the results. The improvement in resolution from the HLM to the ILM is demonstrated in Figures 25a and b for a coastal example and Figures 26a and b for a fluvial situation.

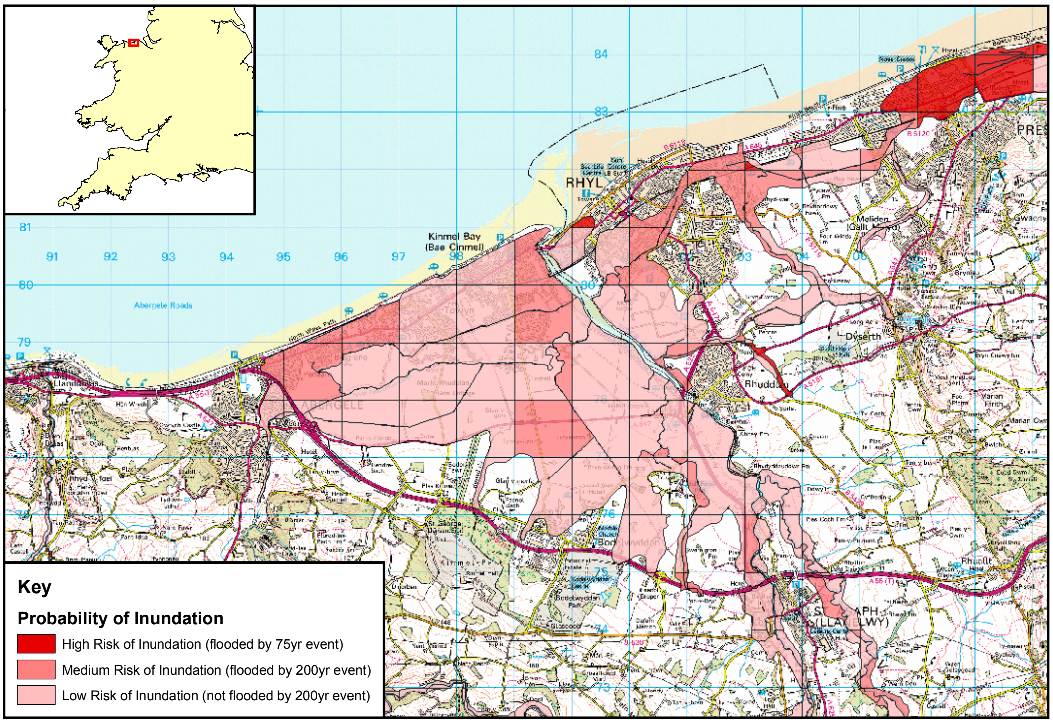


Figure 25a Pensarn to Kinmel Bay Coastal Floodplain – North Wales – Results from NaFRA 2002 supported by the RASP HLM

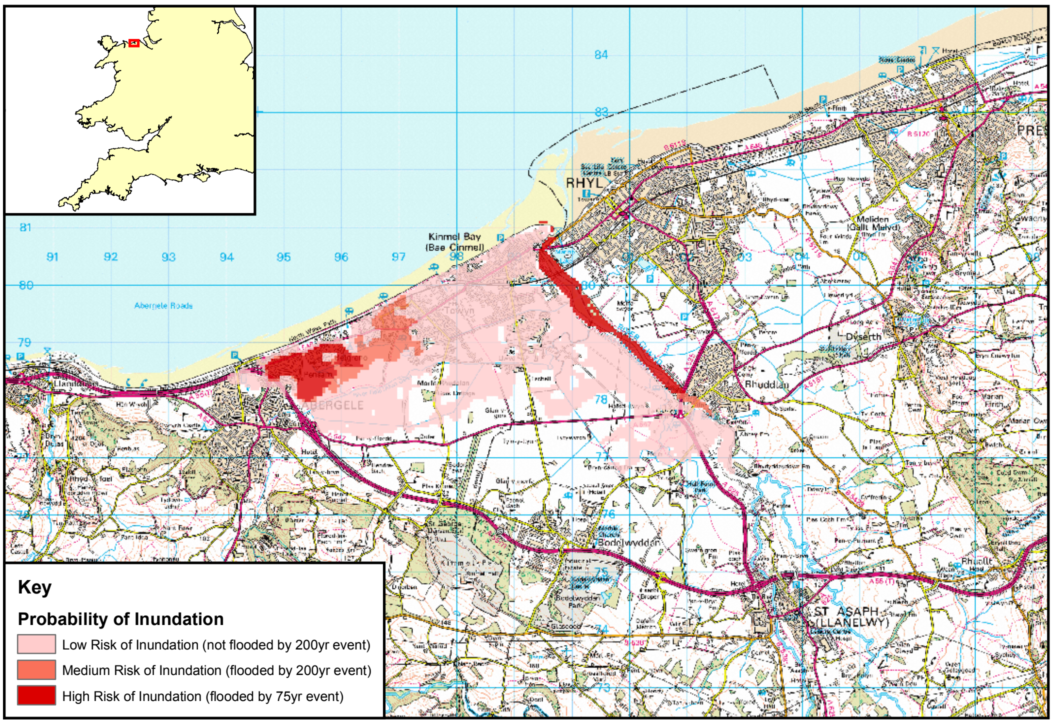


Figure 25b Pensarn to Kinmel Bay Coastal Floodplain – North Wales – Completed using the RASP ILM

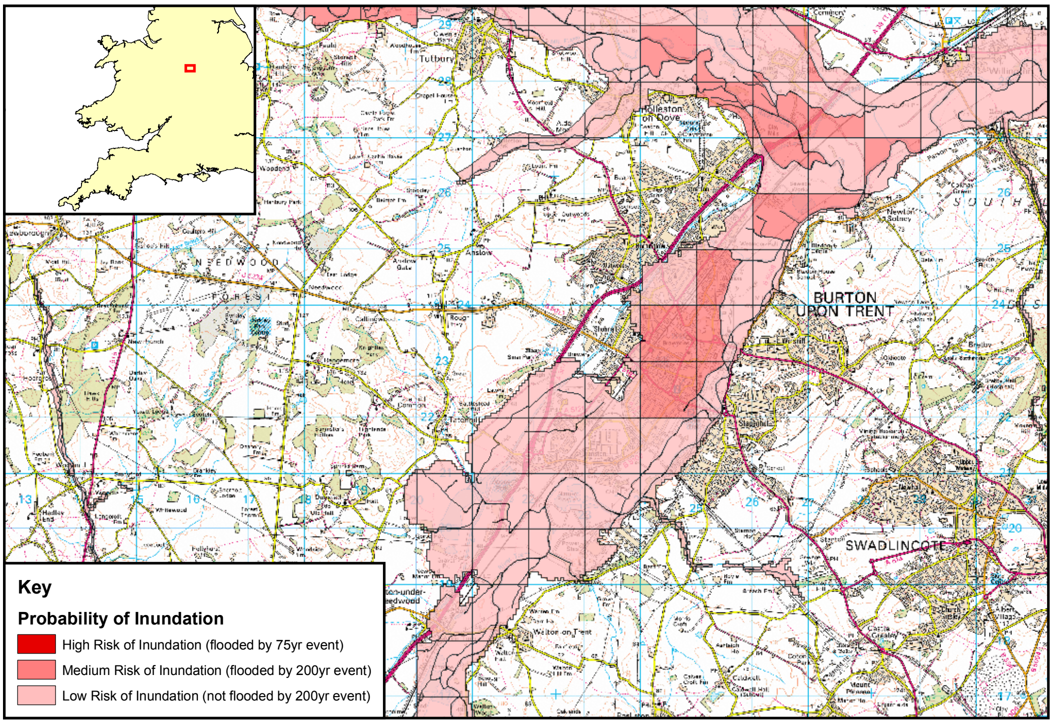


Figure 26a Burton-on-Trent Fluvial Floodplain, Midlands Region – Results from the NaFRA 2002 support by the RASP HLM

