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Guide to risk assessment for reservoir safety management

Volume 1: Guide

Report – SC090001/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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The work of the Environment Agency's Evidence Directorate is a key ingredient in the partnership between research, guidance and operations that enables the Environment Agency to protect and restore our environment.

This report was produced by the Research, Monitoring and Innovation team within Evidence. The team focuses on four main areas of activity:

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- **Delivering information, advice, tools and techniques**, by making appropriate products available.

Miranda Kavanagh

Director of Evidence

Executive summary

We face a considerable challenge in ensuring acceptable performance and managing risk from reservoirs and dams in the short to longer term while avoiding unnecessary expenditure on physical interventions. The wide variety of dam types and forms, together with the physical settings in which they are located, further complicates the task. Even with this complexity, however, the concepts of ‘risk’ and ‘performance’ provide dam managers with a useful framework with which to:

- analyse and understand the critical components of dams and the systems within which they function
- target appropriately effort to collect further data, carry out an assessment or intervene physically (if required)

An Interim Guide to Quantitative Risk Assessment for UK Reservoirs was published in 2004 to provide a tool for the management of reservoir safety. In 2009 the Environment Agency conducted a scoping study (SC070087/R1) which established the need to update this guidance. It recommended that the update should include a review of the risk management framework for reservoirs and that this, and the procedures developed, should meet the needs of a wider range of users and the ‘reservoir industry’. It also needed to mesh more coherently with current UK government flood risk assessment policy and practice.

This document, the update, has also sought in addition to the above to provide a guide that is simple to read and to apply – explaining and guiding the user in a practical manner through the steps of the risk-based approach to the risk assessment for reservoir safety. It provides an introduction and explanation of the basic concepts through to detailed application of the methods. It includes appropriate links to other reference documents and useful guidance that should help users to apply best practice in undertaking risk assessments for reservoirs, large and small, in the UK.

The guide has two volumes.

Volume 1 provides an overview of the role of risk assessment in reservoir safety management and the key concepts on which it is based. It also describes the framework for tiered risk assessment.

Volume 2 Part 1 provides the methodology for the three tier approach to risk assessment for reservoir safety management together with examples of its application. Part 2 provides more detailed justification or background information on aspects of the risk assessment methodologies and approaches. This may be used to gain a deeper understanding of the methods used to provide for appropriate use of the methodology and is therefore essential background reading for engineers who apply the guidance.

Acknowledgements

This guidance document has been prepared by the Environment Agency with significant assistance from HR Wallingford, Jacobs, Atkins Ltd, Sayers & Partners, Samui, RAC Engineers and Economists, and United Utilities – along with the help and support of the Steering Group (Tony Deakin, Geoff Baxter, Dave Hart, Timothy Hill, Ian Hope, Kenny Dempster, Jon Green and Malcolm Eddleston). Key contributors include:

- Atkins Ltd (Andy Hughes)
- HR Wallingford (Michael Wallis and Alexandra Topple)
- Jacobs (John Gosden)
- RAC Engineers and Economists (David Bowles)
- Samui (Mark Morris)
- Sayers And Partners (Paul Sayers)
- Stillwater Associates (Alan Brown)
- United Utilities (Keith Gardiner)

The risk assessment methodology was tested on a series of dams in England and Wales. These were conducted by engineers at Jacobs, Atkins Ltd, and HR Wallingford with assistance from the reservoir owners who contributed funding, and engineers who provided data and information on the reservoir dams including. Key contributors include:

- Bristol Water
- Canal and River Trust
- Dŵr Cymru Welsh Water
- Northumbrian Water
- Severn Trent Water
- United Utilities

The guidance has also benefited from feedback and comments from many others during its development including inspecting engineers, supervising engineers, reservoir owners/undertakers and managers, representatives of the National Farmers Union, the Country Land Owners Association, the English Golf Union, the Angling Trust, and other professional partners and consultants. In an open process, three freely accessible consultation workshops were held and well attended. Those who participated receive our particular thanks. All the debates and comments have helped to develop the guidance into a stronger document that should enable reservoir safety risk assessments to be conducted in a robust and consistent way, founded on good practice.

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1 Introduction

Ensuring the acceptable performance of reservoir assets and the management of risk is a considerable challenge. The concepts of risk analysis, which include the consideration of projected performance, can provide reservoir managers with a means to assess and understand the manner in which a dam might fail, and how a reservoir system response to a rare event might contribute to that failure. Such evaluations can assist in the targeting of effort and resources for risk management in an effective way.

An Interim Guide to Quantitative Risk Assessment for UK Reservoirs was published in 2004 to provide a tool for the management of reservoir safety (Brown and Gosden 2004). In 2009 the Environment Agency conducted a scoping study which established the need to update this guidance (Defra and Environment Agency 2009). It recommended that the update should include a review of the risk management framework for reservoirs and that this, and the procedures developed, should meet the needs of a wider range of users and the ‘reservoir industry’. It also needed to mesh more coherently with current UK government flood risk assessment policy and practice.

This guide, the update, presents a three tier approach to risk assessment of reservoirs. Tier 1 is qualitative while Tiers 2 and 3 are quantitative. Although anyone familiar with the concepts of risk assessment could potentially apply the qualitative assessment method, the main users of the quantitative approaches are intended to be reservoir owners/undertakers, consulting engineers, inspecting engineers and supervising engineers who have knowledge and experience of engineering of dams. It is expected that the application of reservoir safety risk assessment to reservoirs regulated under the Reservoirs Act 1975 will typically be overseen by inspecting engineers. However, the approach is equally applicable to those smaller reservoirs that are not classified.

The risk assessment methods are applicable whether the owner/undertaker has a single dam or a portfolio of dams, and can be applied to all types and sizes of reservoirs, including service reservoirs. Proper adoption of the risk management concepts will provide a transparent management framework, and will help to demonstrate compliance with reservoir safety legislation and duty of care. However, use of the methods described in this guide is not a statutory requirement.

This guide is intended to provide practical advice and guidance on the use and application of risk analysis, assessment and management for UK reservoirs. It provides:

- an introduction to, and explanation of, a framework for UK reservoir safety risk management as the context within which reservoir safety risk assessment is undertaken
- an explanation of a tiered and proportionate approach to using risk assessment methods to support reservoir safety management – whether you are an owner/undertaker of a single, small earth dam or a multinational organisation responsible for many different types and sizes of dams and reservoirs
- a tiered, structured procedure for identifying potential failure modes as a preliminary step in all risk assessments
- an explanation of and reference to tools and approaches for predicting:
    - internal and external threats and loads
    - reservoir and dam system response

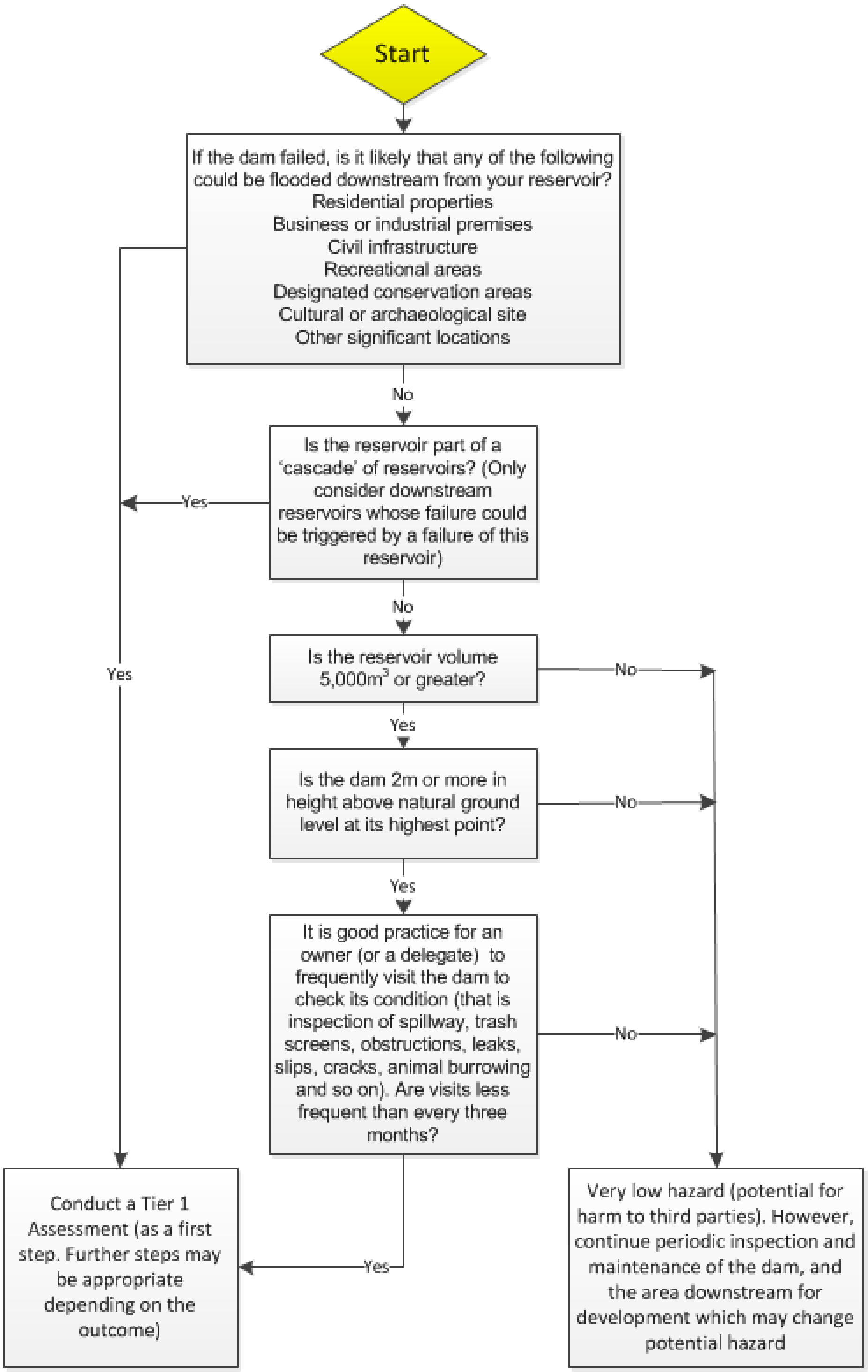
  - release, routing and consequences of flood water from reservoirs
- guidance that may be used by reservoir owners/undertakers, inspecting engineers and supervising engineers to help them use the outcomes of risk assessment for managing reservoir safety and to meet the requirements of legislation in England and Wales
- guidance that supports reservoir owners/undertakers in using the outcomes of risk assessment in managing operational and management risks efficiently and effectively
- worked examples for a variety of pilot site applications for Tier 1 and Tier 2 types of assessments

