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Small Reservoirs Simplified Risk Assessment Methodology

Guidance Report

Project: FD2658

Flood and Coastal Erosion Risk Management Research and Development Programme

HR Wallingford
Working with water

Small reservoirs simplified risk assessment methodology

Guidance report

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Executive Summary

The law that governs the safety of reservoirs in the UK is changing. This means that the legal responsibilities of reservoir owners will depend on whether their reservoir is classed as 'High risk' or not. Table ES.1, below indicates the typical types of reservoirs that will be classed as 'high' or 'not high' risk.

Table ES.1: Typical reservoir risk classification types

Risk Category	Typical reservoir types
High	• Reservoirs in dense urban areas • Reservoirs with high dams (>5m) or large volumes of water (>100,000m^3) • Reservoirs perched on hillsides above properties
To be determined	• Any reservoir where it is not immediately obvious that it could pose a danger to people and property if the dam were to fail suddenly **Use this guide to help you better understand the risk posed by your reservoir**
Not high	• Reservoirs in remote or rural areas • Reservoirs with low dams (<2m) or small volumes of water (<10,000m^3) • Reservoirs surrounded by flat land far away from any properties

Note: *These are typical examples for the guidance of the reader. Each case will be considered on a site-specific basis by the Environment Agency.*

This guide explains the factors that can affect the risk category of a reservoir and this document is likely to be useful to you if:

- The reservoir you are considering has a volume smaller than 100,000m^3
- You are considering building a new reservoir and wish to minimise the risk it poses to others
- You are trying to understand why the Environment Agency has designated your reservoir as 'High risk'
- You live downstream of a reservoir and wish to understand the risk it poses to you.

This document is not a technical design manual for reservoirs, but will point the reader to suitable references for the design of reservoirs, and will explain the types of professional engineers involved in reservoir safety in the UK and how they can assist you further.

The document also contains:

- Background information on the law governing reservoir safety
- A glossary of terminology regarding reservoirs
- Tips to help the reader in the scoping of a new low-risk reservoir
- Explanation of the Environment Agency technical method for the initial risk designation of a reservoir
- Description of a simplified, alternative methodology for risk designation that may be used
- Guidance on the range of more detailed types of risk assessment that are available.

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Key contributors include:

- HR Wallingford (Alexandra Topple and Craig Goff)
- Samui (Mark Morris)
- Stillwater Associates (Alan Brown).

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- Paul Sayers and Partners (Paul Sayers)
- RAC Engineers and Economists (David Bowles).

The guidance has also benefited from feedback and comments from many others during its development including representatives from Defra, Environment Agency, National Farmers Union, and the Angling Trust.

We hope you find this document useful and welcome your feedback. Please contact Mr Craig Goff (c.goff@hrwallingford.com) if you have suggestions for future revisions of this guide.

Contents

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1. Introduction

This guide explains the different methods available to you to understand the risk posed by (generally) small reservoirs. It aims to help inform decisions on the planning, design and management of reservoirs, and to help minimise the risk posed to those living and working downstream of a reservoir.

1.1. Why would you use this guidance document?

Research has been undertaken to produce an appropriate simplified method for reservoir risk categorisation based on dam breach flood effects. This guide:

- Explains how a reservoir can pose a risk to those downstream
- Explains the method the Environment Agency uses to assess reservoir risk
- Provides simplified guidelines (a step by step process using look up charts) to allow you to assess the effects of a dam breach
- Provides advice on where to find supporting information and more detailed methodologies
- Demonstrates the simplified methodology through a typical case study.

The guide only focuses on earth structures which come under reservoir safety legislation which is enforced by the Environment Agency in England. It also outlines the responsibilities of a reservoir owner, and provides signposting to those considering building a new reservoir on best practice for design, construction and environmental issues.

1.2. The layout of this guidance document

An overview of the layout of this guidance document in given in Figure 1.1. Chapters 2 and 3 provide background information on reservoir safety legislation, and key factors to consider if you are thinking of building a new reservoir. Chapter 4 explains the potential risks posed by reservoirs, and details on how the Environment Agency assesses risk from reservoirs.

Chapter 5 introduces the new simplified risk categorisation method that you can undertake for your specific site. Chapter 6 describes how and when it might be appropriate to undertake more detailed, in depth analysis, and finally Chapter 7 provides guidance on where to find further information.

A full step-by-step example of applying the methodology (from Chapter 5) is included in Appendix A, and a nomenclature can be found in Appendix B.

Chapter 1: Introduction	*Introduction*
Chapter 2: Overview of reservoir safety	*This gives an overview of the current legislation in the UK for reservoirs and gives guidance on good practice for reservoir safety management*
Chapter 3: Things to consider if you are planning to build a new reservoir	*Signposting to further guidance when planning to build a new reservoir*
Chapter 4: Understanding the risk posed by reservoirs	*Defines what risks are, and how to assess the potential impact of a reservoir failure*
Chapter 5: Reservoir flood assessment – Simplified method	*A methodology is provided to allow estimation of the potential impacts of dam failure, taking into consideration local and site specific features*
Chapter 6: Reservoir flood assessment – Detailed method	*Guidance for use of methods provided under the Risk Assessment for Reservoir Safety Guide*
Chapter 7: Where to find further information	*Signposting to further guidance*
Appendix A: Worked example	*A worked example, the step by step process of the simplified method for reservoir risk categorisation.*

Figure 1.1: Document layout

1.3. Definitions

This section explains the meaning of the engineering terms used in the document, in alphabetical order.

Cohesive soil

Soil made up of mainly clay, which tends to shrink on drying and expand on wetting.

Consequences

The consequences are the impacts of an event (e.g. a dam breach) on people, structures, economic activity, the environment and cultural heritage.

Dam Breach

The removal of a section of the dam embankment due to erosion, foundation movement or excessive flood leading to the release of stored water.

Erosion

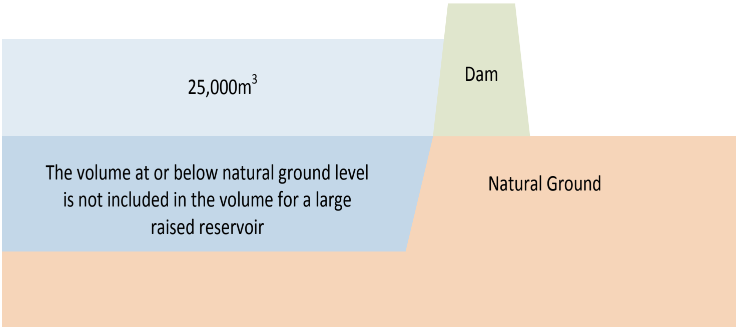
The removal of soil by natural effects such as rainfall, river and flood flows, undermining or gravity, or by leakage through a dam or human and animal activity.

Flow path

The direction of the escaped water from the reservoir and the route it takes.

Large raised reservoir

The Reservoirs Act 1975 applies to "large raised reservoirs", also known as regulated reservoirs. This is where the volume held above the surrounding land is more than 25,000 cubic metres (m^3). This is equivalent to about 5 million gallons of water, or 10 Olympic swimming pools.



Panel Engineers

Panel Engineers are a group of specialist civil engineers ("qualified civil engineers" within the meaning of the law) appointed by the Secretary of State who are experienced and qualified in reservoir safety. The Reservoirs Act 1975 requires them to oversee the safe construction, operation and maintenance of reservoirs and inspect their safety. A panel engineer must be appointed when a new reservoir is built or repairs and changes are made to existing ones. The times when a reservoir owner would require a Panel Engineer is explained further in Chapter 2.

- Construction Engineer
  A Construction Engineer is appointed to supervise the design and construction of a new reservoir or modification of a reservoir to make it larger.
- Inspecting Engineer
  An Inspecting Engineer is appointed to inspect a reservoir, identify and make recommendations in the interest of safety when appropriate. They visit the reservoir at least every 10 years. Their role is to assess the safety of the reservoir.
- Supervising Engineer
  A Supervising Engineer is appointed to supervise the operation and maintenance of the reservoir at all times. They visit the site at least once a year, and provide advice and guidance to reservoir owners. The Supervising Engineer is usually the first point of advice in reservoir safety matters for an owner.

Risk

The combination of the negative consequences (hazard) of an event and the chance (probability) of those consequences occurring. Although there are technical differences between 'hazard' and 'risk', for simplicity and in order to match the Environment Agency approach, we have used the term 'risk' throughout this document to mean both consequence, hazard and risk.

Topography

The nature of the land surface, i.e. flat, sloping, hilly, mountainous, etc.

2. Overview of reservoir safety law

The Reservoirs Act 1975, (as amended by the Flood and Water Management Act 2010), applies to large raised reservoirs, and the law places a legal responsibility on the reservoir owner for the safety of their reservoir.

2.1. UK Legislation on reservoirs

2.1.1. Reservoirs Act 1975 (RA1975)

The Reservoirs Act 1975 replaced the original Reservoirs (Safety Provisions) Act 1930 and its goal is to prevent uncontrolled releases of water (i.e. dam break floods) from reservoirs. The original Act of 1930 was introduced following several dam failures in the nineteenth century that caused significant damage and killed hundreds of people downstream.

A large raised reservoir as defined by the Reservoirs Act 1975 is where the volume held above the surrounding land is more than 25,000 cubic metres (m^3), see section 1.3. Under the Act reservoir owners and operators (known as 'Undertakers') are responsible for the safety of their reservoirs. The law is in place to encourage good practice and ensure reservoir owners act responsibly.

Reservoir owners are required to appoint a qualified Panel Engineer to supervise the design and construction of their reservoir (Construction Engineer), continually supervise the reservoir when built (Supervising Engineer), carry out an inspection every ten years (Inspecting Engineer) and supervise and certify any recommended measures to be taken in the interest of safety (Qualified Civil Engineer, QCE).

2.1.2. Flood and Water Management Act 2010 (FWMA2010)

The Flood and Water Management Act 2010 amends the RA1975 by introducing a number of changes consistent with a more risk-based approach. As a dam owner, the most important of these changes to you are likely to be:

- The reduction in the capacity threshold of a large raised reservoir from 25,000m^3 to 10,000m^3. (Note: at the time of writing the government have not yet confirmed if the capacity will be lowered to this or another level agreed by Ministers.)
- A reduction in the regulatory burden of owners of reservoirs that are not 'high risk'.

The classification of a reservoir as 'high risk' or not will be determined by the Environment Agency, based on their view of whether human life could be endangered. For the purposes of this guide the legislation, (which incorporates the amendments to the RA1975 by the FWMA2010) will be referred to simply as UK Law.

Figure 2.1 is a simple explanation of the responsibilities of a reservoir owner through the life cycle of their large raised reservoir, whether their reservoir is designated as high or low risk.

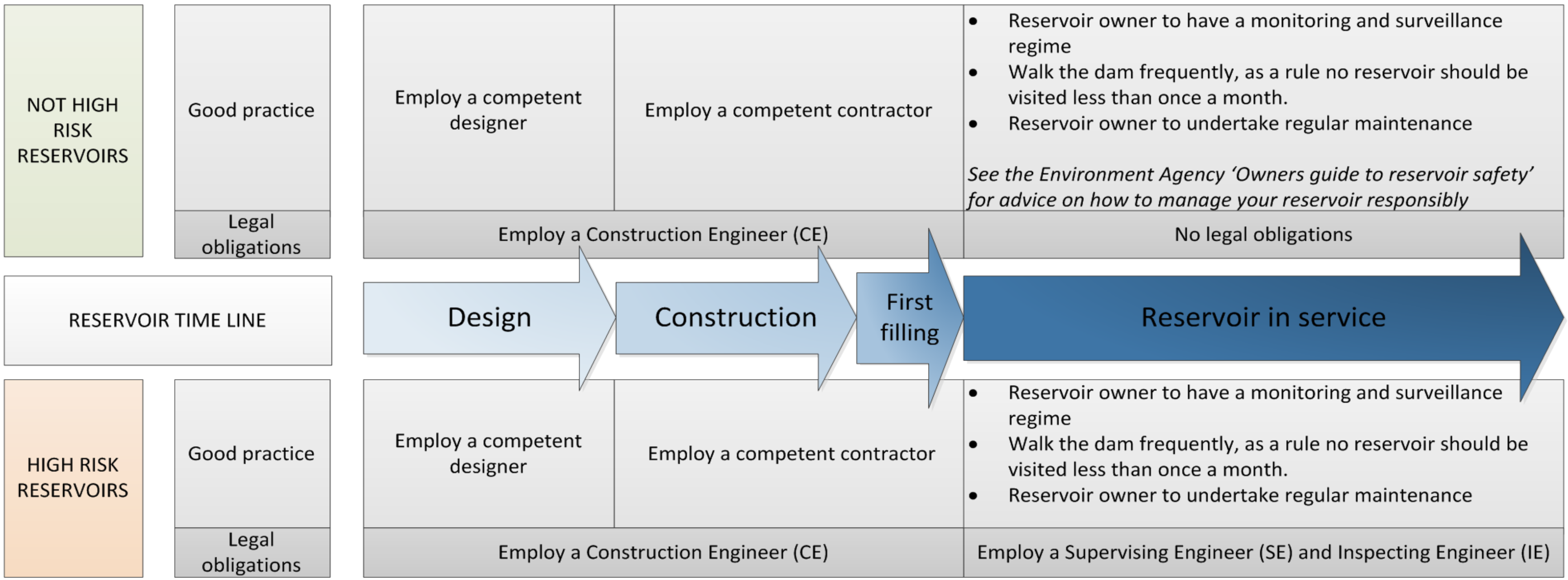


Figure 2.1: Legal responsibilities of the owner and best practice throughout the reservoir timeline

3. Things to consider when planning to build a new reservoir

This section describes how the design, construction and maintenance of the dam and reservoir it retains affect the risk posed to third parties.

3.1. Feasibility stage (location and size)

The largest influences on the risk posed by a reservoir are its location and size, and these require careful consideration. Useful summaries of the issues to consider when you are about to purchase or build a small reservoir are given in the following:

- The Environment Agency Guide "Thinking about an Irrigation reservoir" available on the Internet (and the associated Technical report). *Web search keywords: EA irrigation reservoir.*
- Similar leaflets available on the internet produced by the Isle of Wight area of outstanding natural beauty (AONB) and Suffolk Coast and Heaths AONB. *Web search keywords: Farm reservoir design.*
- Part 1 of the CIRIA Guide to small embankment reservoirs (Kennard et al, 1996). *Web search keywords: CIRIA small embankment.*

However, it is also important to think about the risk that the reservoir will pose to people downstream, and whether there are ways that this can be reduced by your choices of location and size of the reservoir. Factors in planning a reservoir that affect the risk are summarised in Table 3.1.