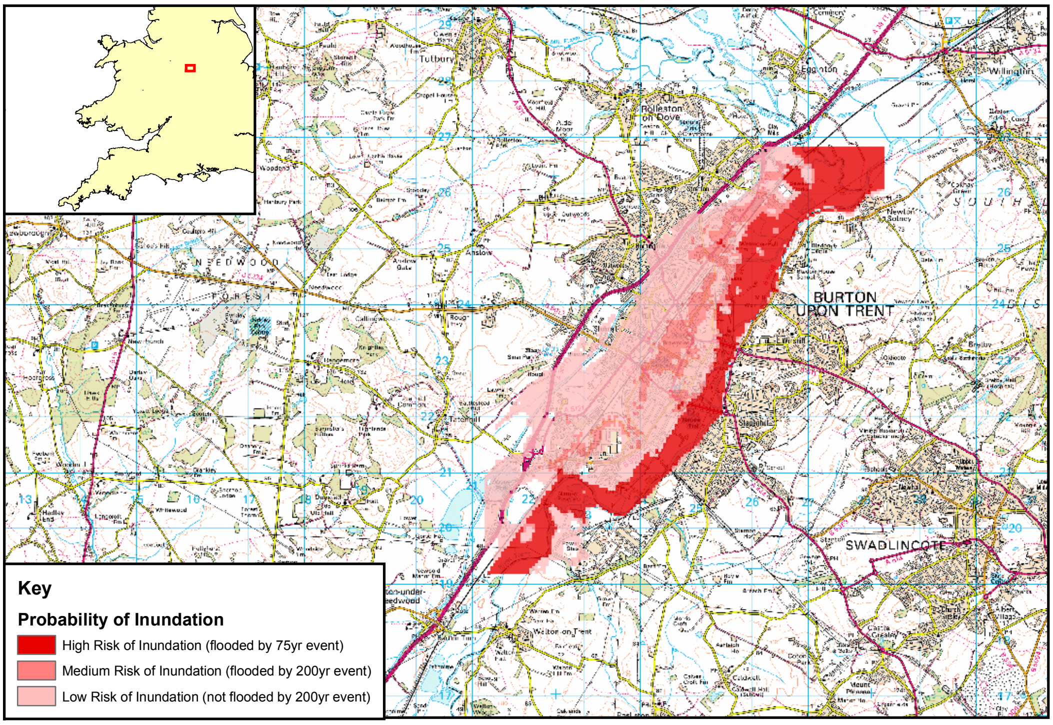


Figure 26b Burton-on-Trent Fluvial Floodplain, Midlands Region – Completed using the RASP ILM

(Note: The dark red on the east of the river reflects inundation of a low lying area with no raised defences. Model results from the ILM cover a more limited area than those taken from the national assessment using the HLM.)

3.2.5 Receptor terms – Estimating flood damage and flood risk

The RASP methods are focused towards providing an estimate of inundation probability (depth, velocity etc). Therefore they are capable of utilising any data receptors where potential damage can be expressed as a function of either flood depth or velocity (or derivative terms such as the rate of rise). However, the flood spreading model selected by the user will dictate the reliability of the flooding parameters. For example, the simple parametric model used within the HLM cannot provide flood velocity terms. Equally, duration dependent impacts cannot easily be determined. However, at more detailed levels of analysis both flood depth, velocity and duration can be utilised in determining potential impacts.

Typical map based output includes a spatial distribution of economic damages and the relative contribution to risk provided by each defence. These typical outputs from the HLM and ILM are shown in Figures 27a,b and c.

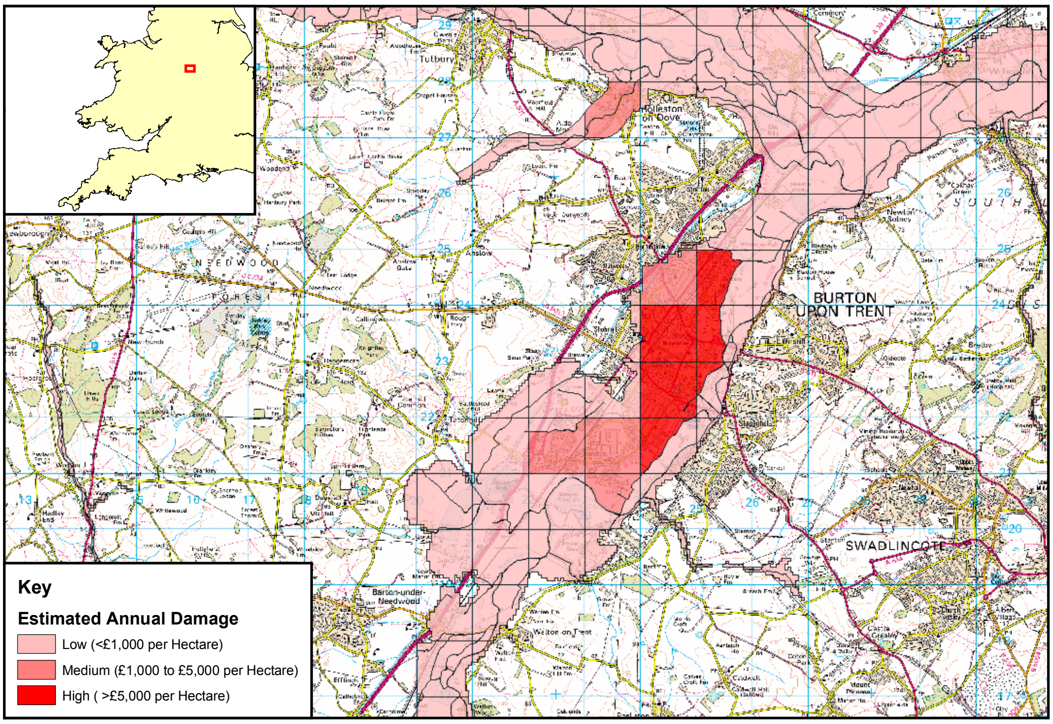


Figure 27a **Spatial distribution of economic risks at Burton-on-Trent from the HLM**

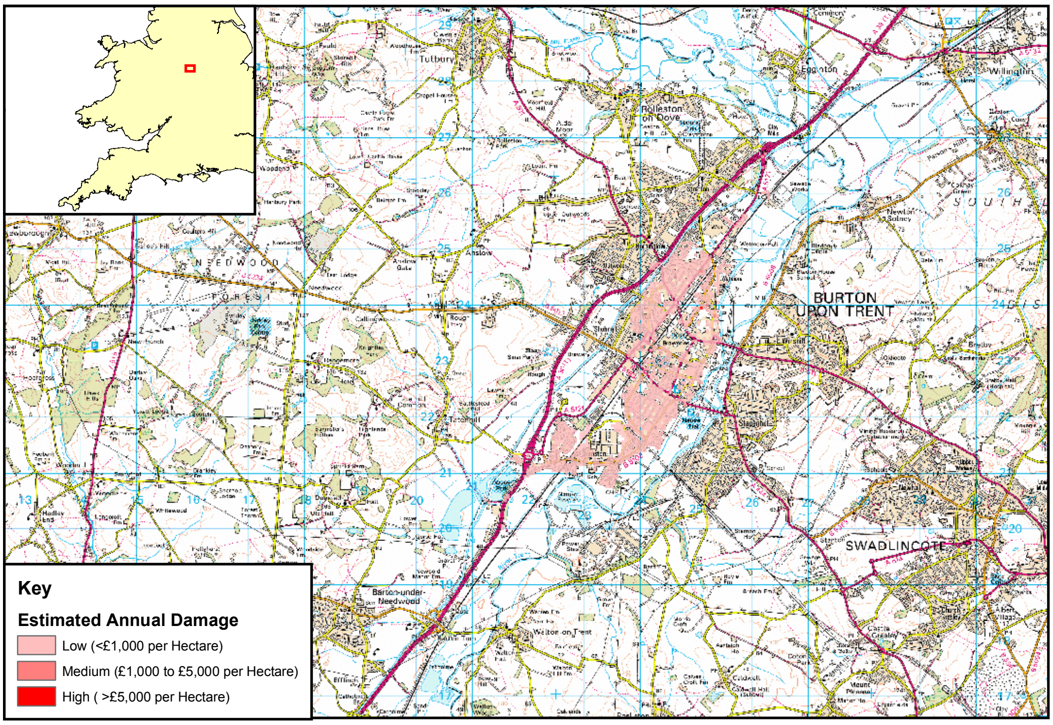


Figure 27b **Spatial distribution of economic risks at Burton-on-Trent from the RASP ILM**

