Department for Environment Food & Rural Affairs

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Design, operation and adaptation of reservoirs for flood storage

Report – SC120001/R

Flood and Coastal Erosion Risk Management Research and Development Programme

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Doug Wilson

Director of Research, Analysis and Evaluation

Executive summary

Effective flood risk management in the UK demands a holistic approach to determine the most effective solutions in providing protection to persons, properties and important infrastructure. The development of flood storage reservoirs on or adjacent to watercourses is a proven approach to mitigate flooding and represents one of many actions that can be taken to address flood risk on a catchment-wide basis. Many flood storage reservoirs have been constructed in the UK. Drawing on experience, this report provides guidance on the design, operation and maintenance of flood storage reservoir structures. Existing reservoirs originally formed to secure reliable water supply or to provide some other function can also provide a level of storage mitigating flood risk. The report covers the adaptation of existing reservoirs to formalise the use of reservoir storage for flood protection purposes.

The report is intended for use by a wide range of stakeholders including planners, developers, reservoir owners, asset managers, designers, contractors, regulatory engineers/advisors, environmentalists, educational institutions and the public. It references more detailed guidance where available, drawing on international practices and case studies as well as UK strategy documents, codes, standards and engineering guides. Examples are provided to illustrate lessons learned from the operation of existing flood storage reservoirs and to inform good practice in design, operation and maintenance.

The report is presented in 6 sections. Recognising that users may be interested in particular aspects of flood storage reservoirs rather than the subject as a whole, the sections have been written to support this approach, with references made where necessary to other sections to minimise repetition of content. The report is presented as follows.

Section 1: Introduction

This section explains the scope of the guidance offered in this report. It provides references to government strategy documents on flood risk management which provide the context for the use of flood storage reservoirs within wider national flood risk management strategies. It defines flood storage reservoirs and provides the scope of the type of structures and operational functions covered by the report. Background information on the ownership and number of flood storage reservoirs is also provided.

Section 2: Planning and preliminary design

The development of structures to manage floodwater and mitigate flood risk requires the involvement of a wide range of specialists. Every flood risk management project will present a unique set of challenges, constraints and stakeholder involvement. This section covers the typical steps required to carry out option studies and to develop planning and preliminary design proposals for a flood storage reservoir where it has been concluded that such a structure could form part or all of a flood control project. Typical design layout concepts are explained and the advantages of various approaches detailed. Planning and environmental legal considerations are also covered.

Section 3: Detailed design

This section covers detailed design aspects including:

- the standards for design
- hydraulic design and debris and erosion control

- design of new dam embankments
- modification of existing dam structures
- landscape and environmental design
- designing for effective and efficient monitoring, operation and maintenance
- health and safety aspects

Section 4: Operation and maintenance

This section covers the operation and maintenance of existing flood storage reservoirs. It explains the typical types of structures and devices in use and the associated power and control systems. Guidance is provided on measures to:

- improve operational reliability
- support effective monitoring and surveillance
- address issues of animal damage
- reasonably ensure the health and safety of operatives and the public at reservoir sites and associated off-site locations.

Section 5: Adaptation of existing reservoirs for flood storage

The majority of UK reservoirs provide some degree of flood protection to downstream areas. Drawing from national and international examples of dual-use reservoir operation, this section explains the benefits and challenges involved in formalising the use of existing reservoirs to serve a flood protection function. Guidance is provided on how adaptation works can make good use of otherwise obsolete water supply reservoirs and provide flood risk reduction benefits.

Section 6: Concluding remarks

The final section sets out the main conclusions from the report.

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- Jackie Banks, Environment Agency (PSG Chair)
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Contents

1 Introduction

1.1 Background

1.1.1 Strategic flood risk management context

The importance of watercourses for water supply, irrigation, transportation and industry has led to the development of many urban areas near watercourses in the UK. These urban areas are therefore within naturally flood-prone land that has become increasingly susceptible to flooding as a result of urbanisation or other changes within the watercourse catchment area.

The major effects of urbanisation on the flood risk from a catchment area are:

- an increased proportion of impermeable ground cover (for example, roads, car parks, roofs) generating a larger proportion of run-off from the rain falling on it
- a faster response time and greater peak flow rates
- the provision of stormwater drains and culverted or 'improved' watercourses which increase the flow velocities and thereby further shorten the response time of the catchment
- the infilling or obstruction of the natural floodplain which reduces the available flood storage in the valley and can lead to increased flood levels

The observed evidence for changes in watercourse flow in the UK due to climate change is limited (Hannaford 2013). However, the Government Office for Science's 'Foresight – Future flooding' report predicted that climate change will be an important factor in increasing flood risk, and that both the number of people in danger from flooding and the costs of damage from floods will rise significantly, particularly through the impacts of more stormy weather (Government Office for Science 2004). Future changes in the amount and pattern of precipitation in the UK could have the potential to increase the severity of urban flooding.

The Foresight – Future flooding report identified catchment-wide strategic storage as one of the most resilient intervention options available to reduce the risk of present day and future flooding. The government strategies, 'Making Space for Water' (Defra 2004) and 'Future Water' (Defra 2008), also identified the need for a holistic and integrated approach to manage flood risk in urban areas, with particular emphasis on strategic catchment-scale flood storage.

The provision of flood storage by forming a reservoir on or adjacent to a watercourse is one approach that can be adopted to reduce the threat from fluvial flooding as part of a catchment-wide strategy. For guidance on further fluvial flood defence options refer to the Environment Agency's 'Fluvial Design Guide' (Environment Agency 2009a).

This report provides guidance on the design, operation and maintenance of flood storage reservoirs and how existing reservoirs can be adapted or operated differently to provide a flood storage function.

1.1.2 What is a flood storage reservoir?

A flood storage reservoir, for the purposes of this guide, is an artificially raised body of water used to store water temporarily and thereby mitigate flood risk. This is different to the statutory definition of a 'reservoir' contained in the Reservoirs Act 1975 and is a practical term used in this guide to cover all sizes of flood storage reservoir. Reservoirs that are not regulated by the Reservoirs Act 1975 are referred to as 'non-statutory'.

Flood storage reservoirs are normally located either upstream of an urban area to mitigate flood flows from reaching that area or downstream of a newly developed urban area to mitigate the impact of that development on areas further downstream.

There are 2 typical configurations (Figure 1.1) for a flood storage reservoir:

- the reservoir can be built on the line of the watercourse ('online') by constructing a dam across the watercourse
- the reservoir can be built offline by constructing a bunded basin adjacent to the watercourse

Both online and offline reservoirs have some common features such as an earth embankment to retain floodwater and some form of control structure to limit the rate at which the stored floodwater is released to the receiving watercourse.

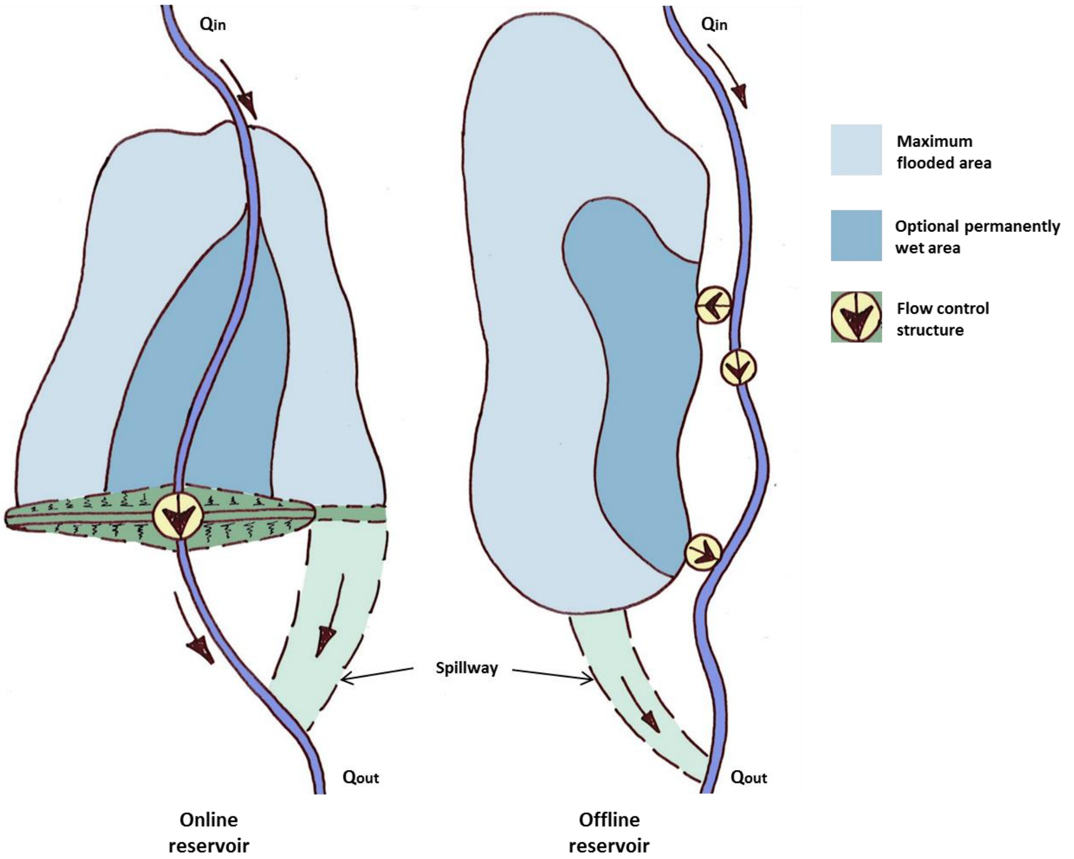


Figure 1.1 Function and components of typical flood storage reservoirs

Online flood storage reservoirs require a flow control structure (see Section 3.2.1). In the event of a large storm, the reservoir fills as the inflow exceeds the outflow. Water might eventually discharge over a spillway if the magnitude of the flood event exceeds the design flood event.

Offline reservoirs feature control structures to divert water into and out of the reservoir.

The concepts of online and offline flood storage are further described in Section 2.2.

Floodplains that are modified to augment their natural flood storage and attenuation characteristics are often described as ‘washlands’. Such areas are not specifically covered by this guide. Where washlands have been altered to perform as a flood storage reservoir, the guidance for offline flood storage reservoirs will normally apply.

Flood storage reservoirs are normally empty, or mostly empty, so as to provide an available volume for flood storage. Wet storage areas contain water under dry weather flow conditions, and dry storage reservoirs do not contain any significant water volume under dry weather flow conditions.

The latter part of this guide covers the adaptation of existing reservoirs for flood storage. It is important to note that a reservoir’s flood storage function may be incidental to its primary function.

Other terms commonly used interchangeably for a flood storage reservoir include:

- flood detention reservoir
- flood retention basin – a flood storage reservoir designed to retain a permanent pool of water
- balancing pond – a term normally applied to smaller urban flood storage basins designed to mitigate the flood risk from a specific urban development
- flood storage area – a term often applied to smaller flood storage reservoirs

For consistency, the term ‘flood storage reservoir’ is used throughout this guide.

The flow chart shown in Figure 1.2 is intended to help in the identification of flood storage reservoirs. This simplistic approach is not exhaustive and professional advice should be sought to correctly identify a flood storage reservoir. Further scientific approaches to identification are available; reference can be made to Yang et al. (2011).

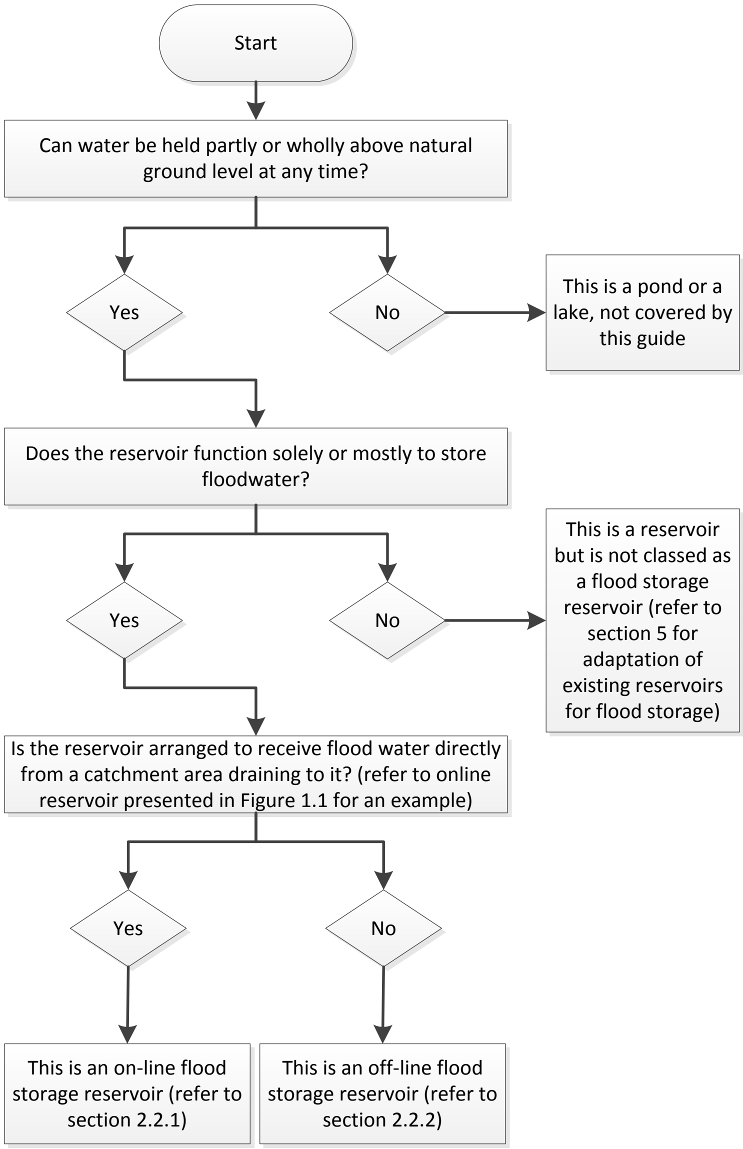


Figure 1.2 Do I own a flood storage reservoir?

1.1.3 Historical context

A small number of flood storage reservoirs in England and Wales are over 100 years old. The majority were constructed in the latter half of the 20th century, particularly with the development of 'new towns' in the 1970s, and into the 21st century (Pepper et al. 1998).

Figure 1.3 shows the number of flood storage reservoirs constructed per decade since 1940. Records indicate that 12 flood storage reservoirs were constructed prior to 1940. In the period between 2010 and 2015, a further 25 flood storage reservoirs were constructed.

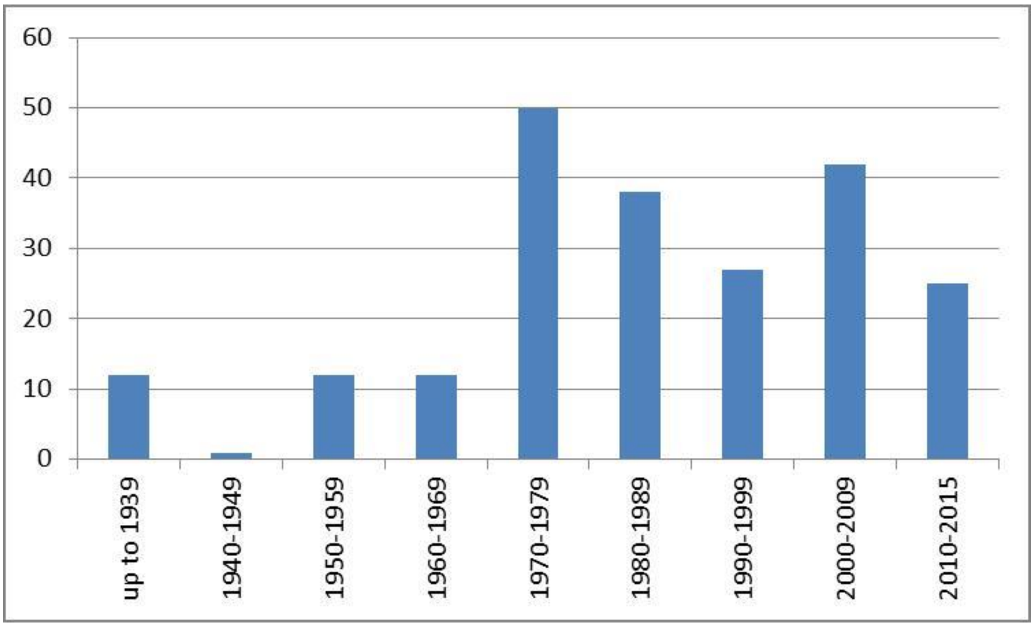


Figure 1.3 Flood storage reservoirs constructed by decade in England and Wales

Source: Environment Agency and Natural Resources Wales statutory undertaker records

1.1.4 Number of flood storage reservoirs in England and Wales

Over 250 flood storage reservoirs in England and Wales are currently regulated under the provisions of the Reservoirs Act 1975. There are also numerous non-statutory flood storage reservoirs. The implications of reservoir safety legislation are described in Section 2.3.10.

1.1.5 Operators of flood storage reservoirs

The majority of flood storage reservoirs in England and Wales, regulated under the provisions of the Reservoirs Act 1975, are operated by the Environment Agency and Natural Resources Wales, respectively; these 2 bodies also act as regulators.

Figure 1.4 illustrates the operators of statutory reservoirs primarily used for flood storage in England and Wales. No information is available on the ownership of reservoir structures where flood storage is a secondary function.

In Scotland, flood storage reservoirs are predominantly operated by the local authorities, with the Scottish Environment Protection Agency (SEPA) providing the role, from 2016, of the regulator under the Reservoirs (Scotland) Act 2011.

In Northern Ireland, flood storage reservoirs are predominantly in the public sector, with the Rivers Agency undertaking the role of the enforcement authority.

Many other organisations such as local authorities, water companies and Highways England own and operate flood storage reservoirs. This ownership is normally due to site-specific benefits such as the protection of critical infrastructure and organisational benefits including the management of public relations.

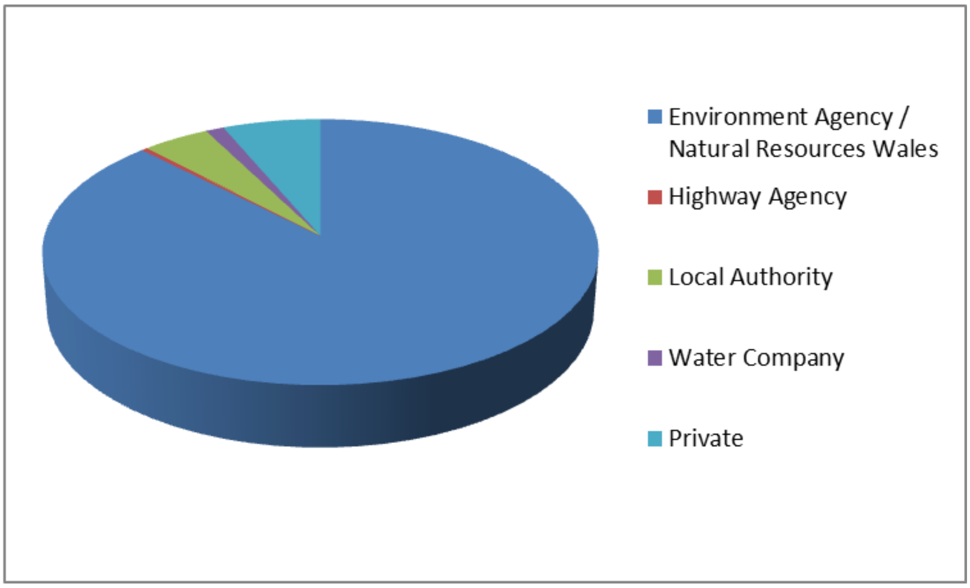


Figure 1.4 Operators of flood storage reservoirs in England and Wales

Source: Environment Agency and Natural Resources Wales statutory undertaker records

1.2 Scope of the guide

1.2.1 Scope

In 2007 Defra commissioned a strategy report to determine the strategic direction for reservoir safety research in the UK for the next 5–15 years (Defra and the Environment Agency 2009). One of the projects recommended in this report, and also nominated by the Institution of Civil Engineers (ICE) Reservoir Safety Advisory Group as a priority, was to revise the available guidance on the design of flood storage reservoirs. This recommendation was due to significant changes since the publication of earlier guidance (CIRIA 1993) including developments in relation to climate change, reservoir safety legislation, environmental protection, and health and safety.

The main focus of this guide is the design and operation of flood storage reservoirs that function as part of a catchment-wide strategy for flood control. Although flood storage reservoirs can be designed primarily to improve water quality or to provide some other primary benefit, this guide deals with the design and operation of reservoirs for which the primary benefit is flood risk reduction. Sustainable drainage systems, which include flood detention basins, are not specifically covered by this guide. Reference can be made to ‘The SuDS Manual’ (CIRIA 2015) and the ‘National Standards for Sustainable Drainage Systems’ (Defra 2011).

This guide aims to give a balanced factual treatment of the subject area and does not seek to promote the use of reservoir development in favour of alternative approaches to flood risk management. The guide is intended for application within the UK, though users should note that it draws primarily from experience gained at sites within England and Wales.

This report was commissioned by the Environment Agency to collate current best practice and research relating to the design, operation, maintenance and adaptation of flood storage reservoirs into guidance that can be easily applied by owners, undertakers, engineers and other stakeholders.

The Environment Agency is the regulator of the Reservoirs Act 1975 in relation to England. The contents of this guide should not be taken to reflect any approach to regulation under the Act and independent legal advice should always be obtained if necessary. As the regulator, the Environment Agency has worked with the ICE in the production of 'A Guide to the Reservoirs Act 1975' (ICE 2014) from which more information can be obtained.

1.2.2 Structure of the guide

The guide is presented in 5 sections as summarised below.

- Section 1 – Introduction
- Section 2 – Planning and preliminary design of flood storage reservoirs
- Section 3 – Detailed design of flood storage reservoirs
- Section 4 – Operation and maintenance of flood storage reservoirs
- Section 5 – Adaptation of existing reservoirs for flood storage

The adaptation of existing reservoirs for flood storage use is considered separately to the design, operation and maintenance of dedicated flood storage reservoirs because the experience of such adaptation within the UK is limited, the stakeholders are sometimes different, and the types of technical issues and risks are distinct.

The level of detail varies between sections and topics according to the maturity of existing guidance. Where guidance exists but is presently disparate, the guide brings it together into a single source. Where recognised, authoritative and accessible guidance already exists, the guide references such guidance rather than reproducing it.

1.2.3 Target readership and use of this guide

The purpose of this guide is to meet the demands of a wide range of potential users and stakeholders including planners, developers, structure owners, asset managers, designers, contractors, regulators, environmentalists, educational institutions and the public. It aims to provide information to support decision-making rather than directing it.

Principally the guide is intended for:

- those who seek to gain a broad appreciation of the subject of flood storage reservoirs (Section 1)
- those involved in the planning, preliminary design and option appraisal of flood storage reservoirs (Section 2)
- designers and specialists developing detailed design proposals (Section 3)
- owners and managers involved in the operation and maintenance of existing assets (Section 4)
- planners, engineers and other specialists considering the adaptation of existing reservoirs to provide or increase a flood protection function (Section 5)

The guide has been prepared with the separate uses in mind and, as such, each section can be read in isolation from the others. However, to avoid duplication of material, cross-references to other sections are provided where appropriate.

The guide should be of interest even to those with long experience in the development or management of flood storage reservoirs as it provides references to current relevant regulations, standards and guidelines.

1.3 Methodology

The development of new flood storage reservoirs, or the adaptation of existing reservoirs for flood storage, is a complex task involving a broad range of stakeholders and specialists. No two reservoir developments are identical and practitioners need to draw on guidance developed from case studies and the experiences of those involved in the development of many similar structures. Case studies for this guide were selected to illustrate typical concerns, risks, liabilities and issues that can affect many flood storage reservoir schemes.

The experience of practitioners was captured through a literature review and questionnaires to the industry, along with consultations and technical workshops.

The experience of owners and operators was collated from 2 separate technical workshops. The first involved the development of new flood storage reservoirs, along with the management of existing flood storage reservoirs, and the second focused on the issues associated with the adaptation of existing reservoirs for use in flood mitigation. The participants at each workshop included the relevant range of stakeholders.

Some of the issues raised through the technical workshops have no commonly accepted approach and would require specific research and industry consultation that is beyond the scope of this guide. Where this is the case, the guide indicates emergent good practice but does not seek to create new knowledge or reconcile all viewpoints.

A Project Steering Group made up of Environment Agency users (including reservoir safety, environmental, landscape architecture and legal representatives), representatives from water companies, academia and Panel Engineers – was formed to steer the guide’s production, drawing on their extensive experience on flood storage reservoirs.

2 Planning and preliminary design of flood storage reservoirs

2.1 Introduction

2.1.1 The use of storage for flood protection

The decision to create a new flood storage reservoir is usually driven by a need to reduce peak flows that would exceed the capacity of the downstream watercourse and thus improve the downstream standard of protection. Alternatively storage might be provided to restrict the flood run-off from an urban development area such that the pre-development flood peak flows are not exceeded. In both cases the provision of flood storage acts to reduce the flood peak flows downstream of the reservoir by attenuating the incoming flood flows. This typically benefits all downstream reaches and reduces flood risk at a community or catchment-wide level, as opposed to other flood protection measures which may only provide local benefits.

Figure 2.1 shows the ideal case of a flat topped outflow hydrograph. This means there is no storage of floodwater until the maximum permissible outflow is reached. This would be based on the discharge capacity, without significant flooding, of the downstream watercourse. Once the storm event has passed, the flood storage reservoir releases water in preparation for the next storm event. The hydrograph illustrated is hypothetical and its achievement would require significant mechanical control.

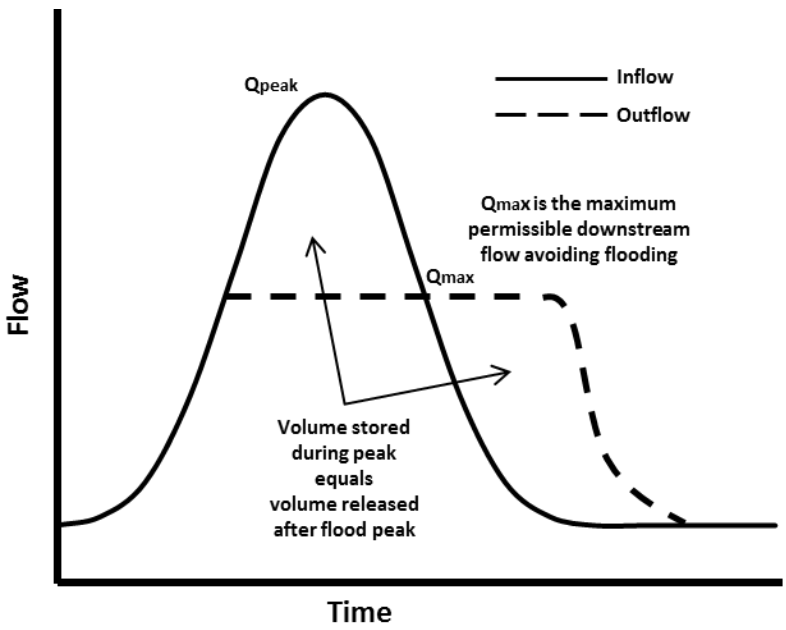


Figure 2.1 Ideal outflow hydrograph for maximum useful storage

Comparing the ideal outflow hydrograph with a practical example (Figure 2.2), it can be seen that the control device affects the flow passed downstream, initiating storage, before the watercourse threshold is reached. In addition the peak flow has been delayed.

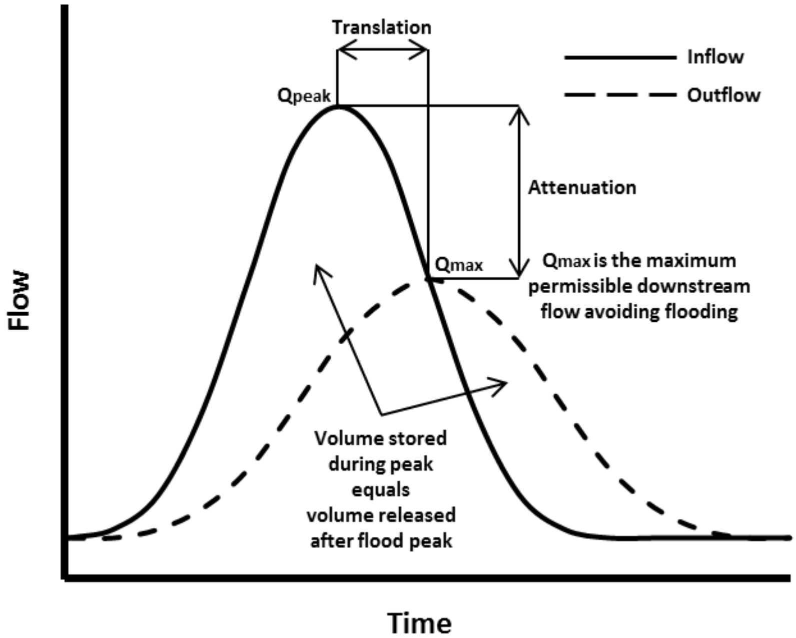


Figure 2.2 Practical utilisation of storage

If the inflow exceeds the available storage, the overflow spillway starts to operate in a controlled manner to prevent vulnerable sections of the dam from being overtopped. In this instance the storage has reached its capacity prior to the flood peak and additional flows are sent downstream via the spillway (Figure 2.3). The overall effect of flooding has been reduced but, as the permissible downstream flow has been exceeded, flooding will occur.

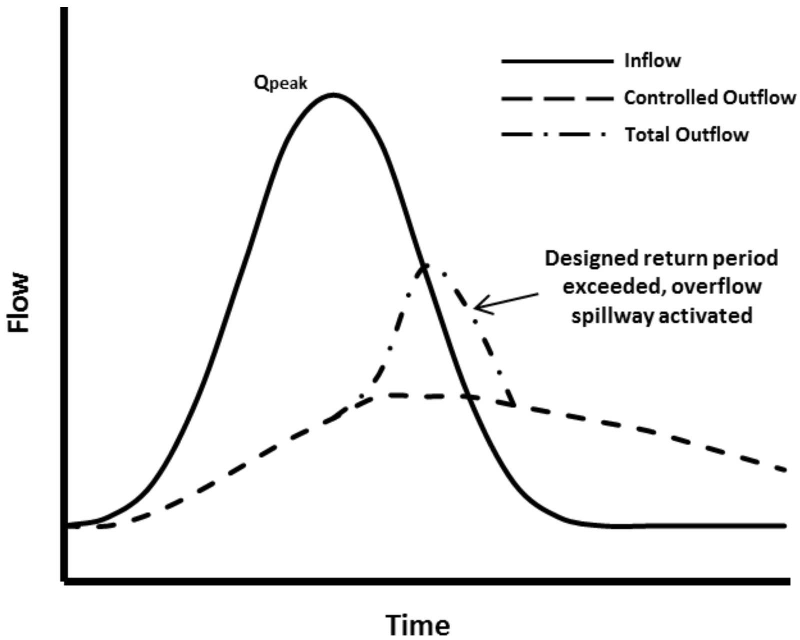


Figure 2.3 Example hydrograph when design return period is exceeded

Catchment solutions that work with natural processes are always desirable. They include:

- natural upstream storage (for example, ponds and moorland drains)
- tree and hedgerow planting to improve infiltration
- measures to reduce run-off from urbanised areas (for example, permeable surfacing)
- flow interception measures (for example, ploughing)

In combination, such measures can make a significant impact on flood peak levels and could reduce the size of a flood storage reservoir or completely avoid the need for structural measures.

The decision to design and construct a storage reservoir for flood protection requires a detailed understanding of the downstream fluvial flooding mechanisms and consideration of the downstream watercourse capacity. Alternatives to flood storage may be considered to manage downstream flood risk. These might include:

- property level protection and flood resilience measures
- increased watercourse conveyance achieved through enlargement or a supplementary watercourse
- raising the watercourse banks or walls

To achieve the most cost-effective and catchment-wide solution, it is essential that downstream channel works and upstream flood storage measures are designed holistically. Relatively minor works for an area at greatest risk of flooding can increase the allowable discharge from a flood storage reservoir, thus requiring a smaller reservoir. It is also important to recognise that local works to protect properties can effectively increase the flood risk at any properties further downstream.

2.1.2 Initial selection of reservoir sites

Once the decision to progress the planning of a flood storage reservoir has been taken, the designer first needs to define the broad functional characteristics of the reservoir. This process is by necessity iterative, but in most areas there will be a limited number of suitable reservoir sites. In practice these will define a range of available flood storage volumes and hence limit the range of schemes that can be considered. Box 2.1 gives details of what makes a good flood storage site.

Box 2.1: What makes a good flood storage site?

- **A suitable location within the catchment for the purpose intended**
    - Location is situated on a suitably large proportion of the catchment upstream of the location where protection is needed
    - Location to have sufficient storage volume
    - Location to have a suitable site for the impoundment structure
    - Location to ideally have a wide floodplain to allow for a low dam height to be developed
    - Location to have suitable construction, operation and maintenance access routes

- **Suitable foundation conditions**
  - Ground conditions to be relatively impermeable
  - Suitable ground properties for founding dam and hydraulic structures.
- **Local availability of suitable construction materials**
  - Site with potential for onsite borrow areas
  - If offsite borrow areas, what are the transportation distances?
- **Low impacts on the environment**
  - Low landscape and heritage impacts
  - Minimum adverse impact on ecological resources
- **Low third party impact**
  - Minimum adverse impact on landowners
  - Minimum adverse impact on local residents
  - Consider land use impacts
- **Opportunities for environmental enhancements and third party benefits**
  - Examples include improved quality of recreation and amenity through environmental enhancements and improved water quality through wetland creation

2.1.3 General planning design philosophy

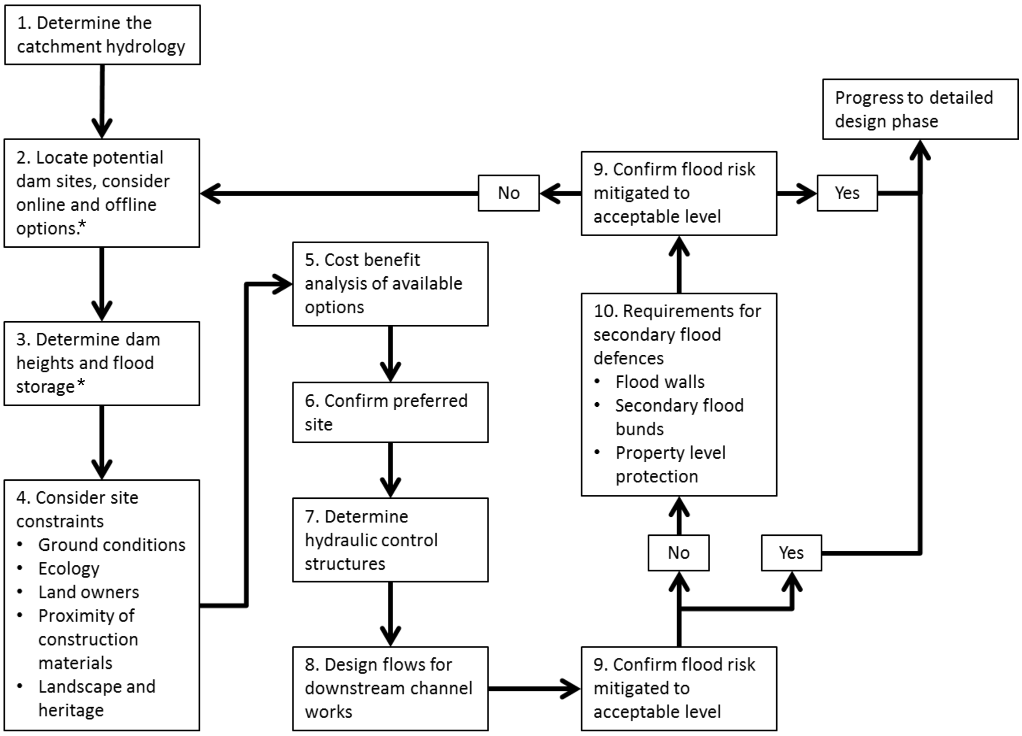
Once available dam sites have been identified, an exercise can be carried out to size the schemes for planning and appraisal purposes. The process is illustrated in Figure 2.4 and can broadly be summarised as follows.

- Determine the catchment hydrology (Section 2.4) so as to define the design inflows to the reservoir site and the flood flows at downstream points of interest – taking into account the downstream catchment area and any tributaries. The advice of an experienced hydrologist should be sought to do this. Flood storage reservoirs in the UK are often designed to contain the 1 in 100 year flood at reservoir top water level where site conditions allow (see Section 3.1.1 for standard of protection design requirements). A spillway will normally be provided to pass flows in excess of this flood magnitude.
- Select available dam sites and determine the reservoir depth–area–storage relationships (see Section 2.7).
- Consider site constraints by looking at available information. If data are not available, it may be desirable to carry out site studies. These studies should help to inform risk levels and either provide confidence over a chosen location or rule it out from further consideration. Consideration should be given to:
  - geotechnical engineering including ground conditions (see Section 2.8)
  - proximity to suitable construction materials (see Section 2.9)
  - the environment and ecological quality (see Section 2.5)

- land-use studies and investigations (see Section 2.6)

- Carry out a cost-benefit analysis of the options and appraisal report. These reports will confirm that the correct solution has been reached and provide funders with the confidence to invest in the scheme. This process will also promote a preferred option (see Section 2.10).

- Select approximate hydraulic characteristics of the control structure(s) and carry out a flood routing analysis to estimate the outflow hydrograph from the reservoir and review with respect to the target flow (see Section 2.7).



*Decisions on reservoir size and location to be determined considering the impact on people and infrastructure.

Figure 2.4 Flow chart of generic initial design process

The initial appraisal and sizing of a storage scheme is a matter of identifying the least-cost combination of storage and downstream measures for the required standard of protection. The following guidance assumes that:

- a storage scheme has been selected

- a peak outflow from the storage reservoir has been defined to suit an existing or proposed downstream watercourse capacity

2.2 Flood storage design concepts

2.2.1 Online storage

Online flood storage is where water is stored temporarily within the watercourse, its floodplain and adjacent land during the passage of floods by forming a dam across the watercourse and floodplain. Under normal flow conditions, water passes through the flood storage reservoir without being permanently retained. When flows exceed the capacity of the control structure, the storage area becomes active. Online flood storage reservoirs are generally suited to watercourse reaches within a predominantly rural setting.

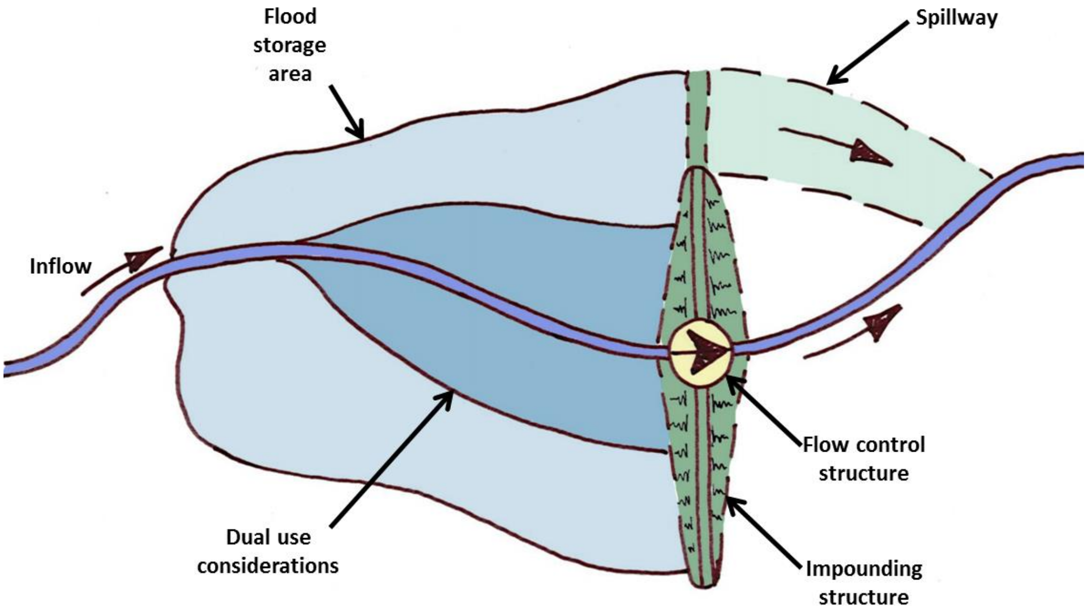


Figure 2.5 Graphical representation of an online flood storage reservoir

The type and size of the control device are critical to the sizing and operation of the flood storage reservoir. In general terms, where the control opening is relatively large there will be less attenuation of peak flood flows and the dam height is reduced as less floodwater will need to pass into storage. Conversely, a small control opening will act as an efficient throttle to the flood passage, leading to a high standard of protection downstream but the dam will need to be higher and more costly in order to be able to store the greater volume of floodwater. This is simplistic as certain types of control structures can be provided which vary the degree of throttling over time to help improve the balance between the amount of throttling and the cost of the dam structures.

The basic components of an online flood storage reservoir are shown in Figure 2.5 and illustrated in Figure 2.6. They include:

- a **dam across the watercourse** – usually an earth embankment, though concrete/masonry walling or other materials can be used
- a **control device**, such as an orifice plate, usually situated within the dam structure on the line of the watercourse to control the outflow from the flood storage reservoir
- a **spillway** to pass safely extreme floods that are greater than those for which the flood storage reservoir is designed to retain without compromising the integrity of the dam – in some cases a section of the dam crest can be designed to be overtopped such that a separate spillway structure is not required

There are 2 main types of control device: fixed controls and mechanical/variable flow controls. See Section 3.2.1 for examples of hydraulic control devices and the design requirements for each.

Figure 2.6 Spring Gardens flood storage reservoir: an example of an impounded online flood storage reservoir

2.2.2 Offline storage

Offline flood storage reservoirs are storage basins located adjacent to a watercourse. Generally, offline flood storage reservoirs are suited to lower watercourse reaches where there are wide flat areas adjacent to the watercourse. An offtake structure is designed to convey watercourse water into the reservoir when flow conditions exceed a certain value, thereby limiting peak flow rates in the watercourse. In some cases, a weir structure is placed downstream of the offtake to allow greater control of the flow conditions past the offtake.

Under normal flow conditions, the reservoir is bypassed and is substantially dry. Under flood conditions, water is diverted into the reservoir until the watercourse flow rate subsides below that required for flood control or until the reservoir is full. Water is conveyed back into the watercourse as the flood subsides.

