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PAMS (Performance-based Asset Management System) – Phase 2 Outcome Summary Report

Project: SC040018/R1

Flood and Coastal Erosion Risk Management Research and Development Programme

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Our work includes tackling flooding and pollution incidents, reducing industry's impacts on the environment, cleaning up rivers, coastal waters and contaminated land, and improving wildlife habitats.

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E: enquiries@environment-agency.gov.uk.

Author(s):
Dr Mervyn Bramley
Ben Gouldby
Anthony Hurford
Jaap-Jeroen Flikweert
Dr Marta Roca Collell
Paul Sayers
Jonathan Simm
Michael Wallis

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Research Contractor:
HR Wallingford Ltd., Howbery Park, Wallingford, Oxfordshire OX10 8BA Tel: 01491 835381.
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Environment Agency's Project Manager:
Geoff Baxter, Evidence Directorate

Theme Manager: Geoff Baxter, Sustainable Asset Management (SAM)

Collaborator(s):
Halcrow
John Chatterton and Associates
Royal Haskoning

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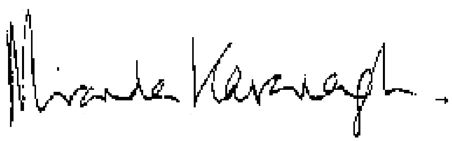


Miranda Kavanagh

Director of Evidence

Executive summary

What the Phase 2 project set out to do

1. Managing flood defence assets[1] to ensure their acceptable performance over time is a considerable challenge. The PAMS project was established to develop test and document a suite of methods and tools which could deliver step-by-step improvements in the way the Environment Agency and other operating authorities manage flood and coastal defence assets. In doing this, the so-called **P**erformance-based **A**sset **M**anagement **S**ystem (PAMS) would provide evidence to support asset managers and practitioners across the delivery of the entire asset management cycle, in particular in planning when and how to make asset management interventions. The **P**erformance-based **A**sset **M**anagement **S**ystem is thus intended to be a suite of methods and tools to support performance-based asset management, and not an asset management software system in itself.

2. The main issues that the PAMS project was required to address were:

(a) difficulties in achieving a meaningful assessment of the condition (including the effects of deterioration of elements) of assets through monitoring or inspection;

(b) the complexity of each asset system with a number of different components, all of which contribute to its state and the way it performs in a flood event;

(c) the potential complexity of the relationship between the condition of individual assets or the overall system and its performance in response to the 'loading' from flood events;

(d) difficulties in assessing the improvement in performance resulting from interventions ranging from routine maintenance (such as clearance of vegetation) to major refurbishment or change to individual assets (such as heightening of a waterfront wall).

3. The specific objectives defined when the project was originally established in late 2004 were:

1. to provide *guidance for asset inspection and condition assessment* linking asset function, condition and performance, and indicating whole-life risk through the use of simplified deterioration models;
2. to develop the *framework and tools for decision support*, drawing on existing appraisal tools, and provide guidance for options appraisal or decision support for asset management and related plans;
3. to do three *case studies* with business staff and real data and systems to develop and demonstrate the methods and to provide reports, training materials and tools to enable implementation;
4. to *link asset management and performance-based principles* (such as probability of breach or overtopping) more fundamentally to ongoing work in National Flood Risk Assessment (NaFRA) or National Assessment of Defence Needs and Costs (NADNAC).

[1] Flood defence assets include channels, walls, embankments, gates and pump systems – and the asset systems they compose.

4. The project had to link in with the ongoing development and implementation of the Environment Agency's own asset management policies and procedures in line with its Asset Management Strategy. It was also required that as far as practicable the products from the PAMS project should be able to be adapted to support coastal erosion management (i.e. Coast Protection). However, was not part of the PAMS Phase 2 project.

How the project team went about the project

5 The Phase 2 project was carried out by a collaborative team of researchers and practitioners led by HR Wallingford Ltd and working with Environment Agency and coastal authority staff. Work activities ranged from (a) applied research including field studies, (b) development of procedures, prototype models, guidance and recommendations, to (c) helping to implement specific deliverables.

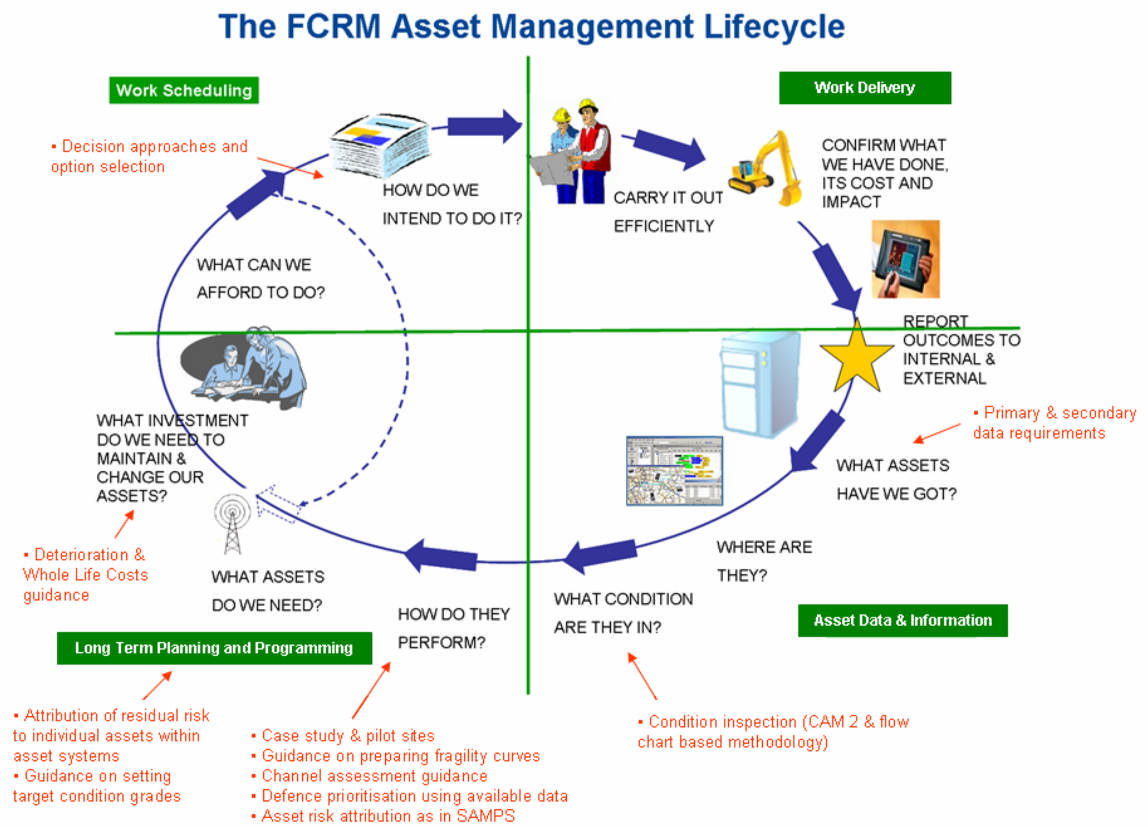
6. The project team developed a series of high level principles to guide the workThese principles are:

- adopting a tiered approach to risk assessment, with actions and level of detail proportionate to the estimated risks;
- understanding the potential failure modes of assets in order to focus on appropriate inspection, risk assessment and management activities;
- understanding the performance of an asset across a range of potential loadings including its resilience to loadings beyond the design standard;
- adopting a systems approach to focus attention (inspection, investigation, intervention) on weak points in the overall asset system;
- being able to attribute flood risk to specific defences and channel lengths;
- making decisions about assets based on an appreciation of whole-life costs.

What the project delivered

7. The products (tools, techniques and guidance) generated by the Phase 2 project are listed at the end of this executive summary (and repeated in Appendix 3). Each product is designated as: **E**mbedded (**E**) into practice (in the Environment Agency but not necessarily other operating authorities); working tools **D**eveloped (**D**) and ready to proceed to embedment; or **R**esearch (**R**) carried out to produce and test a prototype product. This reflects the staged and long-term process of producing outputs for practitioners and implementing them into business use. The diagram below indicates where some of these products contribute to the FCRM asset management lifecycle.

8. Within these work packages can be found a series of 14 Measured Steps Forward (MSFs) which were added to the project at the request of the Environment Agency's Asset System Management (ASM) business. This was to enable the early and staged embedding of some parts of the PAMS risk and performance framework into Environment Agency tools and procedures. Some of the project deliverables are thus already embedded into Environment Agency operational practice (and have the potential to meet the needs of other Operating Authorities). For example, one MSF identified flood risk and performance related issues for the gap-analysis used in the ASM programme to deliver System Asset Management Plans (SAMPs) for each of the Environment Agency's 3000 asset systems.



Value of the pilot projects

9. Three pilot projects were carried out to ensure that practical issues of real asset systems, limited data and information and asset managers were addressed. The chosen pilot sites were: (1) the Thames estuary (linked to the TE2100 strategy project) representing an estuarine defence system, (2) the Great Eau river (Lincolnshire) representing a channel-dominated fluvial system, and (3) West Bay (Dorset) representing a coastal defence system. A fourth pilot was independently commissioned by the Humber strategy team to examine Sunk Island on the North shore of the outer Humber estuary. The 'integrated' approach enabled us to study the complete process through which the asset management planning must pass in order to deliver clear conclusions on management options. The pilots have illustrated how the PAMS tools are particularly helpful in making investment decisions on the one hand for high risk or complex systems and on the other in situations where maintenance of assets might potentially be withdrawn.

10. The pilot projects covered:

- initial assessment of the management issues and available data for the system;
- setting up a GIS system to reflect the local situation in sufficient detail to assess and evaluate flood risk in the system and its components;
- carrying out any necessary further survey or engineering site investigation;
- adjusting input parameters and models accordingly to assess system or asset performance and to attribute and evaluate flood risk;
- providing decision support information for planning or interventions.

11. Each pilot system had quite specific characteristics and management issues. The benefits (Appendix 3) were delivered through the logical application of appropriate tools and techniques. In all cases, Asset Managers developed an improved understanding

of their particular asset system which they felt enabled them to allocate asset management resources better.

12. Thus future benefits from the Phase 2 project can derive both from the use of new or improved tools, techniques or methods, and directly from Asset Managers who develop progressively better understanding about their asset systems.

Improved guidance for asset inspection and condition assessment (Issue (a))

13. Here the issue was the subjectivity of the (2005) visual inspection method for asset inspection. An evidence-based and less subjective approach was developed for asset condition assessment, building on the potential failure modes of each asset type. An essential link between condition and performance was thus established. This enabled the development of a rational series of performance features for inspection of each main asset type that was linked back to the characteristics of their failure modes.

14. An improved approach to asset condition assessment, with the application of performance features, has been developed with Environment Agency ASM and **e**mbedded (**E**) in its updated Condition Assessment Manual (CAM2). A series of *Flow charts for* assessment of performance features has also been developed for embankments, vertical sheet piled and gravity walls, covering the majority of Environment Agency asset types. Testing of the flow charts on 139 assets around the country led to a proposed method for calculating overall condition grade scores (the worst performance feature score) which is compatible with scores obtained by the traditional visual approach.

15. The project team recommends **d**eveloping the flow charts and method further, along with carrying out more research to validate the link between visual condition assessment and performance, in particular to develop a more robust link between condition grade and overall probability of failure of the asset (as now being calculated by the RAFT field assessment tool – see paragraph 26).

16. A further part of the concept developed by the team is that of the inspection process triggering appropriate action. This action can be direct intervention in the asset or more detailed expert inspection. Guidance on action triggers have been added as footnotes to the inspection flow charts.

Improved understanding of asset deterioration (Issue (a))

17. Here the issue was lack of clear guidance on asset deterioration. Time curves for assets to deteriorate from one condition grade to another and maintenance costs were also prepared in this project, to assess the likely timing of the need for interventions and to help calculate whole-life costs. These are being further developed under a separate research project on deterioration and whole-life costs.

Methods of assessing asset performance under load (including fragility) (Issue (c))

18. Here the issue was to improve representation of the way that asset performance in terms of resilience or failure responds to loading (principally related to water level or waves). This can be a very complex matter. Thus the effort put into assembling evidence on any asset's performance under load must be (a) proportionate to the perceived risks of asset failure (likelihood and consequence) and (b) fit for purpose in assessing the potential options for intervention. The project evaluated and tested a range of approaches to describing asset response, including traditional deterministic

methods (single value of loading), generic fragility curves and a reliability tool developed under the FRMRC and FLOOD*site* consortia projects.

19. The project team recommends that a tiered approach is **d**eveloped (**D**) with guidance covering the spectrum of methods from simple qualitative screening to bespoke structure-specific probabilistic assessments. The project team recommends an *appropriate* use of probabilistic methods in the description of asset response, particularly for decision support with management of complex, high consequence or costly systems and where the decision is finely balanced or critical. 20. Fragility curves, which present the way that the likelihood of asset failure increases with increasing load, are now utilised in several other fields of risk-based asset management. They are important in their own right in flood risk management as a means of understanding and presenting evidence on asset response across a range of loadings. They were adopted in generic form prior to PAMS in the RASP methodology developed for national flood systems analysis (NaFRA) to represent the fragility of defences in various condition grades. Demonstration of the appropriate application of refined structure-specific curves to asset management of flood defences in this project has helped to develop a better understanding of how and when to utilise fragility methods.

21. The Phase 2 project has produced guidance on how to prepare asset-specific fragility curves. This approach has been trialled successfully on the West Bay and Thames pilot sites, where it is embedded in the TE2100 assessment methodology for asset refurbishment, change or replacement. The Phase 2 guidance shows, not surprisingly, that bespoke curves for specific assets can be very different from generic curves. The project team recommends **d**evelopment (**D**) of the guidance as a working tool, in particular adding more failure modes to the structure-specific fault trees, especially those requiring numerical models (e.g. slope stability of flood embankments). However, it should be supported by visual and expert asset inspections where necessary.

22. Such analyses do not however help in targeting localised weak spots (e.g. at abutments or in non-homogeneous materials) which is why they should be supported by effective site-specific visual and expert (where necessary) asset inspections.

Channel condition assessment and management (Issues (a) and (c))

23. As rivers and watercourses are frequently also flood defence assets, the Phase 2 project established condition grading methods for channels. The appropriate management of channel roughness and cross-section (which could involve either reprofiling or blockage removal in channels) leads to reduced flood risk by maintaining flood water levels within defined bounds. The Phase 2 project has provided new *guidance on visual channel condition assessment* which is now **e**mbedded (**E**) in the Environment Agency's CAM2.

24. The project has also established outlined procedures for the newly available Conveyance Estimation System (CES) to help in the planning of maintenance for a channel whose performance is limited by channel roughness or blockage. 25. Use of this approach to evaluate different channel maintenance strategies on the Great Eau; the pilot showed the effects of maintenance on water level regime, and provided evidence to optimise flood risk reduction within a maintenance budget.

Risk and performance based framework for decision-making (Issues (b) and (d))

26. Here the underlying issue was how to compare the effectiveness of different asset management interventions and, to quote UK government guidance on risk assessment, to ensure that 'the level of effort put into assessing each risk is proportionate to its priority (in relation to other risks) and its complexity (in relation to an understanding of the likely impacts)', (DETR, 2000). The approach developed under the Phase 2 project, as with NaFRA and Catchment Flood Management Plans, has been to use flood risk as the 'common currency' for comparison. Computational analysis using RASP-based methods has been developed and tested for analysis of performance of flood risk management systems, in particular the *attribution of flood risk to individual assets* (or lengths of linear defence assets). As a consequence of understanding the value of risk attribution within asset systems, a simplified approach to assessment of asset criticality has also been developed, the RAFT tool which enables field based assessment of asset criticality without reference to computational modelling.

27. Asset fragility (representing the risk of failure by breaching) and asset crest level and profile (representing the risk of overtopping) provide an essential input to assessments of risk attribution. They enable a comparison of the impacts on the overall flood risk managed by an asset system with the various assets in that system being in different conditions. Generic fragility curves (para.18) enable a first estimate of this. Experience with the pilot projects showed that preparation of bespoke curves for critical assets in a system is both achievable technically and can significantly improve the risk management decision.

28. With risk attribution, it is possible to *assess the impact of different asset management strategies on risk reduction* (or in the case of do-nothing scenarios, the risk increase) within a whole asset system and the risk reduction associated with the interventions to various assets. These changes in flood risk can then be compared with the costs of these intervention using established cost-benefit approaches.

29. Multiple asset management strategies can be considered in this way, depending on the nature and timing of various interventions that might be made. These different routes and their associated costs and benefits can be termed 'decision pipelines. Clearly selecting the timing and nature of asset improvements has to take account of factors such as asset deterioration and climate change impacts. The Phase 2 project recognised that automated methods of solution searching may be used in the long term, but it was concluded that, for the time being, asset managers will prefer to be in direct control of selecting the preferred asset management solution. They will also need to be aware of the extent to which funding availability may also constrain the range of solutions that can be considered.

30. The project team recommends **r**esearch (**R**) is carried out to produce software tools and a guide on for the appropriate application of risk attribution to in planning asset management interventions. (Note that this is not a 'one size fits all' recommendation for all assets). We also recommend that the basic concept of flood risk attribution is better utilised by Government and all operating authorities to support both the management and the public understanding of flood defence assets and asset systems. We also recommend that the flood risk attributed to an asset is made available as a field within the Environment Agency's NFCDD or its database successor within any future supporting tools for Asset Management.

Asset management for coastal erosion (Coast Protection)

31. With regard to management of coastal erosion (para 4), the Phase 2 project specified and fed into a scoping study to examine the future requirements and needs for extending the risk and performance based approach to the management of coastal flood defence and erosion protection assets. The primary focus of this 'Scoping Study for Coast Protection Asset Management' (completed early 2009) was on integrating the numerical approaches and the methods used for estimating the probability of (a) shoreline recession and (b) flood risk at the coastline. (These are respectively the RACE and RASP methods). It concluded that there are opportunities for the use of improved tools and techniques for management of asset systems and for individual assets dealing with coastal erosion. Some aspects of these are common with flood risk management assets and the resulting recommendations for future development and research presented in this report have drawn in these common aspects. Other recommendations are specific to coastal erosion risk management and are being promoted in separate parallel proposals within the Defra / Environment Agency Joint Science Programme.

Overall conclusion

32. The PAMS Phase 2 project has successfully developed and piloted a range of tools, techniques and guidance to enable asset managers to understand how the performance of flood defence assets and asset systems respond (a) to flood water loading and (b) to management intervention. The significance of these methods is demonstrated by their positive albeit different effects in each of the pilot studies as well as by the way in which some have already been embedded into practice. The project team is confident that the range of methods is both necessary and appropriate.

33. Six *high level principles* (see paragraph 6) have been established which underpin these methods. In particular, it is clear that flood risk attribution is a powerful concept for focussing management resources on assets associated with higher flood risks. And by adopting a tiered approach, performance-based decision support can be provided at all levels of planning and assessment associated with flood risk asset management ranging from broad screening of systems to detailed site-specific analysis.

34. The PAMS project has met the objectives listed in paragraph 3 above. This Summary Outcome report details how the project has met these objectives – developing approaches, methods and guidance for asset assessment, systems analysis, flood risk assessment/attribution and decision support; testing them through case study application and linking the underlying performance-based principles to ongoing work such as National Flood Risk Assessment (NaFRA) and National Assessment of Defence Needs and Costs (NADNAC).

For example,

Specific Objective	Product
To provide *guidance for asset inspection and condition assessment* linking asset function, condition and performance, and indicating whole life risk through the use of simplified deterioration models	- An updated Condition Assessment Manual – including channels, - improved guidance for asset inspection and condition assessment. It has also developed a set of flow charts that in the future could further improve inspections that would be more closely related to performance-based risk assessment. - Guidance on deterioration rates for different asset types for whole life asset plans
To develop the *framework and tools for decision support*, drawing on existing appraisal tools, and provide guidance for options appraisal or decision support for asset management and related plans;	- A conceptual model for decision approaches and option selection that could fit into the FCRM framework - A flood risk assessment field-based tool (RAFT) – providing a tool to support decision-making for further analysis or data collection - Guidance for managers on setting target condition grades
To do three *case studies* with business staff and real data and systems to develop and demonstrate the methods and to provide reports, training materials and tools to enable implementation; and	- Guidance on the use of information on asset residual risk attribution to linear defences during the development of System Asset Management Plans - Demonstration of the benefits of linking performance-based principles to asset management through the development of site specific fragility curves for pilot sites
To *link asset management and performance-based principles* (e.g. probability of breach or overtopping) more fundamentally to ongoing work in National Flood Risk Assessment (NaFRA) or National Assessment of Defence Needs and Costs (NADNAC).	- A method of flood risk systems analysis to provide decision-makers with information on risk attribution, residual risk, and defence prioritisation.

The ‘product list’ below shows which specific objectives correspond to the products delivered, its location in the reporting and its ‘designation’; (**E**), **E**mbedded into practice (in the Environment Agency but not necessarily other operating authorities); working tools (**D**), **D**eveloped and ready to proceed to embedment; or **(R) R**esearch (see paragraph 7).

Product list (explanation of designations given in paragraph 7 above)

Project ref.	Specific objective	Product	Location of description of Product in this 'Outcome summary report' or other project reports	Designation
WP1	3	Case Studies	See report SC040018/SR2 Pilot site studies	**E**
WP2	2	Early defence prioritisation using available data	Project record.(interim deliverable)	**R**
WP3	1	Condition inspection methodology, including:	See report SC040018/SR3 Development testing and delivery of a condition inspection methodology.	**D**
	1	Flow charts for performance assessment of linear defences	Focus Product 3.1	**D**
	1	Methodology for converting performance feature scores into condition grades	Focus Product 3.3	**D**
	1	Questions to trigger more detailed inspection or interventions	Focus Product 3.4	**D**
WP4	2	RAFT Risk Assessment Field-based Tool	Focus Product 6.1. Detailed description in See report SC040018/SR4	**E**
WP5	2	System analysis tool for risk attribution and defence prioritisation	See report SC040018/SR4 Flood defence systems analysis – methods tools and decision support	**D**
WP6	2	Conceptual model for decision approaches and option selection	See report SC040018/SR4 Flood defence systems analysis – methods tools and decision support	**D**
WP7	2	System development and delivery	See report SC040018/SR4 Flood defence systems analysis – methods tools and decision support	**D**
WP8	2	System architecture and data management	See report SC040018/SR4 Flood defence systems analysis – methods tools and decision support	**D**
MSF1	1	CAM2: Update of the Condition Assessment Manual	Focus Product 3.2	**E**
MSF2	1	Inclusion of channels in the revised condition assessment manual	Focus Product 5.1	**E**

Project ref.	Specific objective	Product	Location of description of Product in this 'Outcome summary report' or other project reports	Designation
MSF3	2	Channel management guidance for Environment Agency Asset Systems Management	Focus Product 5.2. Focus Product 5.3	**E**
MSF4	2	Channel management guidance for Environment Agency Operations Delivery	Focus Product 5.2. Focus Product 5.4	**E**
MSF5	2	Primary and secondary data requirements for PAMS	Chapter 8 and Appendices 8 and 9 of this report	**D**
MSF6	2	Asset residual risk attribution	Project record (interim deliverable)	**R**
MSF7	4	Support for development of data gap identification guidance for Environment Agency staff preparing SAMPs	Project record (interim deliverable). Guidance now embedded in the SAMPs process	**E**
MSF8	4	Environmental and geomorphological context	Liaison role for team (interim deliverable)	**R**
MSF9.1	4	Guidance on deterioration rates for different asset types for whole life asset plans	Project record (interim deliverable). Guidance superseded by reports of subsequent project SC060078	**E**
MSF9.2	4	Guidance on capital and maintenance costs of different assert types for whole life costing	Project record (interim deliverable).	**D**
MSF10	4	Provision and use of information on asset risk attribution for the development of SAMPs	Included by agreement in integrated pilots and systems analysis reports	**R**
MSF11	4	SAMPs area pilots – attribution of residual risk to linear defences	Included by agreement in integrated pilots and systems analysis reports	**R**
MSF12	4	Definition of asset management terms to suit a risk framework.	Glossary of this report	**E**
MSF13	2	Guidance on preparation of site-specific fragility curves for defence assets	Focus Product 4.1. Full details in report SC040018/SR5 Development of fragility curves for use in management of flood defence assets	**D**
MSF14	2	Guidance on setting target condition grades	Focus Product 3.3. Now included in Environment Agency guidance and in a paper (Flikweert & Simm, 2008) in *Journal of Flood Risk Management*.	**E**

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Dave Gillet	Environment Agency
Dave Hind	Environment Agency
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David van Beeston	Environment Agency
Esther Goodwin	Wave Creative Designs
Foekje Buijs	formerly University of Newcastle/HR Wallingford
Fola Ogunyoye	Royal Haskoning
Frances Loran	Halcrow
Gavin Long	University of Nottingham
Geoff Baxter	Environment Agency
Helen Udale-Clarke	HR Wallingford Ltd
Ian Meadowcroft	Environment Agency
Jackie Banks	Environment Agency
Jeremy Brown,	Environment Agency
Jim Barlow	Environment Agency
John Chatterton	John Chatterton & Associates
John Goudie	Defra
John Ray	Environment Agency
John Ryland	Environment Agency
Louise Trim	Halcrow
Lyn Hensman	Environment Agency
Mark Dyer	formerly University of Strathclyde
Mark Morris	HR Wallingford Ltd
Matt Crossman	Defra
Michael Mawdesley	University of Nottingham
Nick Reid	Environment Agency
Nicola Fulford	Environment Agency
Nigel Darling	Environment Agency
Paul Dunning	formerly HR Wallingford Ltd
Pete Reilly	Environment Agency
Peter Robinson	Environment Agency
Richard John	Environment Agency
Roger Spencer	Arun District Council
Roger Bettess	HR Wallingford Ltd
Roger Prestwood	Environment Agency
Steve Pyke	Environment Agency
Suresh Surendran	Environment Agency
Tim Hopkins	Environment Agency
Tony Andryszewski	Environment Agency

Contents

Integrated Project Report
Part A: Setting the scene

1 Introduction: scope and context of project

This report covers Phase 2 of the Environment Agency's PAMS project, where PAMS stands for **P**erformance-based **A**sset **M**anagement **S**ystem. The purpose of the report is to summarise the findings and recommendations from the project. The report is aimed at scientists, practitioners and policymakers in the area of flood risk and management. It provides information on products and recommendations for further work on flood risk asset management. However, it also forms a useful way into the project for practitioners looking for products and tools that may be of use to them, . (The products are summarised in tabular form in Appendix 3.)

The report makes a series of recommendations on the logical next steps for use of already workable tools, for converting other tools into practice and for further research to deal with outstanding issues. In each case the benefits of using these tools both in their own right and in conjunction with other tools are explained.

This chapter starts by setting out the rationale behind the project. The report is split into a number of parts, as outlined below.

- Part A (setting the scene) – this chapter and Chapter 2 set out the underlying concepts and principles for performance based flood risk management.
- Part B covers assessment of individual assets (Chapter 3), assessment of modes of failure and capturing of defence resistance and resilience including fragility curves (Chapter 4) and river channel operation and management (Chapter 5).
- Part C deals with the management of (physical) flood systems, and tackles the attribution of flood risk to defences and channels (Chapter 6) and the evaluation and optimisation of management interventions (Chapter 7).
- Part D deals with the need to confront data dependencies (Chapter 8) and uncertainty (Chapter 9).
- Part E makes recommendations for future research and development (Chapter 10) and draws together recommendations from the entire report (Chapter 11) and references (Chapter 12).

A glossary of asset management terms can be found at the end of the report, along with a series of appendices. The project outputs are summarised in Appendix 3.

1.1 Original project scope

The PAMS project was established to develop test and document a suite of methods and tools which could deliver step-by-step improvements in the way the Environment Agency and others manage their flood and coastal defence assets. In doing this, the so-called **P**erformance-based **A**sset **M**anagement **S**ystem would provide evidence to support asset management practitioners in planning when and how to make asset management interventions. PAMS was thus intended to be a suite of methods and tools to support performance-based asset management, and not an asset management software system in itself.

The main problems that PAMS project was required to address were:

- the complexity of each asset systems with a number of different components, all of which contribute to its state and the way it performs in a flood event;
- difficulties in achieving a meaningful assessment of the condition (including the effects of deterioration of elements) of assets through monitoring or inspection;
- the potential complexity of the relationship between the condition of individual assets or the overall system and its performance in response to the 'loading' of flood events;
- difficulties in assessing the improvement in performance that will result from interventions – which could range from routine maintenance (such as clearance of vegetation) to major refurbishment or change to individual assets (such as heightening of a waterfront wall).

The specific project objectives defined when the project was established in late 2004 were:

- to provide *guidance for asset inspection and condition assessment* linking asset function, condition and performance, and indicating whole-life risk through the use of simplified deterioration models;
- to develop the *framework and tools for decision support*, drawing on existing appraisal tools, and provide guidance for options appraisal or decision support for asset management and related plans;
- to do three *case studies* with business staff and real data and systems to develop and demonstrate the methods and to provide reports, training materials and tools to enable implementation;
- to *link asset management and performance-based principles* (such as probability of breach or overtopping) more fundamentally to ongoing work in National Flood Risk Assessment (NaFRA) or National Assessment of Defence Needs and Costs (NADNAC).

The project also had to link in with ongoing development and implementation of the Environment Agency's own asset management policies and procedures in line with its Asset Management Strategy. Products from the PAMS project should also be adaptable to coastal erosion management.

1.2 Evolution of the project

It became clear during the project that the transition from flood defence maintenance to risk-based asset management would be more effective if some aspects of risk, performance and systems-based methods and analysis were implemented early on and/or progressively. Thus, there was an early opportunity for the on-going research and development in the project to support this process by providing interim guidance to the Environment Agency's flood and coastal risk management (FCRM) Asset Management and Operations Delivery activities.

A series of focused outputs under the title *Measured steps forward in performance-based asset management* (see Appendix 2) were identified and developed through discussions with Environment Agency staff. The criterion for inclusion of such a step was that it would have to be delivered in a timely manner to aid asset management and maintenance activities and similar activities undertaken by other authorities such as Internal Drainage Boards (IDBs); it should also help to update training materials, courses and guidance.

The success of the first set of steps encouraged the development of a second set, along with piloting of a new condition assessment methodology.

1.3 Context for the management of flood risk assets and this research

Flood and coastal defence assets in England and Wales cover 44,500 structures and 24,000 km of coast and riverbank. Annual capital and operational expenditure costs on these approach £500 million. Total replacement costs are in excess of £20 billion. The Environment Agency has well-established procedures for (a) asset inspection and condition assessment, and (b) investment appraisal, prioritisation and resourcing of capital and operational work, although these need to be better linked to risk and performance measures, and to the strategic aims of managing and reducing flood risk. There is a good understanding of the broader function of the asset beyond its flood prevention role in flood risk management (FRM) - consideration is given to safety and environmental function, and to other benefits of assets such as urban regeneration, recreation and amenity. There are, however, relatively poor records of asset (including component) performance, of the internal condition (or 'state') of many fixed assets, and of whole-life ownership costs. Importantly, the Environment Agency has restructured its organisation at national and area level to provide a clearer focus for planning and delivery of asset systems management.

Other flood defence operating authorities tend to have significantly lower turnovers and asset bases than the Environment Agency, but also need to embrace asset management if the *Making Space for Water* "portfolio of FRM measures" strategy is to work, particularly since their combined asset base probably exceeds that of the Environment Agency. Maintenance, monitoring, management and enforcement of smaller watercourses can be particularly poor, increasing local flood risk. The increasingly important interface with sewerage operators on the urban drainage front is drawing the traditional FRM industry closer to the water industry with its well-established water company asset management plans (AMPs) for OFWAT. The FRM industry and the Environment Agency in particular already have many of the processes, tools and structures for delivering asset management in place. The National Flood and Coastal Defence Database (NFCDD) has provided a worthwhile starting point as an overall asset register, but much more needs to be done.

Relative to existing methods of appraisal for new flood defence schemes, current approaches to justifying maintenance needs are often crude, as identified by the report *Operations and Maintenance for Concerted Action* (Posford Haskoning, 2002a). The PAMS project seeks to provide supporting tools and methods to enable flood and coastal defence practitioners to better assess the performance and maintenance requirements of flood defence assets, and enable FRM asset managers to have a better understanding of the effect of their management interventions on flood risk.

1.4 Asset management practice elsewhere

The PAMS Phase 2 project was carried out within the broader climate of development and improvement of asset management practice across all UK infrastructure operators.

Operational organisations in many sectors are rapidly picking up on the potential for achieving benefits from better asset management and more reliable, stable and cost-effective asset performance in terms of improved customer service and relationships with regulators. Asset custodians are increasingly under pressure to demonstrate their ability to monitor and manage the condition and performance of their assets. Also, they have to produce a maintenance policy for optimal performance, longevity and sustainability. Many infrastructure owners, including the Environment Agency (2004), are now adopting the non-prescriptive principles embedded within the British Standard Institution's Publicly Available Specification 55 (BS PAS 55). PAS 55 provides a specification for the optimised management of physical infrastructure assets. As well as providing a route map for asset management, certified compliance allows operators to demonstrate effective management.

Establishing an asset management policy and strategy, together with an implementation plan and operational procedures, should provide an organization with a purpose-made set of processes, tools and performance measures to achieve, through a process of continuous improvement, an optimum approach to the management of its assets. Such a strategy needs to be owned at executive level, be evidence-based as to what is done and why, and be auditable in its application.

The generic *Plan – Do – Check – Act* framework in PAS 55 (see Figure 1.1) provides a template against which industries can develop or check their own approach to the management of physical assets. The framework covers: (a) policy and strategy linked to corporate objectives and acceptable risk (overall business risk, not only flood risk); (b) information, risk assessment and planning including information systems, risk identification and assessment, leading to the asset management plan with its priorities and targets; (c) implementation and operation focused on intervention to maintain, operate and dispose of assets, including such issues as responsibility, training, awareness, communication and emergency response; (d) checking and corrective action including monitoring of performance and condition, asset-related failures, corrective and preventive action; and (e) management review and audit, completing the cycle and leading on to continuous improvement (BSI, 2004).