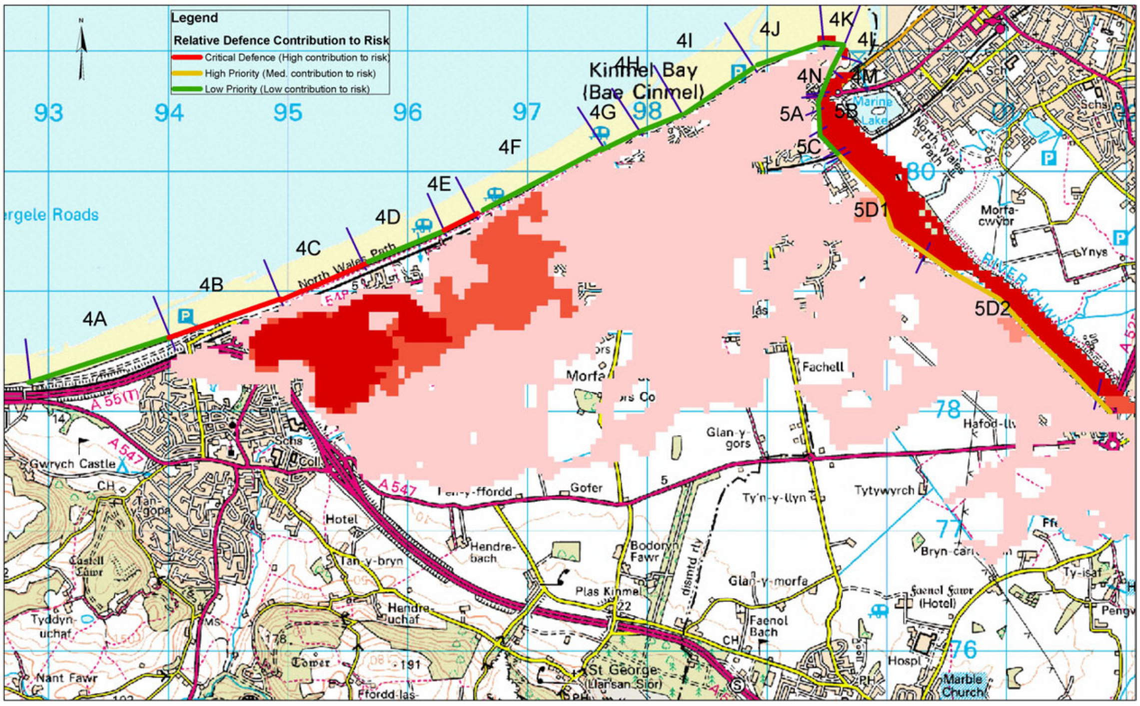


Figure 27c The relative contribution to risk provided by each defence
*(Note – this could be rewritten as "the relative contribution to risk **reduction** afforded by each defence")*

The more detailed analysis provided through the ILM and DLM enables a more useful insight into the relationship between sources and flood risk than can be gauged from the HLM. Figure 28, for example, shows the relationship between loading condition and risk, expressed in expected damages. The bi-modal nature of Figure 28 reflects in part the topography at Towyn that means only a storm surge of greater than ~4m AOD will result in any inundation behind the defence system, whilst a surge of ~5m is required for damage to run into millions of pounds. Overtopping events at lower water levels do occur, but these do not release sufficient water into the floodplain to provide a substantial contribution towards flood risk.

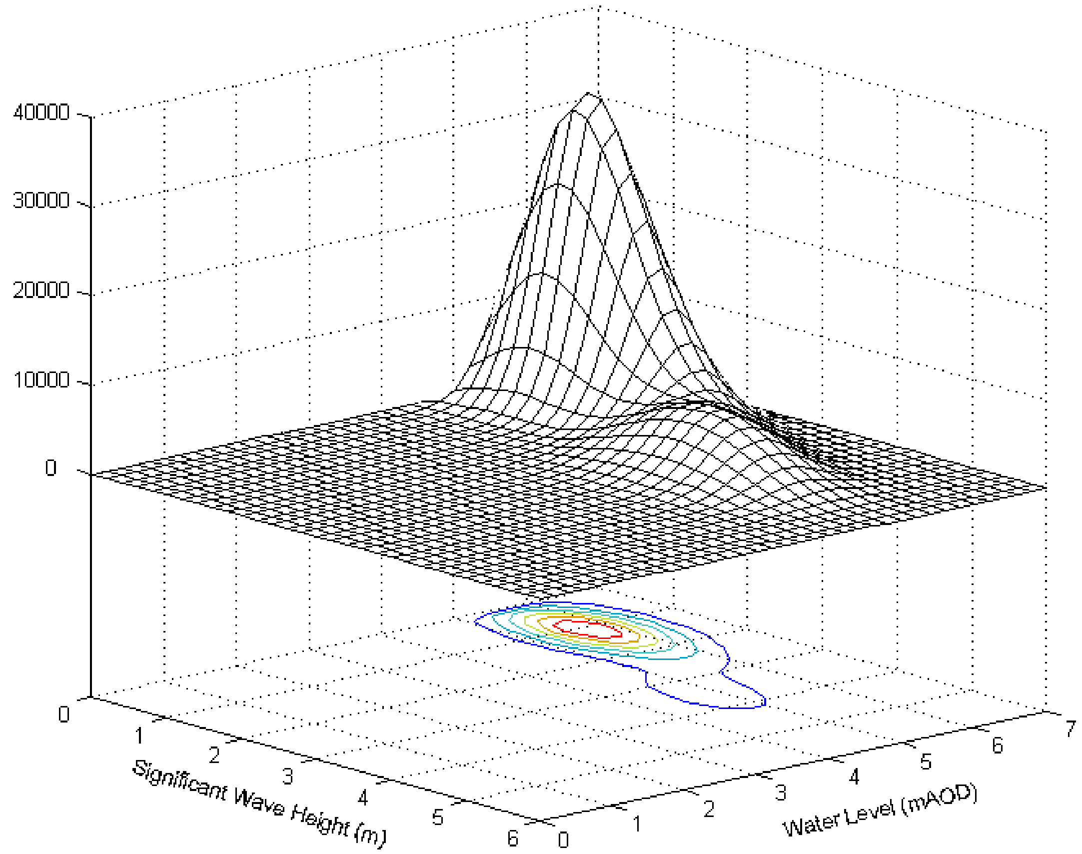


Figure 28 Damage conditional on load – A typical output from the RASP ILM as applied to the North Wales case study. Similar plots could be developed for any joint loading parameters

At the ILM and DL further insight can be gained by comparing the defence system failure density function (Figure 18) with the damage distribution (Figure 28). The resultant plot – taken from the North Wales example – is shown in Figure 29. This provides useful feedback to the decision-maker. In particular, it demonstrates the difference between the loading conditions considered most likely to lead to defence failure and those conditions that contribute most to risk. Although these points may not be co-located, the significant difference between these points for the Towyn example suggests that the fragility of the defences has been under-estimated during low return period storm events.