The basic components of an offline flood storage reservoir are shown in Figure 2.7. They include:

- **Intake structure**: diverts water into the flood storage reservoir when the watercourse flow rate or level exceeds a predetermined value
- **Flood storage reservoir**: typically formed by retaining structures such as embankments or walls that separate the watercourse and the storage area; in most cases, dam structures located away from the watercourse are also required to form the reservoir, though it is unusual for such dams to exceed a few metres in height
- **Outlet structure**: returns the retained floodwater to a watercourse as the flood subsides

- **Spillway (if required):** to pass safely extreme floods that are greater than those that the flood storage reservoir is designed to retain without compromising the integrity of the dam; in many cases, the safety of the dam structures can be assured without the need for protection from overtopping; where there is a risk of overtopping, a spillway is provided or embankments are designed for overtopping

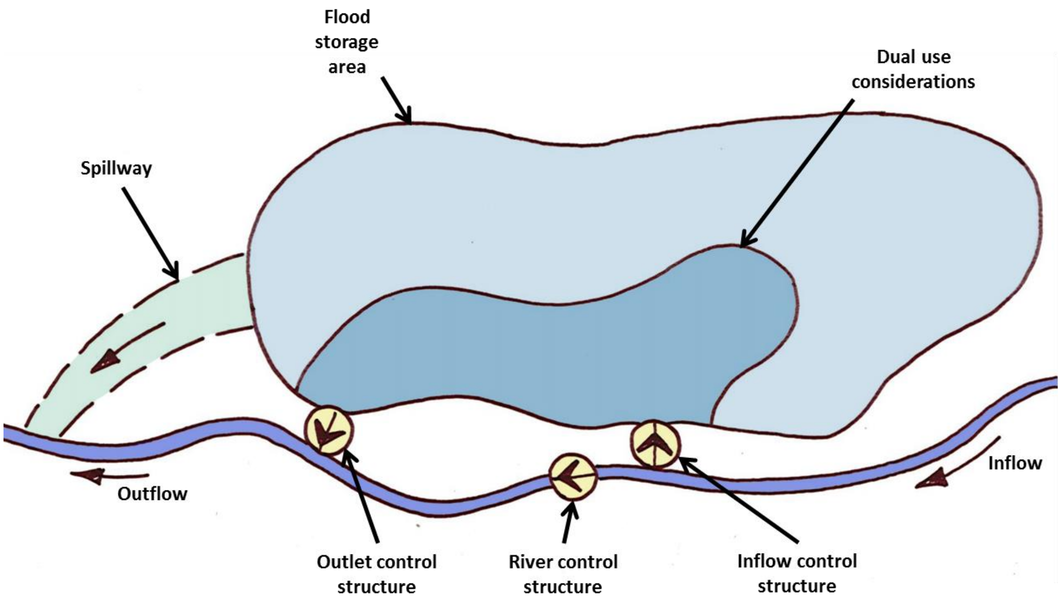


Figure 2.7 Graphical representation of an offline flood storage reservoir

The various forms of inlet and outlet structures, including the design process and examples, are described in Section 3.2.1.

2.2.3 Use of existing impoundment structures

Where there are options to make use of existing structures to form part of a new flood storage reservoir, these can offer reduced scheme costs and environmental impact. Road and rail embankments, for example, including disused rail embankments provide options for consideration for the impoundment of floodwater. Although road and rail operators are often reluctant to allow their assets to be used for impoundment, many historic railway embankments that are now redundant but too costly to remove could be considered for flood storage.

There are engineering challenges associated with using existing infrastructure for flood storage. Abandoned rail embankments, for example, were not usually designed to impound water. Ground investigations can provide some insight to the likely theoretical performance of such embankments and the foundation under flood conditions, but the actual performance might be governed by unseen features or defects which represent a design risk.

As a result of these risks, concerns by the embankment owner or other reasons for not utilising such existing embankments, some new embankments are constructed a short distance upstream of existing embankments. In this case, particular care is needed with respect to:

- the potential for erosion of the existing embankment during the passage of extreme floods – especially if the existing embankment carries a road or railway for example
- mitigation of the design risks associated with the conduit under the existing embankment – in many cases it will be necessary to improve the condition of the conduit to provide the required design life

Any new upstream embankment will alter the conditions experienced at the existing structure. Therefore it is important that the altered design conditions are taken into account in scoping the design.

Other challenges in changing the use of an existing structure are encountered where:

- public rights of way run along disused rail embankments
- embankments are used as green space
- any alteration to the structure might have a visual impact

2.2.4 Active or passive flow control structures

Passive or fixed flow control structures have no moving parts and require no special operation other than general maintenance and clearance.

Active or mechanical flow control structures have moving parts and require operation. This operation is normally electrically powered, but can be manually operated or controlled by means such as a float-triggered actuator.

Active control

With active control it is possible to achieve, or get close to achieving, the ideal flow conditions for flood storage. Gates can remain open to allow all flow to pass until the permissible downstream flow has been reached. Continuous gate movements then maintain this flow with any additional floodwater being stored. This avoids unnecessary storage and allows the basin to be of minimum size.

In locations where land purchase is at a premium or there are physical constraints such as existing infrastructure, savings in land purchase costs may justify the higher costs of complex active control and avoid a reduced standard of protection. In addition, a smaller footprint may cause less conflict with the surrounding land use or protected environments.

Creating the ideal outflow hydrograph might not always be desirable. For example where an urban area has multiple watercourses, a passive control that releases stored water more gradually or an active control linked to one or more flow gauges on other tributaries could be designed to avoid peak downstream flows from coinciding.

Active controls generally need a power supply. Operation could be achieved manually, although this is rare as the gate movements required are often complicated. A reliable all-weather access route should be incorporated to allow operation of gates.

Where electrical power is required, consideration must be given to backup supplies such as generators. Mains supply could be lost during storm events, especially if high winds accompany the rainfall event.

Mechanical and electrical parts need to be exercised regularly to provide confidence that parts will operate when needed.

Vandalism and theft of metals is a considerable risk. The removal of significant parts may go unnoticed due to the low frequency of use. Should a gate fail to operate during a storm event, significant downstream flooding may occur with zero storage being achieved.

Operation of gates can be susceptible to trash blockage. Guidance on debris control is given in Section 3.6.4.

Passive control

Passive control of a typical flood storage reservoir is provided through a pipe or culvert under or through the impounding embankment. A fixed orifice plate is often incorporated across the culvert entrance that can be easily changed for a different size to accommodate any later changes in the scheme design.

The disadvantage of a passive piped control is that it cannot be operated to provide the most advantageous flow regime and as such the flood storage reservoir must be larger and less efficient than with an active solution. Pipes and culvert hydraulic performance is also affected as the headwater and tailwater level rise and fall. This impact needs to be considered throughout the design.

Further types of passive control have been developed such as vortex and baffled devices. These are discussed further in Section 3.2.1 and Appendix A.

2.2.5 Provision of permanent water retention storage

Although the majority of flood storage reservoirs are designed to drain dry following flood events, it is possible to design such reservoirs to permanently retain a pool of water. This can be achieved, for example, by excavating fill material from the reservoir area such that the borrow area extends below the original watercourse bed level allowing the area to fill with water when in service. This approach is often used where the reservoir is in an urban setting and can provide a visual amenity, environmental enhancement and ecological enhancement.

The benefits and risks of providing a permanent pool of water vary in each case under consideration. Some potential considerations include:

- **Silt management**: any permanent pond will reduce in capacity over time due to sedimentation unless maintained through silt removal works – this might be viewed as a benefit or a liability
- **Surveillance**: if the upstream face of the embankment cannot be viewed under normal flow conditions due to impounded water or water margin vegetation such as reeds, the condition of the structure cannot be assured by those tasked with reporting on its condition
- **Public safety**: reasonable precautions are needed to mitigate public safety risks at the flood storage reservoir
- **Environmental benefits and management requirements** such as habitat creation and design considerations to avoid areas of stagnant water and/or insects

Case study 2.1: Cobbins Brook flood alleviation scheme

The material used to construct the flood storage reservoir was taken from borrow areas within the reservoir basin. The excavations were shaped to blend into the surrounding landscape, leaving a number of ponds and creating a range of wetland habitats including wet woodland, seasonal ponds and lowland meadows.

(a) Cobbins Brook borrow area reinstated as a wetland pond. The photograph was taken in November 2009 immediately following construction.

(b) Cobbins Brook borrow area reinstated as a wetland pond. The photograph was taken in May 2013 following establishment of the site.

Photographs courtesy of ATPEC Ltd

2.2.6 Other uses for flood storage reservoirs

Many of the flood storage reservoirs in the UK are set in rural environments where the secondary use of the land is for agriculture. Where reservoirs are within urban environments, numerous possible uses are made of the storage basin area such as parklands and sports fields. The use of the flood storage area for car parking should be avoided as parked cars can float and block outlets during a flood. Further design guidance is provided in Section 3.5. Particular consideration during the planning phase should be given to:

- public safety and evacuation of the area when the reservoir is in operation
- how flood-borne sediment and debris might affect the area and associated management options
- drainage of the area: if parklands and sports fields remain waterlogged for an extended period following floods this will affect the scheme viability – in some cases land drains and/or sumps and pumps are used to ensure that the secondary use is viable shortly after flood events
- opportunities for environmental improvement, nature conservation and ecology

Within rural environments the main considerations are:

- Crop damage: compensation arrangements may apply
- Livestock: check that animals can escape the rising floodwater and consider the risks associated with livestock on embankments
- Access: impacts on public rights of way and minor roads

- Opportunities for environmental improvement, nature conservation and ecology

In terms of access, it may be necessary to establish alternative routes, set restrictions or provide signage to mitigate risks associated with temporary loss of access routes. Consideration also needs to be given to emergency access requirements and operational access to structures during flood events where deemed necessary. This applies not only to access routes within the storage area itself, but accessibility on local roads. For example, where the only local road to the site is prone to flooding, this is likely to make the site unviable. A review of local access routes and flood risk is therefore appropriate.

Further consideration should be given to the incorporation of:

- permanently wet areas that could provide ecological enhancements and recreational water sport opportunities
- wetland areas (wet/dry), predominantly for ecological enhancements with possibly opportunities to incorporate nature trails

Within wetland areas, consideration should be given to avoid the formation of islands that could strand and endanger individuals or livestock during a flood event. For very large flood storage areas, however, the use of islands for refuge could be seen as desirable.

2.3 Legal considerations

2.3.1 Planning and consents

The consents required to construct or modify a flood storage reservoir should be discussed and agreed with the relevant authorities at an early stage in the project to define the work required and avoid delays in implementation.

Table 2.1 provides a summary of current important European Union (EU) legislation and is intended to aid discussions with the relevant authority and to highlight typical issues that may arise. However, legal requirements are subject to amendment and confirmation of what current consents are required should form part of early discussions with the relevant authorities. The UK legislation responding to the key directives is discussed below.

Table 2.1 Key EU directives

Directive	Purpose	Requirements
Floods Directive	The directive requires Member States to: • assess whether all their watercourses and coastlines are at risk from flooding • map the flood extent and assets and humans at risk in these areas • take adequate and coordinated measures to reduce this flood risk	Requires the preparation of flood risk management plans. Encourages coordination with the Water Framework Directive and river basin management plans to make the most of opportunities to deliver multiple benefits, streamline delivery or to coordinate monitoring and stakeholder engagement
Water Framework Directive (WFD)	The directive requires Member States to achieve 'no deterioration' of WFD status for water body or quality elements and no prevention of actions identified as needed to achieve 'good ecological status or potential'.	At project level, a WFD assessment is required to support applications for flood defence or land drainage consent and planning permission. Schemes should also seek to deliver WFD actions as part of environmental enhancements where possible, for example, via mitigations.
Habitats Directive	The directive forms the cornerstone of the EU's nature conservation policy. It protects over 1,000 animals and plant species, and over 200 'habitat types' (for example, special types of forests, meadows and wetlands) that are of European importance.	Requires the protection of Special Protection Areas (SPAs) and Special Areas of Conservation (SACs), known as Natura 2000 sites (or European sites in the UK). Under UK policy, proposed and candidate SPAs and SACs, and Ramsar sites are also given the same protection. Works that are likely to affect a European site (including proposed works outside the site boundary) require an Appropriate Assessment to assess whether there may be adverse effects on the site.
Environmental Impact Assessment (EIA) Directive	The directive applies to the assessment of the environmental effects for public and private projects that are likely to have significant effects on the environment.	Requires the preparation of an Environmental Impact Assessment (EIA) if the new dam falls under the mandatory requirements of Schedule 1, including 'Dams and other installations designed for the holding back or permanent storage of water, where a new or additional amount of water held back or stored exceeds 10 million cubic metres'. Or under Schedule 2, which states that the 'construction of dams and other installations to hold water or store it on a long-term basis' might require EIA. Advice in the UK is sought through the local planning authority.

A summary of the possible issues that typically arise during the implementation of flood storage projects are set out in Table 2.2. This is not an exhaustive list and advice should always be sought from the regulating authorities. It should also be noted that public bodies in the UK have a duty to conserve and enhance biodiversity, so far as it is consistent with the exercise of its functions under a variety of legal statutes including the Natural Environment and Rural Communities (NERC) Act 2006 (England and Wales), Nature Conservation (Scotland) Act 2004, Wildlife and Natural Environment Act (Northern Ireland) 2011, the Countryside and Rights of Way (CROW) Act 2000, Environment Act 1995 and Water (Northern Ireland) Order 1999.

The regulating authorities referred to in the Table 2.2 include:

- **England**: Natural England, Environment Agency, Historic England, local planning authorities, Lead Local Flood Authorities (LLFAs) and Internal Drainage Boards (IDBs)
- **Wales**: Natural Resources Wales, Cadw, local planning authorities
- **Scotland**: Scottish Natural Heritage, SEPA, Historic Scotland, local planning authorities
- **Northern Ireland**: Department of Environment Northern Ireland (DOENI) Environment and Heritage Service Northern Ireland, EHS(NI); Northern Ireland Environment Agency (NIEA); Rivers Agency (an agency within the Department of Agriculture and Rural Development); local planning authorities

More information can be found on the NetRegs website for Scotland and Northern Ireland (www.netregs.org.uk), the Planning Portal (www.planningportal.co.uk) and the websites of Scottish Natural Heritage, Natural England, Natural Resources Wales, Department of Environment Northern Ireland, Environment and Heritage Service Northern Ireland, Historic Scotland, Historic England and Cadw.

Table 2.2 Summary of important considerations for planning and consents

Key issue	Commentary
Does the scheme involve works in or near a main river or an ordinary watercourse?	Consent is required in the UK to carry out works that affect a main river (a watercourse marked as such on a main river map, and can include any structure or appliance for controlling or regulating the flow of water into or out of a main river) or an ordinary watercourse (a watercourse through which water flows (other than a public sewer) which does not form part of a main river). Guidance on consents for work in watercourses is available from the Environment Agency, SEPA, DOENI and Natural Resources Wales. Note in England consenting on main rivers is the responsibility of the Environment Agency and for ordinary watercourses it is the responsibility of the LLFA and the IDB.
Does the works involve impoundment?	Guidance is provided by the regulatory authorities including Environment Agency, SEPA, DOENI and Natural Resources Wales.
Does the work involve alteration to ‘flood management assets’?	Guidance is provided by the LLFA and IDB.

Key issue	Commentary
Are the works likely to cause pollution to surface and groundwater resources	Guidance is provided by the regulatory authorities including Environment Agency, SEPA, DOENI and Natural Resources Wales.
Are there protected wildlife sites or species present?	The Conservation of Habitats and Species Regulations 2010 (as amended by the Conservation and Species Amendments Regulations 2011 and 2012) provide additional protection for certain species known as 'European protected species'. The Regulations also provide for the designation and protection of 'European sites'. This supplements national legislation including the Wildlife and Countryside Act 1981. Guidance is provided by the regulatory authorities including Natural England, Scottish Natural Heritage, DOENI and Natural Resources Wales as well as the Environment Agency and SEPA. Badgers are protected under the Protection of Badgers Act 1992 and a common concern at UK reservoir sites.
Are there invasive species present?	Guidance on the responsibilities for biosecurity and legal duties not to spread non-native invasive species (under the Wildlife and Countryside Act 1981) is provided by regulatory authorities including Natural England, Scottish Natural Heritage, DOENI and Natural Resources Wales as well as the Environment Agency and SEPA.
Will fish or eel passage be affected?	It is an offence to: • obstruct the passage of salmon, migratory trout or eels • cause direct mortality to fish • cause the degradation of habitats for fish • allow any deleterious matter to enter a river or watercourse (except under licence) There is a requirement to construct eel and fish passes at obstructions to allow upstream migration and downstream passage of eels, salmon and migratory trout. Eel and fish screens to prevent harm may also be required. Technical fish passes may require Fish Pass Approval under Salmon and Freshwater Fisheries Act (SaFFA) licensing. Conditions on licences to protect fish, fish passage or habitats maybe required.
Are heritage features present?	Known designated heritage assets include World Heritage Sites, scheduled monuments, listed buildings, conservation areas, battlefields and registered parks and gardens. Consent is required for works to scheduled monuments and listed buildings. Note that unknown features may also be present. Guidance on consents is available from Historic England, Historic Scotland, DOENI and Cadw.
Is there likely to be a significant impact on the landscape or views? Are protected trees present?	Landscapes with varying degrees of protection may fall under Conservation Areas, Registered Parks and Gardens, National Parks, Areas of Outstanding Natural Beauty, Heritage Coasts and World Heritage Sites. Other landscapes may also be considered under Natural England's 'All Landscapes Matter'.

Key issue	Commentary
	Under the National Planning Policy Framework (NPPF) and the European Landscape Convention, not only ‘designated landscapes’ but also the wider landscape should be recognised and evaluated. Tree preservation orders may also be in place. Guidance is available from the local planning authority, Natural England and Scottish Natural Heritage.
Is planning permission required?	Planning authorities will advise whether proposed works are permitted development or require planning permission. The NPPF also provides policy guidance relating to sustainable development in open countryside. A flood risk assessment may be required if the proposed works or changes in use are located in flood risk areas or if the proposed works are larger than a hectare. An EIA may be required and it is good practice to obtain a screening opinion for all projects from the local planning authority.
Does the scheme fall under relevant reservoir safety legislation?	For a flood storage reservoir to fall under reservoir safety legislation, a dam, barrier or detention embankment must be present and the retained volume of water raised above the level of natural ground must exceed a threshold value defined in national legislation. At the time of publication the threshold values are 25,000m^3 in England and 10,000m^3 in Scotland, Wales and Northern Ireland. An All Reservoirs Panel Engineer will need to be appointed under the provisions of the relevant legislation and will be required to oversee the design and construction of the reservoir. The relevant national Enforcement Authority must be informed prior to construction of a new reservoir.

Legal requirements are subject to change and advice should always be sought from the regulating authorities. The following section discusses some of the typical consenting regimes and considerations that may arise.

2.3.2 Water Framework Directive

The WFD was transposed into law in England and Wales by the Water Environment (Water Framework Directive) (England and Wales) Regulations 2003, and in Scotland by the Water Environment and Water Services (Scotland) Act 2003.

The directive aims for all water bodies to achieve good status. For surface waters, good status consists of ‘good ecological status’ (or good ecological potential where artificial or heavily modified[1]) and ‘good chemical status’. Ecological status and ecological potential are assessed using a number of biological, hydromorphological, physical and chemical considerations.

[1] An artificial or heavily modified water body is a body of water that has been significantly altered by physical modifications (heavily modified) or created (artificial) for specific uses. Good ecological potential recognises that the modifications to a water body that are necessary to maintain its use will prevent it from reaching good ecological status.

The Environment Agency and Natural Resources Wales are the lead authorities for the WFD in England and Wales, respectively. Their guidance, ‘Assessing new modifications for compliance with WFD’ (Environment Agency 2010a) defines the process of assessing the impacts of new modifications in the water environment to ensure compliance with the WFD.

The directive’s requirements will need to be considered at all stages of a watercourse planning and development process. The development of a new flood storage scheme has the potential to affect WFD objectives and therefore the current and future status of a water body that may be affected by the new scheme will need to be considered.

In the context of the WFD, the water environment includes watercourses, lakes, estuaries, groundwater and coastal waters out to 1 nautical mile. These are more broadly classified as surface waters (including natural, artificial and heavily modified water bodies) and groundwater.

If a WFD assessment is required, the assessment will consider the proposed new flood storage against the WFD status and objectives for water bodies that may be affected.

The WFD requires that the current and future status of a water body be considered when all new activities in the water environment are planned. This would include consideration of mitigation measures identified within the relevant river basin management plan where a water body is artificial or heavily modified. An assessment of the potential impacts on planned mitigation measures is part of the WFD assessment.

2.3.3 Nature conservation – protected sites and species

Environmental legislation in the UK encompasses a range of statutory instruments including those with the aim of conserving and enhancing biodiversity.

The construction of a new flood storage reservoir has the potential to adversely affect habitats and species and would need to comply with the overall objective of no net loss of biodiversity – an aim of the EU Biodiversity Strategy to 2020. The construction and operational activities must comply with international, European and UK nature conservation legislation, and with national and local biodiversity policies. The principal mechanisms for wildlife protection in the UK are the Wildlife and Countryside Act 1981 and the Conservation of Habitats and Species Regulations 2010 (as amended by the Conservation and Species Amendments Regulations 2011 and 2012).

The Wildlife and Countryside Act 1981 implements the Convention on the Conservation of European Wildlife and Natural Habitats (Bern Convention) in Great Britain and European directives on natural habitats, wild fauna, flora and birds. The Act covers:

- the protection of wildlife, including birds, their nests and eggs, wild animals, mammals and wild plants
- countryside and national parks, and the designation of protected areas
- public rights of way, including footpaths and bridleways

The Conservation of Habitats and Species Regulations 2010 (as amended by the Conservation and Species Amendments Regulations 2011 and 2012) provides additional protection for those species known as European protected species. It also provides for the designation and protection of European sites. European sites include SPAs, SACs, candidate SACs and proposed SPAs, as well as Sites of Community Importance (SCIs).

In accordance with Article 6(3) of the Habitats Directive, 'Article 6 Assessments' are required where a plan or project not directly connected with or necessary to the management of a European site(s), may give rise to significant effects upon a European site(s). The requirement for Article 6 Assessments has been transposed into UK law under the Conservation of Habitats and Species Regulations 2010 (as amended by the Conservation and Species Amendments Regulations 2011 and 2012) and is commonly referred to as a 'Habitat Regulations Assessment' (HRA) or an 'Appropriate Assessment'. 'Appropriate Assessment' is taken to mean an assessment which is 'appropriate to its purpose under the Habitats Directive and Habitats Regulations'. In the UK, an assessment will be required where a potential plan or project is considered likely to have a significant effect on wetland sites of international importance (Ramsar sites).

Where international and European sites are present, the requirement to carry out an HRA will need to be assessed at an early stage in the decision process for a new flood storage reservoir to accommodate the programme of field survey requirements and to avoid potentially significant problems at a later stage.

2.3.4 Fish passage

Online flood storage reservoirs have the potential to result in the loss of habitat connectivity and habitat fragmentation, which in turn may result in the isolation of aquatic populations and a consequent reduction in gene pool diversity or even local extinction. This is particularly relevant for fish species that migrate between freshwater and the sea, but also for other fish species because all fish species in the UK undertake migration to some degree within the freshwater environment.

The Salmon and Freshwater Fish Act 1975 was created to protect all fish species but particularly the migration routes of salmon and migratory trout. Under this Act:

> 'It is the duty of the owner or occupier that when constructing dams, increasing an obstruction, constructing screens or sluices to make and maintain a fish pass (Section 9) for migratory salmon or trout. The fish pass must be maintained in an efficient state'.

Fish passage in Scotland is covered by the Salmon (Fish Passes and Screens) (Scotland) Regulations 1994 and the Salmon and Freshwater Fisheries (Consolidation) (Scotland) Act 2003.

In 2010, the Eels (England and Wales) Regulations 2009 came into force. Under these regulations there is a requirement to notify the Environment Agency of the construction, alteration or maintenance of any structure likely to affect the passage of eels and to construct and operate an eel pass to allow the free passage of eels. This may include removal of any obstruction, the use of eel screens to prevent entrainment or impingement from water abstraction and discharge points and, if necessary, the use of a bywash to return unharmed excluded eels to the waters they came from.

In addition to these pieces of legislation, the Habitats Directive and Water Framework Directive offer protection to fish. These may need to be considered depending on the location of any flood storage reservoir.

Relevant information dealing with fish pass construction and design can be found in the 'Fish Pass Manual' (Environment Agency 2010b) and 'The Eel Manual – Elver and Eel Passes' (Environment Agency 2011a).

There are a number of technical guides to fish passes or fishways, but a good overview can be found in 'From Sea to Source: International guidance for the restoration of fish migration highways' (Gough et al. 2012). This guidance constitutes the first global guidance for the restoration of fish migration in watercourses. It builds on worldwide case studies so that developers can gain from the experience of others providing solutions for hazards and obstacles as well as guidance on monitoring programmes.

The River Restoration Centre's 'Manual of River Restoration Techniques' includes case studies dealing with obstruction of fish migration and habitat impacts (River Restoration Centre 2013).

2.3.5 Invasive species

The Great Britain Non-Native Species Secretariat provides a useful and comprehensive collection of information on invasive species recorded in the UK. The website (www.nonnativespecies.org) provides species ID sheets and information on individual species. This information covers all groups and in addition provides guidance on risk analyses, action plans, species alerts and links to relevant legislation.

2.3.6 Landscape

Article 1 of the European Landscape Convention defines landscape as:

> 'an area, as perceived by people, whose character is the result of the action and interaction of natural and/or human factors'.

The preamble to the convention sets out that

> 'the landscape has an important public interest role in the cultural, ecological, environmental and social fields, and constitutes a resource favourable to economic activity and whose protection, management and planning can contribute to job creation; … is an important part of the quality of life for people everywhere: in urban areas and in the countryside, in degraded areas as well as in areas of high quality, in areas recognised as being of outstanding beauty as well as everyday areas'.

This emphasises that all landscapes are valued, whether designated or not.

Protected/designated landscapes and landscape features include:

- National Parks
- Areas of Outstanding Natural Beauty
- historic landscape including designed parklands and gardens
- 'important' hedgerow under the Hedgerows Regulations 1997
- trees covered by Tree Preservation Orders

Urban designations may also include Conservation Areas.

2.3.7 Heritage

Heritage is a collective term used to cover a number of subject areas, including:

- archaeology
- individual historical buildings and structures
- historic townscape
- historic landscape including designed parklands and gardens

- industrial heritage and development
- designed parklands and gardens
- ancient hedgerows
- battlefields and war memorials

All these heritage assets are subject to different designations and consenting regimes.

A system of protection, research and interpretation is promoted in the UK with different national agencies responsible.

The process for consent applications varies between authorities. It is recommended that experienced practitioners consider the cultural heritage significance associated with the site at an early stage. This will allow the potential impact on the historic environment to be assessed, and inform any decisions that may arise from potential conflicts and, if required, to make applications for flood storage reservoirs affecting heritage features.

The heritage of a site must be considered during the design of a flood storage reservoir to:

- protect heritage assets that are irreplaceable
- record and preserve historic features for future generations if appropriate
- interpret heritage features, encouraging a better understanding of an area's past use and development
- allow early identification of heritage so suitable project budgeting is incorporated

There is a considerable risk that unknown heritage features will be discovered during the construction phase. Should this risk be realised, there is the potential for significant delays and cost to the project while it is being investigated and mitigation measures are taken.

2.3.8 Planning permission

Planning decisions in the UK are policy-led. This means that applications for planning permission must conform to national and local planning policy to be successful.

The national planning policy for England is set out in the National Planning Policy Framework (NPPF) (DCLG 2012). The NPPF should be read as a whole, but the most relevant section with regard to floodwater management is Section 10: Meeting the challenge of climate change, flooding and coastal change.

The national planning policy for Wales is set out in the Planning Policy Wales 2016. (Welsh Government 2016).

Local planning policy is determined at a local authority level. Each local planning authority is required to publish a local plan and make it available for view on the local authority website. There may also be supplementary planning documents setting out further policy for design, heritage and similar issues. These are adopted and published at the discretion of the local authority.

Local authorities offer a pre-application consultation service, where planning officers meet with prospective applicants. The aim of this service is to establish whether a local authority will support a planning application and what supplementary reports and information may be required to support the planning application. Pre-application consultation with the local authority early in the process is always recommended.

Assuming that the proposal does not fall under the EIA regulations (see below), a typical range of documents to support a planning application would be:

- flood risk assessment (where the site is located within an Environment Agency flood zone 2 or 3 or the site area exceeds 0.5 hectares)
- planning statement
- tree survey to BS5837
- preliminary ecological appraisal and protected species reports as appropriate
- construction traffic management plan
- agricultural land assessment
- contaminated land assessment
- heritage and landscape assessment

All works affecting main rivers and ordinary watercourses will need consents and WFD assessment whether or not planning permission is required.

The time period for determining a planning application for a flood storage reservoir will be 13 weeks, or 16 weeks if the scheme is an EIA development. The determination period only starts once the application is declared valid by the local authority (that is, it is satisfied it has the information needed to determine the application and the fee has been paid).

The planning process encourages public participation. All information submitted to the local authority will be available for public comment. Scheme promoters should take public opinion into account prior to submitting planning applications and formal public consultation may be appropriate depending on the circumstances of the scheme.

Previous projects have demonstrated the value of a consultee newsletter. This provides a simple means for making project team members and consultees aware of current issues, progress and any deadlines for stakeholder inputs to the consultation process.

Environmental impact assessment

There are a number of parliamentary orders and regulations governing the content of planning applications. The most important with regard to the construction of flood storage reservoirs are the Town and Country Planning (Environmental Impact Assessment) Regulations 2011 (the EIA Regulations) as amended in 2015.

Environmental impact assessment (EIA) is a process to determine the potential effects of a scheme on the local environment. Schedule 1 of the EIA Regulations specifies mandatory requirements for an EIA assessment, while Schedule 2 specifies a range of developments where an EIA might be required, subject to defined threshold criteria and the potential effects of the project on the local environment.

A Schedule 2 development under the EIA Regulations includes the ‘construction of dams and other installations to hold water or store it on a long-term basis’ if the area exceeds the threshold of 1 hectare. The process for determining if EIA is required is known as screening. This is a process set out in the EIA Regulations where applicants provide prescribed information to the local planning authority. The local planning authority is required to respond to the applicant confirming if an EIA is required within 21 days.

The exception to the process set out above is where the proposed reservoir would be located in what the EIA Regulations define as a sensitive area. Sensitive areas include:

- National Parks
- the Broads and Areas of Outstanding Natural Beauty
- World Heritage Sites
- scheduled monuments
- European designated sites under the Habitats and Species regulations
- Sites of Special Scientific Interest (SSSIs)

Proposals in sensitive areas should always be subject to a screening request irrespective of the size of the proposal. If the development is defined as falling under the EIA Regulations, a scoping opinion from the relevant authority will define what issues need to be addressed in the EIA that will support a planning application.

How long does the planning and consents process take?

Adequate time should be allocated for planning to gain all the required permissions. This process could take a minimum of 2 years to complete, with a 3-year programme being more realistic. However, it can take much longer depending on the complexity of the scheme or if significant land ownership negotiations are required.

Box 2.2: High level example programme from planning to construction for a new flood storage reservoir

Depending on the complexity of a scheme, this programme may need to be extended. It is provided to give the reader a general understanding of the challenges to obtain planning permission. The process assumes all land ownerships is agreed and in place; if this is not the case the timeline could be considerably longer. For complex schemes, it would not be unreasonable for the process to take up to 10 years.

- **Year 1.** Start the planning process. Hold initial discussion with the local planning authority, the Environment Agency and other key stakeholders. Collect available site data including flow data, ground information and topographic information. Apply for pre-planning application advice.
- **Year 2.** Commence environmental studies, hydraulic modelling, flood risk assessments and any other site specific studies highlighted through initial stakeholder engagement. Continue to engage consultees through progress update, newsletters and public workshops.
- **Year 3.** Apply and obtain planning permission. Commence the detailed design phase, on completion tender work for construction.
- **Year 4.** On completion of all studies, agreement of planning permissions and award of construction contract the construction phase can commence.

Where to get good advice?

The most commonly used strategy is to hire a consultant with reservoir design capabilities. The reservoir engineer will be able to advise on technical issues arising during the planning phase. They will also be able to continue support into the detailed design and construction phases. The design consultant will not build the structure and a separate construction contract will be required. Other technical support, such as ecologists, fluvial geomorphologists and planning experts may be required and this advice can be procured separately or may be available in-house from larger consultant organisations.

An alternative approach is to hire a design-and-build contractor with experience in flood storage reservoirs. They could provide competent technical experts and a complete service through planning, design, construction and commissioning.

Both options have benefits and it is very much the choice of the client which to choose. It is wise to ensure the engineer chosen has adequate experience in the design of flood storage reservoirs.

If the reservoir falls within the scope of the Reservoirs Act 1975, an All Reservoirs Panel Engineer appointed under its provisions will be required to oversee the design and construction of the reservoir (see Section 2.3.10).

2.3.9 Land ownership

Land negotiations will be required for the construction of nearly all new flood storage reservoirs. This process can take the form of land negotiations or compulsory purchase orders where available. Both can take significant time to complete. Land negotiations should be conducted by a specialist and should commence at the earliest opportunity. The agreements will need to take into consideration the requirements of the landowner and may therefore place unexpected constraints on the design process.

Land purchase agreements need to be carefully thought through with due consideration of the area and frequency of flooding of the reservoir area. The 3 main land purchase considerations are as follows:

- Purchase the entire area to be flooded.
- Purchase the footprint of the dam structure, including access around its toe.
- Purchase the required access routes.

Further consideration could be given to leasing land or the opportunity for a grant deed.

If only the dam embankment area is purchased, an agreement with the landowner(s) of the reservoir basin area will be needed with regard to the areas affected by flooding. Such agreements will need to consider how compensation is given to the landowner. For example, compensation may be a lump sum or per event payment above a threshold level.

As a minimum, the agreement will have a ‘right to flood’ clause. Also typically included in the agreement will be a list of restrictions that the land cannot be used for. Some of the most important aspects to consider are:

- exclusion of cattle or horses from the dam structures (embankment only)
- car parking
- hay making

- public events
- tree planting on and alongside the embankment and basin

Any obligations should bind current and future owners, so as to run with the land and should be registered as such on title deeds.

2.3.10 Reservoir safety legislation

Many flood storage reservoirs fall within the ambit of national reservoir safety legislation, which provides statutory controls on how reservoirs are designed, constructed, altered and monitored to promote reservoir safety.

Reservoirs with a raised capacity of 25,000m^3 or above located in England and 10,000m^3 or above located in Wales are covered by the Reservoirs Act 1975 with some differences applying between the two countries in terms of application. Reservoirs of raised capacity more than 10,000m^3 located in Scotland are covered by the Reservoirs (Scotland) Act 2011. Reservoirs of raised capacity more than 10,000m^3 and located in Northern Ireland are covered by the Reservoirs Act (Northern Ireland) 2015.

General guidance from Defra and the Environment Agency can be found at: www.gov.uk/guidance/reservoirs-owner-and-operator-requirements

Guidance is available on the application of the Reservoirs Act 1975 to reservoirs located in England (ICE 2014).

Guidance from Natural Resources Wales on reservoirs located in Wales is given at https://naturalresources.wales/water/reservoir/reservoir-safety-guidance-for-owners-and-operators/?lang=en

Guidance from SEPA on reservoirs located in Scotland is given at www.sepa.org.uk/regulations/water/reservoirs/

Guidance on the reservoir safety legislation for Northern Ireland is not currently available. Reference can be made to the Northern Ireland Assembly website at:

http://www.niassembly.gov.uk/

Under recent changes to reservoir safety legislation, the regulatory controls are set according to a risk-based approach. The enforcement authorities (Environment Agency for reservoirs in England, Natural Resources Wales for Wales and SEPA for Scotland) will determine the risk category associated with dam failure and the risk of public endangerment. For 'high-risk' reservoirs in England, for example, panel engineers must be appointed to:

- oversee the design and construction of the reservoir
- carry out routine visits and to report on the condition of the reservoir on a yearly basis
- carry out detailed inspections at intervals not exceeding 10 years
- supervise the completion of recommended statutory measures arising such as remedial and improvement works
- oversee the design and construction of any works which alters the statutory reservoir capacity as defined above
- oversee any design and construction works to remove the reservoir

Under the relevant national legislation, obligations are placed on the operator or owner (termed the 'undertaker' under English and Welsh legislation) to maintain records and provide information.

At the early planning stage for a new statutory flood storage reservoir, it is recommended that an appropriate panel engineer is appointed to act in the capacity of Construction Engineer for the reservoir. A Construction Engineer must be appointed before any new statutory reservoir is impounded. The current list of panel engineers is available on GOV.UK.[2] A Construction Engineer will typically be drawn from the list for All Reservoirs Panel Engineers. For the development of non-statutory flood storage reservoirs, the appointment of a Panel Engineer is not a legal requirement but is recommended nevertheless.

When the Construction Engineer is satisfied that the completed reservoir is performing to their satisfaction, a 'Final Certificate' will be issued and the reservoir will formally enter service. A Supervising Panel Engineer will then be appointed to visit the reservoir regularly and prepare yearly statements. Periodic inspections by an independent Inspecting Engineer will also be required. The enforcement authority might opt to assign the reservoir risk designation after receipt of the construction certification.

2.4 Hydrological and hydraulic modelling studies

2.4.1 Catchment studies

Catchment studies are required to support the estimation of potential flood run-off. Run-off from a particular rainfall event is influenced by various factors including soils, topography, stream networks, land use and the size of the catchment area. Of these, the most significant are typically the size of the catchment area and the land use, in particular the extent of urbanisation which increases both the amount of run-off and the speed of response to rainfall.

Catchment characteristics of any UK catchment whose area is larger than 0.5km^2 are available from the Flood Estimation Handbook Web Service (https://fehweb.ceh.ac.uk). These may be supplemented by information obtained from maps and site observations.

2.4.2 Identification of potential areas of flood storage

Potential areas for flood storage may be identified from a range of sources including maps, site observations, aerial photography and LiDAR. Figure 2.8 shows an example of a LiDAR map of a flood storage reservoir.

Flood storage reservoirs may be online or offline (see Section 2.2). If they are offline consideration should be given to flow paths from the watercourse to the storage area and subsequently back to the watercourse. Consideration should also be given to how extreme flows will be managed.

[2] www.gov.uk/guidance/reservoirs-owner-and-operator-requirements#when-to-appoint-a-panel-engineer

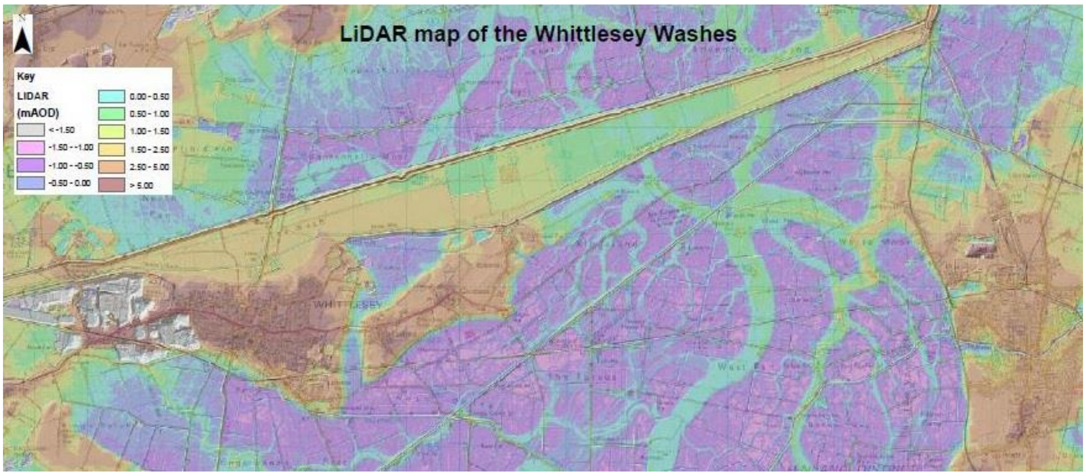


Figure 2.8 LiDAR map of Whittlesey Washes flood storage reservoir

2.4.3 Flood studies, flood routing and storage sizing

The advice of an experienced hydrologist should be sought during the planning and design of flood storage reservoirs. Flood study requirements, including flood estimation, routing and storage sizing, are covered in the following references.

- 'Fluvial Design Guide' (Environment Agency 2009a)
- 'Flood Estimation Guidelines' (Environment Agency 2015a) – available electronically on request from the Environment Agency (enquires@environment-agency.gov.uk)
- 'Design of Flood Storage Reservoirs' (CIRIA 1993)
- 'Small Embankment Reservoirs' (CIRIA 1996)

Some details of the last 2 of these reports have been superseded as the methods of the 'Flood Studies Report' (Institute of Hydrology 1975) have largely been replaced by the 'Flood Estimation Handbook' (FEH) (CEH 1999). However, the structure of the approach remains broadly unchanged. Flood estimation using the FEH makes use of catchment characteristics derived from the FEH Web Service; this updates and replaces the FEH CD-ROM application (CEH 2009).

A range of rainfall run-off models are available; reservoir flood estimation typically uses the FEH rainfall run-off method or the Revitalised Flood Hydrograph (ReFH) method.

In planning and designing flood storage reservoirs, flood estimation work is required in relation to:

- reservoir sizing and determining the optimum standard of flood protection (typically for return periods up to 100 years) that the selected site(s) can support (see Section 3.1.1)
- extreme flood event estimation to consider the safety of the reservoir against breaching (spillway design and/or tolerance to crest overtopping) (see Section 3.1.2)

In relation to the latter design requirement and following the approach described in Floods and Reservoir Safety (ICE 2015), the design flood return period and the 'safety check' flood return period are determined by the category of the dam which relates to reservoir risk. The majority of flood storage reservoirs fall into 'dam category A' whereby 10 or more inhabitants could be endangered in the event of a dam breach. In this case, the appropriate design flood is the 10,000-year flood and the safety check flood is the probable maximum flood (PMF). The dam structures will need to be designed to accommodate the design flood with an appropriate freeboard, and the dam must be capable of withstanding passage of the safety check flood without failure.