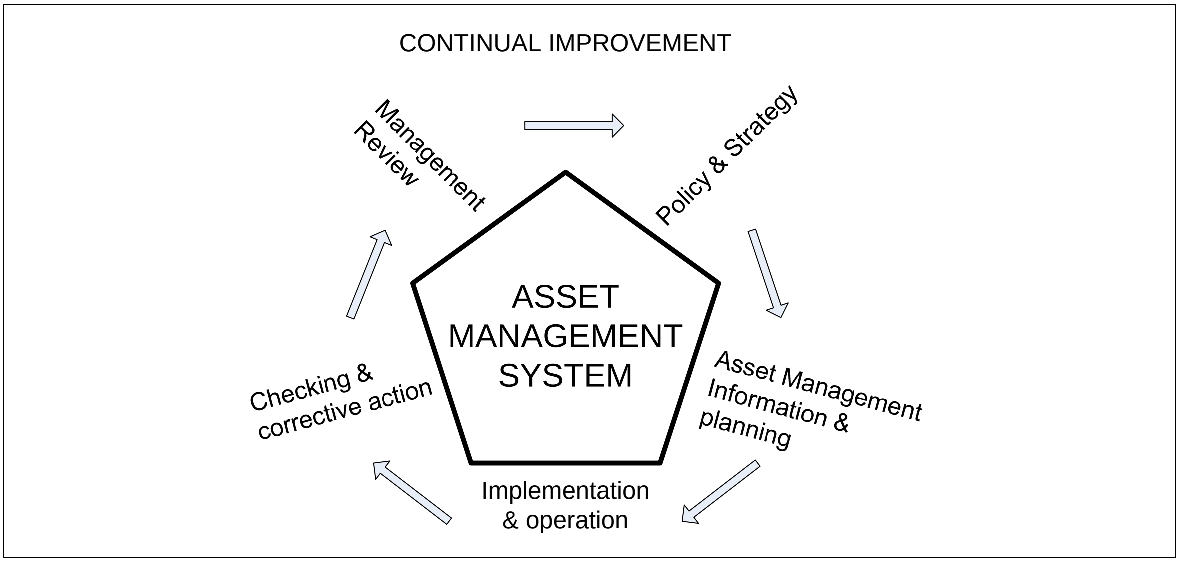


Figure 1.1 PAS 55 'Plan – Do – Check – Act' framework.

1.5 Reasons for investment decisions in FRM

Flood risk management also operates against a changing economic baseline. Changing UK priorities mean that it is no longer possible to justify protecting some agricultural land which may have warranted protection in the past; therefore withdrawal of maintenance of assets is becoming an increasingly important part of asset management.

Improvements following the launch and promotion of asset management within FRM operating authorities are expected to arise both from increased output due to improved programme management and targeting of resources, and from reduced flood risk due to more reliable and predictable asset performance. These improvements will help operating authorities explain their investment decisions by linking these explicitly to flood risk and risk reduction.

The latter requires a better understanding of the condition, performance and criticality of assets and asset systems under present and future loads. The outputs of the Defra/Environment Agency Joint Programme in Flood and Coastal Erosion Risk Management are making a major contribution with improved tools and techniques – for example with the Conveyance Estimation System (CES) for channel performance specification, and with the introduction of "performance features" into the Condition Assessment Manual (CAM) (Environment Agency, 2006a). A further area for research is to improve our understanding of deterioration and whole-life costs of different types of assets and component materials, and along with how to optimise the lifecycle impacts of assets.

FRM asset management needs to be supported by continuing research to identify and fill gaps in current methods and generate guidance and training on good practice.

1.6 PAMS Phase 2 and its link to other projects

The PAMS Phase 2 project draws on a number of other R&D projects under the Joint Defra/ Environment Agency Programme and elsewhere (see Appendix 4). This project builds on research undertaken by initiatives such as the Flood Risk Management Research Consortium (FRMRC) and the European FLOODsite project as well as from Defra and Environment Agencyfunded work such as *Risk Assessment for System Planning* (RASP), *Operations and Maintenance for Concerted Action*, *Embankment Failure Under Extreme Conditions* (IMPACT), *'The Conveyance Estimation System' (CES), the 'Performance and Reliability of Flood and Coastal Defences*, and the 'Thames 2100' project.

One example of this collaboration is the substantial amount of research on condition inspection of assets which was initially undertaken by the FRMRC, including research at the University of Nottingham's (UoN) Centre for Infrastructure, to achieve *A measured step towards performance-based visual inspection of flood defence assets*.

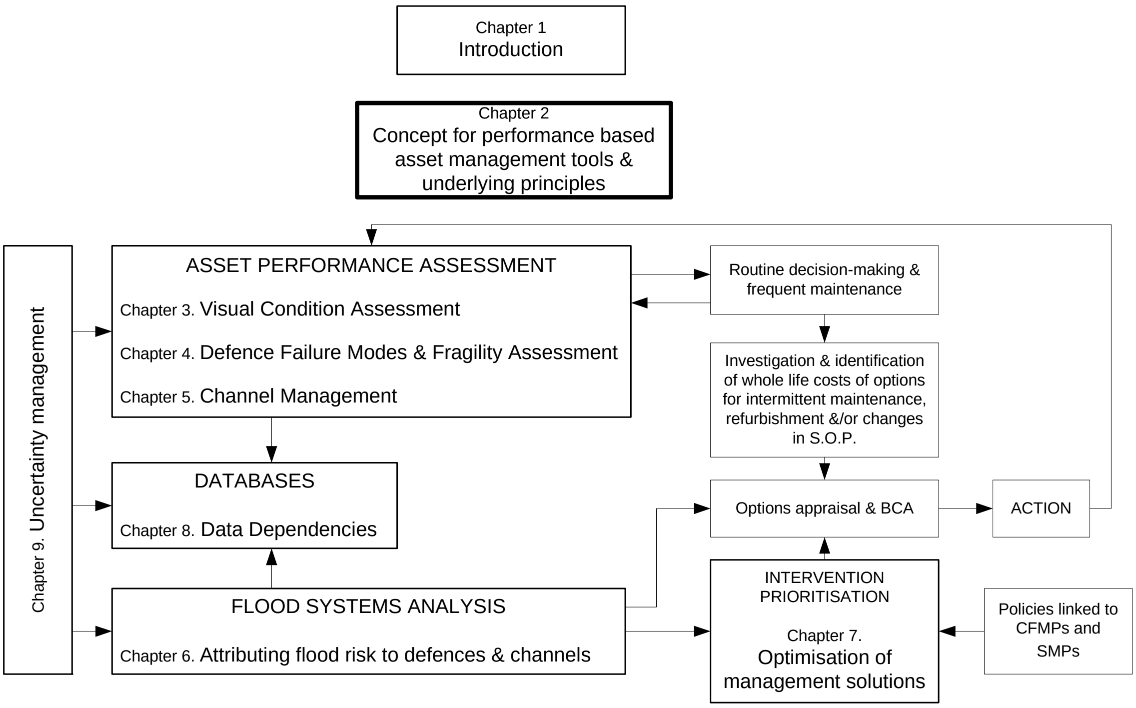
The UoN work (which is a development of the Environment Agency inspection method) was adapted by HR Wallingford Ltd for use in the Thames Estuary 2100 (TE2100) project where a PAMS-type model of the Thames Estuary FRM system was created to identify residual risk associated with defences and to prioritise future actions (repair, replacement, realignment). HR Wallingford Ltd integrated the UoN methodology with other practical work from Defra/Environment Agency R&D projects on *Performance and reliability of flood and coastal defences* and *Reducing the risk of embankment failure under extreme conditions*. Thus the TE2100 condition assessment method built on the former Environment Agency method with new science and practical experience on the mechanisms and indicators of failure.

The TE2100 method was used to inspect the Thames Estuary linear assets and the data was used in a PAMS-type model. Further development and refinement of the condition assessment method boosted our knowledge of failure modes, processes and indicators, and used the experience and knowledge of asset inspectors and managers who were integral to the development and trialling of the methodology.

With regard to coastal erosion, the project has promoted and fed into a scoping study examining future requirements for the management of coastal flood defence and erosion protection assets. The project team also developed links with international research and practice, in particular European research and the emerging requirements of the floods directive. Strong links are being made with US practitioners following the damaging floods and levee failures in New Orleans from Hurricane Katrina. These show the importance of asset inspection, determination of asset fragility and the whole systems-based approach to flood risk assessment and management.

2 Concept for performance-based asset management tools and underlying principles

This chapter sets out the underlying concepts and principles for performance based flood risk management and the kinds of tools needed. It explains the source-pathway-receptor nature of flooding systems and the role of assets as sources (channels) or pathways (defences). It explains the need for assessment processes and how these relate to the nature of asset management and then sets out how improved tools can improve the asset management process, in particular by understanding the way in which the assets themselves are related to the residual risk. The chapter concludes by explaining how tools can be assembled in system modules to meet the various objectives of asset management.



This chapter covers the management of flood systems – underlying principles, need for assessment and analysis, evidential basis for asset management, tools, techniques and guiding principles.

2.1 Flood systems

Flood risk systems often exhibit significant spatial (from national level to local level) and temporal (current and future) complexity and consist of different sources, pathways and receptors. System-based thinking enables the complexity to be broken down without losing the behavioural characteristics of the system as a whole.

The ‘system state’ can be described in a structured source-pathway-receptor (S-P-R) framework. This framework for flood risk is illustrated in Figures 2.1 and 2.2.

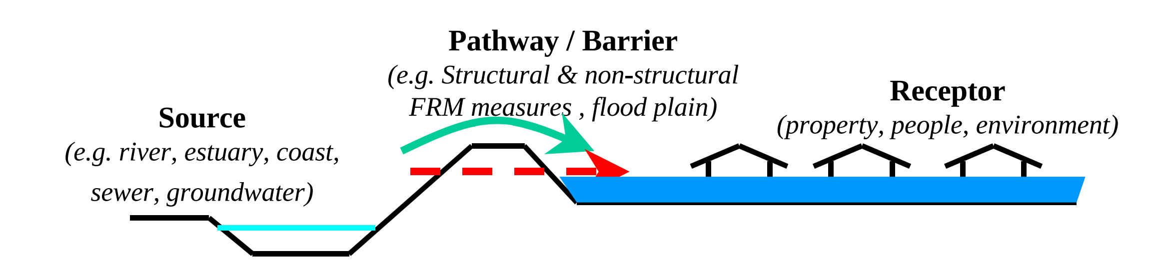


Figure 2.1 Simplified illustration of source-pathways-receptors concept for flooding.

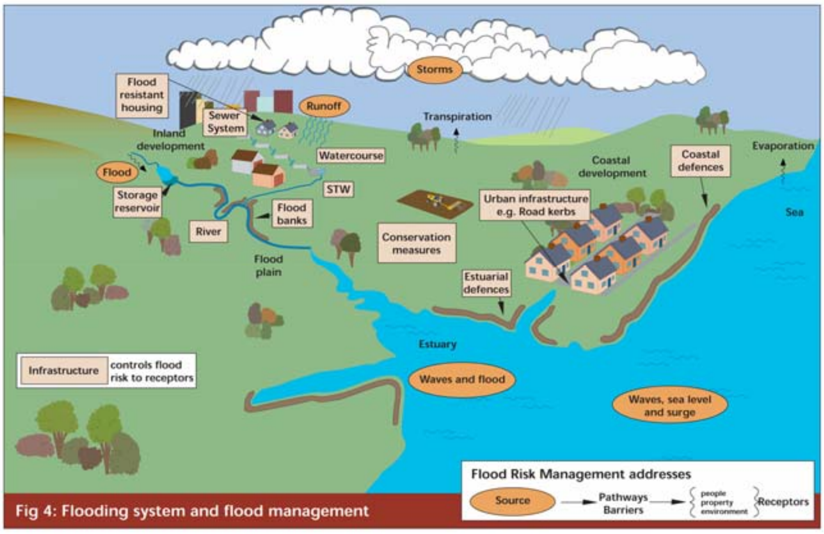


Figure 2.2 Flooding system and flood management (courtesy M Bramley).

Where:

- ***Sources*** are taken to be the hydraulic loadings which impinge on defences including river levels, flows, waves, tidal and surge water levels and their associated probability of occurrence (singularly or jointly).

- ***Pathways and barriers*** are the behaviour of catchments, floodplains and defences, the nature, extent and condition of assets, topography and land use as well as the hydrological and hydraulic factors that determine the patterns and volume of run-off.

- ***Receptors*** are the exposure and vulnerability of the people, property and environmental features that may be harmed by a flood. Flooding receptors, although damaged by inundation, are normally recoverable unless repeatedly impacted or damaged beyond repair.

To support risk management decisions, the significance of (system) changes and effectiveness of possible management responses on risk must be considered and understood. System-based approaches enable the influence of the factors that change the system state (both positive interventions by the flood risk manager, and the external influences such as climate change) to be captured in a structured manner.

Flood systems analysis is therefore a process by which data on flood defences and other parameters can be gathered and recorded, collated with stored data, analysed, and delivered to the user or decision-maker in a manner which allows the testing and selection of maintenance and improvement options. It is a cyclical, iterative process by which effective performance-based management of flood and coastal defence can be delivered if used correctly - encompassing a full system analysis based on the S-P-R consequence model shown in Figure 2.3.

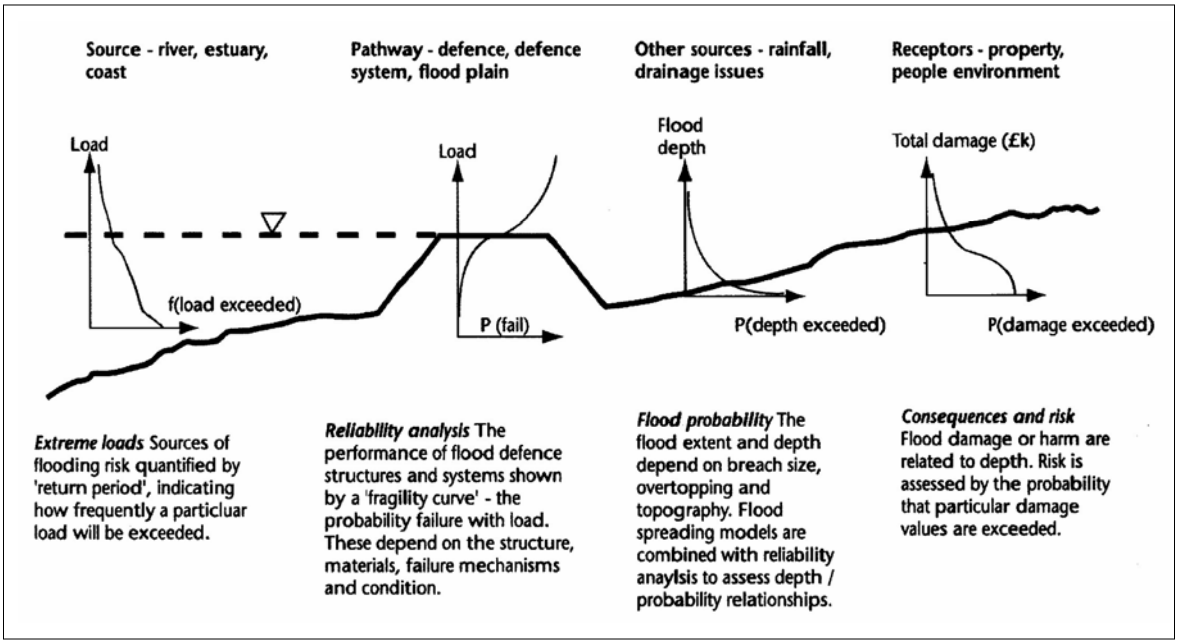


Figure 2.3 Source/pathway or barrier/receptor model for flood risk.

2.2 Assets as sources (channels) or pathways (defences)

In terms of flood risk, the important property of the river channel (with or without raised flood defences) is its ability to pass flows without excessive water levels – a river channel should be managed to ensure an acceptable level of flood risk is achieved. In some cases this may be quantified by expressing the discharge capacity of the channel for a specified water level. In other cases a simpler approach may be adopted. Discharge or carrying capacity is affected by factors such as vegetation reducing flow and by blockage (such as debris or siltation) restricting channel cross-section. Figure 2.4 shows a river channel that has exceeded its carrying capacity, where water is no longer restricted to the river limits - i.e. between the river banks.

Figure 2.4 River flow exceeding channel capacity (HR Wallingford Ltd).

Figure 2.5 shows how flood defences are part of the flood pathway. Here, water is weiring over the crest of the defence and cascading down its rear face – the defence has not failed *per se* – the water level has simply exceeded the design crest height of the structure. Some defence structures are designed for exactly this purpose – mainly to divert high flows from the river system into flood relief or storage areas before they reach more vulnerable areas of the catchment downriver.

Figure 2.5 Water weiring over the defence crest (Courtesy of Arun D.C).

Figure 2.6, on the other hand, shows a structural failure of a flood defence. The flood embankment has recently breached whilst under load from flood waters. Note that the water level does not exceed the crest height of the embankment, indicating that this breach occurred before any overtopping of the crest – indicating that there was possibly a weakness in this structure. Structural failure can also be caused by water overtopping the crest - causing erosion and eventual breach of defences not designed to withstand this eventuality.

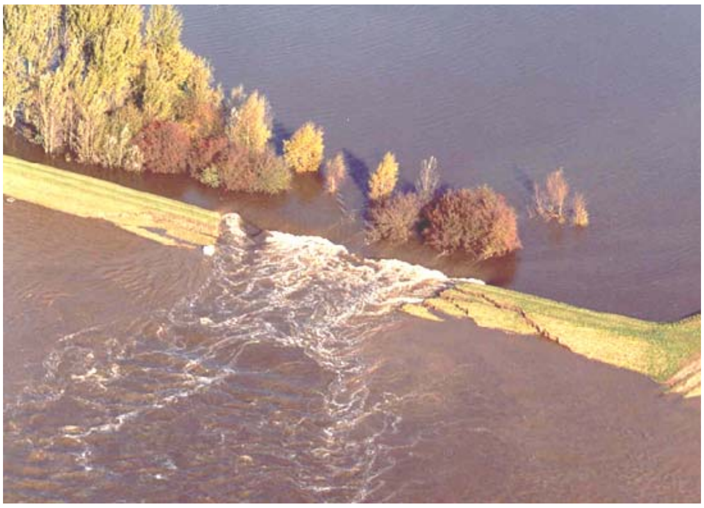


Figure 2.6 Structural collapse of a flood defence under load (courtesy of Environment Agency).

Unlike most other physical assets, FRM assets operate at either low or no load for most of the time. When a flood or storm comes, the asset should perform reliably at the desired standard of protection, but it should also perform predictably and resiliently when the standard is exceeded. FRM assets also need to be adaptable because planning and investment must cater for the uncertainty of future climate change. FRM assets exist within natural fluvial and coastal ecosystems and engineers must – as far as practicable – emulate and intervene with these in an environmentally sensitive and sustainable way.

2.3 Need for assessment

Ensuring the acceptable performance of flood defence assets (such as channels, walls, embankments, gates and pump systems), and the asset systems they compose is a considerable challenge. It requires an understanding of the potential modes of failure of these assets, how these can affect performance and how these are in turn affected by asset deterioration. The wide variety of defence types and, perhaps uniquely to flood defences, interaction between each asset and its physical surrounding (including other assets) further complicates the task. Within this context, the concepts of system analysis, reliability and structured option searching provide useful aids to the asset manager. These advanced tools and techniques enable critical components to be identified and future investment options to be compared within a consistent framework, enabling investment in data collation, analysis or physical intervention (through actions to repair, renovate, replace or indeed remove assets) to be prioritised.

Over recent years significant progress has been made to develop the principles, methods and tools to support better asset management (Defra/Environment Agency, 2002, Evans *et al.*, 2004a&b, Sayers and Meadowcroft, 2005, Simm *et al.*, 2006). These approaches recognise the need to prioritise limited resources to best effect, taking into account the whole-life costs and benefits as well as the uncertainties associated with *do nothing* and *do something* strategies. In providing this support, it is increasingly recognised that to be meaningful the analysis must be:

- ***Systems-based*** - Recognising that the protection afforded to a given person, property or other valued feature in the floodplain (receptor) reflects the performance of the whole of the asset system and how it responds under a wide range of loads (and not the performance of an individual asset during a notional design storm).

- ***Evidence-based*** – Recognising the need for transparent and auditable evidence, whilst acknowledging that much of this evidence is uncertain. Explicitly accounting for uncertainty within the analysis and decision process is a prerequisite of good decision-making.
- ***Hierarchical*** – Recognising the need for progressive refinement of the data and analysis where the level of detail reflects the demands of the decision being made. The accuracy of the analysis/data needs to be *just* sufficient to ensure that the decision is robust (i.e. further refinement would not alter the choice made).
- ***Portfolio of activities*** – Flood risk management is increasingly characterised by the implementation of a portfolio of measures, where the advantages of one compensates for disadvantages of another. The management of the structural/operational assets should be seen as only one, albeit important, component of a wider flood risk management strategy (where structural and non-structural measures act in concert to manage flood risk).

This report describes the state of the art in the assessment of the performance of asset systems, through the use of system analysis and structured reliability analysis, and provides a forward look towards the practical application of formal optimisation and option-searching tools. The limitations of the developments achieved thus far are acknowledged and recommendations made for further research and development.

2.4 Overview of asset management

An *asset* can be described as any feature that is actively managed to reduce the chance of flooding, including:

- a linear asset such as raised defence (levee or dyke);
- a point asset such as a pump, gate or culvert trash screen;
- the watercourse. for example the vegetation and sediment within a channel;
- the coastline, that is the groynes, beach and backshore.

In managing such a diverse range of assets, challenges are invariably encountered:

- ***Incomplete understanding*** – The physical dimensions and properties of an asset are often unknown (or poorly resolved). The physical processes that lead to failure are often poorly understood or incomplete. Different assets will deteriorate at different rates under different management practices, loadings, environmental influences and climate futures. The potential for failure is therefore difficult to determine and varies in space and time.
- ***Variability of impact*** - Spatial variation in the potential impact of failure is often strong and implies that not all assets need to have a common standard or condition.
- ***Complexity*** - The complexity of asset systems and the floodplains they protect make intuition and engineering judgement difficult to apply. This

leaves asset managers with a rational doubt over which action to take and when.

- ***Affordability*** - Budgets are limited and insufficient funds/capacity exist to undertake all desirable works. For example, *$2.2* trillion is the estimated investment needed to raise all linear defences (levees) to a uniform standard and condition across the US (Stockton, 2009). Within England and Wales, the Foresight future flooding project (Evans *et al.*, 2004a,b) estimated that annual investment levels in the UK needed to double from present levels to meet the challenge of rising flood risk. This was confirmed in the Environment Agency's (2009a) long-term investment strategy, which suggests that in England and Wales a steady increase in investment is needed to build and maintain flood and coastal risk management assets. 2010-2011 levels are only £570 million and this will need to increase to around £1,040 million a year (plus inflation) by 2035 if current protection levels are to be maintained.

2.5 Better asset management – Rising to the challenge

Around the world, innovative tools and techniques are being developed to support asset managers in overcoming the challenges they face through the following.

(a) Better evidence on individual assets (understanding the asset base)

In England and Wales, the Environment Agency has stated that it will have succeeded in its asset management role when it knows exactly: "*what assets we have; where they are; what standard of protection they provide; how they were constructed; their current engineering integrity; and, how they work together to provide a flood defence system.*" (Tim Kersley – Head of Asset Management Environment Agency, 2008). Similar, seemingly basic requirements exist around the world and across different sectors (within rail, road and so on). In this context, a *better understanding* is characterised as:

- *An improved understanding of the nature of the individual assets managed* **–** including direct access to basic parameters such as location, condition and standard of protection an asset affords. More accurate and useable information on probability of failure, dominant failure modes and the critical contributing uncertainties is also required.

- *An improved understanding of the role of individual assets within the context of an asset system* – including direct access to information on how an individual asset contributes to risk and, importantly, where key data and performance uncertainties lie.

(b) Better decision-making (whole-life risk and performance based approach)

All asset managers seek to make *good* investment decisions: decisions that minimise whole-life costs whilst ensuring communities are appropriately protected from flooding. Achieving this in the context of a large and complex asset base is difficult and needs to be underpinned by a coherent set of consistent decision support tools and techniques that vary in complexity and data demand to reflect the level of risk and the difficulty of the choices being made.

In more recent times these general requirements have been translated into risk-based methods (Sayers and Meadowcroft, 2005, Gouldby *et al.*, 2008, Gouldby *et al.*, 2009) capable of providing a step change in the richness of evidence provided to decision-makers at all levels (at a national, individual flood system or individual asset level). In particular these include:

- *Understanding asset performance and its contribution to the residual risk* – Highlighting those assets, within a system of assets, that contribute most to risk (Figure 2.7, Gouldby *et al.*, 2008) provides a powerful tool in helping to efficiently direct investment. Once risk has been attributed to an asset, the results of a detailed analysis of its failure modes can be used to highlight aspects that contribute most to probability of failure (enabling the asset manager to distinguish the relative importance of raising crest heights or improving asset strength, for example).

- *Understanding assets and their contribution to the uncertainty in estimated risk* – Highlighting which assets contribute most to uncertainty in estimates of risk provides a useful extension to the attribution of risk discussed above. This enables data collection and further engineering investigations to be prioritised on a common basis alongside structural measures. Sensitivity analysis (Gouldby and Kingston, 2007, Gouldby *et al.*, 2009) can help highlight which uncertainties are most important. (*Note*: Local anomalies within the asset and the heterogeneity of the soil conditions, which often form weak points that initiate failure, present considerable challenges demanding significant expert input.)

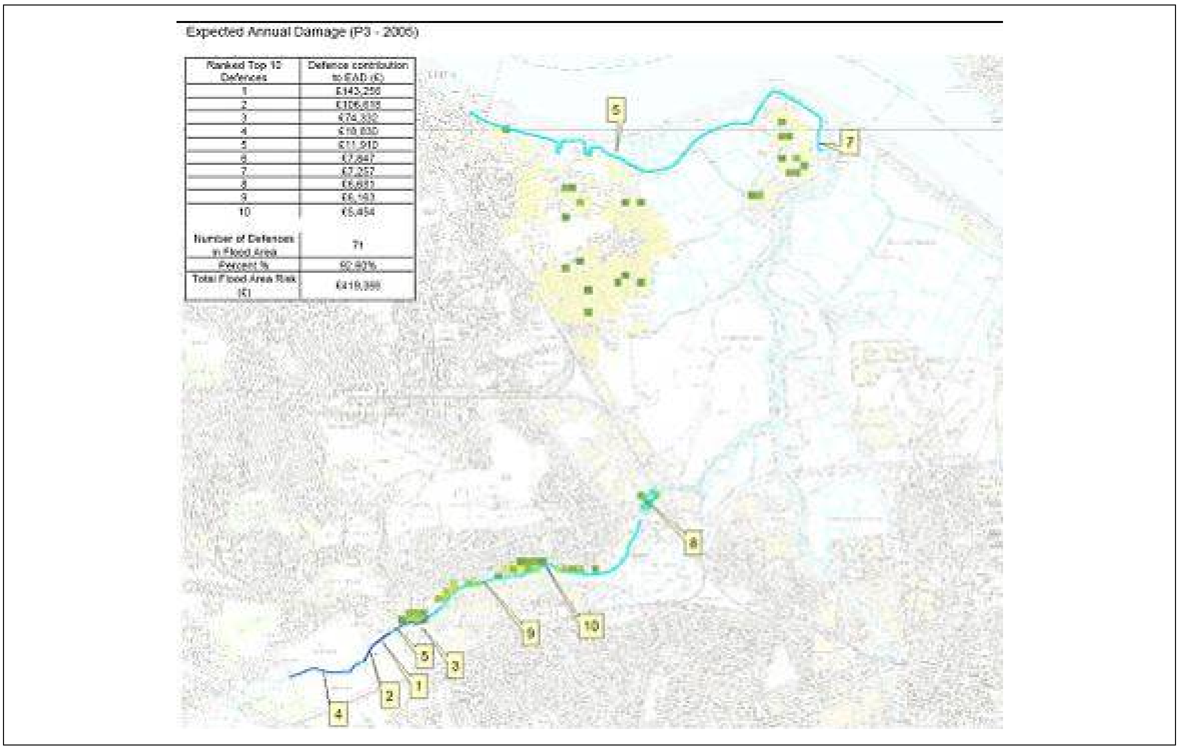


Figure 2.7 Expected annual damages attributed to individual defence assets (as well as spatially within the floodplain) provide a step change in the support provided to asset management decisions (Gouldby *et al.*, 2008).

A hierarchy of analysis, where data and analysis from one level of detail informs and refines the analysis at another, provides an efficient means of developing a level of accuracy appropriate to the decisions being made (Sayers and Meadowcroft, 2005). This is shown graphically in the context of a refined spatial resolution in Figure 2.8; a similar principle is applicable to the reliability analysis, as discussed later in Chapter 4.

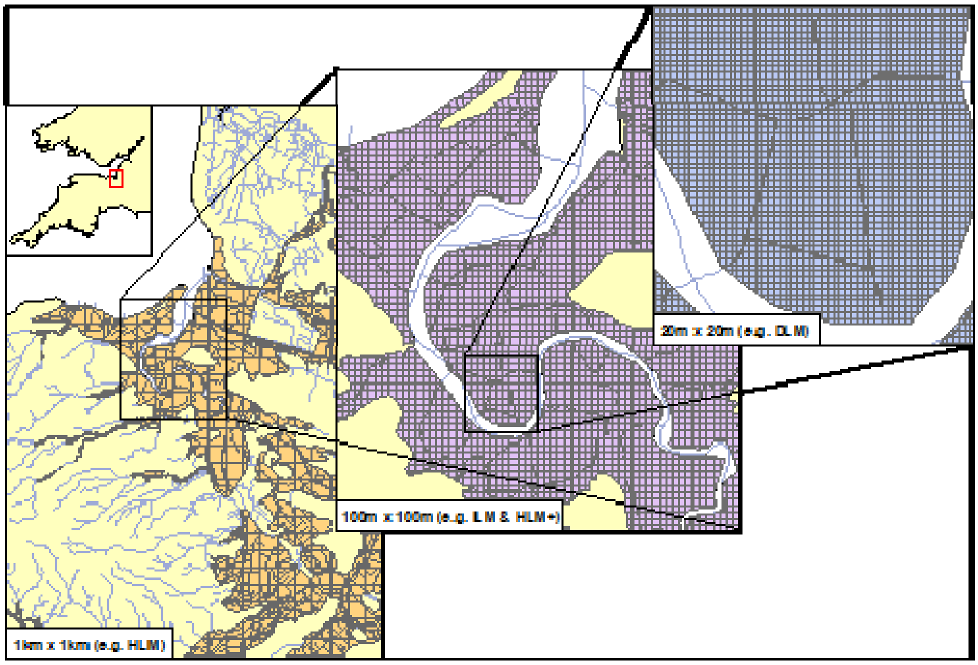


Figure 2.8 Progressive refinement in the spatial resolution of the analysis (Sayers and Meadowcroft, 2005).

- *Optimal investment strategies* **–** Asset managers face difficult choices regarding (i) *Where* to act to improve an asset? (ii) *When* action is required: now or can investment be postponed? (iii) *How* **-** Is it better to collect more data, undertake more analysis or intervene? Increasingly it is not possible, or acceptable, to intuitively determine which option and management strategy is best. Approaches which examine the performance of whole systems and identify whole-system solutions are now needed. As a result, the utility of formal optimisation methods, and their applicability to flood risk management, are being explored and trialled. These initial trials show considerable promise and are discussed further below.

2.6 Asset management tools – Guiding principles

In making good asset management decisions, six best practice principles have been recognised (Table 2.1). These principles underlie the tools and techniques described later in this report.

Table 2.1 Best practice principles in support of asset management tools.

Best practice principles in support of asset management tools (HR Wallingford Ltd, 2008)	
Appropriateness	Appropriate level of data collection and analysis reflecting level of risk associated with an asset and uncertainty within the decision being made.
Understanding	Improving understanding of assets and their likely performance.
Transparency	Transparency of analysis enabling audit and justification.
Structured	Structured knowledge capture encapsulated through fault tree, breach potential and so on.
Tiered assessment and decision-making	In terms of data and modelling approaches
Collect once, use many times	Reusing data through the hierarchy of decision-making stages and supporting tools – from national policy to local detail.

2.7 Asset management tools in system modules

The asset management tools that are needed to translate the *good practice principles* into reality and provide the richness of evidence described in earlier sections can be summarised in terms of a series of key, building blocks or modules (Figure 2.9).