The guide is aligned with current policy for England and Wales. It will be updated as aspects of practice or policy evolve.

If there is any doubt as to whether this assessment methodology is applicable to a reservoir, the pre-assessment screening questions in Box 1.1 should be used. If the answer to any **one** of these questions is ‘Yes’, it is recommended is that at least a ‘Tier 1’ risk assessment (see section 4.5.1) be conducted.

Box 1.1 Pre-assessment – screening questions

The questions in the flow chart below are designed to determine whether a reservoir and downstream area have physical characteristics which, in the event of failure of the dam and subsequent flooding, could pose a hazard to people, property and the environment.



2 Role of risk assessment in reservoir safety management

This chapter has the following sections:

- Overview of UK reservoir safety management
- The reservoir risk management cycle
- Assessment of different user needs and potential benefits

2.1 Overview of UK reservoir safety management

Reservoir safety management is the process of managing the risk of an uncontrolled release of the contents of a reservoir. It is the responsibility of the reservoir's owner or undertaker. Routine activities include:

- operations and maintenance
- monitoring
- reservoir keeper examinations
- maintenance of an on-site emergency plan

For reservoirs classified under the Reservoirs Act 1975, the safety of a reservoir is overseen by an inspecting engineer (see Box 2.1) who may require changes to the scope and frequency of routine activities. On-going surveillance is conducted by a supervising engineer (see Box 2.1) and includes the submission of an 'Annual Statement' – often referred to as 'an S12'. At the time of writing, reservoirs over 25,000m^3 in capacity are required to be classified under the Reservoirs Act 1975 (see the Act for definition) ,and those classified as 'high risk' reservoirs must comply with supervision and inspection requirements[1] .

The inspecting engineer can require an owner/undertaker to conduct non-routine activities, for example, studies to assess the performance of a dam and its compliance with accepted good practice. An inspecting engineer may also recommend that activities are undertaken to improve reservoir safety.

These requirements are enforced by the enforcement authority, which is the Environment Agency in England, and Natural Resources Wales (NRW) in Wales[2], and the Scottish Environment Protection Agency (SEPA) in Scotland. There is currently no comparable management framework for regulating reservoir safety in Northern Ireland. In the absence of legislation, reservoir owners/operators in Northern Ireland are responsible under common law for ensuring that the reservoir is operated and managed in a safe manner.

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[1] Note that recent amendments to the 1975 Act, as defined in the 2010 Flood and Water Management Act would not change these requirements.

[2] From 01 April 2013, Natural Resources Wales (NRW) take over the functions previously carried out by Environment Agency Wales

Box 2.1 Useful definitions from the Reservoirs Act 1975

The inspecting engineer

‘The undertakers shall have any large raised reservoir inspected from time to time by an independent qualified civil engineer (‘the inspecting engineer’) and obtain from him a report of the result of his inspection’. *(Section 10, para 1)*

The supervising engineer

‘At all times when a large raised reservoir is not under the supervision of a construction engineer, a qualified civil engineer (‘the supervising engineer’) shall be employed to supervise the reservoir and keep the undertakers advised of its behaviour in any respect that might affect safety, and to watch that the provisions of section 6(2) to (4) or section 9(2) and of section 11 [of the Act] are observed and complied with and draw the attention of the undertakers to any breach of those provisions’. *(Section 12, para 1)*

S10 Inspection

‘Unless it is at the time under the supervision of a construction engineer (or of an engineer acting under section 8 or 9 [of the Act] a large raised reservoir shall be inspected under this section—
(a) within two years at most from the date of any final certificate for the reservoir given by the construction engineer responsible for the construction of the reservoir or for any alteration to it;
(b) as soon as practicable after the carrying out of any alterations to the reservoir which do not increase its capacity but are such as might affect its safety and which have not been designed and supervised by a qualified civil engineer;
(c) at any time when the supervising engineer so recommends;
(d) within ten years at most from the last inspection or within any less interval that may have been recommended in the report of the inspecting engineer on the last inspection’. *(Section 10, para 2)*

‘As soon as practicable after an inspection under this section[of the Act], the inspecting engineer shall make a report of the result of the inspection, including in it any recommendations he sees fit to make as to the time of the next inspection, or as to measures that should be taken in the interests of safety’. *(Section 10, para 3)*

S12 Annual Statement

‘It shall be the duty of the supervising engineer, so long as any matters are noted as matters that need to be watched by him in any annex to the final certificate for the reservoir or in the latest report of an inspecting engineer, to pay attention in particular to those matters and to give the undertakers not less often than once a year written statement of the action he has taken to do so’. *(Section 12, para 2)*

Certification under Section 10(6)

‘Where an inspecting engineer includes in his report any recommendation as to measures to be taken in the interests of safety, then subject to any reference of the matter to a referee in accordance with this Act the undertakers shall as soon as practicable carry the recommendation into effect under the supervision of a qualified civil engineer; and that engineer shall give a certificate, as soon as he is satisfied it is so, that the recommendation has been carried into effect’. *(Section 10, para 6)*

For reservoirs below the threshold of 25,000 cubic metres, safety regulation is managed by the Health and Safety Executive (under the Health and Safety at Work (etc) Act 1974) and local authorities (under the Building Act 1984). This guide, and in particular the Tier 1 assessment, was designed with these applications in mind and should also be considered applicable to owners of non-classified reservoirs. This is in line with good practice in the UK and overseas to undertake or update a risk assessment of reservoirs as part of a periodic safety review. Further risk assessment may be justified as a result of such a review or at other stages in the reservoir risk management process.

The level of detail included in such an assessment should depend on the level of confidence required to support various types of reservoir safety decisions.[3] This can be expected to vary with the level of risk posed by a specific reservoir and the inspecting engineer's and owner's/undertaker's requirements for confidence and defensibility in supporting their decisions. Societal concerns, including the perspectives of other stakeholders such as the population at risk or others who would be potentially affected by a dam failure, should also be considered.

It is important to identify the lack of knowledge (and thus the uncertainty) about the factors that determine the performance of a reservoir and the risks that these pose. This guide therefore uses a tiered approach to risk assessment. The different tiers in this approach provide tools and methods that are proportionate in terms of level of effort required, detail considered, and confidence in their outcomes.

This framework and its associated tools and methods provide an approach that allows the reservoir owner or undertaker, inspecting engineer and supervising engineer to better understand and evaluate reservoir safety risk in a structured way. This in turn allows for risk-based decision making which can reduce risks to people, the environment, the economy and the owner/undertaker, while maintaining an important reference to accepted good practice.

2.2 The reservoir risk management cycle

Managing the risk of an uncontrolled release of the contents of the reservoir is an on-going cyclical process. Figure 2.1 shows this process for a single reservoir. It illustrates how the routine and non-routine reservoir safety management cycle of activities (shown by the box on the left side as outer and inner loops respectively) interact with the tiered risk assessment approach (shown by the middle and right side boxes).

