Environment Agency

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Risk assessment for flood incident management

Impacts of failure of flood defence asset and operation

Science Report – SC050028/SR3

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SCHO0307BMIM-E-P

The Environment Agency is the leading public body protecting and improving the environment in England and Wales.

It's our job to make sure that air, land and water are looked after by everyone in today's society, so that tomorrow's generations inherit a cleaner, healthier world.

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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Steve Killeen
Head of Science

Executive Summary

Background

The Environment Agency's project *Risk Assessment of Flood Incident Management* (FIM), led by HR Wallingford (HRW), aims to develop and disseminate a systematic, risk-based methodology and guidance to assess and make decisions about FIM. The current phase of the project (Phase 1) is a review and scoping study intended to identify and define realistic requirements for such a system. It comprises a number of work packages (WPs) that address different aspects of flood incident risk, and progress in parallel to develop diverse, but compatible, frameworks. This report presents one Work Package (WP2) of the project.

Objectives and scope of WP2

WP2 considers the impacts of the failure of flood defence assets and operations on the risks associated with the overall FIM system. The specific objective of WP2 was to outline a framework to identify vulnerable or critical *assets* and *operational failures* during flood incidents.

'Assets' include active defences (such as barriers, pumps, gates and demountables), passive defences (such as embankments) and control and communication systems (such as control rooms, monitoring devices and radio networks). 'Operational failures' include both the unavailability of operational personnel because of the flooding, such as the inaccessibility of a control centre, and the errors made by operational personnel.

WP2 has a particular emphasis on active defences because other Environment Agency projects are looking at linear and passive defences. The focus is also on active failures of physical assets, operations, people and procedures, rather than on latent organisational aspects.

Results – a proposed framework

In developing a framework, we adopted generic principles of good regulation and the best examples common to all types of environmental risk assessed for the Environment Agency. More specific requirements for FIM were derived by taking into account the decision contexts in which the framework may be used, including setting policy, capital investment, maintenance planning and performance evaluation. Each of these may involve comparisons between options, assessments of particular options or the identification of critical elements. The framework also needs to be applicable to any stage of the FIM lifecycle: the decisions it informs may relate to, for example, planning, design, implementation, operation or monitoring. It also has to be applicable at various geographic scales (national, regional, catchment etc.) and at system, subsystem or component levels, and to be able to make the best use of the generally sparse data available.

A key element of the proposed framework is that the system is described in terms of *functions* (such as containing or removing floodwater, or enabling access) rather than physical system elements or operational tasks. This helps to focus attention on the risks associated with the system, rather than on unnecessary detail about the design of the system itself. It is also applicable at any stage of the system lifecycle. In particular, it can be used at the conceptual design stage, when we know what functions the system is intended to perform, but have not yet allocated them to specific people, procedures or equipment. Indeed, a major use of the framework is to help the designer decide how the necessary functions can be best allocated.

For each function, the framework identifies and assesses the likelihood of its various potential modes and degrees of failure. It then identifies the hazards that these failures may lead to in the 'outside world', and presents the risk in terms of the nature, probability and severity of the consequences that may result from these hazards.

The framework was refined and demonstrated by applying it to two simple but credible case studies, using it to assign priorities to improvements to defence assets and to specify reliability targets at the design stage.

Lessons learned

The main lessons from our investigations are:

- the importance of understanding the *decision context* in which any FIM risk assessment is to be used, as this determines the exact way in which the generic steps are implemented;
- the importance of defining a clear and appropriate *framing of the risk assessment question* and of *the risks to be considered* – real decision problems are not usually framed in terms directly amenable to risk assessment.

While the WP2 framework was developed principally for application to active flood defence assets and operations, the above points equally apply to other elements of FIM systems or, indeed, to a holistic flood risk assessment.

Outstanding issues

In the example applications, the framework was implemented in a simple, tabular form, to consider the functions of the flood defence assets one by one. In reality, there are many interactions between the elements of the FIM system, and if these are not considered it is likely that important hazards will be overlooked. However, if we attempt to identify and model interactions the quantity of data required and the workload to process and interpret it become unmanageable in all but the simplest cases. The approach described here provides a sound conceptual framework for risk assessment at any level of detail, but its limitations must be recognised. The complexity of FIM systems does need to be addressed.

Recommendations for Phase 2

In whatever way the assessment steps and tools are defined, we suggest that Phase 2 should include the key features of the framework that have been seen to facilitate systematic and comprehensive assessment in this WP, as follows:

- encouraging a clear understanding of the decision context, a clear framing of the risk assessment question and precise definition of the system boundaries and the risks to be considered;
- a clear conceptual framework and associated terminology;
- function-based breakdown of the system.

We tentatively suggest that the most worthwhile development to propose for Phase 2 is a holistic system model that explicitly tackles uncertainty and complexity, building on the work under WP3 and WP4, respectively.

The risk indicators proposed in WP1 provide a sound foundation on which to ensure all the aspects of flood risk are considered, but we suggest that the outcome indicators should be broadened to be certain that the themes of the Environment Agency's *An Environmental Vision* (Environment Agency 2002) are reflected. These themes are as follows:

- quality of life;
- environment for wildlife;
- clean air;
- clean water;
- clean land and healthy soils;
- greener business;
- sustainable resource use;
- limiting and adapting to climate change; and
- (reduced flood risk)[1].

In addition, we propose a further indicator:

- effective operation and regulation

since the aspirations related to each theme will not be realised unless the Environment Agency is able to discharge its duties effectively.

There is a need to adapt or develop generic data and methods to assess human reliability, to make these relevant to FIM.

A point for discussion is whether the Phase 2 development should focus on particular decision contexts, or aim to be generally applicable. This may require some further consultation with potential users and providers, to ensure that the work fills the most important gaps and best complements existing approaches.

Some more specific questions that should be explored in Phase 2, together with those from other WPs, are as follows:

- Should safety, environmental, property and reputational risks be weighted and combined into some unified metric? If so, how?
- How are tolerability criteria for flood risk to be defined? Currently, there is no comprehensive regulatory guidance on what levels of risk can be tolerated, although work is ongoing in these areas.

Reference

Environment Agency, 2002. *An Environmental Vision.* Bristol: Environment Agency.

[1] WP1 indicators could themselves be seen as subsets of 'reduced flood risk'. Although 'reduced flood risk' is a theme in its own right, other, wider concepts may need to be taken into account. For example, the way in which floods are managed can have impacts on the theme of sustainable resource use.

Contents

1 Introduction

The Environment Agency’s Risk Assessment of Flood Incident Management (FIM) project, led by HR Wallingford, aims to develop and disseminate a system-based methodology and best practice guidance on risk assessment and management that will enable the Environment Agency to enhance the reliability and efficiency of FIM. This report presents one Work Package (WP2) of the FIM project, which was carried out by RM Consultants Ltd (RMC). WP2 considers the impacts of failure of flood defence assets and operations on the risks associated with the overall FIM system.

1.1 Background

Effective FIM depends on the operation of complex, interacting systems over a wide range of conditions. These systems have many different functions, such as forecasting, warning, emergency planning, emergency operation and the behaviour of institutions and individuals. All of these can fail to perform as intended in many different ways. Each failure can have consequences that propagate to other subsystems and then to the whole system.