In routing extreme flood events through the reservoir, it is acceptable to assume that the reservoir is empty at the commencement of the flood. In the case of flood storage reservoirs, note that it may not be appropriate to apply the quoted standards where it can be shown that the incremental effect of dam failure on the downstream population is small. To inform the appropriate safety check design standard a range of extreme flood events with and without dam failure should be assessed. At the planning stage, it may be appropriate to simply assume that the relevant standard in Floods and Reservoir Safety will be appropriate for the final design, recognising that some efficiency might be gained from detailed design studies of incremental flood risk.

The PMF is usually assessed by applying the estimated probable maximum precipitation (PMP) to a rainfall run-off model of the catchment as described in the FEH.

2.5 Preliminary environmental design

2.5.1 Initial data gathering

Environmental design principles should be considered in parallel with the technical design of a flood storage reservoir throughout the design and implementation process. Consideration should also be given to maintenance procedures and responsibilities (see Section 3.6). This should include:

- consideration of possible future funding of maintenance operations
- setting maintenance objectives to:
  - achieve potential environmental benefits
  - meet asset management requirements
  - maintain structural embankment integrity

Collation of baseline background data should identify the site-specific constraints and opportunities. This will include the consideration of both statutory and non-statutory designations and current legislation requirements, such as the presence of internationally and nationally protected sites and species, as well as defining the user groups who may have a vested interest in the site. Often environmental issues are viewed as problems but creative approaches can enable projects to achieve multiple benefits, perhaps wider than the original aims of the project.

Geomorphology and sedimentation

As the operation of a flood storage reservoir is likely to alter the fluvial geomorphology and sediment regimes of the associated watercourse, a geomorphological assessment should be made during the planning phase so that the baseline is understood. Analysis will then be required at the detailed design stage to understand how the construction and operation of the flood storage reservoir will alter factors such as the watercourse discharge, sediment load and the channel morphology. The design of the watercourse should ideally mirror the existing; where the existing has been heavily modified, however, there may be opportunities to enrich the environment by incorporating meanders and ecological enhancements.

The ‘Guidebook of Applied Fluvial Geomorphology’ (Sear et al. 2003) should be consulted for further detailed advice on channel design and assessment.

Biodiversity

The provision of a new flood storage reservoir may result in a significant change in habitats and land use. These modifications may lead to impacts and loss of biodiversity. Conversely, some options may result in beneficial effects depending on regional location, the waterbodies affected and local conservation drivers.

To evaluate ecological constraints and impacts (both negative and positive), an early understanding of the habitats and species present is of paramount importance. This understanding should be sought at the initial stages in the process and may include a Phase 1 Habitat Survey, reported in the form of a Preliminary Ecological Appraisal (PEA). The PEA should also include a desk study highlighting any protected sites and habitats and species of conservation importance (such as those on the S41 and S42 lists). Ideally the results of the PEA should inform the options decision process. The objectives of doing this, where possible, at an early stage would be to:

- avoid ecological damages and adverse impacts
- maximise potential positive effects
- include high level conservation drivers in the optioneering process

Available guidance on early project phase surveys includes:

- Handbook for Phase 1 Habitat Survey – a technique for environmental audit’ (JNCC 2010)
- ‘Guidelines for Preliminary Ecological Appraisal’ (CIEEM 2013)

For an online flood storage reservoir, a River Habitat Survey (RHS) and a River Corridor Survey (RCS) are standardised methods to collect hydromorphological and ecological information on a water body. The length of water body surveyed should extend beyond the estimated area of the new reservoir – typically 500m beyond the area of influence of the scheme as this needs to be reviewed on a site-specific basis. This data can be used to determine aquatic habitat loss and the availability of these habitats in stretches not affected by the flood storage reservoir. Available guidance includes:

- ‘River Habitat Survey in Britain and Ireland’ (Environment Agency et al. 2003)
- ‘River Corridor Surveys’ (NRA 1992)

Note that a certified surveyor is required to undertake River Habitat Surveys.

Following initial surveys, recommendations may be made requiring further detailed ecological assessment, for example, where the potential for the presence of species and habitats with legal protection or of conservation importance has been highlighted.

The PEA, species-specific surveys and botanical surveys should be undertaken by qualified and experienced ecologists following acknowledged best practice guidance. A list of this existing guidance for species surveys is provided in Appendix D.

Further detailed surveys that are likely to be required may include:

- specific protected species surveys, terrestrial and aquatic species
- macrophyte surveys following UKTAG (2014) guidance
- macroinvertebrate surveys following BS EN ISO 10870:2012 (BSI 2012a)
- invasive species surveys
- mesohabitat mapping to determine the presence and location of habitats for protected species

Fish passage

To reiterate the legal considerations in relation to fisheries (see Section 2.3.4), the Water Framework Directive and the Eels Directive incorporate requirements to allow the free passage of fish and eel as part of weir design. The Fish Pass Manual (Environment Agency 2010b) presents and describes approaches for fish pass measure design as well as critical design considerations.

Fish passage is not only affected by physical barriers. Care should therefore be taken at the design stage to remove the potential for behavioural impact such as long dark culverts, water temperature fluctuations and potential to strand fish.

Flood storage can also have adverse impacts on geomorphological process by altering the hydro-peak of flood events, thus reducing the ability of a watercourse to clean and maintain habitat. Control structures can also prevent gravels and sediment moving downstream. These impacts should be minimised by careful planning at the design stage.

It is vital to hold initial discussions with the regulating authorities at an early stage to identify the availability of existing data and the requirement for additional survey work.

Landscape and green infrastructure

Landscape characteristics are a complex interaction between natural and human influences including geology, soils, topography, land cover, hydrology, historic and cultural development, and climatic considerations. This relationship between physical and socioeconomic influences makes one landscape different from another and creates a distinctive 'sense of place'.

An understanding of the most important landscape characteristics and their interrelationship with heritage, recreation, biodiversity and amenity, using existing landscape character assessments as useful starting points, should be key drivers influencing the site selection.

Green Infrastructure strategies and landscape capacity studies, where available, are also an excellent basis for identifying potential sites for flood storage reservoirs and potential opportunities to achieve multiple benefits from the proposed scheme. Examples where these have been realised include the iconic and award winning Sutcliffe Park, part of the River Quaggy Flood Alleviation Scheme in London. Potential multiple benefits include:

- increased public use of urban parks/open green space through incorporation of landscape enhancements
- ecological enhancement and meeting WFD objectives
- potential management strategies for sediment movement (depending on the geomorphological processes present)

- reduced visual intrusion and potential enhancements through careful site selection and design
- reduced objections through the planning approvals process
- identification of potential landscape maintenance and management assistance from third parties

The presence and quality of green infrastructure can confer important economic benefits and improvement to public health and well-being through increasing the attractiveness of the surrounding area in urban areas (Gore et al. 2013).

Heritage

The Fluvial Design Guide (Environment Agency 2009a) sets out a five-stage process for landscape and heritage assessment applicable to flood storage reservoirs. It is advisable to include a heritage professional in the design process to:

- ensure statutory requirements are met
- minimise harm to the historic environment

Assessment of heritage significance at an early stage in the project will highlight potential heritage assets and further evaluation or mitigation can then be agreed with the relevant authorities – Historic England, Historic Scotland, Cadw or NIEHS – and the local planning authority as appropriate.

Note that the time required for heritage assessment can be significant and should not be underestimated in the planning phases of the project.

2.5.2 Landscape and heritage considerations in design

It is essential that landscape and heritage are considered at the outset of the project to enable a clear project plan and programme to be developed. The main factors to consider regarding the landscape and heritage issues are shown in Table 2.3. This is not a definitive list and many activities may be required at different stages depending on the nature of the project.

Table 2.3 Landscape and heritage issues to consider at different stages of a flood storage reservoir project

Development stage	Landscape issues	Heritage issues
Planning phase	• Identify landscape designations such as National Parks and Areas of Outstanding Natural Beauty. • Report on their potential implications.	• Identify heritage designations such as scheduled or listed status or presence of conservation areas that require further investigation or may necessitate additional mitigation work.
Preliminary design and assessment	• Identify the key landscape characteristics and sensitive visual receptors to inform site selection, optioneering and design. A site visit by a landscape architect is essential at an early project stage.	• Desktop study of existing heritage material • Site walkover survey (non-intrusive) of assets with potential heritage values. A site visit by a heritage professional is essential at an early project stage.

Development stage	Landscape issues	Heritage issues
	• Carry out a site appraisal of the baseline landscape features in plan form. • Outline design proposals (including mitigation and enhancement) sufficient to allow negotiation with consenting authority. This may include a landscape master plan, visualisations or photomontages. • Carry out a landscape and visual impact assessment to inform the assessment of options and to feed into the EIA (if required) or to support planning application. • Future maintenance of the asset should be considered at an early stage of the project as this will inform the detailed design.	• Heritage impact assessments of options
Detailed design	• Landscape proposals for mitigation and enhancement works • Landscape design to determine softworks (planting) and hardworks	• Proposals for mitigation of heritage issues • Ensure conditions placed on heritage issues are followed. • Complete evaluation of historical assets in advance of the main works to avoid potential delays during construction.
Establishment, maintenance and management	• Agree appropriate funding, a delivery mode and duration for the initial establishment of any softworks and a schedule for handover to the body that will be responsible for longer term maintenance and management. • Develop a Landscape and Ecological Management Plan to guide the future management of the site.	• Ongoing review and interpolation of data for assets with known heritage value

Where to get good advice

Appointing landscape and heritage professionals at the outset reduces the risk of delays and unforeseen construction costs.

Common landscape and heritage techniques

This section outlines common landscape techniques and tools that should be adopted during flood storage reservoir design works. The Fluvial Design Guide (Environment Agency 2009a) sets out the process in more detail.

- **Landscape character assessment**. This is the process of identifying and describing variation in the character of the landscape. Landscape character assessment documents identify and explain the unique combination of elements and features that make landscapes distinctive by mapping and describing character types and areas. Guidance on landscape and seascape character assessments is given on GOV.UK (https://www.gov.uk/landscape-and-seascape-character-assessments).
- **Landscape and visual impact assessment**. This technique is used to assess the effects of change on the landscape. It is used to help locate and design the proposed change so that negative landscape effects are avoided, reduced or offset. The 2 aspects of the assessment – landscape and visual effects – are independent but related. For more information, refer to 'Guidelines for Landscape and Visual Impact Assessment' (Landscape Institute 2013).
- **Landscape masterplanning and detailed design**. The purpose of a landscape masterplan is to enable all aspects of a flood storage reservoir, such as access roads and structures, to be presented and coordinated. The plan is a comprehensive set of strategies and guidelines to be used on projects. Detailed landscape plans develop the landscape design to provide, for example, sufficient detail for a planning application to enable accurate costings and for use for construction depending on the specific stage of the project.
- **Visualisations and photomontages**. These are often required for planning to determine the assumed effects of a storage reservoir. Photomontages are a visualisation that superimposes an image of the proposed development on a photograph. The detailed methodology is set out in Landscape Institute Advice Note 01/11 (Landscape Institute 2011).
- **Landscape and Ecology Management Plan**. This plan aims to guide the future management of a site. It is commonly intended to cover the first 5 years of management, typically a planning requirement. Ideally this should be an open-ended document that can be updated over time to accommodate a review of the success of the regime and revised if considered necessary. Prescribed management works are also intended to generally increase the botanical diversity and habitat structure at the site for the benefit of local wildlife and invertebrates.
- **Written Scheme of Investigation.** This sets out the procedures and methodology for archaeological investigations to be undertaken before, or during construction of a flood storage reservoir. Investigation may comprise non-intrusive survey such as a geophysical survey, or intrusive investigation such as trial trenching or an archaeological excavation.
- **Conservation Management Plan**. This plan sets out proposals for the conservation of heritage assets. It contains mitigation proposals for preserving and enhancing heritage assets within the design and details to ensure the maintenance and long-term viability of any heritage assets incorporated in the scheme.

2.6 Land-use studies and investigations

2.6.1 Consultations

When dealing with consultees, care should be taken to ensure contact is made with all relevant internal subdivisions of that organisation to ensure that the most relevant information is obtained in regards to guidance and required applications. More information can be found on the NetRegs website for Scotland and Northern Ireland NIEA, the Planning Portal and the websites of Scottish Natural Heritage, Natural England, Natural Resources Wales, Department of Environment Northern Ireland, Environment and Heritage Service Northern Ireland, Historic Scotland, Historic England and Cadw.

Consultation with other potentially affected third parties early in the project development is strongly recommended. This may include user groups and other bodies that may have an interest in the site and may have relevant local knowledge of issues and constraints. They could include:

- ornithological societies
- angling groups
- county wildlife trusts
- affected residents
- affected landowners and occupiers
- recreational users including navigation interests

2.6.2 Existing utilities and services

During the outline design stage, the dam footprint, watercourse diversions, the flooded area and any other work areas should be checked carefully for the presence of underground or overground services and utilities. The accuracy of the plans should be checked at each stage of the design process as new services may have been installed or mapping of each service may have been improved.

Having identified all the services in the area of interest, the constraints should be managed through the design and early communications with the undertakers responsible for each utility. If possible, new structures should be arranged to avoid service diversions.

Where it is not possible to eliminate a constraint, the designer should work with the service provider to find the best solution. Options to consider include:

- **Diverting the service away from the new flood storage reservoir**. This will avoid any future maintenance agreements and separate the 2 assets. The cost and practicalities of diverting the service will need to be considered. For example, a gravity sewer may already be at its critical gradient and extending its route may not be an option.
- **Protection of the service through the flood storage reservoir.** This may include concrete surrounds, bridging structures over services, exclusion zones, raised or sealed manholes, and temporary works designs during the construction phase. Access to maintain the services will need to be considered and agreed with the provider; future maintenance tasks should

be designed to avoid the need to damage critical parts of the flood storage reservoir such as the embankment, control structures and spillways.

Services passing under the footprint of a dam is highly undesirable and may not be approved by the design consultant or the Construction Engineer. Certain types of services such as pressurised water mains pose a risk of erosion in the event of a pipe burst and this risk is not usually tolerated within a dam foundation.

2.6.3 Public access

Public rights of ways are paths on which the public have a legal right to pass and re-pass. New flood storage reservoir sites that are crossed by public rights of way will need to manage this process through correspondence with the local authority. Further information can be found in the Environment Agency's 'Access for All Design Guide' (Environment Agency 2012a) and 'Outdoors for All: Fair Access to a Good Quality Natural Environment' (Natural England 2015).

Permissible rights of way passing across a new reservoir site may need to be diverted and an agreement with the landowner of the path will need to be reached.

During the planning stage, footpath diversions should be identified. Footpaths should ideally not pass over the dam embankment. Where possible, the path should be diverted around the dam area or otherwise suitably surfaced to prevent damage by erosion. Access at proposed structures and equipment should be restricted or prohibited.

If a structure is likely to draw attention, the designer can consider the incorporation of barriers which have a clear segregation from the equipment and help to keep the public safe. It should be recognised that, if members of the public are encouraged to take much longer routes than those that can be achieved by crossing barriers, then some will attempt to shortcut their routes by climbing fences and potentially causing damage. Some understanding of public access requirements in the area of the structures will assist in planning any necessary restrictions.

2.6.4 Topographical surveys

For preliminary design purposes, an Ordnance Survey (OS) map with contour lines can provide approximate reservoir storage characteristics and site boundaries. The quality of this information can be improved by incorporating LiDAR data or topographic survey data. As many flood storage reservoirs are relatively shallow and large in area, LiDAR data may not be of sufficient accuracy.

For detailed design purposes, a full topographic survey providing spot levels of the site and incorporating all key surface features such as existing watercourses, manholes, service markers, overhead lines, trees and hedgerows should be undertaken. This survey will form the basis of all construction drawings and may provide the basis for cadastral mapping and quantity measurements during construction.

2.7 Preliminary structural design

2.7.1 Hydraulic control and reservoir sizing

Having identified the preferred site and approximate storage requirements for the reservoir, a preliminary design can be developed to refine the information needed to assess the scheme, including matters of cost and land take. The capital and operational costs can usually be minimised by planning the reservoir and reservoir structures to be as small as possible. The decision will usually be based on a variety of legal, hydraulic, environmental and operational and land-use reasons.

General

Reservoirs over a certain size fall under the ambit of reservoir safety legislation (see Section 2.3.10).

Land ownership considerations can also affect the storage design. If there are specific areas, infrastructure, property or other features that cannot be inundated, the storage may have to be limited to suit. An alternative approach is to make use of flood bunds to protect the features during the design event, though this can create its own problems such as trapping natural drainage routes.

Flood management and hydraulics

The selection of the type of hydraulic control device and the sizing of the reservoir and dam structures should be considered in parallel. The size of the reservoir storage required is directly linked to the adopted size and form of hydraulic control.

In consideration of the wider catchment flood management strategy, it may be desirable to provide for a greater amount of flood storage than is necessary to restrict the outflow to the design requirement.

Offline storage reservoirs can cover relatively large areas of bankside land at shallow depths. Where it is advantageous or necessary to adopt a smaller reservoir area of greater depth to provide the required storage, a feeder watercourse to convey floodwater from a point on an upstream reach can be considered to provide the requisite hydraulic head in flood conditions to fill the reservoir to capacity. Such watercourses are often designed to be hydraulically efficient to minimise the associated land take and costs. Maintenance requirements to keep the watercourse free of obstruction should be considered.

In sizing an online flood storage reservoir, consideration needs to be given to how extreme flood events will be managed. Sufficient space will be required to allow extreme flood flows to pass around or over the dam embankment without endangering the safety of the dam or any critical downstream structures. Embankments are often positioned just upstream of features such as buildings or road and rail embankments, which can restrict the options available for dealing with large flood events. This can affect the position of the embankment and hence the reservoir footprint for a given storage volume. Training embankments (Figure 2.9) can be considered, where space allows, protecting property or infrastructure from extreme floods.

Figure 2.9 Examples of training bunds to protect rail and road infrastructure
Photographs courtesy of ATPEC Ltd

Environmental

The reservoir storage size and location in the landscape have an impact on the environmental conditions within the reservoir basin. The range of flood depths, the duration of the inundation and the rate at which the reservoir fills and empties all need to be considered.

Consideration will need to be given to the presence of any shallow depressions within the reservoir basin that could result in stagnant water being retained or lead to the stranding of fish or mortality through water quality issues or increased predation. Stagnant pools will eventually be infilled through siltation, which might then pose a long-term problem of contaminated ground. In addition these pools could constitute a potential health hazard, for example, *Escherichia coli*.

With suitable consideration for issues relating to water quality, designing sustainable wetland features can bring environmental benefits. In England, the Environment Agency can advise on a suitable planting for areas that are inundated permanently or for prolonged periods.

The ground investigation work (see Section 2.8.2) should aim to secure sufficient suitable material for the reservoir embankments from within the flood storage area to avoid the importation of material if at all possible. This may bring wider benefits to the environment and the local community.

Operations and land use

In locating and sizing the reservoir basin, consideration should be given to the potential impacts on third parties, provisions for access to the reservoir structures and land use within the reservoir basin. It will be necessary to ensure that any routes to the dam embankment remain accessible, for example, to provide emergency access to operate equipment and clean trash screens during a flood event.

The depth and duration of flooding should be considered in relation to the impact on land use following flood events. The nature of the catchment area influences the impact following flood events in terms of the degree of saturation, pollutants, silt and debris. For example, developing a flood storage basin within parklands where the catchment area includes significant contaminated land could potentially pose a health hazard.

2.7.2 Embankment preliminary design arrangement

The great majority of flood storage reservoirs make use of dam embankments to create the raised storage. At the preliminary design stage it is generally necessary to determine the following salient aspects.

Preferred dam location(s)

The preferred embankment location(s) derives from a wide range of considerations described in this section and local site factors. For flood storage reservoir development, there are usually a number of sub-options for dam location, arrangement and height.

Reservoir site options might typically be appraised against the criteria such as:

- construction considerations such as ground conditions, access arrangements and proximity to suitable fill material
- opportunities for secondary reservoir uses including recreation and agriculture (see Section 2.2.6)

- public safety including public rights of way, interaction with equipment and rising floodwaters
- legislation and planning requirements and constraints (see Section 2.3)
- proximity to existing infrastructure, including services (see Section 2.6.2)

There may be a need to provide one or more secondary defences on the edge of the reservoir extent so as to protect an asset that cannot be allowed to flood for one or more reasons. Examples include environmentally sensitive areas or houses located just within the reservoir basin area which would otherwise flood on account of the reservoir development.

Environmental considerations should be considered from the outset of the project and opportunities and constraints used to inform the decision-making process. Environmental guidance is covered in Section 2.5.

Landscape and heritage requirements can influence the allowable reservoir footprint and dam crest level. Landscape design tools and design requirements are detailed in Section 2.5.2.

Landowners and stakeholders need to be consulted through the planning process; these consultations can present opportunities and constraints and are discussed in section 2.6.1. Compensation for landowners is discussed in section 2.3.9.

Dam height

Dam height is determined on the basis of the hydraulic modelling studies, taking into consideration the stage–area–volume characteristics of the site. Many flood storage reservoirs are designed to withstand some degree of overtopping of the dam crest, either by floodwater or wave action. In such cases, a freeboard allowance to reduce this risk might not be provided. A freeboard to the main embankment crest is normally provided where there is a separate spillway structure designed to accommodate extreme flood events.

Dam footprint

Once the dam height is determined, the footprint of the engineered fill can be determined by consideration of the crest width and the slope of the upstream and downstream shoulders. As a guide, a minimum crest width of 5m should be used. In the event that repairs are required, this width is sufficient to allow vehicular access along the dam crest. Some embankments incorporate a permanent track or road.

The upstream and downstream slopes of homogeneous clay embankments typically lie in the range of 1V:3H to 1V:4H – the former usually sufficient for stability, the latter sometimes required to promote safety in grass cutting operations. Where sacrificial fill is to be used to supplement the engineered fill, much flatter slopes might be warranted locally to serve those requirements. For example, flatter slopes on the downstream face might be warranted to limit overtopping design velocities and the potential for erosion of the face (with or without specific erosion protection measures).

Dam type

The most common form of dam type used for flood storage reservoirs is a homogeneous earthfill embankment. For dams of modest height (typically up to about 3m), flood retaining walls could be considered, giving a reduced footprint compared with embankment dams. In some cases, a hybrid approach of embankment and walling can provide the ideal solution. The depth and form of foundation cutoff required might influence the dam type selection.

Online or offline arrangement

The decision for online or offline storage is normally driven by local topography and/or land-use constraints (see Section 2.2). Offline storage is more common where watercourse gradients are relatively shallow, or where use is to be made of an existing open space within an urban setting such as a parkland. Online storage is more commonly used on relatively steep watercourses or where there are no overriding constraints to utilising storage on both sides of the watercourse.

Control structure(s)

The selection of the type of control structure affects the storage design and requirements for access and maintenance. The control structure design is generally determined through iterative use of flood routing analyses to produce an acceptable outflow hydrograph from the reservoir.

The environmental impact of the structure will also need to be considered. For example, localised variations in water velocities can cause upstream and downstream geomorphological impacts as well as affecting the ecology and potential for fish passage.

Spillway arrangement

For the majority of flood storage reservoirs, specific provision is required to pass extreme flood events in excess of the scheme design event (that is, the design that provides the requisite standard of protection – see Section 2.1.3). In many cases it may be possible to incorporate the spillway within the dam crest length rather than having a separate structure. An integral spillway is often feasible with low embankments of homogeneous clay fill. For dam heights of more than a few metres or where the dam shoulder material is of more erodible material, a separate spillway might be preferred. The design consultant or Construction Engineer should be consulted to advise on an appropriate arrangement.

In configuring the spillway arrangement, consideration should be given to erosion control on the spillway structure and at the toe of the embankment. Where the spillway is located close to the line of the natural watercourse, it should be possible to provide a cost-effective arrangement. Otherwise a spillway channel may be required to convey floodwater back to the natural watercourse, with training walls or embankments as necessary to protect properties or infrastructure.

At the preliminary design stage it is not normally necessary to carry out hydraulic modelling studies. Where uncertainties arise that require modelling to resolve, conservative assumptions should be made to inform the preliminary design.

It is important to ensure that the spillway arrangement does not pose any risk of erosion of the dam, such as at the downstream toe area. Toe protection systems can on the ground surface or buried under topsoil (see Figure 2.10).

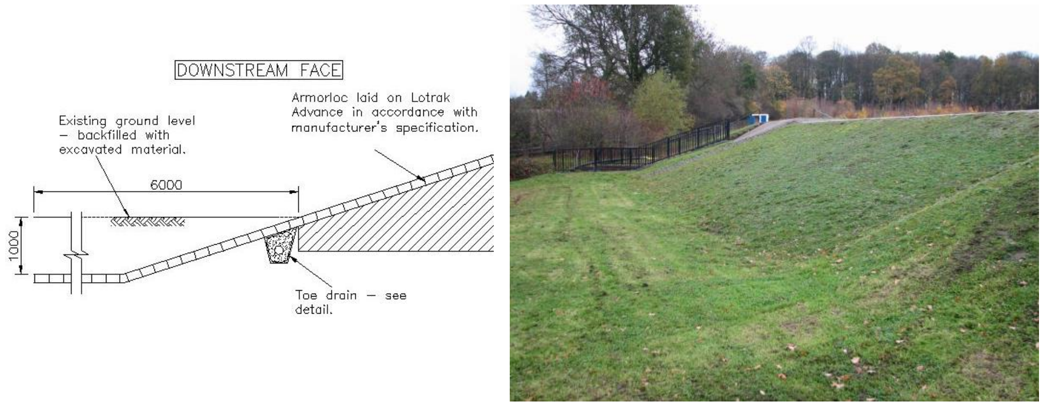


Figure 2.10 Example of buried toe protection

Photograph courtesy of ATPEC Ltd

Surface protection

The ideal form of surface protection for the great majority of flood storage reservoir embankments is grass.

Where water is retained permanently, then some form of surface protection over the range of normal water levels is needed to protect the upstream face from the effects of wave damage. For reservoirs that are normally dry, grass is normally sufficient to resist erosion from wave action as the reservoir water level is in a state of transition throughout the passage of the flood such that wave energy is not concentrated at a single elevation for a long enough period of time to cause damage.

The design of grassed embankments is covered in Section 3.6.7 and the maintenance of grassed slopes is covered in Section 4.4.1. Every reservoir should be assessed on an individual basis: it is possible that some flood storage reservoirs will warrant a rip-rap or some other form of wave protection on the upstream face.

If the crest is to be routinely used by traffic, erosion protection such as cellular concrete blocks may be warranted to resist rutting.

Cost optimisation

To optimise costs it is desirable to minimise the size of the embankment. This can sometimes be achieved through valley-side features or existing man-made structures (for example, an existing embankment) at the site of interest that allow for a volume-efficient design to be developed. Options appraisal is discussed in Section 2.10.

2.8 Geotechnical engineering

It is widely accepted that preliminary geotechnical studies are a vital element in managing ground risk in construction. This preliminary investigation normally takes the form of a desk study, with significant benefit being added by a site walkover. This process should be undertaken prior to the planning and scoping of any ground investigation.

This section sets out the processes typically involved in undertaking a preliminary geotechnical study and provides some guidance and references for the effective and efficient execution of such a study.

In planning and undertaking geotechnical studies, specialist professional advice should be sought. The UK Register of Ground Engineering Professionals (www.ukrogep.org.uk) provides guidance on suitably qualified individuals.

2.8.1 Preliminary studies and investigations

Various standards and guidance set out the need for, and principal features of, a geotechnical desk study for UK locations.

The 'ICE Manual of Geotechnical Engineering' (ICEMGE) highlights the importance of a preliminary study and provides some useful guidance and a list of hazards to consider at this initial stage (Burland et al. 2012, Volume 1, Chapter 43).

The 'UK Code of Practice for Ground Investigations' (BS5930:2015) (BSI 2015) states that a desk study is essential. It sets out the typical sources of information available and the types of information that are typically obtained. These include:

- OS mapping
- British Geological Survey for geological mapping, soil surveys, mapping and the most recent addition of historical borehole logs (www.bgs.ac.uk/data/boreholescans)
- Environment Agency web-based data including flooding, landfill and groundwater records (http://apps.environment-agency.gov.uk/wiyby/default.aspx)
- aerial photographs and satellite imagery
- historical mapping
- commercially available geological hazard mapping such as ground stability, shrink/swell, landslip and other ground hazard mapping.
- Coal Authority and any other mining reports
- unexploded ordnance mapping
- geographical information about the natural environment – for example, MAGIC (www.magic.gov.uk)

Some of these data sources are freely available on the internet. Users should investigate them carefully and also consider other sources such as local libraries, archive centres and local land users.

All desk studies should include a site reconnaissance to inform the findings and to assist in planning future ground investigations. The ICEMGE (Burland et al. 2012) suggests that this should take place approximately two-thirds of the way through the period assigned for the preliminary investigation.

Specific consideration should be given to access, obstructions, water supply and land ownership with a view to planning the intrusive ground investigation phase.

Where land contamination is suspected, the preliminary studies should be carried out in accordance with 'Investigation of Potentially Contaminated Sites: Code of Practice' (BS 10175:2011+A1:2013) (BSI 2011).

'Geotechnical Engineering of Dams' (Fell et al. 2014) emphasises the importance of geotechnical inputs throughout the project planning and in particular the pre-feasibility and site selection phases.

Aspects worthy of particular attention in relation to planning for a flood storage reservoir include:

- the ground model (part of the geotechnical triangle, as defined in the ICEMGE) including the geology, nature, disposition and continuity of strata; plus the groundwater conditions including the hydrogeological setting, groundwater levels and their likely fluctuations as well as piezometric profiles within the strata
- foundation conditions including strength, compressibility and watertightness
- requirements for foundation and/or abutment treatment for stability and/or watertightness
- material availability – it is normally preferable to win the embankment material from the reservoir area wherever feasible
- sourcing suitable borrow areas for embankment material (ideally with a short haul distance) if material is not being won from the reservoir basin area

The list above is by no means exhaustive and the references cited within this section should be read before undertaking a preliminary study.

2.8.2 Ground investigations

Ground investigations are critical to informing the design of a flood storage reservoir. In general terms the more extensive (and higher quality) the ground investigation, the lower the design and construction geotechnical risks.

Although ground investigation is included within this section on planning and preliminary design, it is important to highlight that ground investigations should be undertaken in a phased approach to inform each stage of design. Table 44.3 of the ICEMGE (Burland et al. 2012) notes the typical cost of site investigations (not including the preliminary investigations) for embankment dams as being in the order of 0.89–3.3% of the capital works cost. However, these data date from 1972 and the cost of investigations will be both site and hazard dependent.

It is important that the preliminary studies and site walkover feed into the planning and scope of the ground investigation. The methods and scope of ground investigations will vary depending on the site and the project scale. Some of the key issues to consider in planning a ground investigation for a flood storage reservoir include:

- different methods of ground investigation for different phases of investigations
- the depth of intrusive investigation to ensure adequate data are obtained should foundation treatment or extensive cutoffs be required
- testing of borrow areas or material being won from the reservoir footprint
- testing and selection of clay fill for compaction, including suitable laboratory testing for moisture content, liquid and plastic limits, particle size distribution and compaction properties
- in situ permeability testing to calculate seepage rates and cutoff requirements (see Section 49.8 of ICE, 2012)

The ICEMGE (Chapters 44–50) provides guidance on best practice for ground investigations (Burland et al. 2012). Geotechnical Engineering of Dams (Fell et al.

2014, Chapters 4 and 5) is also a useful reference. All investigations should be undertaken in accordance with BS 5930:2015 (BSI 2015) and related subsidiary standards.

The use of geophysical surveys should be considered. Techniques vary from the use of gravity, magnetometry or electrical field methods to ground penetrating radar, LiDAR and thermal infrared. The usefulness and suitable scope of geophysical surveys in the investigation of sites for new flood storage reservoirs depend on the scale and nature of the site in question. For some cases, including geophysical techniques in the preliminary planning and design phases can significantly reduce project risk and uncertainty. Guidance on different techniques is presented in the ICEMGE (Chapter 45).

2.8.3 Ground improvement and cutoff

The ground investigation results and initial embankment design calculations will inform the decision as to what foundation treatment, if any, is required. In the majority of cases, where the embankment is to be founded on clay, sands or gravels with good engineering properties, no foundation treatment may be required other than the removal of topsoil and any organic material from the dam footprint area.

Should ground improvement or a cutoff be required, the solution will need to be identified at the planning stage as different options will influence the final design of the embankment. The various solutions are detailed in Section 3.3.3.

2.9 Sources of suitable materials

An important part of the preliminary design phase is defining the source of materials to construct the dam embankment and to classify these materials.

2.9.1 Embankment construction

The most common material used for flood storage reservoir embankment construction is clay. Brown (2008) examines typical clays used in UK flood reservoirs and states that clays/silts of ‘intermediate’ plasticity are preferred (see Figure 2.11) as they avoid the 2 problems of erodibility in low plasticity clays and silts, and volume changes (swelling and shrinkage) in very high plasticity clays.

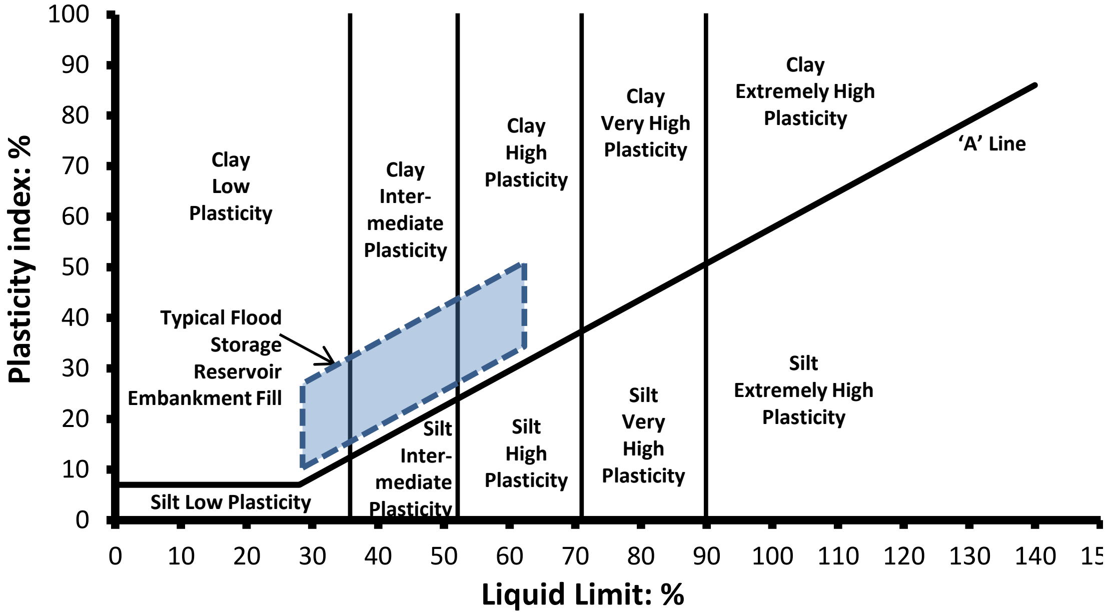


Figure 2.11 Typically used types of clay materials

Note: Modified from Brown (2008)

Sands and gravels are also suitable materials for stability and strength, but they need to be supplemented with a clay core or some other means to provide an acceptably low permeability structure. This is discussed in more detail in Section 3.3.6. In contrast to permanently impounded reservoirs, embankments for flood storage reservoirs are not required to be of very low permeability to perform well in service.

Useful guidance and explanations of shear strength, compressibility and permeability of embankment materials and soil foundations are given in Geotechnical Engineering of Dams (Fell et al. 2014, Chapter 6).

2.9.2 Challenging materials

The typical materials for embankment construction are considered to be those discussed in Section 2.9.1 and Figure 2.11. However, it is accepted that these might not always be available and more difficult materials might be necessary to incorporate into the design, possibly with an alternative form of cutoff design

The following materials are considered to be particularly difficult materials to work with and come with some guidance for their use.

Peats/organics

Every effort should be made to avoid building on peat or organic materials where possible. The high compressibility, low strength and susceptibility to swelling and shrinking make them a particularly challenging founding material of potentially high permeability.

Silts

Silts can vary enormously in consistency from hard/compacted materials to very soft/loose materials. They are particularly susceptible to disturbance, including during investigations. It is often difficult to measure their true properties accurately and, during construction, their strength can break down alarmingly – especially in the presence of water. Single-sized silts are difficult to compact. Their permeability can be higher than desirable and they can also be frost-susceptible.

Glacial till

'Glacial till' as identified on some geological maps (and previously as 'Boulder Clay' on older geological maps) can contain very good engineering materials. However, it is inherently variable and can contain materials ranging from coarse sands and gravels to gravelly clay. These materials can be mixed and vary from one to another in a matter of metres. Careful investigation is advised. Clayey tills are now identified as Diamicton on the most recent maps.

Chalk

Depending on its condition, chalk can be a good engineering material. However, Grade Dm chalk sometimes previously referred to as 'putty chalk', can have very poor properties (CIRIA 2002a, Chapter 3). Chalk is susceptible to deterioration when it is handled, which can make it difficult to use in earthworks, particularly in poor weather. It is also frost-susceptible.

Highly permeable materials

Where these materials are present, designers will need to consider leakage and stability of the embankment and associated reservoir. Steps might need to be taken to reduce leakage including, potentially, lining the reservoir or embankment areas. Under these conditions a site underlain by such materials may prove to be unsuitable or uneconomic. Linings are often used for farm lagoons in the UK. but are not commonly used for flood storage reservoirs. Chapters 31–38 of the ICEMGE (Burland et al. 2012) provide a useful reference for materials with more challenging engineering properties.

2.9.3 Land contamination

It is generally undesirable to site a flood storage reservoir in an area of contaminated land as there is the potential for contaminants to be mobilised during flood events and causing pollution. The relevant local authority will be able to advise on areas that have been designated as contaminated and any restrictions on their use.

Early studies should consider land contamination issues if only to rule this out as an influencing factor, particularly if the site is in an urban or suburban setting.

If land contamination is identified as a potential risk, competent professionals should be engaged to provide advice on the appropriate management actions. Soil contamination can be included in the scope of ground investigation work.

2.10 Option studies

2.10.1 General approach

An option study for a flood risk management project is carried out to:

- understand the existing flood problem

- define potential options to manage the problem
- select a preferred option for further development

The appraisal process is iterative. Several cycles of option definition and assessment are usually necessary to understand all of the issues associated with a scheme and how they influence the choice of the preferred option. This process, which is illustrated in Figure 2.12, needs to include the wider environmental considerations alongside the engineering approach in the design development.

Publically funded flood risk management projects in the UK should follow the appropriate national appraisal guidance. The following sections, prepared broadly in line with the approach set out for England in the 'Flood and Coastal Erosion Risk Management Appraisal Guidance' (FCERM-AG) (Environment Agency 2010c), draw the reader's attention to particular issues associated with flood storage reservoir projects.

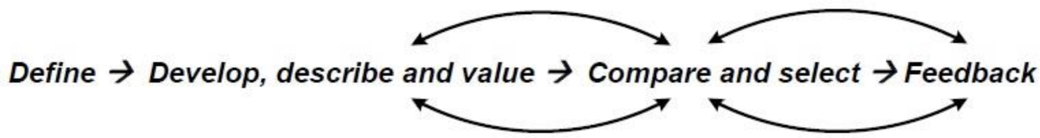


Figure 2.12 Iterative appraisal process for flood and coastal erosion risk management (FCERM) projects

Note: Extracted from FCERM Appraisal Guidance (Environment Agency 2010c, p. 3)

2.10.2 Understand and define the problem

The options study should start by gaining a clear understanding of the problems that are to be tackled, without seeking to predetermine the solution.

While the guidance below relates to flood storage projects and primarily to fluvial flooding, it is important that all sources of flooding in the study area are fully understood so that the proposed solution addresses flood risk holistically.

Clear statements describing why the project is needed should be prepared, including assessments of risk and consequences. The following aspects need to be considered:

- the boundary of the project area (see below)
- the appraisal window (usually 100 years for flood storage schemes)
- current probability of flooding (existing standard of service)
- how the probability of flooding could change
- consequences of flooding (positive and negative)
- how the consequences of flooding could change over time and why
- quality and relevance of available information

Boundary of the project area

In the case of flood storage schemes, it may be necessary to compare the benefits of several community-based flood defence schemes against a catchment-wide storage scheme that could have an impact on many communities. It is important therefore to consider carefully the boundaries of each scheme for the purposes of appraisal.

2.10.3 Set the objectives

Once the problem has been defined, objectives can be set for the project. Objectives are important as they define the direction of the project and may be referred back to at various stages to ensure that its original intention is being fulfilled.

It is vital that the project's objectives are consistent with:

- the wider strategic and legislative framework for the area
- the policies, duties, standards and targets of the authorities responsible for the scheme
- the interests of promoters, partners and stakeholders

Primary objectives are crucial to the delivery of the project as opposed to secondary objectives that could provide opportunities and enhancements.

2.10.4 Baseline scenarios

The appraisal process should be proportional to the type and complexity of the project being considered. In most cases, however, schemes involving flood storage will require cost-benefit analysis – as opposed to simpler appraisal methods such as cost effectiveness analysis.

Cost-benefit analysis involves assessing both the costs and benefits of a project so it is possible to evaluate whether the project is worthwhile (that is, the benefits outweigh the costs).

In order to carry out a cost-benefit analysis, a baseline option has to be defined. This is a yardstick or datum that defines a scenario against which other options are compared.

Do-nothing

For flood storage projects it is most common to use a 'do-nothing' scenario as the baseline. It is important to describe this scenario carefully to illustrate what is expected to happen if absolutely nothing is done (that is, all expenditure ceases in the project area). The appraiser should consider:

- the likely deterioration, failure/loss and time to failure of existing flood defences
- the effect of ceasing maintenance and operation of the downstream defences and watercourse
- how the frequency and severity of flooding events will change
- the impacts (positive and negative) that occur as a result

Assumptions will usually need to be made to define this scenario. Sensitivity testing, as defined in the FCERM Appraisal Guidance for England (Environment Agency 2010c), can be carried out to determine the importance of these assumptions to the overall appraisal.

Do-minimum

The ‘do-minimum’ scenario is defined as the minimum amount of action or intervention necessary to deliver the legal requirement or to sustain the existing standard of service within the project area.

2.10.5 Identify a long-list of options

Having defined the baseline, a ‘long-list of options’ should be defined which partly or fully address the problem at hand. Options should be defined in outline only at this stage, the intention being to list out a portfolio of options that will be refined to remove those that are totally impracticable and to refine, combine or select elements of those that are more promising. A wide range of options can help to provide an audit trail and explain to stakeholders why a given option has been selected or rejected.