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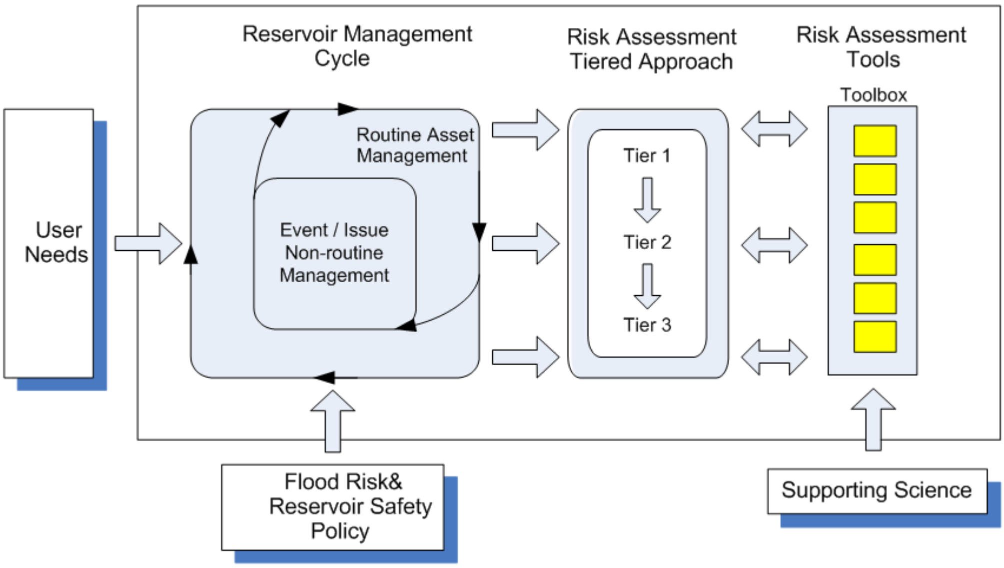
[3] This approach is referred to as a 'decision-driven' (NRC1996) approach to determining the level of sophistication.

Figure 2.1 Integrated reservoir safety risk management cycle



Key routine and non-routine activities conducted under existing UK reservoir safety practice are shown in Figure 2.2.

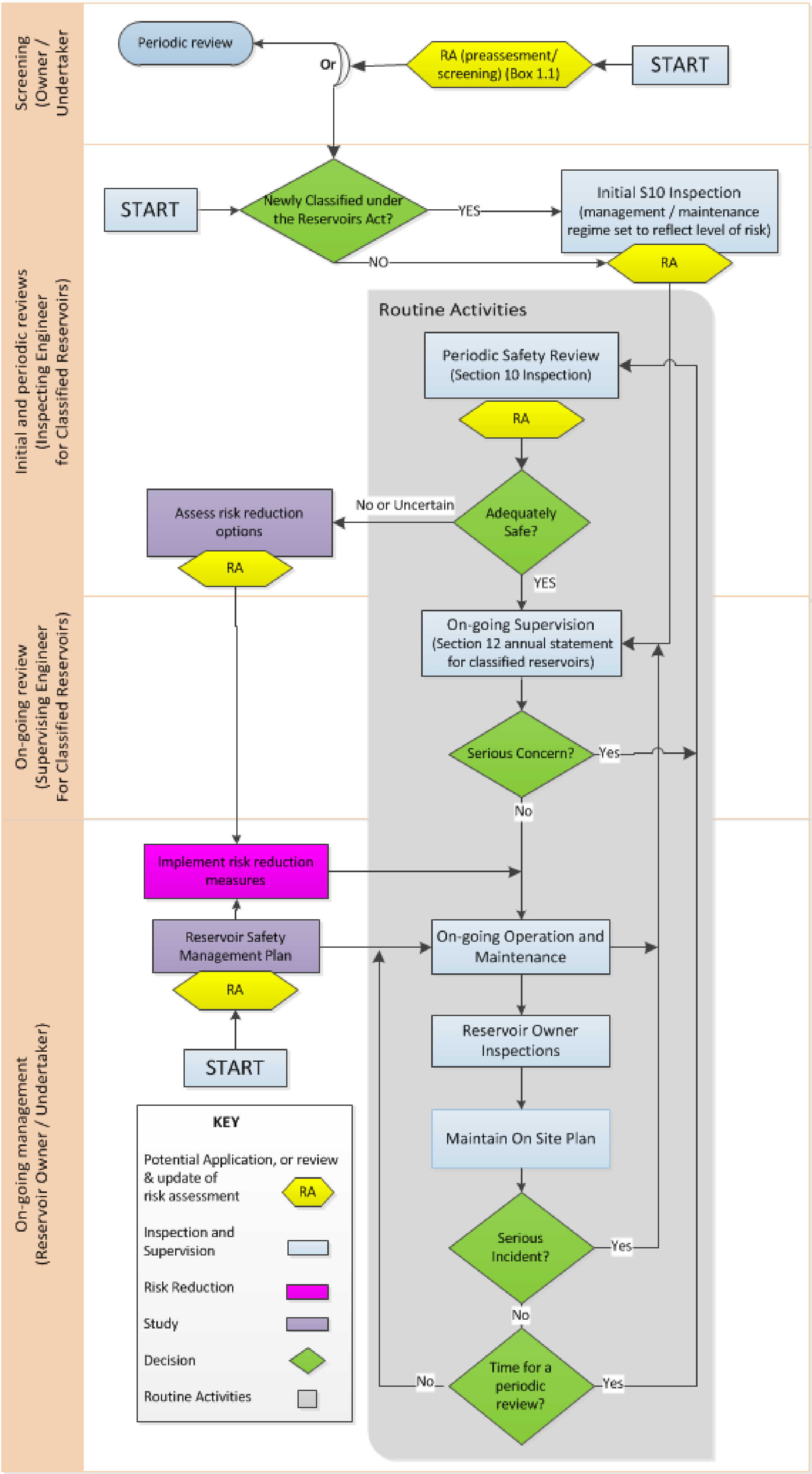
Particularly for unregulated reservoirs, it should first be determined whether or not a risk assessment is required. Box 1.1 will assist with this decision.

If it is already known that a risk assessment is required (as is normal for regulated reservoirs) then the risk assessment forms part of the normal management review process. The decision points (diamond shapes in Figure 2.2) in this process can be informed using the outcomes from a risk assessment or from previous risk assessments that are reviewed and updated with new information.

By following the processes shown in Figure 2.2, the impact of potential measures taken to reduce or manage reservoir safety risk can be assessed. Year-to-year changes in the assessed risk posed by a given reservoir can be recorded alongside expenditure in managing risks (for example, surveillance, measures taken). Such recording of activities and tracking of changes in risk and expenditure may be of particular interest to owners/undertakers of portfolios of reservoirs and should be encouraged as good practice.

Figure 2.2 also shows three broad process blocks. The main 'owner' of each process block is shown to the left and includes the reservoir owner or undertaker, the inspecting engineer and the supervising engineer.

Figure 2.2 Existing UK reservoir safety management process illustrating the potential role of risk assessment in decision-making



Under existing reservoir legislation in England and Wales, each recommendation in the interest of safety is set a 'date for completion'[4] by the inspecting engineer. The date is set with due regard to:

- the level of safety of the dam
- the severity of the defect
- the risks posed
- the need for time to complete design, planning issues, approvals and so on

The enforcement authority expects the recommendations to be completed by that date and can enforce sanctions if the recommended actions are not completed in a timely manner.

If the situation is regarded as an 'emergency', a very short timescale will be set and short-term measures to reduce the risk on an interim basis may be required.

The information provided by application of this guide can be used by inspecting engineers, owners or undertakers and others to help to prioritise and determine the urgency for recommended activities.

Risk assessment also has a role in the planning, design and construction of reservoirs that take a risk-based approach. Many of the same tools can be applied to assess potential threats and to manage potential risks during and after construction. Subsequent routine management activities should then be able to draw upon these studies and develop the risk assessment used at the design stage.

2.3 Different user needs and potential benefits

The reservoir owner/undertaker, inspecting engineer, supervising engineer and enforcement agency can all benefit from including risk assessment in the reservoir safety management framework.

2.3.1 Reservoir owner/undertaker

For reservoirs that need to be regulated, the Reservoirs Act 1975 requires the reservoir owner/undertaker to carry out certain tasks, to retain a supervising engineer and appoint an inspecting engineer every few years to carry out an Inspection (safety review) .

The owner/undertaker of a dam is responsible for the safety of their reservoir. As such they need to demonstrate that 'good endeavours' and procedures have been used to ensure that risks to the public are 'as low as reasonably practicable' (ALARP).

Owners/undertakers of reservoirs that do not need to be regulated under the Reservoirs Act (that is, currently reservoirs of less than 25,000m^3) do not have to retain a supervising engineer (or appoint an inspecting engineer), or comply with these requirements. However, this does not mean that a risk assessment of their reservoir is not desirable or even advisable.

Some owners/undertakers already use risk assessment to help improve and inform their risk management process and ultimately to improve reservoir safety as well as their management of the business risk associated with reservoir ownership. For owners

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[4] Under The Flood and Water Management Act 2010, the phrase 'as soon as practicable' is no longer recognised.

of regulated reservoirs, this is a pro-active approach rather than waiting for the independent Section 10 inspection (see Box 2.1) to identify potential safety issues. It can also inform surveillance activities, for example, the regular visit by a ranger or other site staff, which is a form of risk management activity that includes an observational form of risk assessment used to assess the condition of a dam and to record its condition.