Several risk management approaches are in use or being developed for flood risk management in general. However, these have mainly focussed on the longer term mapping of flood probabilities and the planning, design and maintenance of defences rather than on the management of actual flood incidents. The FIM project aims to develop a systematic, risk-based approach to assign priorities and make decisions about FIM.

1.2 The flood incident management project

The overall FIM project objective is:

‘To develop and disseminate an improved system-based methodology and best practice guidance on risk assessment and management, in order to enhance the reliability and efficiency of the Environment Agency’s flood incident management.’

The current, first phase of project (Phase 1) is a review and scoping study intended to identify and define in more detail the needs for risk assessment systems. It identifies coherent and realistic concepts and methods, and undertakes a limited demonstration to test, refine and demonstrate them. This will provide a sound basis of requirements and recommendations for a fully operational system to be developed in Phase 2 of the project. Further work will then be required to support the delivery and implementation within the Environment Agency.

Phase 1 comprises six work packages, as listed in *Table 1.1*.

Table 1.1 Work packages within the FIM project.

Work Package	Title and Objectives
WP0	Definition of outputs and boundary setting
WP1	Current FIM system risks of failure To define what is meant by a 'failure' of the FIM process. To produce an outline method by which failure points in the existing forecasting, warning and response system can be identified. To define the response part of the FIM process. To assess what does and does not provoke a response among key groups other than the Environment Agency.
WP2 *(the subject of the present report)*	**Impacts of flood defence assets and operational failure** To identify the risk of failure of active flood defence assets (for example, gates, demountable flood defences) as a result of operational issues (for example, access to a site, breakdown in communication) and to develop a conceptual framework to assess the risk of such failure and identify vulnerable and/or critical or high-risk asset components.
WP3	Risks and consequence of failure of reactive mitigation measures To identify the interdependence between the supporting infrastructure, such as communications, power supplies, water, sewerage, health and transport (roads and bridges), that has an effect on FIM. To assess the causes and consequences of the failure of the supporting infrastructure and to produce a conceptual framework to analyse and assess the aggregate risk as a result of failure of the support infrastructure.
WP4	Understanding and application of complex system risk assessment models Investigate complex systems models (for example, non-linear dynamics, emergent models, game theory, Markov processes, genetic algorithms and graph theory) with respect to their application to risk assessment in FIM, and to outline requirements for a complex systems model of the FIM system.
WP5	Recommendations to minimise FIM system vulnerability Review of international sources on risk management that are useful to FIM. Identify recommendations to manage risk effectively across the FIM process.
WP6	Project management

WP1, WP2, WP3 and WP4 each addressed different aspects of risk, and progressed in parallel to develop diverse, but compatible, frameworks. In WP5, methods to integrate these frameworks to propose an overall system model to be developed within Phase 2 of the study will be investigated.

1.3 Objectives and scope of WP2

The specific objective of WP2 is to outline a framework to identify vulnerable and/or critical *assets* and *operational failures* during flood incidents.

In general, 'assets' can be taken to include:

- active defences, such as barriers, pumps, gates and demountables;
- passive defences, such as embankments, walls and overflow channels;

- communication and control systems, such as control rooms, monitoring devices and radio and telephone communications.

'Operational failures' are taken to include:

- unavailability of operational personnel because of flood effects, such as the inaccessibility of a control centre or asset;
- errors by operational personnel.

WP2 has a particular emphasis on active defences because other Environment Agency projects, such as the development of the PAMS - Performance-based Asset Management System (Environment Agency 2005) and RASP - Risk Assessment of flood and coastal defence systems for Strategic Planning (HR Wallingford, 2002) - are looking at linear and passive defences. The focus at this stage is also on active failures of physical assets, operations, people and procedures, rather than on latent organisational and cultural aspects.

However, it is important that the FIM system should be seen holistically, and we have therefore considered how assessment methods specific to these areas of focus can fit into the assessment of the wider FIM system. We have also considered how the approach proposed here can be integrated with, or complement, those being developed under WP1, WP3 and WP4.

1.4 Overview of method and structure of report

Section 2 presents a review of available data for the risk assessment of flood defence assets and operations.

Section 3 describes the concepts of risk assessment, and proposes an associated terminology. Section 4 identifies the general principles and user requirements that informed the development of the framework. Section 5 shows how an FIM system can be defined in terms of its boundaries and a conceptual model.

Section 6 proposes an assessment framework to meet the user requirements, based around the conceptual model and taking account of the availability of data. The approach is based on a *functional* breakdown of the FIM system. Assets or operations are defined in terms of their functions, such as containing or removing floodwater, or enabling access. For each function, we identify and assess the likelihood of its various potential modes and degrees of failure, the hazards that these failures may present to the 'outside world' and the probability and severity of the consequences that may result from those hazards.

Section 7 concludes by summarising the findings to date and the proposed next steps.

2 Review of available data

WP2 began with a review of what data already existed, or could be obtained, that would be of use in the risk assessment of asset and operational failure. Although this has been described as the first step, it is in reality iterative with later steps – the availability or potential availability of data being one factor, but not the only factor, that affects the way that the assessment framework is developed.

2.1 What data are required

However, as the risk assessment framework evolves in detail, it is evident that certain broad classes of data will generally be required for any application:

- reliability data for equipment and assets (for example, failure rates per year or on demand, intervals between inspection and/or maintenance);
- human error rates;
- rates of occurrence of operational failures (for example, failure to implement active flood defence because of health and safety issues, such as the depth of flood water or lack of suitably trained staff);
- information on failure modes – the various different ways in which a system element may fail (for example, a gate may become stuck in either the open or closed positions);
- information on incident management procedures.

2.2 Data sources

Data sources were identified in a review of the literature and case studies on asset and operational failure and impacts during incidents. Key references included:

- the earlier Environment Agency Failure on Demand project (RMC and Peter Brett Associates 2004) for active components (gates, pumps etc);
- the PAMS (Environment Agency 2005) and RASP (HR Wallingford 2002) methods for passive, linear defences;
- case studies of recent floods – post-incident reports on Boscastle, Carlisle, Central European and New Orleans floods;
- FIM procedures as described on the Environment Agency intranet;
- participant discussions – in particular the FIM project workshop facilitated by HR Wallingford in November 2005 (HR Wallingford 2005).

2.3 Data availability and future data gathering

Table 2.1 summarises, in broad terms, what data are currently available for system elements within the scope of WP2.

Table 2.1 Data availability.

System element		Data known to be available, but not collated for risk assessment	Data already collated in form suitable for risk assessment
Discrete	pumps/ pumping stations		x
	culverts		x
	gates		x
	locks		
	outfalls		x
	screens		x
	barriers		x
	weirs		
	spillways		x
	temporary/ demountable defences	?	
	dams	x	
Linear	river embankments/ levees		x
	dykes (coastal)		x
Surface water	storm drains,	x	
	storm water sewers,	x	
Communications	forecast and warning systems		x
	communications (e.g. telephone, radio, telemetry or satellite systems)	x	
	control centres	x	
	monitoring devices eg level gauges	x	
Supporting infrastructure	transport networks	?	
	utilities -electricity, water, gas	x	
Human	operational staff - human error	x	
	operational staff - unavailability	?	