Table 3.1: Feasibility stage - Factors to consider

Factors to consider	Factors that would reduce the risk posed by a reservoir
Houses and other places with people present in the potential inundation area	Site reservoirs in rural areas away from houses. Do not build upstream of streams/rivers which have mills and houses on or very close to them. Site reservoirs in locations where a breach flood would not impact critical infrastructure such as busy roads or railways.
Should you place a dam across a river to form a reservoir ('impounding' reservoir) that is filled by river flow, or build it completely of raised banks away from the river ('non-impounding' reservoir) where it is filled by pumped inflow?	Non-Impounding reservoirs are normally lower risk as they do not have to cope with flood waters from the surrounding lands – only rainfall on the surface.
Slope of the land below/around the proposed dam site	Flatter ground means that the dam breach flood wave would spread out in all directions, and therefore water depth would reduce more quickly than when is funnelled down a valley.
Volume (or capacity) of water stored	Smaller volumes mean that the water has less potential for damage in the event of a dam breach.
Height of dam retaining the reservoir	Lower dams mean that the water has less potential for damage in the event of a dam breach.

If you are planning a new reservoir you should also consider the adjacent land, and its ownership. Is the land use likely to change in the future? Could future development then change the risk category of your reservoir giving you additional responsibilities?

3.2. Design stage (material and construction techniques)

As well as the location and size of a reservoir, another major factor that affects the risk is the quality of its design and construction. Table 3.2 lists some factors involved, and suggests how good design can reduce these risks. Guidance on engineering issues and further details are given in documents such as those listed in Section 3.1 in relation to planning reservoir location and size.

Table 3.2: Design stage - Factors to consider

Factors to consider	Factors that would reduce the risk posed by a reservoir
Type of material used to build dam	Less erodible soils take longer to erode, leading to a gentler flood wave in a dam breach situation. Generally dams built of cohesive soils such as clay would be the lowest risk, whilst dams built of sand (even with a geo-membrane liner) would be the highest risk.
Crest width and slopes	Wider dam crests and flatter slopes mean that more soil has to be eroded before the full depth of stored water can be released, thus making the dam breach flood wave gentler than a narrow crested or steep sided dam.
Vegetation or other protection on land side dam slope	Good quality grass will help protect the soil from being eroded during any overtopping, and will also help you watch the condition of the dam in the long term. Trees and other vegetation planted on the dam hinder inspection and can channel overtopping flows into much more damaging flow paths. In the long term, large trees also pose a risk to the dam in stormy weather, because if they fall the root ball can be so large that a blown over tree can cause the dam to breach. A tarmac road or other man-made surfacing on the crest or downstream slope can also reduce risk by increasing the resistance to erosion.
Dam profile	Water flowing down a continuous slope is less destructive than water falling down a stepped slope or one that changes angle suddenly. Therefore to reduce risk, try to avoid crest walls, and berms on the land side slope.

Those considering new reservoirs are advised to seek professional advice at all stages of the project, from initial consideration of location, size and feasibility, through design and construction and then during commissioning and operation.

For reservoirs which retain more than 25,000m^3 of water[1] it is a legal requirement to appoint a Construction Engineer, as described in Section 2.2. Even where the reservoir is smaller than this, it is still good practice to obtain professional advice.

[1] FWMA2010 provides for this figure to be reduced to 10,000 cubic metres if the relevant part of the legislation is implemented. There is also a provision for Ministers to amend the volume by Order.

4. Understanding the risk posed by reservoirs

This section demonstrates how to assess the potential impact of a reservoir failure, by considering the surrounding area (Figure 4.1). It explains the factors that can affect the risk category of a reservoir and gives you guidance if:

- You are considering building a new reservoir and wish to minimise the risk to others
- You are trying to understand the risk categorisation of an existing reservoir
- You live downstream of a reservoir and wish to understand the risk it poses to you.

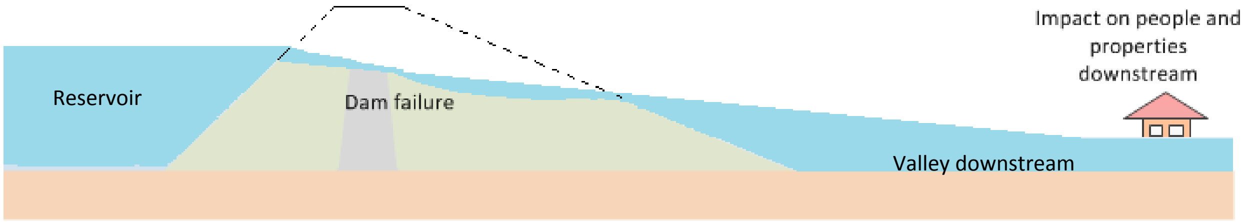


Figure 4.1: Impact on people downstream

4.1. Environment Agency categorisation of reservoirs

The Environment Agency enforces application of the Reservoirs Act for all large raised reservoirs in England. As part of the FWMA2010 changes to the law, the Environment Agency will be re-categorising reservoirs.

In their current methodology, all large raised reservoirs will be assessed to determine if they are 'high risk' and this will be dependent on whether the Environment Agency feels that human life could be endangered.

Those that are classified as 'high risk' will be subject to the standard regulation currently in force. Those that are assessed as 'not high risk' will need to be registered but will not be subject to full regulation.

This process is being undertaken by the Environment Agency based on its Reservoir Inundation Mapping (RIM) plans, and advised by a panel of engineering experts. The assessment process will consist of 3 tests, which are summarised in Table 4.1. All 3 tests will be undertaken, although not necessarily in the order listed in this guide. The reservoir is categorised as 'high risk' if it is found to be 'high risk' for any of the three tests. This is a simplified method and does not include consideration of additional tests.

Test 1 uses an approach defined by the Health and Safety Executive (HSE) as the risk to an individual person, and is based on research undertaken on the depth and velocity of flows that would cause structural damage to houses (Binnie 1991). Tests 2 looks at the extent of the flooding, and Test 3 looks at the combined risk to the society or community downstream.

Table 4.1: Environment Agency tests to determine if a reservoir is high risk

Test for determining high risk		Comments
Test 1 - Force of inundation (Figure 4.3)	If the velocity of the flow of water escaping from the reservoir, multiplied by the depth of water at an individual house is high enough to cause structural damage to the property, the reservoir is high risk. This is taken to be greater than $3m^2/s$.	This is not necessarily the first house downstream of the reservoir. The velocity of the flow of water can increase if the valley narrows or steepens further downstream.
Test 2 - Extent of Inundation (Figure 4.4)	If more than 200 people (~83 houses) or 20 businesses would be flooded by the escaped water from the reservoir, the reservoir is high risk.	Within the flood outline from the reservoir count the number of properties and businesses within the flooded area in order to estimate the number of people that could be affected. (See Note 1.)
Test 3 - Likely Loss of Life (Figure 4.5)	If the combined risk to life (the 'Likely Loss of Life' or LLOL) within the flood is greater than 1.0 fatality, the reservoir is high risk.	See the Test 3 flow chart example on how to calculate the risk to life. It is based on the average time the population are likely to be within the given location of the flood outline.
Additional Test(s)	There may be other unusual factors that can lead to a high risk designation such as the potential damage to critical infrastructure or the environment. The Environment Agency will consider all such factors on a case by case basis.	This could for example include destruction of a busy road or railway line with a moving population, or the destruction of a chemical plant leading to the release of a hazardous substance.

Notes:

1. *Examples of residential, business and recreational premises include, but are not limited to, houses, flats, hospitals, prisons, offices, warehouses, caravan parks, camping sites, sporting venues and places of worship*
2. *For Test 1, the Environment Agency express the units for this test as $m^3/s/m$. Dimensionally this is the same as m^2/s.*

Sources: Environment Agency, Health and Safety Executive.

4.2. The EA Reservoir Inundation Mapping (RIM) methodology

The Environment Agency is responsible for the enforcement of reservoir safety measures in England and, as part of this role, assesses and categorises the flood risk from reservoirs. For existing large raised reservoirs, flood maps are available online which show what might happen in the event of catastrophic dam failure. These maps may be found by searching online for *"Am I at risk of reservoir flooding?"*

The Environment Agency Reservoir Inundation Mapping (RIM) flood maps are generated by a computer model considering how the dam might fail, and then where the water would flow. Their original purpose was for emergency planning so they err on the side of caution. Site specific details such as local topography, the materials that the dam is made of and the shape of the reservoir are not considered in this initial assessment.

The analysis of failure is calculated using a simple equation (See Box 4-1 below) and the inundation area is predicted using computer models. Once the models have predicted which areas might be flooded, an assessment of the potential impacts (i.e. the number and extent of flooded properties, businesses etc.) can be undertaken and a risk category allocated for the reservoir.

When writing to existing reservoir owners to inform them of the provisional risk classification, The Environment Agency will send either:

- A notice ('the Provisional Designation Notice') stating that the reservoir has been assigned a high-risk provisional designation; **OR**
- A letter stating that the reservoir has not been assigned a high-risk designation.

Included with the notice/letter will be the decision form used by the Environment Agency in making the designation.

If, as a reservoir owner, you are satisfied that the Environment Agency's designation is appropriate for your reservoir you don't need to do anything further. If you have received a high-risk provisional designation then, if you have not made any representations to the Environment Agency within approximately 3 months of the Provisional Designation Notice, you will receive another notice ('the Final Designation Notice') through the post confirming the final designation of your reservoir.

Box 4.1: The Environment Agency RIM methodology for breach flow

Example of the Environment Agency RIM method for calculating the potential release of water from a reservoir

The reservoir flood risk maps are created from numerical modelling of potential flood flows. Prediction of the catastrophic release of water from the reservoir is made by assuming reservoir conditions and applying a simple formula for predicting how large the rate of release of water might get.

The Environment Agency assumes that at the point of failure, water levels in the reservoir will be above the dam crest level by 0.5m. The height of the dam plus 0.5m is then used in the following equation, along with the estimated volume of water stored when the water level is at crest level plus 0.5m:

$$Q_p = 0.607 V_w^{0.295} H_w^{1.24}$$

Where:

Q_p	Peak flow rate released from the reservoir
V_w	Volume of water stored above ground level at the time of failure
H_w	Height of the water level above ground level at the time of failure

This equation (Froehlich, 1995) is based upon analysis of historic dam failures. It provides an approximate estimation of potential flow rate, but does not take into account site specific dam and topographic features. It therefore provides an initial estimate for consideration and emergency planning, rather than an exact prediction.

4.3. Screening process to assign a reservoir risk category

The suggested screening process to allow the reader to identify whether a reservoir is high risk or not, is set out in Figure 4.2. This approaches the three tests in order of simplicity so that if the reservoir is classified as 'high risk' by the simplest test, there is no need to proceed to the more complicated ones. The Environment Agency, using computer modelling, may well approach the tests in a different order, but the end result is the same – classification as 'High risk' by any of the tests will lead to a 'High risk' designation.

The various methods referred to in this chart can be found in the following chapter of this guide.

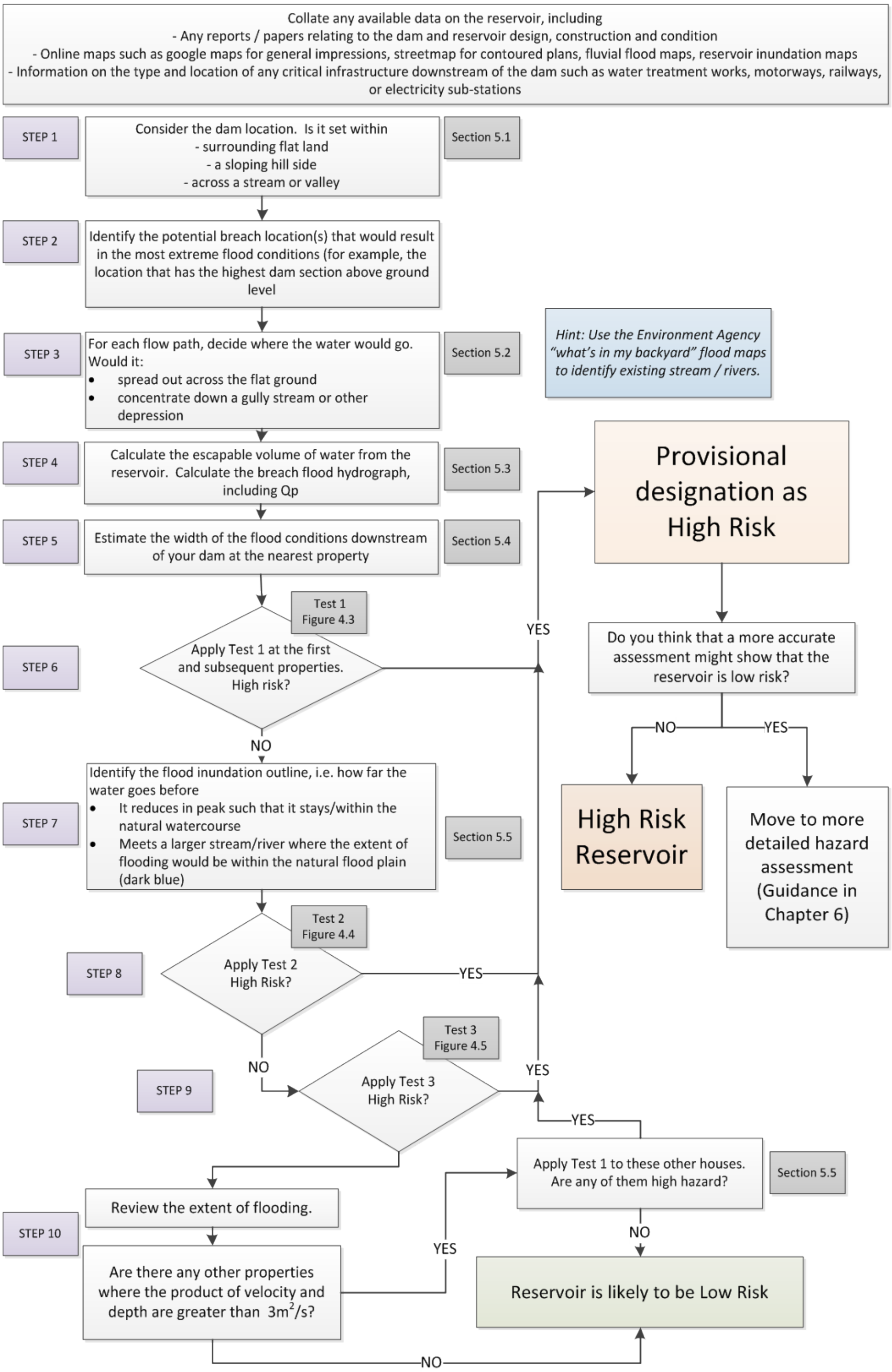


Figure 4.2: Suggested process to assign a reservoir risk category

The following 3 flow charts demonstrate how to undertake the 3 tests which will categorise your reservoirs as high risk or not high risk.