For schemes where flood storage is considered as a possible approach, options will typically involve various combinations of upstream storage sites, reservoir sizes and varying degrees of downstream watercourse works. Other options to meet secondary objectives (for example, habitat creation or recreational or landscape benefits) might also be included at this stage.

2.10.6 Screening and shortlisting

Having identified a long-list of options, the next step is to screen the options to identify those which are technically viable, have acceptable impacts on the environment (or impacts that can be mitigated to a tolerable level) and are broadly economically worthwhile.

This stage of the appraisal process is generally carried out at a high level, with an increasing level of detail involved as the work progresses. Screening should:

- identify any absolute showstoppers or constraints on the nature, extent or timing of the work (for example, due to access, designated sites, protected species, buried services or contaminated sediment)
- give an outline indication of the technical, environmental, operational and economic merits of each option
- prepare an order of magnitude cost estimate at an early stage to ensure that the scheme is broadly viable
- consider the impacts of each option on the wider catchment, not just the immediate study area

The aim of the shortlisting exercise is to provide a reasonable number of options for further development and appraisal. The exact number of options selected will depend on the nature of the scheme. As a general guide, a maximum of 6 options including the do-nothing and do-minimum baselines is usually sufficient to cover a range of risk management scenarios.

Although some quantitative analysis is usually required at this stage, much of the shortlisting process can be carried out using a qualitative appraisal against key criteria.

2.10.7 Define, quantify and value costs and benefits

Once options have been identified they are valued in order to compare their relative merits and to select a preferred option for further development and implementation.

Costs

The shortlisted schemes are usually developed and refined to a level where a whole-life cost estimate can be produced. This might be achieved by estimating the most important quantities and benchmarking against previous similar projects, or through the use of cost curves.

Uncertainty in whole-life costs can be accommodated either by adding optimism bias as a percentage of cost (for initial assessments) or by adding a contingency sum or developing a quantified risk register for detailed assessments. These costs will include all significant social, environmental and economic impacts.

Benefits

The multi-criteria appraisal for social, environmental and economic benefits should be identified by following regional guidance (that is, FCERM-AG for England). The evaluation of the environmental and social benefits can be challenging to quantify and should only be monetised when they represent significant benefits.

Guidance for assessing flood damages, including direct damage to residential and non-residential properties, or infrastructure and indirect damage due to cost of emergency services, road and rail disruption can be found in the Flood Hazard Research Centre's Multi-coloured Manual (Penning-Rowsell et al. 2013).

Cost-benefit analysis

Cost-benefit analysis involves comparing the whole-life benefits (or damages avoided) and the costs of doing something with the baseline costs of do-nothing (walk away, cease all investment) or do-minimum (continue as at present).

To be economically viable, a project requires a benefit-cost ratio greater than one or a net present value greater than zero, or an internal rate of return greater than the cost of capital to the appraising body.

Whole-life costs and benefits should be discounted to present value, taking into account time preference, a preference to receive goods or services now rather than later. In the UK, the test discount rate for economic appraisal of public sector projects is given in the Green Book (HM Treasury 2011). A full treatment of the topic is not within the remit of this guide.

Climate change

The effect of climate change in increasing risk over time may form part of the baseline scenarios or a form of sensitivity analysis on option outcomes. For further guidance, the reader is referred to the 'Adapting to Climate Change' supplement to the FCERM Appraisal Guidance (Environment Agency 2011b).

3 Detailed design of flood storage reservoirs

3.1 Standards for design

It is vital to select and agree the relevant standards for reservoir structures and components before commencing the detailed design.

There is no single standard covering flood storage reservoir design. The design must be developed with reference to several standards and guidelines as may be applicable to the structures identified at the preliminary design stage.

Due to the nature and potential scale of flood storage reservoirs, in either a rural or urban context, good practice in adopting an integrated approach to environmental and engineering design should be adopted and this has been assumed in this guide.

In general terms, the standards and guidance can be categorised into the following groups.

3.1.1 Standard of flood protection

The standard of protection for the population benefiting from the reservoir should be determined through the application of national policy guidelines as far as practicable. Details of the NPPF (DCLG 2012) and planning practice guidance can be found on the GOV.UK website. The application of this guidance in determining the flood risk standard of protection is beyond the scope of this document. Reference can be made to ‘Rainfall Runoff Management for Developments’ (Environment Agency 2013a), which provides advice on the sizing of flood storage facilities including provisions for climate change allowance. Flood estimation for small catchment areas is the subject of ongoing research (Environment Agency 2012b).

The guidance applies to flood mitigation of both new urban developments and previously developed catchments. For new developments, the Environment Agency normally require that for return periods up to and including the 100-year event (1% annual exceedance probability), the developed rate of run-off into a watercourse is no greater than the undeveloped rate of run-off. The 1% annual probability represents the boundary between medium and high risks of fluvial flooding defined in Planning Policy Statement 25 (DCLG 2009), which was superseded by the NPPF in 2012. The NPPF recommends an increase of 30% on rainfall intensities when designing to 2085 and beyond to provide a factor for climate change. This standard will normally apply when protecting new developments. When designing a flood storage reservoir upstream of an existing urban area to improve the standard of protection, it might not be practicable to provide this level of flood protection and the required standard will be that derived from cost-benefit analysis.

3.1.2 Flood estimation standards for spillways

In consideration of the safety of the embankment from overtopping and erosion under extreme flood conditions, the provisions of ‘Floods and Reservoir Safety’ (ICE 2015) should be considered. The FEH (CEH 1999) describes the current methodology for determining flood hydrographs for storage design purposes. In applying the FEH to determine extreme flood hydrographs, use should be made of the currently applicable extreme rainfall depth–duration–frequency information and rainfall–run-off model with provision for climate change. See Section 2.4 for further discussion on hydrological analysis.

3.1.3 Geotechnical standards

It is considered good practice for the geotechnical planning and design to be undertaken by a competent geotechnical advisor and designer. The ICE recommends appointing an advisor from the UK Register of Ground Engineering Professionals (RoGEP) (www.ukrogep.org.uk), though their particular suitability to the project depends on issues such as:

- relevant experience with the anticipated ground conditions
- experience of previous projects
- understanding of the investigation and design process associated with water-retaining structures

Foundation design should be to Eurocode 7 (BSI 1997) (BS EN 1997-1:2004+A1:2013 and BS EN 1997-2:2007, and their associated National Annexes), or other international standard as appropriate. Notwithstanding this, as noted in the Eurocode basis of structural design: 'For the design of special construction works (for example, nuclear installations, dams, and so on), other provisions than those in EN 1990 to EN 1999 might be necessary' (BSI 1990).

Dam embankments for flood storage reservoirs in the UK should be designed to international best practice. There are currently no international standards which specifically apply to flood storage reservoirs, but general dam engineering principles and standards should be applied. The US Department of the Interior's Bureau of Reclamation (USBR) (www.usbr.gov) maintains design standards for embankment dams which are commonly applied internationally. Similarly the US Army Corps of Engineers maintains a series of engineering manuals on the design of earthfill dams (USACE 2004).

Many of the principles of design in Chapter 9 of the 'International Levee Handbook' (ILH) (CIRIA 2013) and the 'Application of Eurocode 7 to the Design of Flood Embankments' (CIRIA 2014) are also relevant to flood storage embankments. However, where there is conflict between standards for levee design and standards for earthfill dams, the latter should be applied.

3.2 Hydraulic design

3.2.1 Conveyance structures overview

The hydraulic design aspects of flood storage reservoirs cover the following flow conveyance structures:

- for online flood storage, the device that controls flows passing downstream and therefore the rate at which impounding occurs in the reservoir
- for offline flood storage, the various devices that control the relationship between flows passing downstream and flows passing into storage, together with the means of evacuating water from the reservoir after the flood has passed

- for all flood storage reservoirs, the means of handling the effect of extreme floods, normally by the inclusion of a spillway

Figure 3.1 depicts the types of conveyance structures likely to be adopted for the various flow control functions in online and offline flood storage reservoirs (hydraulic design equations can be found in Appendix A). There are 2 categories:

- fixed devices (passive), that is with no moving parts
- mechanical devices (active)

Within fixed devices, there is a special category of vortex and baffled devices, in which the hydraulic performance advantages of mechanical devices is achieved – to at least some degree. These include the Hydro-Brake®, which utilises a vortex control. A more recent development is the use of a baffled orifice, which has been adapted from the design of flow-setting 'modules' now widely used in irrigation engineering.

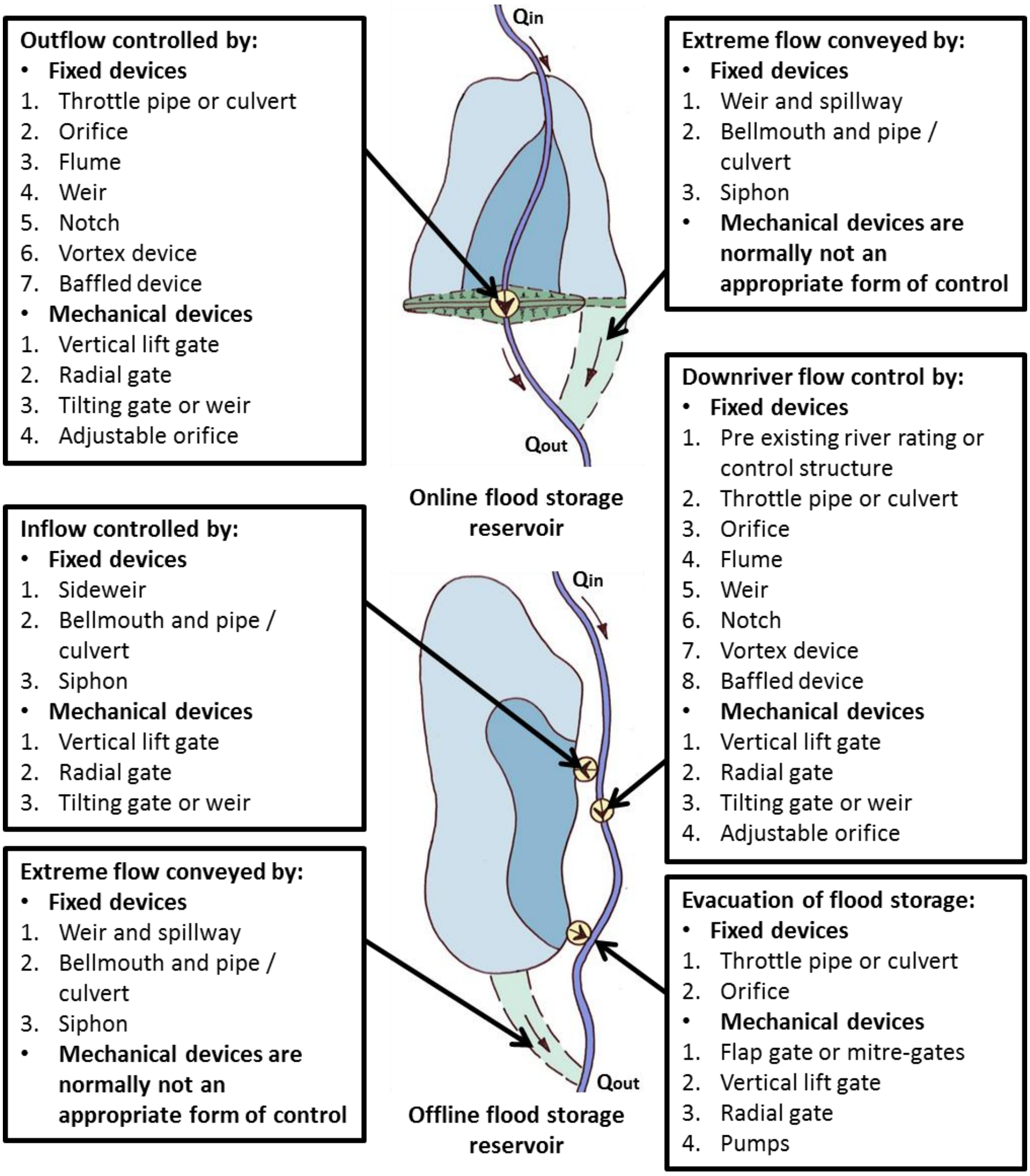


Figure 3.1 Control and flow conveyance devices

Mechanical devices include:

- powered gates (normally electrical)
- float-operated gates or tilting weirs
- flapgates and mitre-gates, which open when the water level on one side is higher than on the other
- adjustable orifices and flapgates, typically controlled by a float
- pumps

In theory, powered gates and other mechanical devices can offer the prospect of 'ideal' or near-ideal performance for the control device. A truly ideal device would allow the flow passed downriver to be equal to the inflow until it reaches a target value, and then to remain at that target value at all upstream water levels until the available flood storage has been exhausted. In practice, such behaviour can be realised only by a fully automated gated system that responds perfectly to measured flow. However, the use of powered or other sophisticated mechanical devices is only likely to be justified – both with respect to project economics and the maintenance and operational resources of the owner – on large flood storage reservoirs. For most medium-sized and small flood storage reservoirs, it is normal to opt for simpler fixed devices, together with simple unpowered mechanical devices where appropriate.

Powered gates are normally not appropriate for the conveyance of extreme floods, because of the risk of wrong operation, including through loss of power, in adverse weather.

In addition, there are energy dissipation and erosion control measures associated with some of the conveyance structures. These are considered separately later in this section.

The suitability of different devices in various applications depends on their basic hydraulic behaviour, which is the relationship between the upstream water level and the discharge being passed. In some cases, the downstream water level is also relevant. Before covering the devices in more detail (in Appendix A), it is therefore appropriate to present and contrast their hydraulic behaviour. General discharge equations for weirs and orifices are as follows:

Orifice $Q = C_C A\sqrt{2g\Delta H}Q = C_C A\sqrt{2g\Delta H}$

Weir $Q = C\sqrt{g}BH^{1.5}Q = C\sqrt{g}BH^{1.5}$

where: Q = discharge (m^3/s)
g = gravitational acceleration ($9.807 m/s^2$)
C_C = contraction coefficient for orifice (normally between 0.6 and 0.95)
A = cross-sectional area of orifice (m^2)
ΔH = head difference between upstream water level and centre of orifice or downstream water level if higher (m)
C = weir coefficient (normally between about 0.5 and 0.7)
B = crest length of weir (in metres)
H = weir head (upstream water level relative to crest of weir) (in metres)

The flow behaviour of a pipe or culvert acting as a throttle is similar to that of an orifice, with the flow increasing as about the square root of the head. The hydraulic behaviour of a rectangular cross-section flume is broadly the same as that of a weir, with the flow proportional to the head raised to the power 1.5.

An orifice, pipe or culvert acting as the primary flow control device in an online flood storage reservoir is reasonably effective, because the rate at which flow is passed downriver increases as the head to the power 0.5. So if designed to limit the flow passed downriver to (say) $10m^3/s$ before the reservoir storage is exhausted, at around half depth the flow would be about $7m^3/s$. Although this means that too little flow may be passed downriver, leading to additional flow passing into storage, it is generally the case in a typical online impoundment that the top half of the overall available depth provides some 75–85% of the total storage. Hence this element of ‘inefficiency’ of storage deployment normally has a limited and acceptable effect.

In contrast, a weir or flume deployed as the primary flow control device in an online flood storage reservoir is less effective, due to the 1.5 power. Taking the same example, with the downriver flow limited to $10m^3/s$, the flow at half depth is much less, at only $3.5m^3/s$, and so would result is about twice as much ‘wasted’ storage as the comparable orifice control. Nevertheless, there are situations where this form of control is appropriate, for example, where there is permanent storage within the reservoir and the additional depth available for flood storage is limited, or progressive mitigation of downriver flows over a wider range of flows is required.

The same behaviour of a weir, with the discharge increasing as the head to the power 1.5, makes it the normal device of choice for the following applications:

- flow into an offline flood storage reservoir (where the downriver flow is often throttled)
- the discharge of extreme floods from an online or offline flood storage reservoir

The weir crest lengths required are often large. Indeed, in the case of the spillway, it often occupies all or most of the crest length of the dam impounding an online flood storage reservoir. In rare cases it may be advantageous to adopt a siphonic overflow structure to limit the rise in flood level during an extreme flood, or to accommodate the structure within a smaller footprint.

3.2.2 Evacuation of offline flood storage reservoirs

If a flood storage reservoir is filled to above the level of an inlet weir and the spillway (if any) is at a higher level, the initial stage of evacuation – once watercourse levels start to fall – will include the return of flows to the watercourse over the inlet weir. For the continued evacuation of an offline flood storage reservoir, the following options may be considered:

- throttle pipe or culvert
- orifice
- flapgate or mitre-gates
- vertical lift gates or radial gates
- pumping

Fixed devices, such as a pipe, culvert or orifice, would start to evacuate the flood storage reservoir (albeit at a limited rate) as soon as it starts to fill, provided that the water level in the receiving watercourse is below the water level in the reservoir. By the same token, they would also of course provide an additional inflow route, if the water levels are reversed. Provided that they are sized accordingly, this behaviour may well be acceptable. The key is likely to be whether, by making the outlet small enough for the effects during filling to be acceptable, the outlet is large enough to evacuate the offline storage sufficiently quickly. Their hydraulic behaviour is described in Appendix A.1.

To overcome one of the potential disadvantages of a fixed opening, a flapgate (or mitre-gate) may be deployed, so that evacuation would only occur if the water level in the reservoir is higher than in the receiving watercourse by an amount sufficient to open the gate(s). The discharge characteristics of a flapgate are given in Appendix A.5.

Mitre-gates would normally be expected to open at a very small head difference and, once open, to provide very little obstruction to the flow so that the hydraulic behaviour would depend on the watercourse, culvert or other conduit within which they are located.

The acceptability of the flapgate (or mitre-gate) option will of course depend on appropriate sizing to evacuate the storage quickly enough while not overloading the downstream watercourse during the flood.

Where greater control and automation (or post-flood manual operation) are required, mechanical devices such as gates are deployed; the hydraulic behaviour is described in Appendix A.4.

Pumps are a last resort and are usually only deployed in cases where all or part of the storage is at a level below the downstream watercourse. This might apply, for example, where a disused quarry is used for flood storage. For further guidance on pump design, please seek the advice of a suitably qualified mechanical engineer, as the design of pumps is not covered in this guide.

3.2.3 Overflow weir and spillway design

The functions of the overflow weir and spillway are to:

- convey extreme floods safely
- prevent overtopping of any embankments that impound water (unless they are designed to be overtopped), which could result in erosion and ultimately lead to a catastrophic release of water

The spillway normally starts operating once the storage capacity has been fully depleted by the incoming flood. If blockage or some other form of failure of the control structures occur, however, the overflow weir and spillway could be called on to act under flow conditions much less severe than those for which they are primarily provided.

The following forms of overflow and spillway arrangement are, in principle, possible for the conveyance of extreme floods through an online flood storage reservoir or out of an offline flood storage reservoir:

- overflow weir, with a spillway chute leading to the receiving watercourse
- shaft spillway, leading to a pipe or culvert
- siphons

An overflow weir and spillway chute is often incorporated into the embankment dam retaining an online flood storage reservoir, with a lowered part of the dam crest (sometimes the entire dam crest) being set to the required level and the downstream face of the dam, together with a strip of land beyond, protected to withstand the forces created by the flowing water. Where an overflow weir is a separate structure, various crest profiles are available, most of which offer superior performance over that of the standard broad-crested weir. In addition, there is the possibility of using a labyrinth weir to increase the effective weir crest length within a restricted footprint.

A shaft spillway might be deployed at sites where the valley sides are too steep to accommodate an open spillway, with the culvert located in the abutment, or beneath or through the dam.

Where siphons are used, they normally deploy the entire head available from the full flood storage reservoir to the receiving watercourse. Depending on the proximity to the receiving watercourse, a separate spillway chute or culvert would not always be required.

The hydraulic design of the various features associated with overflow and spillway design can be found in Appendix B under the following sub-headings:

- overflow weirs
- labyrinth weirs
- shaft and culvert spillways
- siphons
- spillway chutes
- stepped and baffled spillways
- reinforced grass and similar forms of spillway

In cases where 2 or more components – for example, a primary spillway associated with the flow control structure, plus an auxiliary spillway over the crest of the dam – are provided, the rating curves for each should be individually estimated, referenced to a common datum, and then added together.

Consideration should be given to minimising hard surface structures. Where a spillway will operate only rarely, a subsurface protection system will allow for a grassed surfacing to be used, while recognising that some degree of damage and reinstatement work might be required following an extreme flood event. For this approach to be adopted, it must satisfy reservoir safety requirements.

3.2.4 Energy dissipation

Energy dissipation needs to be considered as part of the design of the following features at flood storage reservoirs:

- the flow control device (whether at an online flood storage reservoir or at the diversion structure for an offline reservoir) that delivers controlled flows downriver
- the evacuation structure from an offline flood storage reservoir
- the overflow weir and spillway

In cases where the heads involved are small and the flows are conveyed in part-full pipes or culverts, as is often the case for the outlets from flow control devices, the first option to consider is whether the energy can be satisfactorily dissipated, normally via a hydraulic jump, within those durable structures. In situations where this is not possible and a specific energy dissipater is required to deal with flows at high velocity directed into a natural watercourse or an earth-lined channel, options for energy dissipation include:

- hydraulic jump stilling basin (for example, USBR design or the one at St Anthony Falls in Minneapolis, USA)
- USBR impact-type outlet basin
- Contra Costa outlet basin
- straight-drop stilling basin
- tee-fitting on a pipe outlet
- rip-rap or gabion apron (and similar)

Further guidance on the design of energy dissipaters can be found in Appendix C.

An energy dissipation structure is not always required, for example in cases where the velocities are modest or the spillway flow plunges into deep water. However, surface protection can be subjected to additional erosive forces where it lies beneath a hydraulic jump.

The energy dissipation arrangements may be designed to a lesser return period than the spillway itself, provided that this does not pose a threat to the integrity of the dam impounding the flood storage reservoir. Indeed, in many cases, the greatest energy dissipation requirements occur with modest flows, rather than at more extreme flows. This is because rising tailwater levels at greater flows tend to cause a reduction in the head difference and therefore the energy dissipation needed. In some instances, generally associated with larger flood storage reservoirs, energy dissipation for the flow control device is provided as part of an overall structure that also includes an overflow weir.

3.2.5 Erosion control

The need for erosion control measures will normally be advised by a consultant engineer. Areas where erosion protection should be considered include:

- upstream and downstream of hydraulic structures
- around infrastructure interacting with the watercourse (for example, bridge piers)
- along section of watercourses where erosion could affect the performance of the flood storage reservoir or adjacent infrastructure
- along sections of watercourse where erosion would pose a health and safety risk to the public

Common forms of erosion protection include:

- rip-rap
- course block stone
- gabion baskets and mattresses
- reinforced earth
- revetments
- erosion control planting
- use of coir rolls, faggots and coir blankets

The form of protection used will generally depend on:

- water velocities
- material availability
- cost
- maintenance considerations
- geomorphological impacts
- landscape works

General guidance on the design of erosion protection can be found in the 'Manual on Scour at Bridges and Other Hydraulic Structures' (CIRIA 2002b) and 'The Rock Manual' (CIRIA 2007).

3.3 Embankment design

3.3.1 General principles

Geotechnical design should be undertaken in accordance with Eurocode 7 (BS EN 1997-1:2004 and BS EN 1997-2:2007, and their associated National Annexes). A useful reference is 'Application of Eurocode 7 to the Design of Flood Embankments' (CIRIA 2014).

Eurocode 7 defines a number of 'Design Situations' and, for each of these, EN 1997 requires that the designer verifies that the applicable Ultimate Limit States (ULS) and Serviceability Limit States (SLS) are not exceeded.

Design of an embankment cross-section requires consideration of several specific design areas. These important design processes and considerations are summarised in the following sections, with reference to the Design Situations defined in Eurocode 7.

Further advice on the environmental considerations of the design and ongoing maintenance of embankments is included in the Fluvial Design Guide (Environment Agency 2009a) and should be considered alongside the engineering design.

3.3.2 Design situations

CIRIA (2014) identifies the most common design situations as:

- construction
- normal conditions
- flood
- rapid drawdown after flood

For each of these, a number of different Design Situations could arise from variations in:

- bank geometry
- soil model
- water levels

- seepage conditions
- permanent, variable and accidental actions (loadings)

A large number of potential design situations can therefore be generated. However, these can usually be reduced to a more manageable number by inspection, leaving only the critical design situation to be addressed by calculation. Table 3.2 of CIRIA (2014) gives guidance in this respect.

Ultimate Limit States

Table 3.1 gives the typical applicability of the 5 ULS states to embankment design in relation to flood storage reservoirs.

Table 3.1 Limit states of embankment design

ULS name	Description	Flood storage reservoir failure mechanism
EQU	Loss of equilibrium of a structure considered as a rigid body	Not usually applicable to flood storage reservoir structures
STR	Internal failure or excessive deformation of a structure	Not generally applicable to flood storage reservoirs unless a structure is used to support the ground (for example, sheet pile wall)
GEO	Failure or excessive deformation of the ground	Mass instability of slopes or whole embankment
UPL	Loss of equilibrium due to uplift by water pressure or other vertical actions	Buoyancy; ground heave
HYD	Hydraulic failures due to hydraulic gradients	Hydraulic heave, internal erosion

Serviceability Limit States

SLS can include:

- settlement
- rutting
- desiccation cracking
- animal burrowing
- seepage deterioration
- wave–wash erosion

The requirements to meet these criteria, and the acceptability limits in each case, have to be determined on a case by case basis.

Geotechnical risk categories

Detailed guidance on the partial factors to be used in the verification of the various limit states and Design Situations is given Section 5 of CIRIA (2014).

3.3.3 Foundation treatment and cutoffs

The ground investigation results and initial embankment design calculations will inform the decision as to what foundation treatment, if any, is required.

In the majority of cases, where the embankment is to be founded on clay, sands or gravels with good engineering properties, no foundation treatment may be required other than the removal of topsoil and any organic material from the dam footprint area.

Foundation improvement might be warranted to control the amount of settlement of the finished embankment in service. Settlement over a long section of the dam crest will reduce the standard of protection provided by the structure. Localised (differential) settlement could cause concentrated overtopping flows with the capacity to erode the downstream face of the embankment and threaten dam safety. See Section 3.3.8 for further discussion on settlement.

The most common reason for foundation treatment is to improve the performance of the dam in terms of foundation seepage (see Section 3.3.5)

Where foundation treatment is required, the following options might be considered:

- **Dig and replace.** Careful consideration should be given to the availability of appropriate fill and suitable spoil disposal areas within the vicinity of the works. Digging below the water table is also hazardous and requires careful environmental control.
- **Pre-loading.** Where materials beneath the embankment are loose or poorly consolidated, ground improvement by pre-loading can be a viable option. The time constraints, double handing of material and availability of suitable material are all issues that need to be considered.
- **Vibro-compaction/vibro-replacement.** The densification of the underlying materials beneath the embankment by inserting a heavy vibrating poker. This is particularly effective for homogenous sand with a low silt/clay content.
- **Grouting.** In heavily fractured rock, this remains a proven and effective method of improving bearing capacity and watertightness. However, in soils the volume and extent of grouting is often very difficult to control and thus it is suitable only in rare instances.
- **Soil mixing.** This can include either dry soil mixing (principally for soft clays, peats and organic materials) or wet soil mixing (granular or stiffer materials) to improve the underlying material through panels, blocks or grid layouts. For flood storage reservoirs this is unlikely to be a suitable or economical solution.
- **Sheet piles** can be driven into most soils so long as there are no large obstructions such as boulders. Sheet piles are quite commonly used at flood storage reservoirs to improve seepage control within the foundation. Where sheet piles are used to improve watertightness, they should not also form the dam crest (level of protection) unless care is used in the design to prevent erosion of the embankment fill downstream of the piles in the event that the dam crest is overtopped during an extreme flood event.

Chapter 59 of the ICEMGE includes a table comparing different ground improvement techniques (Burland et al. 2012). Chapter 25 of the same document also provides useful background on the role of ground improvement. Further guidance can be found in the ILH (CIRIA 2013).

3.3.4 Fill materials and compaction requirements

The engineering properties of the proposed embankment fill material are important in terms of:

- engineering properties
- consistency
- performance under compaction
- performance in service

Soils that have a significant clay fraction are generally used, but more permeable materials can be considered providing that it can be demonstrated that the material meets appropriate standards in terms of stability and seepage performance.

Typically embankment fill materials for flood storage reservoirs have the following properties:

- Plasticity: in the range shown in Figure 2.11
- Clay content: 20–40%
- Undrained shear strength: in the range 40–100kPa
- Typical target compaction requirements in the range of 90–95% of standard Proctor maximum dry density

Materials with properties outside these ranges might be acceptable through appropriate design development.

The plasticity of clay fill can be significant with respect to the risk of swelling, drying and cracking. Desiccation cracking of the dam crest has the potential to affect the watertightness and stability of the crest section under flood loading (Dyer et al. 2009).

It is important to determine the type of fill required for the design at an early stage. Small embankments are usually of homogeneous fill construction comprising clay or a clayey soil. Larger embankments should consider the use of a central core or cutoff wall flanked by granular material. The decision will depend on many factors, notably the local availability of suitable materials to minimise haul distances and costs. The slope angles are normally dictated by the safe operation of grass cutting machinery and may be slackened further to blend into the surrounding topography.

3.3.5 Seepage control

Seepage control is usually not a critical design constraint for flood storage reservoirs as they are not intended to store water over long durations. Nevertheless, embankments will need to satisfy the UPL and HYD limit states (see Table 3.1 and Section 3.3.2). Seepage leading to internal erosion (a HYD case) is a significant issue and must be considered during design. Both seepage through the embankment fill and the foundation must be considered. Guidance on the calculation of foundation seepage flow is provided in Chapter 16 of the ICEMGE (Burland et al. 2012). The permeability of materials used to form flood storage embankments is ideally in the order of 10^{-7}m/s or less, but higher permeability values might be tolerable through careful design.

High hydraulic gradients can lead to piping failure through or beneath the embankment structure. Lengthening the seepage path by installing a cutoff, or mitigating the risk of internal erosion by applying filter material, is a common approach to secure the safety of the dam in service.

The 2 most common methods to lengthen the seepage path through the foundation are:

- clay-filled key trenches
- sheet pile cutoffs

In addition, the seepage path can be extended through the use of berms on the downstream toe.

The most efficient solution for seepage control should be determined through seepage modelling studies. These typically consider:

- the permeability of the founding material
- the depth of the permeable horizon
- the seepage exit gradient at the downstream toe of the embankment

Sections 9.7 and 9.8 of the ILH (CIRIA 2013) are useful references for control of seepage and internal erosion respectively. Chapter 10 of Geotechnical Engineering of Dams (Fell et al. 2005) also provides useful guidance for the control of seepage, internal erosion and piping for embankment dams.

3.3.6 Slope stability

A slope stability analysis of the proposed embankment cross-section is required to verify the GEO ULS as part of the embankment design. Chapter 11 of Fell et al. (2005) is a useful reference point for undertaking slope stability calculations. Chapter 23 of the ICEMGE (Butland et al. 2012) is also a useful source for understanding the principals and requirements of slope stability analysis.

The detailed application of both CIRIA (2014) and Eurocode 7 to slope stability in water-retaining embankments is complex and subject to varying interpretations. Issues include the definition of a “design groundwater level”, the application of partial factor multipliers to take account of consequence, and the changing location of the critical slip surface depending on the partial factors applied. Hughes (2016) presents a useful critique of these issues, and provides guidance on which approaches may provide the most consistent results.

In the majority of situations, Limit Equilibrium Analysis (LEA) is considered to be suitable for flood storage reservoir embankment stability checks. In some more complex situations, however, there may be the need to use numerical methods such as finite element analysis (EA) (Mathews et al. 2014).

Section 9.10.1 of the ILH (CIRIA 2013) suggests geotechnical categories that may apply to levees and are equally applicable to flood storage reservoir embankments.

Slope stability analysis should consider both normal and unusual load cases with appropriate factors of safety, with the latter including prolonged impoundment where the phreatic surface has become fully established within the body of the dam. This situation can arise either due to a succession of flood events or where there is a problem with the reservoir outlet facilities such as a seized gate.

Due to the nature and purpose of flood storage reservoirs, rapid drawdown is common and should therefore be one of the Design Situations checked as part of the slope stability calculations. In practice, upstream slope failure at flood storage reservoirs is rare and any such failures tend to be shallow in depth (Figure 3.2). Shallow slope failures present a maintenance burden, but are unlikely to pose any significant risk to the structural integrity of the embankment.

For larger flood storage embankments, particular attention should be paid to the construction case. Rapid placement of cohesive fill limits the opportunity for pore water pressures to dissipate and effective stresses within the embankment material can be dramatically reduced compared with the steady state case. Careful limits on placement rates during construction should be specified and monitoring of pore water pressures using piezometers should be carried out.

Figure 3.2 Shallow slope failure at Swanage flood storage reservoir following impoundment in October 2013

3.3.7 Drainage

Drainage in the upstream shoulder is not normally required. In some existing flood storage reservoirs where slope stability has not been adequately designed, however, retrospective slope and toe drainage may be a solution to avoid shallow slope failures.

Drainage on the downstream shoulder may be required if permanently wet zones are planned or if design requirements recommend, for example, a clay core requiring a filter layer. Examples of internal drainage can be found in the ILH (CIRIA 2013).

Flood storage reservoirs generally have limited or no drainage due to the limited duration of impoundment and the homogeneous embankment construction.

At relatively large embankments, consideration should be given to providing toe drainage at the downstream toe of the embankment and/or the downstream mitres. These drains should be designed with sufficient capacity to accommodate the anticipated flows and spare capacity to provide resilience. The drains should reliably remove water away from the embankment toe and normally discharge back into the watercourse. If appropriate, provision can be made for flow monitoring at collection chambers. Seepage monitoring requirements are detailed in Section 3.6.10.

3.3.8 Settlement

Typically the design of a flood storage reservoir will allow for the anticipated amount of settlement over the design life. The embankment crest elevation can be adjusted to accommodate the predicted lifetime settlement to avoid the need for crest raising works. Note that settlement can occur both beneath and within the embankment fill.

Settlement can be a significant design constraint, for example, when:

- actual settlement greatly exceeds the predicted values – this is most likely if the embankment is founded on very compressible layers such as peat or organic silt
- excessive settlement threatens the stability of the embankment – large settlements, often associated with ‘spreading’ of the embankment base on its foundation, can lead to cracking and ultimately to instability
- large settlements affect embedded structures, such as pipes and culverts, which can be damaged or induce leakage and potentially internal erosion
- large differential settlement in the embankment (for example, due to sudden changes in foundation conditions) can lead to cracking of the embankment fill

3.3.9 Seismic design

The UK National Foreword to Eurocode 8 (BSI 1998) states:

> ‘There are generally no requirements in the UK to consider seismic loading, and the whole of the UK may be considered an area of very low seismicity in which the provisions of EN1998 need not apply. However, certain types of structure, by reason of their function, location or form, may warrant an explicit consideration of seismic actions.’

Flood storage reservoirs would typically not fall in to this category. Seismic design cases are therefore not usually taken into consideration in the design of UK flood storage reservoirs. This is because the likelihood of a significant seismic event taking place at the same time as a significant flood is considered to be very small.

General guidance on the seismic design of UK dam structures is given in BRE (1991) and ICE and DETR (1998).

3.3.10 Wave erosion control

Specific wave erosion protection is not normally required for flood storage reservoirs provided the upstream face is maintained with a good standard of grass cover.

For reservoirs that permanently retain water, suitable protection should be provided such as stone pitching to suit the particular site requirements.

3.3.11 Instrumentation

Dam instrumentation can be installed to check that design conditions are being satisfied in service, or to monitor for potential forms of deterioration.

The commonest type of instrumentation applied at flood storage reservoirs is crest settlement monitoring. Settlement pins are commonly deployed to monitor crest levels at regular intervals and the data plotted to identify any trends in deformation.

Piezometers are not commonly used at flood storage reservoirs, but might be deployed within the foundation downstream of the cutoff to assess the effectiveness of the cutoff during flood events, or during construction to monitor the development of pore water pressures. For such a provision to be effective, vibrating wire piezometers and a data logger should be used as the changes in foundation pressure might vary rapidly.

3.4 Modifications to flood storage reservoirs

3.4.1 Legal requirements

The legal requirements associated with the planning of modifications to the design of a flood storage reservoir will depend partly on the status of the reservoir under national reservoir safety legislation. The reservoir safety legislation provisions differ according to country. The provisions for reservoirs located in England are described in A Guide to the Reservoirs Act 1975 (ICE 2014). In all cases, including non-statutory reservoirs, the owner has a duty of care under law to the safety of others. Design modifications should only be carried out with the advice of appropriate professional engineers. In the case of statutory reservoirs, changes to the design of a reservoir will usually require the services of a panel engineer. Further information can be obtained from the appropriate enforcement authority (Environment Agency, Natural Resources Wales or SEPA).

3.4.2 Enlargement

Reservoir enlargement might involve:

- crest raising
- introduction of transfer facilities to adjacent storage areas
- enlargement of the reservoir basin through excavation

Any work that affects the manner in which a reservoir is operated or the loadings that could be applied to reservoir structures or their foundation will need to be carried out in a manner similar to that for a new reservoir to ensure that all impacts are allowed for in the modified design. In the case of statutory reservoirs, a panel engineer must be appointed to oversee the design and construction of any modification works.

3.4.3 Removal/discontinuance

Reservoirs can be altered to reduce the volume of stored water during a flood event or removed completely from the watercourse. Any works undertaken to reduce the volume to below the threshold set in reservoir safety legislation is termed ‘discontinuance’. The Reservoirs Act 1975 makes particular provisions for discontinuance: such works must be supervised by a panel engineer.

Reservoir removal works typically require planning consent and environmental licensing to implement.

3.5 Detailed environmental design and land use

3.5.1 Landscape

The environmental design proposals should be developed alongside the structural design process. Ideally, a landscape architect will be integrated into the engineering team to inform and help develop an acceptable scheme that considers engineering constraints such as buildability and reservoir safety as well as environmental constraints and opportunities.

The preliminary work (see Section 2.5) should have identified the presence of protected landscapes, wildlife sites, heritage assets and other planning constraints. Following on from this, the detailed design will need to consider incorporation of mitigation measures to ameliorate potential adverse effects on landscape character and visual amenity. Issues to consider include:

- local topography
- geology/soils
- existing vegetation and future land-use objectives
- important views and vistas
- recreational and other users of the site

Site selection should aim to utilise the variation in existing local topography where possible to help integrate the scheme into the surrounding landscape. Embankments are potentially prominent elements for flood storage schemes, particularly where a steep engineered profile is adopted to minimise the overall footprint. Embankments are normally finished with grassed surfaces to facilitate visual inspection. Ideally an embankment should form naturally out of higher ground or surrounding features, helping it to be seen as part of the landscape setting rather than an artificial feature. This could be achieved through:

- widening the embankment and grading out the slopes into the wider landscape
- over steepening the embankment on one side to create a gentler slope on the opposite side without increasing the overall footprint

This may rely on an engineering slope stabilisation solution to retain steeper gradients and incorporation of ‘sacrificial shoulders’ along part of an embankment length.

Where structures are required such as walls, fencing, railings, signage and access gates, the local landscape character should be considered to ensure that the detail is sympathetic to the landscape setting and local vernacular. This is pertinent for all elements of the flood storage reservoir including the embankment, basin, watercourse and control structures.

Detailed design documents will set out the landscape proposals as part of the scheme. These are likely to include a landscape master plan as well as more detailed hard and soft works drawings. A landscape and ecology management plan should also be included to set out the site-specific management objectives and regime such as:

- the management of wildflower meadows on embankments
- tree and scrub planting on sacrificial shoulders beyond the clay core

This plan should be proportionate to the landscape implementation works and future management requirements.

The management objectives should be considered and monitored throughout the whole project lifespan and landscape, ecological and horticultural advice sought as appropriate.

3.5.2 Vegetation

Planting and grass seed mixes need careful consideration to ensure engineering and environmental objectives are met. Planting on engineered fill of embankments can:

- affect their integrity
- have an impact on the ability to undertake statutory inspections
- have the potential to block structures

One of the most common problems on embankments is the failure to establish good cover and the creation of problems due to the use of inappropriate seed mixes. The successful establishment of grass cover, trees and shrubs is directly linked to the quality and management of the subsoil and topsoil. Good practice in the management of soils during the construction phase is essential (see Section 4.3.1). Consideration of subsoil and topsoil availability, their suitability to support good vegetation growth and the overall depths required needs to be integrated into the design development of embankments and other earthworks.

Suitable grass seed mixes for embankments need to fulfil a number of requirements:

- to create a closed sward to protect the embankment
- be able to withstand a maintenance regime to create a low sward to facilitate engineering inspections
- respond to the geographical location

Including a wider range of species may help to achieve wider ecological objectives such as supporting the National Pollinators Strategy (Defra 2014).

Trees should not be planted on engineered fill or within 5m of the toe of embankments. Trees should also be excluded from the vicinity of spillway structures whether these are on or off the footprint of the embankment. Should trees be required in sensitive locations to integrate the scheme into the landscape or where excess material is available, the inclusion of sacrificial slopes (Figure 3.3) can be incorporated into the design subject to any constraints imposed by the consultant or panel engineer.