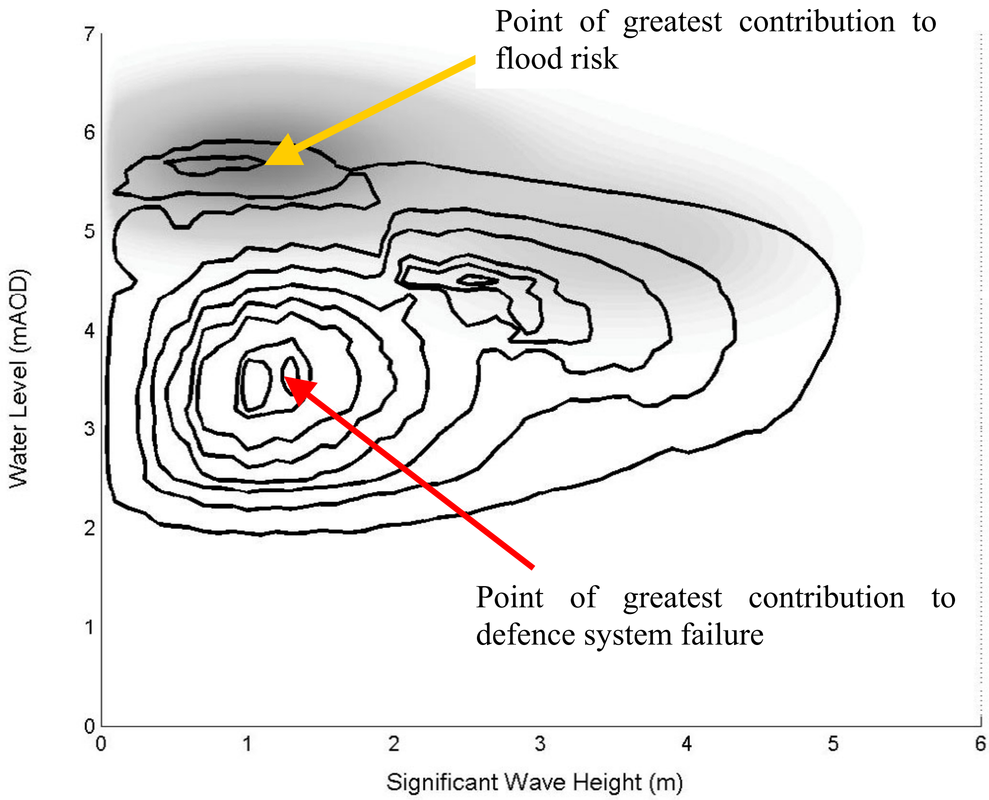


Figure 29 Contours defining the $P(D_s|H_s, W).f(H_s,W)$ surface that has been superimposed on the risk surface, with darker shades representing a greater risk contribution

A summary of key differences between the analysis tiers in terms of integrating flood probabilities and receptors terms is provided in Figure 30.

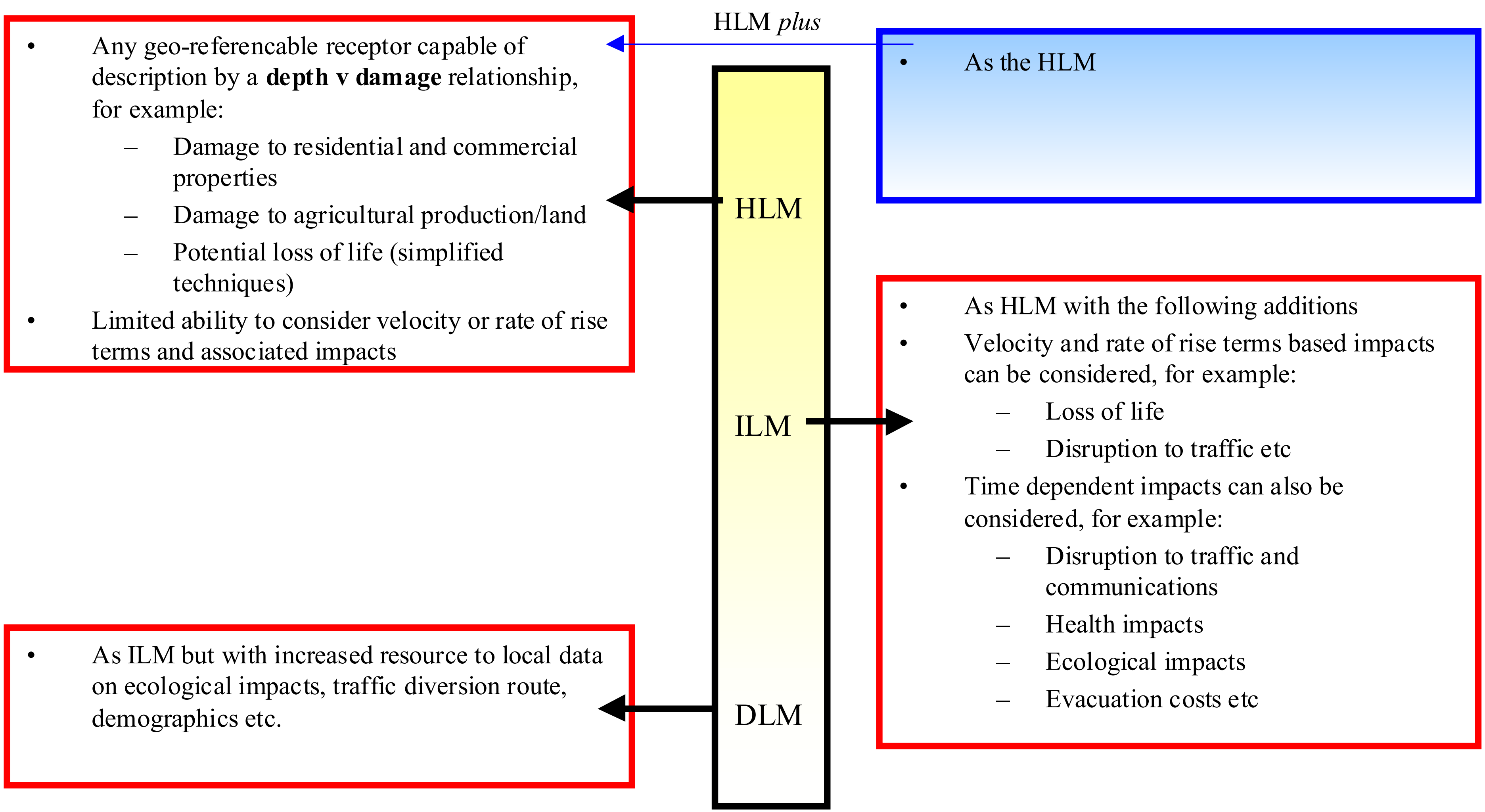


Figure 30 Receptor terms – Key differences between the analysis tiers

3.3 Summary of outputs

As seen in Table 1 the decisions supported by RASP range across the present flood management functions of the Environment Agency. In particular, they seek to support the notion that all flood management decisions should be based on consistent data regarding the spatial distribution of present day flood probabilities taking account of defences, likely loading and the floodplain topography. The way in which this information is used to inform decision-making will necessarily vary to take account of the management instruments available to each specific flood management function. For example, decisions to improve defence infrastructure taken by the Operations and Improvement function; or planning advice given by the Regulation function of the Agency (see Figure 3).