Data exist, or could reasonably be obtained for most elements, although they vary greatly in the extent and applicability, and it may be impossible or impractical to fill all the gaps within foreseeable timescales. A key requirement for the framework is therefore that it should be able to support decisions under uncertainty, that is help the user to reveal and where possible minimise uncertainties, and provide systematic means to trace and explore their impacts on conclusions.

In general, it is expected that subjective data-elicitation methods will need to be applied in any given study. There is a large body of literature on specific techniques to elicit estimates from expert participants, both in individual interviews and in group sessions. All the methods are designed to help participants derive parameter values for models that best reflect their experience, and that minimise, or at last reveal, uncertainty and bias.

An important specific gap in the data is in the area of human error. Generic methods and data exist to assess human reliability in other contexts (for example, control rooms, aviation, emergency management, etc.), but these have not, to our knowledge, been adapted for FIM.

This is a particular concern, given anecdotal evidence from FIM staff (backed up by more substantial studies in other domains) that about 80 per cent of what are commonly classed as 'asset' failures are actually caused by human error or unavailability rather than by equipment failure itself. As part of Phase 2, it could be useful to review generic data and develop methods to assess human reliability relevant to the FIM field.

A function-based breakdown of the system is proposed in this study, so it is not necessary to define a detailed taxonomy of system elements at this stage. Current taxonomies, such as those in the earlier work on reliability of active defences by RMC and Peter Brett Associates (2004), are principally based on a breakdown by physical asset type, but these will need to be adapted and used in accordance with the particular needs of each application. The taxonomy should be risk-driven rather than data-driven.

3 Guiding principles and user requirements

This section defines the general principles on which to develop risk assessment frameworks intended for Environment Agency use, and the more specific user requirements for the FIM framework and WP2 in particular.

3.1 Guiding principles

The Environment Agency is committed to general principles of good regulation and best practice in all types of environmental risk assessment. To help meet this commitment we adopted the following generic principles in the design of the framework:

1. *Human-centred and deliberative.* Risk assessment should be a tool to encourage and inform discourse between participants, not just for technical analysis. The process of using the framework can therefore be as important as its products. The design of the framework must also consider the ways the framework would be implemented in practice (for example, whether in group sessions or by an individual analyst) and how the findings can most usefully be communicated.
2. *Broadly based.* The framework must encourage a broad interpretation of risk, and consider the social and psychological aspects of risk toleration as well as the more 'traditional' probability and consequence measures.
3. *Related to Environment Agency aims*. While the interpretation of risk is broad, the framework must also relate risks to our specific statutory duties, values and aims – in particular the themes of the Environment Agency's *An Environmental Vision* (Environment Agency 2002).
4. *Usable.* It should be possible to apply the framework to support real decisions without an excessive overhead cost in terms of specialist knowledge or time required. Users must remain in control of the process, and be aware of its limitations. ('Users' here includes both those who will actually operate the framework, for example entering data and performing analyses, and those who will interpret and base decisions on its results.) The conceptual models of the environment and of risk should be readily understandable. The framework must be as easy to learn and use as possible, given the inevitably complex nature of the decisions it is intended to support. It must be flexible, and offer a variety of tools.
5. *Scientifically sound*. The framework must be conceptually sound and theoretically rigorous, and make the best use of available evidence and science.
6. *Transparent*. The framework must help the user to identify and document the assumptions and limitations in their assessment, including the reasons for subjective judgements.
7. *Proportionate.* The framework must be applicable at various levels of detail, as appropriate to the decision stakes and the resources available.
8. *Supports decisions under uncertainty.* Given the major gaps and uncertainties in data (Section 2), as well as in models complex systems, the framework must support decisions under uncertainty. It must help users to reveal and where possible minimise uncertainties, and provide systematic means to trace and explore their impacts on the conclusions.

Trade-offs often have to be made between these principles. For example, a compromise is often necessary in practical assessments between usability and scientific rigour. The appropriate balance between conflicting principles will vary with each application. The requirements of usability (4) and proportionality (7) themselves reflect this, and we should not dictate the level of detail, but allow the user to make choices appropriate to the application.

3.2 Specific user requirements for FIM and WP2

Specific user requirements for the FIM assessment framework, and for the WP2 aspects of FIM in particular, can be derived by considering the various potential users of the framework and the various dimensions of the decisions that it may be used to support. The framework must be able to represent various:

- *Decision contexts*. These include setting policy and making strategic decisions about capital investment, maintenance planning and performance evaluation. Each of these may involve comparisons between options, assessments of particular options or the identification of critical elements.
- *Lifecycle stages.* The framework is concerned with risks during flood incidents, but the decisions it informs may relate to any stage in the lifecycles of policies, programmes and projects: planning, design implementation, operation and monitoring.
- *Scales and levels of detail*, such as geographic scale (national, regional, catchment-specific or more local) and subsystem or component levels within systems.

The emphasis is on developing a framework to provide a high-level, holistic system view that enables the user to identify critical aspects that can, if required, be subjected to more detailed analysis using other models. To attempt to represent all levels of detail would result in an unmanageably complex framework.

4 Risk assessment concepts and terminology

The language of risk assessment can cause confusion, since terms such as ‘hazard’, ‘consequence’ and even ‘risk’ itself are defined and used in many different ways by different practitioners, according to personal preference and the specific standpoint of the assessment. For example, from a flood-defence engineer’s point of view a flood incident may be seen as the *consequence* of a failure of flood defences. For householders on the flood plain, it may be seen as a *hazard* – a potential event that can cause harm. The emergency services may see it as a *cause* – the initiating event for their response operations.

It is probably unrealistic to expect that the Environment Agency could impose a standard terminology, given the wide range of potential users and participants in flood risk assessment, although the European Union (EU) Sixth Framework research project *FLOODsite* has proposed a standard glossary (Gouldby and Samuels 2005). It is, however, essential that the terminology used in any risk assessment should be conceptually rigorous, clear and internally consistent. There is more than a simple issue of labelling at stake – conceptual and scientific validity can be undermined by loose or inconsistent terminology.

The terminology used in this study is based on one devised for use in safety risk assessments of air traffic management systems (Eurocontrol 2004). It represents the culmination of several years’ work to resolve difficulties and errors that arose from loose definitions of concepts and terminology. Of all the schemes used in various domains it is probably the most rigorous. In particular, it recognises how important it is to define clearly the system boundary and the risks ‘of what, from what and to what’. *Figure 4.1* illustrates this scheme.