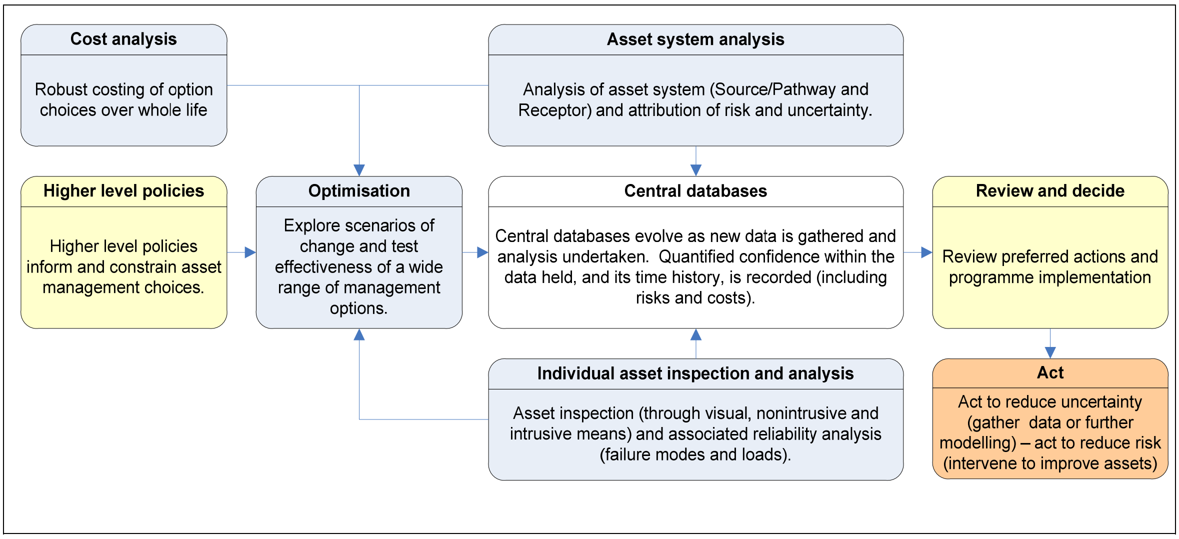


Figure 2.9 Basic building blocks of tools and techniques that support asset management under development as part of the PAMS project.

Each of these building blocks provides a key input to the asset management process:

- ***Individual asset inspection and analysis*** – Visual, non-visual and intrusive inspection methods are used here. Currently, the assessment of condition grade is carried out using a visual methodology. The approach is much more clearly structured and related to potential failure modes and this is described in the project *report FDR002 - PAMS Asset Inspection Methodology*. Non-visual and intrusive investigations are used to determine details of geometrical and engineering parameters.

As part of this module, Reliability analysis is used to express the performance of an asset in a given condition in terms of its likelihood of failure under a particular hydraulic loading. The project *report FDR003 – Development of fragility curves for use in management of flood defence assets* explains how these fragility curves may be derived, although a brief summary is given in this report for completeness.

- ***Common/central databases*** provide a means of accessing data and evolving data quality. Within England and Wales, for example, the National Flood and Coastal Defence Database (NFCDD) provides a common home for asset data, regardless of ownership. Although not without technical and organisational difficulties, an NFCDD (or its equivalent) provides a central component of any asset management system without which data collection and analysis are easily duplicated.

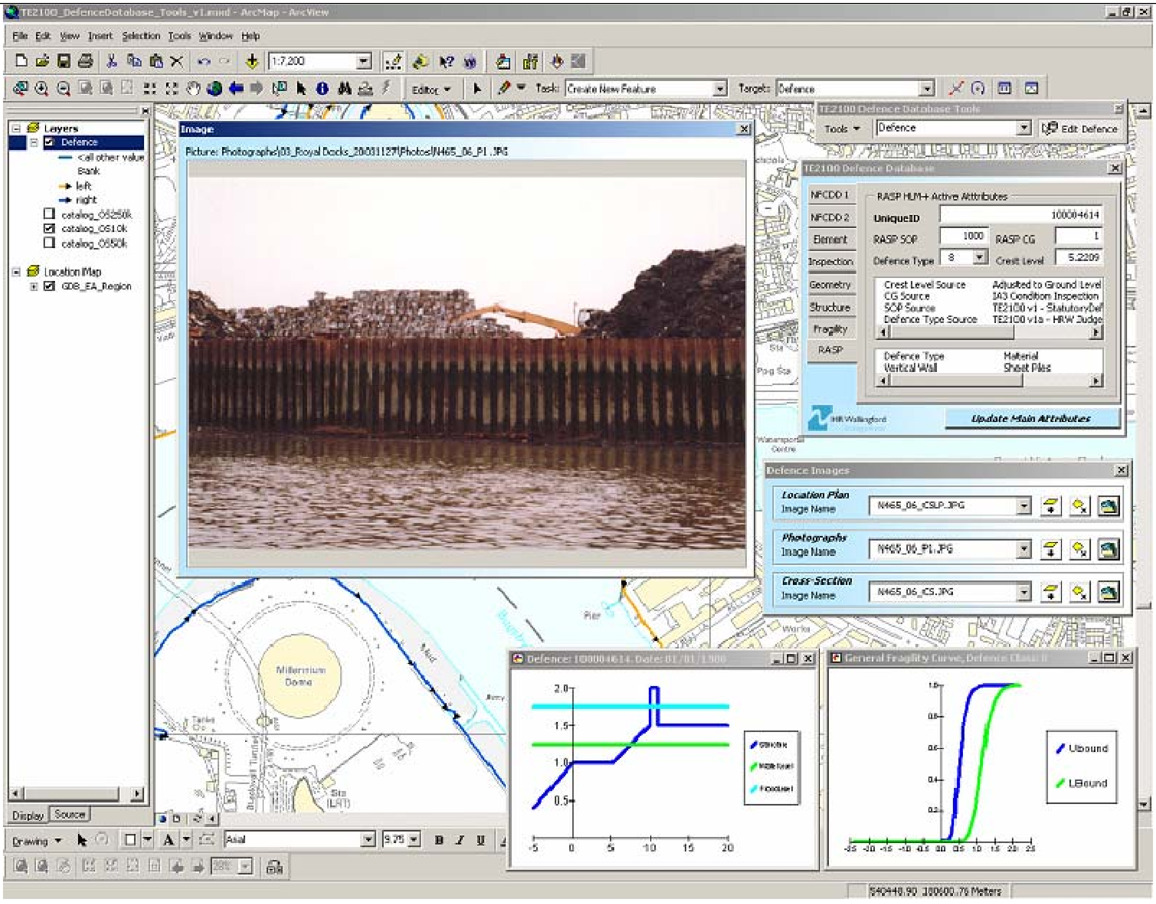


Figure 2.10 Example of common asset database used and shared across the Thames Estuary Planning for Flood Risk Management 2100 (Sayers *et al.*, 2006).

- ***Asset system analysis*** – Risk-based management requires a comprehensive consideration of the sources, pathways and receptor impacts (Sayers *et al.,* 2002). In the context of asset management, the performance of the *asset system* as well as individual assets need to be assessed against all loading conditions. An ability to analyse the system behaviour is therefore a vital step in identifying critical components. Methods in support of this analysis are discussed in Chapter 6.

- ***Optimisation –*** Often, asset management consists of a range of physical interventions and data improvements staged in time and space. Formal optimisation methods are currently the subject of research (Gouldby *et al.*, in press). An initial application is discussed in Chapter 7.

- ***Higher level policies and constraints*** - Asset management takes within the context of higher level policy goals, guidelines on risk assessment, health and safety legislation, environmental regulation, affordability and so on. Understanding these goals and constraints is a fundamental aspect of good asset management and informs the criteria by which options are judged and the preferred approach selected.

- ***Review and decide*** – Expert judgement will continue to feature strongly in the asset management process, from the input data through to confirming the preferred course of action. Incorporating the expert judgement in an unbiased and transparent manner is problematic. Considerable progress has been made in recent years to integrated expert judgement and quantified analysis tools (Simm *et al.*, 2008, Hall and Solomatine, 2008). In particular expert judgement can be used to validate model inputs and provide credibility to (and validate) the outputs from the analysis. The decision-maker also needs to be confidence that the decision made stands up to uncertainty in the data, predicted impact of the action and the associated cost. Quantified uncertainty propagation methods (Gouldby *et al.*, 2009) together with multi-criteria decision-making provide efficient methods to support the decision maker in identifying robust .

- ***Act*** to implement the decision.

The logical suite of tools, techniques and processes[2] to support these modules are envisaged to form part of the supporting tools the Environment Agency will use for asset management. In this respect a 'tool' might comprise anything from procedural guidance to reports to software.

A further issue is that the costs and risk associated with different flood risk systems can vary and hence the tools needed may be different. High cost or high risk flood systems may justify a complex mix of tools to assess them because of their criticality. On the other hand, for low cost or low risk flood systems rather simple tools may suffice. Whichever tool is adopted, it should be appropriate for the management of that system and enable better decisions to be made than would be possible without the tool.

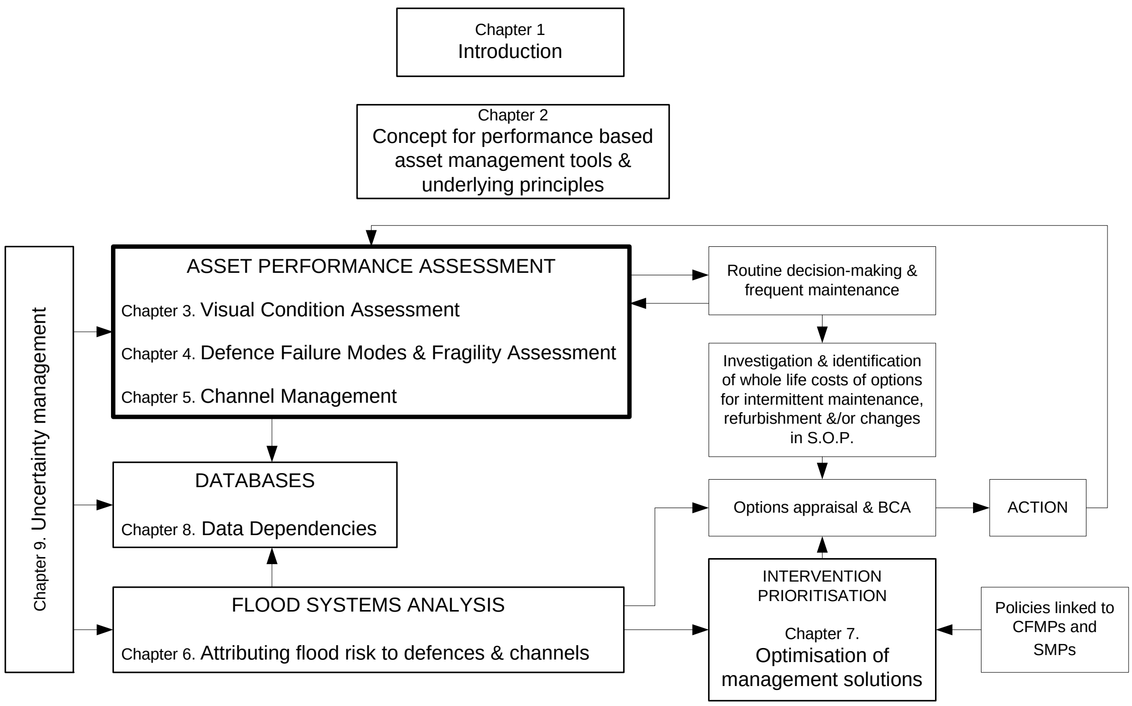
[2] For clarity: a *tool* is something like a model or a guidance flow chart, a *technique* is a technical procedure which makes use of one or more tools, and a *process* relates to an agreed or specified series of actions required to achieve an objective of an Operating Authority.

Part B: Managing individual assets

This section discusses the management of individual assets, assessment of modes of failure and capturing of defence resistance and resilience in various forms including fragility curves and finally river channel operation and management.

3 Visual condition assessment for defences and channels

This chapter describes covers the assessment of individual assets using structured visual inspection. It sets out the current approach and ways in which visual assessment could be improved by making a better link between condition and performance. The concept of performance features (visual indicators of actual or potential failure processes) is introduced and the flow charts which the project has produced to assess these. The way in which this activity was used as an interim measure to update the Condition Assessment Manual is described. The use of the performance feature assessments to generate an overall condition grade is then described and how the resulting scores were calibrated against current assessment methods in order to ensure a measure of consistency. A method for setting target condition grades and the chapter concludes with an explanation of how inspection can be used to trigger further activity (detailed investigation or intervention).



3.1 Introduction

Visual condition assessment is an important part of monitoring the condition of FCRM assets. Monitoring can also include:

- Physical survey techniques to determine changes in the location or surface profile of assets, including remote techniques such as photogrammetry and now more commonly LIDAR. An example of this approach would be the long-term beach profile monitoring carried out on the south coast of England, originally based on photogrammetric analysis of aerial photography.
- Intrusive and non-intrusive investigation of the condition of structures and their component parts and materials. Non-intrusive technologies such as

geophysical survey methods are increasingly being used to complement traditional intrusive investigation methods, even if only to identify the location of potential structural or geotechnical anomalies.

Visual inspection of flood defence assets, however, remains an important part of the process. In most of England and Wales, it has been carried out by the Environment Agency since its inception in 1996. Prior to this the National Rivers Authority carried out visual inspection of flood defence assets, albeit in a less formalised way. The current process of visual inspection involves the inspector assigning a grade of one to five (very good to very poor) to each element of an individual asset guided by a condition assessment manual. From these (sub) gradings an overall condition grade is calculated using a weighted combination method. Elements are identified (or checked) and coded according to type and material via a simple diagram and table on the asset inspection form. Overall condition grades can also be assessed directly using a manual override.

This visual assessment of the condition of defences is important in terms of using the information for management and reporting purposes but also in communicating with the public and with other government departments and agencies.

The significance of the information for management purposes relates to:

i. Assessment of the state of the defence. This affects the condition of its related asset system as a whole and hence the present flood risk. This is an important process for understanding the particular state of the defence structures and asset system as a whole. Although a snapshot of condition at a particular point in time, repeated assessment or monitoring of this condition records changes over time.

ii. Decisions which may need to be taken on the management of that defence. Comparison of actual condition with minimum or trigger conditions or use of systems analysis can help to suggest interventions to prevent unwanted deterioration in structures or in the level of performance of the defence system.

The significance of the condition of the defences in terms of communication with others has been in the use of condition grade as a metric against which the performance of the Environment Agency's flood risk management function has been monitored. (In particular, the National Audit Office has used it in this way and has sometimes been critical of the failure to meet targets, although differences in interpretation have meant that NAO saw targets as minimum conditions below which defences should not fall, whereas others have seen them as aspirational targets to achieve).

3.2 Limitations of current approach to visual assessment

Several problems are evident with the prevailing approach to condition assessment. Some of these remain intrinsic to the concept of visual assessment but others, related to the guidance documentation and procedures available in 2004, are amenable to improvement.

i. There may be limited 'linkage' between the assessed visual condition and the likely *performance* of the asset under extreme flood loading. In particular, the guidance did not make clear the link to the likely *modes of failure*. In some instances, the guidance could produce condition grading at odds with the likely performance of the defence.

ii. The lack of linkage between condition grade and performance/failure modes was further compounded by the normal practice of building up the condition grade from assessment of the condition of individual defence elements. In particular:

   - Whilst the grading of defence elements is a practical solution to the visual inspection process, it has no scientific basis in the determination of overall performance.
   - Weighting of the contribution of individual elements to overall condition is highly subjective and not necessarily related to their contribution to modes of failure. The approach varied from use of the condition grade for the weakest element to an average of the grades for all elements.
   - The guidance provided for condition grading of elements covers a broad range of performance features. For example, a condition grade of three given to an embankment slope could indicate poor quality of grass cover, or minor cracking, or slipping of slope, or the presence of burrowing animals.

iii. Despite the availability of guidance in the Condition Assessment Manual and a supporting training programme, assessment of condition grades remained potentially too subjective and hence subject to excessive variability between different observers.

iv. The guidance in the first edition of the Environment Agency Condition Assessment Manual confused the assessment of defence state with the triggering of any action that should arise as a result.

3.3 Making a better link between condition and performance

There are a number of potential modes of failure for any flood defence structure, most of which can be represented by physical process or statistical models. Understanding these failure modes (and any linkage between them) is important for condition and performance assessment for two main reasons:

i. To allow indicators of these failure modes to be included in condition assessments.

ii. To ensure that the right process-based models are applied when analysing the performance of defences.

In order to develop such a link, the PAMS project working with the FRMRC examined the range of potential failure modes applicable to defence structures and identified how the presence of incipient failure in these modes could be evidenced in visually observable *performance features*. These identified features:

- relate directly to imminent failure modes or indirectly to a partial failure process within a failure mode;
- may be evidence of more than one failure mode;
- by their nature and relation to failure modes are not restricted to a single traditional surface element of the defence and may be evidenced in several elements;
- have to be able to be assessed in a consistent manner;

- have to be sufficient in number to cover all failure modes without providing too large a workload burden on the inspector.

A major challenge here was that fact that many of the features associated with incipient failure in a particular mode are buried in the structure or not observable for some other reason and so assessment of such features would have to be omitted or included via some 'proxy' observable feature. Thus, the final choice of performance features was a balance between what it is possible to assess visually and the failure modes that need to be considered. Ideally, the selected set of performance features needed to have some link to all relevant failure modes, even if only indirectly.

Having identified these performance features, first proof-of-concept flow charts for assessing the performance features were prepared under FRMRC WP4.3, and these were converted under PAMS into an initial working methodology and guidance. The method involved producing individual failure mode scores from a weighted combination of performance feature scores, reflecting the perceived contribution of each performance feature to the process of failure in the relevant failure mode. These failure mode scores were combined to produce an overall condition grade for the structure.

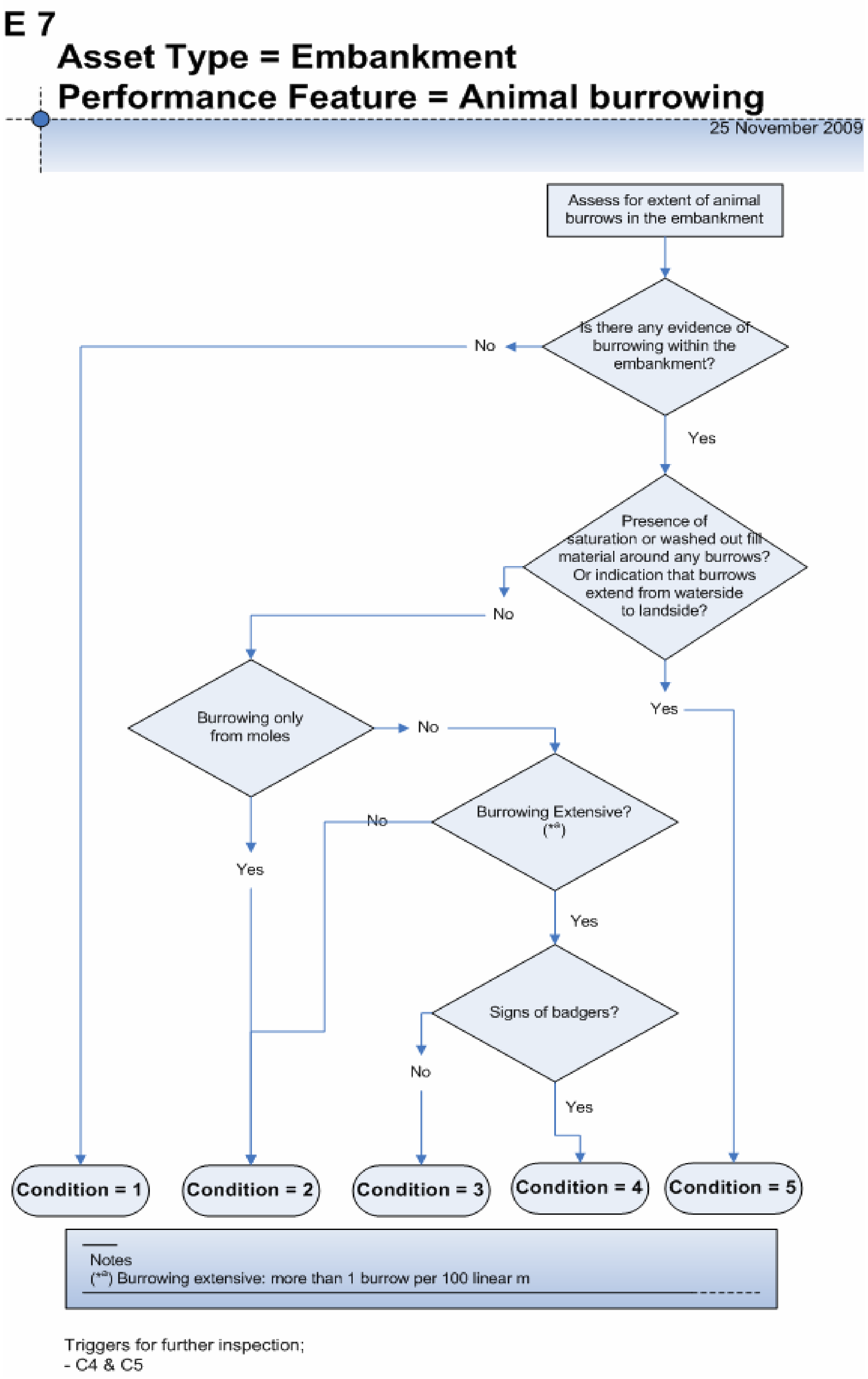
Trials were conducted as part of the TE2100 project which showed that these could be used as part of a programme of condition assessment to deliver useful condition grading results. These, and subsequent trials have also emphasised the benefits of consistency of appraisal in using the new approach and the value of inspectors being trained to think about the possible ways in which structures might fail.

3.4 Flowcharts for performance features

In the light of the TE2100 trials and other experience from team members, the PAMS team made a number of revisions to the performance feature flow charts. *Flow charts for assessment of performance features* are now available for implementation for embankments, vertical sheet piled and gravity walls (see Focus Product 3.1). The background reports for the flowcharts explain their background, including how each of the performance features relates to the failure modes, structure of the charts and reasoning behind the features and parameter values used in the flowcharts. The background notes also identify trigger points within the flowcharts for further inspection (see Section 3.7). However, before these can be fully introduced into the business, further steps are required (see Recommendations 3.1 and 3.2 below)

FOCUS PRODUCT 3.1: Flow charts for assessment of condition of performance features of fluvial and coastal linear defences.

(Figure for illustrative purposes only)



3.5 Updating Condition Assessment Manual

Because it would not be possible to introduce the flow chart-based assessment of performance features without further development, it became apparent that it would be useful to introduce immediately into the Environment Agency the new terminology and related principles of performance-based condition assessment. The PAMS team were asked to lead an already planned revision/update to the Environment Agency's visual asset Condition Assessment Manual (CAM2). In CAM2 (see Focus Product 3.2), a new narrative consistent with principles of performance-based asset management was introduced and all the images and definitions were revised in consultation with Environment Agency asset inspectors and managers. The thinking behind the flow charts also enabled the introduction of performance features into the CAM, but without making it illogical or unusable alongside existing condition assessment guidance, or confusing to the user. The confusing descriptions of 'trigger' maintenance actions that might be associated with a particular condition grade were omitted. The revised CAM has been in service in the Environment Agency since it was introduced in 2006/2007.

FOCUS PRODUCT 3.2: Revised Environment Agency Condition Assessment Manual (CAM2) for use with current condition assessment approach.

This includes:

- performance-based asset management narrative
- clarified descriptions of condition grades
- performance feature ideas
- revised images
- maintenance actions

3.6 Setting target condition grades

An analysis of generic fragility curves using target conditional failure probabilities was carried out and suggested that in many cases 'good condition' (condition grade 2) would not be required for reasonable performance, although 'poor condition' (condition grade 4) was generally inadequate. While the extra cost of maintaining to 'good condition' (condition grade 2) compared with maintaining to 'fair condition' (condition grade 3) can be significant, the analysis suggests that the difference in performance is small.

It was therefore possible to build on the Environment Agency's existing condition grade target-setting methods and set out (Flikweert and Simm, 2008) a more rational and performance-based approach to target setting which:

- Assumed a default target of 'fair' condition (CG3) for most flood defence assets.
- Used a higher condition grade target for some assets, where needed, if it improves performance and if there is no better alternative.

- Made sure that the condition stays above the level at which performance is significantly affected. If target condition grades are lowered and the consequential cost savings to be realised, it is essential to understand the target represents a minimum standard to which the defence must comply at all times, avoiding any perspective that suggests the target only represents an aspirational vision.

FOCUS PRODUCT 3.2: Methodology for setting target condition grades of defences based on their required risk-based performance.

This methodology has been embedded into Environment Agency operational practice.

3.7 Piloting of performance feature flow charts and calibration of condition grades

Final comprehensive piloting of the visual inspection methodology was focussed on two main elements:

i. trialling the guidance flow charts;

ii. testing and validating the method of calculating the condition grade by comparing different ways of combining the performance feature scores with the condition grade as recorded in NFCDD.

157 defences were inspected to gather data to calculate condition grades and to test the flow charts. These comprised the following defence structure types:

Embankments	53	Anchored sheet piled wall	16
Earth retaining gravity wall	54	Cantilevered sheet piled wall	11
Free standing gravity wall	14	Beaches	9

The defences inspected were located in the following areas:

River Witham, Boston, Lincolnshire.	Island of Jersey.
Louth Canal, Lincolnshire.	Isle of Grain, North Kent.
Long Eau, Lincolnshire.	Pagham to Ferring, West Sussex.
River Leen, Nottingham.	West Bay, Dorset.
River Trent at West Stockwith and Shardlow.	

Trialling of the flow charts generated a large number of comments and suggested improvements to the flow charts. These require a comprehensive revision (not conducted under PAMS Phase 2). The process also suggested that there was a need to supplement the guidance flow charts with example photos and/or figures.

The aim of evaluating different methods to calculate overall condition grade scores was to find an approach which gave similar scores to that which would have been obtained by the traditional visual approach. This was not least because of the need to avoid a sudden shift in metrics as observed by external auditors such as NAO.

The previously suggested method which emerged under FRMRC relied on assumptions regarding the contributions of different performance features to failure modes and on the degree of dependency or independency between the different failure modes themselves. These relationships, however, are not known (and would require considerable research effort (see recommendation 3.3). Nonetheless, various calculation methods were used to find a ‘best fit’ result compared to results from the existing inspection method (CAM 2). Condition grades were derived for the mean, dependent case (or maximum performance feature score), independent case, and geometric mean of the dependent and independent cases, giving a different spread and ‘balance’ (or distribution) of condition grades for each calculation method. Of these, the approach that represented the closest match to the spread of grades produced by the method currently employed (NFCDD/CAM 2) was that of the dependant case (Max FMI). However, even this produced a notable redistribution of grades, a 20 per cent change between grades 1, 2 and 3. Thus, the complexity of the combination method was not justified by the results and created unnecessary masking of raw data that would be provided by inspectors.

Another approach was considered. Distribution of the mean and maximum (worst case) of raw individual performance feature scores was examined. The results indicated (Figure 3.1) that the closest fit to the current grading system is that of selecting the maximum performance feature score. There is a tendency for the overall condition grade at condition grades 1 and 2 to be worse, but for the critical condition grade 3 (normal target condition grade), and for condition grades 4 and 5, the match is very good. The transparency of the approach – the inspector knows his worst performance feature score will give the overall performance feature score – also commends this approach.

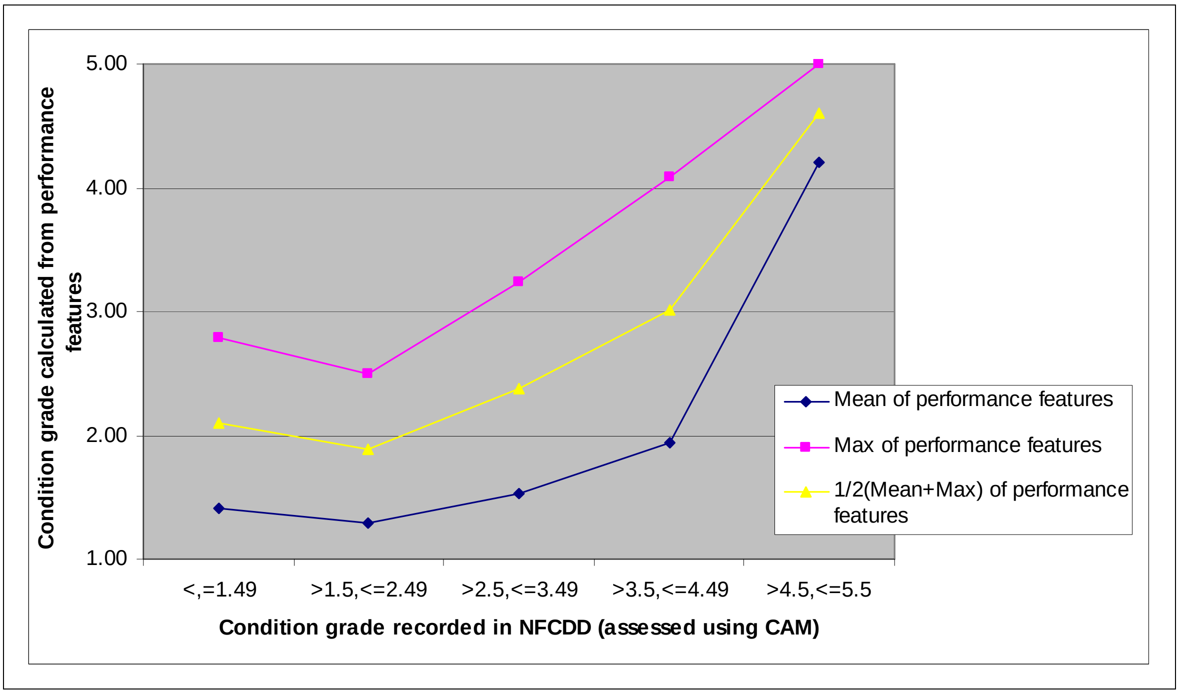


Figure 3.1 Comparison of mean and maximum performance feature grades with current (NFCDD) defence condition grades.

FOCUS PRODUCT 3.3: Methodology (maximum performance feature score) for converting performance feature results into an overall condition grade, calibrated to be generally consistent with that obtainable using the current condition grade approach.

3.8 Triggers for further investigation as a result of visual condition assessment.

Asset inspectors are the eyes and ears of the competent authority 'on the ground'. The inspection methodology, in addition to facilitating data collection and recording on asset condition, must also enable the inspector to 'flag' information or 'trigger' other actions that might be important or required for various reasons. This would primarily concern the need for more detailed inspection to ascertain the state of the defence asset, but might also relate to public or operational safety, recreational use, environmental protection and conservation, access rights or commercial use. Actions will vary depending on the type of flood defence asset being assessed (sheet piled wall, embankment, channel, gravity wall and so on). They may also vary depending on the location or environment of the asset (coastal, rural, urban, fluvial or combinations of these).

The Environment Agency *Work Instruction (no.148-05, 29/04/08) for the Production of Performance Specification for Flood Risk Management Systems and Major Assets* (148-05, 29/04/08) requires that maintenance standards and inspection frequencies be set for each flood defence asset. The inspector should also be able to notify asset managers of any urgent actions that might be required. A set of three questions have been developed (on inspection frequency, deterioration, and urgency - see WP3 Report) for the inspector to answer as part of the asset assessment process to a) provide a mechanism by which 'bottom-up' knowledge/information can be fed into the management and decision-making process, and b) capture information not gathered as part of the condition grading methodology, but still pertinent and important to effective management of the asset.

Report SR3 contains a full set of triggers to identify cases that require further detailed inspection from the point of view of flood defence performance.

FOCUS PRODUCT 3.4: Response 'trigger questions' for inspectors to answer during asset inspection.

The answers to these questions (based on inspection frequency, deterioration, and urgency) can trigger the need for more detailed investigation or physical interventions.

Recommendation 3.1: That action be taken to bring the new condition assessment methodology, including both performance feature assessment and use of trigger questions, into practice on a trial basis on a number of Asset Systems of the Environment Agency. It is suggested that perhaps 30 systems (about 1%) be selected and for these systems, both the existing and the new performance feature approach be run in parallel.

Recommendation 3.2: That (in parallel with the trial implementation) further development of the existing performance feature flow charts be undertaken, including:

- responding to the detailed suggestions arising out of the PAMS Phase 2 piloting;
- adding images to the flow charts to supplement the advice given; therein
- finding ways of better capturing the performance feature assessment for composite structures, dual structures and point structures.

Recommendation 3.3: That longer-term scientific research be considered to assess the contributions of different visual performance features to failure modes and on the degree of dependency or independency between the different failure modes themselves.

Recommendation 3.4: That further research (R) be conducted to validate the link between visual condition assessment and performance, in particular to develop a more robust link between condition grade and overall probability of failure of the asset (as, for example, now being calculated by the RAFT field assessment tool from generic fragility curves).

Recommendation 3.5: That a methodology be developed within sea defence and coast protection for assessing the condition/performance of beach system structures, including control structures (groynes, breakwaters etc) and shoreline system features (dunes, ridges, salt marsh etc), in a manner consistent with the conclusions emerging from the PAMS/RACE scoping study.

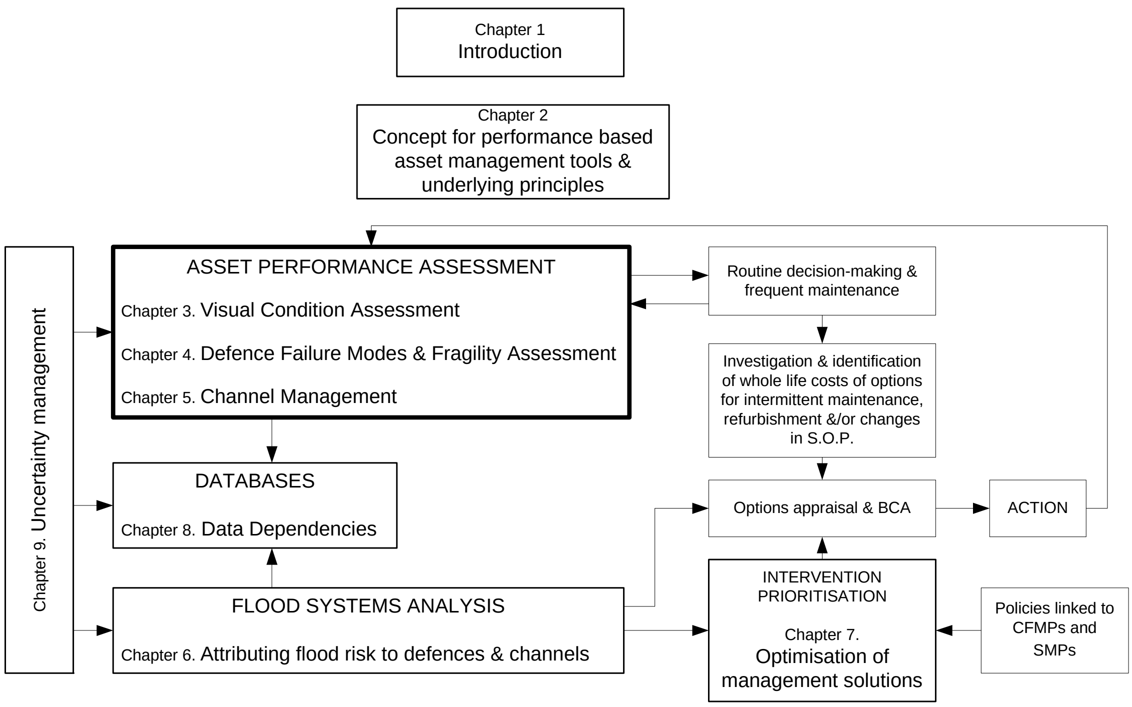
3.9 Condition assessment for non-flood-defence performance

The development of a new assessment methodology did not set out to capture or assess triggers for performance criteria for other functions, although an assessment of these would be required to ascertain a future overall asset condition index.