Risk assessment outcomes can also be used to:

- programme works
- justify funding for maintenance and capital expenditure
- prioritise and justify the urgency of works
- identify where the largest benefits and greatest reductions in risk can be achieved

In some cases the outcomes of a risk assessment can also be used to show that proposed works are not justified, perhaps because the cost would be too disproportionate to the potential reduction in risk.

The logical and auditable process of risk assessment, particularly when conducted or audited by a third party, can be used to build a defensible business or safety case, particularly for owners/undertakers with large portfolios of reservoirs. It can also serve a similar role for the owner/undertaker of a single dam where there are conflicting demands on resources.

One of the most valuable parts of a risk assessment process is the identification of potential modes of failure and this is now recognised as good practice in the UK and overseas. An understanding of potential modes of failure can be used to target surveillance and monitoring in the short and long term. This can also form the basis for a risk assessment to inform decisions on whether or not structural or non-structural risk reduction is justified in the longer term.

Risk assessment provides an opportunity for the owner/undertaker of a single reservoir (and their panel engineers) to improve their understanding of potential modes of failure including their mechanisms, likelihood and consequences. An assessment of these risks can then be related to other risks facing their organisation. It can also be valuable to communicate these insights, in an appropriate manner, to stakeholders (for example, the local authority, a fishing club committee or the owner of a nearby stately home).

All owners/undertakers will benefit from including a risk assessment with the periodic safety review conducted by independent inspecting engineers. These benefits are discussed in section 2.3.2.

Owners/undertakers can also use risk assessment at a strategic level. Reducing the risks posed by dam failure to tolerable levels (if required) takes time and planning. They can develop a reservoir safety management plan to:

- document their understanding of the risks they face
- demonstrate how and when risks to the public will be reduced to be ‘as low as reasonably practicable’ (ALARP), consistent with accepted good practice and as soon as reasonably practicable

2.3.2 Inspecting and supervising engineers

The purpose of visits by supervising and inspecting engineers is to recognise any change in the condition or performance of the structure that may indicate that there is a problem (for example, commencement of a failure process). This in itself is an observational form of risk assessment.

A supervising engineer will usually visit a reservoir regulated under the Reservoirs Act once or twice a year. The owner/undertaker or their staff should do so more frequently.

An inspecting engineer may visit perhaps only once in a ten-year period during which an informal, mainly observational risk assessment is carried out. This assessment can be supported by other information such as instrumentation data, and flood, seismic and stability assessments.

The inspecting engineer’s report should summarise all works identified to give direction to an owner/undertaker on what to do to improve the safety of the structure. The report should state explicitly the significant failure modes identified through a potential failure mode identification process (see Volume 2 of this guide). This process is based on the inspector’s knowledge of the structure, including its form of construction, geology and historical performance. Although not a legal requirement, it is recommended that it should also include the equivalent of a Tier 1 qualitative risk assessment.

As shown in Figure 2.2, risk assessments can be used by inspecting engineers as an important part of carrying out their responsibilities for:

- periodic safety reviews – Section 10 inspection
- post-incident reviews
- proposed risk reduction measure approval, supervision and post-implementation review – certification under Section 10(6)

The supervising engineer can benefit from the improved understanding of potential failure modes developed in risk assessments conducted by the inspecting engineer in fulfilment of their statutory duties, or from assessments by the inspecting engineer directly for the owner/undertaker during the development of a reservoir safety management plan.

A completed risk assessment can be updated using any new information and better understanding. If a greater level of detail of risk assessment than a previous assessment is justified, it is preferable that it builds on the earlier assessment in a scalable manner.

3 Key concepts

This chapter covers the following topics:

- What is a reservoir system?
- What is risk?
- What is probability?
- What is a risk assessment?
- What is risk evaluation?
- What is uncertainty?

3.1 What is a reservoir system?

For the purpose of conducting a reservoir safety risk assessment, this guide proposes a broad definition of the reservoir system that includes the features and factors listed in Table 3.1.

Table 3.1 Aspects included in the definition of the reservoir system

Aspect	Definition
Physical features	The reservoir system including surrounding hillsides, the dam(s) and their abutments and foundations and other reservoirs in cascade. All appurtenant structures Electromechanical equipment All instrumentation and communication systems Any other natural or man-made physical features relevant to the safe operation of the reservoir
Operational features	Maintenance, monitoring, surveillance and inspection procedures Any manuals and software needed to operate automated or remote control systems for reservoir operations upon which safe reservoir operation depends including: • inflows and discharges • information such as inflow flood forecasts • management systems • communications and decision protocols
Human factors	Includes maintenance, monitoring and surveillance, supervision and inspection All management aspects of the owner/undertaker or operating organisation on which safe reservoir operation depends

3.2 What is risk?

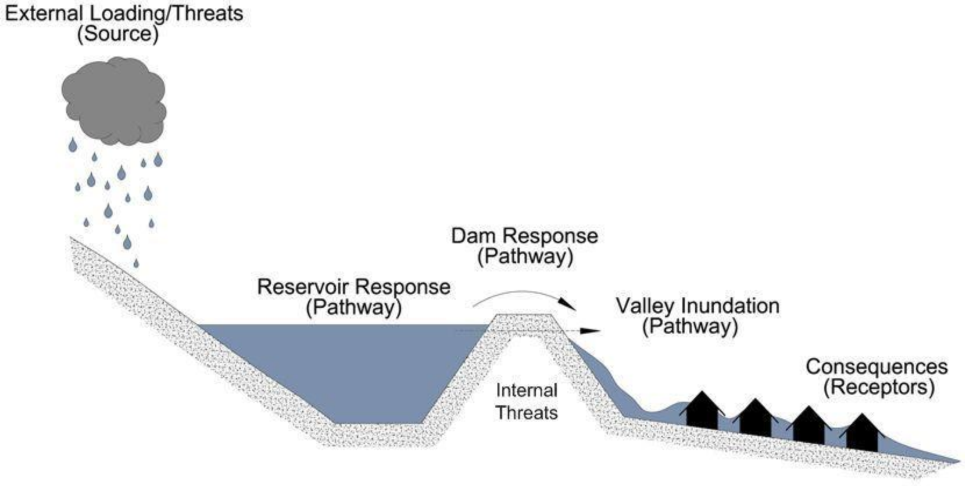
Risk is the likelihood of negative consequences posed by a threat. In the context of reservoir safety it is a function of:

i. The **chance** of a flood occurring downstream of the reservoir based on consideration of the **source** of the threat (for example, extreme rainfall event, internal erosion of the dam or earthquake), the performance or 'response' of the reservoir and dam when that threat occurs, and the nature of the downstream valley[5] (the so-called **pathway** of the risk)

ii. The **consequences** of a dam failure considering the vulnerability and exposure of the **receptors** (for example, people, property and environment) to floodwater

This general description of reservoir safety risk is illustrated in Figure 3.1.

Figure 3.1 Source–pathway–receptor risk model as applied to reservoirs



Both the chance that a dam might fail and the likely consequences of that failure can change over time. The chance (or 'probability') of dam failure can change for various reasons such as structural degradation, the impacts of climate change and land-use change. Similarly the consequences of dam failure (flooding) can change for many reasons such as growth in the population in areas below a dam, or perhaps because the value of property below the dam has increased.

It is therefore crucial that reservoir safety risk analysis methods and decision-making processes are able to support (as a minimum) 'what-if' testing (or 'sensitivity testing') to take into account these changes over time to gauge their effect on the estimated risk of dam failure.

Based on the general definition of risk given above, risk is a function of the chance (probability) of a flood or other threat occurring **and** the chance of a reservoir dam failing, and the consequences of subsequent flooding in the downstream area. It could refer to the loss of habitat, economic damage, the number of lives lost and so on. Thus risk can be viewed in simple terms as:

$$\text{Risk} = \text{fn (probability, consequences)} \qquad (3.1)$$

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[5] In addition to the downstream valley, pathways that lead to negative consequences of dam failure can also exist upstream on or surrounding the reservoir, and remote from the reservoir such as via water diversions or non-physical factors such or indirect economic losses or loss of reputation of the reservoir owner.

In mathematical terms, risk is expressed using the probability distribution of consequences. This is because the level of impacts or consequences of the dam failing depends on:

- the size and scale of the threats to the dam (for example, intensity of the storm)
- the way the dam fails (that is, by which failure mode)
- the time when the dam fails (day/night, weekend/weekday, winter/summer and so on)

Different levels of impact have different probabilities of occurring as a result of the failure of a dam. Each of these combinations of factors can be referred to as a ‘scenario’. Risk is therefore more generally considered to be a function of the scenario, probability of failure and the consequences (Kaplan and Garrick 1981):

$$\text{Risk} = \text{fn (scenario, probability, consequences)} \qquad (3.2)$$

In cases where risks are associated with relatively high probabilities and low consequences (for example, minor car accidents), the average level of risk can be calculated by summing all the products of probability and risk for all failure scenarios of the dam. This leads to the following simplified expression for average annual risk:

$$\text{Average annual risk} = \text{probability} \times \text{consequence} \qquad (3.3)$$

Average annual risk can be expressed in economic terms as £ per year, or perhaps in terms of number of lives per year. However, this term can be misleading as high probabilities with low consequences, and low probabilities with high consequences can end up with the same numerical value. For example, the same numerical value of 0.01 lives per year can be calculated from the loss of one life with a probability of 1 in 100 as well as from 100 lives lost with a probability of 1 in 10,000.)