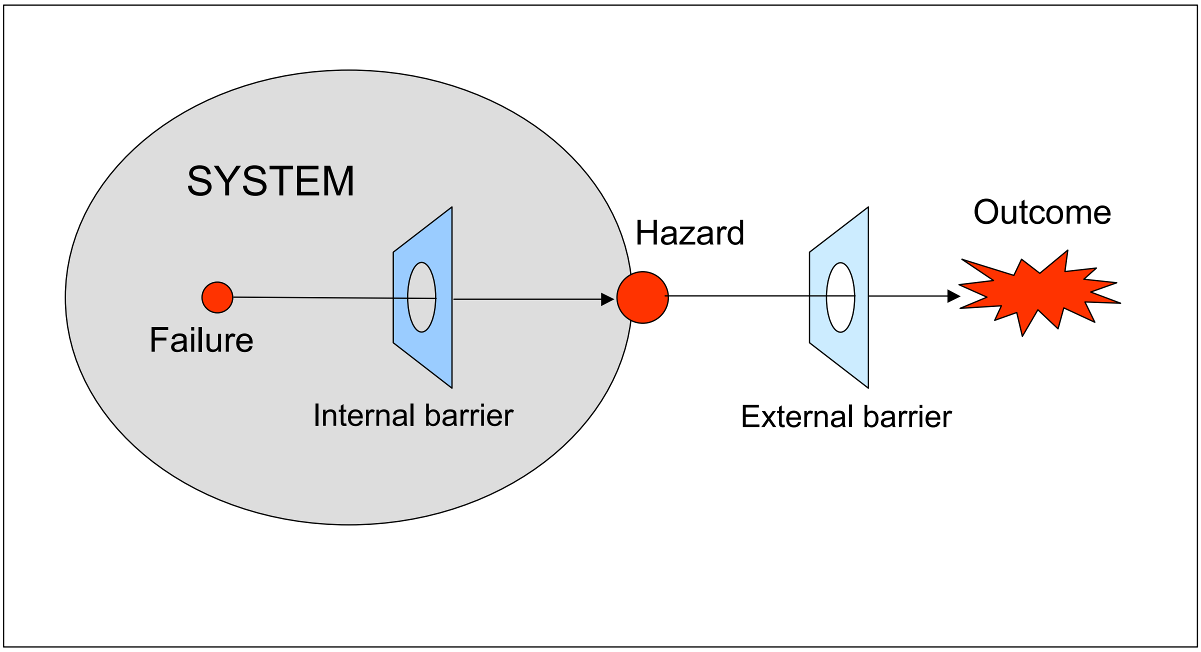

Figure 4.1 Risk concepts and terminology.

Table 4.1 expands on the definitions and illustrates how the scheme could be applied to a relatively simple example – the engineered braking systems of a car.

Table 4.1 Risk concepts and definitions.

Term	Definition	Examples
Failures	Unwanted events that occur within the system. Failures can vary in *degree* and in *mode*. For example, a pipe failure may be a sudden, full-bore rupture, or a continuous slow leak, and the risks associated with these are different.	Hydraulic pipe failure. Brake pedal jammed. Brake pads worn away.
Hazards	The (potential) results of failures at the system boundary, that is, the potential effect of the failure as it may be manifested in the 'outside world'. A hazard *may* be prevented from occurring, or be reduced in degree, by *internal barriers* within the system. Equally, some failures are benign – they cannot present any hazard.	The car will not slow down and stop as required when the driver presses the brake pedal. An internal barrier in this case is the redundancy in the system – there are separate brake systems for the front and rear wheels.
Outcomes	Potential results of the hazards in the 'outside world'. A hazard may have effects on many different elements of the outside world, and we therefore need to define carefully the *receptors* – who or what may be affected, and the *nature of the harm*. Outcomes may be prevented or reduced by *external barriers*.	The outcomes include the car running off the side of the road at a corner, or colliding with a wall or another road user. Types of harm and receptors include, for example, damage to the natural environment, economic loss to a community and death or injury of the car occupants or others. External barriers include the driver slowing the car by changing into a lower gear, other road users seeing and avoiding the affected car in time and the crashworthiness of the car, other vehicles and crash barriers alongside the road.
	Severity is a measure of the magnitude of the harm.	For example, the severity of colliding with another vehicle is likely to be greater than that of running off the road onto a grass verge.
Risk	Likelihood (probability or frequency) of a given harm occurring or, more generally, the expectation value (or some other statistical measure) of the harm	Risk could be defined as, for example, the probability of the car occupants being killed from this cause, per mile or the expected number of other road users killed, in the UK, in a year

It might be considered that 'hazards' can occur even without failure of the FIM system – the flood may already have occurred, or be unpreventable, even if the FIM system works entirely as intended. It is not practical, necessary or even desirable to prevent every flood incident. This emphasises how important it is to define carefully the system considered in any particular risk assessment, as well as the generic terminology and concepts. For example, is the FIM risk assessment part of a wider assessment of flood risk, or does it take as its starting point the occurrence of a flood incident, and assess only the component of risk due to the manner in which the incident is managed? This issue is discussed further in Section 5 (system boundaries) and in Section 6, under the topic of framing the risk.

In the FIM context, harm can be measured in terms similar to the outcome performance descriptors proposed in WP1:

- environmental damage;
- economic damage;
- injuries;
- loss of life;
- victim trauma, stress, etc.;
- reputation of the Environment Agency and others.

We suggest that this set of indicators could be redefined somewhat and broadened. In particular, 'environmental damage' could be expanded, when considered in greater detail, to ensure that all the themes of the Environment Agency's *An Environmental Vision* (Environment Agency 2002) are reflected. The themes are listed below, with more detailed definitions given in Appendix A.

- quality of life;
- environment for wildlife;
- clean air;
- clean water;
- clean land and healthy soils;
- greener business;
- sustainable resource use;
- limiting and adapting to climate change;
- (reduced flood risk)[2].

In addition, we propose a further indicator:

- effective operation and regulation.

While it may never be possible to quantify all these indicators, they should at least be considered qualitatively when the assessment is framed and the results interpreted. Flooding is an issue that has multi-dimensional impacts, and it is important to avoid too narrow a focus.

[2] WP1 indicators could themselves be seen as subsets of 'reduced flood risk'. Although 'reduced flood risk' is a theme in its own right, other, wider concepts may need to be taken into account. For example, the way in which floods are managed can have impacts on the theme of sustainable resource use.

5 System definition

The system to be assessed is defined in terms of its boundaries and a conceptual model of its elements.

5.1 System boundaries

In accordance with the need to take a high-level, holistic view, the system boundaries must be wide enough to capture all system elements, and their interactions with each other and with the external environment, as illustrated in *Figure 5.1*. Wherever the boundaries are drawn, interfaces with the 'outside' must be identified and included in the conceptual model.

Figure 5.1 System boundaries for flood incident management).

5.2 Conceptual model

The FIM system is complex. Even within the limitations of the WP2 scope, there are many interacting elements:

- *people* (staff involved in forecasting, warning, operational response and emergency services, the public, etc.);
- *physical elements* (the catchment, water levels and flows, flood defence assets, control centres, communications systems, etc.);
- *non-physical elements* (procedures, tasks, operations, information flows, etc.).

Any holistic conceptual model has to include all the above, but there are many ways in which the system can be characterised and modelled to capture them. For example, the system could be defined primarily in terms of physical components. At the simplest level, this could be a list of physical elements, or an influence diagram or a network model, for example, could be used to express the relationship between elements . The people and non-physical elements associated with each physical element can then be 'attached' to such a model. Alternatively, the system could be defined principally in terms of non-physical elements, with each task, operation or procedure examined and the associated physical elements attached to each such task.