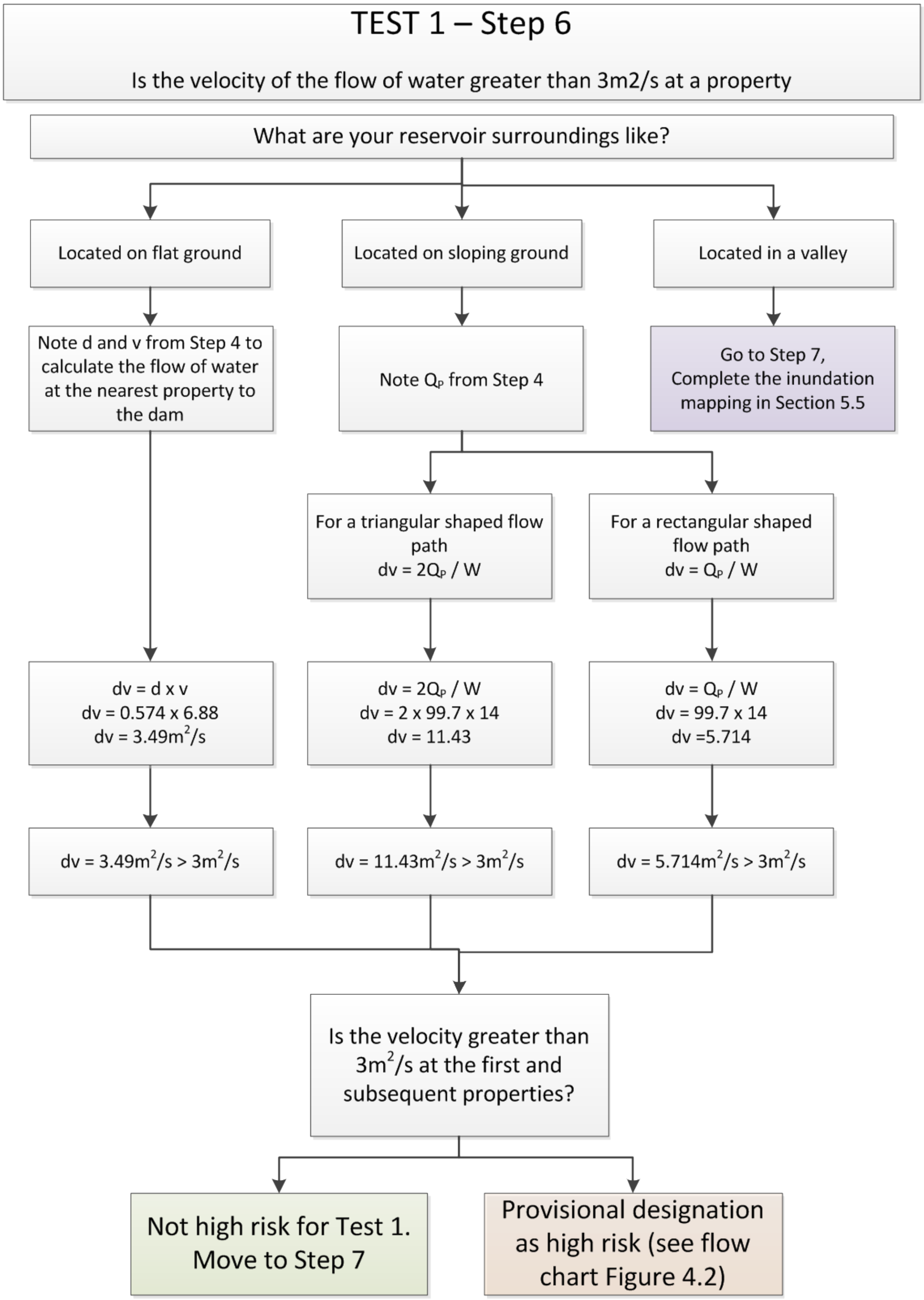


Figure 4.3: Test 1 – Force of inundation

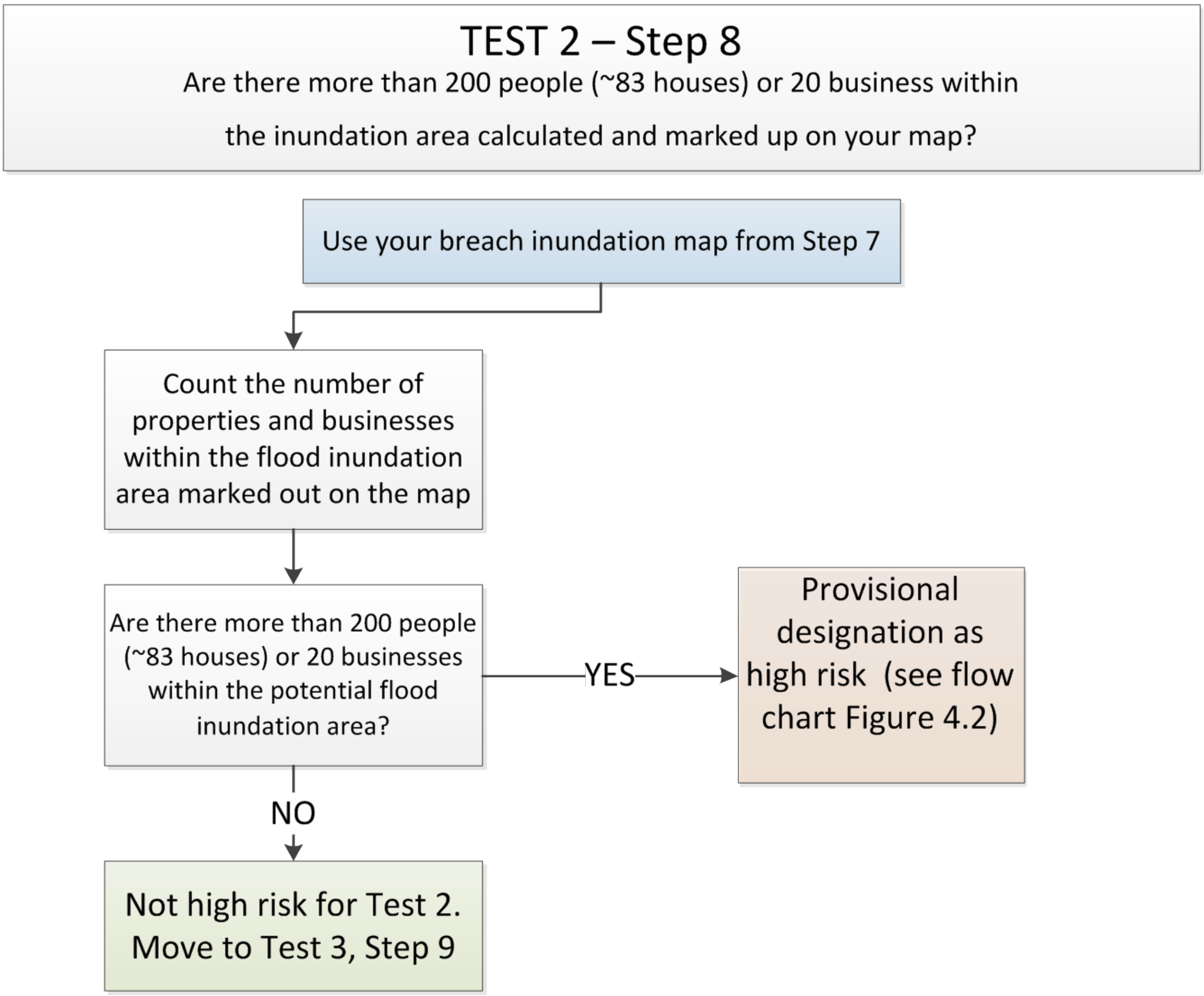


Figure 4.4: Test 2 – Extent of inundation

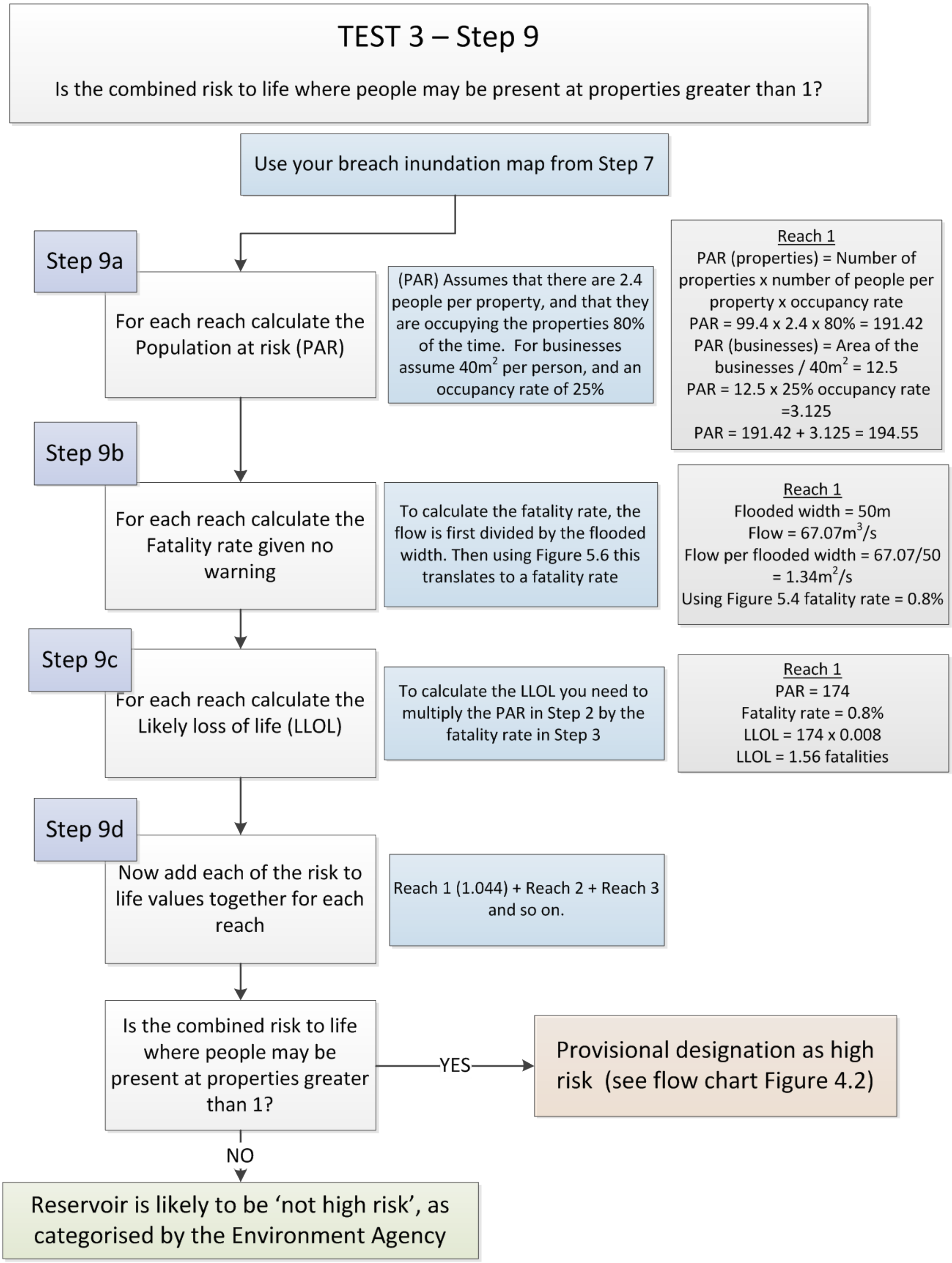


Figure 4.5: Test 3 – Likely Loss of Life

4.4. Data requirements

The process to assess the risk posed by a reservoir will require various types of data, as summarised in Table 4.2 and illustrated in Figure 4.6, Figure 4.7 and Figure 4.8 below.