For reservoirs whose failure could lead to high consequences with low probabilities, and especially for owners with limited assets, use of the average annual risk definition given above has limited value for practical risk management. Instead the more complete definition of risk that considers the probability distribution that fully characterises the risk of dam failure in terms of the probabilities of various magnitudes of life loss, economic/financial and other consequences should be considered. It is the full magnitude of these consequences and not their average values that the owner would be responsible for if a failure were to occur.

Risk analysis of a reservoir system, conducted on a periodic basis, contributes to decision-making by allowing decision-makers to calculate the overall level of risk associated with a reservoir system, with the reservoir dam itself, and the receptors in the protected area. It also enables the identification of components of the reservoir system or more broadly the source–pathway–receptor system (Figure 3.1) which potentially contribute most to the risk. This information can help to prioritise management actions that can be taken to reduce the risk.

3.3 What is probability?

Probability can be a confusing concept and is best described using an example.

Take flooding for instance – one of the main threats to the safety of reservoirs. Floods are random, episodic events. Large floods are rarer than medium-sized or small floods. The probability of each size of flood event can be characterised as the chance that it will occur in any one year – or its ‘annual probability’. Floods are not like earthquakes or volcanic eruptions which recur periodically after tension builds up; instead they have the same probability of occurrence each year. A very large flood might have an annual probability of only 1% (or 1:100 chance of occurring in any one year), whereas a smaller flood may have an annual probability of occurrence of 10% (or 1:10 per year). Thus, a 10% chance event is 10 times more likely in any year than is a 1% chance event, but both are possible in any given year. This is illustrated in Table 3.2.

Note: This definition of ‘annual probability’ has largely replaced the traditional and potentially misleading term ‘return period’.

Table 3.2 Flood frequency terminology

Annual probability	Annual chance
10%	1 in 10
5%	1 in 20
2%	1 in 50
1.3%	1 in 75
1%	1 in 100
0.5%	1 in 200
0.1%	1 in 1000

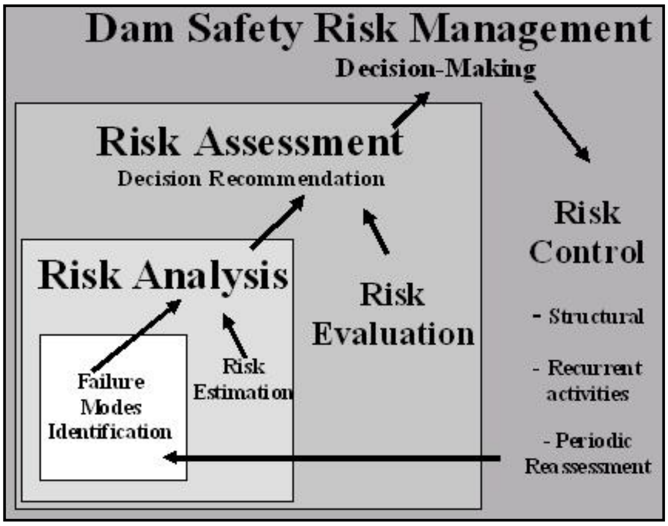
Given that such threats or ‘loading’ events occur to reservoirs, there is also a probability associated with a dam failing during such an event. This probability of dam failure varies with age, design, size and construction of dam, and so on. Different methods are available (described in Volume 2 of this guide) to estimate the probability of dam failure for different kinds of dams and different kinds of threats.

3.4 What is a risk assessment?

A proper risk assessment is made up of various components (Figure 3.2). It should include:

- risk analysis
- risk evaluation
- formulation of options for decision-making

Figure 3.2 Interrelationship between components of risk assessment and risk management



Source: adapted from Bowles et al. (1999)

Risk analysis involves both the identification of risks and the estimation of the level of that risk.

The **management of risk** then utilises the findings of the risk assessment by considering new options, or improvements to existing measures to control risks. Decisions can then be made on appropriate course(s) of action to take so that risks can be reduced or at least maintained at a tolerable level.

In reservoir management this process is repeated or updated periodically to check that the risk situation has not changed, or as needed to reassess possible changes in risk, for example, if changes are planned to the reservoir system or to the dam.

Box 3.1 summarises the basic steps of the risk assessment process. A risk assessment should commence with a clear ‘definition of purpose’. This includes identifying:

- the decisions the risk assessment is intended to inform, including all decision bases
- the desired level of confidence in the assessment as determined by the reservoir owner/undertaker, inspecting engineer and other stakeholders

To be consistent with the Flood Risk Regulations 2009, the first step in the risk assessment process should also include an identification of the drivers and pressures affecting reservoir safety decision-making.

The Flood Risk Regulations 2009 implement in Great Britain the requirements of the European Floods Directive (2007/60/EC), which aims to provide a consistent approach to managing flood risk across Europe. The Water Environment (Floods Directive) Regulations (Northern Ireland) 2009 do the same in Northern Ireland.

Box 3.1 Basic steps in a risk assessment process

Identification of risks

The first step is to select the extent and level of detail or complexity for the risk assessment. This builds on the statement of purpose and on an identification of the ways in which a failure could occur (commonly referred to as a 'failure mode'), as shown in the central box in Figure 3.2. The step involves listing and describing all potential failure modes including details of:

- the relationship between each failure mode
- the types of consequences of failure it is relevant to consider to satisfy the statement of purpose

Investigations and analyses may be needed to assess the credibility (plausibility) of some failure modes.

A structured and systematic process should be followed to ensure the identification of potential failure modes is completed adequately and with the desired level of confidence.

The process of identifying failure modes may include investigations or analyses to narrow the list of credible failure modes to a subset of those it is justified to include in the risk assessment in order to achieve the statement of purpose with the desired level of confidence. These are referred to as 'significant' failure modes. The list of failure modes considered to be significant can vary for the same dam with different risk assessment purposes – as can other aspects of the risk assessment such as the level of detail and types of consequences that are addressed (people, economy, heritage, environment and so on).

This step also includes the identification of the system loading conditions (that is, which threats) to be used in the next step – risk analysis.

Analysis of the risk

The second step is risk estimation, which is the process of determining the response of the system (sometimes called 'fragility') to threats and the associated probability of failure. Traditional engineering analysis, reliability analysis and engineering experience and judgement are all important in estimating system response relationships.

Risk analysis also includes an estimation of the consequences for all the significant failure modes. Consequences are a function of many factors including:

- the amount of water in the reservoir
- the nature and extent of the dam failure
- the extent and character of the resultant flooding
- the season of the year
- warning time
- the effectiveness of evacuation and emergency action plans

Dam break modelling provides the basis for the estimation of the consequences of dam failure for:

- each failure mode
- a range of exposure conditions affecting potential life loss (that is, day/night, season of year and so on)

- other factors such as rapid, complete failure and inundation versus partial, slow failure and inundation

The 'no failure' case should also be considered to allow incremental consequences to be determined. These are defined as the difference between the consequences estimated for failure and no-failure scenarios for flood-related failure modes.

As shown in Figure 3.2 risk analysis involves both risk identification and estimation of the level of risk. It involves combining the probabilities and consequences to obtain estimates for all significant failure modes and then presenting the results in a suitable format so that they can be readily interpreted and used to support reservoir safety decision-making.

Evaluation of the risk

The process of examining and judging the significance of the estimated risk is termed 'risk evaluation'. Risk evaluation is discussed further in section 3.5.

3.5 What is risk evaluation?

3.5.1 HSE tolerability of risk framework

The process of examining and judging the significance of estimated risks is termed 'risk evaluation'.

The Health and Safety Executive (HSE) has a well-established framework for risk evaluations conducted in the UK called the Tolerability of Risk (TOR) (HSE 2001). It is widely used for regulating risks to society and the public that are associated with hazardous industries, but it can also be used to evaluate the risks associated with reservoirs. The framework has significantly influenced the development of risk evaluation approaches for dams in Australia (ANCOLD 2003) and North America (CDA 2007, Munger et al. 2009, USACE 2011).

Risks to other entities, such as businesses, or to the reservoir owner/undertaker themselves can also be considered in the overall risk evaluation process.

Under the TOR framework, the process of risk evaluation is not complete until it has been demonstrated how the risk can be reduced to be 'as low as reasonably practicable' – referred to as the ALARP principle.