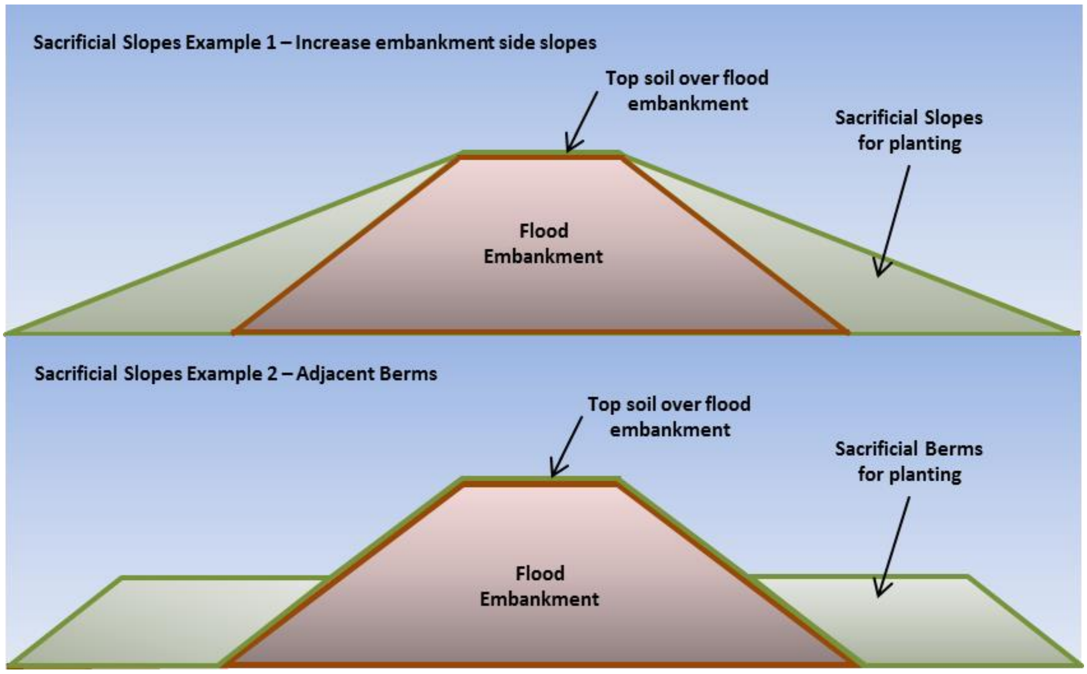


Figure 3.3 Examples of sacrificial slopes for planting

Existing vegetation on the site or along the scheme boundary should be surveyed to identify any key ecological constraints (see Section 2.5). Individual trees or grouping of trees may be protected by Tree Preservation Orders and consent will be required if existing trees on site require removal or may be affected by the proposed works. Where existing trees are present, the recommendations in the BS 5837:2012 (BSI 2012b) should be followed and a supporting arboricultural survey is likely to be requested to support a planning application. Under the Hedgerow Regulations 1997, 'important' hedges are protected and advice should be sought from the local planning authority and from the Forestry Commission where the felling of trees is required. Existing veteran and mature trees, as well as important hedgerows, should be maintained onsite where possible to help integrate the development and to retain key features in the landscape. An ecologist may need to confirm the presence/absence of protected species such as bats in the trees and badger sets within the proposed construction boundary.

Local authorities have their own requirements for the replacement of trees and hedgerows where removed to accommodate development. It is common to specify the species of trees and shrubs to match the species present onsite or those lost for construction. However, it may be desirable to replace some species with more appropriate species dependant on what the planting aims to achieve (for example, habitat enhancement or visual screening) (Figure 3.4).

Figure 3.4 Example of tree screening: Radlett flood storage reservoir in 2005 and 2014

Photographs courtesy of ATPEC Ltd

Where permanent water will be held in the reservoir, marginal and emergent vegetation could achieve multiple benefits of visual and biodiversity enhancement, providing a filtration system for silt and pollutants (see Section 3.6 for more detail) as well as acting to arrest wave erosion.

3.5.3 Heritage assets

Where important heritage assets have been identified, it will be necessary to consider their physical conservation or preservation of their setting within the design. In order to conserve a heritage asset, its heritage significance needs to be assessed to understand the asset's most valuable aspects (English Heritage 2008).

Understanding how the setting of heritage assets contributes to their significance is a fundamental consideration for scheme design. This may be particularly important where projects would potentially alter the visual, aural and landscape context of designated heritage assets including designated views and other significant views in the landscape. However, the importance of setting is not limited to designated assets or to these factors alone.

Opportunities for enhancing heritage assets and their setting should be identified and assessed at the project development stage. Enhancement can include:

- conservation and restoration of heritage assets
- improving access and appreciation through vegetation clearance
- providing interpretation information

Within the wider landscape, historic views may be restored, or a local or landscape context that enhances an asset's setting may be provided. Designing new features, such as field boundaries that use materials appropriate to the local historic landscape character can also contribute to conservation.

Historic buildings and historic landscape features should be retained and integrated into the design wherever possible. Reuse can include:

- entire buildings and structures that may be conserved and restored
- historic boundaries, such as fences and walls, which are restored in situ or re-sited

Historic materials may be identified in the project baseline or encountered later on during construction of the works. These may include internal and external structural elements from historic buildings or other structures, local brick or stone stock. There may be an opportunity for these materials to be incorporated into the scheme design.

The landscape design needs to be sympathetic to the setting of heritage assets and the historic landscape character. Considerations should include the scale and form of earthworks, planting, tree density and cover, and final water levels.

3.5.4 Land-use considerations

The designer will normally see flood alleviation as the primary objective. However, multiple benefits should be considered from the outset and should take account of adjacent land uses. In many cases statutory requirements will need to be considered, for example, a scheme in an SSSI.

It is important to understand the important characteristics associated with the principal consideration of flood storage to understand the suitability of secondary options. This will include, but not be limited to, flood frequency, water depth, flood duration and water quality.

Often more than one additional use will be incorporated into the design of a flood storage reservoir, such as a wetland area used to create ecological enhancements combined with recreational nature trails and bird hides.

Agriculture

It is possible for the reservoir basin to be used to grow crops. However, the risk of flooding should be considered and the potential for reduced yields or complete loss needs to be factored into the economic viability. Crops that can resist a degree of flooding would be desirable. Guidance on crop growth can be found in Chapter 4 of 'Achieving More: Operational Flood Storage Areas and Biodiversity (Environment Agency 2009b). In addition, the risk of blockage to watercourses and trash screens must be managed during the harvest process; for example, a hay bale rolling into the watercourse and blocking the control pipe would result in the reservoir impounding.

A flood storage reservoir can be managed to hold livestock, subject to any local byelaws or other restrictions. Larger species such as cattle and horses should be kept within the reservoir basin, as they can significantly damage the embankment while tracking over it. The animals should be managed with suitable stock fencing. Sheep might be allowed on the embankment as well as the basin due to their smaller size. Sheep can also be used to manage grass and remove or reduce the need for grass cutting. See Section 3.6.6 for further discussion on animal management.

Issues such as soil compaction and adverse effects on existing land drains need to be considered for the future viability of the proposed land use.

Recreation

There are many opportunities to incorporate recreational features within the basin of a flood storage reservoir. Many of the following can be seen in Figures 3.5 and 3.6:

- open green space and parklands
- nature trails and hides
- playing fields and hard courts
- golf courses
- skate parks
- children's playgrounds

Figure 3.5 Recreational playing fields in the reservoir basin

Photograph courtesy of ATPEC Ltd

Figure 3.6 Inch Park flood storage reservoir on Braid Burn, Edinburgh: the scheme incorporates permanent wetland area (foreground), sports fields (background) and landscape infrastructure to create public spaces

Photograph courtesy of Michael Spencer

However, measures need be put in place to make the area fit for purpose after a flooding event. Sediments may contain harmful substances: this risk is generally increased in urban areas. Key risks include:

- hydrocarbons (diesel, petrol, oils)
- bacterial infection from waste including *Escherichia coli* and Salmonella
- deposition of heavy metals (if the site is located near a source of contamination)

The inclusion of car parks should generally be avoided within the basin as cars can float and block hydraulic structures.

Permanently and temporarily wet areas

Wetlands can be incorporated into the flood storage basin either as areas of permanent water (as shown in Figure 3.7) with a constant through flow of water, or temporary where under certain weather conditions the water body could dry up between flood events. Issues of water depth and quality will influence the potential use for water-based recreation.

Figure 3.7 Simpson Balancing Reservoir in Milton Keynes adapted in 2004 to incorporate amenity ponds

Photograph courtesy of I. Kirkpatrick

3.5.5 Habitat creation

The operation of flood storage reservoirs often mimics that of a ‘washland’ habitat – an area that naturally becomes immersed in water during times of high water levels and can include a diverse range of target habitats such as wet woodland and floodplain meadow. Washlands are acknowledged as providing an important mechanism by which UK Biodiversity Action Plan (BAP) targets can be achieved. Flood storage reservoirs are already making a significant contribution to national BAP targets; 5.3% of the UK’s existing flood storage reservoirs support national or international designated habitats (Environment Agency 2009b).

While the primary focus of a flood storage reservoir is to attenuate floodwaters, a holistic approach should be adopted to identify multiple benefits. Where feasible and appropriate, the design should incorporate suitable conditions to support target habitats. It is possible for flood storage reservoirs to have multiple functionality, delivering landscape and biodiversity enhancements as well as creating a sustainable solution to flood storage.

Incorporating appropriate habitats within the flood storage reservoir can also have other benefits. Woodland within washlands has been shown to have benefits such as reducing diffuse pollution, retaining sediments and run-off, and moderating watercourse temperature and therefore can be useful in meeting water quality objectives. Riparian woodland also can have relatively higher soil infiltration rates; a study at Pont Bren in mid Wales found that soil infiltration rates were up to 60 times higher within young native woodland shelterbelts compared with grazed pasture (Environment Agency and Forestry Commission 2011) and can also reduce water velocities.

Biodiversity targets should be considered at the outset of the design process to prevent conflicts of interest later on. The successful establishment of habitats within a flood storage reservoir will depend on the impact or influence of flood storage reservoir operation on habitat characteristics, primarily:

- the use of the land
- the frequency and duration of inundation
- the seasonality of flooding
- the size of the flood storage reservoir
- the practicalities of attenuating floodwater

The drainage characteristics of the soil type present is also important, though to a certain extent this can be engineered or managed. To fully exploit the flood storage reservoir's capacity for biodiversity enhancements, and ensure success in establishing habitats and promoting their longevity, understanding these factors is key.

In summary the questions to be addressed during the design outset are:

1. What habitats are already present in the proposed flood storage reservoir location? What are the soil characteristics and what is the current water regime?
2. What magnitude of change to the flood regime will the habitats be subject to once the flood storage reservoir is constructed? Will these still be viable?
3. If still viable, what biodiversity enhancements can be made to the habitats?
4. If creating areas of new habitat, what is appropriate for the location and flood regime?

Caution should be taken in incorporating existing high biodiversity value habitats into flood storage reservoirs, as even a small change in the floodwater regime could lead to deterioration of the habitat's biodiversity. In terms of increasing biodiversity, it is often more effective to enhance a low value habitat to increase biodiversity than it is to create a habitat from scratch; however, high value habitats can be incorporated into the design.

Habitat improvements may include enhancements for fish, mammals, invertebrates and reptiles. Flood storage reservoirs can be enhanced by introducing permanent wetland areas or scrapes, which could benefit various species communities. Again the most important consideration in relation to introducing specific enhancements is to understand the baseline ecology of the location and what is appropriate to the site. Thus it is essential for baseline studies to be carried out at the outset of preliminary design (see Section 2.5).

As discussed in Section 2.5, the operation of a flood storage reservoir is likely to alter the fluvial geomorphology of the associated watercourse, Analysis at detailed design to understand how the construction and operation will alter factors such as the watercourse discharge, sediment load and the watercourse morphology. The design of the watercourse should ideally mirror the existing situation; however, where the existing has been heavily modified there may be opportunities to enrich the environment by incorporating meanders and ecological enhancements.

The Guidebook of Applied Fluvial Geomorphology (Sear et al. 2003) should be consulted for further detailed advice on watercourse design and assessment. Re-meandering of watercourses benefits biodiversity by increasing microhabitats, promoting opportunities for invertebrates and fish species. Biodiversity is also encouraged by the increase in flow and morphological diversity. Appropriate BAP habitats that could be created or enhanced within this flood storage reservoir include floodplain grazing marsh, reed beds and wet woodlands.

Best practice methods for online reservoirs have been collated in the ‘Manual of River Restoration Techniques’ (River Restoration Centre 2013). This includes case studies, and although it primarily deals with restoration techniques, it provides a compilation of techniques that can be used for the purpose of enhancement of river habitats. In addition, the ‘Water Framework Directive Mitigation Measures Online Manual’ (Environment Agency 2013b) offers information and guidance on mitigation measures for a wide range of flood risk management schemes.

Defining which habitat is appropriate for which site

As described earlier, the main factors determining potentially suitable habitats for a specific flood storage reservoir are:

- **Duration of flooding**. Surface water being present for prolonged periods will limit soil aeration and low growing vegetation will ‘drown’.
- **Seasonality of flooding**. Relatively few plant communities are able to tolerate flooding and waterlogged soils in summer, but a number can tolerate this outside the growing season in winter.
- **Soil drainage characteristics**. Between flood events, freely draining soils will re-aerate rapidly, allowing non-wetland specialist plants to persist (subject to the duration of flooding). At the other end of the scale, soils that do not readily drain may produce anoxic conditions and will only support species adapted to this.

A number of studies have produced high level matrices to provide guidance as to where the tolerance of habitat types lies in terms of the above parameters. Achieving More: Operational Flood Storage Reservoirs and Biodiversity (Environment Agency 2009b) includes a matrix of the 4 most widespread UK BAP habitats found in existing UK flood storage reservoirs and their tolerance to flood and soil water regimes. The 4 habitats included are:

- coastal and floodplain grazing marsh
- wet woodland
- lowland meadow (including MG4 and MG8 grassland – National Vegetation Classification (NVC))
- reedbed

The English Nature study, ‘Integrated Washland Management for Flood Defence and Biodiversity’ (Morris et al. 2003) considered a wider range of habitats. As the principles of flood storage reservoirs and washland are the same, this study can also be used at a high level approach to decide on which habitats are suitable to be considered (Table 3.2). Specialist input into the design and planning of habitat creation/enhancement could further define these habitats so that many could count towards UK BAP targets.

Table 3.2 Habitat matrix: washland classification by flood and soil water regimes and related habitat types

	Winter flooding only			Flooding at any time of year		
	Rapid soil drainage	**Moderate soil drainage**	**Slow soil drainage**	**Rapid soil drainage**	**Moderate soil drainage**	**Slow soil drainage**
Short duration flooding	Arable Hay meadow Pasture Alder woodland	Flood meadow Pasture Alder woodland	Flood meadow Inundation pasture Alder woodland	Water meadow Pasture Alder woodland	Inundation pasture Alder woodland	Inundation pasture Rush pasture Swamp Willow carr
Medium duration flooding	Hay meadow Pasture Alder woodland	Flood meadow Pasture Alder woodland	Flood meadow Inundation pasture Willow carr Swamp	Pasture Rush pasture Willow carr	Inundation pasture Rush pasture Swamp Willow carr	Inundation pasture Rush pasture Swamp Willow carr
Long duration flooding	Flood meadow Pasture Willow carr	Inundation pasture Rush pasture Swamp Willow carr	Inundation pasture Rush pasture Swamp Willow carr	Swamp Willow carr	Swamp Reedbed	Swamp Reedbed

Notes: [1] The table gives broad habitat types, which do not constitute in themselves BAP habitats or high value habitats.
[2] Adapted from Morris et al. (2003, Table 2.2).

Where to get design advice

Achieving More: Operational Flood Storage Areas and Biodiversity (Environment Agency 2009b) contains more detailed advice on the process of designing flood storage reservoirs with integrating biodiversity, including a key to guide on biodiversity potential, useful case studies and advice on design resilience for climate change.

To incorporate biodiversity into the design, input and communication between the engineers and the environmental specialists is paramount. Table 3.3 lists the types of specialists who may need to be included in the design team depending on the scope of works.

Table 3.3 Design team specialists

Type	Role
Geomorphologist	• At preliminary design undertakes geomorphological assessment for baseline. • At detailed design undertakes geomorphological modelling and can advise on the impacts/benefits of proposed design on the existing watercourse.
Freshwater ecologist	• At preliminary design undertakes baseline ecological studies on existing watercourse.

Type	Role
	• At detailed design can advise on the impacts/benefits of proposed design on the existing watercourse and input into the design of flood storage reservoir habitat enhancement/creation.
Terrestrial ecologist	• Undertakes baseline ecological studies (Phase 1 habitat survey and species-specific surveys) at preliminary design. • At detailed design can input into the design of habitat enhancement/creation.
Species specialist ecologist (for example, ornithologist, entomologist)	• At preliminary design undertakes baseline ecological studies. • Input into mitigation of impacts of construction and input into design of species targeted enhancement/creation
Botanist	• At preliminary design undertakes baseline ecological studies (National Vegetation Classification). • At detailed design can input into mitigation of impacts of construction and into habitat design/enhancement of habitat. • Input into ongoing maintenance and management programme
Chartered landscape architect	• From inception, through the environmental design concept and appraisal stages plus assisting in the outline design • At detailed design undertakes landscape design, planting specification and production of management and maintenance programme. • Input to delivery of softworks including establishment, aftercare maintenance and handover
Arboriculturalist	• A preliminary design undertakes tree assessment survey to indicate the health and viability of existing trees, • At detailed design, a tree assessment survey will help to inform landscape design, tree protection measures and planting specification.

3.5.6 Fish passage

Relevant information dealing with fish pass construction and design can be found in the Fish Pass Manual (Environment Agency 2010b) and the Eel Manual (Environment Agency 2011).

When considering fish passage, the natural channel should ideally be left undisturbed allowing the natural characteristics of the watercourse to be preserved. Ideally the original bed should be left in place by using an arch culvert, but where a pipe or culvert is used to pass under or through an embankment, the original bed invert should be maintained and a natural bed incorporated along its length. Consideration will need to be given to reducing flow capacity and flow velocities due to the potential for changing bed profiles.

Changes in water depths, watercourse velocity and the length (darkness) of the structure can be as much a barrier to fish passage as a physical obstruction. Careful design is needed to maintain or improve the ecological status of the watercourse.

Debris screens should only be included in the design as a last resort. If required then free passage of fish needs to be considered, bar spacings should be appropriate and a free gap maintained under the screen from the Q95 water level to stream bed. A bar spacing of 250–300mm will have a minimal impact on water velocity, when the screen is clear.

Where permanent impoundment cannot be avoided and a head drop occurs between the upstream and downstream watercourse levels, consideration must be given to how fish and eels will navigate past the obstruction. It might be appropriate to incorporate one or a combination of the following fish pass solutions:

- natural bypass channel
- Larinier fish pass
- pool and traverse fish pass
- eel matting
- rock ramp fish pass
- brush pass

The designer will need to take into account the flow through the structure at top water level and adjust the outflow from the flood storage reservoir accordingly to limit the downstream flows.

3.6 Operation and maintenance: considerations for design

3.6.1 Introduction

This section considers typical operational and maintenance (O&M) matters to be considered at the preliminary and detailed design stages of flood storage reservoir development. The O&M of existing reservoirs is covered in Section 4.

For a reservoir to function effectively and efficiently over its design life so as to provide a flood protection function, a wide range of asset management activities are essential. These activities are linked to the particular operational design arrangement, the proposed nature of the structure and aspects relating to the setting of the reservoir. As with other phases of the scheme design, both the engineering and environmental design issues need to be considered.

By considering the scope and frequency of such activities, the designer can make important contributions which will allow the reservoir to function more effectively and to reduce the level of investment required to maintain the asset over its useful life.

3.6.2 Regulatory requirements

Health and safety

Under the Construction (Design and Management) Regulations 2015, when preparing or modifying a design, the designer must take into account the foreseeable risks to:

- those using the structure as a place of work
- those tasked with maintaining the structure
- those involved or affected by the construction activities

In planning, managing and monitoring the pre-construction phase, it is the responsibility of the Principal Designer to reduce risks to health and safety as far as reasonably possible. It is the responsibility of the Principal Designer and Principal Contractor to prepare and develop an O&M manual and a health and safety file. These are working documents that can be updated as necessary through the construction phase and in the event of future design changes.

The O&M manual should contain details of:

- the scope and nature of the construction work covered by the manual
- how to operate and maintain all mechanical and electrical equipment
- general maintenance instructions
- details of all pertinent information gathered during the design phase including the location of all utilities and services

The O&M manual should aim to:

- provide information that will allow the operator to operate the structure safely and efficiently
- provide information for asset managers to allocate suitable resources for maintenance activities

The ILH (CIRIA 2013) provides suggestions for the contents of an O&M manual for similar types of structures.

Reservoir safety

For reservoirs falling under the Reservoirs Act 1975, the panel engineer (the ‘Construction Engineer’ during the planning, design and construction phase) should be consulted on O&M matters that are critical to the safety of the structure. Typical issues might include:

- access provisions for surveillance of critical areas such as the embankment crest and downstream toe
- debris management control and monitoring arrangements
- power and control systems for active hydraulic control devices

These and other aspects of O&M are covered in more detail in the sections below.

3.6.3 Access provisions

Suitable access provisions to key parts of the reservoir site are essential for effective operation, monitoring and maintenance.

Access provisions during the construction phase are usually greater than when the reservoir is in service on account of particular provisions put in place to allow for construction activities. For example, there may be no permanent vehicular access to the toe of an embankment which runs parallel to a watercourse to form an offline reservoir. In such situations, any vehicular access for future repair work would have to be along the embankment crest and the embankment design would need to accommodate this unless special provisions are made with the landowner(s) beyond the toe areas.

Normally, vehicular access is required to control structure areas, for example, for screen debris removal or gate replacement.

The means by which grass on embankments will be cut should be considered in terms of vehicular access requirements, including the transportation of suitable equipment to the site. Access tracks should not normally have a gradient steeper than 1 in 10 to avoid vehicles grounding. Where this poses a potential problem, grade transitions should be designed accordingly. Vehicular access should not expect to utilise the dam crest for access. An access strip alongside the defence including the reservoir structures is the preferred approach.

Where all-weather vehicular access is needed, a range of options could be considered. Where access along the crest of an embankment cannot be designed out, tyre rutting poses a potential problem and a threat to preserving the dam freeboard. This risk can be mitigated by reinforcing the crest surfacing, for example, using cellular concrete paving or crushed concrete. Alternatively a gravel track could be provided if this is considered appropriate from a landscape and visual intrusion perspective. Asphalt-paved tracks can also be considered, but are less commonly adopted for flood storage reservoirs except where there is public access provided to the embankment crest. A hardcore track overlain by topsoil and grassed is only suitable for use by light equipment such as mowers. Plastic cellular systems between kerbs set directly on clay are not preferred due to poor drainage and softening of the dam crest; in addition, these systems may not provide sufficient grip for vehicle access.

Online reservoir embankments are often placed in close proximity to property boundaries to maximise the reservoir storage space available within the land plot. It is essential that adequate space is provided around the downstream toe areas for maintenance and surveillance work. Seepage through a dam foundation might arise several metres beyond the downstream toe. It is therefore appropriate to leave sufficient space between the toe and the property boundary to monitor and maintain dam performance. An access width of 6–10m typically suffices. Alternatively an agreement on an easement could be made with the downstream landowner, but in this case, boundary fences can hinder the effectiveness of the arrangement.

Figure 3.8 Long grass on the downstream embankment face and trees/shrubs at the toe area prevent effective surveillance of the embankment performance

Where it is necessary to maintain or provide public access to the reservoir area, the requirements of the Equality Act 2010 apply and it is therefore important to ensure access is provided on equal terms regardless of age, social group, ethnicity or disability. Introducing a sloping or stepped path over a flood defence can be a major impediment to access for disadvantaged users.

Any public pathways within the reservoir inundation area will need to be cleared of debris following a flood event.

The health and safety of the public must be considered in planning the routing of footpaths, fencing, gates, resting areas and warning signs. Public safety issues are covered in Section 3.7.

If considering re-routing footpaths it is also important to consider the impacts on any nearby residents, for example, in terms of their privacy and vulnerability to crime.

3.6.4 Debris management

Overview

Debris management, sometimes referred to as trash management, is an important consideration for flood storage reservoir design and is particularly relevant for online reservoirs. Vegetative debris, such as tree debris, tree trunks and cut grass or man-made debris such as plastic bags, shopping trolleys and general rubbish, can pose a significant risk to effective reservoir operation and dam safety.

A blocked debris screen prior to a flood event will mean that the reservoir is partially impounded and unable to provide the design storage when the flood event commences. Blockage during an impoundment could give rise to embankment overtopping at a greater frequency or to a greater extent than allowed for in the design. Although some degree of screen blockage can and should be allowed for in the hydraulic design, a poorly designed screen can lead to near-complete blockage.

In relation to flood storage reservoirs, debris management can be relevant to:

- coarse debris (for example, tree trunks and boulders)
- general debris (for example, tree branches, cut vegetation, household waste and plastic bags)
- both of the above

Fine screens, as sometimes used at the outlets from fishery reservoirs, should not be used at flood storage reservoirs.

The design of the debris management facilities is also important from the maintenance perspective. A safe and efficient means of clearing accumulated debris must be provided. Debris screens can be designed for manual or automatic cleaning. Instrumentation or surveillance systems are usually required to inform screen cleaning requirements.

The ideal arrangement for debris management is for there to be no screen at all, as this can reduce capital and operational costs and improve performance reliability, but this is often not possible for practical reasons. Hydraulic control devices will usually require a screen to prevent blockage. It may be possible to provide a control structure in the form of an open channel, such as a flume, which typically requires no debris management provision. The question of debris management is therefore an important aspect to consider through all stages of the reservoir design.

An important reference for the assessment and design of debris screen is the ‘Trash and Security Screen Guide’ (TSSG) (Environment Agency 2009c). This guide was prepared for UK application and should be considered in the design of screens for UK flood storage reservoirs. It covers:

- debris assessment
- assessment of existing screens
- new screen design
- monitoring and operational considerations

Chapter 9 of 'Flood Risk: Planning, Design and Management of Flood Defence Infrastructure' (ICE 2012) reviews available screen design and management tools and illustrates many examples of screen design. Wider experience on debris control structures and equipment from the USA is covered in USBR report R-92-05 (Wahl 1992).

Debris screens are distinct from security grilles, though some debris screens effectively act as a security grille. Security grilles are covered in Section 3.6.

The decision to provide a screen should be considered carefully. Although many screens have proved to function effectively in preserving the design hydraulic capacity of the control device during flood events, there are also many examples where screens have not performed well, either contributing to flooding, causing unnecessary overtopping damage or placing an unreasonable maintenance burden on the operator. The main options are:

- design the flood storage reservoir to allow passage of all debris
- provide a screen
- reduce the debris at source such that a screen can be discounted

The last option is rarely adopted as measures put in place as part of the project development may be difficult or impractical to manage effectively in the longer term.

If a screen is required, its design should be such that the risk of screen blockage is less that the risk of the control structure blocking if no screen is used.

Some reservoirs feature bypass facilities that allow flow to bypass the screen or to bypass the entire structure so that blockages can be cleared. This approach may be attractive where there is considerable uncertainty over the anticipated debris loading and risk of blockage. However, a well-designed screen should not usually warrant the cost and complexity associated with bypass arrangements.

Generally, screens do not obstruct the passage of wildlife so this is not normally a key consideration in the decision to provide a screen.

Figure 3.9 Flume control on a walled flood control dam

Debris assessment

The guidance available details methods for assessing the risk of debris blockage. Although these have been developed principally in relation to stormwater culverts, the principles are generally applicable to hydraulic controls for flood storage reservoirs.

The potential sources and nature of the debris within the catchment area of the control point in question should be assessed. Common sources of debris include:

- trees and other vegetation within the reservoir area or close to the watercourse within the catchment area
- farms (for example, straw bales)
- urban areas (for example, household waste, plastic bags, shopping trolleys, bottles)
- known locations of illegal rubbish dumping (fly-tipping)

Farm debris such as hay and hay bales have been known to pose a particular risk to screen blockage. However, the most common threat is that of tree debris.

Flood Risk: Planning, Design and Management of Flood Defence Infrastructure (ICE 2012) discusses methods for assessing debris risk and estimating debris loading on screens. Where no or little site information is available on the likely annual amount of debris, this can be estimated using the debris loading chart from the TSSG. This is reproduced in Figure 3.10.

Using the methodology set out in the TSSG, the debris loading chart, together with information on watercourse steepness, can be used to design the area of the trash screen. Large tree debris, if present, is normally treated separately from general debris and tree interception is normally carried out a short distance upstream of any secondary screen, which could be damaged by the force of tree trunks.

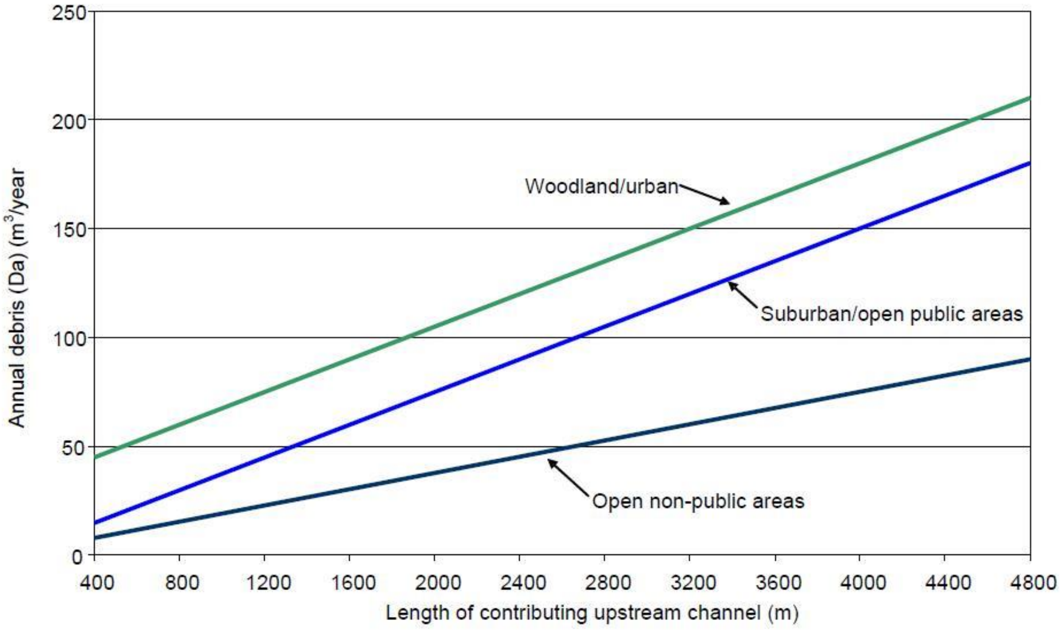


Figure 3.10 Amount of debris expected for different catchment types

Notes: Da = maximum debris amount (that is, anticipated maximum amount of annual debris arriving at the screen in non-routine events.
Source: Environment Agency (2009c, Figure 7.4)

Debris management

Some projects are designed specifically to allow for debris passage past the dam. This approach is attractive where large quantities of debris are anticipated during flood events. The transport of debris within the reservoir basin and past the defence can be an important consideration in bringing wider benefits to reservoir creation. This is well illustrated in the discussion of the Burn of Mosset (Scotland) case study presented in Flood Risk: Planning, Design and Management of Flood Defence Infrastructure (ICE 2012).

To reduce the risk of existing fallen trees being transported to the control structure, tree trunks can be secured to the ground. This approach may be attractive to preserve the environmental benefits of such features. Alternatively it may be desirable to simply relocate such items but such work would require the agreement of riparian owners.

Consideration should be given to any culverted sections of the main river or tributaries upstream of the reservoir. It may be appropriate to develop a strategy of measures across various locations to reduce the impact of debris at the main control structure.

Where a culvert is proposed as the main control structure, it is possible to reduce the risk of culvert blockage and avoid the use of a screen by considering the aspects of the conduit design such as the following.

- **Culvert number and size.** Try to avoid multi-barrel arrangements and provide to largest practicable size.
- **Bends and changes in section area.** These can increase the risk of debris blockage.
- **Culvert length.** Try to minimise the length of the culvert as much as practicable.

- **Open channel flow**. A conduit designed to operate as an open channel will be less at risk of blockage than a pressurised culvert.

Screen design

Screen design is covered in detail in the TSSG (Environment Agency 2009c). Screens should be designed to:

- allow passage of the design flow through a partially blocked screen area
- prevent blockage of the control structure
- facilitate safe, efficient screen cleaning
- allow free passage of fish
- be structurally sound under all load conditions

Coarse screens can be located at the entrance to a control structure inlet, or be located separate and upstream of a general debris screen. Coarse screens are usually vertical poles across the main watercourse (Figure 3.11). Multiple rows of coarse screens are sometimes used to improve effectiveness. General screens typically comprise thick section sloping bars with multiple stages as necessary to facilitate cleaning.

Solid chequer plating is usually used at screen platforms to provide a stable walking area to gain access to the screen panels for raking. However, the use of solid plating effectively reduces the screen area so its use should be minimised where applied to the area passing flow. By drilling holes in the chequer plating, the surface can better drain and will be less slippery when accessed.

Figure 3.11 Tree catcher for the Moray Council flood storage reservoir

Photograph courtesy of Michael Spencer

General debris screens are usually fitted within the upstream headwall/inlet to the control structure. The main components typically comprise:

- a sloping screen (single or multiple stages)
- a horizontal screen or screens

- working platform(s) for debris clearance
- access provisions for conduit inspection and maintenance
- perimeter fencing
- water level monitoring instrumentation

The design of the screen area and the bar spacing are critical considerations in terms of the screen effectiveness, security against near-total blockage and headloss evaluation. The latter influences the risk of embankment overtopping and is therefore crucial to the overall safety evaluation of the dam design. The screen effectiveness depends on many factors including approach geometry, screen spacing in relation to debris item lengths and the screen angle. Screens set at 60° to the horizontal have been found to be more effective than screens set at 45°.

The screen design should reflect the proposed method of screen cleaning. The screen design must consider the safety of operatives involved in removing debris and accessing the culvert (see Section 3.6). Figure 3.12 shows an example screen requiring manual raking to remove debris.

Figure 3.12 Simple screen without an intermediate platform, cleaned by manual raking from the sides and bed

Photographs courtesy of ATPEC Ltd

Debris clearance

The maintenance requirements of a trash screen are imperative to the successful operation of a flood storage reservoir incorporating a trash screen. These must be fully assessed and agreed with the operator. Maintenance activities include regular clearing of the screen and safe disposal of accumulated debris.

In addition, the design should consider how debris should be removed from the screen in the event that it becomes blocked during a period of flooding. Once a screen becomes completely blocked it may not be safe to clear it: the design should allow for early access to the screen area after the flood subsides to facilitate a safe means of clearing the blockage.

There are 2 approaches to debris removal from screens:

- periodic clearance by:
  - manual raking
  - mechanical grab systems or mobile plant such as a grab lorry
- automatic screen cleaning by machine

Figure 3.13 shows examples of screens cleared by manual raking or using a grab lorry.

Figure 3.13 Screen design allows for manual raking or cleaning by grab lorry

Photographs courtesy of ATPEC Ltd

The preferred approach depends on the nature and quantity of debris, though the site location and other factors may also influence the decision.

Although automatic machines avoid the health and safety risks associated with manual raking, they are only suitable where the nature of the debris can be handled reliably by the mechanism. They must be reliable in adverse weather conditions and can be subject to vandalism or power supply reliability issues. But where the anticipated debris loading is such that manual raking cannot be relied on to clear the debris quickly enough, they offer an option to provide safe, high-capacity cleaning. However, the following considerations will often make automatic screen clearance impractical for flood storage reservoirs.

- The screens are often too steep to allow for manual screen clearance as a backup provision in the event of malfunction.
- Even on a continuous cycle the capacity of the machine might be exceeded during a flash flood.
- Large awkward items of debris cannot be handled.

Screens intended for manual raking have specific design requirements to facilitate safe, efficient cleaning; reference should be made to the TSSG (Environment Agency 2009c). The requirements for manual cleaning should be minimised as far as possible through careful design. For example, the bar screen spacing should not be so fine as to unnecessarily trap small debris such as leaves that would otherwise pose no risk of blockage of the control structure. The poor design of the screen shown in Figure 3.14 does not allow efficient manual raking over its full extent.

Figure 3.14 The intermediate horizontal support bar of this screen is insufficiently recessed to allow efficient manual raking over the screen's full height

Photograph courtesy of ATPEC Ltd

Water level monitoring and/or a closed circuit television (CCTV) system should normally be used to inform the extent of debris accumulation on a screen. It is considered good practice to install a pressure transducer either side of the screen to:

- assess the head difference across the screen

- inform remote operators of any need for debris clearance, particularly during the passage of large flood events

The design should consider where debris is to be stored once removed from the screen. If the intention is to store debris at the reservoir site temporarily prior to removal, the selected site should be above the highest water level to avoid the debris being re-floated and transported back onto the screen during a subsequent, more extreme flood event.

Large debris from coarse screens is normally removed by mobile plant once the flood has subsided. It is important that the proposed access arrangement does not introduce a risk of damage to any of the dam structures through the removal of large items of debris such as tree trunks.

The design should consider the provisions required to isolate the screen and control structures for inspection and maintenance activities. Some headwalls provide for stoplogs to be installed upstream of the screen. Where stoplogs are provided, consideration should be given to their secure storage at the site in an area not prone to flooding. Where the project involves multiple control structures, it may be possible to use one set of stoplogs to serve multiple sites. The design should consider how the stoplogs will be lifted, transported and deployed.

Where gates or screens are installed, it is necessary to consider the steps required to replace the equipment in the event that the equipment reaches the end of its design life, becomes damaged or key parts require repair. In all cases, consideration should be given to the lifting requirements, whether lifting will be achieved by permanent installations (such as gantries) or by mobile lifting plant, and where such plant can be sited to ensure safe working and without damaging the embankment or other structures.

Figure 3.15 shows an example of two-stage screen retrofitted to a headwall.

Figure 3.15 Two-stage screen retrofitted to a headwall: the platform and steps are constructed from a non-slip, free draining, glass-reinforced plastic grating

Photograph courtesy of ATPEC Ltd

3.6.5 Sediment management

Flood storage reservoirs act as detention basins during flood events and can accumulate sediment deposits within the reservoir area. The performance of flood storage reservoirs in removing pollutants is beyond the scope of this guide. Reference can be made to CIRIA (1993) on this subject.

Fine sediment

As the reservoir level varies over the course of the flood, the deposition of fine sediment is usually well distributed over the reservoir basin.

At online reservoirs, the design should consider the geomorphological impact of the control structure. Wherever velocities are reduced there will be the potential for deposition. Once fine sediment becomes consolidated it may affect the performance of the hydraulic structures during a flood event and therefore warrants pre-emptive maintenance work to remove the deposits.

Deposition of fine sediment within the reservoir basin can lead to downstream fine sediment starvation, which has the potential to cause bed and bank erosion. Where this is a concern, a geomorphological investigation should be conducted to assess the potential for maintaining sediment transport and advise potential mitigation measures.

Some degree of deposition of fine sediment near trash screens is common as the flow is presented to a relatively wide hydraulic section past the screen. This can present a maintenance burden, though in most cases, the fine sediment does not accumulate to an extent to pose a serious operational concern. Fine sediment deposition appears to be a particular problem where multiple screens are deployed.

Where appropriate, measures can be considered to reduce the fine sediment loading from areas vulnerable to erosion within the reservoir area or from the wider catchment area. A range of options for managing sediment erosion or attenuation should be investigated by an experienced geomorphologist.

Coarse sediment

Coarse sediment is not normally a major concern in the design of flood storage reservoirs within the UK as the course sediment yield of most UK catchments is relatively small.

A course sediment transport regime should be investigated so that transport of material through a control structure can be understood and maintained to support the existing habitats and ecological value. Where bed deposits serve such an ecological value, design flow velocities need to be evaluated to ensure that the bed material is not routinely scoured out.

3.6.6 Animal management

Animal activity can pose a wide range of threats and maintenance issues at flood storage reservoirs. Animal risks can usually be considered in terms of either livestock or burrowing animals.

Livestock

Many flood embankments are located in rural areas and livestock management can be an important issue.

Where sheep are present, experience has shown that they do not pose any serious threat to reservoir structures, provided that any feeding areas, including water troughs, are kept at distance from the structures. Sheep can be used to maintain short grass cover in lieu of grass cutting but any thistles and so on, will still require cutting. Some minor rutting of the embankment surface can result, but this does not normally affect effective surveillance. Note that sheep may choose not to graze on the slopes of an embankment.

Cattle and horses should not be allowed access to reservoir structures unless special provisions are made to prevent erosion of accessible areas; an example of cattle poaching is shown in Figure 3.16.

Escape routes and refuges should be considered throughout the design phase including the arrangement of fencing and location of gateways.

Figure 3.16 Serious cattle poaching on the downstream face of a flood storage embankment

Photograph courtesy of ATPEC Ltd

Burrowing animals

In most cases, specific measures to reduce the threat of burrowing animals are not warranted as part of the design of a flood storage reservoir. Where a problem is anticipated, the design options include those listed in Table 3.4.

Table 3.4 Strategies for dealing with burrowing animals

Strategy	Comment
Adopt a site for the embankment well away from areas of known high activity.	This will often be appropriate if there are alternative sites of near-equivalent suitability and characteristics.
Fence off the embankment area using specialist netting affixed to posts around the dam area.	This approach is not generally preferred as such fences can inhibit the passage of other non-threatening animals through the area and may also affect the visual impact of the site. Any fencing increases maintenance tasks and costs.
Place steel wire mesh placed under the topsoil.	This is an expensive option that will only be warranted where rabbit or badger activity is significant and cannot otherwise be mitigated. Experience indicates that rabbits will often find the edges of the mesh and burrow under them.
Use sacrificial material on the dam slopes to mitigate the risk of damage from burrows.	Burrowing only within sacrificial fill will preserve the engineering properties of the main dam. However, burrows can be very extensive. So while this approach reduces risk, it provides no security against damage to the engineered section.

Once badgers have established within an embankment, it can be very time-consuming and costly to remove them and to repair the damage. For further information on burrowing animals, refer to Section 4.3.2. Refer to Natural England guidance on managing rabbits (TIN003) and badgers (TIN005) (Natural England 2007a, 2007b).

Figure 3.17 Rabbit burrow damage (left), Badger damage (right)

3.6.7 Grassed slope design

Short grass cover (as shown in Figure 3.18) is usually the preferred form of surface protection for flood storage embankments where water is not permanently retained.

For online reservoirs that permanently retain water, some form of surface protection will be needed to counter erosion due to wave action. For slopes that only have to counter wave energy for a short duration as the reservoir fills and empties, grass cover is usually sufficient.

Figure 3.18 Short grass provides for effective surveillance of embankment condition

All grassed slopes should be designed to facilitate safe, efficient grass cutting. Many slopes at reservoirs have been designed at a slope which is flatter than that warranted through slope stability analysis to facilitate grass cutting. A slope of approximately 1V:4H has commonly been considered as sufficiently shallow to facilitate safe grass cutting and the harvesting of the grass clippings by standard machinery for silage or some other use. New grass cutting equipment and technologies have been developed which may provide safe use on steeper slopes, but this approach can necessitate the purchase of expensive machinery and might not provide the optimal approach in the long term. The designer should ensure that the slope angles are consistent with the intended equipment for grass cutting.