Table 4.2: Data required for risk categorisation

Element	Data required for screening following principles of Environment Agency methodology (Chapter 5)	Additional data require for more detailed risk categorisation (Chapters 6, 7)
Reservoir	Stored volume Shape of reservoir (used to infer surface area)	Change in volume and area with elevation
Dam	Height Freeboard	Cross section Erodibility of material forming the dam, and its foundation
Valley downstream	Ordnance survey 25,000 scale map (5m contours, all buildings)	More detailed mapping with 1m contours or better
Impact on people	Number of properties and businesses	GIS database with plan areas of non-residential buildings

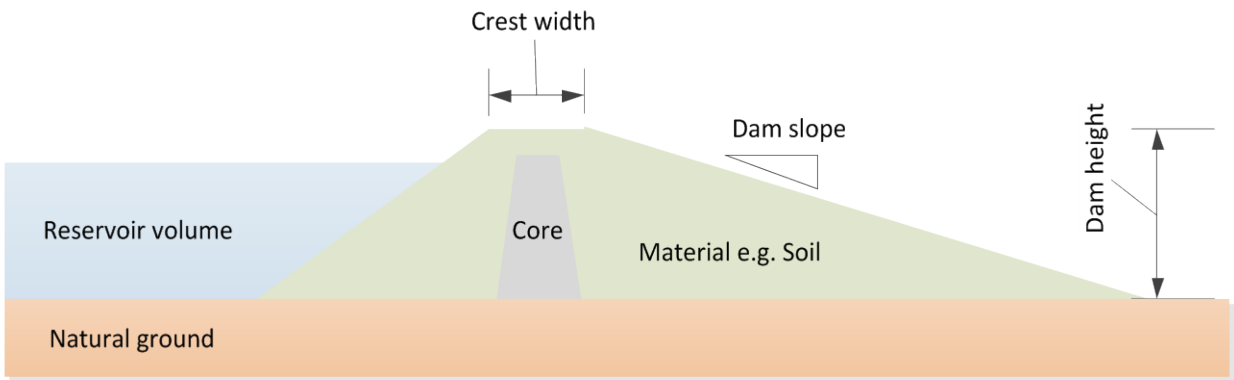


Figure 4.6: Cross section of a dam

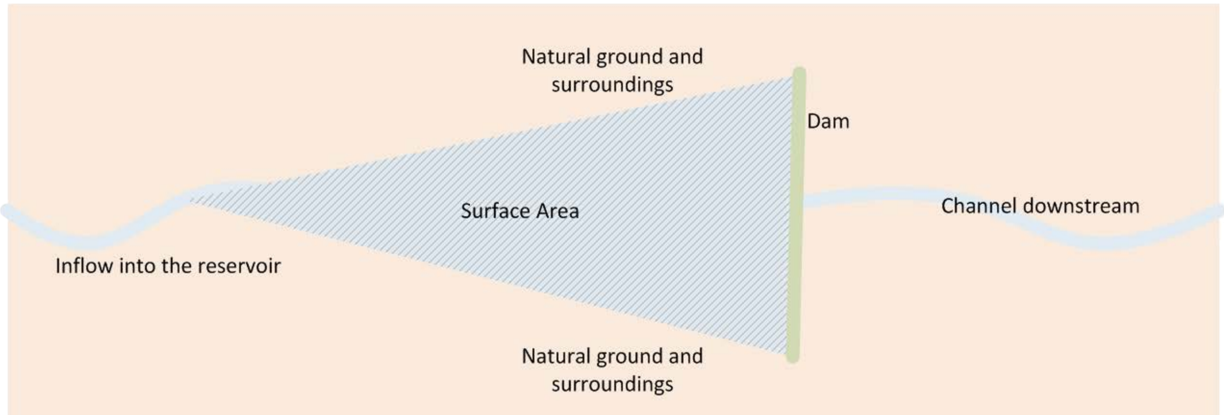


Figure 4.7: Plan of a typical impounding reservoir

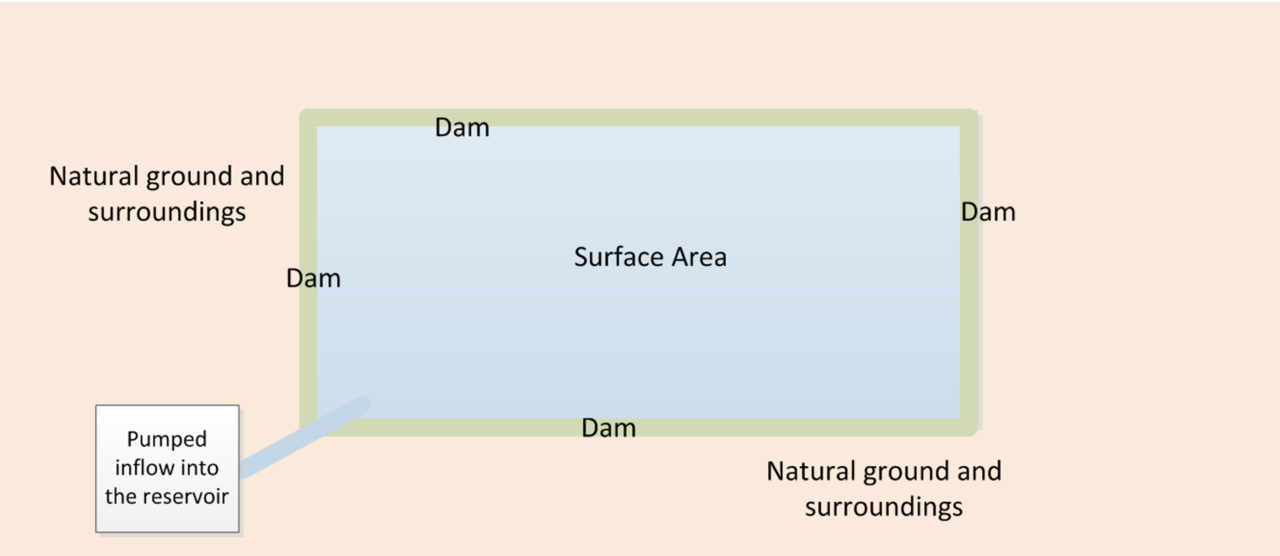


Figure 4.8: Plan of a typical non impounding reservoir

4.5. Guidance on assessing the consequences of dam failure

The sections below provide some general guidance on assumptions that will need to be made to undertake any of these assessments and the screening process outlined in Section 3.3 above.

4.5.1. What to consider when assessing the breach of a reservoir

If you are planning a new reservoir or assessing the risk of an existing reservoir, you need to consider where the water might go if the dam breaches. If a dam breach results in water flowing through areas containing properties, people or other infrastructure then the dam poses a risk to them.

The process which leads to a breach and the point along the dam that this process is likely to occur, needs to be predicted. Failure can occur at any point along the dam length.

If you have a small dam constructed across a natural valley or water course, the breach is unlikely to change the impacts of failure since regardless of this location, the breach flood water would follow the same route down the valley. However, where the reservoir is perhaps constructed on flatter ground, and a breach at different locations around the dam could result in water flowing in different directions, then it becomes important to consider the potential impacts that could occur along each of these flow routes. This is also the case for non-impounding reservoirs which could breach in numerous locations around the perimeter.

In summary, for any given reservoir the possible route(s) that water could take if the dam were to breach should be considered. For each route identified, the breaching process that could give rise to the most extreme flow conditions should then be considered. It is recognised that for most reservoirs there will only be one route identified.

4.5.2. Flood route and extent of flooding close to the dam

In the area close to the reservoir, the behaviour of the dam breach flow will depend on the slope of the surrounding ground and any significant obstructions to flow such as hedgerows.

In order to predict the extent of the flood inundation in the event of dam failure, the following points should be considered:

- Water flows downhill; consider the land surrounding your reservoir and identify the direction of the natural land slope;
- Look for any natural (streams/rivers) or man-made (drainage ditches) drainage systems and note the route that any surface water takes to drain from the land;
- Look at the overall topography and consider how water might be contained, trapped, channelled and directed by land features such as variations in ground level, outcrops etc.;
- Consider the effect that features such as hedges, roads, walls, fences, railways, houses etc. would have on the passage of flowing water. (For example, would the water be diverted around the end of a wall, or simply stored behind it until it reached the top of the wall and overflowed?);
- Dam breach can often result in fast flowing water, which can erode the soil and deposit large amounts of earth and debris. Think about whether the dam is easily erodible. What is it made of? Does the dam have protective layers built into it? What might happen to it in the event of a dam breach.

This process, allows quick identification of the likely dam breach flood route, and can be used to undertake the initial screening process mentioned in section 4.3.

To undertake a more detailed assessment of the potential flood inundation extents and impacts, a more complicated method is shown in Chapter 6.

In order to help you predict where the water might go, a series of charts showing how water spreads out from a breach is provided in Chapter 5.

> **Note:**
>
> River networks and indicative inundation areas can be found for England and Wales by looking at the Environment Agency "What's in my backyard?" online flood maps. *Web search keywords: Environment, Agency Backyard*

4.5.3. What area is the flood from my dam likely to cover?

In order to assess the potential impact of a dam break flood you need to decide how far from the dam you will consider. In practice, the distance depends upon the nature and size of the land upstream of the reservoir that drains rainwater into it, the volume of water in the reservoir and the nature of the land downstream of the dam. As the flood water moves along a river or valley the water tends to spread out, and the potential danger and force of the flood reduces. Hence, the further the flood water travels away from the dam the lower the danger of the flood becomes. Where the water passes through a narrow constrained area like a gorge this effect is minimal; where the flow can spread and there are natural obstructions, such as trees on a floodplain area, this effect can be large.

The assessment should continue for as long as the flood water poses a significant threat over and above normal, natural drainage or flood flow conditions. The limit for analysis will often be defined by a location where the stream joins a significantly larger river, or the coast.

5. Reservoir flood assessment – Simplified Method

The methodology described in this chapter explains how you can undertake a simplified dam breach flood assessment. The process can be undertaken using a combination of judgment and some simple calculations, and is shown in detail in Appendix A. The process takes into account some local details regarding the reservoir and dam construction; this may mean that results differ from the more general assessment that the Environment Agency would undertake as part of its reservoir risk categorisation process. As a screening method and following the precautionary principle, it generally errs on the side of caution.

5.1. Reservoir location (Step 1)

The area in which a reservoir is constructed affects how and where flood water may travel in the event of dam failure. It also affects the storage capacity of the reservoir and hence the rate at which water might be released. Referring back to section 3.1 and Table 3.1, consider whether your reservoir is constructed:

- on an open area of flat ground (hence the reservoir is bunded on all sides);
- on sloping land (hence the reservoir is constructed into, on or against a hillside);
- across a stream or valley.

5.2. Potential breach locations and flood routes (Step 2)

In order to undertake a risk categorisation it is necessary to consider how the dam might fail and where the water might flow. When a non-impounding reservoir is constructed on flat ground, failure might occur at any point around the reservoir. Water would spread widely across flat ground, entering the local river network.

Reservoirs constructed on hillsides and across streams or valleys offer a clearer view of how the dam might fail and where the water might flow (i.e. downhill). In all cases you need to identify, and asses, all credible failure locations and flow paths, particularly those which could impact on spaces occupied by people, such as houses, camp sites, offices and other work places.

For an initial assessment, ignore how water might be affected by things such as roads, buildings, fences etc. Simply consider how the landscape slopes and hence the general direction in which flood water would flow. Looking at 1:25,000 scale maps (see StreetMap online) will help in this process by showing land contours and details of the land drainage system.

Once the general direction of flood flow has been established, consider how local features might affect the flow route. Features that are likely to affect the route of flow, by blocking and diverting the flow, include:

- Elevated roads
- Railway embankments
- Buildings
- Walls
- Fences/hedges.

Taking these into consideration requires judgement as to whether or not the feature would pond or divert water and whether the structures would be destroyed in the process. A major embankment or cutting will divert the flow away from its natural path and therefore you should undertake a more detailed assessment as described in Chapter 6.

5.3. Estimating flood flow from a dam breach (Step 3 and 4)

Potential flood flow from a dam can be estimated by considering the dam height, stored volume of water and type of reservoir. The volume used here will be the volume of water at dam crest level and therefore the depth of water will be the same as the dam height, and the storage volume of the reservoir will need to be increased by the amount of freeboard between the spillway crest and dam crest levels.

The type of soil used for dam construction also affects the way in which failure might occur, (refer to Section 3.2 and Table 3.2) however for this simplified analysis it has been assumed that the soil has been weakened and is quite erodible. As a first step, you should estimate the peak breach flow (see section 5.3.1 and 5.3.2) and run Test 1. If you need to progress to Test 2 or 3 you will need to estimate more breach parameters (see section 5.3.3).

5.3.1. Defining escapable volume (Step 4)

The volume of water that could escape should be taken as being to the crest of the dam, as the reservoir may be higher than the normal storage volume for reasons including heavy rain or accidental over pumping. This volume will depend on the shape of the reservoir, as shown in Table 5.1.

Table 5.1: Derivation of escapable volume

Reservoir shape	A – flat ground	B – sloping ground	C – across a stream
Reservoir area when full to spillway A_S	$V_S/(H-F)$	$2\ V_S\ /\ (H-F)$	$3\ V_S\ /\ (H-F)$
Reservoir area at dam crest A_{DC}	A_S	$2 * V_S * H\ /\ (H-F)^2$	$3 * V_S * H^2\ /\ (H-F)^3$
Escapable volume V_{DC}	$H * A_S$	$H * A_{DC}\ /\ 2$	$H * A_{DC}\ /\ 3$

where:

H – Height to dam crest (m)

F – Freeboard (m) – typically 0.3m for non-impounding reservoirs on flat ground, and greater for impounding reservoirs

Vs – stored volume (to spillway or other overflow)

V_{DC} – stored volume if reservoir full to dam crest

Calculation of the escapable volumes shown above for the three types of reservoir assumes idealised geometric conditions, whereby a reservoir constructed on:

i. Flat ground – has the same water area throughout its height, resulting in a cube shaped reservoir volume;
ii. Sloping ground – has a uniform and continuous slope, resulting in a wedge shaped reservoir volume;
iii. Across a stream – has uniform and continuous slopes both across and along the reservoir, resulting in a pyramid shaped reservoir volume.

5.3.2. Estimating peak breach flow (Q_p) from a failed dam (Step 4)

Figure 5.1, Figure 5.2 and Figure 5.3 show plots of peak breach flow (discharge) from the dam, related to the reservoir locations. Figure 5.1 – flat land, Figure 5.2 – sloping land, Figure 5.3 – in a valley. Four lines are shown, relating to the dam height. To calculate potential peak breach flow from your reservoir:

Select the best graph associated with your type of reservoir location and then select the line on this graph that relates to your dam height.

Next consider your reservoir volume. Trace up to the line for your dam and across to a value of peak discharge for that dam height and reservoir volume. Please note that for relatively small reservoirs, the peak discharge of a low dam may be larger than the peak discharge of a high dam for the same reservoir volume. The reason for this is that the surface area of a reservoir with a high dam is smaller. The discharge out of a reservoir with a high dam therefore leads to a faster drop in water level in the reservoir which gives a lower peak discharge.

(NB: A dam height of 3m would give a result half way between results from the 2m and 4m high lines).