3.5.2 What level of risk is tolerable?

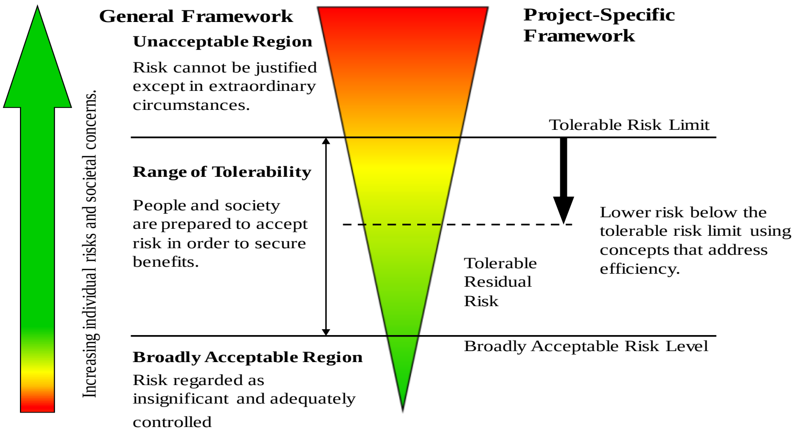
The HSE Tolerability of Risk framework is based on the way that risks are managed in everyday life. It aims to be transparent and to encourage the participation of all stakeholders, including those that are at risk.

The TOR framework is an approach to managing risks to individuals and to society. Societal risk addresses how large numbers of people might be affected in an event and the potential for triggering a socio-political reaction. As explained in HSE (2001a) and Le Guen (2010), assessed individual and societal risks can be assigned to one of three categories as illustrated by the regions shown on the left-hand side of Figure 3.3:

- **Broadly acceptable** – risks compared with those that people live with every day and which they regard as insignificant and not worth worrying about (for example, health risks associated with using mobile phones)

- **Unacceptable** – risks are generally believed by individuals and society to be not worth taking regardless of the benefits (for example, building residential areas on toxic landfills)
- **Range of tolerability** – individuals and society are willing to live with the risks so as to secure certain benefits, provided that they are confident that they are being properly managed, and that they are being kept under review and reduced still further if and as practicable (for example, vehicular and airline travel).

Figure 3.3 Tolerability of risk framework



Source: Munger et al. (2009), adapted from HSE (2001a)

Except in exceptional circumstances, risks that fall in the unacceptable region must be reduced by structural or non-structural measures, irrespective of the cost, to bring them down into the range of tolerability.

Even if a risk is in the ‘range of tolerability’, it should be reduced to be ‘as low as reasonably practicable’ (ALARP). The ALARP principle is met when it is deemed grossly disproportionate in terms of expending resources to gain any further reduction in risk.[6] Application of the ALARP principle therefore requires the formulation of risk control (or ‘treatment’) options. These might, for example, include structural measures, improved monitoring and surveillance, emergency action planning and staff training.

In traditional reservoir safety practice, dam safety is periodically reassessed. These reassessments should include a review and update of any earlier risk assessments as appropriate, as shown by the line that links ‘Risk Control’ to ‘Failure Modes Identification’ in Figure 3.2.

3.6 What is uncertainty?

Risk assessment of reservoirs is not a definitive science. There are inherent uncertainties associated with various aspects of the assessment process and with the methods used for the analysis of risks.

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[6] This was established by the landmark legal finding that spells out this principle [Edwards v. The National Coal Board (1949 1 All ER 743)].

Risk analysis requires uncertainties to be formally addressed and their importance determined in the context of the specific reservoir and the decision(s) to be made.

Scientifically, there are two forms of uncertainty:

- natural variability – or ‘randomness’
- knowledge uncertainty

Natural variability refers to the randomness of natural events. These uncertainties are routinely dealt with in dam safety risk assessment and in flood risk management through, for example, consideration of the variation in flood events with a range of annual exceedance probabilities.

Knowledge uncertainty refers to our imperfect and incomplete understanding of all aspects of risk including:

- the loads a reservoir is subject to
- the performance of the reservoir system under those loads
- the potential consequences of failure

These knowledge uncertainties reflect uncertainties about the available information itself, including the data and models used to develop that information. Such uncertainties are typically considered less formally when compared with natural variability.

In traditional standards-based engineering management, this type of uncertainty is often managed through use of:

- safety factors
- extreme load combinations
- conservative expert judgment

4 A framework for tiered risk assessment

This chapter has the following sections:

- Principles underpinning the tiered system
- Application of the framework
- The tiered system
- Preparing for the risk assessment
- Differences between tiers
- Selecting an initial tier of assessment

4.1 Principles underpinning the tiered system

The assessment of the user's needs and the principle of proportionality (discussed in section 2.3) lead to a tiered approach to risk assessment and associated tools. The principles and approach for the tiered framework are introduced in this chapter.

Factors that govern the definition of the tiers of risk assessment and their associated tools include:

- user needs and purposes – described in Chapter 2
- degree of risk posed by a dam – see overview of guiding principles given in Chapters 2 and 3
- effort (cost) of the analysis selected – which to needs be proportionate to the risk and appropriate to the purpose of the analysis as discussed in Sections 2.2 and 2.3
- quality of available tools to assess the significant risks at the subject dam
- quality of available information, which can be improved to some degree by investigations and analyses where the cost is justified by the benefits of the increased value in decision-making
- degree of uncertainty and the degree of defensibility and confidence required in the risk assessment results

It may not be possible to justify investing time to analyse in detail threats and failure modes that do not contribute much to the overall risk. In a tiered approach, therefore, the quality of tools selected to analyse these at a specific dam may vary depending on which threat or failure mode dominates the risk of dam failure.

Another significant consideration of analytical tools in a tiered approach is that the criterion for what constitutes the 'optimum' tool for a particular user will vary. For example, the owner/undertaker of a small dam who wants to use risk assessment to better understand the issues at the dam, or to check a risk assessment carried out by others, wants simple transparent methods, which could perhaps be applied using a calculator and paper, whereas an engineer or a specialist risk consultant may prefer a AutoCAD or a GIS-based software approach.

The framework therefore has to allow for a range of potential users and provide a range of tools for the risk assessment.

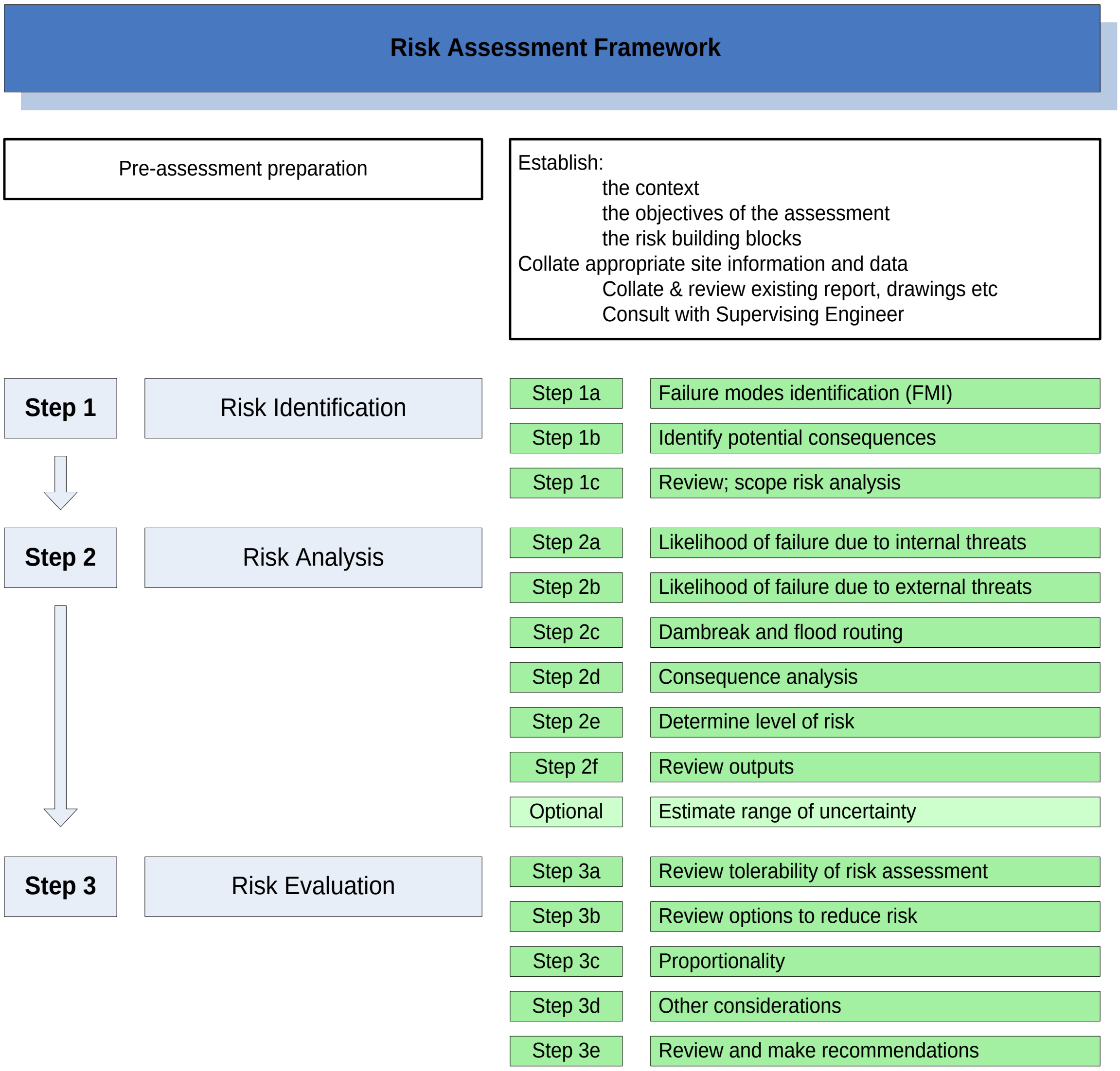
4.2 The risk assessment framework

BS EN 31010 states that (BSI 2010):

> 'risk assessment is that part of risk management, which provides a **structured process** that identifies how objectives may be affected, and analyses the risk in term of consequences and their probabilities before deciding on whether further treatment (risk reduction) is required'.