Grass cutting is particularly difficult where grassed surfaces adjoin vertical concrete surfaces such as headwalls or pass under fencelines. Such arrangements necessitate strimming, which greatly increases the maintenance requirement. These issues can be addressed by the design team in specifying suitable paving materials adjacent to walls and under fencelines so that strimming can be avoided.

It is important to select the grass seed mix for the works specification carefully. Suitable grass seed mixes for embankments need to fulfil a number of requirements. The mix needs to:

- create a closed sward to protect the embankment
- withstand a maintenance regime that produces a low sward in order to aid engineering inspections
- respond to the geographical location

Specialist suppliers are able to provide advice on grass species and mixes to suit the particular requirements. Wildflower mixes should generally be avoided but including a wider range of species may help to achieve wider ecological objectives.

The grass cover should be cut as necessary – typically at least 3–4 times each year – to enable effective surveillance of the structure. For sacrificial (non-engineered) slopes, this requirement can be relaxed. The aim should generally be to keep grass length less than 100mm in length throughout the year.

The maintenance regime and associated funding for ongoing landscape maintenance, including grass cutting, should be agreed during the design phase.

Further advice on the environmental considerations of the design and ongoing maintenance of embankments is included in the Fluvial Design Guide (Environment Agency 2009a) and should be considered alongside the engineering design.

3.6.8 Power supplies

Although the power requirements for installations of this nature are not large, the rural nature of many typical locations may restrict the availability of power. Early contact should be made with the relevant distribution network operator to ensure an adequate power supply is provided.

Buried supply cables generally provide a more reliable source of power, although the cost is significantly higher than the use of overhead cables. In a rural area, the extensive use of overhead cables within the supply network will probably negate the benefit of providing the new supply cabling underground unless these cables originate at a reliable point in the network. Underground cabling should not be buried through or under dam embankments.

Where the powered equipment provides a safety critical function, the need for backup power or alternative means of operation will need to be addressed. For manned sites, or sites that can easily be attended in the event of a mains power failure, the most effective solution is usually to have a means of manual operation. For remote, unattended sites utilising automatic operation, the system will need to be assessed for reliability, including considering the reliability of the power supply. A similar approach of assessing risk and reliability should be used on all sites to ensure an adequate level of redundancy is provided.

For low demand applications such as instruments and controls, the use of solar and wind generation can be considered. One advantage is that the generation device can be located close to the demand, reducing the need for distribution cabling. The use of an appropriate battery capacity can ensure that the system has a reasonable period of operation in the event of generator failure and sufficient to allow an alternative generation source to be provided.

If a mobile or fixed generator set is used to provide either the main or backup source of power, attention must be paid to the issue of fuel storage and adequate bunding of the fuel tanks, engine and any pipework to avoid the risk of pollution due to a fuel or oil leak. Backup systems should be tested and exercised regularly.

Where it is anticipated that the site will have mains electricity, lighting should normally be provided to critical areas such as access routes, screen areas and other areas where operators may need to work during the hours of darkness.

Lighting requirements fall into the following 3 categories.

- **General access lighting** is needed to allow operators to safely access areas of the plant. This is generally of quite a low level and attention should be given to minimising light pollution by the selection of appropriate lamps and fittings. Depending on the frequency of site manning, this lighting can be controlled by timers, passive infrared sensors or dawn/dusk sensors, or by appropriately placed switches.

- **Task lighting** is provided where operators may be required to work during the hours of darkness. This lighting should be provided at a level sufficient for the tasks being carried out and is normally switched on by the operators as required.
- **Emergency lighting** may be required in buildings or other enclosures.

Guidance on lighting design can be found in BS EN 12464-2:2014 (BSI 1999b) and the CIBSE Code for Lighting (Raynham 2013).

3.6.9 Telemetry, alarms and controls

Where it is necessary to monitor the site from a remote location, telemetry is used to provide monitoring of, for example, equipment status and water levels. In this case, many clients will have their own preferred system but for other applications a number of proprietary systems are available. In some cases, the telemetry system can provide a control function but this should usually be avoided as difficulties with communication may result in the equipment not operating. Where remote telemetry control is used, adequate backups and contingencies need to be in place. The preferred approach is to have control provided locally and monitor the system with the telemetry system. In the event of alarm conditions, the telemetry system can prioritise alarms and many systems can initiate an SMS text message or email to selected operations staff if required.

The telemetry system can also be used to record historic data, which may be of use in reviewing the performance and operation of equipment and monitoring trends in parameters such as water levels.

Where a site is monitored from a remote location, communication between the 2 locations is important. The usual methods are via a fixed telephone line, use of the mobile phone network or in some cases by use of private radio equipment. Each method has various advantages and disadvantages, and specialist advice should be sought. Where radio is considered, it is important to ensure the supplier includes a survey to check the signal will not be disrupted by interference from other nearby equipment or radio transmissions.

Where automatic controls are used, they should be assessed to ensure a suitable level of reliability. For safety critical functions, it is likely that a number of layers of redundancy will be required. The risk and reliability should be assessed to ensure an adequate level of reliability is provided.

It is common practice to install water pressure transducers upstream and downstream of debris screens to alert the control room of any significant head loss arising from screen blockage. High differential water levels can initiate an alarm at the control room to alert the operations manager or the local controls can initiate a SMS text message to notify selected operations staff.

Usually non-contact devices such as ultrasonic measurement are used for this kind of application and this has the advantage that the same instrument can often also provide the reservoir level. Where contacting types such as floats or pressure transducers are used, care is required to ensure reliable operation. In some cases difficulties have been found with sensor tubes becoming unreliable due to siltation at the bed of the watercourse. The siting and elevation of the transducers requires care for reliable operation. The use of stillage tubes – usually made of plastic, stainless steel or galvanised steel – within the main control structure is preferred to the use of pipes leading to stilling chambers enclosing the transducers situated offline. The latter are prone to silt accumulation and require periodic flushing out of silt.

Gauge boards should be installed to provide readings of water depth – either in metres (m) or metres above ordnance datum (m AOD) – between the upstream toe and the dam crest. A staggered set of boards is appropriate for all but very low embankments. They should be set to be easily read from a location accessible when the reservoir is full.

3.6.10 Monitoring and surveillance provisions

Surveillance systems

Most flood storage reservoirs do not require remote monitoring and surveillance. However, CCTV systems can be used to help monitor the condition of sensitive equipment such as automatic screen cleaners (Figure 3.19) and become an effective tool to aid in incident response. Concerns over vandalism may also justify the use of CCTV equipment. CCTV signage should be erected in line with the Data Protection Act 1998.

As part of the design process, any permanent column for CCTV equipment should be assessed for its aesthetic impact.

Figure 3.19 Solar panel operated CCTV at Swanage flood storage reservoir taking still images

Notes: The camera is pointed at the trash screen and spillway to indicate to operations staff when screen cleaning or maintenance works are required.

Crest monitoring

To assist in the maintenance of a fixed standard of protection, some flood storage embankments feature a crest kerb set in mass concrete. These can help to visually identify any damage to the crest. Kerbing can also help to mitigate damage due to unauthorised excavations on or through the crest. It is possible to add wording such as 'Do not remove, flood defence asset' to the kerbing to provide additional warning.

The position of the kerbing on the crest should be considered carefully to minimise the risk of damage from grass cutting machinery or other vehicles on the crest. The kerbing should be set back from the edge of the crest such that it is well supported.

Where kerbing is provided (Figure 3.20), it is normally used for the purposes of periodical crest level surveys. Where kerbing is not provided, crest surveys are carried out by either using survey pins installed within the crest at regular intervals or by surveying crest levels at ad hoc locations along the highest point on the crest. The latter approach is less reliable for monitoring purposes.

Figure 3.20 Crest kerbing

Seepage monitoring

Seepage monitoring systems such as toe drains are not normally required for flood storage reservoirs as the hydraulic loading is transitory in nature. If water is to be permanently impounded, or if the design indicates that the reservoir will need to store floodwater for a protracted duration, seepage monitoring should normally be provided or its exclusion justified.

Where a toe drainage system is deemed necessary, provision should be made for measuring any such flows.

Other monitoring

Other forms of dam performance monitoring, such as piezometric monitoring, are not normally required for flood storage reservoirs. For statutory reservoirs the Construction Engineer will specify the monitoring requirements.

Where embankment monitoring for settlement and internal stresses is recommended, the use of remote sensing should be considered. These systems can support an online early warning system, real-time emergency management and support routine asset management. For further guidance refer to Modes of Dam Failure and Monitoring and Measuring Techniques guide (Environment Agency 2011c).

3.7 Health and safety

3.7.1 Operative health and safety

The design must consider the health and safety of operatives under the provisions of health, safety and welfare regulations. Typical provisions at flood storage reservoirs include:

- fencing to guard against falls from height (for example, headwalls)
- steps and handrails for any steep points of access to mitigate trips and falls
- ladder cages, fall arrest systems and so on for points of vertical access
- signage of any particular hazards (for example, confined spaces, electrical shock)

Consideration should be given not only to the tasks that may have to be done, but also the differing conditions under which they may have to be done (flood, ice, night-time and so on). Such considerations at flood storage reservoirs might include things like provisions to limit the amount of manual handling through the use of portable winding equipment. Guidance on the application of suitable provisions is available from the Health and Safety Executive (HSE) website (www.hse.gov.uk).

Specific guidance relating to lifting operations and work equipment in line with the Lifting Operations and Lifting Equipment Regulations 1998 (LOLER)and the Provision and Use of Work Equipment Regulations 1998 (PUWER) is also available on the HSE website.

3.7.2 Public health and safety

Public safety

Design and construction decisions should be taken to eliminate or mitigate risks highlighted by a risk assessment of the health and safety of the public. Consideration should be given to both members of the public who may have legitimate access to structures (for example, on footpaths through parkland) and members of the public who access structures out of curiosity or with intent to vandalise or force access.

If there are control rooms at the site, it is normally appropriate to fit an unauthorised access alarm.

Measures such as life buoys should be considered, especially if the reservoir permanently retains water. Note that where life buoys are provided, the operator has a legal obligation to maintain them under health and safety legislation. Advice on matters of water safety is available through the National Water Safety Forum (http://nationalwatersafety.org.uk).

It has been known for members of the public to clear debris screens themselves rather than waiting for periodic clearance. This risk could be mitigated through appropriate signage.

Exclusion from conduits

Many flood storage reservoirs have conduits that can attract attempts to enter them by members of the public, particularly children. Unauthorised access could lead to entrapment or drowning.

The TSSG (Environment Agency 2009c) provides guidance on the design of appropriate security grilles. A general debris screen at the conduit inlet headwall will normally be effective as a security grille, although a downstream security grille might be warranted. However, security grilles at the downstream end of the conduit may trap debris passing the upstream screens. This risk can be mitigated by designing the screen to 'fail' (swing open) under a significant loading imposed by blockage (for example, by fitting shear pins). A winch system has often been used to allow the screen to be periodically lifted to release debris. However, the wire ropes can corrode and the locking pins can also be difficult to engage such that the grilles cannot be safely secured. Hinged, side-swinging grilles may provide a suitable solution for many sites. It is possible to operate these grills via a lever on the headwall above.

To help prevent small debris being trapped, a gap of approximately 100–140mm should be left below the bottom of the screen to pass low flows and small twigs. If there is a dry weather flow, the gap should be set above the level of this flow.

Security grilles should be designed with a maximum clear spacing of 140mm and 10mm diameter bars at 150mm centres is normally sufficient. Although horizontal bars are preferred in terms of debris performance, they can also be attractive in helping children climb structures and therefore this aspect needs to be considered on a site-by-site basis.

4 Operation and maintenance of flood storage reservoirs

4.1 Introduction

Flood storage reservoirs are generally operated as part of a catchment management system. This requires a reliable means of communication. Reliance on a single system, such as a mobile phone signal or an overhead phone line, should be avoided. There should usually be a facility for mechanical equipment to have a locally operated override so that any issues can be managed accordingly at the site with suitable security provisions to prevent unauthorised operation.

The operation and maintenance of equipment should be carried out by suitably trained and competent persons to suit the nature of the task. Prior to operation, reference should be made to the O&M manual (if available), which will advise on site-specific constraints and any operational or structural limitations. A risk assessment and method statement should also be completed.

4.2 Operation of hydraulic controls

The methods of operating flood storage reservoirs are varied and the choice of method depends upon the way in which the catchment is to be controlled and the topography of the site. While some maintenance features are common, the particular requirements of each type differ and can have a major influence on the lifetime cost of a system.

The main types of hydraulic controls can be categorised into fixed and mechanical devices. See Section 3.2 for the different types of hydraulic controls and their typical arrangements. Fixed devices include:

- uncontrolled side weir
- flow limiter across the watercourse (throttle pipe, culvert, orifice, flume, weir, notch, vortex device or baffled device)

Mechanical devices include:

- gated side weir (vertical lift gate, radial gate, tilting gate)
- gate control across the watercourse (vertical lift gate, radial gate, tilting gate)

4.2.1 Uncontrolled side weir

This is the simplest type of control and requires neither human intervention to operate the flood storage nor any mechanical equipment.

The weir is set at the level where the downstream watercourse can just accommodate the flow. Any additional flow passes over the weir into the offline storage area. This arrangement is simple to operate, but there is no means of control.

Figure 4.1 shows an example side weir.

Figure 4.1 Example side weir – the crest level is defined by the roadway

4.2.2 Gated side weir

The gate, which can take different forms, is kept closed to prevent water entering the offline reservoir until critical levels are reached in the watercourse, whereupon the gate opening is varied to control the forward flow. Gates can be arranged to be 'undershot' (for example, vertical lift gate) or 'overshot' (for example, tilting or fish belly gate) with the water passing under or over the gate respectively.

Figure 4.2 shows an example of a closed fish belly gate.

Figure 4.2 Fish belly gate control shown closed

The rate of storage can be varied to suit the intensity of the storm, though various safeguards are required.

Very small gate openings of any type should be avoided as the water velocity can be enough to cause damage to the gate seals and the supporting concrete structure. The electrical control of the gate should be set so that a minimum opening is achieved before the gate is allowed to stop the flow.

Gates are often designed to operate in response to rising or falling water levels in the watercourse or reservoir. It may be desirable to operate gates as water levels fall in the receiving watercourse. Any necessary controls to manage the head across the gate will need to be programmed into the mechanical, electrical, instrumentation, control and automation (MEICA) management system.

4.2.3 Gate control across the watercourse

As with the side weir, this control can take the form of a vertical gate or 'penstock' (Figure 4.3), which in this case restricts the forward flow by reducing the size of the opening, or a fish belly gate (Figure 4.4) that normally sits flush with the watercourse bed but is raised to limit forward flow by putting water into storage behind a rising weir (the gate). Automatic orifice devices effectively operate in the same manner as automated vertical gates.

The control is operated by monitoring the water level at the vulnerable point downstream and the forward flow reduced as necessary by operating the gate(s).

Figure 4.3 Online vertical penstock control

Figure 4.4 Online overshot radial gate being raised from the watercourse bed

4.2.4 Flow limiter across the watercourse

As with the gate controls across the watercourse, a flow limiter effectively dams off the watercourse but a predetermined forward flow is allowed forward as determined by the size of the pipe, orifice, flume, weir, notch, vortex device or baffled device. Sometimes the forward flow can be increased by opening an adjacent penstock (as in the example illustrated in Figure 4.5) but it cannot normally be reduced.

Figure 4.5 Orifice plate and supplementary control penstock

The arrangement illustrated in Figure 4.5 allows flexibility of operation where 2 or more watercourses feed into the vulnerable point in the watercourse. If the secondary watercourse is not in flood then more water can be passed through the control, but as the secondary watercourse rises, the gate is closed so that the combined forward flow does not exceed the critical level at the sensitive downstream location(s).

4.2.5 MEICA equipment

For the purposes of this section, MEICA equipment relates to reservoir operation equipment and does not cover warning facilities for areas of the basin that need to be checked and cleared of public users before the water level begins to rise.

The uncontrolled side weir arrangement (see Section 4.2.1) does not require any equipment to operate and in this respect it is economical to maintain and operate. The only requirement is the means of recording the depth of water within the basin.

The control systems for gated side weirs (see Section 4.2.2), a gate across the watercourse (see Section 4.2.3) and flow limiting devices (see Section 4.2.4) have much in common. It is usual that the facility will be operated as part of a catchment management system rather than as a local facility. Where this is the case, the operation will be controlled based on pre-set, automatic triggers, or occasionally by manual override from the operation room if the need arises. There should also be the facility to switch to manual operation at the site so that any local situations can be managed.

The high level controls typically required are as follows.

- Monitoring of the water depth (or flow rate) at the critical point of downstream inundation (for example, the first point of flooding or a pumping station) is important. This warning should be in sufficient time and requires the ability to predict the flood passage so that the storage area can be prepared at the appropriate time.
- A communication system so that the onsite operation team can prepare the area and, if necessary operate the facility. It is useful, if in the event of major events at statutory reservoirs, the panel engineer responsible for the safety of the reservoir can be informed to observe the performance of the reservoir during a flood event.
- If the gate is to operate on automatic then at a fixed time before the critical point is reached, the gate is operated. The increment of gate opening will normally be pre-set with a minimum time limit between operations to avoid the system ‘hunting’.
- The gate position should be displayed both in the local control room and at central control.
- The water level in the reservoir area needs to be recorded and displayed at central control.

At the installation, two types of controls are typically required.

- It needs to be possible to switch off the automatic control to allow local operation of the gate. This requirement is also required to enable maintenance inspections of the gate.
- A reliable communication system between the facility and the central control is essential. It may be acceptable to rely on the mobile phone network if the signal is strong enough and reliable, but central control needs to have the number of the operator, which might prove an administrative challenge. In addition, mobile phone networks can get overloaded during a flood event and become unreliable. A dedicated landline or radio system is

more fool-proof, but can still be vulnerable in extreme weather conditions that might be experienced during times of operation. For these reasons a suitable backup system should be considered.

4.2.6 Auxiliary equipment use and storage

Depending on the location and nature of the site, it may be appropriate to provide permanent welfare facilities there to support staff who may need to be at the reservoir for extended periods of time during a flood event.

Such facilities will typically comprise a building (usually combined with a control building) to enable staff to keep dry and warm and with access to toilet facilities. Such buildings can also be used to secure equipment such as screen rakes, safety harnesses and valve keys.

4.2.7 Power supplies (including backups)

On gates where it is physically feasible, there should be a manual operating facility as a final recourse in the event of a power or system failure.

If manual override is not feasible then some means of coupling into standby generators should be provided. These generators can be stored onsite, or kept remotely and brought in when required, although the ability to bring generators to site during a flood operation needs to be carefully planned. The most important considerations are:

- requirements for backup power
- appropriate form of power (electrical, pneumatic, hydraulic)
- onsite or mobile standby provisions
- if mobile, access routes (during flooding) and form of transport
- if permanent, risk of theft or vandalism
- personnel and equipment required to instigate the backup provision
- suitable provisions for refuelling safely

4.2.8 Screen clearance

The TSSG (Environment Agency 2009c) provides general guidance on all aspects of screen design and operation. Operational requirements will depend on the type and size of screen adopted.

Contractors employed to clear screens should be provided with an operational plan setting out the site-specific issues and practices that should or should not be adopted at the site. Manual handling considerations will have been considered at the design stage, but risks can be introduced if work is not carried out in the manner envisaged during the design.

The operational plan will also set out the frequency at which the screen is to be inspected and cleaned under routine and flood conditions. Consideration should be given to dealing with significant influx of debris during extreme flood events such that there are recognised protocols through which operatives are not placed at risk.

During a severe flood, the amount of debris clearance required may exceed the capacity for removing the debris from the site. Temporary debris storage sites should be identified to provide for this situation.

The operational plan should identify where the debris is to be transported to. Debris should be properly disposed of at a licensed waste disposal site.

4.2.9 Reservoir emptying

It is the general aim to return the stored water to the watercourse in a controlled manner, as soon as possible and without the cost of pumping.

With online storage systems with controls across the watercourse, the gate is raised (or lowered depending on type) under control of the downstream water level. This can usually be done on the tail of the flood when the water level is dropping below the critical level.

Online storage systems with fixed controls such as vortex devices or orifice plates are self-controlling and no intervention is normally necessary.

Offline storage systems may employ several systems of emptying. Some systems, but not all, return the stored water through the gate used to fill the reservoir. This is unlikely to fully empty the basin and further drainage may be necessary. Such drains need to extend far enough downstream to have a significant head difference between the floor of the basin and normal river level. A weir is sometimes conveniently placed between the position of the gate and the drain outfall. It is often the case that the catchment management requirements support the use of a weir for flow measurement purposes and this can be incorporated into the scheme. The drains are usually provided with a flap valve at the outfall to prevent water entering the basin at the wrong times. They also usually require a trash screen at the upstream end to prevent the accumulated debris of the flood from entering the pipe. Adopting the same principle as the inlet screens, these should be designed so that they can be raked safely – usually manually.

With gated control structures, reservoir emptying can be closely controlled to suit downstream conditions. Where the reservoir is on one of two or more tributaries leading to an area of flood control, strategic control of the reservoir storage may be adopted to reflect flow conditions on the other tributaries, available storage in any other flood storage reservoirs and flood forecasting. Generally, it is desirable to empty flood storage reservoirs soon after the flood has passed to regenerate the available reservoir storage for subsequent events, but in complex catchments, an early release of storage could increase flood risk.

Where the flood storage reservoir permanently impounds a raised volume of water, it will usually be necessary to provide some form of low level outlet to allow for periodic emptying of the reservoir to carry out any necessary maintenance activities to the dam structure. If this is likely to raise environmental concerns then it might be feasible to use a temporary bund to preserve upstream water levels while the work is being carried out.

4.2.10 Post-flood activities

Following the passage of any significant flood event, it is important for the operators to carry out checks on the structure for any works required to restore the design condition or to minimise maintenance costs. Over time, site managers can gain experience in determining the intensity/duration of flooding that is likely to give rise to particular problems and the nature of the problems commonly associated with the site following a flood event.

The precise requirements for surveillance will vary from one site to another, reflecting the reservoir and catchment characteristics. Typically, post-flood surveillance checks should cover:

- carrying out a visual check for any blockages in control structures or indications of structural damage
- observing the condition of screen structures – if a screen has been heavily loaded then a visual check of the structural members is recommended
- checking that flap valves are clear of debris and remain free to operate
- checking for large amounts of flood debris (wrack) on the dam embankment, which is likely to kill the grass if not removed
- marking and surveying the level attained by the wrack to correlate with water level records
- visually inspecting for evidence of seepage and/or internal erosion
- functioning of control and telemetry systems
- functioning of lighting systems
- checking the condition of access and security facilities

Where combined sewers surcharge during flood events and enter flood storage reservoirs, there will be a risk of pollution on the ground and embankment surfaces once the floodwater has receded. This risk should be evaluated by the operators and testing carried out if appropriate.

Flood events may mobilise large items of floating debris towards the reservoir area, which could pose a threat to operation during subsequent events. The operator should therefore consider a walkover of the area close to the watercourse for some distance upstream of the reservoir to check for any such threats and deal with them accordingly. Blocked bridge openings upstream of the reservoir could pose a threat during subsequent flood events so it is important to consider where such threats might exist and to carry out appropriate checks and actions as necessary.

The recording of actions taken following major flood events will help to develop a checklist of routine post-flood activities. It is also valuable to record the performance of control structures during the event so that any maintenance activities or design improvements can be scoped accordingly. At statutory reservoirs, the supervising panel engineer should be informed of any significant findings and invited to attend the site if necessary.

4.3 Maintenance

4.3.1 Grassed areas and embankments

Embankments may comprise both engineered sections and sacrificial fill deployed for landscape purposes. Maintenance requirements will vary between these sections and should be discussed and agreed at an early stage in the design process.

Areas of sacrificial fill may require little or no maintenance other than periodic clearing of debris, tree management and management of animal burrows.

Engineered sections, where grassed, will usually need to be maintained with a short cover of grass mix. There are recognised specifications and forms of contract which can be deployed such as the Joint Council for Landscape Industries' 'Landscape Maintenance Works Contract 2012' (JCLI 2012) and the 'Manual of Contract Documents for Highways Works Series 3000 (Landscape and Ecology)' (Highways England 2014).

Where the surface incorporates a buried geotextile within the topsoil or a mesh to prevent animal burrowing, it is essential to carry out a visual inspection prior to any grass cutting to identify if any buried protection mesh has become exposed. Cutting should not take place on any areas that contain a fault until that fault has been rectified. Careful management of the cutting operation is required where there is erosion protection to prevent rutting or other damage to the ground surface.

The operator should consider carefully the type of grass cutting machinery used on slopes, both with respect to the safety of the maintenance team and the effectiveness of the cutting. Historically, shallow embankment slopes (typically 1V:4H) have been used to facilitate safe grass cutting operations. The use of remotely operated machinery can allow safe unmanned operation on steeper slopes, but machinery of this nature is usually not designed to remove the grass arisings and might only be practicable for small embankments. A site-specific risk assessment should be carried out before starting work to review the proposed methods. Sites may require different machinery to cut different areas.

The frequency of cutting will vary from site to site and should be set out in the landscape and ecology management plan. Most sites will require several cuts each year to keep the grass short enough to promote continuous, effective visual surveillance (that is, less than approximately 100mm).

Grazing by sheep can be an acceptable alternative to mowing if stocking rates are suitable to graze the entire embankment (see Section 3.6.6). If alternative soft landscaping has been proposed, such as wetland habitats or marshland, site-specific management should be developed during the design process and implemented in line with the landscape ecology management plan.

The long-term landscape management of the flood storage reservoir should be considered during the design phase to ensure the requirements and funding responsibilities are clearly allocated. The landscape and ecology management plan will set out maintenance regimes and management objectives as well as agreed monitoring and review periods.

4.3.2 Animal burrows

Embankments and other critical structures can be damaged by animal burrows.

At online reservoirs, the most common burrows are those belonging to rabbits, moles and badgers. Where there is a wet margin (for example, at an embankment separating a watercourse from an offline flood storage reservoir), damage might also be caused by rodents. The welfare of wild mammals is provided for in law through the Wild Mammals (Protection) Act 1996.

Burrows reduce the shear strength available to resist instability and increase the risk of internal erosion. Crest settlement due to burrows increases the risk of overtopping damage. Burrow orientation can occur at unfavourable angles to potential slip surfaces and lead to a non-uniform reduction in the mass soil strength.

Where animal activity is detected, the animals should be assessed and dealt with in accordance with current guidelines and legislation. Any major repairs to damage to statutory reservoir embankments should always be done under the supervision of a panel engineer (see Section 2.3.10).

It is important to:

- consider the animals near the dam and any evidence of animal damage at nearby sites
- seek specialist advice from the appropriate agency (for example, Natural England, Natural Resources Wales or Scottish Natural Heritage as appropriate) where badgers have caused, or are likely to cause, serious damage
- consider whether special protection measures are needed (for example, badger mesh on embankments or badger proof fencing)

Reservoir operators and advisors should:

- watch for any animal damage at embankments, using photographs as evidence where appropriate
- not investigate the area around a burrow or the burrows themselves without first speaking to an experienced advisor (animal droppings and fresh soil will normally indicate active burrows)
- deal with any issues before significant damage takes place

For online reservoirs, badgers most commonly pose the main threat of significant damage. Badgers are protected under the Protection of Badgers Act 1992 and therefore pose specific problems where encountered at existing embankments. In some cases, extensive damage has been caused necessitating major repair work (Bruggemann 2012). Where badgers are identified as actively damaging an embankment, it may be appropriate to relocate their sett or setts. This should only be carried out through detailed discussion and coordination with the relevant agency such as Natural England.

The following guides may be helpful in dealing with animals:

- ‘A Guide to Rabbit Management’ (CIRIA 2006)
- ‘Rabbits: Management Options for Preventing Damage’ (Natural England 2007b)
- ‘Badgers and Development: A Guide to Best Practice and Licensing’ (Natural England 2007c)
- ‘Invasive Species Management for Infrastructure Managers and the Construction Industry (CIRIA 2008)
- ‘Burrowing Mammals and the Safety of Embankment Dams and Reservoirs: Potential Problems and Solutions’ (McKillop 1993)

4.3.3 Fish and eel passes

On flood storage reservoirs incorporating fish and eel screens and passes, these need to be maintained to promote effective operation. Passes should form part of routine visual inspections. Maintenance activities will vary according to the structure requirements. Typical tasks may include:

- removal of debris causing blockage
- replacement of damaged parts

- recharging of bed material (if required for bed roughness to reduce water velocities)

4.3.4 Concrete and masonry structures

Concrete

Reinforced concrete is commonly used for headwall structures. As flood storage reservoir embankments tend to be of modest height, the structural and hydraulic loadings on concrete surfaces is relatively benign and significant maintenance requirements to concrete elements is unusual.

Damage can occur due to floating debris or poor operation of equipment. There is a wide range of guidance available on concrete repairs, including ISO 16311:2014 on the assessment of damage and repair of concrete structures (ISO 2014). It covers the basic considerations and decision-making for the specification of repair and prevention approaches.

Joints can require re-sealing periodically. Effective joint sealing is often important to prevent loss of embankment material through the joint, as well as protecting the joint surfaces from water and debris ingress.

Masonry

Masonry is sometimes used for headwalls or flumes either in lieu of concrete or to act as a facing to concrete walls to improve appearance. The latter application may use natural stone, but brickwork walling is more commonly used.

Generally, if brickwork is properly designed, detailed and constructed, it is normally very durable and should require little or no maintenance over the life of the structure. However, other associated components such as caps, copings, sills, lintels and sealant joints may require periodic inspection and repair. Neglecting maintenance of these components may lead to deterioration of the structure.

There is substantial literature on the repair and restoration of masonry structures. The Brick Development Association (www.brick.org.uk) is one source of guidance on brickwork. The repair of natural stone components is a specialist subject and the advice of a stone mason should be sought.

4.3.5 Hydraulic controls and MEICA equipment

MEICA equipment will require periodic inspection and regular exercising to prevent equipment seizing and being damaged by remaining stationary for long periods of time.

Some equipment, such as lifting equipment, has a statutory requirement for periodic inspection. The currency of the inspection status should be displayed on the equipment using some form of tagging or other suitable system.

All equipment, but particularly that exposed to water, should be inspected regularly for corrosion and any defects addressed rapidly to prevent deterioration.

Care should be taken to ensuring the manufacturer’s requirements in respect of maintenance are followed and the correct materials are used for lubrication.

4.3.6 Safety equipment

All safety equipment should be checked periodically for damage, function and calibration as appropriate. A checklist can be compiled for this purpose, noting the condition of all related equipment so that any issues can be dealt with quickly. The list might include:

- warning signage (for example, 'confined space')
- barriers
- ladders
- fall arrest systems
- locks
- security grilles
- non-slip surfacing

4.3.7 Access

To secure the site, it is common to use gates at property boundaries. It is important that key holders are carefully selected so that authorised access to the site can be made at any time of the day and night as may be required.

The availability of keys and checks on lock condition should be periodically reviewed to minimise the risk of access issues arising when dealing with any incident at the site.

Numerical combination locks can avoid the need for a physical key to be made available at site (that is, the key code can held at a central location and be passed over the phone if required).

4.4 Monitoring and surveillance

4.4.1 Routine monitoring and surveillance

Crest settlement of embankments is normally monitored, as a reduction in crest level will reduce the standard of protection available. Localised (differential) crest settlement could potentially impact reservoir safety. Settlement must be monitored against a reference datum off the embankment and at a location that is unlikely to be affected by settlement of the dam, or damage due to the public or other factors.

Where toe drains are provided, the flow rates should be measured and recorded when the reservoir is in operation as this can inform the performance of the embankment.

Surveillance downstream of embankments under flood conditions should include areas off the toe where any leakage and internal erosion through the foundation might be revealed by features such as sand boils.

Monitoring of the landscape and ecology management plan should be carried out at the regular intervals stated in the plan.

4.4.2 Monitoring and surveillance under reservoir safety legislation

Reservoirs that meet specific qualifying criteria are subject to reservoir safety legislation. The relevant legislation and criteria vary according to the country in which the reservoir is located. For reservoirs in England, for example, the provisions of the Reservoirs Act 1975 (as amended by the Flood and Water Management Act 2010) apply and are described in ‘A Guide to the Reservoirs Act 1975’ (ICE 2014).

In all cases where the reservoir meets the qualifying criteria, the owner or operator is required to appoint the services of panel engineers to oversee the design, construction and operation of the reservoir. Once the reservoir is in service, a Supervising Engineer takes the leading role in reviewing the performance of the structure with respect to the reservoir flood risk. The Supervising Engineer has no responsibility for the routine operation and maintenance of the reservoir structures but can advise on such matters as they see fit. It is the duty of Supervising Engineers to guide/advise the owner/operator in fulfilling their responsibilities under the relevant reservoir safety legislation. This will typically include water level monitoring, settlement monitoring and the maintenance of statutory records.

4.5 Emergency planning

Recommendations for the preparation of an onsite and an offsite plan to record relevant information to assist responders in the event of a dam breach emergency are given for onsite plans in Defra (2009) and for off-site plans on GOV.UK (https://www.gov.uk/government/publications/reservoir-off-site-plans-documents).

4.6 Post-incident reporting

The Environment Agency administers a database of incidents that have occurred at reservoirs anywhere in the UK. This supports learning and research on reservoir safety matters. Serious incidents at reservoirs located in England must be reported under the amended provisions of the Reservoirs Act 1975. An incident reporting form can be downloaded from GOV.UK (https://www.gov.uk/government/publications/post-incident-reporting-for-uk-dams-procedure-for-reservoir-operators).

Post-incident reporting is currently mandatory for reservoirs located in England and Wales and is likely to become mandatory in Scotland and Northern Ireland as new legislation is implemented. Regardless of location, reporting of reservoir incidents is encouraged.

5 Adaptation of existing reservoirs for flood storage

5.1 Introduction

5.1.1 Scope

Most dams located on watercourses (online reservoirs) provide some degree of flood storage and attenuation of the flood peaks experienced in downstream watercourse reaches. Because this provision is often not formalised, the reservoir operator has no duty or liability to provide any particular standard of protection to critical downstream areas and is not subsidised by any party for the flood protection benefit provided.

The UK has a relatively high population density and there are many developments within areas prone to flooding. Where there are reservoirs within the catchment area, these can potentially be used or modified to improve the standard of flood protection. However, this may change the way in which the reservoir is operated and consequently may impact the effectiveness of providing the primary function of the reservoir as well as operational costs and revenues.

It can be argued that the great majority of reservoirs serve multiple uses. As explained in Sections 2 and 3, new flood storage reservoirs should be designed to maximise the potential benefits to society and the environment as well as to provide their primary function of flood protection. This section is concerned with dual- or multiple-use in the more traditional sense of the term, where flood storage is provided by the reservoir in combination with a further primary or secondary use such as water supply or amenity.

In this section the term ‘dual use’ can be taken to include ‘multiple-use’ as the principles are generally the same. Where dual-use is intended in planning a new reservoir, the guidance in Sections 1–4 will generally apply if flood storage is the principal intended use of the reservoir. If the principal use is, for example, water supply, then the engineering design aspects will differ according to the primary function and such further guidance is beyond the scope of this guide.

This section covers the principles by which an existing reservoir might be adapted to provide (or formalise) a flood protection function. This may or may not involve physical changes to reservoir structures.

The main scenarios covered by this guide are:

- Use of a redundant reservoir, formerly used for water supply or some other function, for flood storage (see Section 2.2.3)
- Development of flood storage reservoirs that are intended to fulfil one or more secondary functions such as an amenity lake (see Section 2.2.6)
- Increasing reservoir storage, typically by dam crest raising, to add flood storage capacity to an existing reservoir
- Changes to a reservoir operational regime to allow for flood storage without increasing the total available reservoir storage

This section focuses on the last 2 scenarios whereby flood storage is provided by adapting an existing reservoir to provide, or to formalise the provision of, reservoir storage to meet a flood protection requirement either by modification of the structures or through changes to the operating regime.

The need to consider reservoir adaptation for flood storage arises from many drivers including:

- pressure to build houses nationally and the associated increase in flood vulnerability
- climate change
- the challenges in developing new 'greenfield' reservoir sites
- provision of multiple benefits from existing infrastructure
- working in partnership with other Risk Management Organisations to maximise benefits of funding

The Flood Directive 2007/60/EC requires EU Member States to develop flood risk management plans. Under the directive, the UK must take into consideration long-term developments, including climate change, as well as sustainable land-use practices. Reservoir adaptation for flood storage represents a relatively sustainable means of improving flood protection.

Water supply companies will clearly need to consider any proposed changes in raw water storage which could affect their Water Resource Management Plan (or national equivalent). The Water Resource Management Plan will typically describe how the company intends to manage and develop water resources to balance supply and demand for water over the coming decades.

5.1.2 International perspective on multiple use reservoirs

In the international context, multiple-use reservoirs may serve 2 or more of following common purposes:

- water supply for industrial or domestic use
- flood mitigation
- recreation
- fishery
- navigation
- irrigation
- hydropower
- power station cooling water
- river regulation for environmental benefits

A study of the impact of flooding worldwide by Doocy et al. (2013) indicates that 2.8 billion people were affected by flooding in the period between 1980 and 2009. Although there is no doubt that reservoirs will continue to play an important role in flood mitigation strategies around the world, the effectiveness of the approach varies considerably from one country to another, principally on account of physiographic, climatic and economic factors.

The 'World Register of Dams' maintained by the International Commission on Large Dams (ICOLD) contains data on over 58,000 large dams (>15m high) from approximately 100 countries. Almost 8,000 of these dams are used for flood control, of which 31% are for single-use reservoirs and 69% are for multiple-use reservoirs (ICOLD 2011) (Figure 5.1).

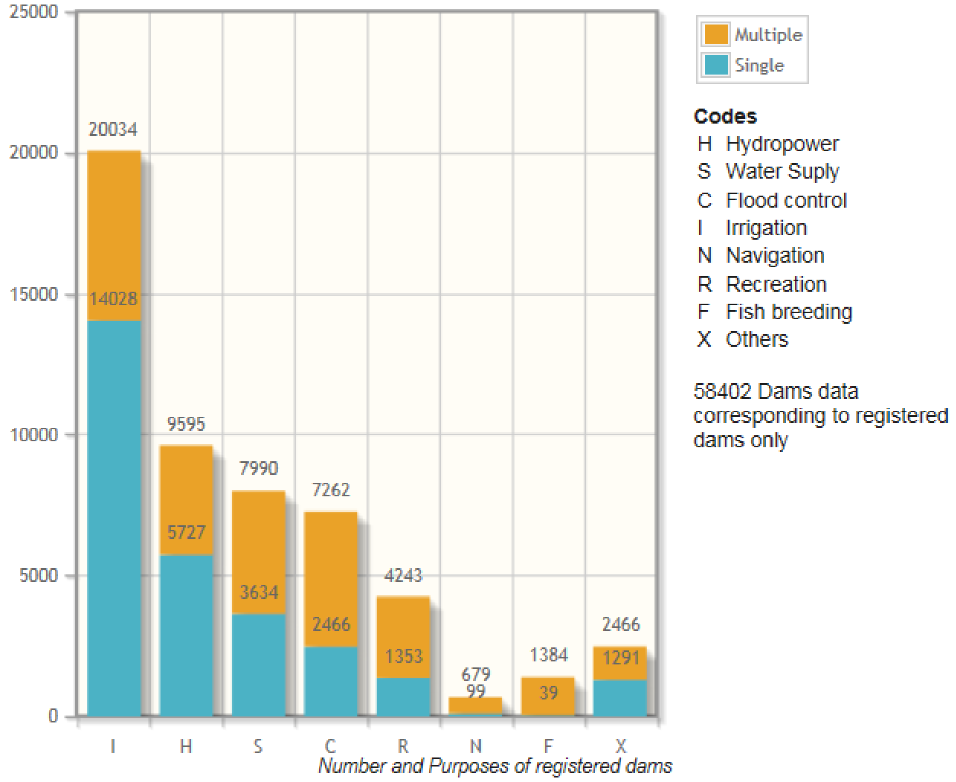


Figure 5.1 Use of reservoirs worldwide based on ICOLD's World Register of Dams

Source: ICOLD (2011)

In contrast, approximately 10% of the statutory reservoirs in the UK are flood storage reservoirs. Notably the great majority of these reservoirs are essentially single-use reservoirs, although many do provide supplementary benefits.

Space constraints and planning restrictions can limit the opportunities for adding reservoir storage to catchments with a recognised flood risk problem. Making good use of existing reservoir facilities is attractive but is subject to many constraints as described in the following sections.

5.2 Design approach

5.2.1 General

Any study to evaluate adding flood storage to existing reservoirs will usually be part of a wider study of the options available, which might also include raising of existing riverside flood defences. The methodology for evaluating and selecting the most appropriate approach is beyond the scope of this guide. Reference can be made to relevant national guidance such as the National Flood and Coastal Erosion Risk Management Strategy for England (Defra and Environment Agency 2011). This emphasises the need to engage with local communities to discuss the risks being faced and the choices that affect them. It also encourages alternative sources of funding to supplement government funding.

Proposals for the adaptation of an existing reservoir for flood storage might be derived from a catchment-wide study of a range of options, or might seek to formalise a flood protection function that an existing reservoir has been proved to provide but cannot be formally managed or relied upon. Depending on the physical and operational nature of the dam/reservoir, local factors and the adaptation proposals, the works might have an impact on:

- land acquisition and the impact on roads/facilities/services/users on the rim of the reservoir
- design of structures (dam, spillway, bottom outlet)
- safety of structures under increased loadings
- access provisions for maintenance or emergency response
- foundation stability and effectiveness of cutoffs under increased hydraulic loading
- consequences of dam breach and the associated risk classification and legal status of the reservoir
- the rate of storage loss through reservoir sedimentation
- reservoir rim stability
- water quality
- morphology of upstream and downstream watercourses
- sedimentation/erosion on river reaches upstream or downstream of the reservoir
- existing vegetation at various stages of maturity with could be designated
- the environment

According to McPherson et al. (2014), the main factors affecting the degree of flood mitigation that can be provided are:

- the operating rules of the storage
- the size of the design flood event
- the catchment size
- the level of water in the dam at the beginning of the event
- the capacity of the reservoir to store floodwaters above its full supply level (FSL)
- the area of uncontrolled catchment downstream of the dam
- the discharge capacity of the spillway

The design approach will need to address both the physical challenges of safely managing floodwaters and the environmental effects of the changes in the spatial and temporal distribution of floodwater.

The sections below focus on adaptation works to make use of existing online reservoir storage. It may also be possible to make use of such storage in an offline capacity by introducing flood transfer tunnels or conduits. However, this type of arrangement is not commonly likely to be viable on account of the cost of water transfer works.