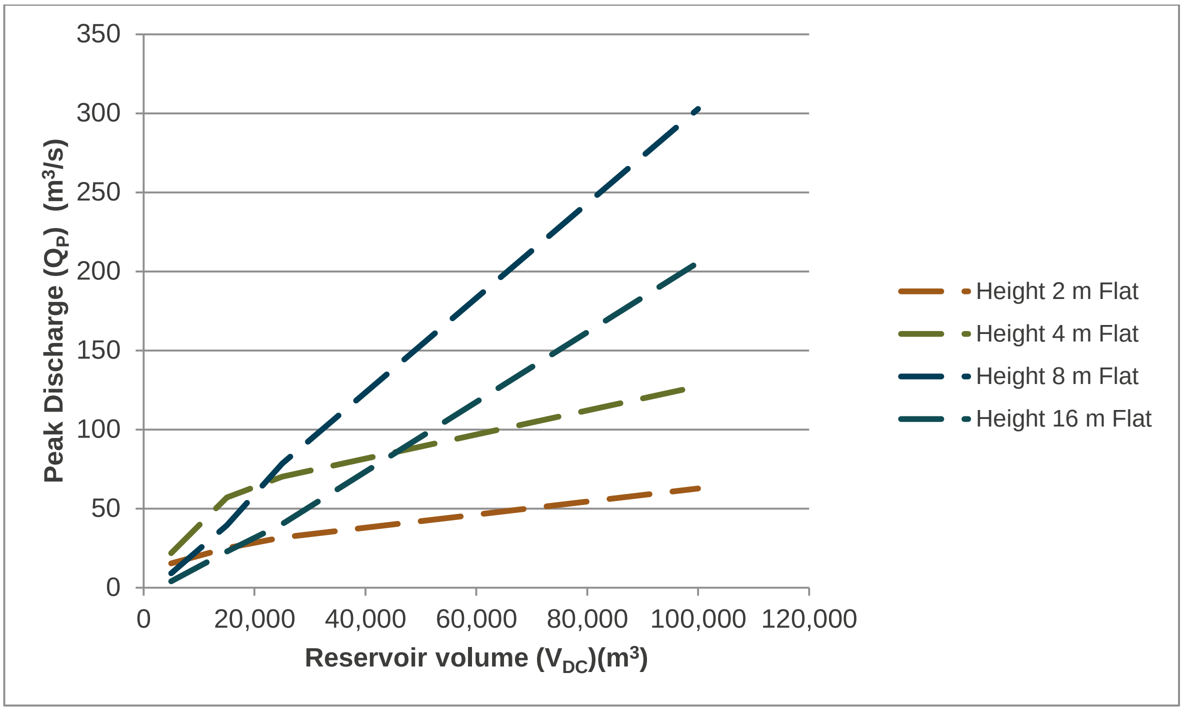


Figure 5.1: Predicting peak discharge flow from a breached dam - Flat

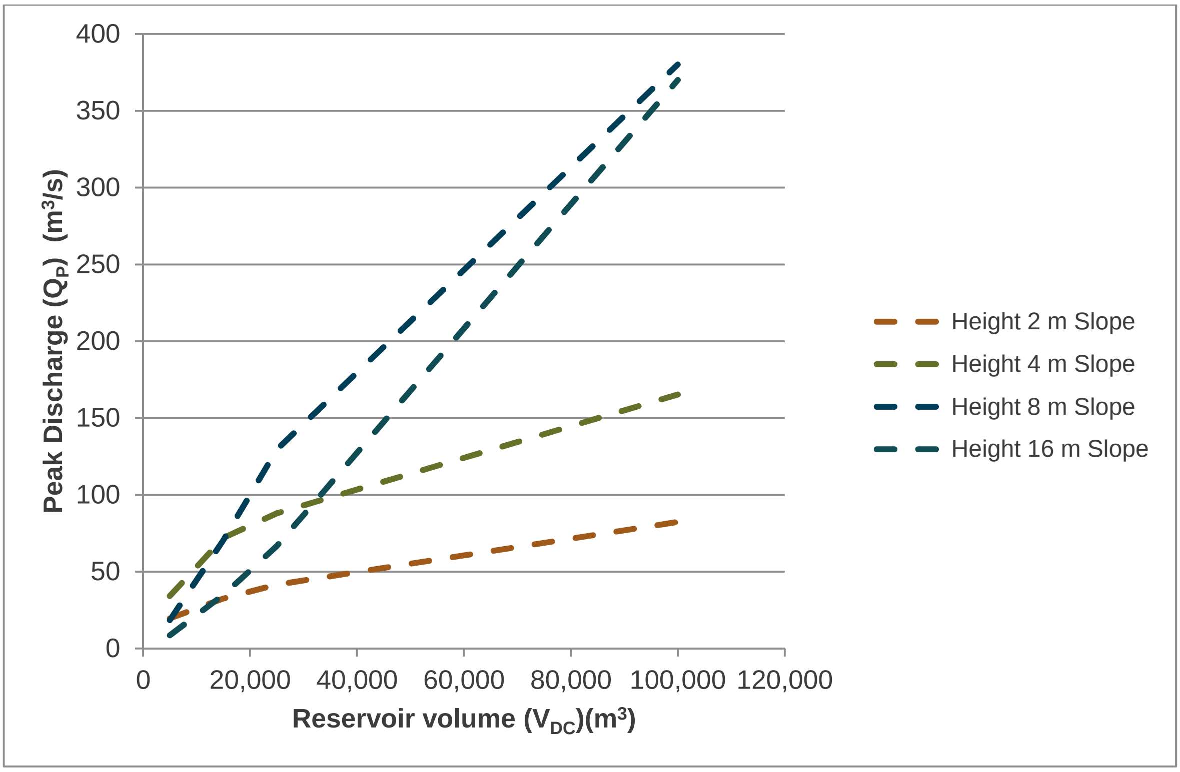


Figure 5.2: Predicting peak discharge flow from a breached dam - Slope

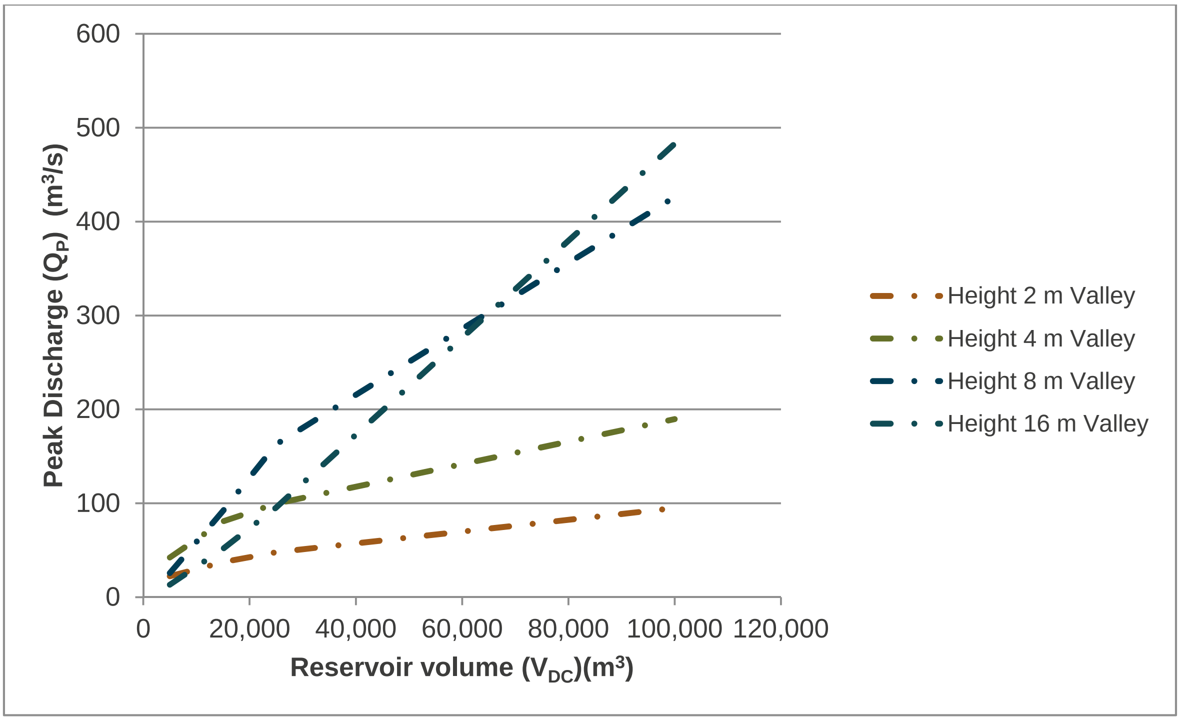


Figure 5.3: Predicting peak discharge flow from a breached dam - Valley

5.3.3. Estimating how fast the water will escape from a breached dam (Step 7g)

This step only needs to be taken if considering far field effects of the breach or for a valley location. For near field on sloping and flat land this section can be skipped.

The timing of the breach flow leaving the reservoir is dependent on a number of factors and can be described graphically using a chart called a ‘hydrograph’. This additional information is needed later in the assessment for considering flood risks further away from the dam. Figure 5.4 shows how the timing of the breach flow leaving a reservoir can be shown approximately on a graph. This is known as the ‘hydrograph’ and the parameters used to describe this are also shown in Figure 5.4.

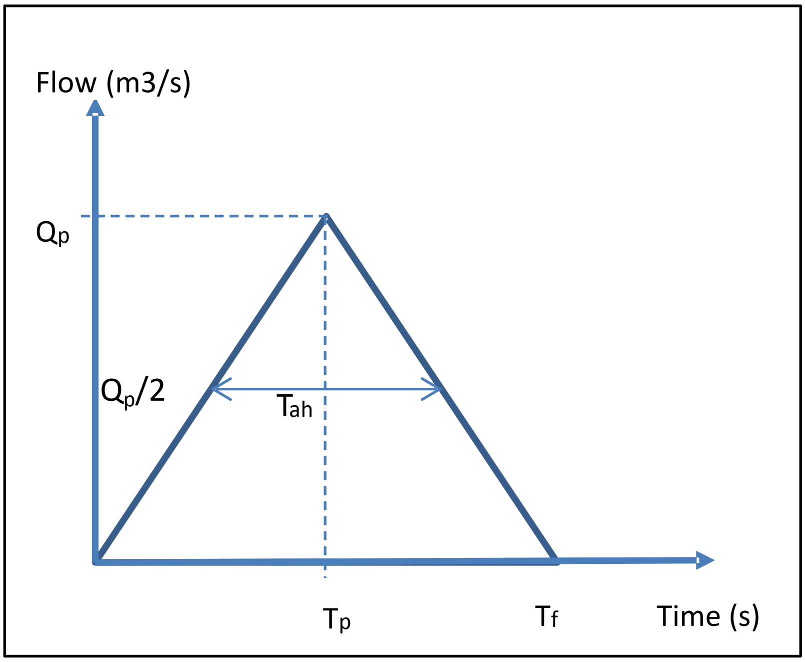


Figure 5.4: The parameters of a dam breach flow hydrograph

The properties of a hydrograph will help you assess the flood passage downstream. Table 5.2 provides the data required to calculate the estimated flood flow. Should you wish to draw your hydrograph, Appendix C provides you with all the data required.

The table in Appendix C provides data associated with different dam heights and stored volumes. For a given dam height and stored volume, data can be read off for:

- Q_p Peak discharge
- T_p Time of peak discharge
- T_f Time of failure (from initiation to complete draw down)
- T_{ah} Half the peak discharge
- B_w Breach width.

To use Appendix C to predict your flood hydrograph undertake the following steps:

- Choose the line closest to the height of your dam, and the column closest to the volume of your reservoir.
- Within that column, choose the sub-column most closely relating to the shape of the reservoir – this will be dependent on the type of land your dam is located on. (a) flat ground; (b) sloping ground, or (c) across a stream or valley.
- Read off the hydrograph parameters Q_p, T_p, T_{ah}, T_f and B_w for your reservoir.
- If your dam height and reservoir volume falls between different rows and columns in the table, look at the results for the two rows/columns either side of your value and estimate (or calculate through interpolation) properties appropriate to your reservoir.

Table 5.2: Breach flow hydrograph parameters (high erodibility dam, piping failure mode)

	Escapable Volume V_{DC} →	5,000m^3			15,000m^3			25,000m^3			100,000m^3		
Dam Height H ↓	**Reservoir Type →**	**a flat**	**b sloping**	**c stream**	**a flat**	**b sloping**	**c stream**	**a flat**	**b sloping**	**c stream**	**a flat**	**b sloping**	**c stream**
2m	Q_p (m^3/s)	15.5	19.6	22.3	25.0	32.5	37.3	31.9	41.6	47.8	62.8	82.4	94.9
	T_{ah} (s)	251	243	225	487	465	431	649	611	556	1,326	1,222	1,111
4m	Q_p (m^3/s)	21.8	34.2	42.2	57.2	72.0	80.7	70.2	88.0	99.7	127.2	165.4	189.7
	T_{ah} (s)	190	134	110	197	193	179	273	268	248	639	611	565
8m	Q_p (m^3/s)	9.1	18.4	25.8	39.4	70.5	91.8	78.5	129.4	162.7	302.9	380.2	426.1
	T_{ah} (s)	605	224	171	371	203	155	275	182	146	247	243	226
16m	Q_p (m^3/s)	4.1	8.6	13.2	22.9	34.9	51.4	40.3	66.7	95.4	205.5	370.1	483.0
	T_{ah} (s)	887	454	327	603	378	230	594	289	223	477	258	196

Source: Small Reservoirs Simplified Risk Assessment Methodology – Research Report

5.4. Estimating local flood impact conditions (Step 5)

Based on identifying the potential flow routes for water escaping from the dam breach (see Section 5.2), consider whether there are any properties that might be affected by flooding near the dam. If there are, then apply the rules of Test 1 (Figure 4.3) see to whether these justify a high risk reservoir categorisation.

The definitions of flood depth and how this relates to the discharge per flooded width are described in Box 5-1.

Box 5.1: Defintions of flood depth

> In a detailed analysis it would be the depth and velocity of water at the individual house (or other occupied space) that would be used in assessing risk. However, for this simplified screening method detailed ground levels and thus variation of flood level across the flow path are not available, so instead the maximum depth and average velocity across the flow path are used for Test 1.
>
> There is a further simplification in that Test 3 uses the average flow across the flooded width (Q/W) to assess the likely fatality rate. It should be noted that this is equal to 0.67dv (and dv = 1.5Q/W), in recognition that Q/W uses an average depth of flooding, whilst dv uses the maximum depth of flooding.

In order to undertake Test 1 (Step 6) you need to calculate flow conditions at the nearest property. The method for analysis depends upon whether your reservoir is constructed on flat ground, on sloping ground, or across a valley.