In one sense the structure of the conceptual model is immaterial, so long as it adequately captures the features of the system and their interactions, but the way that the system is modelled can have a major influence on its usability and can bias the focus of attention. For example, a model that is principally structured around physical elements focuses attention on collecting data according to a physical taxonomy and represents the physical equipment and components. This may be inappropriate if the system being assessed is principally related to people and procedures.

As the uses of the risk assessment framework could be very varied, it seems inappropriate to recommend any one structure of elements (people, physical or non-physical) over any other. Rather than select a structure based on system elements, it is proposed that the system should be conceptualised principally in terms of its *functions* – what the system is intended to do. For example, one function of a FIM system is to 'contain floodwater' and we would consider the hazards that arise from the failure of this function, rather than from the physical elements, such as a gate, or non-physical elements, such as the task 'close gate'. Other functions could include, for example, forecasting flood progress, warning residents, ensuring access for emergency services or evacuating residents. The level of detail required in defining functions will vary according to the system and the purpose of the assessment.

This function-based approach has the advantages that:

- It focuses attention firmly on the risks (or benefits) of the system, which helps to avoid the assessment being drawn into unnecessary detail about the design of the system itself.
- It can be used at any stage of the system lifecycle. This is particularly important at the early conceptual design stage, when we know what functions the system is intended to perform, but have not yet allocated them to specific people, procedures or equipment. Indeed, a major use of a function-based risk assessment framework is to support the allocation of function, by helping the designer decide whether the function is best performed by people, procedures or equipment.

A function-based concept does not preclude the system elements being considered where appropriate. For example, hazard identification brainstorming will typically use lists of physical, non-physical or people elements as prompts. And more detailed assessments of the likelihood and consequence of each hazard may be required, such as a hydrological model of the catchment response or construction of a fault tree to show how component failures may conspire to lead to failure of a particular asset.

Functions can be seen as approximately equivalent to the processes, objects and agents as proposed in WP1, WP3 and WP4, respectively, or at least they can be aligned with them.

6 The assessment framework

The proposed assessment framework is based around the function-based conceptual model derived in Section 5, uses the risk concepts and terminology of Section 3, and aims to satisfy the principles and user requirements from Section 4.

The steps in the framework are in line with generic Environment Agency and government-wide guidance on environmental risk assessment methodologies, such as DoE (1995) and HM Treasury (2005). The generic steps can be represented as shown in *Table 6.1*. A variety of tools, with different levels of sophistication and detail, exist to support the various steps of the framework.

Table 6.1 Steps in the risk assessment framework.

Step		Description of step and tools available
1	Frame the question	Real decisions and questions that face the Environment Agency are not usually framed in terms directly amenable to risk assessment. The critical, and often challenging, first step in risk assessment is therefore to frame the question in a way that both informs the decisions to be made and that is amenable to formal risk assessment. For example, is it required to compare the risks of different options at the design stage or to assess the adequacy of an existing system?
2	Frame the risks	Define the types and measures of risk. What receptors are to be considered? Are safety, environmental and property risks all to be considered, and if so how are they to be weighted and combined? Is the aim to minimise risks to the most exposed individuals or the collective risk to society?
4	Define the system	Define the boundaries of the system to be assessed. It may be easiest to think initially in terms of physical boundaries, such as the catchment or the engineered assets, but as a basis for assessment the definition is also required in terms of its functions – what it is intended to do. This step may be iterative with steps 1 and 2.
4	Define tolerability criteria	Define how it is to be decided whether risks are tolerable.
5	Hazard identification and analysis	Identify the potential failures of the system – how and in what degree it may fail to perform the intended functions, or inadequacies of the functions themselves. Identify the hazards that may result for these failures – the effects as manifested in the outside world. Identify the outcomes of the hazards – the potential harm to the defined receptors. Typically, this involves structured brainstorming between participants that represent all the main areas of domain expertise. Assess how likely it is that each hazard will occur. For each potential outcome, assess its severity (how bad it would be) and the probability of that outcome actually occurring (given that the hazard itself has occurred). Assess the level of risk – this is a function of the likelihood of the hazard and the severities and probabilities of its outcomes, summed over all hazards. (*cont.*)

Step		Description of step and tools available
(5)	Hazard identification and analysis *(cont.)*	Tools available include, for example, the Meteorological Office's probability based rainfall estimate model, models of the chains of cause and consequence (fault trees, event trees, influence diagrams, etc.) and consequence models, such as the Environment Agency Flood Risks to People method, which relates the level of danger to depth, velocity and other flood parameters.
6	Interpretation and risk management	What is required in the interpretation and risk management step will depend on the decision context. In some cases we compare the predicted risk against the criteria set in Step 4 to determine whether the predicted or existing level of risk is tolerable. Or we may wish to set targets on certain system functions, dependent on the predicted level of risk *if* they fail. Interpretation also includes the consideration of uncertainties. What are the main uncertainties in the assessment models, data or assumptions? How might they change the conclusions? In view of these uncertainties, is there sufficient confidence to make a decision? If not, what could be done to reduce the uncertainties? Tools available include Monte Carlo analysis and fuzzy logic techniques. In many cases we will also need to consider what could or should be done to reduce the risk. Tools available include cost benefit analysis and the application of the ALARP (as low as reasonably practicable) principle. Wherever risk reduction measures are proposed, the assessment should return to Step 5 and re-assess as appropriate – the mitigation and/or monitoring methods may change the system functions and hence introduce different hazards.

Importantly, this generic framework will need to be adapted depending on the decision context. Risk assessment may be required to support several different types of decision. The steps as listed above are typical for applications where it is used to compare options or to assess the adequacy of an existing system. However, they would need to be adapted for use in other contexts, such as to develop specifications at the design stage.

7 Example application

This section illustrates the application of the framework to a simple, but credible, system of flood defence assets to determine the priorities for remedial works. Another use of the framework, in a contrasting decision context, is illustrated in Appendix B, which shows how it can be used at the design stage to specify reliability targets for assets.

7.1 Example system

To illustrate the application of the approach, we have used a simple, but credible, model of a catchment and its active flood defence assets, as shown *in Figure 7.1*.