In developing each progressively more detailed tier of the RASP analysis, the basic outputs remain constant, simply the reliability of the analysis improves and hence uncertainty reduces. Therefore, regardless of the level of detail of the analysis, the RASP methodology will deliver consistent, but progressively more reliable, results including an estimate of:

- Failure probabilities for individual defences
- Failure probabilities for a defined system of the defences protecting a given floodplain
- A flood depth (velocity at the more detailed levels) versus probability relationships for an identified areas within the floodplain – referred to as *Impact Zones* (see definition below)
- Total flood risk (defined by any appropriate quantitative risk metric: e.g. number of people exposed to flooding more frequently than once in 200 years on average; expected annual damages etc) for an identified area within the floodplain (i.e. Impact Zone)
- An indication of the contribution to flood risk or risk reduction made by each defence within the defence system
- Associated uncertainties on all outputs.

The key differences in the format and detail of the output between the methods is shown in Figure 31.

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 Performance-based Asset Management System project. Equally, it is envisaged that future updates of the Catchment Flood Management Planning Guidance, Shoreline Management Guidance and supporting Modelling Decision Support Tools will utilise the RASP methodologies.

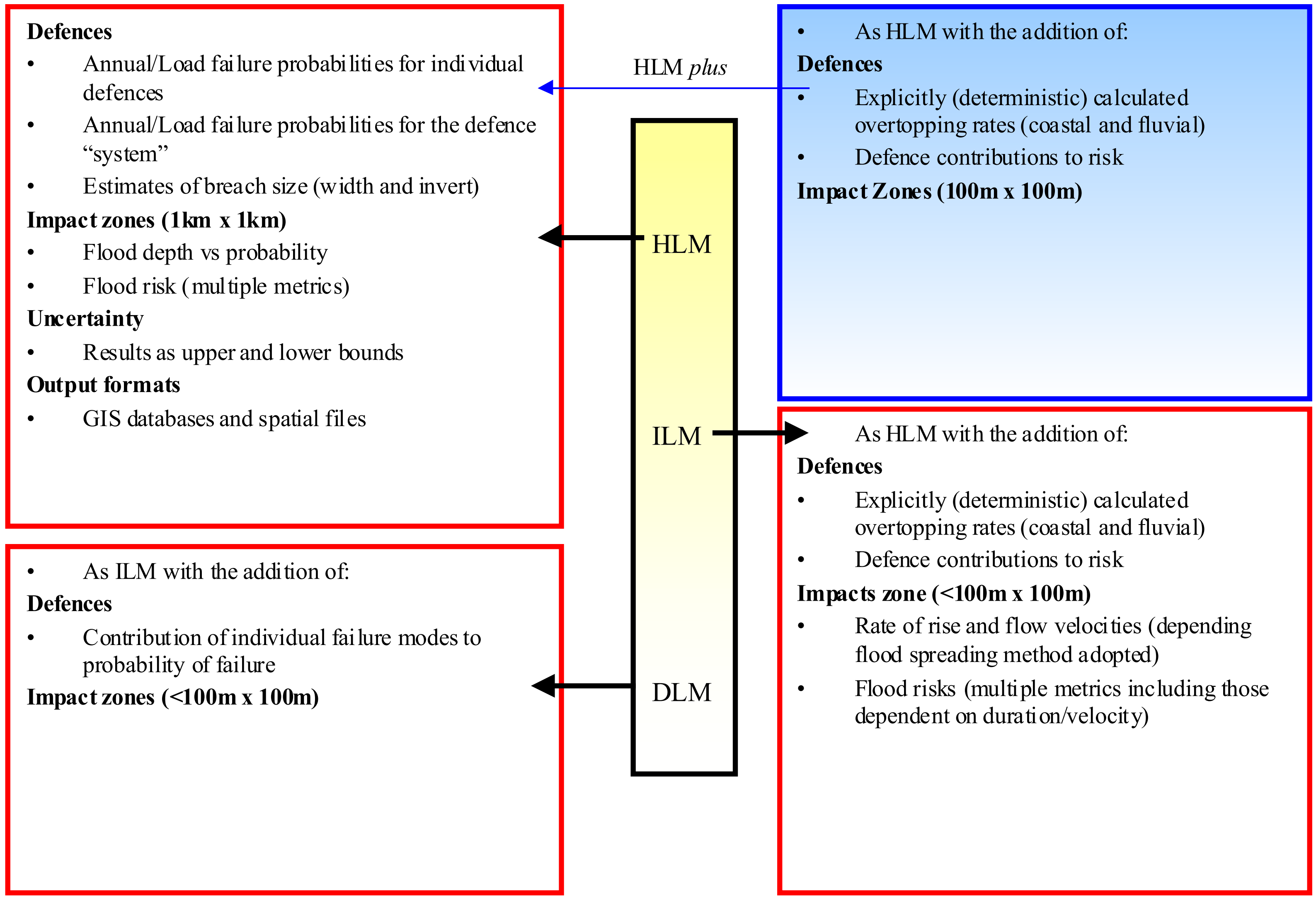


Figure 31 Summary of output parameters – Key differences between the analysis tiers

4. RECOMMENDATIONS

The RASP methods are not aimed at supporting a single decision but rather providing a consistent approach to understanding the behaviour of flooding systems taking account of multiple sources and pathways at multiple scales. The information provided by the RASP methods can therefore be used to support multiple decisions across the flood management functions in a consistent way.

Following on from the significant advances made within the RASP project a number of key recommendations have been identified to achieve rapid and effective exploitation of the methods, including:

- ***Generic research recommendations*** – to underpin general improvements and reduce uncertainty across all three tiers of RASP – see Box 2.

- ***Specific development recommendations*** – to develop specific tools to support specific decisions – see Box 3.

- ***Supporting implementation*** – to facilitate take-up in practice (including the IT infrastructure etc) – see Box 4.

These recommendations are wide ranging as RASP is a 'whole system' tool. Some are already in hand but others will need to be prioritised and justified.

Box 2 Generic research recommendations

Development of the RASP methods has highlighted the need for a number of generic improvements in our understanding of the performance of flooding systems and our ability to model them. These generic issues are summarised in broad priority order below.

Better understanding of defence failure mechanisms and deterioration process
Fundamental to an understanding of risk is an understanding of how defence and other assets perform and fail. On-going research will be required to provide improved knowledge regarding failure mechanisms and deterioration processes. This research will need to consider performance under a range of loading conditions (not simple extreme conditions); time variation in performance and uncertainties. The results should be accompanied by guidance on the visual indicators of deterioration and advice on more detailed measurements. Any algorithms developed should be capable of inclusion within a numerical reliability model as well as simplification for use in the field to support hand-based assessment of asset condition.

Use of continuous simulation data in risk analysis
An understanding of whole life performance underpins successful sustainable management. This includes knowledge of future risks taking account of various time dependent processes – including demographic change, climate change as well as asset deterioration. In recent years new methods have been developed to generate synthetic time series of loads such as river flows or tide levels. These time series methods are attractive in the context of systems reliability analysis because they enable time-dependent interactions, such as the control of flood storage schemes, to be represented. However, because flood defence system failure is associated with extreme events, it is necessary to simulate large data samples in order to include a representative sample of extreme events. Further research is required to develop efficient sampling methods so that the benefits of continuous simulation data can be realised in practical computer run times.

Systems analysis – Extending the framework
At present RASP considers only fluvial and coastal loading and linear defence assets. Achieving integrated flood risk management involves the management of all flood sources (e.g. fluvial, coastal, groundwater and pluvial influences) and responses. However, integration of flooding from sewers, groundwater and pluvial floods in flood system models potentially leads to an escalation of complexity and a multitude of models operating at a range of different scales (temporal and spatial). A conceptual framework is required to enable model-based analysis of coupled systems to happen in practice. This should lead to a programme of research for development of methodologies and case studies.

Formal comparison of methods and the reliability of the RASP levels
Little to no formal analysis has been undertaken as to the gain in reliability achieved by moving from one level of analysis to the next. Such an insight will prove crucial in selecting the most appropriate levels of analysis to support a given decision. It will also help understand the relative improvement in reliability (reduced uncertainty) achieved as the methods evolve and a better understanding of the sources, pathways and receptor terms develop. As a minimum, a structured comparison of results from the HLM, HLM+, ILM and DLM for a number of areas would provide a useful frame of reference to guide future development effort.