Recommendation 3.6: That consideration should be given as to whether long-term research is required to determine an overall condition index which reflects factors other than just flood defence functionality (safety, recreation/amenity, environmental etc).

4 Modes of failure and assessment of defence fragility

This chapter describes the importance of understanding of modes of failure of assets and how they perform across a range of applied hydraulic loads and not just at the design load or standard of protection. The concept of a fragility curve, widely adopted in other countries and disciplines, to describe the probability of failure under varying load is explained. Then the ways in which site-specific fragility curves can be generated or inferred are described. Examples are given of the application of the methods with reference to pilots projects.



The previous chapter emphasised the importance of understanding failure modes when assessing the condition of assets. The condition of defences affects the manner and likelihood of potential breaches and the consequential way in which water will enter the flood plain. The challenge is to understand the linkage between loading (principally related to water level or waves) and asset response in terms of resilience or failure. This understanding can be gained by a combination of scientific understanding, experience, and knowledge of local sites.

Achieving this understanding is potentially complex and the effort put into assembling evidence on any asset's performance under load must be (a) proportionate to the perceived risks of asset failure (likelihood and consequence) and (b) fit for purpose in assessing the potential options for intervention. The project has evaluated and tested a range of approaches to describing asset response, including traditional deterministic methods (single value of loading), generic fragility curves and a reliability tool developed under the FRMRC and FLOOD*site* consortia projects.

4.1 Failure modes and performance across a range of loading

The starting point for this understanding is to identify the two or three most important or critical failure modes and to prepare simple fault trees which take these into account. This is no different from conventional engineering practice, involving the same judgement that engineers would conventionally use in selecting these failure modes and the same equations that an engineer would use for a conventional analysis.

What is different in modern asset management thinking from much conventional engineering design practice is that more than one loading condition is examined. This is not about looking at combinations of fixed applied loads which is common to much structural design, but the need to address defence performance/response for each of the critical failure modes across a range of magnitudes of the critical applied loadings (such as water level), not just at a single 'design point'. This understanding of performance across a range of loading events is important for asset management because:

- There is a small but real risk of failure at low loads because of residual anomalies in the structure.
- Some resistance to failure always remains when defences are overtopped; this resistance can be critical to minimise consequential flooding when events occur which are greater than that for which the geometry (crest elevation, side slopes) of the structure was designed.

This varying performance, following approaches originally pioneered in seismic engineering, can be expressed as a graph showing increasing probability of failure with increasing load. This graph is commonly called a fragility curve. Figure 4.1 illustrates the point. In traditional deterministic design, the assumption is that the probability of failure is zero until the design load event is reached, at which point the probability switches to one. (The risk of failure under design loading at the ultimate limit state (ULS) is minimised by employing partial safety factors on loading and strength.) In reality, at the design load the probability of failure is not zero but a small number. As Figure 3.2 illustrates, as the load rises above the design condition, the probability of failure rises and only after considerable extra load has been applied does it actually approach one. Similarly, there is a small but significant probability of failure at conditions below the design loading.

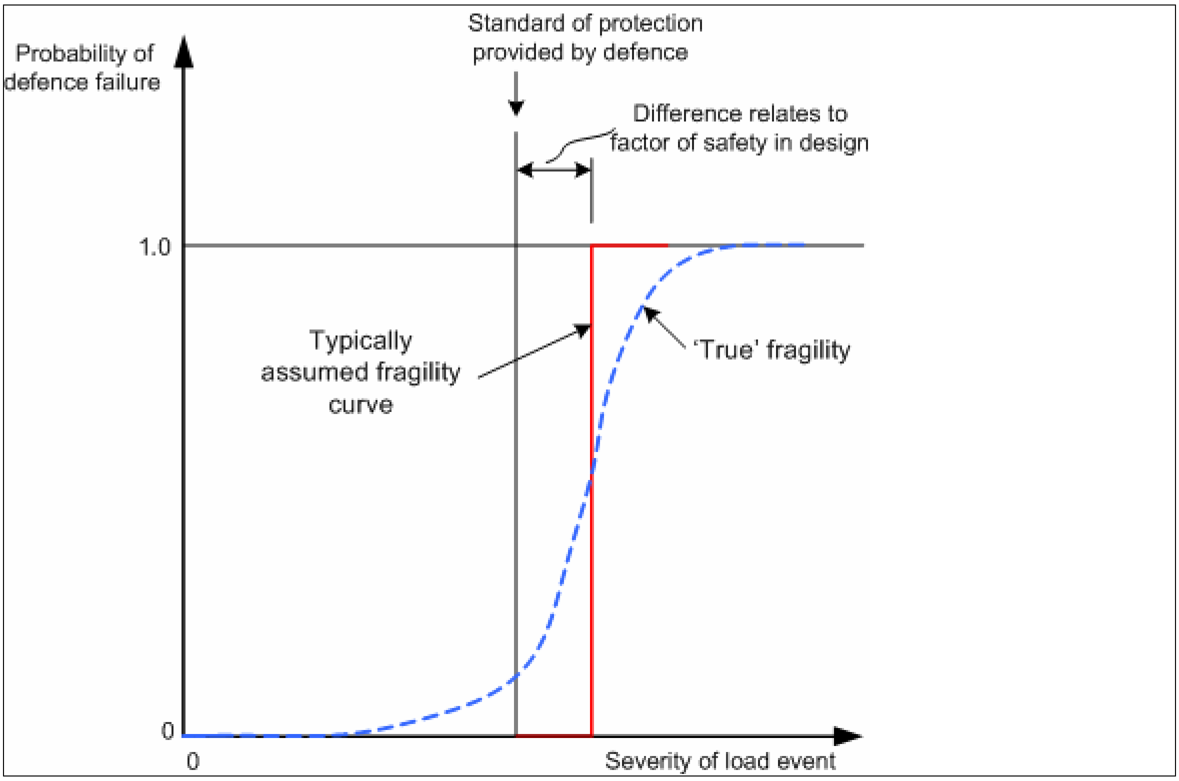


Figure 4.1 Assumed and 'true' fragility curves.

The significance of this varying performance with increasing load for flood risk benefit assessment was first grasped by economists in the USACE (1991, 1993) – although not implemented in terms of engineering systems analysis. When carrying out flood risk systems analysis, it is now seen as crucial to represent this varying performance at sufficient accuracy (see Chapter 7).

A given defence asset can exist in a variety of states. These states are commonly represented by the condition grades discussed in the previous chapter. Different fragility curves are therefore needed to represent these different states. As the defence deteriorates, these curves enable the corresponding variation in performance to be represented.

The form of the actual curves can range from:

- deterministic (single point) or a highly simplified two-point fragility curve (as originally conceived in the US);
- a standardised but approximate fragility curve for a generic asset type (as adopted in the RASP analysis for the now established regular UK national flood systems analysis, NaFRA);
- a site-specific fragility curve, generated for an asset at a specific location.

Using this range of approaches, a tiered approach to assessing and understanding the performance of defences and defence systems becomes possible (as recommended in the Government's guidelines on managing environmental risk):

- More easily justified management interventions can be prioritised using general risk screening methods without resource to fragility curves.
- Generic fragility curves for different asset types can be used for broad scale analysis and to aid the planning of management interventions. At this level,

they provide a basic understanding of the performance of the asset and the system within which it located as it responds to flood loading.

- Site-specific fragility curves (based on some or all of the attributes and parameters of the assets to be assessed) are appropriate when prioritising local management interventions. The associated level of detailed analysis is particularly relevant for the assessment of complex, high consequence or high cost asset systems, or where contentious decisions are envisaged (such as withdrawal of maintenance of defences or reduction in maintenance).

***FOCUS PRODUCT 4.1: Guidance on how to prepare asset-specific fragility curves*.**

This work, summarised in Sections 4.2 and 4.3 of this report, is based on a reliability analysis of multiple potential failure modes linked by fault trees. This approach has been trialled successfully on the West Bay and Thames pilot sites, where it is embedded in the TE2100 assessment methodology for asset refurbishment, change or replacement. The guidance shows, not surprisingly, that bespoke curves for specific assets can be very different from generic curves.

Recommendation 4.1: That guidance be produced on tiered evaluation of defence assets, aimed at asset managers and their consultants, to explain the range of approaches that can be adopted for understanding defence performance, including an *appropriate use of probabilistic methods* in the description of asset response. The guidance would therefore include:

- **As a starting point, a screening process utilising a series of logical questions based on conventional engineering data collection and appropriate consideration and assessment of the failure modes.**
- **Recommendation, where appropriate, to move on to the development of fragility curves by a tiered range of techniques (set out in preliminary form in the PAMS Phase 2 report):**
    - **Lowest level of evaluation, based on selection of standardised fragility curves based on visual condition assessment. (**In fact, at this level fragility curves might not need to be mentioned at all. As explained in section 6.3, the highly simplified approach embedded in the new RAFT spreadsheet tool reduces these curves down to a single annual probability of failure and this is being rolled out within the Environment Agency as a field method for attributing risk to defences.)
    - **Highest level of evaluation – the 'full approach', which involves the use of the RELIABLE tool, should include 2-3 worked examples, one of which might involve use of implicit relationships (e.g. those associated with the numerical models required to analyse slope stability problems in flood embankments).**
    - **Intermediate level of evaluation involving determination of high level fragility curves for selected assets in a system and inferring/interpolating to the remaining assets.**

Where insufficient information is available to develop site-specific fragility curves, it is possible to identify two points on a fragility curve from deterministic design thinking:

- At the normal design point (design extreme water level or overtopping event) in conventional (conservative) approaches to identifying engineering parameters and asset performance, the probability of failure will typically be one to 10 per cent.
- If mean values for engineering parameters (without conservatism bias) are used to identify a hydraulic loading condition at which the factor of safety against failure is about one, at this loading condition the probability of failure will be about 50 per cent.

Identification of these two points for a fragility curve can be useful as a cross-check or as a way of adapting generic fragility curves.

Recommendation 4.2: That, to support recommendation 4.1, the national generic set of fragility curves be improved. Whilst ideally locally generated site-specific or relevant curves would be developed everywhere, this is unrealistic in the short term and significant advantage could be gained by improving the generic curves. This improvement could be achieved by a combination of the following:

- **capturing the results of any available of site-specific analysis (such as TE2100);**
- **using the 50% and 10% 'probability of failure' translation rules;**
- **carrying out improved analysis of the generic structure types using a team of experienced engineers and reliability analysts**.

Recommendation 4.3: That, to support recommendation 4.1, the guidance on simple probability of failure translation rules and the adjustment of generic fragility curves be further improved. Further case studies would not only further validate the approach but give improved guidance. In particular, design methodologies for some failure processes do not use the factor of safety approach (for example, those approaches that use critical values of parameters such as velocity). In these cases, further work would help to tease out appropriate conversion rules.

4.2 Generating site-specific fragility curves

Generating site-specific fragility curves is an achievable task. The process must be based on a clear engineering understanding of the performance of the structure concerned, including:

- Identifying all the key failure modes and their interrelation, ruling out failure modes which generate negligible probabilities of failure.
- Identification of mean values and statistical distributions (in most cases standard deviations will be sufficient) for all load and strength parameters affecting the key failure modes.

- Well-informed choice of equations or other representations that describe the response of the asset to flood loading under each potential failure mode. In many cases this model will be some kind of explicit (ultimate) limit state equation (LSE). In some cases (such as slip failure) this will not be possible and use of implicit models, such as finite element models, may be necessary.

The generation of site-specific fragility curves follows a clearly defined process:

- Recast the limit state equation or model in reliability form: Z (reliability) = R (strength) – S (non-hydraulic loading) – S (hydraulic loading), where R represents the gathering of all terms or parameters which relate to the strength of the structure and S represents the gathering of all terms or parameters which relate to the magnitude of the loading.

- Prepare fault trees that specify the logical sequence of all possible failure mechanisms leading to the failure of the defence.

- For a given hydraulic loading condition, perform a reliability analysis comprising a series of Monte Carlo simulations (across the uncertainty bands for each input parameter). Failure arises in a particular case when the combinations of parameter values in the limit state function Z gives a value for Z which is less than or equal to zero. The probability of failure for that loading is then the number of times when the simulation gives Z as less than or equal to zero divided by the total number of simulations.

- Repeat the reliability analysis for a range of other hydraulic loadings, in each case determining a probability of failure. From the results draw a fragility curve.

To make the above process easier, under FRMRC1 and FLOODsite Task 7, a user friendly and flexible software 'reliability tool' (RELIABLE) was developed to analyse the reliability of flood defences. The tool (see Figure 4.2) includes a total of 72 failure modes represented as simple Limit State Equations (LSEs), a flexible fault tree component, and a probabilistic failure analysis component based on Monte Carlo simulation (MCS).

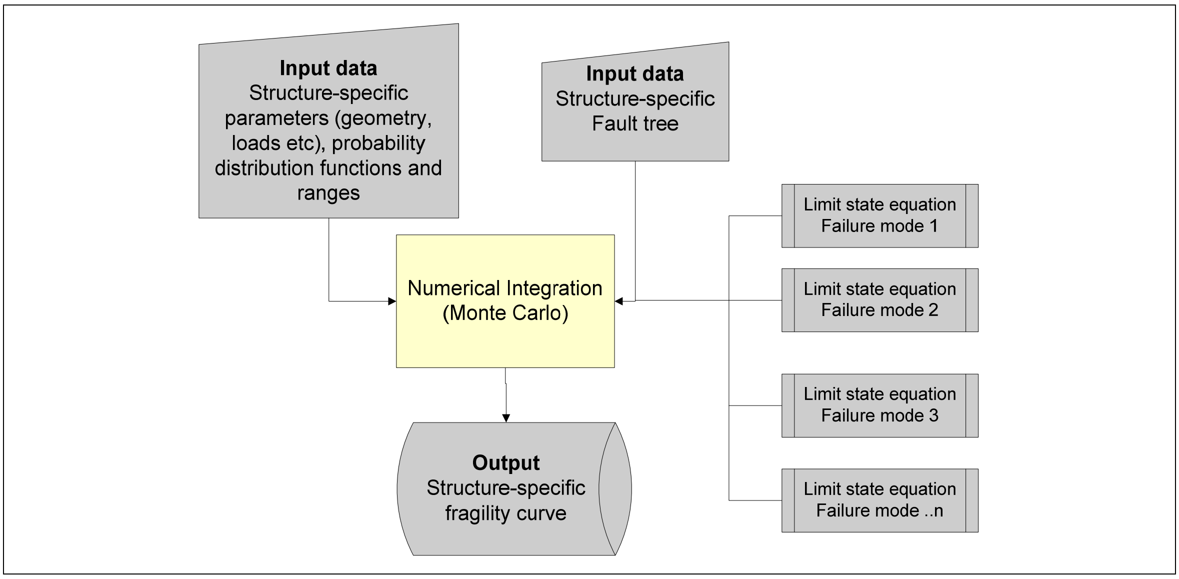


Figure 4.2 RELIABLE – a structured and extendable software tool to analyse the reliability of a defence asset (van Gelder *et al*, 2008a).

Some failure modes are not yet included in RELIABLE. Although there is ongoing work to add more modes, some processes require a more specific representation (for example, via finite element modelling). In these cases, RELIABLE should be used first to generate a fragility curve for all failure modes included therein.

For the failure mode not included in RELIABLE, repeated runs of the structural models (e.g. for slope stability for embankments) should be carried out using the known variability of input parameters. This exercise will yield the probability of failure for a given hydraulic loading. The process can be repeated for other hydraulic loadings and a fragility curve for this failure mode built up. Standard software packages, such as finite element packages for soil slope stability, often contain useful routines to automate this process. Figure 4.2 illustrates the fragility curves for a slope stability failure mode on a Thames Flood embankment, with the corresponding variation in factor of safety given in Figure 4.3. Assuming the additional failure mode is independent from those evaluated in the reliability tool, an overall fragility curve can be generated by combining fragility curves using De Morgan's Law.

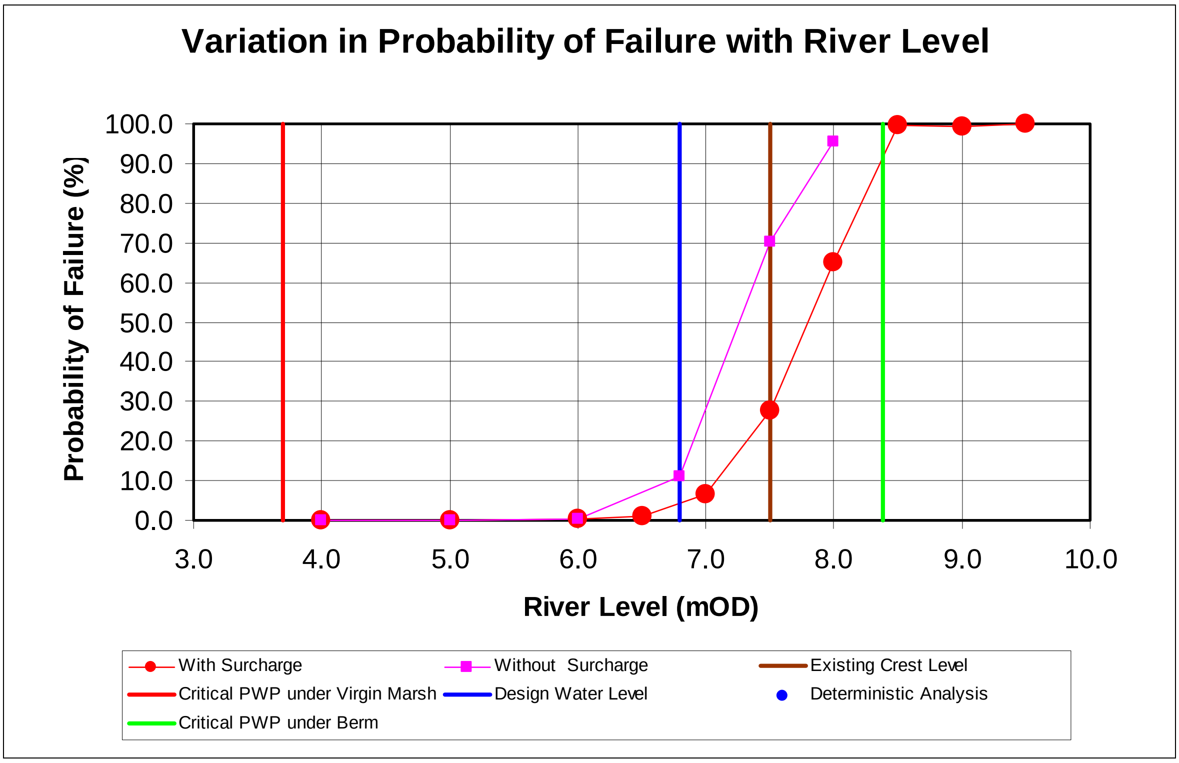


Figure 4.3 Fragility curve for wide multi-bermed embankment in the Thames Estuary.

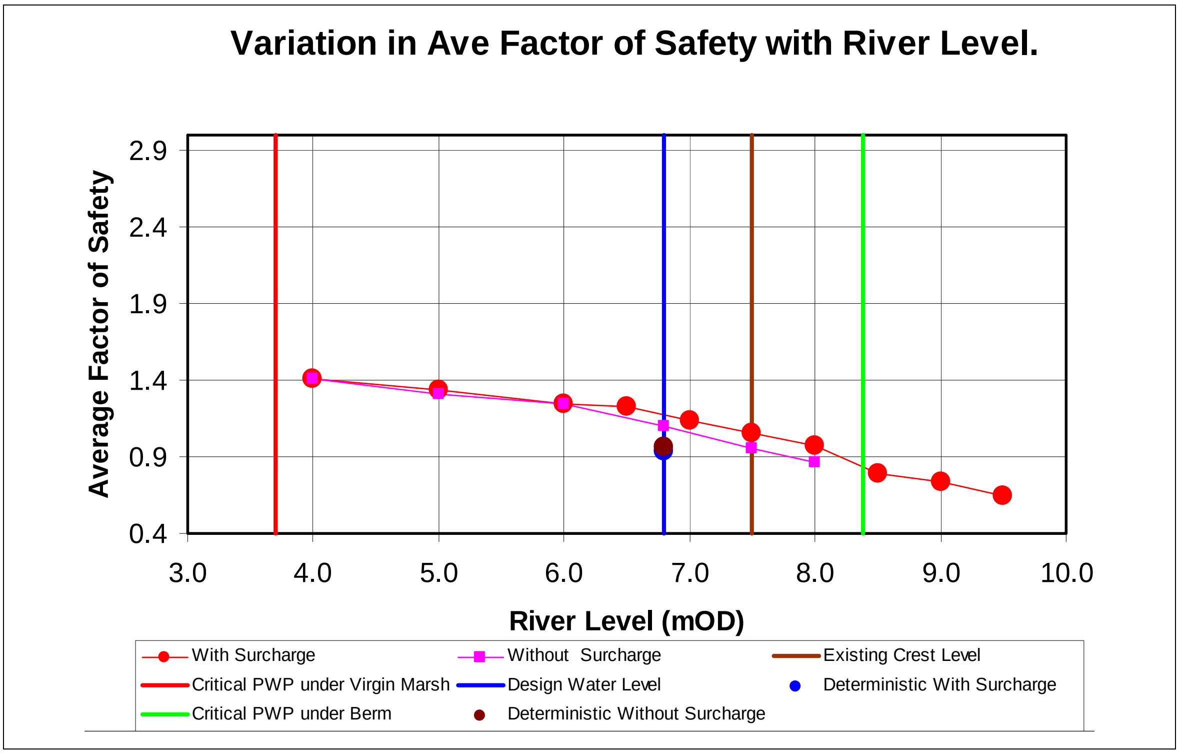


Figure 4.4 Variation of geotechnical factor of safety with water level for a wide multi-bermed embankment – corresponding to fragility curve in Figure 4.3.

Recommendation 4.4: That the reliability tool developed under FRMRC1 and FLOOD*site* be further tested and developed to cover further asset types and limit state equations. This includes:

- **Coding up additional subroutines of failure modes where an explicit equation or model is available and the equation has not yet been implemented in RELIABLE.**
- **Development of approaches (e.g. neural networks) for creating shortcuts to generate fragility curves for failure modes of selected structure-type failure modes where the solution require the use of implicit relationships (e.g. numerical models).**
- **For those modes of failure for which appropriate limit state equations or models do not exist – e.g. for piping of flood embankments – methods for developing and improving fragility curves should be developed and/or recorded. (R)**

In some cases, aspects of the structure or its potential failure modes will not be readily represented by conventional equations and analytical methods. In this case, engineering judgement can be used to reflect general understanding of the particular asset or system. For example on the Thames (TE2100), crest fissuring was simulated by shifting the crest level in the model for overtopping failure mode to reflect the effect of fissuring lowering effective crest level below the as-surveyed level. In a similar way, it would be possible to make a judgement-based adjustment to reflect the increased possibility of piping if, for example, many vermin holes existed in a flood embankment.

Under the pilot projects, development of site-specific fragility curves for real sites, namely the Thames (TE2100) and West Bay exemplar sites, showed that with sound engineering input the resultant curves are believable and consistent with traditional engineering practice as typified by deterministic methods of analysis. The example given in Figure 4.4 from TE2100 shows a situation in which a geotechnical finite element software package was used for the slope stability failure mode and software package, the RELIABLE tool was used for the overtopping failure mode and the crest fissuring adjustment described in the previous paragraph was also made for the overtopping failure in the cases when the embankment was in poorer condition (Grades 4 and 5).

Uncertainty in developing reliable fragility curves can be reduced by:

- local knowledge of structures held by asset managers;
- careful engineering investigations of loadings, structural state and ground conditions.

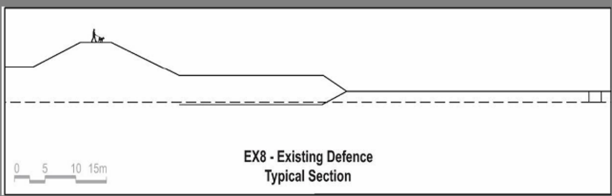
These conclusions on the use of fragility curves have been supported by discussion and exchange of information with leading authorities in the USA and Netherlands and with other researchers, in particular under the EU FLOODsite project.

Exemplar Site:	**EX8 - EXISTING DEFENCE**			
Location:	**DARTFORD MARSHES**	**Grid Reference:**	**TQ 54 77**	
Condition Grade:	**1**	**Existing Defence Height:**	**7.50m**	**AOD**

Description: The current defence comprises of an earth embankment with landward berm. The landward berm is constructed form non cohesive dredged material to provide stability, but primarily to resist uplift pressures. The embankment and underlying cut-off through the berm is constructed from clay. This embankment is located to the rear of an existing older embankment. The embankment was constructed in two primary stages (the berm and the clay embankment) to allow gradual settlement and improvement in the strength of the alluvium to occur between the construction stages. It is understood that the embankment was constructed in the 1970's.

Soft Defences

Site	Failure Mode	Method of Analysis (HRW Formula)	Driver for changing Condition Grade	Condition Grade Impacts	Time	CG Grades Included in Analysis	Comments
	Existing Defence						
EX8	Settlement	Not included	N/A				Not critical as freeboard maintained through crest raising.
	Overall stability	Not included	N/A				Not critical.
	Piping	Unable to assess. No available LSE.	N/A				
	Uplift	SLOPE/W	Permeability of sands and Gravels.			CGs 1 to 5	Critical landward condition.
	Cracking and fissuring	Unable to assess. No available LSE.	N/A				
	Erosion of foreshore causing front face slip	Not included	N/A				Erosion protection provided by rock armouring and revetment - therefore erosion not a concern.
	Low water riverward stability - non-rapid drawdown.	Not included	N/A				Greatest uncertainty in riverward geometry and geotechnical parameters. Rock toe and reveted slope will limit erosion and improve stability. Considered not critical but should be reviewed once more robust information becomes available. Recommendation for future studies.
	Low water riverward stability - rapid drawdown.	Not included	N/A				Stability very sensitive to residual excess pore water pressures in slope which are not quantifiable given our present level of understanding. Rock toe and reveted slope will limit erosion and improve stability. Considered not critical but should be reviewed once more robust information becomes available. Recommendation for future studies.
	Erosion of embankment surface by overflow	Ba1.1	Quality of grass cover			CGs 1 to 5	The potential effects of fissuring on condition Grade 4 and 5 include a horizontal adjustment (0.3m (CG4), 0.6m(CG5) that represents the erosion that can occur at lower water



FAULT TREE

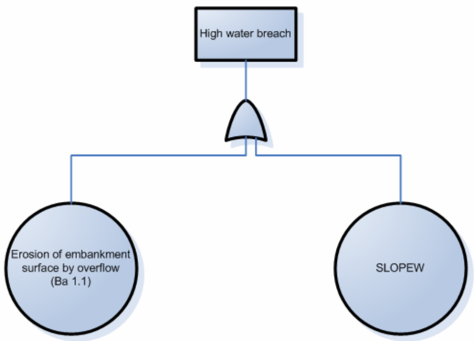


Figure 4.5 TE2100 exemplar structure (embankment) appraisal and fragility curve.

LSEs and PARAMETERS

LSE - Ba1.1 - Erosion of embankment surface by overflow

$$Z = M_R q_c - M_L q_0$$

q_c = Critical overtopping discharge (Resistance)

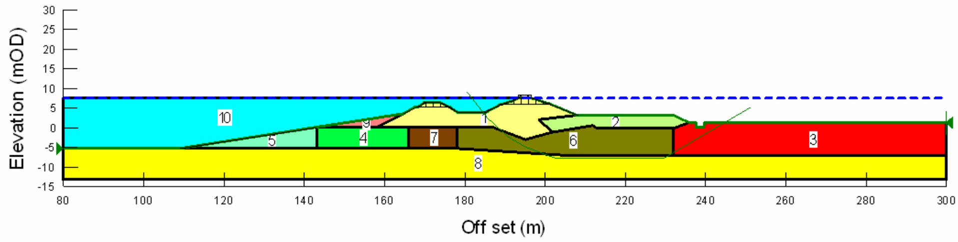
q_0 = Overflow given by broad crested weir equation (Loading)

M_R = factor representing uncertainty on resistance equation

M_L = factor representing uncertainty on loading equation

Name	Distribution	Value/Mean	Std Dev	Description
Hover	-	**	-	Depth of flow over (local) crest - used in loading calc, ** **this is the key hydraulic loading parameter of interest and is systematically varied to determine the fragility curve**
Grav	-	9.81	-	Gravitational constant (g) - used in loading calc
KdKf	N	0.4	0.03	Coefficient for consideration of the crest width B_k and sharp-crestedness of the weir Rk - used in loading calc, KdKf is equal to $CD/(c_v\sqrt{2g}) = CD/\sqrt{2g}$ where the range for CD is 1.4 (broad) to 2.1(sharp crested)
DissCoeff	-	1	-	Dissipation coefficient (c_v) - used in loading calc, set to 1 for the ease of determining KdKf distribution (see above)
GrassRevQ	N	1.05	0.12	Quality factor for grass revetment (f_g) - used in resistance calc, distribution selected to represent poor (0.7) to good (1.4) quality grass
RouF	N	0.059	0.01	Roughness factor by Strickler (k) - used in resistance calc, Manning's n for grassland with height 10cm-20cm (range 0.22-0.28, mean=0.26) was converted to a range for k using the Manning-Strickler equation
InsSlopeAng	-	17.49	-	Angle of the inner slope (in degrees) - used in resistance calc
StormD	LN	3	0.65	Storm duration (t) - used in resistance calc, distribution selected to capture storm durations between approx. 1 and 6 hours
OverPercen	-	1	-	Proportion of time overtopping during the storm duration - used in resistance calc, assumed to be 100%
MBA1_1R	-	1	-	Ba1.1 model uncertainty factor (resistance) - M_R
MBA1_1S	-	1	-	Ba1.1 model uncertainty factor (load) - M_L

LSE - SLOPE/W - Uplift



Material#:1 Description:Water Model:NoStrength Wt:9.807 Piezometric Line:1
Material#:2 Description:Clay Fill Model:UndrainedPhiZero Wt:18.6,Normal(Mean=18.6,SD=0.5) Cohesion:30,Normal(Mean=40,SD=3.5) Piezometric Line:0
Material#:3 Description:Sand Bern Model:MohrCoulomb Wt:18.6,Normal(Mean=18.6,SD=0.5) Cohesion:0 Phi:32,Normal(Mean=33,SD=1,Min=30,Max=36) Piezometric Line:0
Material#:4 Description:Virgin Marsh (No Strength) Model:UndrainedPhiZero Wt:12.8 Cohesion:1 Piezometric Line:0
Material#:5 Description:Foreshore(as Virgin Marsh) Model:SFnDatum Wt:12.8 C-Datum:6.4 C-Rate of Increase:1.63 Limiting C:0 Elevation:1.2 Piezometric Line:0
Material#:6 Description:Sloping foreshore Model:SFnDepth Wt:12.8 C-Top of Layer:6.4 C-Rate of Increase:1.63 Limiting C:0 Piezometric Line:0
Material#:7 Description:Alluvium below berm and new embankment Model:SFnDatum Wt:12.8,Normal(Mean=12.8,SD=0.8) C-Datum:12.04,Normal(Mean=14.04,SD=2) C-Rate of Increase:1.35 Limiting C:0 Elevation:3.2 Piezometric Line:0
Material#:8 Description:Alluvium below old embankment Model:SFnDatum Wt:14.7 C-Datum:14 C-Rate of Increase:1.62 Limiting C:0 Elevation:6.2 Piezometric Line:0
Material#:9 Description:Sands and Gravels Model:MohrCoulomb Wt:19.6 Cohesion:0 Phi:32,Normal(Mean=33,SD=1,Min=30,Max=36) Piezometric Line:1
Material#:10 Description:Mud Model:UndrainedPhiZero Wt:12.7 Cohesion:10 Piezometric Line:0

Correlation between Material Numbers and Region Numbers shown on section.

Material # 1	Region # 10
Material # 2	Region # 1
Material # 3	Region # 2
Material # 4	Region # 3
Material # 5	Region # 4
Material # 6	Region # 5
Material # 7	Region # 6
Material # 8	Region # 7
Material # 9	Region # 8
Material # 10	Region # 9

FRAGILITY CURVE

EX8 All condition Grades

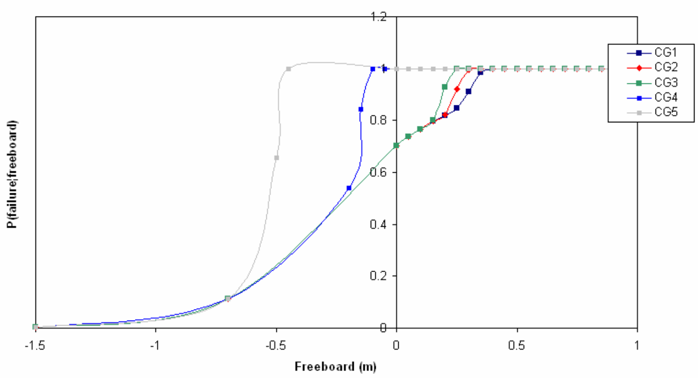


Figure 4.6 TE2100 exemplar structure (embankment) appraisal and fragility curve (continued).