In both cases the first steps are:

1. After having calculated (Q_p) in Section 5.3.2 from Figure 5.1, Figure 5.2, or Figure 5.3, note the distance of the nearest house from the dam, r in metres.
2. Estimate the friction coefficient (n) for the area between the dam and the first house immediately downstream. Typical values of n are given in Table 5.3 below.

Table 5.3: Typical values of friction coefficient n

Type of surface of surrounding land	Friction coefficient, n
Bare soil (agricultural land)	0.020 – 0.040
Short grass (tended playing fields)	0.025 – 0.035
Long grass (wild meadows)	0.030 – 0.050
Woodland (forest)	0.080 – 0.120
Concrete and tarmac (urban areas)	0.012 – 0.017

Source: Chow 1959

Then, depending on whether your dam is located on flat ground or not, you will need to follow the next steps in either section 5.4.1 or 5.4.2.

5.4.1. Estimating local flood impact conditions across flat ground (Step 5 and 6)

- Use this simple method to estimate the flood impact where the reservoir is located on flat ground.
- Estimate the angle of spreading (Ω) in radians. The normal angle is 0.79 radians (45 degrees), as the momentum of flow through the breach means that water near the dam will tend to flow away from the

dam before it spreads out uniformly. (Note: 45 degrees = 0.79 radians, 90 degrees = 1.57 radians, 180 degrees = 3.14 radians).

- Finally, calculate depth (d) and velocity (v) using the following equations. The depth and velocity decrease away from the breach, and the velocity decreases quicker than the depth:

$$d = \left(\frac{13}{3}\frac{n^2 Qp^2}{\Omega^2}\right)^{3/13} r^{-3/13}$$

$$v = \sqrt{\frac{3}{13} d^{7/6} n^{-1} r^{-1/2}}$$

3. **STEP 6**

- If your estimate of d multiplied by v (dv) is more than 3m^2/s, then your reservoir is probably ‘high risk’. If it is less than 3m^2/s then the local flood risk is low, and you should now consider effects further away from the dam.

5.4.2. Estimating local flood impact conditions in other situations

In the situation where your dam has been constructed on sloping ground, or the breach flow path is constrained by topography or man-made obstructions such as hedges, walls and houses, undertake the following steps. Where the dam is across a stream of valley you should go straight to Section 5.5:

- Review how the flood flow might behave near to the dam. Consider how local topography and features might affect the flood flow (Section 5.2).
- To estimate the extent of flooding locally, consider whether there are natural bounds to the flood water. For example, open areas of ground will allow flood flow to pass easily, whilst heavily vegetated, wooded ground would slow the flow down. Water will always flow downhill, hence topography such as slopes, dips and valleys will always dominate.
- On sloping ground with no obstructions that would constrain the flow path, you could use the spreading equation in section 5.4.1, but with a narrower angle of spread to account for the slope. Alternatively you could assume the flooded width at the dam is a multiple of the dam height (say twice) and the flow spreads out by say 1m for every 5m that it travels downstream.

4. **STEP 6**

- Where there is a clearly defined path along which the water would flow, the width of flow can be calculated as follows:
  a. Where the flow path is a valley, you should go straight to section 5.5
  b. Assuming a <u>triangular</u> shaped flow path, with top width of water W and mid height depth of water d, the flow depth times velocity (dv) (which is a measure of the damage that the flow might do) can be calculated as dv = 2Q_p / W
  c. Where the flow path is more of a rectangular cross section, the flood damage potential can be calculated as dv = Q_p / W This assumes a broadly <u>rectangular</u> shaped flood flow section, with flood water width W and depth of water d.

5. If your estimate of dv is more than 3m^2/s, then your reservoir is probably ‘high risk’. If it is less than 3m^2/s then the local flood risk is low, and you should now consider effects further away from the dam.

5.5. Estimating flood impacts further away (Step 7)

5.5.1. General

It is quite difficult to simplify the complex 3-dimensional processes involved in a flood inundation. There are too many variables for graphical methods or manageable look-up tables, so instead it is necessary to carry out a series of calculations.

The method suggested here for valleys is therefore a simplified 1D calculation method showing the reduction of a dam breach wave down a valley or other defined flow path. It is based on the 'Tier 2' methodology in the Risk Assessment for Reservoir Safety guide (EA 2013). However, It includes modifications to adjust the theoretical approach originally developed in Report C542 (CIRIA 2000) in order to be more consistent with output from complex methods, as described below.

Where there is no defined flow path, such as coastal flood plains the user should refer to Guidance Note 4 (Flood mapping) in Environment Agency Report FD2321/TR2, which includes a summary of the methods available for flood mapping in these situations.

5.5.2. Valley routing

The method simplifies the valley to a trapezoidal section, and uses the equations shown in Table 5.4. It is an iterative method where the inundation area is estimated and then flow and inundation width are calculated for each distinct section (reach) of the floodplain. It should be noted that the rate of decay (reduction) in peak flow down the valley is calculated using Equation 5.5.2, but then checked against Figure 5.5. Where L_a is greater than the value in Figure 5.5, it is reduced to that figure.

The full steps necessary in a typical analysis are laid out in Appendix A to demonstrate the calculations behind the method.

Table 5.4: Equations used in valley inundation estimation method

Equation No.	Equation	
Step 7h	Manning n is used to estimate of the peak discharge for the given location: $Q_p = (A^{5/3} S_o^{1/2})/(nP^{2/3})$, which for d<< W_T can be simplified to $d=(Q\ n\ /W\ So^{\ 0.5})^{\ 0.6}$	
Step 7j	Attenuation is calculated by: $Q_p(x) = Q_p(0)\ \exp[-x/L_a]$ Where	
Step 7k	$L_a = k\ W^{-0.2}\ S_o^{1.9}\ n^{-1.8}\ Q_p(0)^{0.2}\ T_{ah}^{\ 2}$	
Where: A Flow cross-sectional area (m^2) d Maximum Depth of flooding above flood plain k Factor with range 1 to 10. Suggest value 1.0. L_a Length over which Q falls to 37% of its value at the start of the reach n Manning's roughness coefficient (0.10, or) P wetted perimeter of flooded section (m)		And the other subscripts on Q and L are as follows R – where flow has reduced such that it is contained in the stream channel/no longer spills onto flood plain

Equation No.	Equation
Q_p	peak discharge at the calculation point (m^3/s)
$Q_p(0)$	Discharge at upstream end of calculation
$Q_p(x)$	Discharge at location x downstream from 0
S_o	slope along the flood plain
S_s	Side slopes of trapezoidal section representing valley immediately above flood plain (Note 3)
T_{ah}	Time period at half discharge (or $T_f/2$)
v	Velocity of flood water (1D analysis, so constant across section)
W	Width of flood plain, for purposes of this simplified dam break analysis – see Note 3 (base width of flooding)
x	Distance between zone intersections (i.e. from $Q_p(0)$ to $Q_p(x)$)

Notes: 1. Refer to Appendix B for fuller definitions of terms and units

2.See Environment Agency project FD2321

3. Valley simplified to trapezoidal section, with base at flood plain level (ignore the stream channel which is normally assumed full or blocked in a dambreak situation)

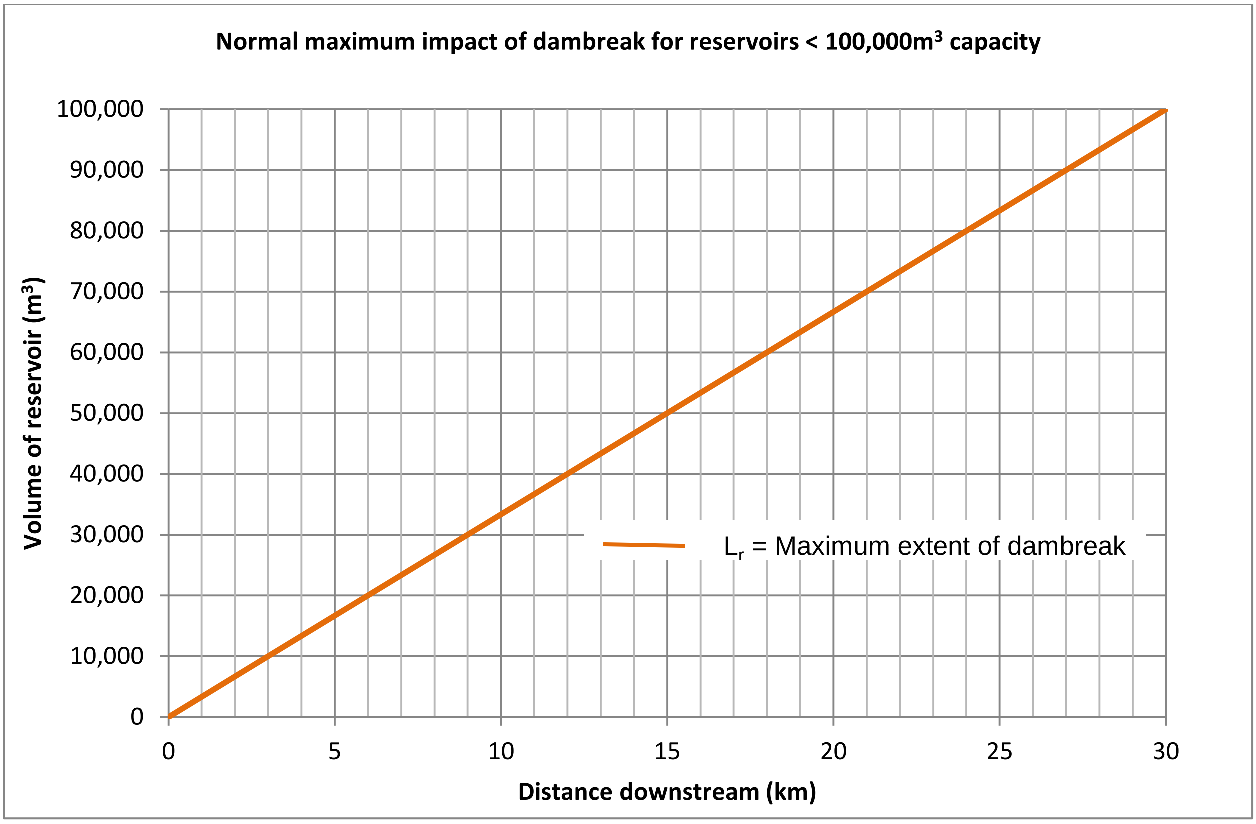


Figure 5.5: The normal maximum impact of a dam breach flood along a valley (Step 7i)

Source: The line is the upper bound to a sample of 52 dambreak assessments on reservoirs with volume of less than 100,000m3 carried out using the EA RIM method. (Sample data kindly provided by Mott MacDonald)

5.6. Consequence assessment (Steps 6, 8 and 9)

The consequence assessment includes applying the three tests in Table 4.1.

STEP 6 Test 1 is about individual risk, and requires dv at the individual "occupied space".

STEP 8 The number and type of properties within the inundation area allow the user to estimate the population at risk (PAR) and then consider Test 2.

STEP 9 Then, using the graph shown in Figure 5.6, the flow per flooded width can be translated to a fatality rate for each reach. Multiplying the PAR by the fatality rate and summing the results for all reaches gives a likely loss of life (LLOL) to allow consideration of Test 3. Where the number is less than 1.0 it can be interpreted as the % chance that the dam breach floodwater would kill one person. For example LLOL=0.9 means there is a 90% chance that 1 person would be killed.

Figure 5.6 is taken from the Interim Guide (ICE, 2004) with the suggested line being for no warning and being a best fit to observed fatalities in flash floods and dam failures provided in the US Bureau of Reclamation Report no DSO -99-06.

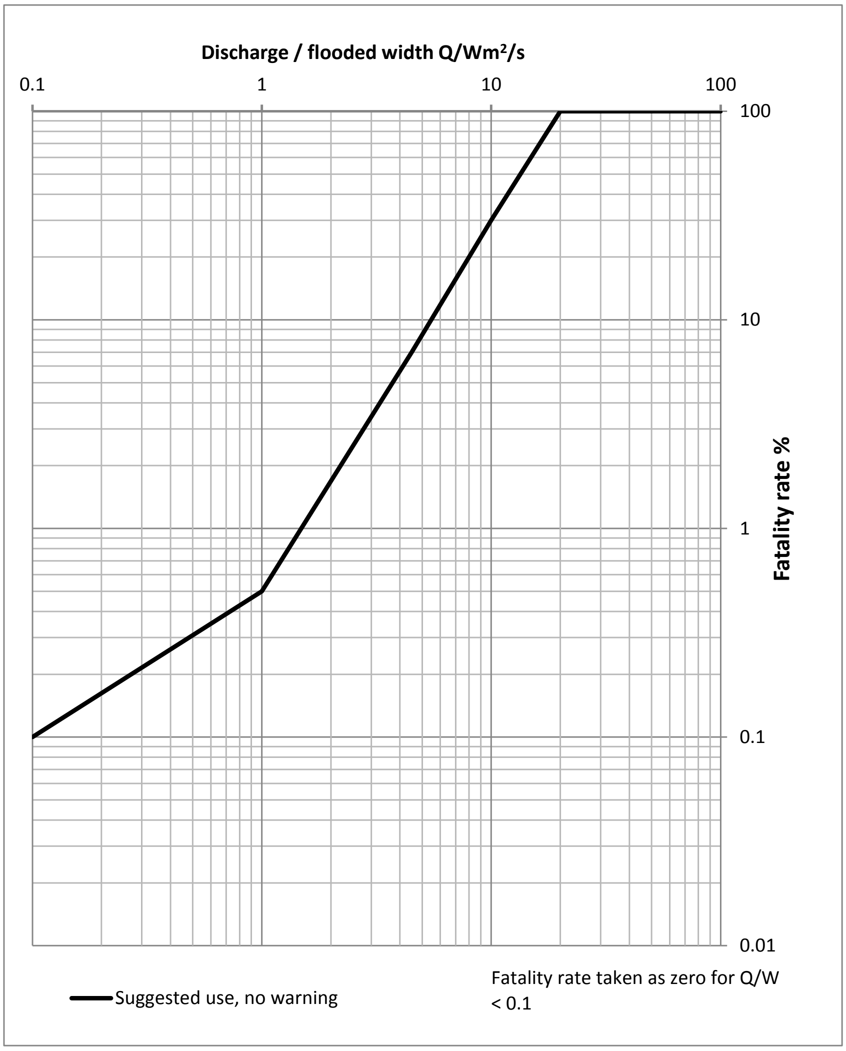


Figure 5.6: Fatality rates for Q/W (no warning)

Source: Interim Guide to QRA, (Brown & Gosden 2004)6

6. Reservoir flood assessment – Detailed Methods

6.1. Introduction

The simplified methods described in Chapter 5, try to make a complex 3D engineering process understandable to most non-technical people. This means that some parts of the process are only rough estimations of what can happen. There are also an infinite number of site-specific factors that can influence the development and passage of a dam breach flood, and it is therefore impossible to present a simple method that will suit every case.