Box 3 Specific development recommendations

Providing support to National Flood Risk Assessments and policy guidance

The higher level RASP methods have already been be exploited to support a range of projects (NaFRA 2002, NaFRA 2004, NADNAC 2003 and Foresight). A number of significant advances can, however, still be made. Detailed recommendations are currently being formulated as part of the NaFRA 2004 study, but the key recommendations are summarised below:

- Continued improvement in the defence data, including for example the development/maintenance of a continuous line of defence information with associated critical parameters of crest level, condition and type.
- Development/maintenance of a national loading dataset, including river water levels and coastal loads.
- Include simple joint probabilities of fluvial and coastal loading.
- Consider the inclusion of a simple spreading tool to enable secondary linear defences to be considered.
- Develop better understanding and communication of uncertainty within results.
- Routinely calculate a range of additional outputs from the high level analysis including: expected annual damages, 'people at risk', whole life assessment of defence needs and costs (taking account of deterioration) and the defence contributions to risk.

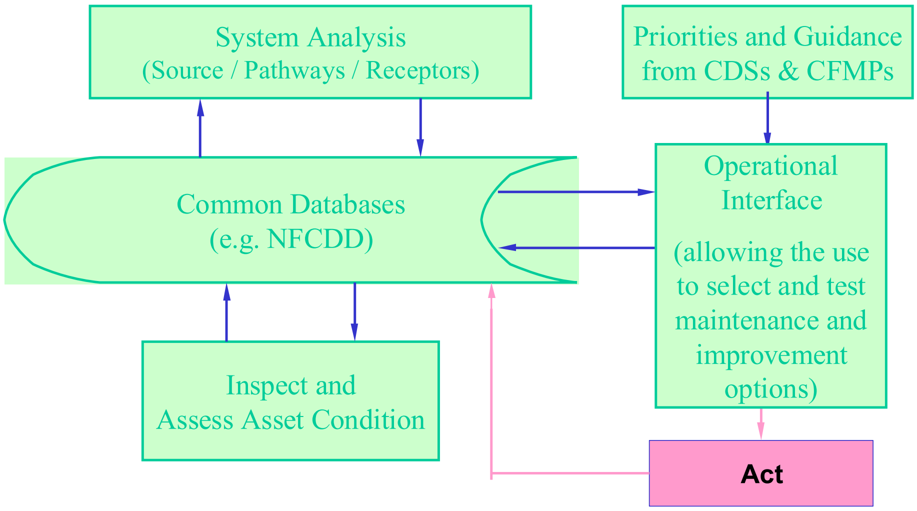
Note: Results from these national studies provide basic information that can be used by all flood management decision-makers in prioritising resources and developing policy. For example, high level national results can be effectively used to support the publication of national risk information; the bi-annual Comprehensive Spending Reviews; national classification of the Flood Warning Flood Risk Areas; regulation and high level spatial planning decisions as well as CFMPs / SMPS and CDSs. Clearly the results from the national assessment may need to be refined by more detailed analysis to support specific decisions.

**Box 3	Specific development recommendations (continued)**

Providing support to Operations and Improvements

A Performance-based Asset Management System (PAMS) is currently being developed that will provide the Environment Agency with an improved approach for deciding how to maintain and improve its flood defence assets. The overall aim of PAMS is to guide efficiently and effectively users when inspecting, maintaining, repairing, and if necessary, replacing flood defences in order to achieve the required performance and to reduce risk. As PAMS is developed it will progressively replace existing maintenance and improvement approaches with a more organised approach that utilises the RASP methods (see the figure below).

As the generic research issues discussed in Box 2 are resolved it is envisaged that these will translated into the more detailed RASP methods and then into the PAMS analysis (as detailed in PAMS Scoping Report – Environment Agency, 2004d).



The above figure outlines structure of the proposed Performance-based assessment management system – The RASP methodologies will be utilised to provide the "system analysis" element of PAMS

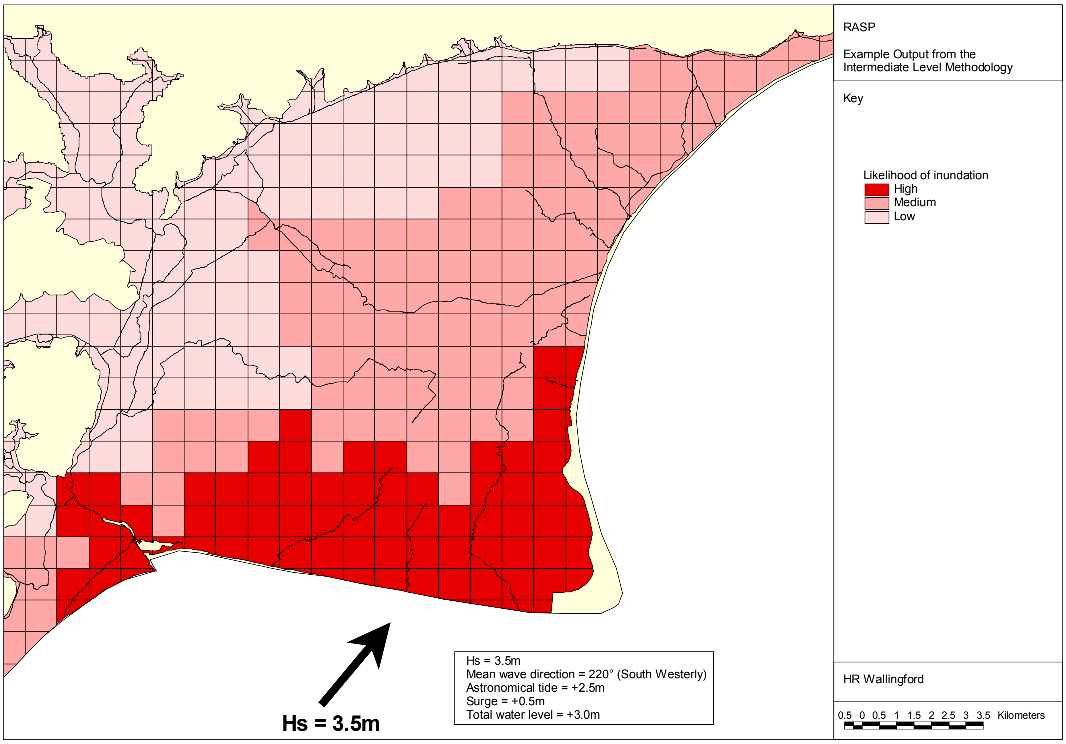
Note: A key focus of PAMS is to develop techniques for improved inspection and condition assessment in support of developing better understanding of defence fragility; that in turn can be utilised within the RASP analysis framework.

Box 3 Specific development recommendations (continued)

Providing support to flood forecasting and warning

The adoption of risk-based methods within flood forecasting and warning has been well recognised by the Agency. In flood forecasting the focus is on understanding the likely flood extent, depths and velocities for a given forecast loading condition. This simplifies the approach to some extent by reducing the need to consider multiple loading conditions. However, flood forecasting and warning is not only considered with understanding the physical flood event but crucially the management response with a view to minimising risk. As with PAMS, therefore the RASP framework presented here could be easily adapted to support a decision tool that addressed the specific issues of the flood event manager in a consistent way.

Note: In the short term it is envisaged that the results from the national flood risk assessment (e.g. NaFRA 2004) will be used to support the assessment of Flood Warning Flood Risk Areas (HR Wallingford, 2004a) - a recommendation reached by Flood Warning staff at a recent workshop. In the longer term, the decision specific tools would be needed to support the spatial definition of FWFRAs and provide real time guidance to support probabilistic "flood" forecasting; moving away from "*source*" forecasting (e.g. water level/wave conditions) to "*risk*" forecasting as recommended in recent Coastal Flood Forecasting Project (HR Wallingford, 2004c).