5.2.2 Increasing reservoir flood storage

The main options for increasing reservoir storage to accommodate flood storage are described below.

Raise the dam crest

To provide flood storage without reducing the volume available for supply, dam crest raising works in combination with spillway modification works can be considered. Most reservoirs have simple overflow weir spillway arrangements. To limit the reservoir outflow to some predetermined design value to protect downstream properties, the design would seek to provide an optimal balance between dam crest raising works and spillway modification work to achieve the flood protection standard at least overall cost. Spillway modifications might need to include improvements to erosion protection measures downstream of the dam, as well as the overflow weir to provide for the increase in energy associated with the higher elevation of spill from the reservoir.

By raising the level to which water is stored under flood conditions, there are many potential impacts on the reservoir basin. These include:

- land acquisition or compensation arrangements for flooding of land around the reservoir rim and upstream of the reservoir on the banks of the watercourse over the backwater range
- possible relocation of access routes (including footpaths) and other services which commonly follow the edge of the reservoir higher up the valley slope
- impacts on the environment through changing the operational water level range
- impacts on the environment by changing the area of reservoir inundation
- a possible requirement to close off low points in the reservoir rim with 'saddle' dams

Floodwater will be detained for a longer duration within the reservoir basin. A greater fraction of the sediment carried with the floodwater will settle out of suspension and be deposited on the reservoir floor. This will affect the storage available for supply and hence the resilience of the reservoir to manage storage under drought conditions. From a water supply operator's perspective, it represents a potential threat to the security of supply. The impact of operational changes on sediment movement will differ from site to site and must be considered at each stage in the design.

Dam crest raising works are quite commonly carried out in the UK. This is normally in response to flood studies indicating insufficient freeboard, that is, the difference in elevation between the spillway sill (top water level) and the lowest point on the dam crest. Sufficient freeboard is required to prevent any significant erosion of the downstream face of the dam by overtopping which might affect dam stability. In some cases, major works to raise the dam crest have been carried out to increase reservoir storage. Where there is a change in the reservoir FSL and retained volume, the provisions of the relevant national reservoir safety legislation will apply.

Case study 5.1: **Abberton Reservoir, Essex, UK**

The raising of Abberton dam is a notable recent example of a UK dam crest raising project. This 15m high earth embankment was raised by 3.2m to increased reservoir yield for water supply (Hird et al. 2012). To meet projected future water demand in the region, options were investigated in the 1990s. The selected option was to raise the dam, thereby increasing reservoir capacity by nearly 60%. The work was designed to be carried out without emptying the reservoir, so the dam axis was moved in the downstream direction and a new downstream shoulder was constructed. The dam embankment had failed during construction in the 1930s. A back-analysis of the failure was carried out using FEA to aid the design. A comprehensive system of embankment monitoring instruments was installed to evaluate the performance of the raised embankment during construction and to assist long-term monitoring.

This case study highlights the range of technical challenges that may need to be faced when raising an existing embankment dam.

Under certain circumstances, it may be possible to consider raising the dam crest using a section of reinforced earth whereby the crest is raised vertically using tied, vertical concrete wall panels. This potentially brings the advantage of not increasing the dam footprint. The technical viability of this solution will depend on the nature of the dam. An important consideration is preservation of an adequate degree of slope stability under various loading conditions. An example of this approach is the Lower Sherburne dam in the USA (ASCE 1994).

In considering the raising of a dam crest, it is important to investigate the geotechnical characteristics of the existing embankment fill. With homogeneous or clay-core earth embankments, the permeability of the material above normal reservoir water level may be compromised by desiccation cracking, tree root action or animal burrows. It may be necessary to remove or treat such material as part of the crest raising works (see Section 3.3.3).

Case study 5.2: **Stoney Wood lake, Barnet, UK**

Stoney Wood Lake is an amenity lake, constructed between 1919 and 1935, located in the grounds of Mill Hill Golf Club, Barnet. In 2005 the Environment Agency undertook a scheme to incorporate a flood storage function. This storage capacity was created by raising the existing dam using steel sheet piles immediately downstream of the existing concrete dam. The retained level of the lake remains unaltered, but during flood conditions outflow is limited, causing the water level to rise 1.74m above retention level. This provides over 41,000m³ of flood storage, enough to store the excess flow arising from a 1-in-25 year event.

(a) View of lake with original dam wall in foreground

(b) Newly finished dam, formed from steel sheet piles, behind the existing concrete dam

Photographs courtesy of ATPEC Ltd

Any option involving increasing the design water level must be assessed in terms of the effects on the dam structure as a whole and the dam foundation. The increase in water pressure on the structure poses an increased risk of failure through internal erosion.

Although flood storage is generally transitory in nature, it is important to recognise that high reservoir water levels might be prolonged through successive storm events within the catchment area. The ability of the core material and any filter layers to limit seepage and prevent internal erosion must be assessed through investigations and analysis. Similarly it will normally be necessary to assess the impact of the proposed operational changes on the seepage and stability performance of the dam foundation.

Spillway modification

Changing the type of spillway represents an alternative means of increasing flood storage and managing flood events without changing the dam crest level or FSL. For example, it is possible to replace an overflow weir with 2 or more gates (typically radial gates), possibly with a sill set at a lower elevation. The FSL and the storage available for supply are unchanged. The gated spillway is capable of discharging higher rates of flow if needed to preserve the safety of the dam during an extreme flood event. A lower degree of freeboard is needed to prevent excessive overtopping of the dam crest and therefore reservoir storage can be assigned to flood storage.

The use of pneumatically actuated rubber dam type gates is becoming an increasingly popular and cost-effective means of providing retrofitted gated capacity to reservoir spillways. Internationally, there are also numerous examples of technical fuse gates that are designed to open when reservoir levels reach a defined threshold.

The Maccheronis concrete gravity dam in Sardinia was recently modified to provide an extra 3m depth of storage by substituting a gated spillway for the original overflow spillway. This allowed water to be safely stored at a higher elevation without compromising flood safety (Lazaro et al. 2006).

Where the safety of a reservoir depends on the automatic operation of gates, a suitable degree of redundancy in the system is required to ensure dam safety where wrong operation could endanger the dam. It is usual to provide for at least one additional gate and at least one backup power supply.

Overflow weirs can be shortened or restricted to increase the degree of flood attenuation within the reservoir. For any flood event, this will increase the flood rise (storage) in the reservoir during flood events. Any such proposal must be reviewed carefully by a qualified reservoir engineer to ensure that reservoir safety would not be compromised by increasing the risk of dam overtopping under extreme flood events.

It is not common to find reservoirs with significantly greater spillway capacity than that required by current engineering guidance on the flood safety of reservoirs. However, where the FSL can be reduced (for example, at obsolete reservoirs – see Section 5.2.4), works to also reduce the spillway capacity might be an appropriate component of the adaptation work.

Case study 5.3: Cheshunt North, Hertfordshire, UK

Cheshunt North Reservoir (photograph a) was originally constructed in the 1830s as an offline water supply reservoir. It was used in the 1900s as an amenity lake and in 1984 it was converted into a formal flood storage reservoir. This was achieved by constructing a side weir on the nearby Rags Brook to take in floodwater and lowering the retained level in the reservoir by cutting a 1,500mm wide by 300mm deep notch into the spillway.

The Environment Agency is the current owner and statutory undertaker and has further reduced the retained water level by cutting an additional 300mm wide by 600mm slot into the spillway (photograph b). Outflows through this slot are limited so, in flood flow conditions, the water level will rise to the original spillway level, providing an additional storage volume of nearly 30,000m³.

(a) General view of Cheshunt North Reservoir

(b) Overflow showing 1,500mm wide notch and 300mm wide slot

Landscape design was of particular concern due to the amenity function and the proximity to residential development (photograph c). The Environment Agency assisted the local angling club by lowering the fishing platforms and providing safe access (photograph d).

(c) Upstream face of dam, showing good reed margin and proximity of residential development

(d) New steps and lower fishing platform following lowering of retention level

This case study demonstrates how making a relatively simple modification to the spillway can add significant flood storage capacity while, with thorough stakeholder engagement, not creating adverse effects on the reservoir's primary use.

Photographs courtesy of ATPEC Ltd

Dam crest modification

An alternative means of allowing reservoirs to store larger volumes of water without raising the dam crest is to carry out modifications to sections of the dam crest, downstream face and toe areas to allow for some degree of overtopping in the dam safety design flood event. This approach will tend to be more feasible with concrete dams or embankment dams of limited height. Larger embankments may have berms or other features which might make this approach difficult to implement.

Designing an embankment to withstand overtopping is common in new flood storage reservoirs (see Section 3.2.3) and the same principles of design apply if retrofitting erosion protection measures to an existing embankment. The measures will normally be restricted to a defined section of the embankment length to effectively form an auxiliary spillway.

Depending on the dam geometry and the flows to be resisted, a range of design options can be considered including reinforcement of the turf with geotextile to the use of stepped or cable stayed precast concrete blocks. Energy dissipation measures at the toe of the dam will be required. Such measures require considerable care in the design and construction. In some cases such works will increase maintenance costs compared with normal grass cutting activities.

Reservoir basin modifications

Theoretically it is possible to supplement reservoir storage through reservoir enlargement (excavation) or by the removal of deposited sediment from the bed of the reservoir. Neither of these approaches would usually be warranted at UK reservoirs.

The enlargement of reservoir storage through excavation is normally prohibitively expensive as well as disruptive to reservoir operation. The removal of sediment from the bed of an existing reservoir by dredging or some other means is not commonly carried out in the UK, as reservoir sedimentation rates are generally low and the cost of dredging can be prohibitive. However, there are examples where this has carried out such as at Sutton Bingham Reservoir in Somerset (Yeoh and Warren 2010).

Lower the full supply level

Where the available reservoir storage is more than that required for the principal use, lowering the FSL is usually possible to generate flood storage without changing the dam crest level. It will often be possible to modify the spillway to introduce a low-flow notch sufficient to maintain the reservoir at a lower elevation under normal flow conditions. It should be recognised that this approach could affect:

- the ecology at the reservoir rim
- access to the reservoir for recreation or conservation purposes
- reservoir water quality (turbidity)
- reduced quality of reservoir releases to the downstream watercourse on account of reduced efficiency of the reservoir as a pollutant/sediment trap
- local groundwater levels
- fish passage
- wave erosion protection measures on the dam embankment upstream face

Lowering the normal reservoir level might not be well received by the local community, who may object to a loss of amenity. Public consultations can mitigate the loss in public relations by effective communication of the reasons for the proposals and the wider community benefits gained in terms of flood protection.

5.2.3 Modifications to reservoir operation

Where dual-use reservoirs have been designed to serve a flood mitigation function, the operation of the reservoir is usually actively managed to maximise the use of the available storage.

Flood control typically conflicts with most other reservoir purposes in that flood management requires a reduction in reservoir storage to accommodate a forecasted incoming flood volume with some degree of uncertainty. The amount of water released ahead of the flood ultimately depends on the operator’s assessment of risk whereby the expected flood damage cost is traded with the cost of the loss of the released storage associated with water supply, hydropower and so on. There is uncertainty in the decision-making process which cannot be eliminated and must therefore be managed. Remote sensing technology and past experience can be used to develop a suitable decision support system.

The adaptation of an existing reservoir to accommodate flood control presents a number of challenges, not least the fact that the provision of reservoir flood storage is usually contrary to the interests of the reservoir owner. In the winter months when the risk of catchment-wide flooding is greatest, the owner of a water supply reservoir will usually wish the reservoir to be full or near-full to provide security of supply through the summer months.

The scope for managing an existing reservoir to accommodate flood storage will depend on many factors and it is recognised that it may only be feasible at a small percentage of the UK reservoirs currently in service. In parts of England where there is considerable pressure on water resources, notably the south-east, the concept of reducing water supply storage to provide storage for flood storage is unlikely to be considered. In northern England, Wales and Scotland, however, the concept might be attractive in areas where the available reservoir storage is greater than that needed to secure drought resilience to a certain level of reliability.

The primary use of the reservoir will also affect the feasibility of the adaptation. It will often be difficult for water supply reservoir managers to consider ‘freeing’ storage for flood protection. Hydropower reservoir managers are likely to welcome any flood flows directed into their reservoirs, as this will increase energy revenues, but any permanent storage provision would mean a reduction in the operating level and a consequential loss of energy revenue.

The flood management approach adopted will be either ‘active’ or ‘passive’ as described below.

Active management

A reservoir operator can maximise the utility of the storage by responding to weather and flood prediction data. In this manner, storage is assigned by releasing water ahead of the flood event if necessary to provide the attenuation required to protect downstream properties. With modern sensing equipment and automation, it is possible to control reservoir releases automatically in response to catchment hydrological conditions. This form of flood management relies on accurate data of existing conditions and the accuracy of weather and flood prediction information. Flood prediction systems typically make use of recorded rainfall data, predicted rainfall (temporal and spatial) and river level telemetry.

Such an arrangement relies on the capability of the reservoir structures to safely draw down the reservoir level and create flood storage within a reasonable timeframe in response to weather warnings. Given the uncertainties involved in weather prediction, the consequences of the loss of water in false alarms must also be considered.

The use and operation of dual-use reservoirs for flood control might be questioned under severe flood conditions. Typically, the FSL is fixed whereby the storage below the FSL is assigned for water supply and the available storage above FSL is for flood storage. Following periods of drought or flooding, there may be pressure on the operator to modify the FSL to provide more drought or flood protection.

Gated spillways are commonly used at such reservoirs. Case study 5.4 relates to an international flood event where the operation of reservoir structures led to a detailed post-event review of the strategies in place and the actions taken by those responsible for reservoir operation.

Case study 5.4: The Brisbane flood of 2010–2011, Queensland, Australia

Prolonged and severe rainfall over a large part of the state of Queensland at the end of 2010, combined with saturated catchment conditions, led to a historic flood event in which more than 30 people died. An area larger than France and Germany combined was declared a disaster zone, affecting more than 2.5 million people and damages of more than A$5 billion. A Commission of Inquiry was set up which reported in 2012 (Holmes 2012).

The Commission evaluated the performance of 3 reservoirs in particular which provide a specific flood mitigation function: Wivenhoe, Somerset and North Pine. Modelling carried out on behalf of the Commission found that, allowing for the operational limits of the reservoirs, the engineers in charge of reservoir operations achieved close to the best possible flood mitigation result for the January 2011 event. However, their actions came under considerable scrutiny.

The Wivenhoe Reservoir was constructed primarily for water supply but also serves flood control, hydropower and recreation uses. It is formed by a 59m high rockfill dam. Under flood conditions it is able to store 225% of the storage available at FSL (100%). Under a water release plan defined in law, excess water must be released from the reservoir with 7 days of it becoming full. During the flood, the reservoir filled to 191% capacity.

The Somerset Reservoir is formed by a 50m high concrete gravity dam and is located upstream of Wivenhoe Reservoir. It has a similar multi-purpose function.

The Commission recommended a review of the protocols under which engineers make decisions regarding the reservoir operations. It considered the operation of the Wivenhoe and Somerset reservoirs in early 2011 and reviewed the flood mitigation manuals for all 3 reservoirs. The manuals described the actions, such as reservoir releases, to be taken by engineers during flood events based on current and forecast conditions within the catchment. The manuals had identified their primary objectives in the following order of importance:

1. To ensure the structural safety of the dam
2. To provide optimal flood protection of urbanised areas
3. To minimise disruption to rural life in the downstream valleys
4. To retain storage at FSL at the end of the flood event
5. To minimise impacts to riparian flora and fauna during the drain-down phase of the flood event

It was noted that the selection of the appropriate operational strategy based on forecasted information introduces an element of subjective judgement. Strategies are liable to change in line with changes in the forecasting of rainfall and streamflow conditions. There was some doubt raised over which strategies were in operation at the dams at specific points in time.

The Commission underlined the following facts in light of the 2011 flood event.

- All reservoirs have physical limits in what they can hold without risking their structural integrity.
- All floods are different and the mitigation provided by a reservoir will depend on the storm location, intensity and duration.
- Dam operators do not have the gift of foresight and their ability to make the best decisions are hindered by the inaccuracy of rainfall forecasting and other

variables. However, they should be prepared to act competently on the best information available to them and report accurately on the actions taken.

The report to the Queensland Flood Commission of Inquiry (Babister 2011) pointed out that floods can readily be analysed after the event when all the data have been collected and analysed. In the flood forecasting environment, however, this task has to be carried out in real-time to inform important operational decisions. Where large flood events occur, many of the data sources may be operating outside of typical ranges. Similarly there may be uncertainties with the dam structures where spillway components such as flood gates may be operating outside of operational experience.

This case study highlights the difficulty in formulating flood management strategies that protect the interests of those asked to implement them. It is essential to record accurately the information used to inform a choice of reservoir operation strategy during flood events.

Lowering the reservoir water level on a short-term basis using bottom outlet facilities to generate flood storage may lead to an adverse effect on the quality of the receiving watercourse. It is possible that this risk could be managed through consultations to gain the relevant discharge consent and implementation of a monitoring programme.

Lowering the level on a seasonal basis may have wider impacts similar to those described above for lowering the FSL.

Bottom outlet facilities are often designed to be operated in either the fully open or fully closed condition. This means that it may be difficult to operate such facilities in a manner that can manage adverse consequences (for example, the effect of highly turbid flow releases on the environment and the potential for bank erosion).

Passive management

With a passive management arrangement, flood storage is provided on a seasonal basis in accordance with an agreement. For example, it might be agreed that on a certain day of the year the reservoir level will not be higher than 2m below FSL. The reservoir is managed through the year, or part of the year, to meet this criterion but no further intervention is made to prevent flooding. This approach carries less flood protection security for downstream communities but is likely to be more acceptable to the reservoir operator. It means that the operator carries no liability beyond securing the agreed amount of flood storage at a particular time of the year.

If the demands for reservoir storage increase over time to provide security of supply, it may be increasingly difficult to honour agreements made with various parties. If no binding legal agreement is in place, the undertaker may not feel able to comply with the agreement (for example, to offset temporary supply deficits elsewhere on a water supply network). The undertaker will have in mind that there are likely to be competing demands on the operation of the reservoir, but that ultimately adherence to the recommendations of panel engineers will be paramount with regard to the reservoir safety itself. In certain circumstances, however, agreements can lead to a reduction in flood risk downstream without significant adverse operational effects.

5.2.4 Use of obsolete reservoirs

There are many hundreds of statutory reservoirs in the UK, mostly small reservoirs, that are no longer used for water supply but continue to be maintained by their owners. In many cases, the owner may be willing to sell such assets to the Environment

Agency, local authority or a consortium for flood management purposes. Such reservoirs may provide secondary benefits such as angling, but represent a liability to their owners due to the costs of monitoring and surveillance and compliance with safety measures instigated under the relevant reservoir safety legislation.

Where such reservoirs provide some degree of flood protection to downstream communities, there may be an opportunity to formalise this function and increase the degree of flood protection. Any of the adaptation options described in the sections above might be feasible depending on the aim of the adaptation, reservoir characteristics, physical and environmental constraints and planning restrictions.

Various studies have been conducted to evaluate the use of existing reservoirs for flood control. For example, McMinn et al.(2010) evaluated a number of reservoirs owned by Scottish Water and concluded that some of them could be used for low-cost flood control purposes through active management of water levels on a seasonal basis.

Obsolete reservoirs may require greater care in carrying out adaptation works than with reservoirs in normal service. For example, if the reservoir has been left in the drained-down condition, there will be greater risk associated with re-filling it as the performance of the embankment may have deteriorated (for example, through root action or the presence of animal burrows). Any vegetation and new habitats within the reservoir basin will require environmental management measures prior to re-filling the reservoir. A programme of monitoring and surveillance will be essential to demonstrate that the reservoir can be used safely under the adapted operational regime.

5.2.5 Studies and investigations

Any adaptation works are likely to require comprehensive studies and investigations to inform the design requirements. These are likely to include, as applicable:

- flood studies
- hydraulic modelling studies
- ground investigations/surveys
- topographic/bathymetric surveys
- asset condition surveys

Adaptation works often involve changing the original design conditions placed on existing assets including embankments, foundation cutoffs, retaining walls, conduits and valves. In some cases the performance of such structures under the original design conditions may be in doubt on account of material deterioration. It is therefore essential to first evaluate the existing condition of relevant structures and equipment to scope the design measures. Any trial testing of structures, if appropriate, must be done in a professional manner and with specialist advice to manage reservoir risk.

5.3 Legal aspects

5.3.1 Planning, consultations, licences and consents

The planning requirements for adaptation works will often be similar in scope to the requirements for a new reservoir (see Section 2.3.1). The actual requirements will depend on the nature of the adaptation design proposed. The planning permission process is likely to consider whether there is a change in the reservoir footprint.

It is recommended to contact the relevant enforcement authority if a regulated reservoir is being modified, a redundant reservoir is being brought back into use or a smaller reservoir is being enlarged. Depending on the precise circumstances this could be a legal requirement under the relevant national legislation.

Under the provisions of the amended Water Resources Act 1991, an impoundment licence is required prior to the construction, alteration or removal of an impoundment structure that would alter the retained water level or flow from the reservoir. This covers works to reduce the FSL as well as works to increase reservoir storage. Certain exemptions apply, for example, in carrying out repairs to structures. Certain types of modifications within watercourses to retain floodwater may be exempt, but the installation of gate structures would require an impoundment licence. Close coordination with the Environment Agency or other regulator is recommended to agree on relevant measures.

Guidance on environmental planning, including the Water Framework Directive, is similar to that of a new flood storage reservoir and is covered in Section 2.5.

5.3.2 Reservoir ownership and management

The owner of a reservoir may not have sole responsibility for managing and maintaining the structures. Under the Reservoirs Act 1975, the term ‘undertaker’ is used to describe the person(s) making use of the reservoir storage or otherwise owning the reservoir.

A Guide to the Reservoirs Act 1975 (ICE 2014) describes undertaker responsibilities for reservoirs in England. Similar arrangements will apply for reservoirs in Wales and Scotland. The Reservoirs Act states that the Environment Agency (or Natural Resources Wales as appropriate) is the undertaker for reservoirs managed and operated by them. In other cases, the undertaker is the person using the reservoir for a particular purpose; in the absence of any particular use, it is likely to be the landowner. Where a statutory reservoir has more than one undertaker, there is usually an agreement made between the parties to share the costs associated with the regulatory controls such as the cost of periodic safety inspections. One party normally takes the role as the lead undertaker and is responsible for communicating with the regulator.

Where a reservoir is adapted to provide a flood storage function, this is likely to affect the undertaker status. For example, in the case that an obsolete water supply reservoir, located on a main river in England, and owned and operated by a water company, is adapted to serve a flood storage function and the Environment Agency take an active role in managing the site, it is possible that the undertaker may change from the reservoir owner to the Environment Agency. In the case that the reservoir is actively used for water supply and is modified to provide flood storage, it is likely that the water company would remain the sole undertaker. An agreement would normally be required to set out the respective responsibilities and cost-sharing measures relating to the reservoir operation and maintenance. Experience indicates that it is desirable for reservoir operation and maintenance activities to be carried out by a single organisation wherever possible.

5.3.3 Funding

A suitable funding arrangement will need to be agreed if option studies indicate that physical works are required to implement adaptation measures.

Government funding for flood risk management projects is available for local authorities, Internal Drainage Boards and the Environment Agency (for schemes in England). The Environment Agency manages the allocation of funding.

The programme of flood resilience improvements is built up of schemes developed and promoted by local authorities, Internal Drainage Boards and the Environment Agency, developed in collaboration with local communities. The current strategy for flood and coastal risk management for England (Defra and Environment Agency 2011) sets out what needs to be done by various organisations including local authorities, Internal Drainage Boards, water and sewerage companies, highway authorities and the Environment Agency. The strategy emphasises community focus and partnership working. Communities within areas at risk should be represented on local flood risk management partnerships to inform decisions on what is needed and who should be asked to contribute towards the investment costs such that costs and benefits are shared equitably.

Case study 5.5: Partnership funding

In 2015, the Environment Agency negotiated £10.5 million of partnership funding contributions for major flood alleviation schemes in Shoreham-by-Sea and Newhaven on the Sussex coast through coordination between Sustainable Places, the National Capital Programme Management Service (NCPMS) and its Partnerships and Strategic Overview (PSO) teams. This enabled delivery of major works that will significantly reduce tidal flood risk to almost 3,000 properties and over 500 businesses.

The teams convinced developers, local councils, Network Rail and Local Enterprise Partnerships to invest in reducing flood risk as a catalyst for regeneration in these areas. These contributions allow Flood and Coastal Erosion Risk Management Grant in Aid funding to be re-invested in other schemes across the country.

A virtual team was put together, led by the Sustainable Places team, to bid for Local Enterprise Partnership contributions. The PSO teams and NCPMS worked closely with developers and Network Rail to develop innovative solutions to meet joint objectives.

The ‘National Strategy for Flood and Coastal Erosion Risk Management in Wales’ (Welsh Government 2011) points out that, although the Welsh Government has provided the majority of the funding for flood management in the past:

> ‘as the level and nature of risk changes in the future, Welsh risk management authorities will need to find other sources of funding to ensure that communities across Wales receive the levels of funding they need to manage the risks they face’.

A number of potential sources of funding are described in the strategy including the private sector.

The Scottish Government oversees the implementation of the Flood Risk Management (Scotland) Act 2009, which established the requirement for Flood Risk Management Strategies and Local Flood Risk Management Plans to be produced. The Scottish Government’s approach is currently set out in a document which describes the responsibilities of the public and communities, local authorities, Scottish Water, SEPA and the Scottish Government (SEPA 2011).

6 Concluding remarks

The use of storage reservoirs to provide flood protection is now well established in the UK, with many hundreds of such structures in operation. As the need for flood protection increases in light of climate change, population growth and industrial development, it is clear that many more flood storage reservoirs will be required in the future.

Although flood storage reservoirs have generally proved to be effective, the planning, design and operation of such structures can be very challenging. Their development typically involves a broad range of technical disciplines and affects many stakeholders. In addition there are numerous legal requirements and constraints which influence the development of flood storage reservoirs.

The use of a flood storage reservoir is one possible approach or component in a wide range of measures that might be necessary to provide an adequate standard of flood protection. The location, size and arrangement of the structure demands thorough planning and the involvement of a multi-disciplinary team. The success of any such development will depend greatly on the initial work to plan and design the facility, as many basic project parameters are set at this stage and can be difficult to amend through the development of the design.

The basic considerations influencing engineering deliberations are those of hydrology, topography, ground conditions and access provisions taking account of constraints posed by land ownership issues and buried utilities. However, it is essential that far wider considerations are reviewed at an early stage to maximise the potential benefits in terms of environmental protection, river morphology, biodiversity and fish passage. The location of the reservoir structures within the landscape and the influence of the structures on local people must also be considered in the planning and discussed through consultation. In addition, thought needs to also be given to the health and safety of the public and the operatives maintaining the structures under normal and flood conditions.

Typically, the dam forming a flood storage reservoir will be an embankment formed of homogeneous compacted soil of low permeability covered by a layer of topsoil and seeded with grass. In UK applications, it is unusual for such dam embankments to have a maximum height of more than a few metres.

Flood storage can be provided ‘online’ of a watercourse or ‘offline’. The approach adopted is entirely site-dependent. The area used for flood storage can normally be used for other purposes, such as agriculture or parkland, as well as providing potential for environmental enhancement. Such an arrangement brings both benefits and challenges, which must be managed to ensure effective operation during flood events and a mutually beneficial arrangement between the reservoir operator and other stakeholders. Many flood storage reservoirs permanently retain a relatively small volume of water for environmental and/or social benefits.

There is a wide range of options for flow control. The selection of the most appropriate flow control arrangement can be fundamental to the feasibility and success of any flood storage reservoir project as it affects the reservoir size, construction costs and the operational and maintenance requirements. Similarly, careful consideration must be given to the passage of excess flood flows and energy dissipation to prevent damage to critical structures.

Based on the experience of flood storage reservoirs built in the UK to date, the salient problems experienced at sites in relation to operation and maintenance are:

- debris and silt management
- grass maintenance and cutting
- reinforced grass erosion protection systems
- problems with gates (mechanical, power, control)
- unauthorised access and vandalism

It is essential that operators undertake routine surveillance of structures and carry out testing to ensure that equipment operates correctly under flood conditions in terms of both the reservoir filling and emptying.

There are many opportunities in the UK to make better use of existing reservoir storage for the purposes of storing floodwater. There are hundreds of reservoirs that are effectively obsolete for water supply purposes and some could be modified to function as a flood storage reservoir. Additionally it is often technically feasible to raise the crest of existing dams, modify the spillway arrangement or modify reservoir operation to formalise a flood protection function. Although there are examples of such adaptation works or arrangements, there are considerable challenges, not least because the need to maintain free reservoir storage for floodwater is contrary to most operators' primary requirements, for example, to store as much water as possible for reliable water supply during drought periods or to maximise energy production.

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List of abbreviations

AOD	above Ordnance Datum
BAP	biodiversity action plan
CCTV	closed circuit television
CFD	computational fluid dynamics
Defra	Department for Environment, Food and Rural Affairs
DOENI	Department of the Environment Northern Ireland
EIA	Environmental Impact Assessment
FCERM	Flooding and Coastal Erosion Risk Management
FCERM-AG	Flood and Coastal Erosion Risk Management Appraisal Guidance
FEA	finite element analysis
FEH	Flood Estimation Handbook
FSL	full supply level
HRA	Habitat Regulations Assessment
HSE	Health and Safety Executive
ICE	Institution of Chemical Engineers
ICEMGE	ICE Manual of Geotechnical Engineering
ICOLD	International Commission on Large Dams
IDB	Internal Drainage Board
ILH	International Levee Handbook
LLFA	Lead Local Flood Authority
MEICA	mechanical, electrical, instrumentation, control and automation
NPPF	National Planning Policy Framework
O&M	operation and maintenance
OS	Ordnance Survey
PEA	preliminary ecological appraisal
PMF	probable maximum flood
RCS	river corridor survey
RHS	river habitat survey
SAC	Special Area of Conservation
SEPA	Scottish Environment Protection Agency
SLS	Serviceability Limit States
SPA	Special Protection Area

SSSI	Site of Special Scientific Interest
TSSG	trash and security screen guide
ULS	Upper Limited States
USBR	United States Bureau of Reclamation
WFD	Water Framework Directive

Glossary

Abutment	The ground at either end of the dam structure onto which the dam formation ties into.
Bathymetric survey	Ground level survey below normal water level.
Bellmouth spillway	Free-standing overflow structure comprising a cup-shaped overflow weir, vertical shaft and near-horizontal discharge conduit. Also known as a ‘Morning Glory’ spillway.
Berm	Horizontal ledge formed in the side slope of an embankment or cutting.
Borrow area	Area of excavation where the material excavated is to be used in construction.
Catchment	The land area that drains (normally naturally) to a given point on a river, drainage system or body of water.
Climate change	The Intergovernmental Panel on Climate Change (IPCC) defines climate change as ‘change in the state of the climate that can be identified (for example, using statistical test) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer’.
Conduit	A pipe or channel for conveying water.
Construction Engineer	A construction engineer is appointed to supervise the design and construction of a new reservoir under the Reservoirs Act 1975 or to modify a statutory reservoir such that the reservoir capacity is changed.
Control structure	Device constructed across a channel or connecting a watercourse to an offline flood storage reservoir to control the discharge passing the device and the water level on either side of the device.
Conveyance structure	Structure used to convey water, including pipes and channels.
Culvert	An enclosed structure through which water can flow. Culverts vary in shape. A pipe is a form of circular culvert.
Dam crest	The flat section or near-flat section on the top of the dam embankment.
Depth–area–storage	Relationship between depth, surface area and resulting storage volume of a reservoir basin.
Design flood event	Magnitude of the flood adopted for the design of the whole or part of a flood defence system, usually defined in relation to the severity of the flood in terms of its return period.
Design flood return period	A statistical term defining the probability of occurrence of an event. Thus a 1-in-50 year flood (also referred to as the 50-year flood) is one likely to be equalled or exceeded on average only once in a 50-year period.

Design life	The period of time a structure is designed to effectively function.
Discontinuance	Any works undertaken to reduce the reservoir volume to below the threshold set in the relevant reservoir safety legislation.
Erosion	Process by which particles are removed by the action of flowing water or waves.
Fish pass/eel pass	Structure to enable fish (or eels) to gain access past a weir, dam or other structure in a river that would otherwise be impassable.
Floodplain	Any area of land over which water flows, or is stored during a flood event or would flow but for the presence of flood defences.
Flume	Hydraulic structure used to control flow.
Freeboard	The height of the top of a bank, floodwall or other flood defence structure, above the design water level. Freeboard can be seen as a safety margin that makes allowance for uncertainty associated with the potentially damaging effects of flood rise or wave action.
Geomorphology (fluvial)	The processes of water and sediment movement in river catchments and channels and their floodplains and the effects produced by those processes.
Geophysical survey	Survey methods that survey subsurface features such as archaeological features. The techniques most commonly applied to geophysical surveys are magnetometers, electrical resistance meters, ground-penetrating radar and electromagnetic conductivity meters.
Hydraulic jump	Abrupt rise in water level, accompanied by surface disturbance and air entrainment, when flow changes from supercritical to subcritical flow with an associated dissipation of energy.
Impoundment structure	An impoundment is a structure within inland waters that can permanently or temporarily affect flow rates and store water.
Probable maximum flood (PMF)	The theoretical maximum flood that can occur.
Probable maximum precipitation (PMP)	Theoretically, the greatest precipitation for a given location and storm duration that is physically possible.
Rapid drawdown	Sudden drop in water level that can potentially impair the stability of a dam or flood embankment.
Runoff	Rainfall (or snow melt) that runs off the surface of the ground towards a watercourse.
Scour	Erosion of the bed or banks of a watercourse by the action of moving water.

Security grille	A screen comprising closely spaced bars, designed to prevent harm to unauthorised persons within a closed space.
Sediment	Natural material transported by the flow of water in a watercourse and which may be deposited within a channel bed or within a reservoir area.
Trash or debris screen	A screen comprising closely spaced bars placed upstream of a hydraulic structure to prevent waterborne debris from blocking an opening or culvert or damaging pumps.
Undertaker	The person(s) making use of the reservoir storage or otherwise owning the reservoir as defined in the Reservoirs Act 1975.
Watercourse	Defined natural or man-made channel for the conveyance of water.
Wrack (flood debris)	Debris transported by flood and deposited on the banks of a watercourse or reservoir.

Appendix A Flow control structures

A.1 Flow control using pipes, culverts and orifices

The hydraulic behaviour of pipes, culverts and orifices is essentially proportional to the operating head to the power 0.5. However, there are particular issues associated with the use of a plain pipe or culvert as a control device due to the occurrence of different modes of flow. Because of these complexities of flow behaviour, the hydraulic assessment of culverts occupies a complete chapter of 60 pages in the 'Culvert Design and Operation Guide' (C689) (CIRIA 2010). Figure 6.10 of that publication lists 8 specific flow types, whose numbers are given in parentheses after each of the principal flow modes described below:

- part-full flow with subcritical flow throughout the culvert (Types 3 and 4)
- part-full flow, with critical flow at the entrance and supercritical flow in the culvert (Type 1), but with the possibility of a hydraulic jump forming within the culvert (depending upon the tailwater level)
- full flow throughout the culvert, with the entrance submerged, but the tailwater level below the crown at the outlet (variant of Type 5)
- full flow throughout the culvert, with the entrance and outlet both submerged (Type 5)
- entrance control with the entrance submerged, the culvert part-full throughout and the tailwater level below the conduit crown at the outlet (Type 2)
- entrance control with the entrance submerged and the culvert part-full at the upstream end, followed by a hydraulic jump within the culvert and the downstream end running full (with the tailwater level either above or below the crown at the outlet) (not listed in CIRIA C689)

Types 6, 7 and 8 in CIRIA C689 are similar to Type 5, except with the addition of weiring flow over the embankment through which the culvert passes.

Fortunately for the designer, a number of the flow modes can be either avoided through appropriate design, or can be disregarded because their occurrence has no material effect on the overall hydraulic behaviour. The principal objective of the hydraulic design of a flow control device should be to arrive at a design for which the hydraulic behaviour is entirely predictable, with no ambiguity as to the stage/discharge rating.

In general, the detailed hydraulic performance of a pipe or culvert during part-full flow conditions is unimportant for the overall design and performance of a flood storage reservoir because there is normally very little storage being utilised at the low water levels that apply before the pipe or culvert entrance is submerged. However, the design needs to avoid any problems associated with part-full flow, such as air being trapped and impairing the hydraulic performance at the transition from either part-full flow to full flow or from part-full flow to entrance control.

The last of the flow modes listed above – with a hydraulic jump occurring within the culvert – can lead to unstable flow conditions, with the trapped air pocket shrinking due to air entrainment in the hydraulic jump, resulting in either a transition to full-bore flow, or in a gulp of air being sucked into the entrance to replenish the entrained air. This threat can, however, be overcome by appropriate design, such as venting the culvert crown just within the entrance, so that entrained air can be replaced and the air pocket is kept at essentially atmospheric pressure.

Figure A.1 illustrates the flow modes that are normally applicable for a simple pipe or culvert used as a flow control device, which may be summarised as follows:

Mode A Entrance control (equivalent to CIRIA C689 Type 2 at high heads and Type 1 at low heads)

Mode B Downstream control, with the culvert running full throughout or with subcritical part-full flow throughout (equivalent to CIRIA C689 Type 5 at high heads and Type 3 or 4 at low heads)

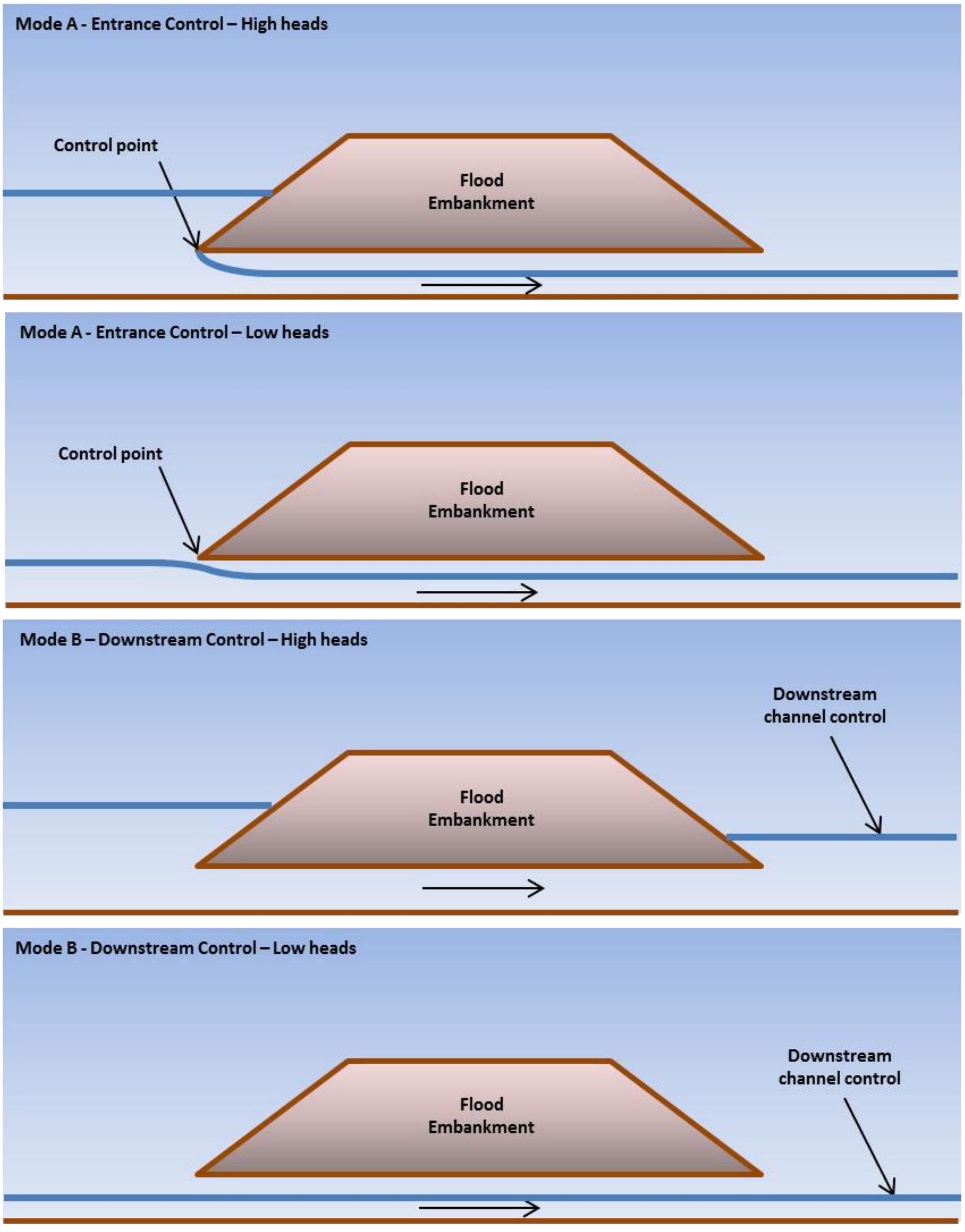


Figure A.1 Typical flow modes for culverts

A relatively simple hydraulic design approach that may be used for initial planning is given below. However, once the outline design has been settled, it should be checked – and if necessary refined – according to the applicable approaches given in CIRIA C689 Table 6.1 using the flowchart in CIRIA C689 Figure 6.15. Section 6.14 of the same publication lists and gives guidance on the use of the software solutions for culvert hydraulic performance.

Mode A (entrance control) is covered by graphical solutions available in the textbooks as follows:

Rectangular culverts: Chow (1973a), Figure 17-29 (Imperial units only)
Henderson (1966), Figure 7-21

Circular culverts: Chow (1973a), Figure 17-30 (Imperial units only)
Henderson (1966), Figure 7-20 (part-full flow only)

Table A.1 gives equivalent equations for rectangular culverts, with the coefficients suggested by Henderson (1966). The transition between the entrance being unsubmerged and submerged occurs when the 2 equations give the same flow. These equations can be readily adapted to circular culverts – with sufficient accuracy for most purposes – by simply setting the height *D* to equal the diameter and setting the width *B* to the diameter factored by π/4, to give the equivalent flow area.