To undertake a detailed reservoir risk categorisation, specifically tailored to your site conditions, it is recommended that you consult a professional. They are likely to use a range of numerical models to predict the breach flow and subsequent flooding impacts. These tools are described in the following sections. (Further information can be found in the Risk Assessment for Reservoir Safety guide (EA 2013), in the section on Tier 3 assessments.)

6.2. The dam breach

The prediction of dam break conditions is an important component of a reservoir risk categorisation, since the predicted rate of release of water from the reservoir can directly affect the severity of the flood and therefore the risk it poses. Methods for breach prediction vary according to the type of dam structure and even the quality of construction. Recommended approaches for different dam types are summarised in Table 6.1.

Table 6.1: Methods for predicting breach for different dam types

Dam Type	Methods
Earthen (and some Rockfill)	Use of a simple rapid breach prediction model (e.g. AREBA (Van Damme et al., 2011)) for entry level or homogeneous dam analysis OR use of numerical breach growth prediction model (e.g. HR BREACH/EMBREA, WINDAM) for more accuracy.
Concrete or Masonry	Use of the CIRIA Report C542 guidance on potential breach size and rate combined with numerical modelling of discharge OR Structural analysis, combined with hydraulic flow model.
Service Reservoir	Visual assessment and judgement[2] for breach size and rate combined with numerical modelling of discharge OR Structural analysis, combined with hydraulic flow model.
Rules for assessing cascade failure	Use of a simple rapid breach prediction model (AREBA (Van Damme et al., 2011) for entry level analysis OR use of numerical breach growth prediction model (e.g. HR BREACH/EMBREA, WINDAM). Each of these models predicts the breach initiation and growth process, hence when linked with dynamic flow models automatically predict conditions that would occur during cascade failure.

Source: RARS Guide (EA 2013), adapted from Table 19.3.1

[2] Assessing the way in which a service reservoir may breach requires an assessment of how the structure could fail. Since each design may be different, judgement is required to determine potential mechanisms and in particular the speed with which such as failure could occur.

6.3. The breach flood

Since dams can fail in a multitude of ways, and the hydraulic conditions that arise from a dambreak are very extreme, there can be relatively large uncertainties within the predictions, compared to the prediction of natural flood conditions.

Predicting flood conditions downstream should be undertaken using rigorous 2D flow models (such as InfoWorks-RS, Tuflow FV or ISIS-2D) suitable for simulating extreme and rapidly varying flow conditions. These models should not be simplified river flooding flow models, which are not designed to cope with the extreme and rapidly varying conditions found during dambreak. Consideration should be given to possible knock-on effects (i.e. secondary dams, blockages and failures) and sensitivity to modelling parameters.

6.4. The consequence assessment

The impact of the flood on the people and properties downstream should be considered in detail and will be based on the results of the breach flood modelling. Assessment of how the depth and velocity of the flow is likely to affect people in different areas can be undertaken using the method described in CIRIA Report C542, the Interim Guide to QRA (Brown & Gosden 2004) and the Risk Assessment for Reservoir Safety guide (EA, 2013).

7. Where to find more information

If you would like to learn more about reservoir safety for the design, construction, operation, or maintenance or reservoirs, you may find the following references useful.

7.1. Legislation

HM Treasury, (1930), *Reservoir safety provisions act 1930* Her Majesty's Stationery Office (HMSO)

HM Treasury, (1975), *Reservoirs Act 1975* Her Majesty's Stationery Office (HMSO)

HM Treasury, (2010), *Flood and Water Management Act 2010* Her Majesty's Stationery Office (HMSO)

7.2. Publications/References

Binnie & Partners (1991). *Estimation of Flood Damage Following Potential Dam Failure: Guidelines*, Department of the Environment, HMSO, Marlow.

Brown, A.J and Gosden, J.D. (2004) *Interim guide to Quantitative Risk Assessment for UK reservoirs*. ICE, Thomas Telford Ltd., London. ISBN:0727732676.

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Environment Agency, *Thinking about an irrigation reservoir? A guide to planning, designing, constructing and commissioning a water storage reservoir*. Cranfield University.

Froehlich, D.C. (1995) Peak outflow from breached embankment dam. *ASCE Journal of Water Resources Planning and Management* 121(1), 90-97.

HR Wallingford, (2013) *Small Reservoirs Simplified Risk Assessment Methodology – Research Report.*

ICE 1998. *Flood and Reservoir Safety*, 3rd edition. Institution of Civil Engineers Thomas Telford, London.

ICE 2000, *A guide to the Reservoirs Act 1975*, Institution of Civil Engineers, Thomas Telford, London.

7.3. Websites

The British Dam Society www.britishdams.org

The Environment Agency www.environment-agency.gov.uk/reservoirsafety

Natural England www.naturalengland.org.uk

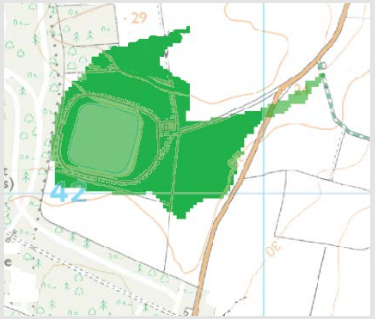
The Countryside Council for Wales www.ccw.gov.uk

Appendices

A. Simplified method for reservoir risk categorisation

The method described in Chapter 5 in general terms is demonstrated below on a step-by-step basis, using example data. For completeness all steps and tests are shown, whereas in practice the user would choose only the steps applicable to their particular site and would also stop the analysis any time they achieved a ‘high risk’ designation from any of the tests described in Tables 4.3 – 4.5.

Table A.1: Simplified method for reservoir risk categorisation

Step	Action	Output	Commentary	Worked example		
Fig 4.2	**Consider near field effects for all surrounding land types (Flat land, sloping land or valley)**			**Flat Land**	**Sloping land**	**Valley**
Step 1	Consider the dam location			Dam is located in a remote area in flat farmland	Dam is located in a remote area in a sloping valley	Dam is located in a remote area in a valley
Step 2	Identify the potential breach location(s) that would result in the most extreme flood			Breach location identified at the point where housing is nearest	Breach location identified at the point where housing is nearest	Breach locations – highest point (worst for downstream valley) and outlet works on left abutment near house on side of valley
Step 3	For each flow path, decide where the water would go					

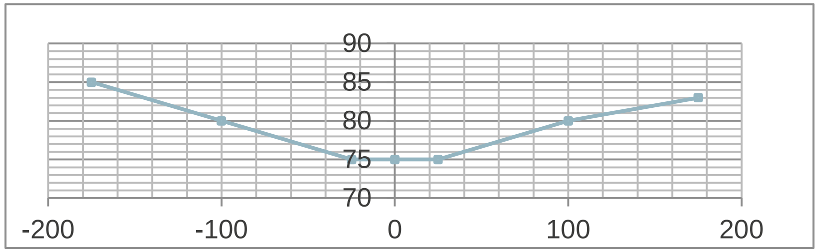
Step	Action	Output	Commentary	Worked example		
Step 4	Calculate the escapable volume using the equations in Table 5.1 and using Table 5.2 determine the peak flow for the reservoir	Q_P	Increase the reservoir capacity (V) to total escapable volume at dam crest level (V_T) For each example: H = 4m V_S = 22,000 F = 0.3m	$A_S = V_S$ / (H-F) A_S = 22,000 / (4 – 0.3) A_S = 5945m^2 A_{DC} = AS A_{DC} = 5945m^2 V_{DC} = H x A_S V_{DC} = 4 x 5945 V_{DC} = 23,780m^3 Using Figure 5.1 Q_P = 60 m^3/s	A_S = 2 x V_S / (H-F) A_S = 2 x 22,000 / (4 – 0.3) A_S = 11,891m^2 A_{DC} = 2 x V_S x H / (H - F)^2 A_{DC} = 2 x 22,000 x 4 / (4 – 0.3)^2 A_{DC} = 12,865m^2 V_{DC} = H x A_{DC} /2 V_{DC} = 4 x 12,865 / 2 V_{DC} = 25,730m^3 Using Figure 5.2 Q_P = 80 m^3/s	A_S = 3 x V_S / (H-F) A_S = 3 x 22,000 / (4 – 0.3) A_S = 17,837m^2 A_{DC} = 3 x V_S x H^2 / (H - F)^3 A_{DC} = 3 x 22,000 x 4^2 / (4 – 0.3)^3 A_{DC} = 20,847m^2 V_{DC} = H x A_{DC} / 3 V_{DC} = 4 x 12,865 / 3 V_{DC} = 27,796m^3 Using Figure 5.3 Q_P = 110 m^3/s

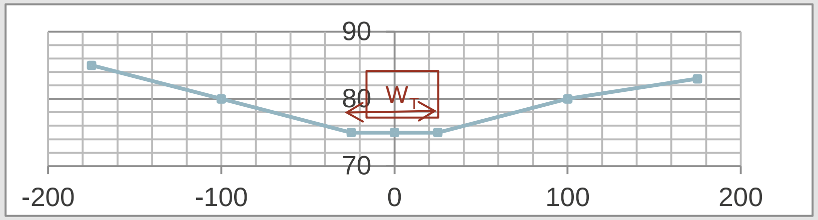
Step	Action	Output	Commentary	Worked example		
Step 5	Estimate the flood conditions downstream of your dam if there are properties close to the dam and the friction coefficient (n) for the area between the dam and the first house	W d v	For flat land use spreading equation with 45 degrees This example using n = 0.040 for bare soil agricultural land r = distance from the dam to the nearest property	$Q_P = 60\ m^3/s$ r = 30 m n = 0.040 Ω = 0.79 $d = \left(\frac{13}{3}\frac{n^2 {Q_P}^2}{\Omega^2}\right)^{\frac{3}{13}} r^{-\frac{3}{13}}$ $= \left(\frac{13}{3}\frac{0.040^2 60^2}{0.79^2}\right)^{\frac{3}{13}} 30^{-\frac{3}{13}}$ $d = 0.574$ $v = \sqrt{\frac{3}{13}} d^{7/6} n^{-1} r^{-1/2}$ $= \sqrt{\frac{3}{13}} 0.574^{7/6} 0.040^{-1/2} 30^{-1/2}$ $v = 6.88$	Assuming a clearly defined flow path The width of flow can be calculated W = 2 H + r /5 W = 2 x 4 + 30 / 5 W = 14m	For the nearby house, dv = Q/W So dv = 110 / 14 = 7.86 $dv = 7.86 m^2/s$ Go straight to Section 5.5, Figure 4.2 Step 7 for houses further afield.

Step	Action	Output	Commentary	Worked example		
Step 6	*Apply Test 1*	*dv*		*d x v = 0.567 x 6.88* *dv = 3.49m²/s* *3.49 m²/s > 3m²/s* *HIGH RISK*	*Triangular shaped flow path=* *dv = 2QP / W* *dv = 2 x 80 / 14* *dv = 11.43 m²/s* *Rectangular shaped flow path* *dv = QP / W* *dv = 80 /14* *dv = 5.714 m²/s* *11.43 m²/s or 5.74 m²/s > 3m²/s* *HIGH RISK*	
Figure 4.2 Step 7	**Consider far field effects (Sloping surrounding land or valley)**			**This method is used for all land types. Sloping land example has been continued through.**		

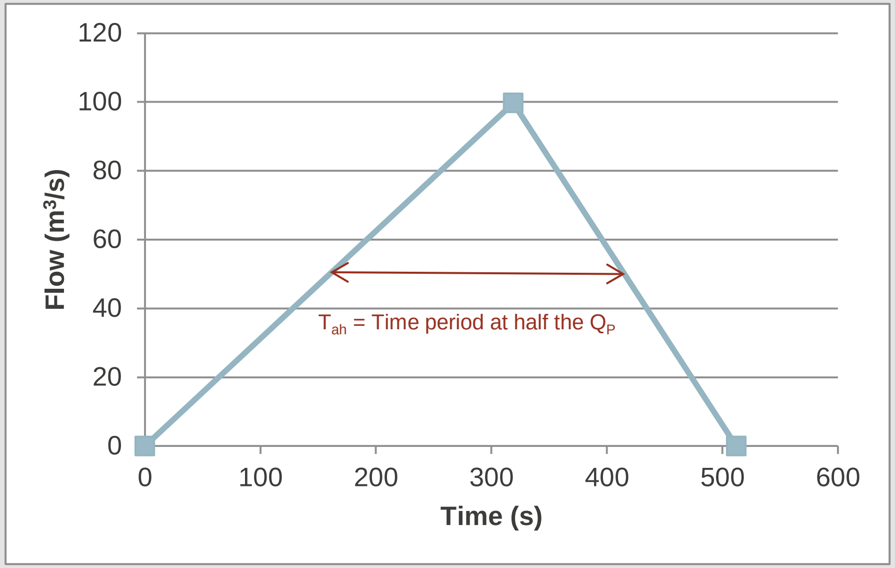
Step	Action	Output	Commentary	Worked example
Step 7a	Decide how far downstream the water might go before it reaches a much larger river, or reduces such that it can all flow in the stream bed rather than the flood plain		Use Figure 5.3 to check maximum normal distance. It may be shorter if the stream joins a major river first.	The reservoir sits within a shallow valet, with a clearly defined drainage path downstream. The water would flow through one property located approximately 30m downstream of the dam.
Step 7b	Check that there are no obstruction such as large road or rail embankments with small culverts through them which would affect the dam break flow		Refer to Section 5.2 of this report – if such obstructions are present then you should undertake a more detailed analysis (see chapter 6)	Then the flow crosses over / under a main road and then the drainage route is across farmland until it reaches the main river.