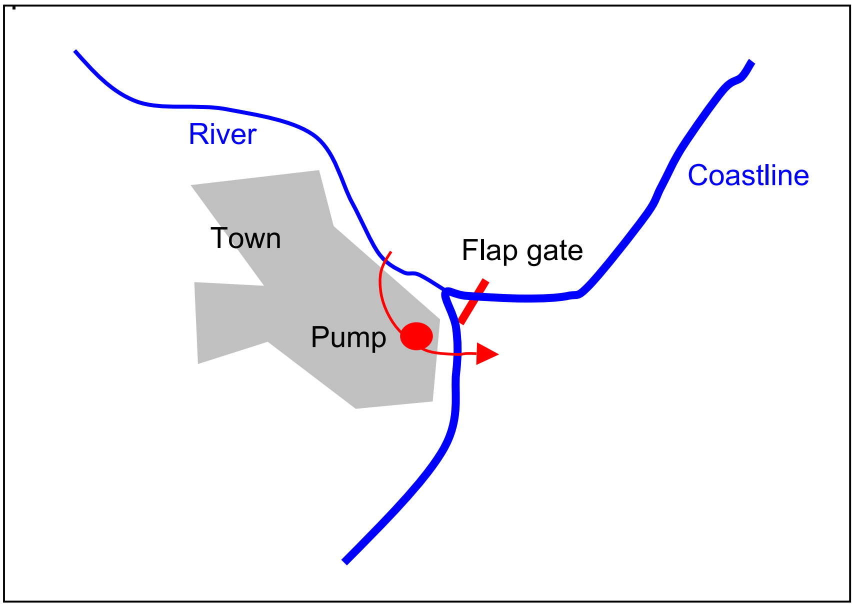

Figure 7.1: The example system.

This hypothetical catchment is typical of many around the coasts of England and Wales, in which a small town is located on the mouth of a river, where it runs out to sea.

The town is protected from tidal surges by a tidal flap gate and pumping station at the mouth of the river (as well as various embankments and passive defences). At most stages of the tide the flap is open and allows the river flow to discharge into the sea.

On a few occasions each year, when the tide is abnormally high, say over 4.0 m above ordnance datum (AOD), the pressure of the sea water closes the flap, which prevents the tide from running up the river and potentially flooding parts of the town. When the flap is closed, it is necessary to pump water out from the river into the sea to prevent the river water backing up against the gate. A water-level sensor on the river side of the flap gate activates pumping.

7.2 Risk assessment: setting priorities

In this example we imagine that the system has been under-performing – it is considered that there have been too many failures and. consequent flooding of the town. The budget does not allow for both the flap gate and the pumping station to be improved or renewed, so a risk assessment is required to support a decision about which improvement works should take priority.

Step 1: Frame the question

The question to be answered in this example can be framed as, 'Which currently presents the greater risk – failure of the flap gate or of the pumps?' Other factors may, of course, enter into the actual decision – for example, the relative costs of the works required and the practicality of scheduling them into the maintenance plan – but we assume for this simple example that these are outside the scope of the risk assessment itself.

Step 2: Frame the risks

In this case we assume that risk is defined as the expectation value of the harm that results from failure of either the flap gate or the pumps. We also assume that all the possible types of harm (as in Section 4) have been considered and ranked on a weighted, aggregate scale of 1 to 5.

Step 3: Define the system

In this example, the system considered consists only of the flap gate and the pumps. In a more realistic, detailed application we would probably need to consider other elements of the system, such as the passive defences along the coast.

Step 4: Define tolerability

In this example we look at a comparison between the risks of two options – renew the floodgate or renew the pump system – rather than assess the risk against an absolute target.

Step 5 Hazard identification and analysis

Table 7.1 presents the hazard identification and analysis.

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Table 7.1 Example hazard identification and analysis.

Asset	Function	Failure mode	Probability of failure on demand[1]	Demand rate (2)	Failure rate per year[3]	Hazard[4]	Severity ranking of outcomes[5]	Risk rating[6]
Flap gate	Allow fluvial flow to discharge	Fail to open when required	0.01	20	0.2	Fluvial flow backs up against gate – fluvial flooding occurs	3[7]	0.6
	Prevent high tide running up river	Fail to close when required	0.01	20	0.2	Tide runs up river – tidal flooding occurs	4[7]	0.8
Pump	Discharge fluvial flow against high tide	Fail to operate when required	0.002	20	0.04	Fluvial flow backs up against gate – fluvial flooding occurs	3[7]	0.12

[1] Data could be derived from historic experience and/or subjective elicitation. In this example we used (rounded) values from the Failure on Demand study (RMC and Peter Brett Associates 2004). In a detailed study, we would also take account of any 'internal' barriers to propagation, such as the provision of duplicate redundant pumps, or whether there are any automated detection systems to reveal failures.
[2] How often the function is required to be performed each year. In this example, the number of closures required is equal to the number of number of occasions when the tide rises over 4.0 m AOD. The number of openings required is the same, being equal to the number of times that the tide falls back below 4.0 m AOD.
[3] Failure rate per demand times demands per year. Note that where the failure is related to a continuous process – for example, blockage by trash – rather than discrete events the failure rate will be easier to evaluate directly in per year terms.
[4] Description of nature and extent of effects on the 'outside world' – that is, at the boundary of the system being assessed.
[5] For simplicity, we assumed that a single weighted sum is adequate to describe all the types of harm and that severities are to be ranked on a scale of 1-5 (from minor nuisance to catastrophic, say). In reality, such scales need to be calibrated carefully. The assessment of outcomes must take account of deliberate mitigations and/or circumstantial factors in the 'outside world', such as topography, vulnerability of exposed population, whether flood warnings are available, accessibility by emergency services, etc
[6] Risk rating = failure rate × severity. The units in this case are arbitrary, and interpretation needs to take into account how the failure rate and severity scales are defined – for example, whether they are linear or logarithmic
[7] There is likely to be more warning of tidal flooding – surges can usually be predicted some days in advance, whereas a high fluvial flow may result from a sudden, intense rainstorm over the catchment area (such as occurred at Boscastle). However, tidal flooding is likely to be more extensive than fluvial, and is also likely to re-occur on the next few tides. On balance, a higher severity has been assigned to tidal flooding.

Step 6 Interpretation and risk management

In this hypothetical example, we can see that the flap gate is more critical than the pumping station. The total risk associated with the gate, over both functions, is 1.4 (on our arbitrary risk-rating scale) as compared with 0.12 for the pumps.

Looking in more detail at the two functions of the gate, closing it against an exceptionally high tide is seen as more critical than opening it to allow the river to discharge.

This type of assessment could be used to support decisions about which asset – the gate or the pumps – to renew first, or which functions of each asset are most critical. Of course, other factors enter into the decision, in particular the relative cost and practicality of the improvement works to each asset, and their likely effectiveness in reducing risk. These factors are not included in the proposed framework as described, but could, in principle, be built into it without any great conceptual difficulty.

8 Conclusions

8.1 Achievements and lessons learned

WP2 has set up a conceptual model and framework to identify and assess the risks associated with operational and asset failures during a flood incident. The key features of this approach, which help to encourage and facilitate rigorous, systematic and comprehensive risk assessment, are:

- emphasis on clearly defining the boundaries of the system;
- clear and generally applicable conceptual framework (and terminology);
- analysis based on breaking the system down into functions, rather than system elements – this focuses attention on risks, rather than unnecessary detail about the system, and it can be used at any stage of the system lifecycle.

The main lessons from our investigations are the:

- importance of understanding the *decision context* in which any FIM risk assessment is to be used, as this determines the exact way in which the generic steps are implemented;
- importance of defining a clear and appropriate *framing of the risk assessment question* and of *the risks to be considered* – real decision problems are not usually framed in terms directly amenable to risk assessment.