Recommendation 4.5: That current flood risk management methods for determining the fragility of earth flood embankments be reviewed jointly with the reservoir safety programme (also within SAM Theme), with particular reference to the scoping research recently undertaken on QRA (qualitative risk assessment) and modes of embankment dam failure. The Environment Agency should ensure that future methodologies for assessment of flood embankments and for dam embankments associated with small raised reservoirs (less than 25,000 cu m) are appropriately consistent.

Recommendation 4.6: That work be carried out to develop fragility relationships for sea walls (for a range of condition grades) which take account of both loading (forcing) conditions and some characterisation of beach system state. At present the generic RASP fragility curves are linked to the wave overtopping loading, but it is known that this is imperfect as it does not completely reflect the significance of beach level in front of the wall and its relation to toe level. In RACE the 'fragility' curves are time dependent and, whilst at a national scale this is adequate for coastal erosion assessment, there is a failure to capture the link with beach physical processes.

Recommendation 4.7: That the extent to which defence fragility varies through the season of the year be examined. For example, under the seasonal variation of the incipient wave climate, beaches often assume different surface profiles in the winter and the summer. This can lead to a significantly different performance when extreme events occur.

Recommendation 4.8: That the relationships be examined between the 'frequency domain' assessments of defence failure via fragility curves and the 'time domain' analysis of breach initiation, growth and consequential flooding. This is partly already being addressed under FRMRC2.

Recommendation 4.9 That a way be developed of describing the fragility (including modes of failure) of groynes and other beach and wave control structures in a manner which is linked to their functional requirements and the behaviour of the beach system with which they are associated. This recommendation is therefore linked to Recommendations 4.6, 4.7 and 4.8 because failure of beach control structures to retain beach material only impacts on the beach system over a period of time. The understanding of these mechanisms and their impact on performance and the development of any associated tools are essential to permit attribution of erosion risk (benefits) to individual (or groups of) coastal control structures. As such, these developments are as important as making the connection between risk and conveyance management in rivers.

Recommendation 4.10: That the work carried out as part of the RAFT study (see Chapter 6) to establish fragility curves for non-linear assets such as culverts, flap gates and flood gates be extended to derive fragility curves for other common/critical types of non-linear assets (e.g. screens). In each case, the requirements for data collection should be established, including the type and accuracy of data required for systems analysis (see Chapter 8).

Recommendation 4.11: That, reflecting the importance of culverts in asset management, a short note be prepared based on the Culvert Design and Operation Guide (CDOG) to explain how the assessment and management of culverts should be linked into the assessment and management of other assets.

4.3 Translation of site-specific fragility curves to a wider asset base

A further consideration in systems analysis is that defences can be assumed to perform independently once the distance between defence cross-sections exceeds 300 m for hard defences (or 600 m for soft defences). This would mean that a new fragility curve would need to be developed for every 300 or 600 m of defence and this would clearly involve disproportionate effort.

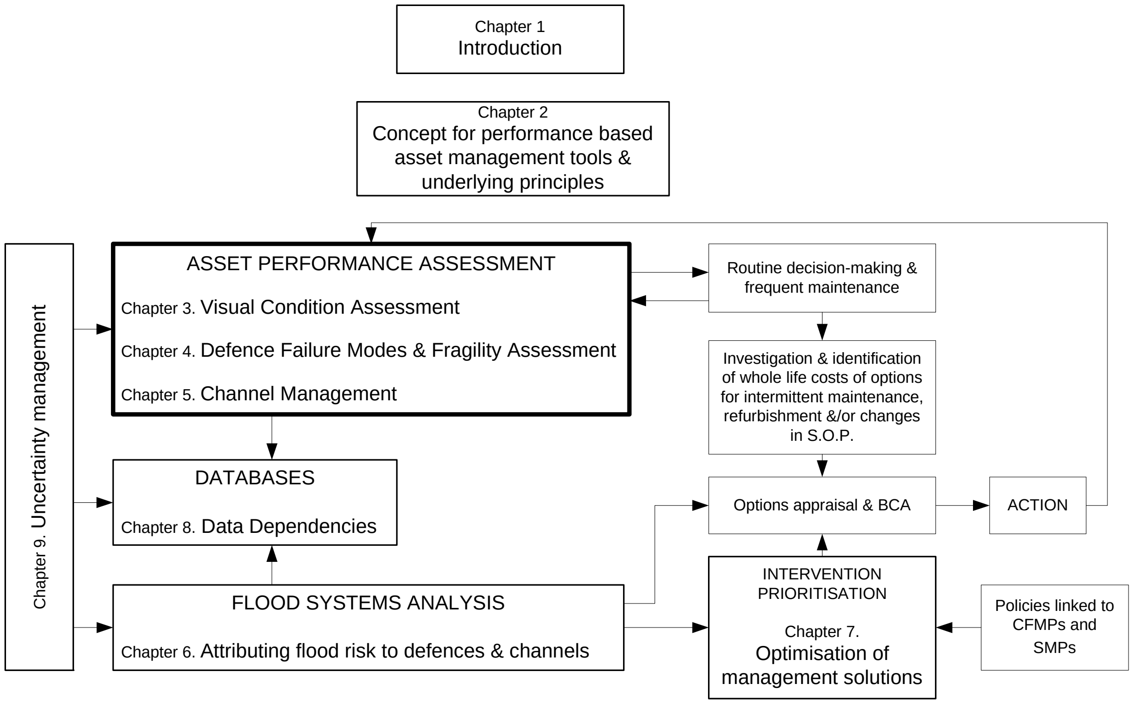
One way to avoid having to develop fragility curves for every defence is to develop new curves for representative defences. The approach involves selecting a number of ‘exemplar’ defences, each of which has a structural form, associated geology and hydraulic loading environment representative of a number of defence lengths in an asset system. The fragility curves for this exemplar defence should then be developed for all potential condition grades and can be used for similar defences in the system.

Identifying which exemplar defence is representative of which other defences can be achieved by a combination of two methods:

- Comparing basic information about the structural form of the assets (such as RASP type, plans, sections and photographs, crest level) on an asset-by-asset basis.
- Identifying a mapping between the exemplar defence and national asset classification (RASP type) allocated to remaining defences of similar type.

5 Channel management

This chapter starts by explaining why it is important to manage the conveyance of river channels and the impact of channel management activities. It sets out a better way of making a connection between channel management activities and channel performance and a tiered process for assessment. The approaches are explained with reference to one of the project pilots and the report concludes by summarising the supporting and emerging research in this area.



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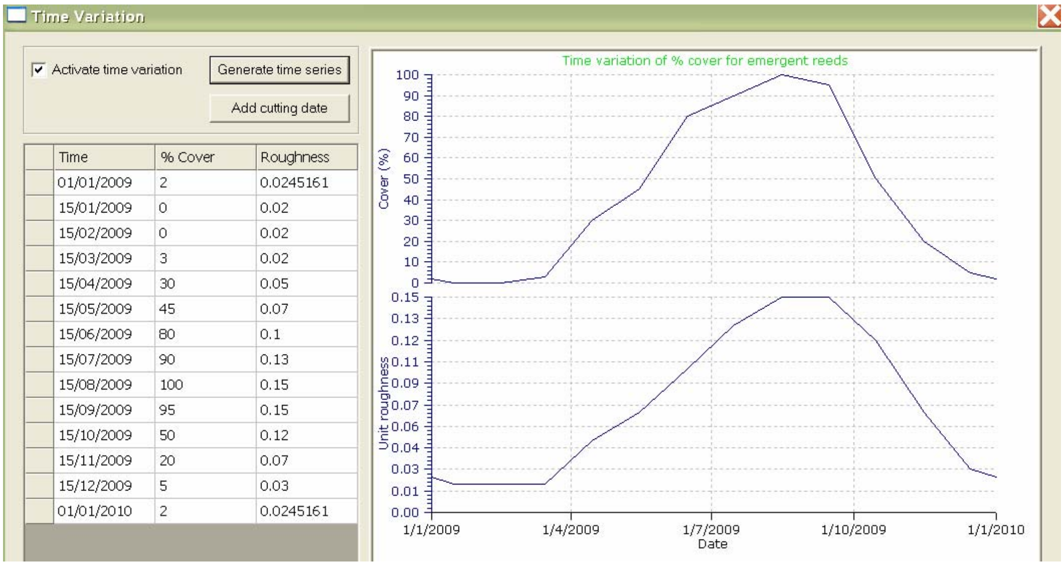
5.1 Why manage channels and watercourses?

River channels and watercourses should be managed to ensure an acceptable level of flood risk. At a catchment or sub-catchment scale, this will include identification of the necessary balance between flow and flood storage. Once such strategic decisions have been made, the key property of the channel (in terms of flood risk) is its ability to pass flows without excessive water levels. Conveyance is a quantitative measure of this ability. It relates the total discharge to a measure of the gradient of the channel:

$$Q = K\,S^{1/2}$$

where K (m^3/s) is the conveyance, Q (m^3/s) is the discharge and S is the uniform gradient.

Vegetation and its overgrowth is one of the main factors influencing flow capacity, hence river conveyance. Its influence is captured mainly by roughness coefficients and also by hydraulic radius (as a reduction of flow area). The growth cycle of vegetation causes a variation of roughness coefficients during the year. Maintenance works, for example cutting, vary the growth cycle of vegetation and hence the flow resistance.



Time	% Cover	Roughness
01/01/2009	2	0.0245161
15/01/2009	0	0.02
15/02/2009	0	0.02
15/03/2009	3	0.02
15/04/2009	30	0.05
15/05/2009	45	0.07
15/06/2009	80	0.1
15/07/2009	90	0.13
15/08/2009	100	0.15
15/09/2009	95	0.15
15/10/2009	50	0.12
15/11/2009	20	0.07
15/12/2009	5	0.03
01/01/2010	2	0.0245161

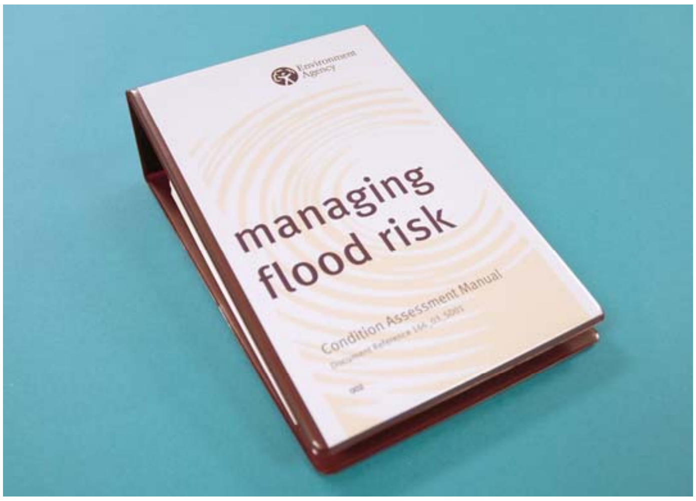
Figure 5.1 Example of emergent reeds growing in the channel of Great Eau (left) and time variation of percentage of cover and unit roughness for this type of vegetation provided by the CES Roughness Advisor (right).

Sediment deposits and channel blockage can also reduce the watercourse flow area and conveyance, whereas dredging, desilting and blockage removal will improve these.

The effects of vegetation overgrowth and sediment deposits vary with channel size. For example, vegetation growth is likely to have a larger impact on conveyance in small shallow channels than in wider and deeper channels. Any management actions must be properly assessed because they have a big impact on flow velocities and depth and hence on channel habitats and diversity. For example, over-sized channels are not sustainable because sediments tend to deposit in them and hence the channel requires regular dredging.

FOCUS PRODUCT 5.1: Guidance on the assessment of condition grades for vegetation and blockage in channels.

This guidance is contained within the revised Environment Agency Condition Assessment Manual (CAM2) prepared as part of this project (see Focus Product 3.2 – Chapter 3).



5.2 Impact of channel management works

River channels within England and Wales exhibit a wide spectrum of natures from completely engineered to completely natural. The engineering issues associated with maintenance will depend on where in this spectrum a particular channel lies. Channels may have their conveyance capacity restricted by various means such as natural growth of vegetation or sediment deposition, or 'unnaturally' by fly-tipping waste and by debris blockage at structures such as culverts and trash screens. The roughness of a channel also has an effect on water flow – engineered channels are often smooth, offering less resistance to water flow than channels of a rougher or rockier nature.

Management strategies may affect both the cross-section (desilting/dredging/blockage removal) and the hydraulic roughness (vegetation removal/cutting). In the source-pathway-receptor framework, the management of channels modifies water levels in the watercourse (source). The sensitivity of water level changes associated with different management options varies for different channels.

It is envisaged that management strategies would be prioritised based on:

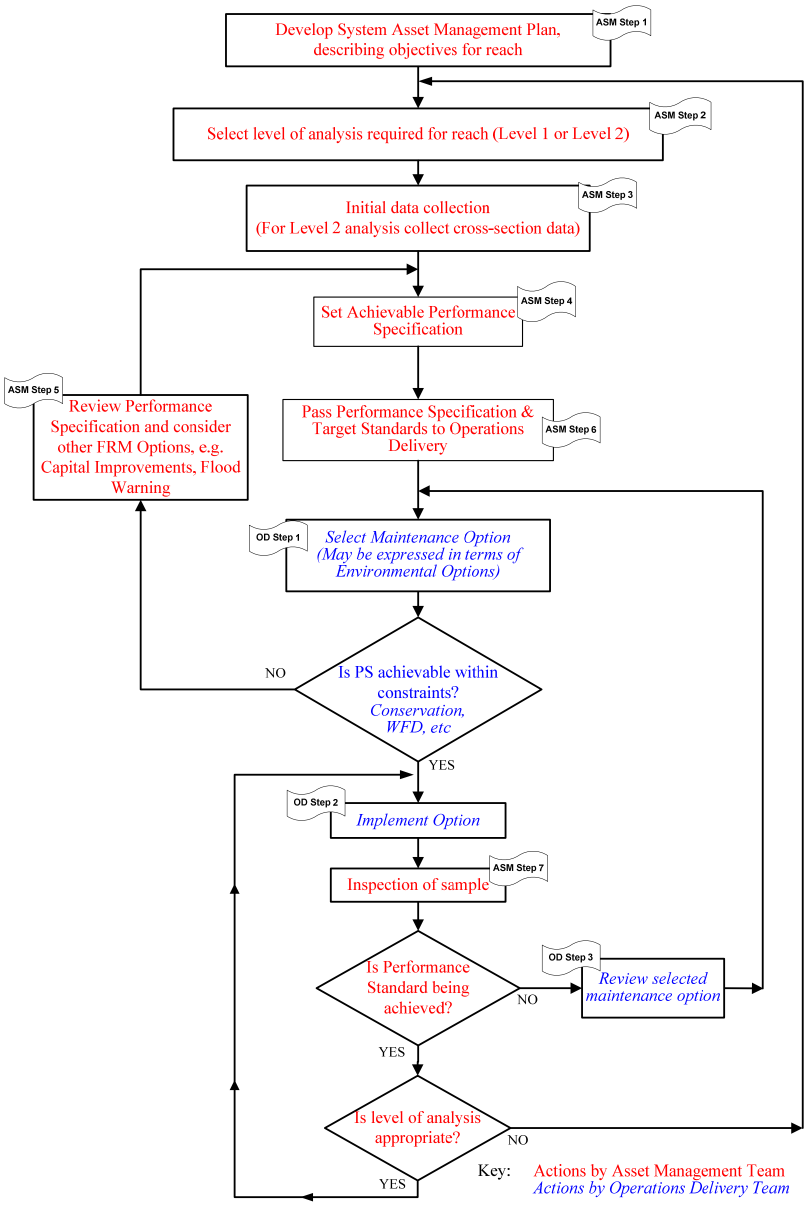
- feasibility of implementation (for example, access may only be possible to one bank);
- ease/cost/environmental impacts of implementation (for example, no local facility for recovery of dredgings);
- morphological benefit (such as channel in equilibrium);
- ecological benefit (promotes habitat, improves water quality and so on);
- other criteria and constraints, for example in terms of potential impact on fisheries, navigation, biodiversity and ecological status.

5.3 Making a better link between channel management and performance

During the course of the project, it became apparent that it would be useful to provide guidance on the setting of performance standards. The PAMS team were therefore asked to provide this guidance in draft form to the Environment Agency. These guidance documents (Focus Products 5.2, 5.3 and 5.4) outline a process for establishing performance targets for each channel reach (excluding natural channels), based on the most critical locations within reaches.

FOCUS PRODUCT 5.2: Flow chart for overall process of managing the conveyance of channels

(Figure for illustrative purposes only)



In the guidance, selection of target condition grades takes into account the probability of flooding and potential consequences, that is, the risk of flooding. The guidance is to ensure that the specified performance targets are achievable through maintenance of the existing channel cross-section (without channel deepening or widening, other than removal of accumulated material). Managers are then responsible for determining and carrying out any work required to achieve this performance. Periodic conveyance assessments of sample systems are undertaken by managers to confirm that the channel is meeting the required performance.

When evaluating the appropriateness of a management scenario, water levels obtained under that scenario are compared with those specified in the performance targets. There are three possible outcomes:

i. Water levels match the performance target. This implies that the management option considered is appropriate.

ii. Water levels are lower than the performance target. This implies that the management regime being considered might be relaxed.

iii. Water levels are higher than the performance target. This implies that the performance of the system will not achieve the required target performance and the management scenario needs to be improved.

FOCUS PRODUCT 5.3: Development of guidance for setting channel management performance standards

(Text in box for illustrative purposes only)

STEP BY STEP ACTIONS FOR ASSET SYSTEMS MANAGEMENT FOR SETTING AND MONITORING CHANNEL PERFOMANCE STANDARDS

STEP

1. Establish and assess nature of reach and record in System Asset Management Plan and on NFCDD.
2. Decide on required level of analysis: Level 1 or Level 2
3. Gather baseline information (e.g. cross section surveys) and
4. Define the Performance Specification for each reach. (conduct channel sensitivity analysis, using modelling - for example CES, or similar where appropriate) and enter into NFCDD.

   Determine Target Performance Standards for reaches based on most critical locations.

   - For a Level 1 reach; produce the Performance Specification in terms of required Condition Grade and the period of validity for the reach.
   - For Level 2 reach; produce the Performance Standard in terms of discharge and water level, or channel cross sectional area and water level, or discharge, cross-sectional area <u>and</u> water level – and the period of validity for the reach.

5. (If PS is not achievable within constraints - review Performance Specification and consider other options).

6. Pass reach Performance Specification and Target Performance Standard to Operations Delivery.

7. Plan and conduct detailed assessment on sample of reaches.

   - Level 1 channels; inspect approximately 1% of ‘Level 1’ reaches in the system annually
   - Level 2 channels; inspect approximately 5% of ‘Level 2’ reaches in the system annually.

   (Inspections should take place ideally shortly <u>in advance</u> of intervention/management measures being undertaken by Operations Delivery). Results of assessments are passed to Operations Delivery.

FOCUS PRODUCT 5.4: Guidance for exploring channel management options against performance specifications

(Text in box for illustrative purposes only)

STEP BY STEP ACTIONS FOR OPERATIONS DELIVERY FOR EXPLORING CHANNEL MANAGEMENT OPTIONS AGAINST PERFORMANCE SPECIFICATIONS

1. Selection of reach management options
   - For Level 1 reaches:
     Select/decide on management measures and intervention schedule(s) to achieve specified Condition Grade as supplied by Asset Systems Management. (Intervention option may be expressed as an 'Environmental Option')

   - For Level 2 reaches:
     Select/decide on management measures and intervention schedule(s) to achieve Specification and Target Performance Standards as supplied by Asset Systems Management. (May require the use of modelling, for example, CES or similar tool) Intervention option may be expressible as an 'Environmental Option'.

   The required Target Performance Standards could be achieved by different management strategies affecting both the cross-section (de-silting/dredging/blockage removal) and the hydraulic roughness (vegetation removal/cutting). It is envisaged that these strategies would be prioritised based on:

   - Feasibility of implementation (e.g. access may only be possible to one bank)
   - Ease / cost / environmental impacts of implementation (e.g. no local facility for recovery of dredgings)
   - Morphological benefit (e.g. channel in equilibrium)
   - Ecological benefit (e.g. promotes habitat, improved water quality)
   - Other criteria and constraints

   Note any constraints on Management Options (fisheries, navigation, conservation, biodiversity) and amend intervention measures accordingly.

2. Plan and undertake management measure(s).

3. Review reports of detailed assessments of channel performance by ASM and amend maintenance regimes where necessary to achieve the target performance standard.

5.4 Tiered approach to assessment of channel performance and management

The guidance makes clear that in many cases, assessment of channel performance can be based on visual inspection - 'simple' or Level 1 assessment. However, in complex cases or where the potential risk is high, 'detailed' or Level 2 assessments are appropriate and here CES can be used to establish more reliable estimates of the discharge capacity of a channel.

Recommendation 5.1: That the development of management strategies of river reaches should take account of the conveyance characteristics of each reach, determined in either a qualitative of quantitative way.

The CES is a free software tool (http://www.river-conveyance.net) that enables the user to estimate conveyance or carrying capacity of a channel. The CES includes three key components:

- the "Roughness Advisor" which provides advice on surface friction or roughness, including the variation in vegetation growth through the year (see for example Figure 5.2);

- the “Conveyance Generator” which determines the channel capacity based on both the roughness and the channel morphology;
- the “Uncertainty Estimator” which provides some indication of the uncertainty associated with the conveyance calculation.

The Roughness Advisor of CES enables the vegetation roughness coefficient associated with different management scenarios to be determined. For example, if water levels under a management scenario are higher than the performance target, CES could be used to assess the impact of cutting vegetation over a larger proportion of the bed.

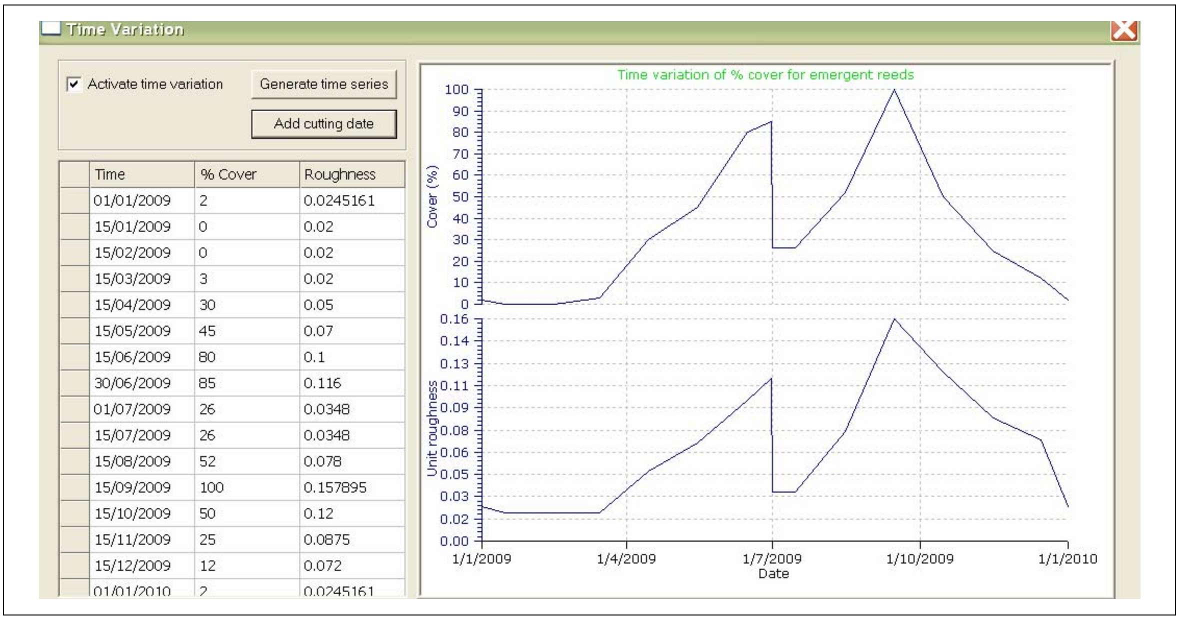


Figure 5.2 Example of influence of cutting vegetation in July on the roughness coefficients estimated with the Roughness Advisor of CES.

In tidally dominated reaches, storage effects may be important; for example, flood levels upstream of a tidal barrage may be dominated by the volume of available storage. For such systems, it will be necessary to run a dynamic hydraulic model (such as INFOWORKS RS) of the river system in conjunction with the use of the CES.

In some cases it may be necessary to set the performance target for specific times of the year. For example, during the winter months a higher target performance may be required, but during the summer months maintenance may still be required to maintain a lower target performance (Figure 3). If critical conditions vary through the year, different events corresponding to these different conditions may be considered. For example, the winter flood may be represented by the 100-year flood but the summer requirement may be expressed as a lower flow. The management scenario, for example when and how often to cut vegetation, is subject to the constraint of not allowing deterioration in the required condition grade.

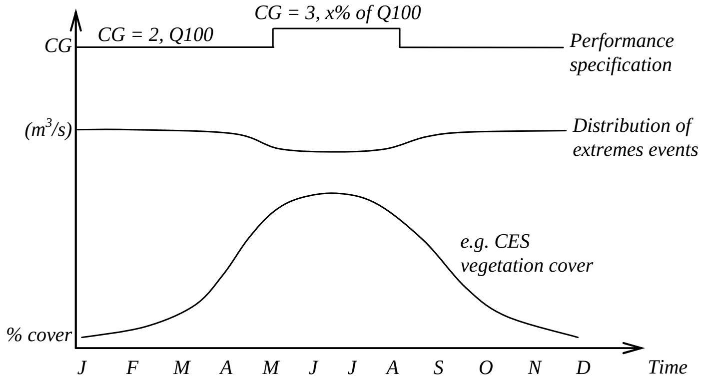


Figure 5.3 Example of changes in variation roughness and magnitude of extreme events providing possibility of reduction in required performance specification.

5.5 Which level of analysis should be adopted?

The decision on the appropriate level of analysis for a river reach should be kept under review. For some reaches for which a detailed analysis was originally specified, experience may lead the managers to relax or vary the need for such an analysis. Conversely, concern about a particular reach or event may lead a manager to undertake a Level 2 analysis for which the initial specification was for Level 1. At both levels, some basic information on each channel reach will need to be recorded and collated, but for a Level 2 analysis, more reliable information will be needed on channel cross-sections and channel vegetation types.

5.6 Piloting of channel management performance assessment

The PAMS system model was applied to Great Eau river system in Lincolnshire to quantify flood risks associated with different channel management. The method involves the integration of a full range of loading conditions (extreme water levels in the river) with the performance of defences, represented through fragility curves, allied to a flood spreading method, which enables economic consequences to be determined, expressed as expected annual damages (EAD). The different management scenarios were translated into different channel roughness coefficients and channel cross-section shapes.

The model demonstrated the complexity of the Great Eau system where upper reaches are “flow dominated” and channel management has a much bigger impact than in lower reaches which are “storage and tidal dominated”.

The results also revealed a strong interaction between the upper and lower reaches of the rivers and the potential of some changes to the current maintenance strategy not to improve the situation, but merely to transfer flooding problems from one area to another. Indeed, the modelling concluded that the current management scenario seems to be the most efficient from a benefit-cost point of view; increasing maintenance will not bring more benefits (expressed as a reduction in the EAD) and dredging the main channel may reduce the probability of inundation in some areas but would not bring any substantial reduction in the final EAD values.

Recommendation 5.2: As demonstrated by the Great Eau pilot, sensitive channel systems or catchments should be subjected to modelling and systems analysis to ensure that the wider effects of making a change in management approaches in a particular reach or sub-reach are properly understood.

Recommendation 5.3: That, when applying the PAMS tools to estimate flooding areas from fluvial systems, the volume of water that can spread into the floodplain due to overtopping or breaching be properly assessed, for example by use of a hydraulic model.

The application of system-based approaches developed under the PAMS Phase 2 project provides a more coherent understanding and justification for management actions. Different management scenarios and associated water levels in the channel and expected risks can be consistently compared. The results obtained from the tools help asset managers to make decisions.

5.7 Related research and development

A number of projects were drawn into or linked with the PAMS Phase 2 project to underpin or develop approaches to performance-based asset management of channels. In other cases, the PAMS project promoted new research. In particular, the following have contributed, or will contribute, to a greater capability to predict flood water level in channels either for a given condition of channel roughness or blockage or due to the form of the in-line structures within it:

- Research on the Conveyance and Afflux Estimation Systems (CES/AES) and the subsequent project *Maintaining the science relevance of the Conveyance and Afflux Estimation Systems* recommends areas of further work. From this research, the most relevant areas to channel management are those on the update of the Roughness Advisor and development of channel maintenance support to explore "what if" scenarios for different management regimes.

- The River Sediments and Habitats Phase 2 research project should enable asset managers to take better account of sediment and ecological processes in the management or improvement of rivers for flood risk. Five river systems were studied that have all experienced different types of management and have different environmental settings. Under this project, additional objectives aim to produce practical outputs to improve sediment management in channels to meet short-term needs.

- The Environment Agency project *Assessing the benefits of channel management - Methods to translate changes in channel management to changes in flood risk* applies expert rules to translate changes in the management of channel vegetation and river sediment into changes of conveyance. This study also estimates the likely impact of these changes in conveyance into changes in river levels for a range of return period storm events.

- The new CIRIA Culvert Design and Operation Guide (CDOG) to be published in early 2010 provides revised approaches to hydrology and hydraulic assessment of culverts and also methods for assessing siltation and debris load that clearly influence conveyance capacity. A key premise of the guide is that culvert performance must be assessed within the context of channel performance upstream and downstream.

- The Environment Agency's updated Trash and Security Screen Guide sets out each step of the risk assessment, design and operational management of trash screens (often associated with culverts). The recommended risk-based approach uses a scoring system based on identifying hazards and assessing the probability of them occurring. Trash screens and their blockage clearly may affect conveyance.

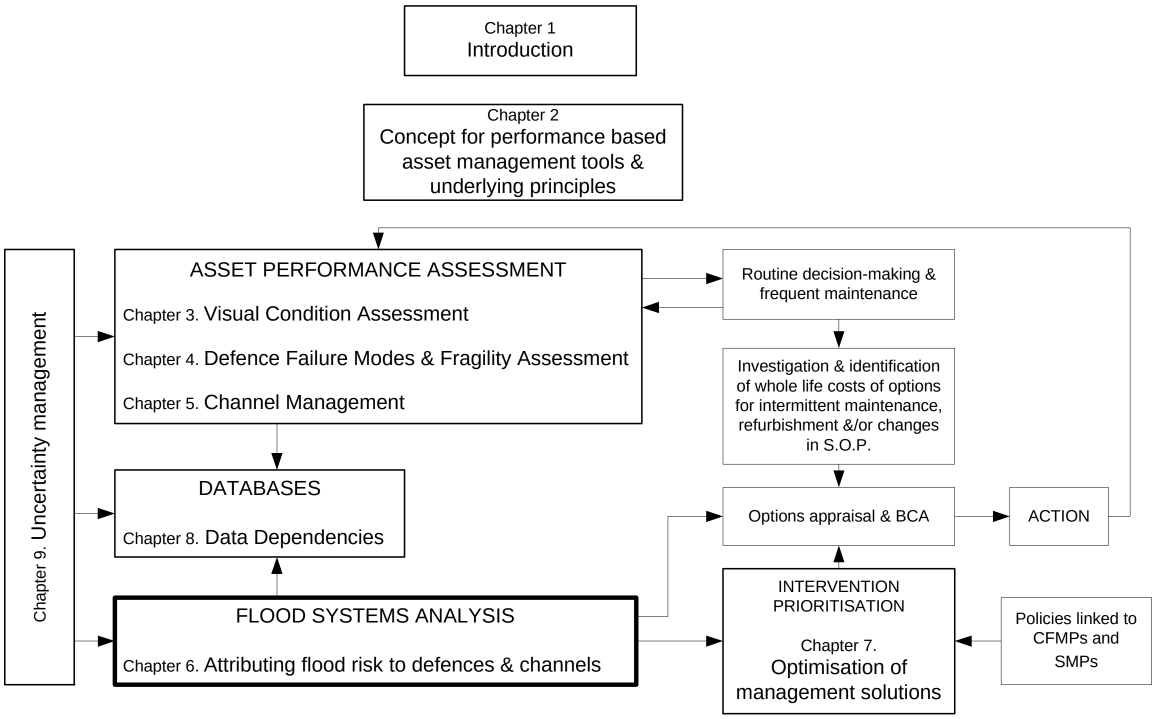
- The Environment Agency operating instruction on conveyance management (currently in draft form) provides standards and guidance on how to specify channel performance for a given flow and channel condition and how to carry out conveyance assessment. In particular, it encourages the use of modelling tools (e.g. CES) in to assess water levels.

Part C: Managing physical flood systems

This part of the report deals with the management of (physical) flood systems and tackles the attribution of flood risk to defences and channels and the evaluation and optimisation of management interventions.

6 Attributing flood risk to defences and channels

This chapter explains the approach to attributing residual risk in the floodplain to defence assets, based on the probabilities of flooding and breaching and the consequences of the resultant flooding. Examples are given of the application of the process with reference to pilots at West Bay Dorset and Sunk Island on the Humber estuary. The chapter concludes with a brief description of the new RAFT simplified risk attribution process.