Figure 4.1 illustrates the structured process designed for reservoir safety management and is applicable across all tiers of the system. Note that some steps are optional and may only be appropriate for some reservoirs.

Figure 4.1 Risk assessment framework



4.3 The tiered system

The tiered system consists of three tiers:

- Tier 1 is qualitative – the simplest approach, comprising a qualitative assessment of risk

- Tier 2 consists of basic quantitative analytical tools
- Tier 3 involves quantitative methods with a range of degrees of detail

Table 4.1 describes the tiers in more detail.

Table 4.1 Tiered analysis

Tier	Type of risk assessment	Description
1	Qualitative	Ranking of potential failure modes, order of magnitude likelihood and consequences estimates using a descriptive risk matrix Optional sensitivity analysis
2	Basic quantitative	Threshold analysis using manual calculations (that is, with a basic calculator) Optional sensitivity analysis
3	Detailed quantitative	Range of levels – include system response curves, with range of initiating events (threats) using computer software for risk calculations Ways of dealing with uncertainty range from formal sensitivity analysis to full uncertainty analysis.

Failure mode identification (FMI) underlies each of the tiered approaches. A basic approach to FMI is recommended for Tier 1, with a more detailed approach adopted for Tiers 2 and 3. Details of all the methodologies, including look-up tables, checklists and examples to assist the user can be found in Volume 2 of this guide.

4.4 Preparing for the risk assessment

The preparation, or ‘pre-assessment’ stage, is an important part of the risk assessment process. It should set out what level of assessment is required and what level of confidence is required in the results. The methods outlined in Volume 2 of this guide allow the user to assess the risk in either a qualitative (Tier 1) or quantitative (Tiers 2 and 3) manner depending on their needs.

In each tier, the same elements of risk must be addressed. It is important to:

- consider which ‘loads’ or ‘events’, or combinations, could lead to failure and flooding
- determine the consequences of these dam failure scenarios

It is vital to identify and gather information on the dam before carrying out the risk assessment. The amount of information available will vary greatly from site to site.

For regulated reservoirs, talking to the supervising engineer will help to identify issues of concern. Consulting the supervising engineer is considered an essential part of the process of gathering information for the risk assessment.

4.5 Differences between the tiers

The main differences between the three tiers are outlined below and detailed for the various steps of the risk assessment process in Table 4.2.

4.5.1 Tier 1 risk assessment – qualitative

A Tier 1 risk assessment might be carried out for any reservoir as an initial assessment and data collection exercise by the owner or a reservoir engineer. Where risks are already known to be high, however, it may be decided to proceed directly to a higher tier without conducting the Tier 1 analysis.

Much of the effort needed to conduct a Tier 1 risk assessment is typical of the minimum that might be expected by an inspecting engineer performing a Section 10 inspection. The effort involved in including a risk assessment in an S10 inspection is therefore not as great as it would be if the risk assessment was a separate exercise.

A key step in the Tier 1 analysis is the FMI process. Having identified different failure modes, the failure likelihood and failure consequences for these different failure modes are mapped using expert judgement onto a simple risk matrix (high, medium, low and so on) and incorporating a broad scale consequence assessment. This provides a simple, systematic method of the risks that is also effective and transparent.

Volume 2 provides an explanation of the methods recommended or available for performing all the steps in Tier 1, along with initial checklists to support the FMI process and development of the risk matrix. Some of the steps are optional and not essential for a basic risk assessment, although it is prudent to consider if they might be of value on a case-by-case basis.

4.5.2 Tier 2 risk assessment – simplified quantitative

The Tier 2 risk assessment can build on a Tier 1 analysis or it may be the first analysis applied to a particular reservoir. A Tier 2 analysis should be carried out where a quantitative rather than qualitative assessment of risk is required.

Like Tiers 1 and 3, a Tier 2 risk assessment starts with an FMI analysis. The level of FMI analysis for Tier 2 is more detailed than for Tier 1, but the same as for an entry-level Tier 3 risk assessment. The FMI analysis for Tier 2 includes more detailed consideration of potential failure modes and is preferably undertaken by a small team including the supervising engineer and reservoir keeper rather than just a single person (as is the case for Tier 1).

The Tier 2 assessment consists of a simple quantitative assessment of risk, initially using existing available data. The assessment has a number of steps of analysis including items such as:

- estimating probability of failure due to external, internal and other threats
- assessing the hydraulics of dam break and flood routing
- estimation of economic damages and likely loss of life
- risk analysis calculation
- tolerable risk evaluation, including ALARP assessment

Each of these steps involves use of simple or simplified methods that enable the overall assessment to be completed with 1–2 days of effort and without the need for analysis software.

However, this level of analysis does include the introduction of event trees and/or fault trees to aid the understanding and assessment of different failure modes but without detailed numerical assessment of the trees.

Volume 2 provides an explanation of the methods recommended or available for performing all steps in Tier 2, along with initial checklists to support the FMI process and development of the risk matrix. Some of the steps are optional and not essential for the risk assessment, although it is prudent to consider if they might be of value on a case-by-case basis.

4.5.3 Tier 3 risk assessment – quantitative

A Tier 3 risk assessment can either build on a Tier 1 or 2 analysis, or it may be the first analysis applied to a particular reservoir.

A Tier 3 analysis should be carried out where a Tier 2 analysis has identified areas of concern and a more detailed understanding of the risks (and the uncertainties involved) is required to support decision-making. It could also be the starting point if it is recognised that a Tier 3 risk assessment is needed from the outset.

Unlike Tiers 1 and 2, Tier 3 analysis consists of a range of methods for a more detailed quantitative assessment of risk. The methods of analysis may extend to more complex numerical methods, including a more rigorous analysis of failure modes and their interdependencies, along with uncertainties.

The selection of the appropriate level of detail for a Tier 3 analysis requires greater thought than is the case for Tiers 1 and 2 where the steps are more scripted.

The level of effort for Tier 3 can vary significantly but should be justified on a decision-driven basis.

Table 4.2 Differences between the tiers

Step		Tier 1	Tier 2	Tier 3
1a	**Failure modes identification (FMI)**	Review all available information. Interview supervising engineer and reservoir owner. Consider the list of core failure modes that are credible and significant (internal erosion in embankment to be considered in all cases). If additional credible and significant failure modes are identified, consider use of Tier 2 or 3.	As Tier 1 but potential failure modes starting with blank sheet rather than focusing on core failure modes list. Checklists are used.	As Tier 2 and in addition: • involve reservoir team • prepare detailed description of each credible and significant failure mode • develop event trees or fault trees
1b	**Identify potential consequences**	Subjective review of step 1a implications Normally rainy day only	Normally simplify to two scenarios (sunny and rainy day)	Move to greater range of consequence scenarios.
1c	**Review; scope risk analysis**	Determines the risk assessment scope and draws on experience and judgement		
	Uncertainty	Normally consider single point value for each parameter, but with explicit statement about confidence in estimates with the option for simple sensitivity analyses.	Probabilities and consequences are estimated as single point estimate, often selected to be conservative following a precautionary approach.	At entry level uses computer-based calculations including fragility (system response) curves. May extend to using Monte Carlo analysis with frequency (uncertainty) distributions of all inputs that may significantly affect decisions that are to be informed using risk estimates.
2a	Likelihood of failure due to internal threats			
	Embankment dams	Uses a matrix of intrinsic condition and current condition.	Uses the probability of failure for the average dam from historic data. Then adjusts to the specific dam using condition mapping score, and adjusts to probability	Uses event trees built upon detailed analysis and use of US Bureau of Reclamation (USBR) toolbox on piping failure.