Step	Action	Output	Commentary	Worked example
Step 7c	For all the contours in the length measure the distance along the streamline between the points where two consecutive contours cross the floodplain. Calculate the bed slope of the flood plain, S_o between each of the contours	S_O	S_o equals vertical distance (or contour interval) divided by horizontal distance.	The longitudinal drainage slope between the park lake and the main river is approximately 10m drop along 1500m length. Hence $S_O = 0.007$ For this example just one length has been analysed. Length1: 0-1500m $S_O = 0.007$
Step 7d	Split the inundation area into 3 to 5 subdivisions (reaches), at significant changes in valley shape or slope. In each decide the representative bed slope for the dambreak analysis	S_O	The first section is probably best just downstream of the dam, where flow is first controlled by the valley geometry	Sub divided the valley at points. - Change in shape - Change in slope Only one section analysed.

Step	Action	Output	Commentary	Worked example
Step 7e	In each reach decide upon a trapezoidal shape that is roughly the cross section on the flood plain (ignore the stream bed which is normally assumed full or blocked in a dambreak situation) a) measure the distance between contours across the valley and up the side of the valley. Use this to decide the valley side slopes b) Then decide the valley base width in each reach	S_S W_B	On a 1:25,000 scale map the contours are normally at 5m intervals. It is more important to get the correct top width, than base width, so the base width can be estimated by calculating the valley width at a selected contour above the stream bed, then projecting the side slopes down to infer the valley width at the flood plain. Think about what would be more critical in each location; narrower flooding will give higher velocities and more risk to people, whilst wider flooding will potently affect more houses	This results in WB = 50m with the sections as: -175 / 83mOD -100 / 80mOD -25 / 75mOD 0 / 75mOD +25 / 75mOD +100 / 80mOD +175 /85mOD 

Step	Action	Output	Commentary	Worked example
Step 7f	Make an initial estimate of W_T, the flooded width at the first section	W_T	An initial estimate is the width of fluvial flooding on the EA website (where available), as many valleys are trapezoidal such that a doubling of depth only gives small increase in width	An initial estimate of 50m width is made (judgement using the available mapping data from the EA website). W_T = 50m 

Step	Action	Output	Commentary	Worked example
Step 7g	a) Calculate L_a, the rate of decay (attenuation) using k of 1.0	L_a	Use equation 3 from table 5.4 You will need Qp(0) and Th, the output from Section 5.3 $L_a = K\, W_T^{-0.2}\, S_O^{1.9}\, n^{-1.8}\, Q_P(0)^{0.2}\, T_{ah}^{2}$	Tah = Calculated using the data obtained from the Table 5.2 using the escapable reservoir volume calculated in Step 4 $Q_P = 99.7$ $T_P = 319$ $T_f = 512$ $T_{ap} = 87$ $T_{ah} = 248$ $B_{Wf} = 9.2$ $B_{WP} = 14.2$ $K = 1.0$ $S_O = 0.007$ Plot the hydrograph as demonstrated in Figure 5.4. T_{ah} = Time period at half the Q_P $T_{ah} = 248s$

Step	Action	Output	Commentary	Worked example
		L_a		 $L_a = K\, W_T^{-0.2}\, S_O^{1.9}\, n^{-1.8}\, Q_P(0)^{0.2}\, T_{ah}^{2}$ $L_a = 1 \times 50^{-0.2} \times 0.007^{1.9} \times 0.040^{1.8} \times 99.7^{0.2} \times 248^{2}$ $L_a = 4281.83$

Step	Action	Output	Commentary	Worked example
Step 7h	b) Check this is reasonable, If it exceeds more than 0.43 times the overall length of dambreak (L_r) shown on Figure 5.3, then reduce L_a to equal 0.43 L_r	L_a	Setting L_a to equal 0.43 L_r should mean that Q reduces to 10% of its initial value at L_r	L_a = 4281.83m Check L_a does not exceed 0.43 L_r Using Figure 5.4 L_r = 8800 0.43 L_r = 0.43 x 6500 0.43 L_r = 3784m L_a exceed 0.43L_r so use 3784m
Step 7i	Use L_a to calculate the peak flow Q_p at the end of the reach	Q_p	Use equation 2 from Table 5.4	(x) = 1500m length for the Length 1. $Q_P(x) = QP(0) \exp [-x / La]$ $Q_P(1500) = 99.7 \exp [-1500 / 3784] = 67.07 m^3/s$
Step 7j	Knowing the valley shape and Q you can calculate a) d the average water depth at the end of the reach b) the flooded width W_T	d W_T	Use equation 1 from Table 5.4. to estimate the peak discharge for the given location: Use $Q_P(x)$ calculates in Step 7j $d = Q_P(x)\ n / W_T\ S_O^{0.5})^{0.6}$	W_T = base width plus 2x sides slopes W_T = 50 + 2(150) W_T = 350 $d = (Q_P(x)\ n / W_T\ S_O^{0.5})^{0.6}$ $d = (67.07 \times 0.040 / 350 \times 0.007^{0.5})^{0.6}$ d = 0.0121m

Step	Action	Output	Commentary	Worked example
Step 7k	If W_T varies by more than 10% from the initial estimate of W_T in step 6, then make a new estimate of W_T, and repeat steps 6 to 10 until the difference between W_T in steps 6 and 10 is less than 10%	W_T	Where this is set up in Excel "goal seek" can be used to automate the iteration process	Repeat Step 7h – 7k with a surface width of flooding.
Step 7l	Repeat steps 7d – 7l for each reach			
Step 7m	Calculate the flow at each reach	dv	dv = Q / W	Reach 1 = Q = 67.07 m^3/s W= 350m dv = Q /W

Step	Action	Output	Commentary	Worked example
Step 7n	Draw the flood width on a map and identify how many properties affected in each reach		A good starting point (where available) is the extent of flooding in a 1 in 100 fluvial flood on the Environment Agency website, which you can mark up to show how much wider the dambreak flooding is.	
Step 8	***Apply Test 2***		***Are there more than 200 people (~83 properties) or 20 businesses within the inundation area calculated and marked up on the map?*** ***Count the number of properties and businesses.*** ***Assume approximately 2.4 people per property***	***Number of properties – 89*** ***= 89 x 2.4*** ***= 213 people*** ***Number of businesses = 2*** ***HIGH RISK***

Step	Action	Output	Commentary	Worked example
Step 9a	*Apply Test 3*	*PAR*	*Is the combined risk to life where people may be present greater than 1?* *Calculate Population at risk (PAR)* *PAR = Number of properties x number of people per property (2.4) x occupancy rate (80%)* *PAR(Businesses) = Area of the businesses / 40m^2*	*89 properties* *2 businesses* *Flow = Q (Calculated in Step 7k)* *PAR = 99.7 x 2.4 x 0.8* *PAR = 191.42* *PAR(Businesses) = Area of the businesses 500m^2* *PAR(Businesses) = 500/40 = 12.5* *PAR(Businesses) = 12.5 x 25% occupancy rate for businesses* *PAR(Businesses) = 3.125* *Overall PAR for Reach 1 = 194.55*
Step 9b			*Fatality rate can be calculated using Figure 5.4.*	*Flooded width = 50m* *Q = 67.07 m^3/s* *Flow per flooded width = 67.07/50 = 1.34m^2/s* *Fatality rate = 0.8%*
Step 9c		*LLOL*	*The likely loss of life (LLOL) is calculated using the Fatality rate,* *The reservoir is high risk if the combined likely loss of life for all reaches is greater than 1 fatality*	*LLOL = Fatality rate x PAR* *Fatality rate = x% Using191 Figure 5.4* *LLOL = 0.008 x 194.55* *LLOL = 1.56 fatalities* *LLOL = 1.56 fatalities > 1 fatality* *HIGH RISK*
Step 9d			*Add each of the risk to life values together for each reach*	

Step	Action	Output	Commentary	Worked example
Step 10	Review the extent of the flooding.		If the results are not reasonable then either refine the various assumptions until you consider the result reasonable, or if the valley is too complicated a geometry then move to a more detailed analysis.	

Fig 4.2	Consider near field effects for all surrounding land types (Flat land, sloping land or valley)		Flat Land	Sloping land	Valley
Step 1	Consider the dam location		Dam is located in a remote area in flat farmland	Dam is located in a remote area in a sloping valley	Dam is located in a remote area in a valley
Step 2	Identify the potential breach location(s) that would result in the most extreme flood		Breach location identified at the point where housing is nearest	Breach location identified at the point where housing is nearest	Breach locations – highest point (worst for downstream valley) and outlet works on left abutment near house on side of valley
Step 3	For each flow path, decide where the water would go				

B. Nomenclature

The following symbols are used throughout this document. This section describes the meaning and units of each symbol.

Table B.1: Notation

Symbol	Units	Meaning	Comments
A	m^2	Flow cross-sectional area	
A_S	m^2	Surface area of the reservoir at the spillway elevation	
A_{DC}	m^2	Surface area of the reservoir at the dam crest elevation	
B_W	m	Breach width	
d	m	Depth of floodwater	
F	m	Freeboard	Typically 0.3m for non-impounding reservoirs on flat ground, and greater for impounding reservoirs
H	m	Maximum height of dam above ground level	
H_W	m	Height of the water level above ground level at the time of failure	This is the value used in the Environment Agency RIM mapping and is different to that of H
k		Factor associated with attenuation length L_a	Factor with range 1 to 10. Suggest value 2.5.
L_a	m	Characteristic length defining the rate at which the peak flood flow attenuates	
n		Manning's roughness coefficient	This coefficient represents how vegetation (or buildings, walls, hedges etc) in the flood plain affects the passage of flood water
P	m	The wetted perimeter of a flooded section	This is the width of the flooded area, plus the height of the sides of the flooded area.
Q_P	m^3/s	Peak flow rate released from the reservoir	
$Q_P(0)$	m^3/s	Flow at the upstream end of a calculation zone	
$Q_P(x)$	m^3/s	Flow at location x downstream along a calculation zone	
r	m	Distance from the dam to the nearest property	
S_o		Slope along a river, valley or flood plain	

Symbol	Units	Meaning	Comments
S_s		Side slopes of a trapezoidal section representing the valley	See Note 3
T_{ah}	s	Time of flood hydrograph at half of the peak flow	
T_f	s	Time of failure	From breach initiation to complete draw down
T_p	s	Time of peak flow	
v	m/s	Velocity of the water	
V_{DC}	m^3	Stored volume if the reservoir is full to the dam crest	
V_S	m^3	Stored volume if the reservoir is full to the spillway level	
V_W	m^3	Volume of water stored above ground level at the time of failure	This is the value used in the Environment Agency RIM mapping, and is different to that of the V_{DC} and V_S
W_T	m	Surface width of flooding at a given location	
x	m	location x downstream along a calculation zone	
Ω	radians	Angle of flow spreading from the dam breach	Note: 45 degrees = 0.79 radians, 90 degrees = 1.57 radians, 180 degrees = 3.14 radians

C. Breach flow hydrograph (high erodibility dam, piping failure mode)

Dam Height ↓	Volume	5,000			15,000			25,000			100,000		
	Reservoir Type ⟶	a flat	b slope	c valley	a flat	b slope	c valley	a flat	b slope	c valley	a flat	b slope	c valley
2m	Qp=	15.5	19.6	22.3	25.0	32.5	37.3	31.9	41.6	47.8	62.8	82.4	94.9
	Tp=	183	218	236	292	350	379	367	441	478	702	848	921
	Tap=	68	79	77	130	137	132	170	177	170	341	354	340
	Tah=	251	243	225	487	465	431	649	611	556	1,326	1,222	1,111
	Tf=	2,966	579	405	4,299	974	672	7,655	1,258	856	10,989	2,438	1,674
	Bwp=	3.9	4.8	5.3	6.7	8.2	9.0	8.6	10.6	11.6	17.1	21.1	23.2
	Bwf=	13.1	9.0	8.2	22.1	15.5	14.0	29.4	19.9	18.0	56.9	39.7	35.8
4m	Qp=	21.8	34.2	42.2	57.2	72.0	80.7	70.2	88.0	99.7	127.2	165.4	189.7
	Tp=	283	254	247	253	255	271	259	299	319	427	503	541
	Tap=	53	37	29	23	49	63	61	90	87	171	179	173
	Tah=	190	134	110	197	193	179	273	268	248	639	611	565
	Tf=	1,872	386	300	3,782	578	421	5,261	718	512	8,192	1,333	924
	Bwp=	6.0	5.9	5.9	6.2	6.6	7.3	6.7	8.3	9.2	13.3	16.4	18.0
	Bwf=	10.9	7.7	7.1	18.3	12.3	11.2	23.6	15.7	14.2	46.0	30.8	27.8
8m	Qp=	9.1	18.4	25.8	39.4	70.5	91.8	78.5	129.4	162.7	302.9	380.2	426.1
	Tp=	224	241	243	326	316	311	380	352	345	371	373	393
	Tap=	80	58	46	100	56	43	110	54	40	28	62	80
	Tah=	605	224	171	371	203	155	275	182	146	247	243	226
	Tf=	1,546	1,968	2,046	2,339	586	561	3,206	507	410	5,477	785	584
	Bwp=	4.2	5.0	5.4	7.7	8.3	8.5	10.2	10.3	10.4	12.2	12.9	14.3
	Bwf=	13.1	11.9	10.4	16.3	12.1	11.1	19.7	13.7	12.6	36.5	24.3	22.0
16m	Qp=	4.1	8.6	13.2	22.9	34.9	51.4	40.3	66.7	95.4	205.5	370.1	483.0
	Tp=	553	403	224	409	292	300	440	333	337	464	451	444

Dam Height ↓	Volume	5,000			15,000			25,000			100,000		
	Reservoir Type ⟶	a flat	b slope	c valley	a flat	b slope	c valley	a flat	b slope	c valley	a flat	b slope	c valley
	Tap=	83	115	60	80	73	60	89	74	60	126	71	54
	Tah=	887	454	327	603	378	230	594	289	223	477	258	196
	Tf=	2,944	5,069	3,021	1,963	2,674	2,205	2,215	2,075	2,018	3,466	918	766
	Bwp=	7.6	7.5	4.4	9.4	6.8	7.4	11.1	8.7	9.3	15.2	16.3	16.7
	Bwf=	24.3	22.5	18.2	24.8	23.6	20.4	25.5	23.8	21.2	32.4	24.1	22.0

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