6.1 Attributing flood risk – the approach

To assess the effectiveness of different asset management interventions, these need to be compared on a consistent basis. The approach developed in this project, as with NaFRA and Catchment Flood Management Plans, was to use flood risk as the 'common currency' for comparison.

To achieve this, computational analysis of flood systems, including defences, channels and other features, using RASP-based methods was developed and tested. One aim of this work was to assess the attribution of residual flood risk to individual assets (or lengths of linear defence assets). Residual flood risk in this context is the flood risk that is still left despite the presence of defences.

The RASP method involves integration of a full range of loading (source) conditions (extreme water levels for fluvial/tidal defences, or extreme overtopping rates for coastal defences) with the performance of defences (Pathway 1), represented through hydraulic overtopping performance and fragility curves, allied to a two-dimensional flood inundation (Pathway 2) simulation, which enables economic consequences for the receptors to be established. A conceptual diagram that depicts the model backdrop is shown in Figure 6.1 and full details of the analytical procedure are given in the PAMS systems analysis report.

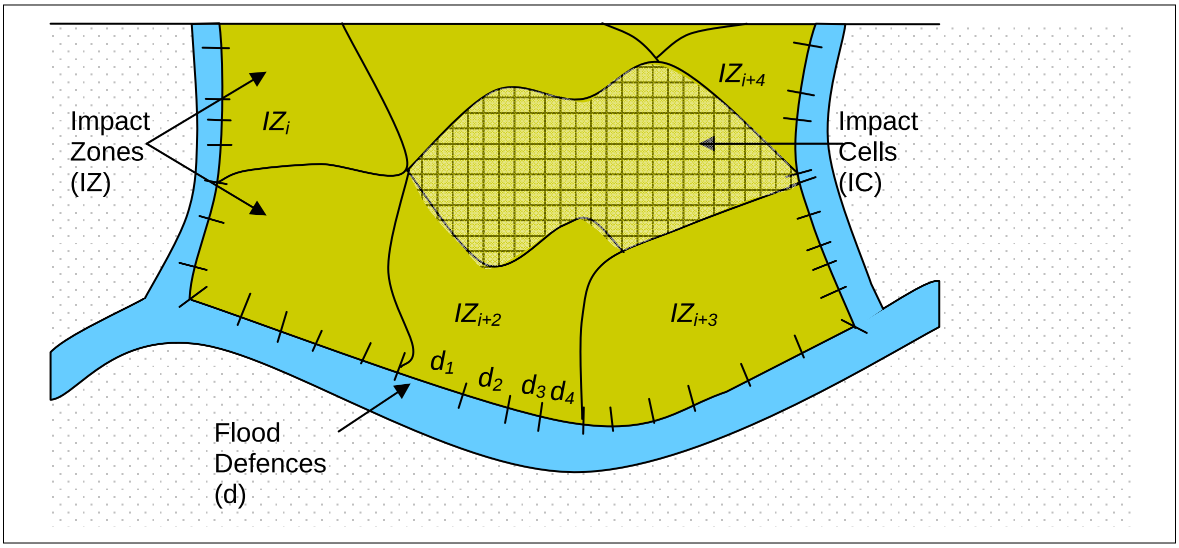


Figure 6.1 Conceptual diagram of backdrop of system model for one flood area (Gouldby *et al*, 2008).

In addition to resolving the spatial distribution of risk within the floodplain, the systems modelling approach described by Gouldby *et al.* (2008) also enables the contribution to risk from individual assets to be resolved. The method of *risk attribution* involves maintaining the relationship between the quantity of water discharged through each asset and the quantified impact of the resulting flood. This ability to trace the flow of water across the floodplain is provided by the Rapid Flood Spreading Method (RFSM, Lhomme *et al.*, 2008) used within system analysis and enables the relationship between inflow and impact to be identified for every system state considered.

The attribution of risk to individual assets is achieved by first developing a relationship between defence assets and adjacent impact zones (topographic watersheds resolved within the RFSM, impact zones, share the same river or coastal boundary from which flood water directly enters the floodplain) and then between adjacent and non-adjacent impact zones (topographic watersheds remote from the river or coastal boundary).

Through the RFSM it is possible to associate the volume of water discharged into each adjacent impact zone to the flood depth (hence consequential impact) in other non-adjacent impact zones by monitoring the flow of flood water as it propagates across the floodplain. Quantified impacts associated with each (non-adjacent) impact zone are apportioned to each adjacent impact zone accordingly (the total consequential impact for the whole flood area is expressed only in terms of the adjacent impact zones).

As the volume discharged into the floodplain is a function of the defence system state, the state of defence assets (failed/not failed) is also monitored. The individual defence contribution to risk can therefore be disaggregated into the assets contribution due to an ultimate limit state failure (breach in the case of a linear defence asset, or pump or gate failure) or serviceability failure (overtopping in the case of a linear defence asset, or capacity exceedence in terms of a pump).

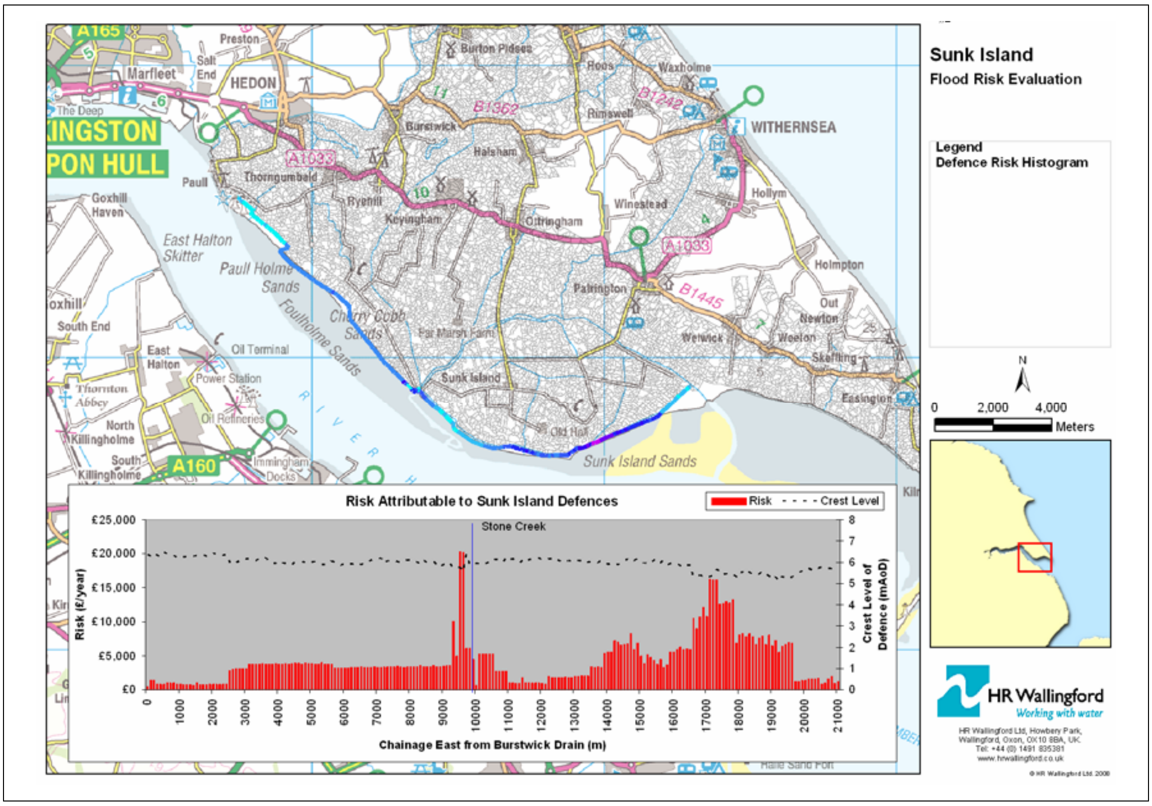


Figure 6.2 Attribution of total flood risk to defences along part of the North shoreline of the Humber Estuary.

This analysis is typically presented in map and tabular format. The pilot study report (FDR001) gives many examples. Of these, the north Humber shoreline (Figure 6.2) was particularly amenable to presentation in graphical form, having a long linear defence. Figure 6.2 shows how the total flood risk (expressed as EAD) can be split up and attributed back to individual defence lengths.

6.2 Risk reduction and option selection

Having identified assets contributing most to flood risk, it is possible using the same analytical process to assess the degree of risk reduction associated with maintenance and capital works schemes on these assets. From this, interventions can be identified that give the most cost-effective risk reduction.

A good example of this can be seen in the West Bay pilot study (for details see report FDR001). West Bay harbour has an entrance which divides two beaches: West Beach, which is defended by a concrete wall with wave-return coping stones and fronted by a shingle mound and East Beach, whose defence is comprised solely of a large shingle ridge. The local Environment Agency asset management team believed the depletion of the East Beach shingle ridge was of greatest concern. For this reason a new fragility curve, which was adjustable depending on the cross-sectional area, was created for this beach using the latest research. Analysis showed that if current rates of depletion of the beach were to continue, risk would rise to unacceptable levels and the beach would become unsustainable as a defence, whereas if a retreated hard defence were installed the risk would be reduced to a minimal value. In a similar way at West Beach, a new reliable secondary flood wall, which could divert overtopping flood water towards the harbour behind the primary West Beach defences, was shown to bring the EAD contribution to risk of the primary West Beach defence from almost £70,000 per annum down to almost zero, easily justifying the construction cost of this modest wall.

We recommend that calculated risk attribution is included as a key data field within NFCDD or its database successor in any future supporting tools for asset managers.

Recommendation 6.1: Research should (R) be carried out to produce software tools and a guide for the appropriate application of risk attribution to planning asset management interventions. (Note that this is not a 'one size fits all' recommendation for all assets).

Recommendation 6.2: That the basic concept of flood risk attribution be more widely utilised by Government and all operating authorities to support both the management and the public understanding of flood defence assets and asset systems.

Recommendation 6.3: That the flood risk attributed to an asset be made available as a field within the NFCDD or its database successor within any future supporting tools for asset management. This would be populated initially from the results of national scale analysis but updated with locally derived information whenever this becomes available.

6.3 Simplified risk attribution process

Full systems analysis at the level of detail required to make risk attributions to individual assets may not be suitable for all asset systems. Environment Agency staff have expressed enthusiasm for using the full systems approach not only for complex high risk situations and but also for situations (such as the north shore of the Humber) where withdrawal of (or reduction in) maintenance of defences is being contemplated.

However, the remaining cases need a simpler evaluation based on site inspections (without recourse to computational modelling even to specific office-based analysis). Furthermore, the Environment Agency has a considerable portfolio of flood defence assets. Each asset has a target condition grade. If the actual condition grade is below this target, the asset is considered unserviceable. The risk posed by such assets is then reported as a key performance indicator nationally to government.

A simplified tool, RAFT or Risk Assessment Field-based Tool (Environment Agency, 2009) was developed (Focus Product 6.1) to assess:

- The probability of failure of an asset at current and target condition grades.
- The potential consequential impacts (expressed in houses damaged, not in financial terms) should a given asset fail.
- The risk (taking account of probability and impact) attributed to an asset in its current condition and assuming improvement to its target condition.

The input data required by RAFT is minimised to support field-based use and chosen because it is readily available or can be gathered through visual field (or simple desk-based) investigation of the asset and its environs.

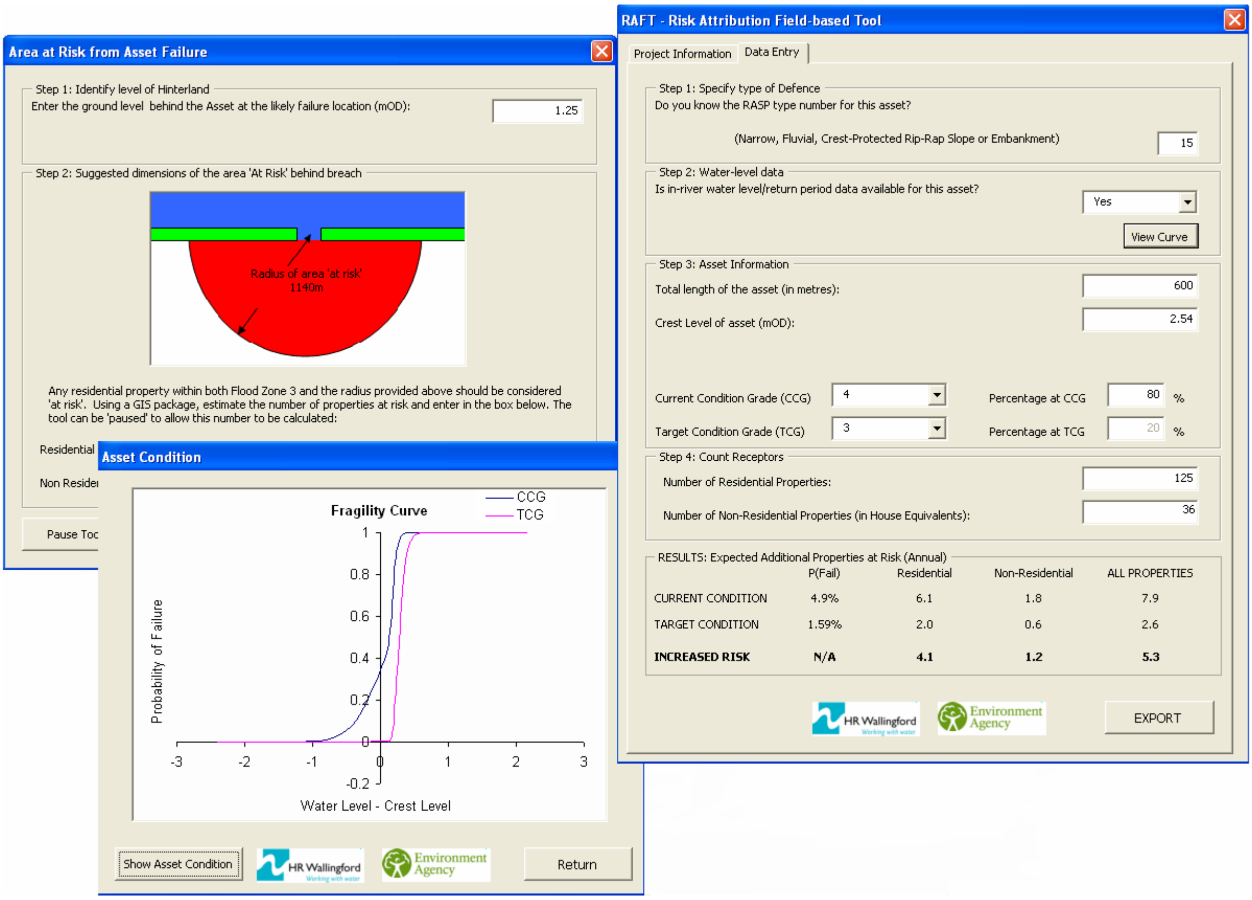


Figure 6.3 A simple relationship between the head of water through the breach and the potential flood extent.

FOCUS PRODUCT 6.1:

RAFT – Risk Assessment Field-based Tool

To estimate the probability of asset failure, RAFT uses a library of the high level fragility curves (described in Chapter 4) and user-defined asset types and surface protection to select an appropriate fragility curve from the built-in library. The user is asked to enter a crest level; an in-river water level (for at least one return period – additional return period levels are automatically generated (fluvial assets only)); a coastal region (enabling an extreme distribution of overtopping rates to be returned from a library of conditions developed as part of the most recent national flood risk assessment (HR Wallingford Ltd, 2009) – coastal assets only); percentage blockage (culverts only). The likely extent of flooding should an asset fail can be entered by the user or be assessed based on the head of water above the floodplain using the simplified advice shown in Figure 6.3. (Detailed knowledge of the topography of the floodplain is not required.) This supports the user in identifying the likely number of properties (residential and non-residential) that may be impacted.

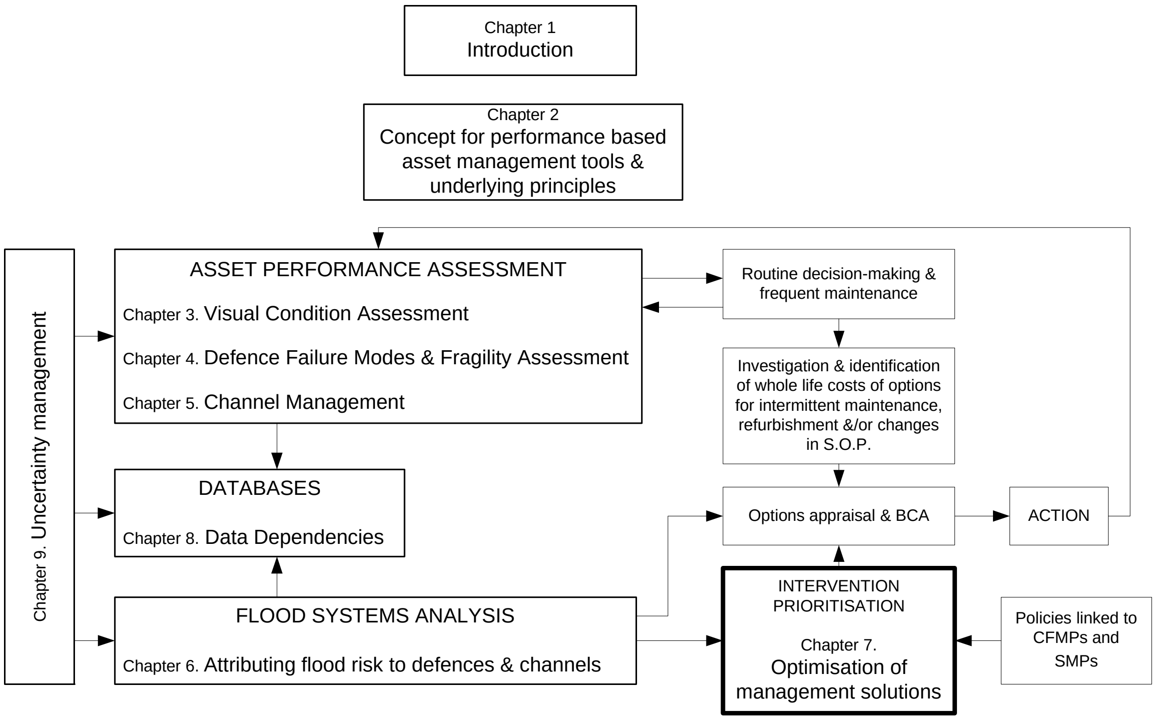
The risk attributable to the asset, in its current or target condition, expressed as the expected annual number of properties flooded, is automatically calculated by the tool as the product of the annual probability of asset failure at its current condition grade (an integration of the fragility curve and loading conditions) and the number of properties that would be affected by a breach.

The RAFT tool is now being widely used in the Environment Agency to make a first assessment of the criticality of assets through a simple field-based activity.

Recommendation 6.4: That the simplified and more detailed tools are developed to operate together – with the value-added information from one tool utilised in the other.

7 Optimisation of management solutions and use of performance-based asset management tools

This chapter discusses developments in the evaluation and optimisation of management interventions. It summarises the kinds of questions that asset managers need to ask and what kind of decision support is appropriate to that process. Recent developments and opportunities in automated solution searching are described.



7.1 Optimising solutions – identifying the asset management questions and developing decision support

With the combination of condition inspection, fragility and risk attribution tools, it is possible to assess the impact of different asset management strategies on risk reduction (or in the case of do-nothing scenarios, the risk increase) within a whole asset system and that associated with interventions to various assets. These changes in flood risk can then be compared with the costs of interventions using established cost-benefit approaches.

The benefits of performance-based asset management thinking include:

- The whole approach to risk and performance management which has been adopted within the SAMP process.
- An analysis of failures of defences in the summer 2007 floods.
- Widespread use of the updated Condition Assessment Manual which was prepared by our team, covering failure modes and performance features.

From this work and the pilot studies carried out on real systems (and associated interactions with local practitioners) the following benefits of PAMS have emerged:

i. The structured condition grading system leads to greater consistency.

ii. Value of fragility analysis and understanding potential failure modes, including incorporation of local knowledge which helps to make the fragility curves more realistic for practitioners and the asset system concerned.

iii. Risk attribution arising out of asset systems analysis supports the understanding of critical assets and planning of asset management activities, including prioritisation of investment.

iv. Understanding deterioration processes is important because of their impact on fragility and failure.

v. Explicit accounting of uncertainty allows practitioners to focus their data collection and arrange for tiered improvements in data and modelling.

vi. A quantified audit trail for decision-making is provided.

The stage is therefore set for the use of these tools to select the best course of action. However, multiple asset management strategies could be considered, depending on the nature and timing of interventions that might be made. Before embarking on a consideration of alternatives, asset managers need to answer a number of key preliminary questions:

- **What is the present day risk?** Where is it? What are the drivers? Breaking this down into its component parts
  - What is the existing probability? Where is it? What are the drivers?
  - What is the existing exposure? Where is it? What are the drivers?
  - What is the existing vulnerability? Where is it? What are the drivers?
  - Which assets contribute the most to flood risk?
- **What is the future risk?**
  - How would an intervention change the risk?
  - How much would a particular intervention cost?
  - Is it better to physically intervene or should more data be collected/ analysis undertaken?
  - Which intervention strategy is best over the medium and longer term (whole-life benefits and costs)?
  - Which strategy offers the most flexibility?
  - Which strategy is robust to possible future change (climate and demographic change)?

- Which are the most important uncertainties in terms of their contribution to the doubt as to what to do for the best?

PAMS tools and systems can be used to explore most of these questions. However, to do this in a structured way, it is helpful to have a decision support framework in which to operate. As part of FLOOD*site*, long-term decision support tools (MaGahey and Sayers, 2008) were developed including the framework shown in Figure 7.1.

Decision support seeks to provide the evidence base to support the selection of preferred investment (actions and strategy). Various considerations are essential to this process beyond hard analysis of flood risk (as described earlier). This includes:

- *Sustainability*: does a particular investment meet the needs of the present without compromising the ability of future generations to meet their own needs (De Bruijn, 2005).
- *Robustness*: the ability of a given investment strategy to perform well in the context of all possible future scenarios. A 'robust solution' is one that is always near (or that does not contradict) the solution initially found by a method, for any acceptable combination of parameter values (Vincke, 1999a&b).
- *Flexibility*: the ability of a given investment to leave the choices to be made in the future as open as possible (Rosenhead, 1989).
- *Adaptability*: the ability of a given investment strategy to adapt following monitoring and observation of what actually happens and the ability to avoid future regrets (Vis *et al.*, 2001, De Bruijn *et al.* 2008).
- *Uncertainty*: recognition and representation of uncertainty due to data, methods and model structures as well as the gross uncertainty associated with future change.

These criteria are almost entirely in keeping with those adopted for Foresight (Evans *et al.*, 2004a&b) and are typically linked to social, ecological and economic needs. Each must be considered in as broadly based terms as possible to assess the likely impact of the investment (for example, a major replacement or new build asset is likely to demand a broader analysis than some local maintenance).

In selecting the best investment strategy, the decision-maker is faced with choosing between many possible options of physical intervention, further data collection and analysis. Underlying this choice is a desire to maintain the flood risk system's ability to perform reasonably well in the context of all plausible futures that may be encountered in the appraisal period (related to the decision criteria given above, that is funding changes and future affordability, climatic conditions, changes in anticipated performance, greater or lower rate of deterioration and so on). This flexibility of management, as far as can be foreseen, can be captured in a decision pipeline diagram, a flow chart of potential future management strategies, as shown by the example in Figure 7.2. The Thames Estuary 2100 project used this kind of approach.

7.2 Automated solution searching

The Phase 2 project recognised that automated methods of solution searching may form part of future decision support tools. The most promising methods likely to support optimisation of investment are based around genetic algorithms (GAs), which can optimise performance across many criteria of interest. GAs are also well established, having been previously applied to various fields within civil engineering (including bridge maintenance, truss design and pipe network design).

Genetic algorithms work by seeking to combine the desirable qualities from solutions already found to create solutions that are even more desirable. By applying Darwinian evolution, the details of a possible solution are encoded into the next iteration of the search. This is done through combining the characteristics of two different ‘parent’ solutions to create a new solution in the hope that these new solutions inherit a combination of desirable features from both parent solutions. The process of selecting solutions and recombining them is repeated over several ‘generations’ (iterations) until the maximum utility of the solution is reached (Philips, 2006).

To explore the utility of GAs in identifying efficient strategies for investment in flood defence maintenance, upgrade and replacement, a pilot study was undertaken as part of the FRMRC1 research programme for a single flood defence system in the Thames (the Dartford to Gravesend Embayment). The GA was programmed to maximise the net benefit of interventions within the flood defence system over the next 50 years. The flood risk system analysis described previously was extended to include a spatially and temporally dynamic representation of the condition of each individual asset within the system, including:

- deterioration in the absence of management or reduced management; .
- condition improvement through repair or refurbishment;
- crest level raising through major change projects.

The demonstration GA was used to explore and evolve alternative interventions over the next 50 years, establishing the utility of different strategies through cost functions; benefit and benefit-cost analysis; and financial constraints, for example an annual budgetary ceiling.

Considerable further research is needed before such a tool could be used in practice and some of this is already underway in FRMRC2. In the meantime, whilst systems analysis approaches are being turned into practice, asset managers may prefer to evaluate asset management options that they select themselves.

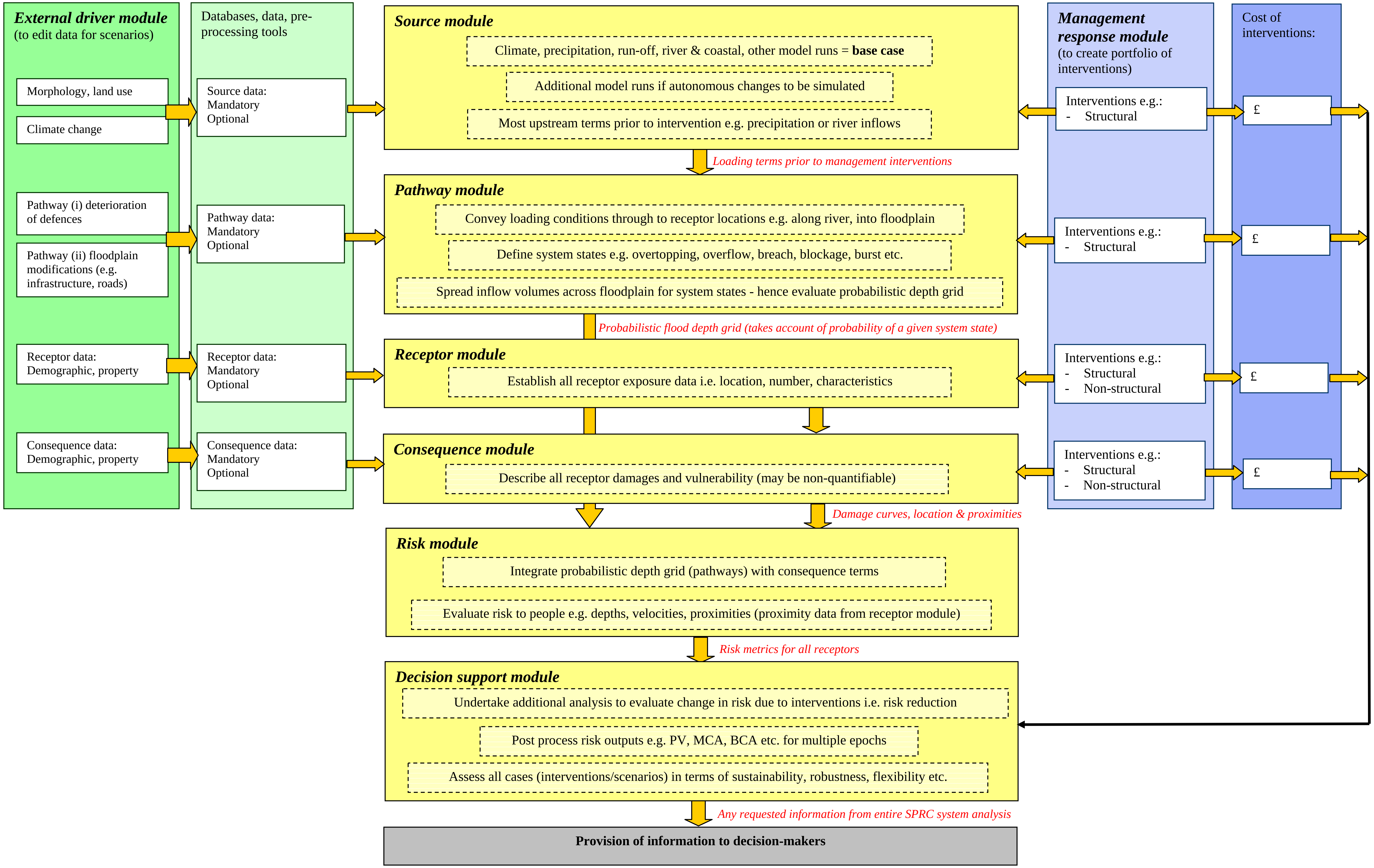


Figure 7.1 Methodological framework – detailed.

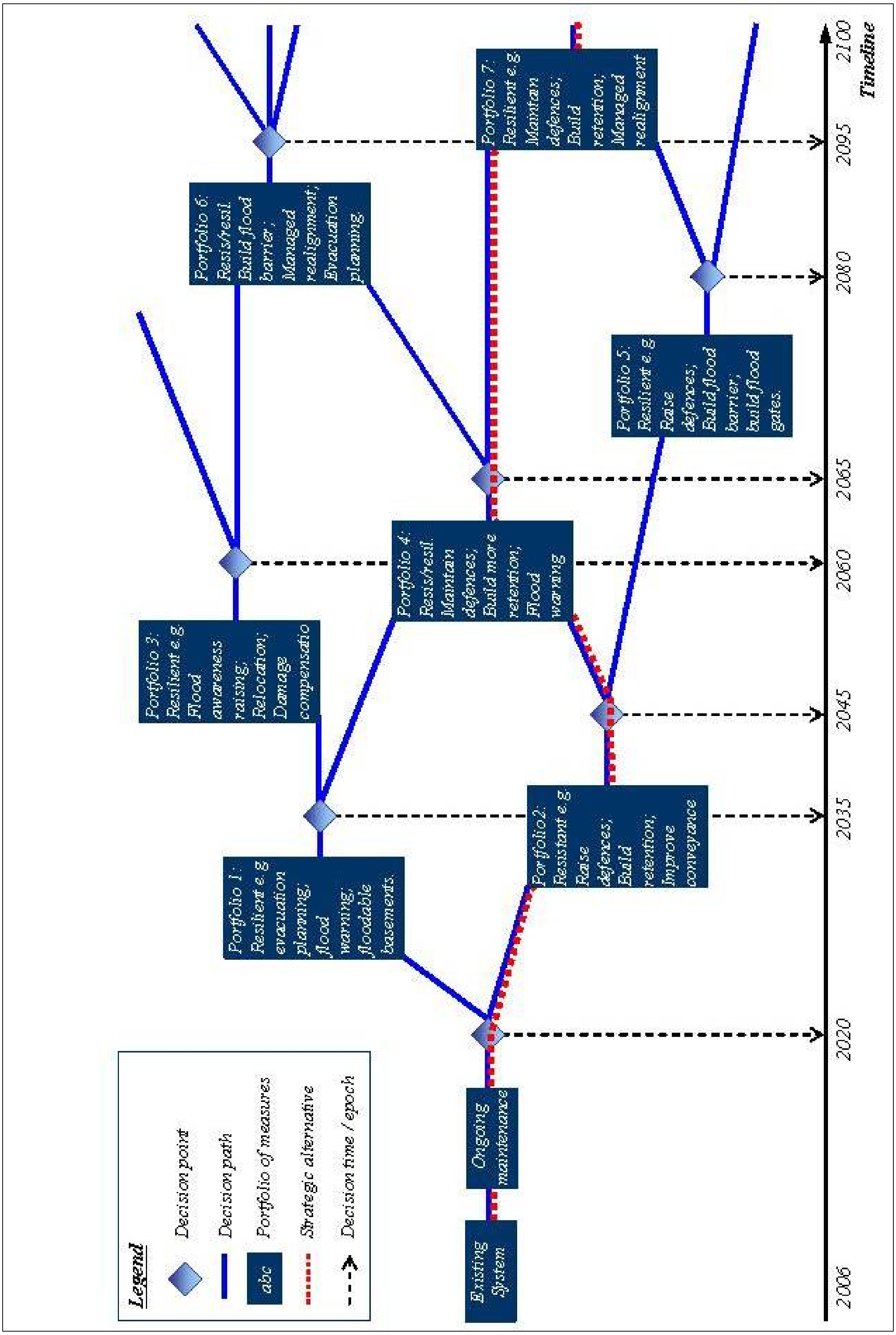


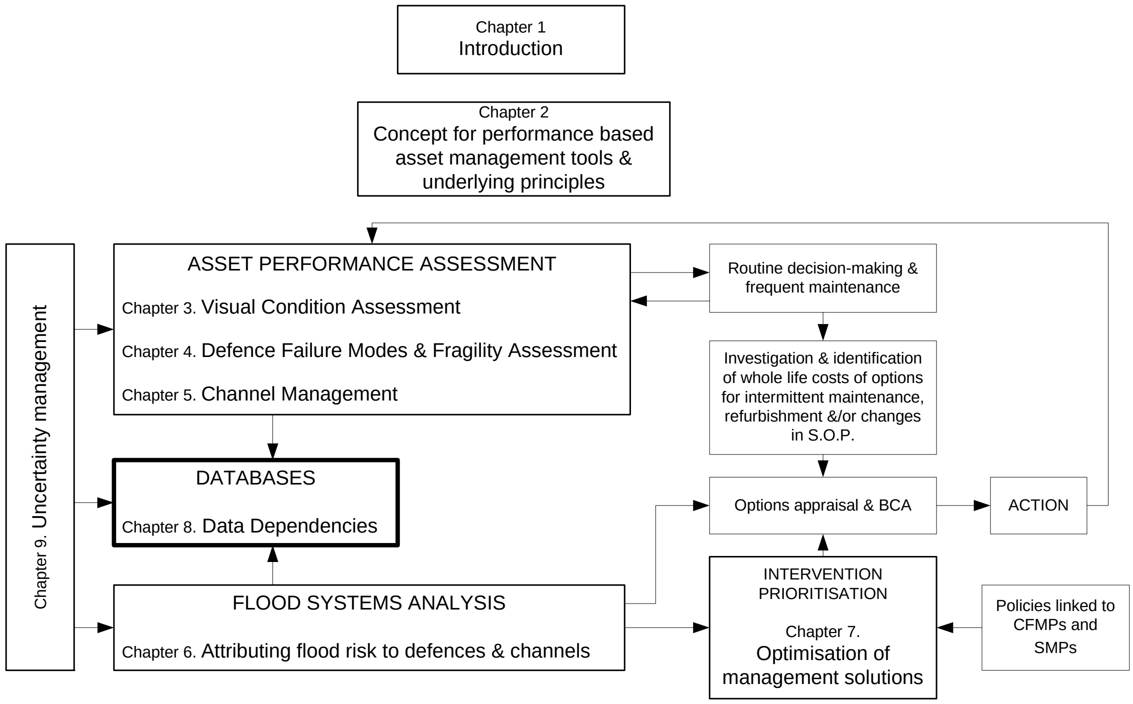
Figure 7.2 Example of decision pipeline with decision points through time.