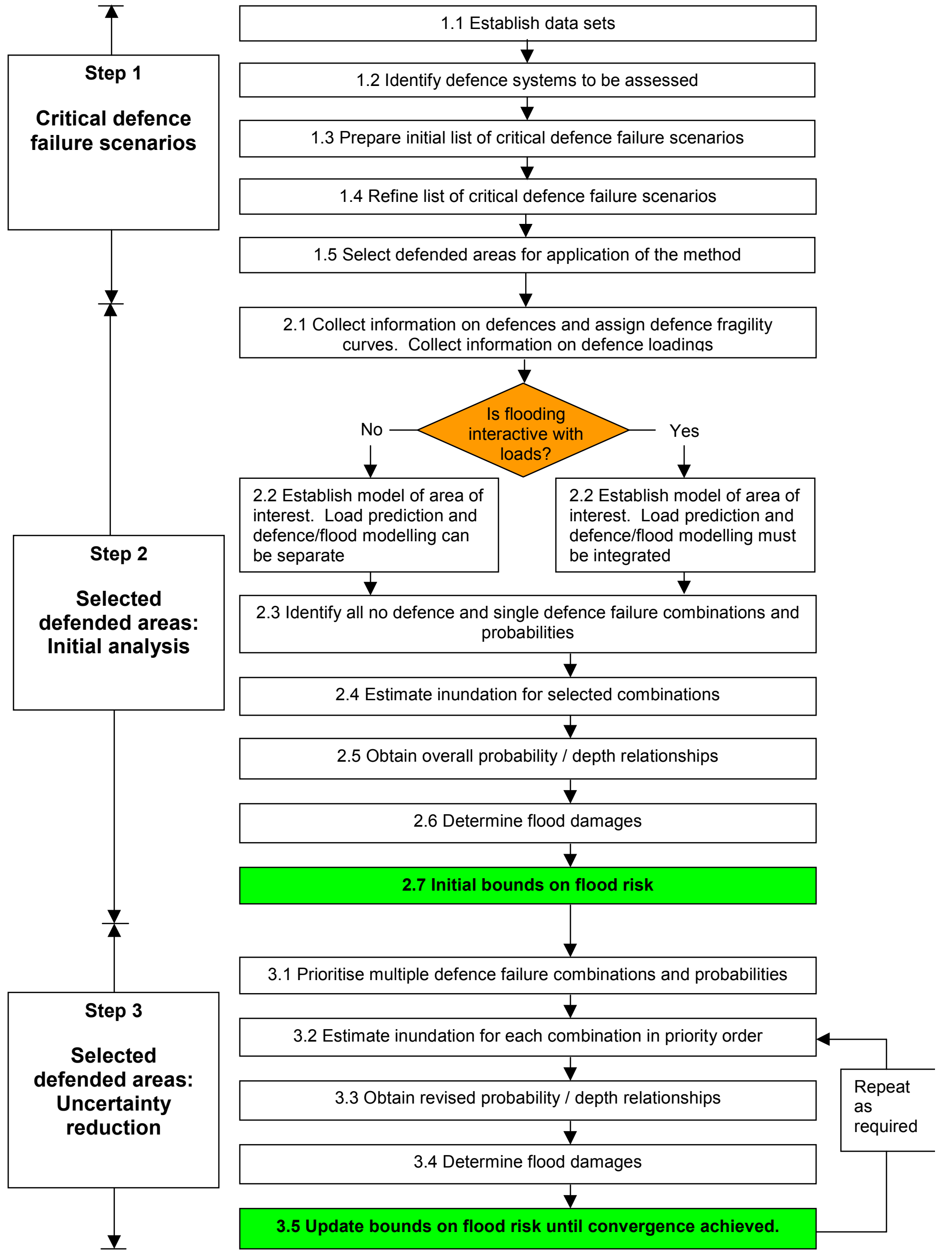


Example of a possible probabilistic inundation forecast using a RASP type approach

Box 3 Specific development recommendations (continued)

Providing support to Catchment and Shoreline/Coastal Defence Management Planning

Broad-scale models are already applied for flood risk assessment as part of the Catchment Flood Management Plan (CFMP)/Shoreline Management Plan (SMP) and Coastal Strategy study process and supported by the Modelling Decision Support Framework (MDSF - Environment Agency, 2003). However these methods failure to recognise the role of defences and the notion of flood system management. It is envisaged that the existing MDSF tool will be developed to adopt the RASP concepts. It is envisaged that the resulting tool will be developed and proven on a series of case studies, including river, estuarial and coastal situations.



A simple flow chart showing how the RASP methods maybe integrated within MDSF.

Box 3 Specific development recommendations (continued)

Providing support to regulation of development

There are three primary factors when considering the sustainability of a development proposal:

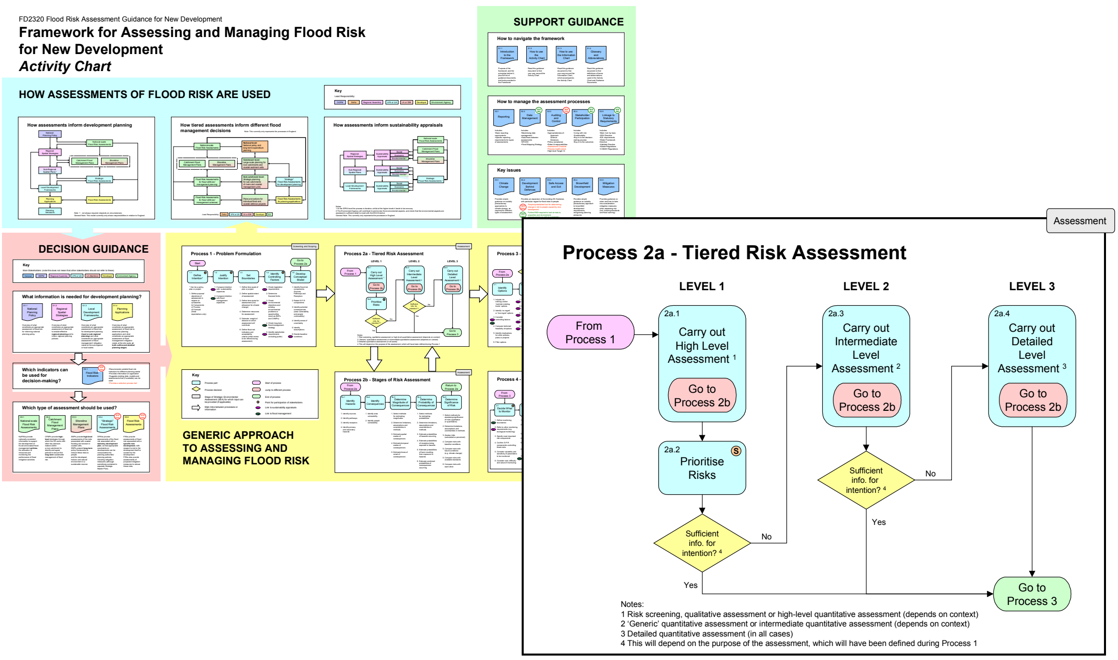
1. Is the development within the natural floodplain for a given return period storm.
2. Change in risk within development boundaries – taking account of protection afforded by defences and receptor exposure and vulnerability.
3. Change in risk remote from the development – taking account of changed run-off, the protection afforded by downstream defences and receptor exposure and vulnerability.

The methodologies developed through RASP will directly support points two and three above. The level of detail will, of course, depend upon the nature of the development site(s).

In the short term it is envisaged that the NaFRA, supported by RASP, will provide a useful tool for exploring national and regional development plans and the implications of proposed future floodplain development.