Step		**Tier 1**	Tier 2	**Tier 3**
	Concrete/ masonry dams and service reservoirs	Uses a matrix of intrinsic condition and current condition.	Simplified event trees using index stability graphs based on standard parameters	Uses event trees.
2b	Likelihood of failure due to external threats			
	Embankment dams	Uses matrix based on standard parameters.	Dam critical load	Stability/ seismic analysis using range of input parameters (Monte Carlo) to assess uncertainty
	Concrete/ masonry dams and service reservoirs		As *Internal threats*	Event tree with site-specific stability analysis (ranging from limit equilibrium to 2D/3D dynamic)
2c	**Dam break and flood routing**	Uses existing maps or proportion of dam height plus estimated inundation area.	Simplified breach (Froehlich) and modified CIRIA C542	Full breach analysis and inundation modelling
2d	**Consequence analysis**	People: uses a qualitative assessment of broad scale number of houses, using a 25,000 scale map. Other receptors: simplified using as a minimum 25,000 scale map	People: uses a simplified quantitative assessment, using 25,000 map and drive down valley. Other receptors: internet based search of government and other databases	Uses a GIS-based assessment.
2e	**Determine level of risk**	5 × 5 qualitative matrix based on Best Practices Training Manual (BPTM). Plot one point for overall probability of failure and worst case consequences	F-N chart with one point for overall risk. Numeric value for individual risk and economic damage. Qualitative matrix for other consequences	Multiple failure modes and consequence scenarios
2f	**Review outputs**	Subjective sanity check on the results. Draws on experience and judgement.		
3	**Risk evaluation**	Review 5 × 5 matrix for tolerability	Review ALARP calculation for tolerability	Review

4.6 Selecting an initial tier of risk assessment

The choice of which tier of risk assessment to undertake for a particular reservoir will depend on a number of factors including:

- the scale of the threats to the dam
- the potential consequences should the dam fail
- the level of confidence in the results that is required

Implicit in a risk-based approach is a tiered approach, where simplistic analysis is carried out first to identify the significant risk contributors, followed by more detailed assessment of these where it is justified.

A Tier 1 risk assessment is likely to be sufficient for small reservoirs in remote areas with little in the way of potential consequences, whereas as large capacity reservoir with a high dam and significant potential consequences should it fail is likely to require the level of confidence that only a Tier 3 assessment can provide. Exceptions might be when a Tier 1 assessment is sufficient for the large reservoir as an initial assessment to prioritise investment in future efforts for more detailed risk assessment, including supporting studies, and for risk reduction actions. It is worth noting that initial risk assessments that have been completed as part of portfolio risk assessment for such large reservoirs in the UK have generally been conducted at a level of detail in the range of Tier 2 to entry-level Tier 3.

Much of the effort needed to conduct a Tier 1 analysis is typical of what might be expected of an inspecting engineer performing a Section 10 inspection. The process works through a limited FMI process and a qualitative assessment of risk. This can be performed relatively quickly and provides a base assessment of risk which will help identify whether the reservoir has any risk issues of concern. Where there is the potential for significant risk to people or other receptors, a more detailed Tier 2 or 3 assessments might be appropriate to resolve uncertainties and support management decisions.

A Tier 2 analysis provides a base quantitative estimate of reservoir risk, whereas a Tier 1 analysis provides a qualitative estimate. A Tier 2 analysis may be undertaken when risk issues have been identified at Tier 1 that justify moving to Tier 2, or it may selected as the initial risk assessment when the owner/undertaker or inspecting engineer already know that Tier 2 is justified because the risk needs to be quantified to support appropriate management actions. It may also be selected when there is a threat or failure mode that is considered significant to the safety of the dam but which is not covered at Tier 1. It is the responsibility of the user to identify any significant failure modes that are not addressed in Tier 1 and to move to a Tier 2 or 3 analysis if these failure modes are not included in the Tier 1 approach.

The Tier 3 analysis introduces more complex methods for analysing failure modes and associated consequences, and the important interdependencies between them. This level of analysis entails the use of more complex models and more in-depth methods for identifying potential failure modes and the integration of these analyses within the overall assessment of risk. The extent to which the analyses may be undertaken varies and will depend on the level of understanding and confidence desired for decision-making.

The effort required for analysis in each of the tiers is generally proportionate to the level of risk. A Tier 3 analysis may be undertaken where an earlier Tier 1 or 2 analysis has identified high potential risks and the magnitude of these risks justifies the effort required to analyse and reduce the uncertainties around the estimates to adequately support management decisions and risk reduction actions. In some cases a Tier 3 analysis may be selected as the initial type of analysis.

It is anticipated that most UK reservoirs will be subject to a Tier 1 analysis and, where potential risks of concern are identified, a Tier 2 analysis to quantify the risks. Tier 3 methods will only be appropriate for selected reservoirs where risks and uncertainties are high, hence justifying the effort required for the more detailed assessment to achieve a higher level of confidence in decision-making. However, many portfolio risk assessments conducted in the UK have been at an entry-level Tier 3 based on the need for confidence in the results.

A summary of the issues affecting the selection process is shown in Figure 4.2.

Figure 4.2 Choosing an initial tier of risk assessment

Selecting the Initial Tier of Risk Assessment

When choosing an appropriate level of risk analysis consider that:

- All levels of analysis build from an initial failure modes identification process
- An initial entry level for risk analysis can be made via any Tier, however the simplest, most rapid assessment method is provided by Tier 1
- Tier 1 provides a qualitative assessment of risk; Tier 2 offers the simplest form of quantitative assessment
- Tier 3 provides a framework for more complex risk assessment, including more detailed analysis of processes and interdependencies. Tier 3 would be used where risks are uncertain and potentially high, requiring a more detailed assessment.
- For each of the tiers the effort required for analysis is intended to be proportionate to the risk and / or user needs. Hence, Tier 1 provides the minimum effort entry level for analysis (qualitative); Tier 2 the minimum effort entry level for quantitative assessment and Tier 3 more complex methods for situations with the potential for higher risks

User Needs	*Tier*	*Outputs*
- Rapid, simple, qualitative assessment - An initial assessment to understand potential risks - Provides support for a Section 10 assessment	**Tier 1 Qualitative** (See Pg. 24)	*- Failure Mode Identification* *- Estimation of likelihood and consequence, represented on an impact matrix (ie. risk described as high, medium, low etc).*
- Quantitative risk assessment	**Tier 2 Simplified Quantitative** (See Pg. 24)	*- Failure Mode Identification* *- Provides numerical estimate of failure probability and risk*
- Quantitative risk assessment - Detailed consideration of specific processes and risks, including interdependencies	**Tier 3 Quantitative** (See Pg. 25)	*- Failure Mode Identification* *- Provides a more refined numerical estimate of failure probability and risk*

References

ANCOLD (Australian National Committee on Large Dams), 2003. *Guidelines on Risk Assessment*. Sydney: ANCOLD.

Bowles, D.S., Parsons, A.M., Anderson. L.R. and Glover, T.F., 1999. Portfolio risk assessment of SA Water's large dams. *ANCOLD Bulletin*, 112, 27-39.

Brown, A.J. and Gosden, J.D., 2004. *An Interim Guide to Quantitative Risk Assessment for UK Reservoirs*. London: Thomas Telford.

BSI (British Standards Institution), 2010. *BS EN 31010: 2010. Risk management. Risk assessment techniques.* London: BSI.

CDA (Canadian Dam Association), 2007. *Dam Safety Guidelines*. Toronto: CDA.

Defra and Environment Agency, 2009. *Scoping Study for a Guide to Risk Assessment of Reservoirs*. Joint Defra/Environment Agency Flood and Coastal Erosion Risk Management R&D Programme. Report SC070087/R1. Bristol: Environment Agency.

Environment Agency, 2011. *National Flood and Coastal Erosion Risk Management strategy for England.* Bristol: Environment Agency.

HSE (Health & Safety Executive), 2001. *Reducing Risks – Protecting People. HSE's decision-making process.* Norwich: HMSO.

Kaplan, S. and Garrick, B.J., 1981. On the quantitative definition of risk. *Risk Analysis*, 1 (1), 11-27.

Le Guen, J., 2010. Exploration of the tolerable risk guidelines for levee systems. In: *Proceedings of the Workshop, Exploration of Tolerable Risk Guidelines for the USACE Levee Safety Program, 17–18 March 2010, Washington DC*. Alexandria, VA: US Army Corps of Engineers.

Munger, D.F., Bowles, D.S., Boyer, D.D., Davis, D.W., Margo, D.A., Moser, D.A., Regan, P.J. and Snorteland, N., 2009. Interim tolerable risk guidelines for the US Army Corps of Engineers dams. In: *Managing Our Water Retention Systems, Proceedings of the 29th Annual USSD Conference*, 20–24 April 2009, Nashville, TN, pp. 1125-1142. Denver, CO: United States Society of Dams.

NRC (National Research Council), 1996. *Understanding Risk: Informing Decisions in a Democratic Society*. Washington DC: National Academy Press.

USACE (US Army Corps of Engineers), 2011. *Engineering and Design. Safety of Dams – Policy and Procedures*. Engineer Regulation ER 1110-2-1156. Washington DC: USACE. http://publications.usace.army.mil/publications/eng-regs/ER_1110-2-1156/ER_1110-2-1156.pdf [Accessed: 25/09/2012]

List of abbreviations

ALARP	as low as reasonably practicable
ANCOLD	Australian National Committee on Large Dams
CDA	Canadian Dam Association
FMI	failure mode identification
HSE	Health and Safety Executive
TOR	tolerability of risk
USACE	US Army Corps of Engineers

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