The above features and lessons are generic, and can be applied to risk assessment frameworks of different types and levels of sophistication.

8.2 Outstanding issues

In the examples developed for this WP, the framework was implemented in a simple, tabular form that considers the system functions of flood defence assets one by one. In reality, there are many interactions between assets, and between assets and other elements of the FIM system, but if we attempt to take account of such interactions the quantity of data required and the workload to process and interpret it rapidly become unmanageable for all but the simplest systems. There is a 'combinatorial explosion' of cases to be considered. On the other hand, if interactions are not considered it is likely that important hazards will be overlooked – the history of major accidents and failures is largely a history of unexpected combinations of events. The approach described here provides a sound conceptual framework for risk assessment at any level of detail, but the limitations of its application within a tabular, function-by-function approach must be recognised. The complexity of FIM systems does need to be addressed, and for this reason we believe that the complex systems approach developed under WP4 should be a key element of future research.

A second outstanding issue apparent from this WP, but that will apply to any risk assessment approach, is the large degree of uncertainty that needs to be accommodated. Our review shows that data on the reliability of assets are sparse and patchy. For human and procedural elements of the FIM system the data are generally even more uncertain.

8.3 Recommendations for Phase 2

The framework was developed principally with the application to active flood defence assets in mind, but this division is somewhat artificial. We believe that one of it's the framework's strengths is that it can equally well apply to other elements of FIM systems or – more usefully – to a holistic assessment. We therefore suggest that the Phase 2 development – however the assessment steps and tools are defined – should consider the critical features, as noted in Section 8.1, seen to be beneficial in this study. To summarise, these are:

- clear definition of system boundaries;
- the conceptual framework (and terminology);
- function-based breakdown of the system;
- understanding of the decision context; and
- clear and appropriate framing of the risk assessment question and of the risks to be considered.

We tentatively suggest that the most worthwhile development to propose for Phase 2 is a holistic system model that explicitly tackles uncertainty and complexity, building on the work of WP3 and WP4, respectively.

The risk indicators proposed in WP1 provide a sound foundation for ensuring consideration of all the aspects of flood risk, but we suggest that the outcome indicators should be broadened to ensure that the themes of the Environment Agency's *An Environmental Vision* (2002) are reflected.

There is a need to adapt or develop generic data and methods to assess human reliability, to make them relevant to FIM.

A point for discussion is whether the Phase 2 development should focus on particular decision contexts or aim to be generally applicable. This may require some further consultation with potential users and participants, to ensure that the developed tool fills the most important gaps and best complements existing approaches.

Some more specific questions that should be explored in Phase 2 are:

- Should safety, environmental, property and reputational risks be weighted and combined into some unified metric? If so, how?
- How are tolerability criteria for flood risk to be defined? For example, is the aim to minimise risks to the most exposed individuals or to minimise the collective risk to society? Currently, there is no clear regulatory guidance on what levels of flood risk can be tolerated in various contexts, nor any firm basis on which to develop such criteria, although the Environment Agency has work ongoing in these areas.

All the above points need to be considered together with those from the other WPs to make proposals for the best way forward in Phase 2.

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Appendix A

Definitions of the Environment Agency vision themes

Appendix A: Definitions of the Environment Agency vision themes (from Environment Agency, 2002)

Quality of life	A better quality of life. People will have peace of mind from knowing that they live in a healthier environment, richer in wildlife and natural diversity – an environment that they will care for and can use, appreciate and enjoy. People will be confident that the environment is well cared for, is not damaged by pollution and does not provide a health risk because of human activities. The environment will be greatly valued and cared for by all sectors of society as a source of food, water, materials, income, recreation, sport and wildlife conservation. Environmental responsibilities will be taken seriously by all and mechanisms to ensure environmental equality and justice will be readily available to all individuals and communities who need them. Information and processes will be readily available to enable citizens, communities, businesses and government and its agencies to agree quality-of-life and environmental targets and the plans that will realise them. Local, regional, national, rural and urban strategies will fully reflect sustainable development principles and will be appropriately linked, and thereby enable effective and integrated environmental protection and enhancement. Sustainability values and working practices within the Environment Agency, including those of openness, collaboration, partnership, participatory decision making, precaution and respect for diversity, will reflect those of key stakeholders and of society in general. The Environment Agency will work with all sectors to enhance the quality of the environment and the services it provides – for business, anglers, the boating community and other users of the waterways, farmers, planners and all sections of the community.

Environment for wildlife	An enhanced environment for wildlife. Wildlife will thrive in urban and rural areas. Habitats will improve in their extent and quality to sustainable levels for the benefit of all species. Everyone will understand the importance of safeguarding biodiversity. Degraded habitats, especially rivers, estuaries and wetlands, will have been restored. Wildlife corridors and their associated habitats will be of high quality, with no artificial barriers to wildlife movement. The UK's Biodiversity Action Plan will have been successfully delivered and priority species will no longer be under threat. Rivers, estuaries, lakes and canals will all support appropriate fish communities. Urban and rural land-use practices will encourage the protection and restoration of habitats, species and natural processes. The management of land for wildlife and landscape benefits will be accepted and supported as a normal activity of rural life. There will be a broad consensus on how biodiversity should be managed against a background of climate change. Threats to the genetic integrity of our native wildlife will be greatly reduced. The Environment Agency will ensure that its activities and those it authorises do not threaten key species and habitats. It will work with many partners at local, regional and national levels to safeguard and enhance biodiversity.
Air	Cleaner air for everyone. We will have cleaner and healthier air. The emission of chemical pollutants into the atmosphere will decline greatly and will be below the level at which they can do significant harm.
Water	Improved and protected inland and coastal waters. Our rivers, lakes and coastal waters will be far cleaner. They will sustain diverse and healthy ecosystems, water sports and recreation (such as boating and fishing), and those uses needed by a thriving and healthy community.
Land	Restored, protected land with healthier soils. Our land and soils in the countryside and towns will be exposed far less to pollutants. They will support a wide range of uses, including production of healthy, nutritious food and other crops, without damaging wildlife or human health. Contaminated and damaged land will be restored and protected.

Greener business	A 'greener' business world. Industry and businesses will value the services that come from a rich and diverse natural environment. In the process, they will reap the benefits of sustainable business practices, improve competitiveness and value to shareholders and secure trust in the wider community. All business activities will have environmental concerns at the heart of their thinking and operations. The adoption of sustainable production and consumption practices will be the norm. Industries will exercise stewardship over their products to ensure that they are compatible with sustainable development. Risk- and incentive-based charging schemes will reward reduced risks to human health and the environment and encourage effective environmental management. The public will use its purchasing and investment powers, and its opinion, to influence industrial performance in terms of human health and the environment. Through the public being better informed and involved, there will be greater general approval of the regulatory process and public confidence in it.
Sustainable resource use	Wiser, sustainable use of natural resources. Business, public agencies, other organisations and individuals will minimise the waste they produce. They will reuse and recycle materials far more intensively, and will make more efficient use of energy and materials.
Limit and adapt to climate change	Limiting and adapting to climate change. Drastic cuts will have been made in the emission of 'greenhouse gases' such as carbon dioxide, and society as a whole will take account of, and be prepared for, the probable changes to our climate.
Reduced flood risk	Reducing flood risk. Flood warnings and sustainable defences will continue to prevent deaths from flooding. Property damage and distress will be minimised. The role of wetlands in reducing flood risks will be recognised and all the environmental benefits from natural floods will be maximised.