In the longer term, as outlined in Box 2, significant work will be required to move towards integrated flood management that includes drainage and groundwater as well as fluvial/coastal issues. It is envisaged that a key element of this work will be to extend the RASP methods to consider impacts arising outside of the natural floodplain.

Note: The linkage between RASP and the regulation role of the Agency is currently being developed as part of a broader study, R&D Project FD2320, led by HR Wallingford titled *Risk Assessment for New Developments.*



Risk assessment and management framework currently under development to support new developments embeds a tiered risk assessment methodology and the RASP approaches

Box 3 Specific development recommendations (continued)

Developing hierarchical methods in support of erosion management

The behaviour of coastal defence structures and systems has much in common with flood defences on the coast. There are, however, significant differences in terms of the way defence failure leads to damage. In the long term, coastal morphology has a very important role in modifying the probability of system failure. Further research is required to develop and demonstrate how risk assessment methodologies can support erosion management.

It is envisaged that a tiered set of risk assessment methods will need to be developed to complement the methods developed here. These will include a simple high level method, for rapid assessment of the risk of coastal erosion, based on readiliy available datasets, and more detailed methods that can be used for strategic appraisal and design of erosion management options

The tiered approach will be informed by existing methods (for example developed by the North West Coastal Group, Liverpool Bay Coastal Group and Suffolk Coastal Group). As with the methods for flooding, the associated uncertainty at each tier will differ, reflecting the nature of the decision to be informed and the timescale they are expected to consider.

Estimation of the probability of coastal erosion requires consideration of: long term (and broad scale) shoreline evolution (geomorphology, shore platform lowering etc), local fluctuations in beach level, the exposure of coastal structures and their reliability, and the susceptibility of the coast to retreat or landsliding. A broad view of the approach that may be adopted is provided below:

Long-term shoreline evolution: This will range from simple methods based on the geomorphological / morphological appraisal techniques, the development of simple conceptual models of landform behaviour to quantified broad scale process-based coastal evolution modelling.

Local fluctuations in beach levels: These will use a combination of local knowledge, statistical analysis of beach profiles and beach scour. This would build on the ongoing research work into the relationship between cliff recession and beach levels undertaken by Dr Lee on the North Norfolk and Suffolk coasts.

Reliability analysis of coastal structures: The concept of defence fragility and the heirachical methods developed in the RASP project will be utilised. Perhaps one important extension, particularly at the high level, will be to examine historical analogues to develop guidance on the post-failure realtionship between coastal defences and recession rates (e.g. the Whitby – Sandsend cliffs)

Susceptibility of the coast to retreat or landsliding: This will make use of methods developed by the research team as part of MAFF funded research on soft coastal cliff recession prediction and management. Included here will be methods based on expert geomorphological appraisal, statistical methods and geotechnical analysis (Lee and Clark, 2002).

It is also likely that future work will be required on the consequences of coastal cliff recession, including direct economic damage (e.g. loss of cliff-top houses), indirect economic losses (e.g. disruption to transportation or business) and the social disruption to coastal communities resulting from the progressive abandonment of eroding coasts (where adopted). It is envisaged that the assessment of direct and indirect economic losses will utilise probabilistic methods established by Hall et al 2000, Sayers et al, 2004).

Box 4 Supporting implementation

Data improvements

Delivering tiered risk assessment in practice relies on access to common databases and the two way flow of data and results/updates. Access to reliable and appropriate data is crucial in making reliable judgements. However, data collection is expensive and inappropriately collected data can be of little use to a decision-maker. The explicit handling of uncertainty within RASP provides a powerful tool for exploring the value of different data collection activities. In the absence of a quantified analysis, experience of the NaFRA studies highlights a number of datasets as fundamental to effective flood management, including (but not limited to):

- Topography and land use data (based on integrated national, regional and local data)
- National wave and water level loading data
- On-going improvements in defence data (particularly basic parameters of location, type, crest and toe level, slope and raised height).

Continued effort into the development of datasets that are able to evolve as new data is gathered will be crucial to underpin our ability to analyse risk and monitor changes in risk with time.

IT support and an open system architecture

As RASP is developed and embedded with specific decision support tools, as discussed in Box 2, it will be important that the IT system supports the use of different analysis modules (for example different inundation models) and enables the different tools to utilise and update common data bases. These two issues will determine the success or otherwise of the vision set out by RASP. Brief discussion of each issue is provided below.

Open architecture – Development of an open architecture framework that functions across all flood management will be a significant task. The first task will be to include a logical map of the software elements and their linkage and use of common resources such as NFCDD and analysis modules. It will also include the user interface, including data entry, modification and display and the level to which these can be common across all tools as well as identifying those items that are specific to each decision.

Common databases - With respect to data management, asset managers and inspectors provide the base defence information for all other Agency functions. This is a vital role and requires asset managers to be aware of the information needs of others and indicates the need for a common database system. These common databases also need to be capable of receiving added-value information on risk and asset risk contributions. NFCDD provides an excellent starting point, supported by other cross-Agency data held by the Technology Group at Twerton, and their importance is likely to increase significantly as all RASP supported Agency tools begin to draw upon them.

5. CONCLUSIONS

The need for improved risk assessment methodologies to support better flood risk management was the primary driver in support of the RASP project. The methods that have been developed will help the Environment Agency and Defra to understand more about how flood defences affect flood risk. In particular, they provide a significantly improved ability to predict the spatial distribution of both the probability and consequences of flooding, taking the influence of defences into account. The RASP methods will therefore directly support the Agency and Defra in better management of risk.

The RASP methods enact the basic cross-government framework for environmental risk assessment and risk management (DETR, 2002) as well as addressing the specific needs of flood and erosion risk management (Environment Agency, 2001). By enacting these frameworks within a generalised hierarchical methodology that combines the *sources* (e.g. the waves and water levels), *pathways* (e.g. the defences) and *receptors* (e.g. the people and property) of risk, RASP provides an important step towards an ability to manage flood risk in a more integrated way.

All tiers of the RASP risk assessment methodologies reflect the data availability and constraints of temporal and spatial scale placed upon on the analysis.

Each tier of the RASP hierarchy considers the flooding systems, where a flooding system is defined by its:

- Loading conditions (coastal waves and surge, and fluvial flows and water levels)
- Linear natural and man-made flood defences
- The performance of the linear defences taking account of both overtopping/overflow and breaching of defences that reflects their type and condition
- The inundation of the floodplain (and propagation of water across the floodplain) following an overtopping or overflow event.

Similar results, but progressively more reliable, are obtained from each tier of analysis, with primary outputs including:

- For each defence within the flooding system
  - A description of defence performance under load (overtopping and breach failure)
  - The contribution of each asset to risk and risk reduction

- For each Impact Zone within the flooding system
  - An estimate of the probability of flooding within a given area of the flood plain (*Impact Zone*) taking account of all scenarios of load and defence failure combinations.
  - A range of risk metrics, such as expected economic damage, for each Impact Zone

The hierarchical approach enables the results from different tiers to be readily aggregated to regional and national scales.

The RASP methods can be used in developing strategies and policies enabling scenarios of change (for example flood frequency, investment in flood defences or floodplain occupancy) to be readily incorporated and analysed.

The utility of the RASP methods have been demonstrated at national-scale through the National Flood Risk Assessment 2002, at a regional scale through a coastal case study in North Wales and a fluvial case study in Burton-on-Trent. Less completely, but equally usefully, the merits of a more detailed analysis have been explored through a case study on the Caldicot Levels.

Over the coming few years significant effort will be required to translate the RASP methods into specific tools to support flood management decisions in practice and this is already progressing through the NaFRA, MDSF and PAMS programmes. These activities will enable a comprehensive picture of the likelihood of flooding and associated risks to be established, taking account of a wide range of loads and wide range of defence failure scenarios. This will help deliver effective integrated management in practice.

6. ACKNOWLEDGEMENTS

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