Part D: Confronting limitations

This section of the report deals with data dependencies and uncertainty.

8 Data dependencies

This brief chapter discusses the importance of data in order to operate asset management tools effectively. It sets out the critical data sets which need attention and recording in an asset management database. More details of data needs and prioritised actions for improvement are given in Appendices 8 and 9.



In this project, we were asked to consider the needs for data for new or improved asset management tools. In coming to our conclusions, we took account of two previous Defra/Environment Agency projects: the flood defence data review (Defra/Environment Agency, 2005) and a project to explore the sensitivity of RASP HLM+ to variations in input data and model parameters (Defra/Environment Agency, 2007).

Availability, accuracy and reliability of source data used for performance based asset management are important to reduce uncertainty in the results and boost confidence in decision-making. A list of data requirements for PAMS type analysis is provided in Appendix 8. This includes all data required to complete a RASP system analysis and additional channel and point asset data which is likely to be required. The data source and measurement technique (if known) are provided. These have been broadly grouped into source-pathway-receptor data types as used in the system analysis.

Critical data items required for PAMS systems analysis and management optimisation are:

- information on loadings: water levels (fluvial) and joint probabilities of waves and water levels (coastal); anticipated changes in these from climate change;
- asset type and materials (in order to select/determine fragility curve);
- actual and target standard of protection;
- crest level;

- condition grade;
- deterioration of condition grade with time;
- replacement and maintenance costs.

For calculating economic benefits, ongoing developments in the Agricultural Land Classification and National Property Databases are also critical to benefit assessment. It is also important to have a way of storing the calculated risk attributed to the defence within the national data repository.

The extent to which data quality (including uncertainty) is dependent on data provenance is well illustrated by the example of the availability of crest level data in the Thames Estuary. As Table 8.1 shows, the accuracy of data can vary from about 0.5 m if the crest level is inferred from the standard of protection down to 0.04 m if it is obtained from a local GPS survey. Ways in which crest level data can be improved for manmade raised defences include use of scheme drawings and reports, or through survey and/or interpretation of LiDAR data. Thus, benefits can arise from conversion of native datasets (e.g. LiDAR, geophysical) to the format required for onward use in risk and performance analysis tools (line and level of defence crest and toe, settlement rates, geotechnical properties and so on).

Table 8.1 Data provenance & accuracy for Thames estuary defence crest levels.

Data source	Standard Deviation	Distribution Type
A Local GPS survey	0.039m	Normal
B Low Level LIDAR	0.21m	
C Land Charge Register Drawings 1997	0.35m	
D Statutory Defence Levels	0.37m	
E Other as-built drawings	0.39	
F IA3 Visual Condition Inspection	0.41m	
G Expert (local) judgement	0.43m	
H Thames Tidal Database (Embayment Strategy Volume 3)	0.45m	
I Estimation from SOP	0.47m	

As a result of discussions over such issues in connection with the pilot projects, Environment Agency staff and other operating authorities have become more aware that data availability, accuracy and reliability are essential to ensure useful outputs from the PAMS tools. Practitioners have thus become more aware of the value of locally gathered data and the way in which improvements in data could help improve decisions in maintenance and investment prioritisation.

Recommendation 8.1: That, in order to improve the quality of FCRM flood system analyses, attention be paid to improving over time the availability, accuracy and reliability of the following datasets:

- **information on loadings: water levels (fluvial) and joint probabilities of waves and water levels (coastal); anticipated changes in these due to climate change;**
- **asset type and materials (in order to select/determine fragility curve);**
- **actual and target standard of protection;**
- **crest level;**
- **condition grade;**
- **deterioration of condition grade with time;**
- **replacement and maintenance costs.**

It is recognised that obtaining and managing data takes time and is expensive and therefore the actions to improve input data quality for PAMS systems analysis included in Appendix 9 have been prioritised.

There are also significant benefits arising from the conversion of native datasets (e.g. LiDAR, geophysical) to the format required for use PAMS analysis tools (line and level of defence crest and toe, settlement rates, geotechnical properties etc).

Recommendation 8.2: That quality flags indicating the level of uncertainty be developed and adopted for all data items to be used by PAMS tools. These flags could be based on a quantitative or qualitative assessment. They will help to indicate where outputs from PAMS analyses based on this data can be considered more or less certain.

Recommendation 8.3: To ensure more consistent flood risk analysis, the way in which level data is collected and used in tools should be standardised. This specifically relates to ground levels, defence crest level and toe levels.

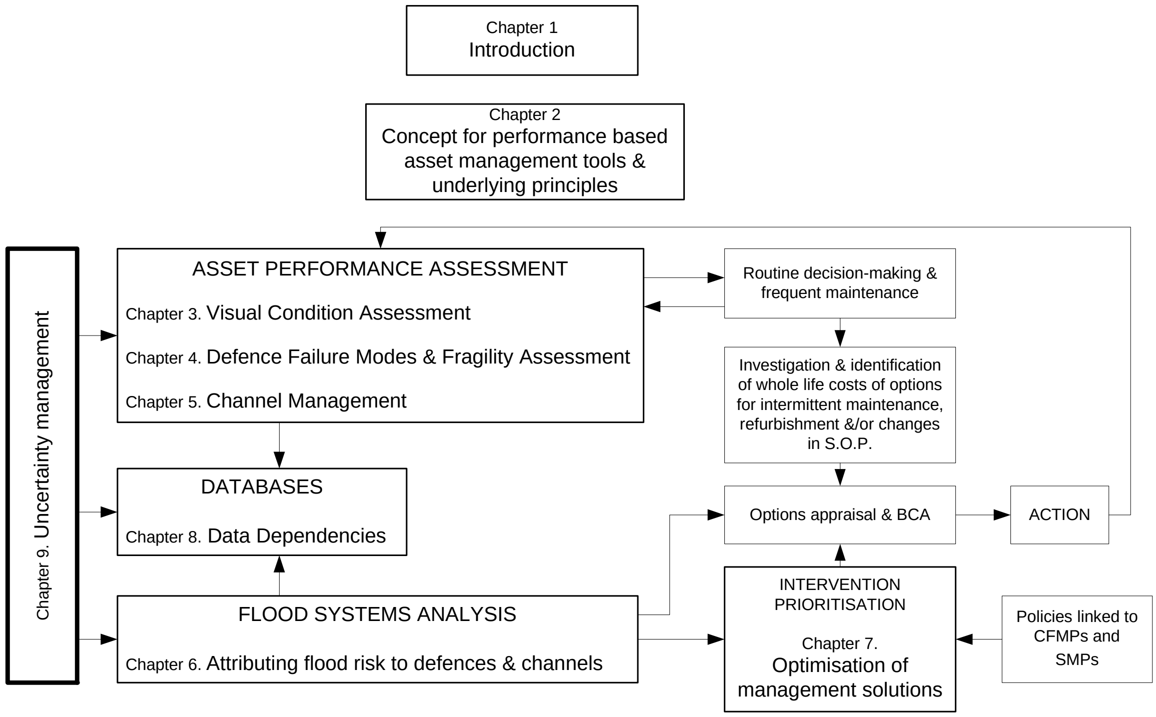
Recommendation 8.4: As performance-based asset management includes benefit-cost analysis, efforts should be targeted at:

- **ensuring that efforts are made to populate the data field for asset replacement costs in NFCDD or its successor asset management data repository (e.g. based on scheme design data);**
- **considering the use (and hence collection) of unit costs;**
- **considering a wider range of costs e.g. channel maintenance, to provide a more holistic assessment of flood risk.**

Recommendation 8.5: That the facility to record condition grades for channel vegetation and blockage be included in the asset management data repository (NFCDD or successors).

9 Uncertainty

This chapter describes the principle kinds of uncertainty which affect asset management data, modelling and decision making. It explains different ways in which this uncertainty can be presented and concludes by explaining ways in which more robust option choices could be made in the face of uncertainty.



Understanding uncertainty[3] within our predictions and decisions is at the heart of understanding risk. In recognising uncertainty, we are able to acknowledge our lack of knowledge of the behaviour of the physical world (knowledge uncertainty), its inherent variability (natural variability) and the complexity of our social/organisational values and objectives (decision uncertainty). Consideration of uncertainty within the decision process attempts to quantify our lack of sureness, and thereby provide the decision-maker with additional information on which to base a decision. Investigation of the sources of uncertainty enables the decision-maker to identify the uncertainties that most influence the final outcome and focus resources efficiently.

Uncertainty can stem from a variety of different sources. These sources are generally categorised under two headings:

(i) Natural (aleatory) variability

Flood and coastal defence engineers are used to handling uncertainties associated with natural variability. Temporal variations in natural forces are well known and, in general, it is not possible to reduce the uncertainty related to the temporal natural variability of our environment. For example, it is, at present, not possible to say when a 100-year return period river discharge will next be observed at any given location on a

[3] 'Uncertainty' - a general concept that reflects our lack of sureness about something, ranging from just short of complete sureness to an almost complete lack of conviction about an outcome (NRC, 2000).

river. A time period of 400 years could pass without observing a 100-year event, but then two could arrive within a year of each other.

(ii) Knowledge (epistemic) uncertainty

Although most engineers and planners are used to dealing with inherent uncertainty associated with natural variability discussed above, the concept and importance of knowledge uncertainty is less commonly considered and formally assessed. For example, a numerical model of wave transformation may not include an accurate mathematical description of all the relevant physical processes. Wave breaking aspects may be parameterised to compensate for lack of knowledge on the physics. The model is thus subject to a form of knowledge uncertainty. Unlike the uncertainties associated with natural variability, it is possible to reduce knowledge uncertainty. For example, if research provides a better mathematical description of wave breaking processes and this is included in the model, or more extensive data gathered so that the model better represents the physical conditions present, knowledge uncertainty may be reduced.

Under the heading of ‘knowledge uncertainty’ different forms of uncertainty can be identified and formally calculated.

9.1 Expressing and presenting uncertainties

Uncertainties can be expressed in different ways, qualitatively and quantitatively (HR Wallingford Ltd (1997):

- Deliberate vagueness: ‘there is a high chance of breaching’.
- Ranking without quantifying: ‘Option A is safer than Option B’.
- Stating possible outcomes without stating likelihoods: ‘it is possible the embankment will breach’.
- Probabilities of events or outcomes: ‘there is a 10 per cent chance of breaching’.
- Range of variables/parameters: ‘the design flow rate is 100 cubic metres per second (cumecs) +/- 10 per cent’.
- Confidence intervals: ‘there is a 95 per cent chance that the design flow rate lies between 90 and 110 cumecs’.
- Probability distributions.

Uncertainty analysis is closely related to sensitivity analysis and by using the Monte-Carlo procedures for propagating uncertainty through the modelling process and the approaches in Saltelli *et al.* (2004), it is possible to undertake a staged sensitivity analysis.

Variance-based sensitivity analysis (VBSA) is undertaken at each stage of the PAMS systems modelling process, with the methods applied within each stage being entirely consistent with those described in Saltelli *et al.* (2004). There is, however, a requirement to undertake additional analysis to relate, for example, the sensitivity of the Stage 3 output (flood risk) to uncertainties associated with the inputs to Stage 1 (such as defence-specific crest level).

For complex models with numerous input variables, propagating uncertainty on all variables through the model can be computationally time-consuming. For the PAMS analysis, this constraint can be overcome by:

- prior screening to identify the primary input variables;
- a staged analysis, whereby the number of variables propagated through each stage is constrained;
- minor modifications to the model structure.

A staged analysis can offer benefits in terms of less computational time (fewer variables propagated through the whole process) and the provision of information at intermediate stages within the overall model structure. Thus, for uncertainty analysis in PAMS, a staged approach is advocated.

A convenient first staging point is the evaluation of volume discharged into the floodplain on each flooding event. A number of defence-specific variables are associated with flood volumes, which can increase computation time if propagated through the entire risk calculation. However, using a staged approach, these variables all reduce to a single variable, the flood volume discharged into the floodplain from a specific defence.

The flood risk analysis method demands evaluation of economic damages (consequences) at various return periods (loading levels). Therefore, for the second stage of the analysis, a convenient output is flood consequence (with associated uncertainty estimates), conditional on loading level.

The final stage involves the evaluation of flood risk, which requires integration of the consequence distributions obtained in stage 2 over all loading levels.

Whilst the procedure outlined here is for three stages of the flood risk analysis, the approach is extendable through additional stages to the level of detail required. For example, uncertainty on breaching for each defence is captured through a probability distribution. There may be a need to understand the relative importance of contributors to breaching uncertainty on the output risks. Is the uncertainty associated with the models of establishing structural failure, or their input variables most significant? It is evident that a Stage ‘0’ could be introduced and an uncertainty and sensitivity analysis on the defence breaching undertaken in order to explicitly address this question.

9.2 Making robust choices in the face of uncertainty

In selecting the best investment strategy, the decision-maker is faced with many possible options of physical intervention, further data collection and analysis. Underlying this choice is a desire to maintain the flood risk system’s ability to perform reasonably well in the context of all plausible futures in the appraisal period (funding changes and future affordability, climatic conditions, changes in anticipated performance, change in the rate of deterioration and so on).

In this context, performance is typically measured in terms of efficiency (such as risk reduction, opportunity benefit) and effectiveness (benefit to cost ratio). The whole-life benefit to cost ratio is a useful single indicator of performance of alternative options. Determining the order of preference, assuming perfect information, would be a straightforward ranking process. Natural (aleatory) and knowledge (epistemic) uncertainties combine to complicate this process.

Classical decision theory (see French, 1986) covers two widely considered approaches to deal with uncertainty. One, based upon Laplace’s principle of indifference or insufficient reason, involves assigning an equal probability to uncertain quantities, and is therefore fundamentally probabilistic. The other is Wald’s Maximin model, which assumes the worst case of uncertainty will always arise and chooses the option that maximises the reward given this assumption; the approach does not involve assigning any likelihood to uncertain quantities.

More recently, Info-Gap approaches that purport to be non-probabilistic in nature developed by Ben-Haim (2006) have been applied to flood risk management by Hall and Harvey (2009). Sniedovich (2007) is critical of such approaches as they adopt a single description of the future and assume alternative futures become increasingly unlikely as they diverge from this initial description. The method therefore assumes that the most likely future system state is known *a priori*. Given that the system state is subject to severe uncertainty, an approach that relies on this assumption as its basis appears paradoxical, and this is strongly questioned by Sniedovich (2007).

A more traditional method that involves Bayesian type probabilistic weighting according to the decision-maker's strength of belief about the system state, was proposed for the Thames region (Mc Gahey and Sayers,2008). In practice, however, it is only necessary to apply these methods to determine the preferred option when performance surfaces for strategic alternatives intersect. Or, in other words, when the preference ordering varies depending on which future scenario arises.

Recommendation 9.1: Uncertainty and sensitivity analysis should be used to improve the confidence in the decisions to be made. Consideration of uncertainty provides the decision maker with additional information on which to base a decision. Consideration of uncertainty can therefore lead to different and more justifiable decisions than studies that do not include uncertainty. A classic example would be a situation where a decision to select a particular form of construction was based on assumed ground conditions, whereas had the true ground conditions been known, a different and ultimately less expensive form of construction would have been adopted.

Recommendation 9.2: That, to facilitate incorporating uncertainty within performance-based asset management, the following practices be adopted:

- **Consistent terminology should be adopted when considering uncertainty, using the terms and definitions detailed above, for example, clear identification of the source of uncertainty: natural variability or knowledge uncertainty.**
- **Improved articulation of sources of uncertainty should accompany all results derived from national, regional and local studies, as well as data measurement activities.**
- **The methodology adopted for handling uncertainty within the evidence presented should be explicitly expressed within any decision-making process adopted.**

Part E: Next steps

This final section of the report makes a series of recommendations for further action. These recommendations build on those in the previous sections of this report.

10 Implementation of performance-based asset management tools

This chapter sets out a series of work packages of further research and development activity that the project team have identified as being worthwhile in order to further develop and bring into implementation the various asset management tools discussed in this report.

10.1 Implementation, development and further research – recommendations

The experience of the PAMS Phase 2 research team over the past 5 years in support of the development of a programme of R&D has enabled the identification of a series of further work packages to deliver improved asset performance tools into the Environment Agency and other operating authorities, including coast protection authorities where these can reasonably use similar tools or approaches.

The work packages identified include within them recommendations for:

- ***Embedment (E)*** – of a working prototype tool, technique or guidance into practice including linking with the development of operational software tools to support asset management and management instructions (AMS etc).
- ***Development (D)*** – of a working prototype tool, technique or guidance up to the point that it is ready for embedment. For development (D) to proceed under the APT project, the research (i.e. the thinking, testing and trialling) will have been largely completed already under PAMS Phase 2 or a related project.
- ***Research (R)*** – where some original thinking and testing of an emerging method or tool that has significant potential for advancing asset management going is carried out. These research activities are most likely to be delivered through a combination of applied research (such as FRMRC2 or future EC projects) as well as directly commissioned Agency studies.

Alongside these, there is a need for further ***Demonstration*** projects.

Within this project, a number of key principles have been identified to guide development and implementation of methods and tools for performance and risk-based asset management. These principles include:

- improving understanding of asset performance;
- provision of justification and auditability for management strategies by transparent analysis methods;
- using risk attribution to defence lengths as an aid to focussing interventions

- capturing knowledge about asset performance through the generation of outputs such as fault trees ;
- ensuring efficiency of data collection, analysis and reporting, following the "do once, use many times" principle;
- tiered assessment and decision-making. – in terms of both data, modelling tools, engineering techniques and guidance

These principles now also underpin the recommendations for further work which follow

Recommendation 10.1: That there should be an umbrella asset performance tools research project, including the following work packages:

1. **Asset inspection and condition assessment**
2. **Individual defence asset performance**
3. **Asset system performance**
4. **Liaison with other research projects and initiatives**

Recommendation 10.2: That the Work Package 1 on Asset inspection and condition assessment should include the following sub-packages:

1.1 Guidance document on tiered inspection and assessment of defence assets (E)

- Designed for direct use by asset inspectors and other asset management staff.
- Overview of possible approaches.
- Explanation of significance of using inspection and investigation to understand failure modes.
- Based on the tiered approach recommended for use in the monitoring programme in SC060078 deterioration and whole life costs project, using findings at the less detailed levels as triggers for more detailed inspections.

1.2 Performance feature flow charts for defences – updating and extension (D)

- Further updating of performance feature flow charts in the light of these trials to make them robust tools for Embedment in practice.
- Development of flow charts for asset types not presently covered, including for beach and wave control structures.
- Inclusion within the flow charts of (immediate) 'triggers' for action based on the results of the assessment.
- By appropriate field trials, ensuring revised flow charts operate consistently with previous assessments with CAM2 and also alongside the methodology for converting the condition grade (CG) assessments on individual performance features to an overall CG (viz. selecting the worst value performance feature for that asset).
- Improving understanding, where possible, of the physics-based link between visual performance features and actual failure-mode related performance

1.3 Guidance on more detailed inspection (E)

taking account of guidance emerging from the deterioration and whole life costs research, and from research conducted by Royal Haskoning on detailed inspection methods and from FRMRC (University of Nottingham) on non-destructive and remote sensing methods.

1.4 Field data conversion guidance (important but optional for this research) (E).

Description of a range of approaches for converting native datasets (e.g. LiDAR, geophysical) to the format required for an onward use in the risk and performance analysis tools (line and level of defence crest and toe, settlement rates, geotechnical properties etc).

NOTE: The trials in the PAMS Phase2 have emphasised the benefits of consistency from using the flow-chart approach to the assessment of asset performance features developed and the value of inspectors being trained to think about the possible failure modes of assets. Thus visual asset inspection contributes strongly to the first 'risk screening' tier of asset performance assessment and should be developed further in Work Package 1 on Asset Inspection and Condition Assessment.

Recommendation 10.3: That Work Package 2 on individual defence asset performance include the following sub-packages:

2.1 Guidance on tiered evaluation of defence assets (E)

Guidance aimed at asset managers and their consultants, to explain the range of approaches that can be adopted for understanding defence performance, including an *appropriate use of probabilistic methods* in the description of asset response. The guidance will therefore include:

- As a starting point, conventional engineering data collection and appropriate consideration and analysis of the failure modes.
- Recommendation, where appropriate, to move on to the development of fragility curves by a tiered range of techniques (set out in preliminary form in the PAMS MSF13 report).
    - Lowest level of evaluation, based on selection of standardised fragility curves based on visual condition assessment. In fact, at this level fragility curves might not need to be mentioned at all, if the approach embedded in the new 'RAFT spreadsheet tool is adopted which reduces these curves down to a single annual probability of failure.
    - Highest level of evaluation – the 'full approach', which involves the use of the RELIABLE tool, should include 2-3 worked examples, one of which might involve use of implicit relationships (e.g. those associated with the numerical models required to analyse slope stability problems in flood embankments).
    - Intermediate level of evaluation, involving determination of high level fragility curves for selected assets in a system and inferring/interpolating to the remaining assets.

2.2 Further development of the reliability tool (RELIABLE) (D) and (R)

Work required here involves:

- Coding up additional subroutines of failure modes where an explicit equation or model is available and the equation has not yet been implemented in RELIABLE. (D)

- Development of approaches (e.g. neural networks) for creating shortcuts to generate fragility curves for failure modes of selected structure type failure modes where the solution require the use of implicit relationships. (e.g. numerical models). (R)
- For those modes of failure for which appropriate limit state equations or models do not exist – e.g. for piping of flood embankments – methods for developing and improving fragility curves should be developed and/or recorded. (R)

2.3 Understanding coastal flood defence failure mechanisms in a load dependent way (R).

At present, the generic RASP fragility curves are linked to the wave overtopping loading, but it is known that this is imperfect as it does not completely reflect the significance of beach level in front of the wall and its relation to toe level. In RACE the fragility curves are time-dependent and, whilst at a national scale this is adequate for coastal erosion assessment, there is a failure to capture the link with beach physical processes. A form of expressing fragility (covering a range of condition grades) is needed which relates to both loading (forcing) conditions and to the way in which beach system performance is characterised.

2.4 Risk performance of groyne and other beach and wave control structure (R)

There is a need to understand failure mechanisms for these various structures and then express their performance in a manner which is appropriate to their function and the function of the beach as a whole. This understanding and any associated tools are essential to permit attribution of erosion risk (benefits) to individual (or groups of) coastal control structures. As such, it is as important as making the connection between risk and conveyance management in rivers.

2.5 Linking fragility to breach (important but optional for this project) (R)

This research will develop a robust working link between the 'frequency domain' assessments of defence failure via fragility curves and the 'time domain' analysis of breach initiation, growth and consequential flooding. This will partly be addressed under FRMRC2.

2.6 Additional guidance on culverts (optional) (E)

Culverts are a major issue in asset management. Is there scope for taking the CDOG (Culvert Design and Operation Guide) and providing a short note on how their assessment and management should be linked into the assessment and management of other assets?

Recommendation 10.4: That Work Package 3 on asset system performance include the following sub-packages:

3.1 Guidance on tiered assessment of asset system performance (E)

The guidance would cover the spectrum of methods from simple qualitative screening through to bespoke structure-specific probabilistic assessments. The project team recommends an *appropriate use of probabilistic methods* in the description of asset response, particularly for decision support with management of complex, high consequence or costly systems. The tiered assessment guidance (avoiding a one-size-fits-all approach) would cover a range of approaches including:

- Appropriate use of NAFRA-scale assessment of risk attribution.

- Use of the new RAFT spreadsheet tool (or its successors) currently under development for asset system management.
- Use of the full risk-attribution approach, using where appropriate:
  - bespoke analysis of loading conditions;
  - development of site-specific fragility curves;
  - appropriate flood spreading models;
  - improved information on damages/benefits, taking account of factors which might be omitted in national scale analysis. e.g. in relation to caravan parks or agricultural land

The approach would involve identifying those systems that contribute most to flood risk by the simplest methods and then focusing the more detailed efforts on these.

3.2 Methods for incorporation of secondary defences (optional) Pilot studies have identified that secondary defences and flood routing can be a significant issue. Analysis of this kind of problem has involved, for example, adaptation of digital terrain models (DTMs) to force water to flow in the right direction in the model. Research is needed to examine more robust alternatives that allow sequential failure of the secondary defences conditional on failure of main defences and which allow their fragility to be taken into account. (This should relate to the approaches already taken in mapping & appraisal, not starting from scratch.)

3.3 Guidance for asset management plan (SAMP) and MTP optimisation (E)

A working guide is needed to indicate how systems analysis can be used to optimise management plans such as the Agency's SAMPs and medium-term plans (MTPs), using the range of techniques described in 3.1). It will describe a range of approaches from manual definition of options through to automated methods for solution searching such as those being considered under the FRMRC2 project. The guidance should also indicate how structured uncertainty and sensitivity analysis should be used to guide decision-making.

NOTE: Core systems analysis tool. It was always conceived that the core RASP engine for systems risk analysis would be common to NAFRA, MDSF2 and PAMS. Hence developments of this are not included. For example, current developments of the Rapid Flood spreading model can and should be used in PAMS type analyses when this is available.

Recommendation 10.5 That Work Package 4 on liaison with other research projects and initiatives include:

- Liaison with projects such as:
  - Deterioration and whole life costs.
  - MEICA assets study.
  - CDOG and related trash screen (RH) and Debris (FRMRC2) work.
  - FRMRC2.
  - Outcome measures and KPI studies.
- Links with the ongoing development of other asset management and data systems within the Environment Agency and elsewhere.

- Liaison and support for the development of operational instructions by the Environment Agency's Asset System Management team (to ensure that Embedment activities are taken right through to operational use).

NOTE: A fixed number of days will need to be specified in the brief for this liaison activity to avoid it becoming an open-ended activity.

Recommendation 10.6. That the performance and fragility group #2 of work items in Appendix 7 identified in the separate PAMS/RACE scoping study in relation to coastal assets be included in this Asset Performance Tools project. To effect this, reference to appropriate work items has already been included in the descriptions of Work Packages 1 and 2 (recommendations 10.2 and 10.3) and in embedded notes within Appendix 7.

10.2 Future uptake – barriers and facilitators

The introduction of formal and structured risk-based approaches to asset management challenges many traditional ideas and can be difficult to achieve in practice. Many of the barriers to uptake of such methods reflect mistrust of new approaches and typical misconceptions around the complexities of risk-based methods. The barriers and opportunities of these approaches are well known (Figure 10.1) and will need to be managed if the tools and techniques are to be successfully taken up by industry.

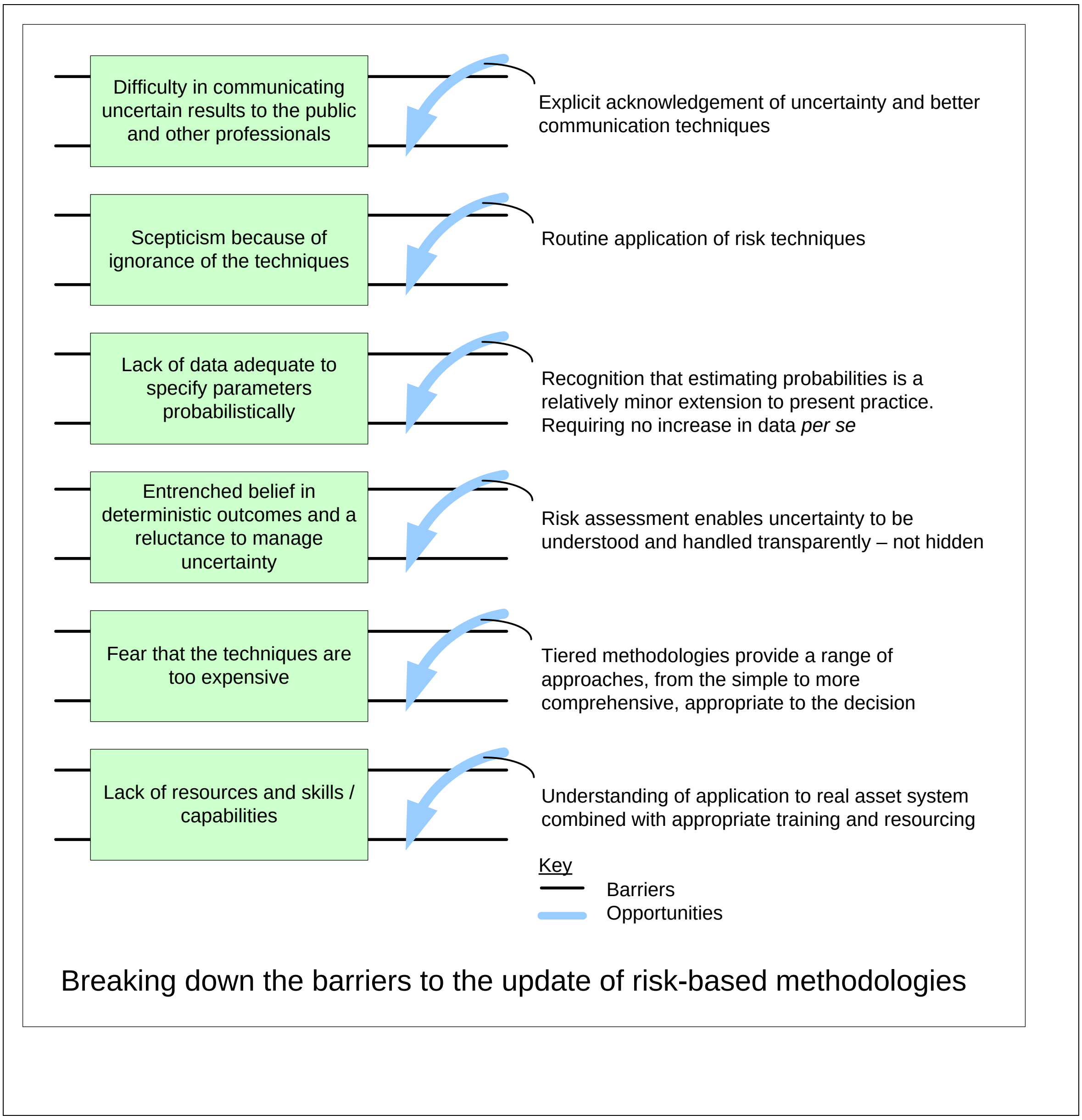


Figure 10.1: Typical barriers and resistance to the uptake of probabilistic methods (after Environment Agency/HR Wallingford Ltd, 2002).

Recommendation 10.7 That a separate project be undertaken to ensure that supporting FCRM asset database has the appropriate rational relationships within the data holdings and hierarchical logical structuring to facilitate use by the PAMS tools (D). Coordination with the future development of the will be important to get the principles correct now, as future modification to the data structures could be difficult/expensive.

Access to, and an ability to record and recall, information on uncertainty together with new datasets – such as attributed risk (breach and non-breach cases), fragility information, potential breach size, deterioration rates – are all pre-requisites to the use of the core (RASP) risk systems analysis tool (Appendix 8). Recognising the time and cost implications, Appendix 9 sets out a prioritised list of data collection and database actions.

Recommendation 10.8 That additional demonstration project(s) be carried out to promote the PAMS tools (E). The pilot studies have suggested that there is a lot of enthusiasm from area teams for this. At least one of the inland demonstration projects/pilots should include modelling of both an IDB system as well as Environment Agency high level carriers. On the coastal side, involvement of one or more local authority would be ideal but this depends on the research having advanced to the point where the system can be modelled appropriately.

Recommendation 10.9: A programme of training and resource development be put in place to make sure that staff in the Environment Agency and other operating authorities can make best use of the range of powerful techniques that have emerged from the PAMS programme (E).