Additional indicators related to **effective operation and regulation**

Internal	Efficiency, safety, legality of internal processes
External	Reputation and relations with sponsors and stakeholders

Appendix B

Example Application 2: Setting reliability targets

Appendix B: Example Application 2: Setting reliability targets

In the main report (Section 7) we illustrated the application of the proposed assessment framework to a problem of the priorities given to improvement works to existing flood defence assets. This second example illustrates how, for the same hypothetical catchment and defence system, the framework could have been used during the initial design of the system to set reliability targets on the flap gate and pumping station. These targets would form part of the design specification.

The assessment process is, in part, the inverse of that in the first illustration. Rather than evaluate the risk using known or estimated failure rates, we assess the severity of the consequences *if* each function fails, and set a reliability target in inverse proportion to that severity. This helps to achieve a 'balanced' design, in which the design effort and resources devoted to the reliability of each function are proportionate to its criticality in terms of risk.

Step 1: Frame the question

The question to be answered in this example can be phrased as, 'What are the required reliabilities of the flap gate and pump, in order to meet a given overall required standard of protection?'

Step 2: Frame the risks

In this case we assume that risk is defined as the expectation value of the harm that results from failure of either the flap gate or the pump. We also assume that all the possible types of harm (as in Section 4) have been considered and ranked on a weighted, aggregate scale of 1 to 5.

Step 3: Define the system

In this example, the system considered consists only of the flap gate and the pump.

Step 4: Define tolerability

We assume that, having considered the various potential outcomes of flooding at this location and discussed them with the various participants (such as the local authority and community) the Environment Agency has decided that the maximum tolerable flood probability is 1 in 100 per year. However, other elements of the overall flood defence system, such as embankments along the coast and weirs upstream of the town, can fail, so we cannot allow the active defences considered here to use up the entire risk 'budget'. We therefore assume that, based on a risk assessment of the wider system, half of the total – 1 in 200 per year – is apportioned to the flap gate–pump system. The aim of the assessment now is to derive, from this system target, more specific reliability targets for the gate and pump.

Because in this case study we are setting targets, rather than predicting risks, we need to evaluate the conditional risk associated with failure of each function – that is, the severity of consequence if the function fails. Then we assign a reliability target inversely proportional to that severity.

Step 5 Hazard identification and analysis

Table B1 presents the hazard identification and analysis.

Table B1: Example hazard identification and analysis.

Asset	Function	Failure mode	Hazard[1]	Severity rating of outcomes[2]
Flap gate	Allow fluvial flow to discharge	Fail to open when required	Fluvial flow backs up against gate – fluvial flooding occurs	3[3]
	Prevent tide running back up river	Fail to close when required	Tide runs up river – tidal flooding occurs	4[3]
Pump	Discharge fluvial flow against high tide	Fail to operate when required	Fluvial flow backs up against gate – fluvial flooding occurs	3[3]

[1] Description of the nature and extent of effects if the failure on the 'outside world' – that is, at the boundary of the system being assessed.
[2] For simplicity we have assumed that a single weighted sum is adequate to describe all the types of harm and that severities are to be ranked on a scale of 1 to 5 (from minor nuisance to catastrophic, say.) In reality, such scales need to be carefully calibrated. The assessment of outcomes must take account of deliberate mitigations and/or circumstantial factors in the 'outside world' such as topography, vulnerability of exposed population, whether flood warnings are available and accessibility by the emergency services. The units of severity are arbitrary, and interpretation will need to take into account how the scale is defined – for example, whether it is considered to be linear or logarithmic.
[3] There is likely to be more warning of tidal flooding than fluvial flooding – tidal surges can usually be predicted some days in advance, whereas a high fluvial flow may result from a sudden, intense rainstorm in the catchment area (such as occurred at Boscastle). However, tidal flooding is likely to be more extensive than fluvial, and is also likely to re-occur on the next few tides. On balance, a higher severity has been assigned to tidal flooding.

Step 6 Interpretation and risk management

Having completed this analysis we can set reliability targets on the system elements in inverse proportion to the severity of their hazard effects. The targets may be either qualitative or quantitative, but they must to be expressed in terms meaningful to the designer and practical and measurable for implementation.

In the present example, we might decide that it is reasonable to specify the targets in terms of failure on demand rates:

F_{go} probability that gate fails to open when required
F_{gc} probability that gate fails to close when required
F_{p} probability that pump fails to operate when required

We assume that the severity scale in this case was logarithmic, that is, for example, that the severity rating of 4 for the effects of the flap gate failing to close is ten times higher than the rating of 3 for its failure to open. Hence, to satisfy the requirement for inverse proportionality of failure rate and severity:

$F_{go} = F_p$ (Equation 1)

$F_{gc} = 0.1F_p$ (Equation 2)

We also need to meet the overall system target that the maximum tolerable flood probability (of any severity) caused by failures of the flap gate–pump system is 1 in 200 per year (or 0.005 per year). To achieve this we must take account of how often there is a demand on either the flap gate or the pumping station. From the first example application (Section 7) we know that this is the same – 20 times per year – for the gate opening, the gate closing and the pump operating. We further assume that the three possible failures are independent, such that the total probability of a failure is simply the sum of the individual probabilities. Hence the failure rates must also satisfy Equation (3):

$20(F_{go} + F_{gc} + F_p) < 0.005$ (Equation 3)

Solving Equations (1), (2) and (3) simultaneously gives the following reliability targets

Asset	**Functional failure mode**	**Reliability targets (failure-on-demand rates)**
Flap gate	Fail to open when required	$F_{go} < 1.2 \times 10^{-4}$
	Fail to close when required	$F_{gc} < 1.2 \times 10^{-5}$
Pump	Fail to operate when required	$F_p < 1.2 \times 10^{-4}$

This simple example serves to illustrate the principle of using the framework to set targets. In a real analysis, many other factors would have to be considered. A few examples are:

- We have assumed that the 1 in 200 per year target applies to a flood of any severity – we would have obtained the same reliability targets if the severities had been scored as 4 and 5, rather than as 3 and 4, for example. A more defensible tolerability criterion would be a ‘sliding scale’ of severities and probabilities.
- The designer would need to consider the relative cost and practicality of meeting these targets. If, for example, the gate could not practically be made to achieve its target, but the pumps could easily go beyond their target, the designer might decide to re-allocate the risk budget between them, provided the overall system target was still met.
- In many cases, failures, hazards and outcomes are dependent in some ways, so it may be necessary to use fault or event trees, or other forms of cause–consequence analysis, to describe these relationships.

List of abbreviations

AOD	Above Ordnance Datum
EU	European Union
HRW	HR Wallingford
PAMS	Performance-based asset management system
RASP	Risk assessment of flood and coastal defence systems for strategic planning
RMC	RM Consultants Ltd
WP	Work Package

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