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12 Glossary

Word or term	Meaning
Adaptive management	An approach to managing systems which have inherent uncertainties that involves learning from the system response to intervention, and using that learning to improve the next stage of management.
Asset	In flood defence or coast protection, any manmade or natural object - such as a raised defence, retaining structure, channel, pumping station, culvert or beach - that performs a flood defence, land drainage or coast protection function.
Asset management	Systematic and coordinated activities through which an organisation optimally and sustainably manages its assets and asset systems - including their associated performance, risks and expenditures - over their life cycles for the purpose of achieving its strategic aims.
Assessment	The process of understanding the state, performance or structural competence of an existing asset or asset system in order to inform the planning of future interventions.
Benefits	In flood defence, land drainage or coast protection appraisal, the value placed on the reduced likelihood of flooding, waterlogging or coastal erosion provided by the asset, asset system or project (see also risk attribution).
Change	In asset mangement, work that alters the standard of service of an asset. For example, raising a flood embankment crest above the original design level, or asset decommissioning.
Characterisation	The process of expressing the observed or predicted behaviour of a system and its elements in order to inform some aspect of decision making.
Condition	State of repair or deterioration of an asset. The condition grade is a systematic evaluation of asset condition by visual inspection
Consequence	Impact such as economic, social or environmental damage of an event such as extreme storm, asset failure or coastal erosion. Can be expressed quantitatively (e.g. monetary value), by category (e.g. high/medium/low) or descriptively.
Control structure	Structures on which there is a fixed (e.g. weir) or adjustable (e.g. gate) control on the head/discharge relationship across them.
Crest level	Level of highest point of an asset at a particular cross section above which above which overtopping could occur.
Critical element	Element of a system, the failure of which will lead to the failure of the system.
Debris	Solid material (sediment or of vegetation or anthropogenic origin) transported in a watercourse, particularly during flood events. Debris can move intermittently and has potential to cause

Word or term	Meaning
	blockages that impede the free flow of water.
Design life	The service life of an asset intended by the designer. This assumes some rate of deterioration up to a point where the asset requires replacement or refurbishment.
Design standard	A performance indicator that is specific to the engineering of a particular defence to meet a particular objective under a given loading condition. With probabilistic methods, the differing design standards and performance can be attached to differing loading conditions (see also fragility).
Demountable defence	Purpose-made flood defence components (often stored off-site) that are temporarily installed above ground on specially designed insitu structural foundations when a defined risk of flooding exists.
Deterministic	Descriptor of method or process that adopts precise single values for all variables and input values, giving a single value output.
Deterioration	Decline in the material properties of some or all components of an asset caused by external agents (e.g. freeze/thaw) leading to a reduction in its structural strength.
Discharge	Flow volume of a river, watercourse, drain or surface flood pathway as measured by volume per unit of time.
Disposal	Activities necessary to dispose of decommissioned assets.
Element	A component part of a system or asset.
Engineering inspection or survey	Detailed assessment of an asset, including its foundations and internal structure as appropriate, to determine its condition, including any structural faults.
Event	Conditions which may lead to flooding or trigger a coastal landslip. An Event is, for example, the occurrence in source terms of critical variables such as a flood water level being exceeded at the same time a specific sea level, or in receptor terms a particular flood depth.
Failure	Inability to achieve a defined performance threshold. "Catastrophic failure" describes the situation where the consequences are immediate and severe.
Failure mode	Description of one of any number of ways in which an asset or asset system may fail to meet a particular performance indicator.
Flood defence asset	An asset that by its failure would increase the likelihood of flooding from any main river, watercourse and/or the sea to people, property or infrastructure.
Flood defence system	Two or more flood defence assets acting to achieve a common goal (e.g. maintaining flood protection to a floodplain area / community).
Flooding system	The broad social and physical domain within which risks arise and are managed. An understanding of the way a system behaves and, in particular, the mechanisms by which flooding might be propagated and receptors could be harmed, is an essential aspect of understanding risk. This is true for an organisational system like

Word or term	Meaning
	flood warning as well as for a physical system of assets.
Flow	General term used to describe movement of water in a particular direction (as distinct from specific descriptors such as discharge or velocity).
Fragility	The likelihood of particular defence or system to fail under a given load condition. Typically expressed as a 'fragility curve' relating load to probability of failure. Combined with descriptors of deterioration, fragility relationships enable performance to be described over time (see also design standard).
Frequent maintenance	Planned activities supporting the standard of service of an asset in a cost-effective manner by reducing its rate of deterioration (Frequent < 5 -yearly interval).
Function	The purpose that an asset fulfils for those who benefit from or use it and the environment in which it exists. An asset will have a primary function of flood defence, land drainage or coast protection plus some secondary functions such as ecological, access, health & safety or amenity.
Functional design	The design of an intervention to address specific performance requirements (aims and objectives) relating to its function.
Frontage	Sub-division of the coastline for asset management purposes.
Harm	Disadvantageous consequence.
Hazard	A situation (physical event, phenomenon or human activity) with the potential to result in harm. A hazard does not necessarily lead to harm – it can be managed.
Hierarchy	Conceptual framework for planning and risk management in which information cascades from a greater spatial or temporal scale to lesser scale, and vice versa.
Infrastructure	Collective term for a group of assets essential to normal life whose primary function is to provide a service to the community
Intermittent maintenance	Infrequent and one-off planned activities that support the standard of service of an asset.
Intervention	A planned activity designed to effect an improvement in an existing natural or engineered system (particularly with asset management).
Limit state	The boundary between safety and failure for a structure. The limit state function Z=R-S is a function of the structure's strength (R) and loading (S) for a particular failure mode. Failure will not occur if the limit state function is positive.
Maintenance	Work that sustains the desired condition and intended performance of an asset.
Operating Authority	An organisation (Environment Agency, local authority or Internal Drainage Board) having powers under the Land Drainage or Water Resources Acts to operate, maintain or improve flood defence assets within its operating boundaries

Word or term	Meaning
Operational inspection	Regular inspection of an asset to check it is in working order and in a safe condition.
Pathway	Route that enables a hazard to propagate from a source to a receptor. A pathway must exist for a hazard to be realised and can be constrained to mitigate risk.
Performance	The degree to which a process or activity succeeds when evaluated against some stated aim or objective.
Performance feature	Visual indicator of asset condition associated with a potential failure mode and used in the process of determining the condition index.
Performance indicator	Meaningful and measurable objective(s) of a particular asset management policy or project. May be technical performance indicators, such as acceptable wave overtopping rates or conveyance capacity, or more generic indicators such as public satisfaction.
Probability	Measure of the chance that an event will occur. Typically defined as the relative frequency of occurrence of that event out of all possible events and expressed as a percentage with reference to a time period e.g. 1% annual exceedance probability.
Probabilistic	Descriptor of method or process in which the variability of input values (e.g. asset loading & strength) and the sensitivity of the results are taken into account to give results in the form of a range of probabilities for different outcomes (e.g. failure).
Probability density function (PDF)	Numerical or graphical function which describes the probability of different values across the whole range of a variable (e.g. flood damage, extreme loads, storm conditions etc.).
Progressive failure	Failure process where, once a threshold is exceeded, some residual strength enables the asset to maintain restricted performance while further progressive loss of strength takes place. Not as dramatic or quick as catastrophic failure.
Raised defence	Any raised structure that protects an area from flooding.
Reach	A length of channel between set boundaries. For asset management purposes, each riverbank or flood defence system is divided into reaches of broadly similar length.
Receptor	The entity (such as a person, property, habitat etc.) that may be harmed by an event via a source and pathway. The vulnerability of a receptor can be reduced by increasing its resilience.
Refurbishment	The process of returning an asset to its original as-designed performance.
Residual life	Service life remaining at a particular moment in time. Residual life can be extended or reduced by altering maintenance practice or by refurbishment.

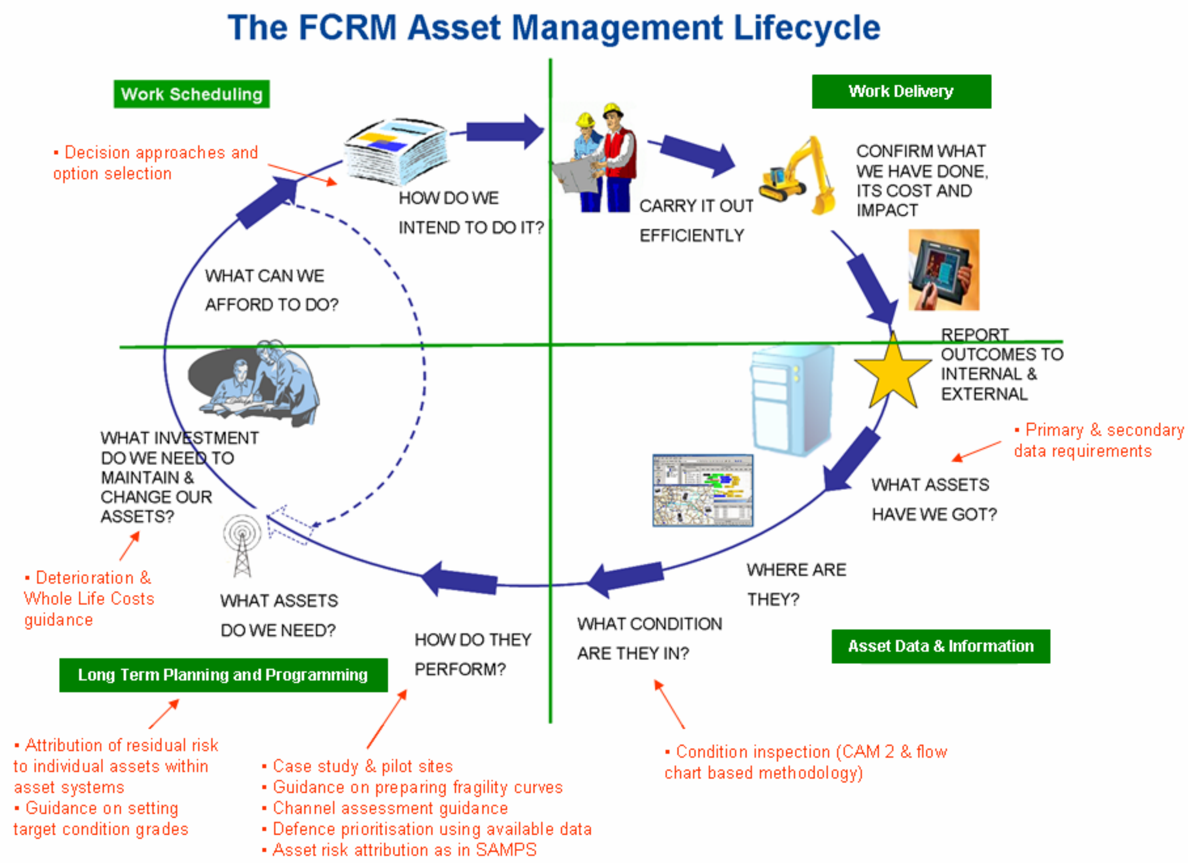
Word or term	Meaning
Residual risk	The risk that remains after risk management and mitigation measures have been implemented. For example, damage predicted to continue to occur during flood events of greater severity than 1% annual exceedance probability.
Resilience	In asset management, the ability of an asset or asset system to resist the damaging effect of extreme loading. Resilience measures can for example help to achieve design standards above the SoP.
Risk	Risk can be considered as having two components - the probability that an event will occur and the consequence associated with that event to receptors. Risk = f (probability x consequence). Flood risk to a receptor can be indicated graphically by a PDF with probability and consequence as the x and y axes. The area under the curve is the overall risk.
Risk assessment	The process of identifying hazards and potential consequences, estimating the magnitude and probability of consequences, and assessing the significance of the risk(s). A 'tiered' approach can be used with the effort in assessing each risk proportionate to its importance in relation to other risks and likely consequences.
Risk attribution	The contribution of specified assets or groups of assets to the overall risk to receptors associated with a flooding system or protected by a flood defence system. This helps interventions to be targeted on managing the greatest risks.
Risk management	The systematic process of risk assessment, options appraisal and implementation of any risk management measures to control or mitigate risk.
Security screen	A screen which prevents unauthorised or accidental access to a culvert or other structure that is hazardous.
Service life	The period of time after construction or refurbishment during which an asset meets or exceeds its functional performance requirements.
Source	The origin of a hazard (e.g. storm rainfall, strong winds, surge etc.).
Standard of Protection (SoP)	In FRM economic appraisal, the probability (annual exceedance) of the flood level associated with the defence (crest level less freeboard).
Standard of service	The performance of an asset at a specific point in time expressed in terms of a physical attribute(s) of the asset or system (e.g. crest level, pump capacity).
System	Assembly of elements, and the interconnections between them, constituting a whole and generally characterised by its behaviour (e.g. elements in a structure; assets in an asset system). Concept also applied to social and human systems.
System asset management plans (SAMPs)	Long-term investment plans for flood defence and coast protection asset systems that identify the investment needed and the benefits they bring.

Word or term	Meaning
Temporary defences	Defences erected or constructed immediately before a flood event to reduce the likelihood of flooding, which are removed after the event.
Trash screen	A screen on the upstream end of a structure, often a culvert, pumping station or weir, whose primary purpose is to prevent debris from entering the structure and causing blockage.
Ultimate limit state	Limiting condition beyond which a structure or element no longer fulfils its intended function(s) e.g. flood defence, amenity etc.
Uncertainty	Lack of sureness about someone or something ranging from almost complete sureness to almost complete lack of conviction about an outcome. Caused by (a) natural variability (inherent uncertainty) or (b) knowledge (epistemic) uncertainty.
Value management	Evaluation process addressing the technical and functional aspects of a project to ensure that a fully integrated approach is taken, all options have been properly assessed, and the proposed outcome is consistent with strategic aims.
Visual asset inspection	Systematic visual assessment of the condition of the visible elements of an asset resulting in the assignment of a condition grade.
Vulnerability	Characteristic of a particular asset, system, or receptor group that describes its potential to be harmed.
Watercourse	Defined natural or manmade channel for the conveyance of drainage and flood water by gravity.
Whole life cost	Total cost of managing an asset over its life, including cost of construction, use, operation, inspection, maintenance and refurbishment, replacement or disposal.
Withdrawal of maintenance	Process of ceasing maintenance of flood defence or coast protection assets because it is uneconomic to continue.

Appendices

Appendix 1 FCRM Asset Management Cycle

The text in red denoted in the FCRM 'Asset Management Lifecycle' shown below corresponds to the 'products' listed in Appendix 2. These indicate where the project outputs will contribute to the management of this process.



Appendix 2 Work packages in PAMS Phase 2

Work Packages

1 Case study and pilot sites

2 Defence prioritisation using available data

3 Develop, test and deliver condition inspection methods

4 Develop, test and deliver risk indexing methods

5 Describe and demonstrate system analysis tools

6 Establish a model for decision approaches and option selection techniques

7 System development and delivery

8 System architecture and data management

Measured Steps Forward

1 Update of the condition assessment manual

2 Inclusion of channels in the revised condition assessment manual

3 Channel management guidance for asset systems management

4 Channel management guidance for operations delivery

5 Primary and secondary data requirements for PAMS

6 Asset residual risk attribution

7 General support to the development of guidance for SAMPs and the subsequent roll-out

8 Bringing environmental context and geomorphological classification into SAMPs

9 Guidance on deterioration and whole-life costs

10 Provision of information on asset risk attribution for the development of SAMPs

11 Area pilots – attribution of residual risk to individual linear assets within an asset system

12 Expressing/ finding alternatives to asset management terms in order to suit a risk framework

13 Representing asset fragility at the local (PAMS) level

14 Guidance on setting target condition grades

Appendix 3 Products of PAMS Phase 2

- **E**mbedded (**E**) into practice (in the Environment Agency but not necessarily other operating authorities).
- **D**evelopment (**D**) of working tool ready to proceed.
- **R**esearch (**R**) required to produce and test the prototype product.

*The following list links to items in italics in the Executive Summary text and the (**E**), (**D**) and (**R**) designations*

Project ref.	Product	Location of description of product in this or other project reports	Desig-nation
WP1	Case Studies	See report SC040018/SR2, pilot site studies	**E**
WP2	Early defence prioritisation using available data	Project record (interim deliverable)	**R**
WP3	Condition inspection methodology, including:	See report SC040018/SR3 *Development, testing and delivery of a condition inspection methodology*.	**D**
	Flow charts for performance assessment of linear defences	Focus Product 3.1	**D**
	Methodology for converting performance feature scores into condition grades	Focus Product 3.3	**D**
	Questions to trigger more detailed inspection or interventions	Focus Product 3.4	**D**
WP4	RAFT Risk Assessment Field-based Tool	Focus Product 6.1. Detailed description in report SC040018/SR4	**E**
WP5	System analysis tool for risk attribution and defence prioritisation	See report SC040018/SR4 *Flood defence systems analysis – methods tools and decision support*	**D**
WP6	Conceptual model for decision approaches and option selection	See report SC040018/SR4 *Flood defence systems analysis – methods tools and decision support*	**D**
WP7	System development and delivery	See report SC040018/SR4 *Flood defence systems analysis – methods tools and decision support*	**D**
WP8	System architecture and data management	See report SC040018/SR4 *Flood defence systems analysis – methods tools and decision support*	**D**
MSF1	CAM2: Update of the Condition Assessment Manual	Focus Product 3.2	**E**

Project ref.	Product	Location of description of product in this or other project reports	Desig-nation
MSF2	Inclusion of channels in the revised condition assessment manual	Focus Product 5.1	**E**
MSF3	Channel management guidance for asset systems management	Focus Product 5.2. Focus Product 5.3	**E**
MSF4	Channel management guidance for operations delivery	Focus Product 5.2. Focus Product 5.4	**E**
MSF5	Primary and secondary data requirements for PAMS	Chapter 8 and Appendices 8 and 9 of this report	**D**
MSF6	Asset residual risk attribution	Project record (interim deliverable)	**R**
MSF7	Support for development of data gap identification guidance for staff preparing SAMPs	Project record (interim deliverable). Guidance now embedded in the SAMPs process	**E**
MSF8	Environmental and geomorphological context	Liaison role for team (interim deliverable)	**R**
MSF9.1	Guidance on deterioration rates for different asset types for whole-life asset plans	Project record (interim deliverable). Guidance superseded by reports of subsequent project SC060078	**E**
MSF9.2	Guidance on capital and maintenance costs of different assert types for whole-life costing	Project record (interim deliverable).	**D**
MSF10	Provision and use of information on asset risk attribution for the development of SAMPs	Included by agreement in integrated pilots and systems analysis reports	**R**
MSF11	SAMPs area pilots – attribution of residual risk to linear defences	Included by agreement in integrated pilots and systems analysis reports	**R**
MSF12	Definition of asset management terms to suit a risk framework	Glossary of this report	**E**
MSF13	Guidance on preparation of site-specific fragility curves for defence assets	Focus Product 4.1. Full details in report SC040018/SR5 *Development of fragility curves for use in management of flood defence assets*	**D**
MSF14	Guidance on setting target condition grades	Focus Product 3.3. Now included in Environment Agency guidance and in Flikweert and Simm (2008)	**E**

Appendix 4 Projects or developments providing inputs to PAMS Phase 2

- Thames Estuary 2100
- Performance and reliability of flood and coastal defences
- National Appraisal of Flood Risk Assessment (NaFRA)
- Risk Assessment for System Planning (RASP)
- Conveyance Estimation System (CES/AES)
- FLOOD*site*, particularly:
  - Task 4 (Understanding and predicting failure modes)
  - Task 7 (Reliability analysis of flood defences)
  - Task 24 (River Thames Estuary pilot)
- Operations and Maintenance Concerted Action
- Embankment Failure under Extreme Conditions (IMPACT)
- Flood Risk Management Research Consortium (FRMRC) phase 1 projects;
  - WP4.1 Geotechnical stability of flood embankments
  - WP4.3 Development of improved asset inspection methodology

Appendix 5 Other projects and development initiatives into which PAMS Phase 2 has linked

- Deterioration and whole-life costs (scoping study underway including interviews with Environment Agency and local authority engineers) – Phase 1 completed early 2009.
- MEICA Scoping; completed 2009.
- CES/AES further development; project now commissioned. Initial recommendations for future developments provided in summer 2009.
- PAMS/RACE – Scoping study for coast protection asset management – completed in August 2009.
- FRMRC2 Infrastructure R&D. FRMRC1 research has been taken forward into FRMRC2. Titles under *Super Work Package 6 – Infrastructure Management* include:

  6.1. Predicting and managing flood risks associated with debris at structures: holistic serviceability approaches.

  6.2 Performance-based inspection of flood defence infrastructure integrating visual inspection and quantitative survey measurements.

  6.3 Broad-scale integration of coastal flood and erosion risk models.

  6.4 Breach size – rapid methods of assessment.

  6.5 Next generation tools to support robust and sustainable asset management.
- Assessing flood risk in pumped catchments (project SC090006)

Appendix 6 Ranking of benefits from proposed embedding work

We believe that as a result of the piloting and '*Development* ' work under PAMS Phase 2 that there are very strong benefits to be achieved by focussing largely on 'Embedment ' work during future projectsThe table below highlights the benefits that could be set out in a Project Form A.

Type of benefit to asset management	Benefit from Work Package		
	Asset Condition	Individual defence assets	Asset systems
Saving in cost of ongoing asset management, including deferred replacement	M	H	M
Greater flood risk reduction for asset system within existing budget	M	H	H
Better evidence to support otherwise poorly justified asset management decision	H	H	H
Better 'bottom up' information on assets (e.g. life; change) to support strategy development	H	H	M
Better understanding of ASM staff about flood risk attribution and performance of system	H	H	H

Appendix 7 PAMS/RACE coastal projects

Item	Framework component
	1 Developments for decision-making and operational support
1	Agreement of coastal risk management risk metrics and weightings
2	Development of a method to evaluate the benefits of changes in beach morphology*
4	Representation of ‘do nothing’ consequences (for erosion particularly)
5	Research to support attribution of erosion risk (benefits) to individual coastal assets or groups of assets (defences, beaches, groynes, saltmarsh)*
6	A better understanding of the performance and risk from natural features such as the collapse of cliffs, breaching of dunes and erosion of saltmarsh*
7	Optimisation of intervention
17	Improving baseline data through inspection and condition assessment of defences (particularly ‘natural’ defences) that more explicitly recognises the relationship between the condition and the performance of an asset
18	Improved visual (and second level) condition assessment methodology of beaches, dunes and saltmarsh*
	2 Performance and fragility research and development
3	Improving knowledge on how defence and protection assets will respond to changing forcing conditions, such as sea level rise and increased storminess, and to deterioration (including assessment of beach schemes over the last 10 years) (largely covered under next item)
8	Understanding of failure mechanisms for seawalls in a load-dependent way (Include in APT package 2.3)
9	Sensitivity of asset condition to external forces (deterioration and failure) (Cover under item 8 and under deterioration and whole-life costs project)
10	Failure mechanisms and deterioration for different cliff (soil/rock) types and recession prediction.
19	Improved visual (and second level) condition assessment methodology of control structures, including seawalls, groynes and offshore breakwaters and monitoring during extreme events. (Include in APT Package 1.2)
	3 Medium-term fundamental R&D on modelling system geomorphology
11	Research to support geomorphological modelling developments to include estuarine shorelines as well as open coasts*

12	Modelling the nature of longshore connectivity of sediment flux effects on performance*
13	Beach system modelling and prediction of effects of control structures*
14	Research to resolve problems with modelling of mixed beaches*
	4 Medium- to long-term fundamental process research
15	Understanding of beach system performance and effects on toe level at the sea wall*
16	Wave processes on permeable/barrier beaches
	5 Short-term/low cost data reviews
20	Review of data requirements for erosion protection structures
21	Review of data requirements for erosion/flood protection performance of natural defences

Appendix 8 Data required for PAMS type analysis

No	Data item	In PAMS?	P/S*	Data source	Measurement technique(s) and accuracy
Source					
1	In-river water levels/loads	Y	P	External models, NaFRA, other	Model/source dependent
2	Coastal water levels/loads	Y	P	External models, NaFRA, other	Model/source dependent
3	Flood depth grids	N?	P	External models, NaFRA, derived from flood contours & DTM	Model/source dependent
Pathway					
Flow path (river)					
4	River Centre Lines	Y?	P	EA DRN	Derived from MasterMap rivers data
5	Channel blockage – CG	Y	P	Will be NFCDD	Visual inspection
6	Channel vegetation – CG	Y	P	Will be NFCDD	Visual inspection
Flow path (floodplain)					
7	Ground model	Y	P	EA Twerton	GPS derived (± 1 cm); Survey (± 10 cm); LiDAR (± 25 cm), NextMap SAR (± 75 cm); OS Profile-derived (± 2.5 m to ± 5 m); hand-held GPS (± 5 m to ± 10 m)
8	Extent of natural floodplain	Y	P	Flood zones, external model, other	Model dependent

No	Data item	In PAMS?	P/S*	Data source	Measurement technique(s) and accuracy
9	Valley type	Y?	S		Derived from floodplain width & longitudinal defence slope
10	Floodplain width	Y?	S		Derived from defence location and Flood Zone 2 boundary
Linear Assets					
11	Defence type	Y	P	NFCDD	Derived from asset data e.g. type, sub-type, material, revetment
12	Crest level	Y	P	NFCDD	LiDAR, SAR, detailed survey, inferred from SoP
13	Standard of protection	Y?	P	NFCDD	Subjective assessment, design standard
14	Condition grade	Y	P	NFCDD	Visual inspection
15	Toe level	Y	P	NFCDD	In situ measurement, remotely sensed (± 1m)
16	Ground level (at defence)	Y	S	Populated from the ground model	As for ground model
17	Location (spatial)	Y?	P	NFCDD	Offset from the river centreline
18	Defence length	Y?	P	NFCDD (includes straight lines)	Captured from the length of the defence spatial data
Non-linear assets (in-line / off-line)					
19	Spatial location	Y	P	NFCDD or similar database	
20	Asset type	Y	P	NFCDD or similar database	
21	Relevant properties for reliability & system analysis e.g. CG, CL, GL, SoP, width, height, shape, length etc.	Y	P	NFCDD or similar database	

No	Data item	In PAMS?	P/S*	Data source	Measurement technique(s) and accuracy
Receptor / Consequence					
Property data					
22	Spatial location 1	Y	P	NPD, EA Twerton, Address Point	Derived from OS Mastermap TOID, represents letterbox
23	Property type (RP / NRP)	Y	P	NPD, EA Twerton	
24	Local authority code	Y	P	NPD, EA Twerton	Derived from an OS boundary dataset defining local authorities
25	Postal area field	Y	P	NPD, EA Twerton	
26	Floor level e.g. basement, upper	Y	P	NPD, EA Twerton	Derived from OS Mastermap
27	MCM code (for NRP)	Y	P	Middlesex MCM Tables	
28	Damages (£/m^2 floor area)	Y	P	Middlesex MCM Tables	
29	Saline uplift with depth	Y	P	Middlesex MCM Tables	
30	Floor area	Y	P	OS Mastermap	Mastermap polygon
31	Spatial location 2 e.g. letterbox	Y	P	OS Mastermap	Derived from TOID of polygon = Address Point, represents letterbox
32	VO Code (for establishing NRP & bulk class)	Y	P	Valuation Office database	
33	Spatial location 3 (point)	Y	P	Valuation Office database	
34	Property ground level	Y	S	Populated from the ground model	As for ground model

No	Data item	In PAMS?	P/S*	Data source	Measurement technique(s) and accuracy
35	Property threshold level	Y	S	Vertical reference frame used within MCM tables. Based on ground model + threshold value.	As for ground model + previous analysis (ref Anglian analysis - J Chatterton, 29/05/2006) has shown the average property threshold to be 0.28 m. For NaFRA 2006, ESG agreed to use a value of 0.25 m.
Other impact data e.g.					
36	Population data for census ED	N?	P	EA	Population census
37	Flood SVI for census ED	N?	P	EA	
38	Agricultural Land-Use Classification	N?	P	Defra, Agricultural Land Classification	Inundation damages in £/ha/year have been defined for each land class, assuming a single flood event lasts one week in duration. This is captured at a scale of 1:250,000.
39	Infrastructure damages	N	P	Exist? (some disruption costs in MCM Chapter 6)	
40	Ecological damages	N		Exist?	

Appendix 9 Summary of findings and proposed actions to support PAMS data requirements (P = Priority)

	No	Data Item	Findings (Information source = Data Review, RASP Sensitivity, Note on Impacts, Other)	P	Proposed Actions
Source	1	In-river water levels/ loads	Major gap in knowledge, poor information for catchment-scale, need to link water levels to individual defences, need more return periods, very high sensitivity especially if SoP is low e.g. high ground rather than raised defences	H	Devote appropriate resources and technology at a local scale. Improve understanding of uncertainty bands. *Required accuracy 1:1,000 year event to within ± 10 cm.*
Source	2	Coastal water levels/ loads	Need to develop a nationally consistent set for joint probability of wave and water levels	M	Develop consistent approach (and source data) for JP. *Required accuracy?*
Source	3	Flood depth grids	Major gap in knowledge	L	Use in PAMS to be confirmed
Pathway	4	River centre lines	New DRN ready in 12 months	M	No specific action
Pathway	5	Channel blockage CG	This is a new initiative under PAMS MSFS 3 and 4.	H	Underway - ASMPs/CAM
Pathway	6	Channel vegetation CG	This is a new initiative under PAMS MSFS 3 and 4.	H	Underway -ASMPs/CAM
Pathway	7	Ground model	Need data flags to indicate accuracy. High sensitivity (this outcome may be exacerbated as ground levels were similar to water levels).	M	Introduce data flags to show existing accuracy and to target improvements, specifically urban areas. *Required accuracy*

No	Data Item	Findings (Information source = Data Review, RASP Sensitivity, Note on Impacts, Other)	P	Proposed Actions
				± 25 cm e.g. LiDAR
8	Extent of natural floodplain		L	Use in PAMS to be confirmed
9	Valley type	Medium sensitivity	L	Use in PAMS to be confirmed
10	Floodplain width	Low sensitivity	L	Use in PAMS to be confirmed
Linear Assets				
11	Defence type	Many noted as 'other', high impact on uncertainty if 'other' is used, two per cent without sub-type information	M	Improve NFCDD data through survey, as-built drawings, aerial photography interpretation, other.
12	Crest level	Seventy-eight per cent unpopulated, evidence of planned work in DAPs, very high sensitivity especially in fluvial areas if SoP is low, need to improve accuracy	H	High priority for data collection especially in high risk areas. Make use of additional levels available from scheme design, reports, survey, LiDAR interpretation, other. Standardise datum with toe level & ground level *Required accuracy ± 10 cm*
13	Standard of protection	Ninety per cent unpopulated, evidence of planned work in DAPs, high sensitivity if error is over 50 years	M	Improve data e.g. original design drawings. *Required accuracy ± 50 years.*

No	Data Item	Findings **(Information source = Data Review, RASP Sensitivity, Note on Impacts, Other)**	P	Proposed Actions
14	Condition grade	Three per cent unpopulated, high impact on uncertainty, very high sensitivity (part expert judgement), more sensitive for CG 4 or 5 than 1 or 2.	M	Revise CG estimates - focus on CGs of 3-5 in high risk areas (e.g. urban) and any unknown CGs above 3+.
15	Toe level	High sensitivity (expert judgement), not well-populated	H	Review of completeness of data (introduce data flags). Undertake further sensitivity testing of this parameter. Standardise datum with crest level & ground level *Required accuracy << ± 1 m (tbc)*
16	Ground level (at defence)	High sensitivity (inferred 7)	M	Standardise datum with crest & toe level
17	Location (spatial)	NFCDD near completion for main rivers and coasts	M	Collect/improve tributary data
18	Defence length	Not always accurate, especially non-straight defences	M	Short-term: use 1:10,000 OS Map. Longer-term: derive from DEM
Non-linear Assets				
19	Spatial location		H	To be populated
20	Asset type		H	To be populated
21	Relevant properties for reliability and system analysis		H	To be populated once reliability parameters defined

	No	Data Item	Findings (Information source = Data Review, RASP Sensitivity, Note on Impacts, Other)	P	Proposed Actions
Receptor / Consequence	Property data				
	22	Spatial location 1 (NRP)	Many property omissions	M	Assess scale of omissions. Address omissions through use of other databases, dialogue with OS to maximise accuracy. Investigate scope/potential of commercial databases e.g. GOAD
	23	Property type (RP/ NRP)	Uncertainty on sub-type information e.g. semi-detached	L	Use of sub-types in PAMS to be confirmed
	24	Local authority code		L	No action
	25	Postal area field		L	No action
	26	Floor level e.g. upper	Very high sensitivity (inferred 28), improve data on flats, upper storeys and basements	H	Scope possible sources of data
	27	MCM code (for NRP)		L	No action
	28	Damages (£/m^2 floor area)	NPD data suitable for broad-scale baseline. Recommends use of council tax band to estimate property capital value, very high sensitivity - especially to floor space, prone to error for large industrial units (linked to flood space)	H	Action via 30
	29	Saline uplift with depth		L	No action
	30	Floor area	Very high sensitivity (inferred 28), improved use of data	H	No action?

No	Data Item	Findings (Information source = Data Review, RASP Sensitivity, Note on Impacts, Other)	P	Proposed Actions
		(TE2100, MDSF2)		
31	Spatial location 2 (OS Map)	Address points linked to wrong footprint e.g. gate house, too many null or zero values	L	Action via 30 – improved methods
32	VO Code (for establishing NRP & bulk class)	NRP valuations often inaccurate, too many null or zero values, too many 'X' values for NRP VO code i.e. no link with MCM code, residential property valuations linked to land registry data (results in biased EAD for low/high valuations)	M	Data: Scope alternative source for valuation data to improve/validate Method: Identify and omit outliers e.g. very low/high contributors to total EAD e.g. by impact zone
33	Spatial location 3 (point) VO		L	No specific action
34	Property ground level	Prone to serious error especially in dense urban areas	H	Improve ground model data and accuracy flags in urban areas
35	Property threshold level	Error due to 34 (above)	H	Action via 34
36	Population data for census ED		L	Ensure use of latest census data (2001, may be 2011 for PAMS?)
Other impact data				
37	Flood SVI for census ED		M	Exploit social research since 2001 together with census data to provide a more comprehensive social-demographic accounting system

No	Data Item	Findings **(Information source = Data Review, RASP Sensitivity, Note on Impacts, Other)**	P	Proposed Actions
38	Agricultural Land-Use Classification (six bands)	1:250,000 scale only appropriate for national scale applications	L	More detail as in PAG3 - consider local farmers, EU subsidies, consult local records, undertake a detailed ground survey. For depth-damage relationships, more research is required. May need to consider waterlogging (for water levels below surface)
39	Infrastructure damages		L	No action
40	Ecological damages		L	No action

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