Table A.1 Simple treatment for culvert hydraulics Mode A (entrance control)

Equation	Coefficients	
	Rounded entrance	**Square-edged entrance**
Entrance submerged (H/D > 1.3 approx.) $Q = C_h BD\sqrt{2g(H - C_h D)}$ where: B = culvert width D = culvert height H = upstream head above culvert invert g = gravitational acceleration	C_h = 0.8	C_h = 0.6
Entrance unsubmerged (H/D < 1.3 approx.) $Q = 0.544 C_B \sqrt{g} BH^{1.5}$	C_B = 1.0	C_B = 0.9

For Mode B (downstream watercourse control), the typical approach to the hydraulic analyses, when the conduit is running full, is as follows.

- For a range of flows, tabulate the downstream water levels, taking the conduit outlet soffit level in place of the tailwater level if the soffit level is the higher.
- For the same flows, compute the friction headlosses in the culvert, using the length, cross-sectional dimensions and assumed roughness value, together with an appropriate equation (Colebrook-White for preference, or otherwise Manning – not Chézy or Hazen-Williams).
- Estimate the formloss coefficients for the entrance, exit and any bends or other features, using standard textbook values (but noting that the exit coefficient is nearly always 1.0).
- For the same range of flows, multiply the sum of the formloss coefficients by the velocity head to obtain the total formloss.

- For each of the flows, add the values of tailwater level (or culvert soffit level), friction headloss and total formloss to obtain the headwater level (strictly speaking the energy level), that is the water level in the reservoir.

For part-full flow conditions (by definition with the tailwater level below the culvert soffit), a backwater analysis may need to be carried out through the culvert. In many cases, however, the friction headlosses can be computed simply based on the flow depth at the outlet. When analysing part-full culvert flows, care needs to be taken to distinguish between water levels and energy levels, always relating headlosses to the changes in energy level.

Orifices for use in flow control come in a number of guises, including:

- a circular or rectangular opening, with machined bevelled edges, within a larger plate
- a similar opening, but without bevelled edges
- a specially fabricated orifice assembly, incorporating features that are designed to achieve a high precision of flow predictability
- an opening that, on one or more sides, abuts the invert and/or walls of the culvert or structure within which it is located
- a gate – usually a vertical lift gate – that is open by a set amount in order to behave like an orifice

The orifice would normally be a supplementary feature of a culvert that passes through or beneath the embankment impounding the flood storage reservoir. It may be positioned at the entrance, at the exit, or at an intermediate point within the culvert, and is often associated with a chamber that provides some form of access to the orifice, together with isolation facilities for inspection and maintenance. The culvert would have a cross-sectional area of at least double the area of the orifice, but normally several times the orifice area, so that the hydraulic resistance associated with the culvert plays a small part in the overall hydraulic behaviour.

In terms of predictability of behaviour, a machined opening approximately centred within a larger conduit, with the edges bevelled out of the flow to achieve a reliable contraction coefficient that is available in the literature, would be favoured. However, the accuracy would be impaired by wear and damage in service, so a more robust solution is likely to be preferred in many cases.

The general equation for an orifice is given by:

$$\mathrm{Q} = \mathrm{C_C A}\sqrt{2\mathrm{g}\Delta\mathrm{H}}\mathrm{Q} = \mathrm{C_C A}\sqrt{2\mathrm{g}\Delta\mathrm{H}}$$

where: C_C = contraction coefficient
A = cross-sectional area (m^2)
ΔH = head difference (m) between upstream water level and centre of orifice or downstream water level (whichever head difference is the smaller)

For a machined bevelled orifice providing a sharp-edged entrance, the value of the contraction coefficient is close to 0.6, whether the orifice discharges freely on the downstream side or is fully submerged. If a rectangular orifice is flush with the floor of the approach watercourse or culvert, this has little effect on the contraction coefficient. If it is flush with the sides, then the coefficient increases somewhat, with a further increase if the orifice is flush with both sides and the floor. The following equation may be adopted (Bos 1989) for a sharp-edged orifice:

$$C_C = 0.61(1 + 0.15r)$$

where: r = the proportion of the orifice perimeter that is flush with the walls and/or floor of the approach conduit

If the flow jet downstream of the orifice is supported on the downstream watercourse floor, then ΔH is measured down to the top of the flow jet rather than to the centre of the orifice.

If the edges of an orifice are rounded, then the coefficient is increased and would typically be about 0.95. The amount of rounding needed to achieve this coefficient is not large and may be taken as one-fifth of the diameter of a circular orifice, or one-fifth of the smaller of the width and height for a rectangular orifice.

A.2 Flow control using flumes, weirs and notches

The discharge passed by a simple flume or weir is essentially proportional to the head raised to the power 1.5. This applies to flumes and weirs in which the flow passage, when viewed from upstream or downstream, is rectangular; this includes weirs and flumes with a horizontal crest and vertical abutments. The term 'notch' would normally apply to a feature such as a vee-notch weir, or a small narrow opening incorporated within a larger weir or flume.

Flumes

Flumes in the UK are normally of the type described as 'long-throated', in which conditions close to critical flow occur, so that the hydraulic performance is close to that predicted by application of the theoretical weir flow equation, which is:

$$Q = \frac{2}{3}\sqrt{\frac{2g}{3}}BH^{1.5}$$

where: H = weir head (upstream water level relative to crest of weir or invert flume) (m)

The hydraulic behaviour of long-throated flumes is covered in detail in BS ISO 4359:2013 (BSI 2013), which covers flumes whose cross-section is rectangular, trapezoidal or U-shaped. Normally, a rectangular-throated flume would be chosen. BS ISO 4359:2013 includes access to spreadsheets that allow the rating curve to be readily calculated. The rating is in relation to a gauging point within an approach watercourse, but the results can be readily converted to the total head in the reservoir (H), either by making the approach watercourse dimensions large enough, or by adding the velocity head in the approach watercourse to the gauged water level.

The following general simplified equation may be adopted for planning purposes for a long-throated flume:

$$Q = \frac{2}{3}\sqrt{\frac{2g}{3}}C_D BH^{1.5}$$

where C_D allows for the effects of the boundary layers that develop within the throat, but can be taken as 0.97. This equation may thus be simplified to:

$\mathrm{Q} = 0.528\sqrt{\mathrm{g}}\mathrm{BH}^{1.5}\mathrm{Q} = 0.528\sqrt{\mathrm{g}}\mathrm{BH}^{1.5}$ (or $\mathrm{Q} = 1.65\mathrm{BH}^{1.5}\mathrm{Q} = 1.65\mathrm{BH}^{1.5}$ in metre-second units)

The above equations apply to flumes that are freely discharging; this requires that the tailwater head should not exceed 0.8 times the upstream head, both relative to the flume invert. This factor applies to rectangular-throated flumes. For trapezoidal and U-throated flumes, see BS ISO 4359:2013.

In the USA and US-influenced territories, a particular form of short-throated flume called a Parshall flume is often deployed for flow measurement. This device is available in 22 sizes, with set standard dimensions, all of which have been calibrated to give the discharge in relation to a pressure head measured at a particular location. They offer no advantage over a long-throated critical-depth flume. Indeed, the fact that their calibration is based on a particular pressure tapping location means that their hydraulic performance in relation to the total upstream head in a reservoir is unknown, making them unsuitable for such use.

Weirs and notches

If a horizontal crested weir is used for flow control, its behaviour would be essentially equivalent to that of a long-throated flume, except that the value of discharge coefficient would usually be slightly different. The form of weir that gives the closest performance to that of a long-throated flume is normally known as a rounded broad-crested weir. Its behaviour is based essentially on critical flow, but boundary layer effects are generally smaller, such that the following simplified equation is often adopted:

$\mathrm{Q} = 0.544\sqrt{\mathrm{g}}\mathrm{B}\mathrm{H}^{1.5}\mathrm{Q} = 0.544\sqrt{\mathrm{g}}\mathrm{B}\mathrm{H}^{1.5}$ (or $\mathrm{Q} = 1.70\mathrm{B}\mathrm{H}^{1.5}\mathrm{Q} = 1.70\mathrm{B}\mathrm{H}^{1.5}$ in metre-second units)

Most forms of weir are ‘short-crested’, which results in reduced pressures between the overflowing water and the weir crest, causing the discharge coefficient to increase somewhat. For a discussion of weir forms, including a more accurate treatment of the broad-crested weir, see Appendix B.

Where a weir is used as a means of admitting flow into an offline flood storage reservoir, it is typically located along the bank that separates the watercourse from the reservoir. In many cases, such a weir comprises a section of the intervening bank that is set to a lower crest level than the rest of the bank and which is specially protected on the crest and downstream face to serve that function. This configuration is known as a side weir, that is, a weir whose crest alignment is approximately parallel to the dominant direction of the approaching flow. Because side weirs are often used in combined sewer overflows, their flow behaviour has been widely researched and is well-described in the textbooks. As a general approximation, which is usually good enough for planning purposes, the standard equation for a broad-crested weir can be used:

$\mathrm{Q} = 0.544\sqrt{\mathrm{g}}\mathrm{B}\mathrm{H}^{1.5}\mathrm{Q} = 0.544\sqrt{\mathrm{g}}\mathrm{B}\mathrm{H}^{1.5}$ (or $\mathrm{Q} = 1.70\mathrm{B}\mathrm{H}^{1.5}\mathrm{Q} = 1.70\mathrm{B}\mathrm{H}^{1.5}$ in metre-second units)

For additional accuracy, refer to the procedure given in ‘Hydraulic Design of Side Weirs’ (May et al. 2003).

If a vee-notch weir plate forms part of a control device, its discharge can be determined from the equation:

$$Q = \frac{8}{15}\sqrt{2g}C_e \tan\frac{\theta}{2}H^{2.5}$$

where: C_e = discharge coefficient for thin-plate vee-notch weir (typically 0.58)
θ = angle at vertex of notch
H = weir head (upstream water level relative to vertex of notch) (m)

For further details of the hydraulic behaviour of vee-notch weirs, refer to BS ISO 1438:2008 (BSI 2008a) or to ‘Discharge Measurement Structures’ (Bos 1989).

In cases where 2 or more components (for example, an orifice or notch, plus a flume or weir) are combined to form the flow control device, then the rating curves for each should be estimated individually – all referenced to a common datum – and then added together.

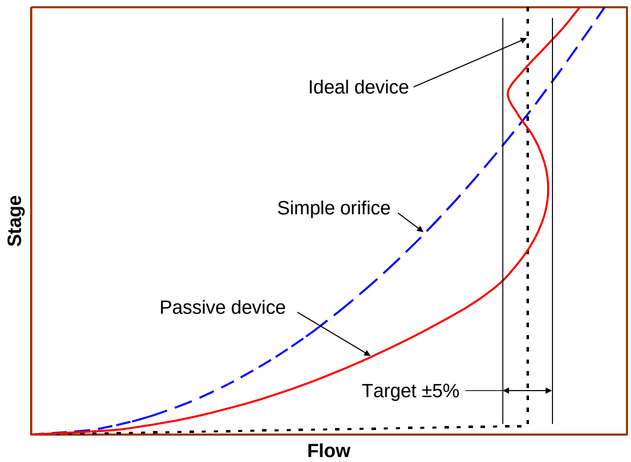
A.3 Flow control using vortex and baffled orifice devices

A number of devices are available whose objective is to improve on the hydraulic characteristics of the simple orifice. The flow through an orifice is approximately proportional to the square root of the operating head. In most applications of orifice flow control to flood storage reservoirs, this results in a significant increase in outflow as the flood storage level rises.

Various forms of passive flow control device have been developed to improve on the performance of a simple orifice and get closer to the ideal performance possible with an actively operated gate. These are:

- vortex type devices – widely used in sewerage systems
- baffled orifices – similar to the ‘modules’ used in irrigation engineering

Figure A.2 shows the general form of rating curve that can be obtained with an optimised passive device, such as a vortex, compared with the rating curve for an orifice and with the ideal relationship.



The ‘ideal’ device is capable of passing up to a given target flow, whatever the water level.

For a simple orifice, the flow is normally proportional to about the square root of the operating head.

Vortex and baffled orifice passive devices aim to pass more flow than a simple orifice at low operating head and less at high heads. Over a wide range of operating heads, the flow passed downstream may be within ±5% of the target value.

Figure A.2 Comparison of hydraulic performance for various devices

Before adopting these devices, it is prudent to check the performance and total costs of the project against those which would apply for an alternative arrangement in which a simpler form of flow control is used and a correspondingly larger amount of storage provided to give an equivalent flood attenuation performance. In some cases, site constraints may preclude the deployment of a larger storage capacity, with a higher peak water level and such sites would favour the adoption of a vortex or baffled orifice device.

Vortex devices

Vortex devices rely on generating an air-filled vortex in the outlet tube. Various different configurations are available and the following advantages are claimed, in addition to the improved storage utilisation.

- There is increased energy dissipation in the vortex, which results in reduced requirements for energy dissipation downstream of the device.
- The risks of blockage are reduced because the overall cross-sectional area is larger than that of a simple orifice with the same flow capacity.
- The water is aerated, which can assist with water quality objectives.
- They are self-cleansing and so have minimal maintenance requirements.

The design of vortex type devices is a specialist matter for which the manufacturer normally takes responsibility to suit the particular application, although there are standard 'off-the-shelf' configurations allowing the designer to pick the most appropriate device. Some software packages include the hydraulic characteristics of typical devices to aid the designer planning for their deployment or simulating the effect of existing devices.

Figure A.3 shows 2 representations of rating curves for vortex devices, with the graph on the left illustrating the range of curves that can apply and the graph on the right highlighting the most important features of the characteristic S-shaped curve.

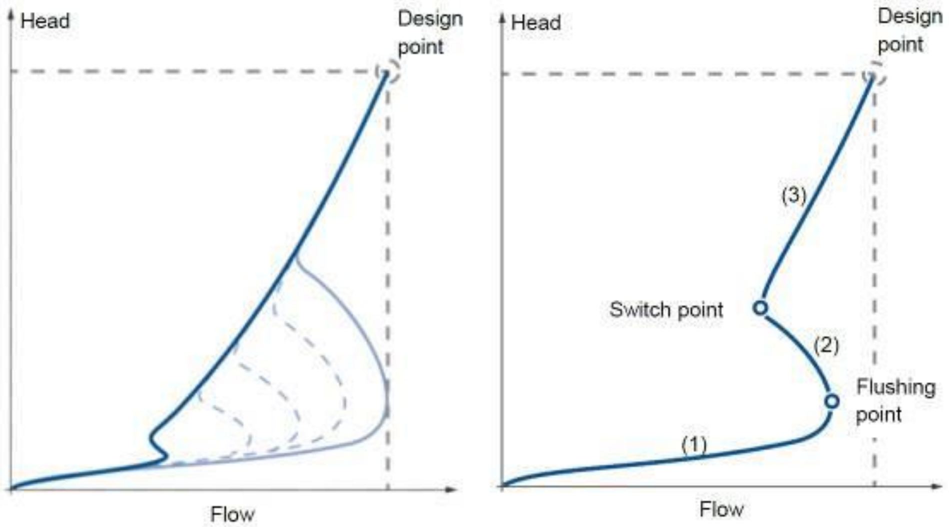


Figure A.3 Range of typical rating curves and terminology for Hydro-Brake® (courtesy Hydro International)

These features of the are as follows.

- **Pre-initiation phase** – at low heads, when the inlet and outlet openings of the device are unsubmerged and act in a similar manner to an unsubmerged plain orifice. The upper end of this phase is the 'flushing point'.
- **Transition phase** – when the inlet and outlet openings become submerged and a vortex begins to form. The flow regime is unstable, with the vortex intermittently forming and collapsing, as there is insufficient energy within the flow to form and maintain a stable vortex. An air pocket becomes trapped and exerts a counter-pressure against the flow of water, resulting in the discharge reducing as the head increases, up to the 'switch point'.

- **Post-initiation phase** – as the head continues to increase and sufficient hydrostatic pressure is generated to displace the trapped air pocket and allow a stable vortex to form with a central air-filled core. The air core reduces the effective cross-section available for the passage of water, but the device otherwise operates in a similar manner to that of an orifice.

When the upstream water level subsides with the flood recession to below the top of the device, the vortex collapses, resulting in a sudden increase in flow through the device.

Vortex devices are generally configured either with a submerged inlet and 'snail' shape to develop the swirl required to form the vortex, or with level inverts and a conical shape to develop swirl (Figure A.3). If appropriate, coarse debris must be excluded from entering the device by installing it behind a suitably sized trash screen.

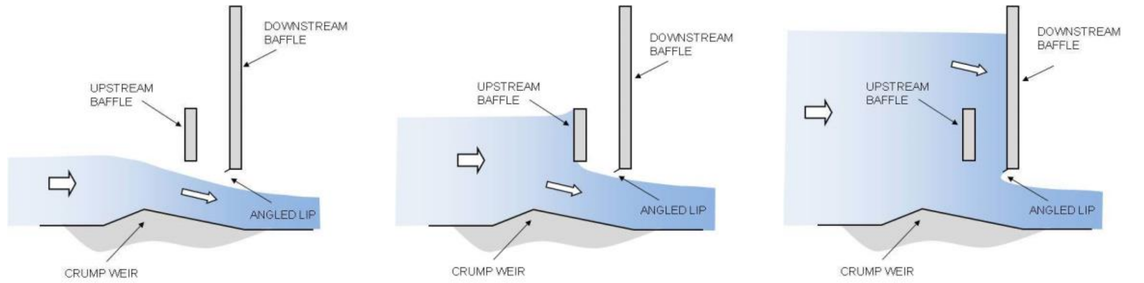
Figurer A.4 shows examples of different vortex devices.

Figure A.4 Examples of 'snail' and conical Hydro-Brake® vortex devices (courtesy Hydro International)

Baffled orifice devices

Baffled orifice devices are based on concepts that have been used for many years in distributor 'modules' in irrigation engineering. Recent physical model tests at HR Wallingford have optimised the design configuration of a double-baffle orifice, which has been adopted at 2 sites so far in the UK (Banbury and Chapelton).

The diagrams in Figure A.5 show the 3 primary flow models for the double-baffle device at the Banbury flood storage reservoir, which was designed to pass an almost uniform flow of around 9m^3/s per opening over a head range of around 2.5–4.5m above the crest of the Crump-type weir. The key feature is the angled lip on the downstream baffle that causes a more severe contraction and hence lesser discharge when it controls the flow at higher heads.



Low head, with the Crump weir controlling the flow

Medium head, with the flow controlled by the upstream baffle

High head, with the upstream baffle submerged and the flow controlled by the downstream baffle

Figure A.5 Flow modes for double-baffle orifice control device

The Banbury flood storage reservoir has a capacity of about $3.0 \times 10^6 m^3$; there are 4 baffled orifices, split between 2 separate outlet structures, which together limit the downriver flow to about $36m^3/s$ (Ackers et al. 2004). At the Chapelton flood storage reservoir, which has a capacity of about $3.8 \times 10^6 m^3$, a single unit allows a pass-forward flow of about $8m^3/s$ (Gowans et al. 2010).

The design of the double-baffle orifice is subject to Froude scaling, making the option broadly adaptable to a wide range of stage/discharge requirements without further model testing for at least initial design appraisal. Because of the potential for the tailwater rating to influence the hydraulic behaviour, it is likely that most proposed applications would require physical model testing or computational fluid dynamics (CFD) to verify and fine-tune the detailed design. Figure A.6 shows the geometry of the Banbury device, together with a rating curve for one of the 2 structures, which each contain twin 1.65m wide orifices.

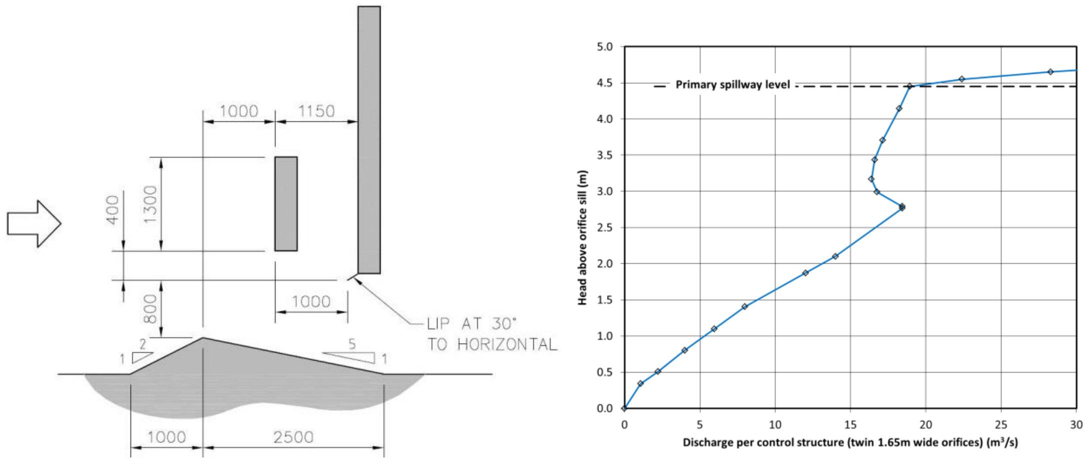


Figure A.6 Geometry and rating curve for Banbury double-baffle orifice

Note: Rating curve includes onset of primary spillway flow.

A.4 Flow control using gates and other mechanical devices

In theory, gates and other mechanical devices can – with suitable automated controls – offer 'ideal' performance for the flow control device, allowing the flow passed downriver to be equal to the inflow until it reaches a target value, then to remain at that target value at all upstream heads until the flood storage has been exhausted. The following devices may be deployed for the control of impoundment in online flood storage reservoirs and for the flow control and diversion arrangements associated with offline flood storage reservoirs:

- vertical lift gate
- radial gate
- tilting gate or weir
- adjustable orifice

Undershot gates, such as vertical lift and radial gates, can be adversely affected by floating debris accumulating against the upstream face above the opening. Debris can also be a hazard for the successful operation of adjustable orifices. Tilting and drum gates allow floating debris to pass over them, but there can be problems with sediment accumulation in the recesses into which they are lowered.

The following options for motive power may be adopted:

- float or displacer
- oil hydraulics
- mechanical

Float or displacer operation normally requires the use of counterbalanced gates so that the driving forces are reduced. There can be problems with debris or ice affecting movement of the gate or floats, or with small pipes associated with float chambers becoming blocked. Gate adjustment usually depends on a single water level (normally downstream): more complex control objectives (for example, involving a combination of levels and/or flows) are unlikely to be practicable with float or displacer operation.

Electrically powered hydraulic or mechanical operation is used for the majority of gates deployed in flood storage reservoirs, allowing the gate opening to depend on any combination of monitored water levels and computed parameters. Although such control systems can themselves be highly reliable, the possibility of mains power interruptions at times of adverse weather means that a backup power supply, together with remote alarms, must normally be provided. The provision of backup power is unlikely to be economic in the case of small flood storage reservoirs.

Some major flood storage reservoirs are manned or are remotely operated, and have complex operating rules or systems that take detailed account of downstream conditions.

Reliability issues associated with the power supply are usually the major risk to the correct operation of gates, with the result that major flood storage reservoirs normally have provision for manual intervention at such times. Whatever form of gate operation is deployed, there is often a risk of unauthorised operation or vandalism, especially for small gates where the operating forces can be overcome by a person or a suitably placed obstruction.

Vertical lift gates

The discharge equation for a vertical lift gate, discharging freely into a watercourse whose floor level is the same as the gate invert (that is without an immediate step down) can be taken as:

$$Q = C_C B d \sqrt{2g(H - C_C d)}$$

where: C_C = contraction coefficient
B = width of gate opening
d = height of gate opening
H = upstream water level in reservoir relative to invert of gate

The contraction coefficient for a gate with a sharp bottom lip can usually be taken as 0.61, although the value rises somewhat if the gate opening is more than around a quarter of the upstream head (the effect being about 2% at a quarter and over 10% when the gate opening is half the upstream head). Note that, if the gate opening exceeds about two-thirds of the upstream head, the flow breaks away from the gate lip and is governed by approximately critical flow, that is, behaving in about the same manner as a long-throated flume.

If the tailwater level is low enough, 'free flow' conditions occur with the jet emerging below the gate lip continuing as supercritical flow, to be followed by a hydraulic jump (for which a stilling basin would normally be provided) at the transition to the usually subcritical tailwater. If the tailwater level is higher, then 'drowned flow' conditions would occur, with the hydraulic jump located against the downstream face of the gate and the opening fully submerged on the downstream side. The transition between these conditions occurs when the tailwater level corresponds to the conjugate depth associated with the flow jet emerging from beneath the gate lip. This is given by the following adaptation of the equation for conjugate flow conditions:

$$y_{TW} = \frac{C_C d}{2}\left(\sqrt{1 + \frac{8Q^2}{gB^2 C_C^3 d^3}} - 1\right)$$

where: y_{TW} = tailwater level relative to invert of gate opening

Figure A.7 shows an example of the relationship between discharge and tailwater level for a vertical lift gate, with a fixed gate opening and upstream head.

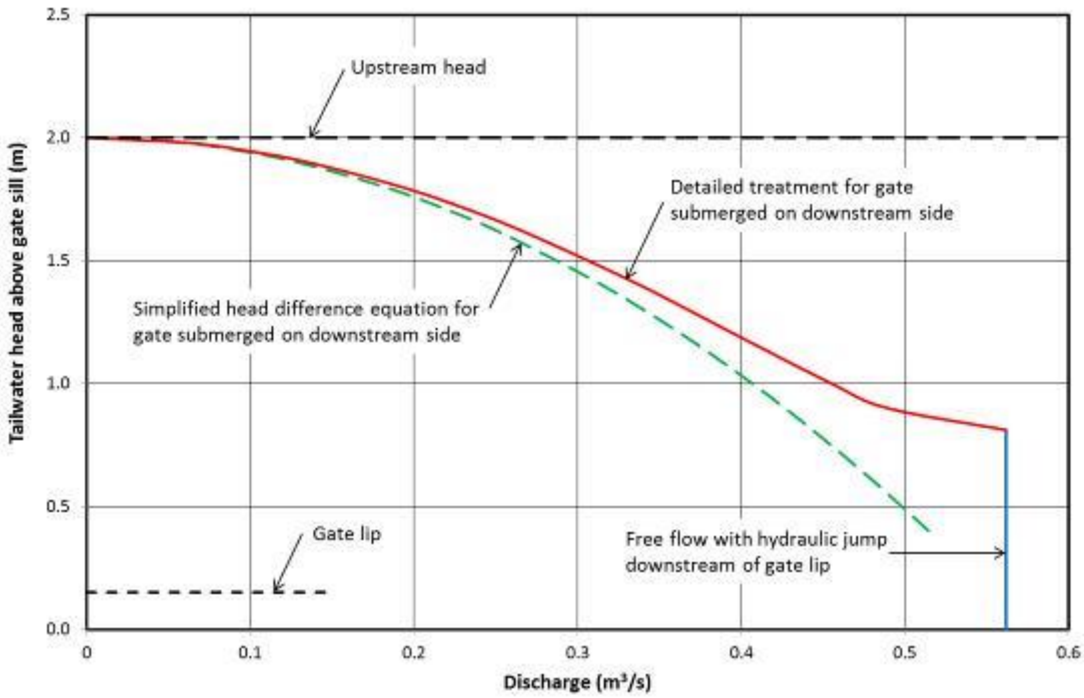


Figure A.7 Effect of tailwater level on discharge past vertical lift gate

If a vertical lift gate is submerged on the downstream side, then a simple non-rigorous treatment is to take the discharge as:

$$Q = C_C B d \sqrt{2g\Delta H}$$

where: ΔH = difference between upstream and downstream water levels

For a detailed treatment for the drowned flow conditions (the red line on Figure A.7), see hydraulics textbooks such as Henderson (1966), Bos (1989) and Miller (1994).

Radial gates

The free-discharge equation for a radial gate (normally called a tainter gate in the USA) is the same as given above for a vertical lift gate. However, because of the angled gate lip, the contraction coefficient is generally increased above the value for a vertical lift gate and can be taken as (Henderson, 1966):

$$C_C = 1 - 0.75\frac{\theta}{90} + 0.36\left(\frac{\theta}{90}\right)^2$$

where: θ = angle (degrees) of the upstream surface of the gate at the lip relative to the horizontal ($\theta \leq 90°$)

As for a vertical lift gate, the value rises somewhat if the gate opening is more than about a quarter of the upstream head, and at a gate opening exceeding about two-thirds of the upstream head, the flow breaks away from the gate lip and flume-type flow conditions again apply. The criteria for free flow and drowned flow are the same as for a vertical lift gate and the same equations may be used.

Tilting gate or weir

A tilting gate or weir comprises a plate or flap, with a horizontal hinge at its upstream edge, which is either flat or convex on its water face, arranged with the primary purpose of allowing the crest level of an overflow weir to be varied. The arrangement normally results in the downstream lip of the flap forming the adjustable crest level and the flap surface at the lip having an angle of between 0 and 90° to the horizontal. Discharge coefficients are given in Figures 3.50 and 3.51 of Kolkman (1994. The discharge coefficients (C_d) in these graphs are based on the following form of the weir flow equation:

$$Q = \frac{2}{3} C_d \sqrt{2g} B H^{1.5}$$

Adjustable orifice

An adjustable orifice typically incorporates a pivoted plate against its upstream face which is arranged so that it obstructs the orifice opening by a variable amount. Devices of this sort can either be controlled by electric motors based on real-time monitoring of water levels and/or flows, or can be float-controlled, with the rising of the float that is attached to the plate causing it to move across and reduce the orifice area by an amount that counteracts the effect of the increased head and allows a virtually uniform pass-forward flow to be maintained.

The best known of the float-controlled devices currently available in the UK is the HydroSlide®, for which a range of orifice diameters from 100mm to 2.5m is available, giving controlled discharges up to about 10m^3/s (Figure A.8). Units commissioned in UK flood storage reservoir schemes during 2015 have diameters of 1.5m and 1.9m, with design pass-forward flows per unit of 3.1 and 7.1m^3/s respectively. Advantages claimed for the float-controlled devices include:

- a virtually uniform pass-forward flow over a wide range of upstream water levels, making best use of the flow capacity of the downstream watercourse and hence giving better utilisation of the available storage
- an ability to adjust the units to give pass-forward flows that are up to 30% greater or smaller than the original design values (should, for example, circumstances change
- lack of reliance on power supplies or communications

The device is potentially vulnerable to debris reducing the flow through the orifice or obstructing the free movement of the float and plate, which could have a positive or negative effect on the pass-forward flow. Therefore, a trash screen is normally recommended.

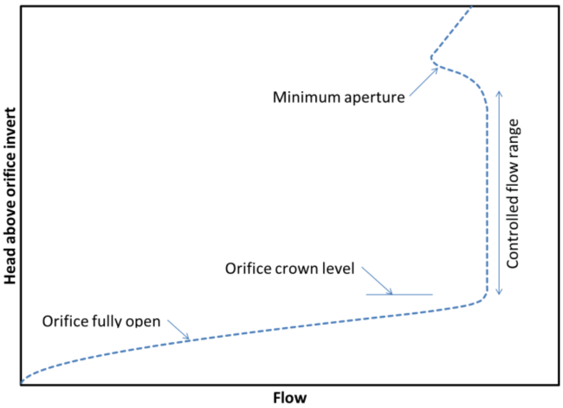


Figure A.8 HydroSlide® installed in Germany and typical rating curve for an adjustable orifice device (courtesy of Hydrok UK)

A.5 Flapgates

The discharge characteristics of a flapgate can be estimated initially using the following equation giving the headloss (in metre-second units):

$$\Delta H = C\frac{Q^2}{2gA^2} + \frac{d}{K}$$

where: ΔH = difference between water levels (strictly speaking, energy levels) upstream and downstream of flapgate (m)
C = a coefficient, value 0.3
Q = discharge (m^3/s)
A = flapgate opening area (when fully open) (m^2)
d = diameter of flapgate opening, or height if opening is rectangular
K = shape/construction factor (9 for circular cast iron, 11 for square or rectangular cast iron, 13 for lightweight flapgates)

For new flapgates, the headloss formulation should be confirmed by the manufacturer or supplier; it should be borne in mind that there is often a higher 'cracking head' required to unstick the flapgate after a period closed.

Appendix B Weir and spillway design

B.1 Overflow weirs

Overflow weirs come in a variety of profiles:

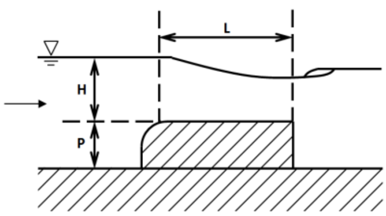
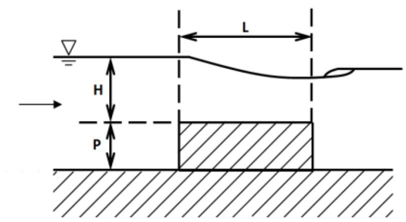
- broad-crested
- rectangular crest
- sharp-crested (thin-plate weirs)
- ogee (WES standard spillway)
- cylindrical
- triangular (including Crump)

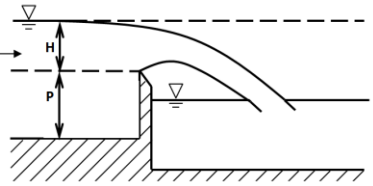
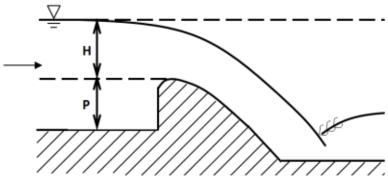
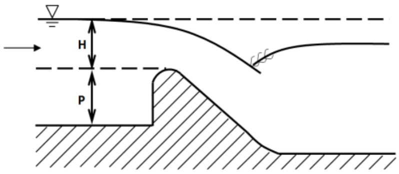
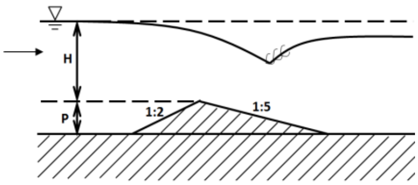
Table B.1 illustrates these and summarises their hydraulic behaviour in terms of the coefficient C_d in the equation:

$$Q = C_d\sqrt{g}BH^{1.5}$$

References giving further details of the hydraulic behaviour of the various weir profiles are also given in Table B.1. Note that some references give the coefficient in relation to different forms of the discharge equation, but the differences are purely numerical factors and so are easily reconciled.

Table B.1 Weir profiles

Type of weir	Diagram	Discharge coefficient* and references
Broad-crested (round nose or trapezoidal)		For a wide weir assume: $C_d = 0.544 \times \left(1 - \frac{0.003L}{H}\right)^{1.5}$ Ackers et al. (1978), Bos (1989), BS 3680-4F:1990 (ISO 4374:1990) (BSI 1990)
Rectangular		Provided 0.08 < H/L < 0.33 and 0.18 < $H/(H+P)$ < 0.36: C_d = 0.544 × 0.848 = 0.46 Otherwise C_d varies. Ackers et al. (1978), Bos (1989), BS ISO 3846:2008 (BSI 2008b)

Type of weir	Diagram	Discharge coefficient* and references
Sharp-crested (thin-plate)		For a full-width weir (no side contractions at the ends of the weir plate): C_d = 0.57 Note that some references give the coefficient in terms of the gauged head rather than the total head, so the applicable velocity head must be added to give the total head. Ackers et al. (1978), Bos (1989), BS ISO 1438:2008 (BSI 2008a)
Ogee (WES standard)		At the nominal design head (basis for geometry): C_d = 0.71 Ranges from 0.54 (for critical flow) at low head to 0.74 at 1.3 times nominal design head. USACE EM1110-2-1603 (USACE 1990), Bos (1989)
Cylindrical		At high heads (H > 1.5r): C_d = 0.544 × 1.48 = 0.80 Reduces at lower heads, down to 0.54 (for critical flow). Bos (1989) (noting the different definition of discharge coefficient therein)
Triangular (including Crump)		For Crump weir (as shown): C_d = 0.633 With 1:2 downstream slope: C_d = 0.683 Ackers et al. (1978), Bos (1989), BS ISO 4360:2008 (BSI 2008c)

Notes: * Discharge coefficients in this table are in relation to the equation $Q = C_d\sqrt{g}BH^{1.5}$.

The broad-crested weir comprises either a rectangular profile with a rounded upstream nose, or a trapezoidal profile with a gentle upstream slope, designed in both cases to achieve virtually critical flow. The equivalent rectangular profile without a rounded nose results in a lower – but variable – coefficient due to the flow separation pocket that forms at the upstream edge of the crest. A sharp-crested (thin-plate) weir, which gives a higher coefficient than a broad-crested weir, is good for flow measurement. However, the machined weir plate is subject to damage and loss of precision, so this form of weir is less suited for use as a reservoir overflow.

The fundamental design concept of the ogee profile is to fill in the air space that occurs beneath the nappe of a sharp-crested weir at its design flow. Because the resulting crest level of the ogee weir is higher than that of the equivalent sharp-crested weir from which it is derived, the discharge coefficient in relation to the ogee crest level is higher than for the sharp-crested weir. This makes the ogee weir profile particularly efficient, passing a rather greater discharge per unit width than a broad-crested or sharp-crested weir.

The geometry of the ogee weir is based on a particular design head, at which the contact pressures between the flowing water and the weir are atmospheric (that is, zero gauge pressure). At lower heads, the contact pressures are increased and at higher heads the contact pressures are sub-atmospheric, resulting in a variable discharge coefficient that increases with head. To avoid excessively sub-atmospheric pressures, it is conventional to limit the maximum head during an extreme flood to about 1.3 times the notional design head on which the profile geometry was based. However, the true check should be that minimum pressure on the crest should not fall below −4m gauge pressure. The references provided include a means of undertaking this check.

A cylindrical profile (in practice either a half cylinder forming the crest of the weir, or a ⅜ cylinder, with a vertical upstream tangent and inclined downstream tangent) also offers high discharge coefficients, which again vary with head. The selection of the radius needed for the avoidance of cavitation depends on the maximum head and guidance is available in the quoted reference.

A triangular profile weir, of which the best known is the Crump weir, with an upstream slope of 1V:2H and downstream slope of 1V:5H, offers a number of advantages:

- a high unit discharge
- a constant discharge coefficient
- a high modular ratio (that is a low vulnerability to flow being impeded by high tailwater levels)
- suitability for flow gauging (if required)

The alternative form, with a 1V:2H downstream slope, results in a higher coefficient and hence larger unit discharge for a given head, but a slightly lower modular limit.

B.2 Labyrinth weirs

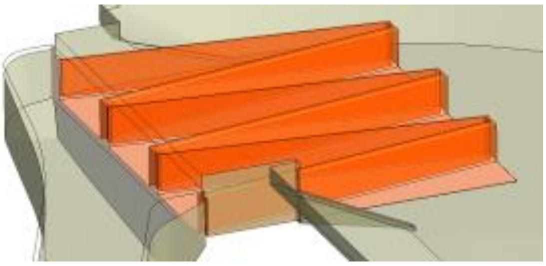
Augmenting the crest length of a weir by arranging it in the form of a zigzag (usually with truncated apexes to avoid unduly tight angles) has been done for many years. Although there was earlier design guidance, the first technical paper presenting reliable design guidance appears to have been only about 20 years ago (Tullis et al. 1995). Since then, a comprehensive guide on the subject has been published (Falvey 2003), which drew on the work of Tullis et al. (1995), and there have been at least 2 specialist conferences on the subject of labyrinth and piano-key weirs (Erpicum et al. 2011, 2013). Following further physical model testing, Crookston and Tullis (2013) have updated the 1995 design guidance.

In broad terms, practical design layouts at reservoir spillways are normally capable of achieving a crest length augmentation factor of 5 to 6. This typically results in an overall structure width of the order of a third to a quarter of the width required to pass the same discharge at the same head over a conventional straight weir, or for a given overall structure width, reducing the required head to pass a given discharge to 40–50% of that required for a straight weir.

For flood storage reservoirs, the site available for a labyrinth weir may be constrained in a manner that prevents such a high weir crest length augmentation ratio being achieved. Hence it may not always be possible to achieve such impressive improvements in hydraulic performance.

The hydraulic design of a labyrinth weir is a specialist matter. For small labyrinth weir structures operating a low head, sufficient reliability can usually be achieved by application of the appropriate empirical design guidance given in the references given above. For larger structures, it would be prudent to augment the empirical design with either physical model testing or CFD.

Figure B.1 shows examples of labyrinth weirs.



CFD image of a labyrinth weir (without flow) at a reservoir spillway

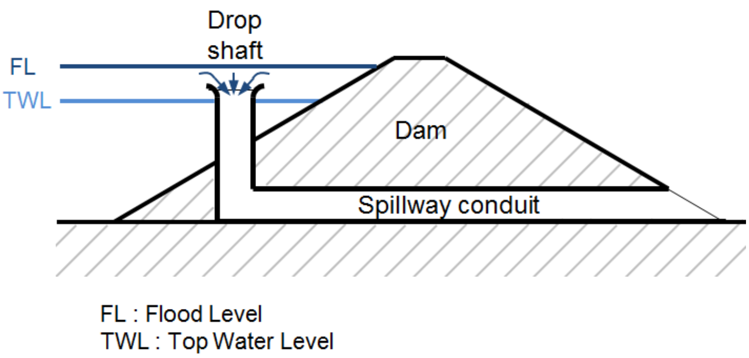
Labyrinth weir at Strathclyde Park, Glasgow

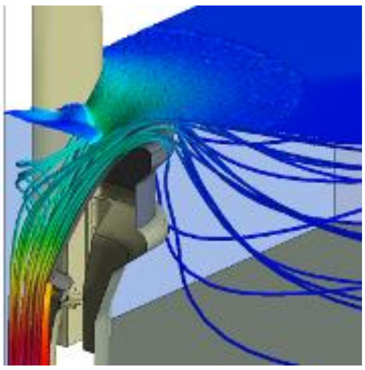
Figure B.1 Examples of labyrinth weirs

B.3 Shaft and culvert spillways

Figure B.2 shows the basic layout of a shaft and culvert spillway. For large structures at impounding reservoirs, the top of the shaft would normally be curved outwards to form a bellmouth (normally referred to as a 'morning glory' in US references). In its simplest form, however, the shaft may take the form of an upturned pipe, which may or may not include a bellmouthed entrance.

Similar in hydraulic behaviour would be an 'overflow box', comprising an open or partly enclosed rectangular chamber within the impoundment area, with weirs around its perimeter, connected to a pipe or culvert to convey flows beneath or thorough the dam and into the downstream watercourse. If used at an online flood storage reservoir, this arrangement would typically be integrated with the flow control arrangements, with the culvert serving both functions.





CFD model of a quarter of a bellmouth spillway, near the transition from weir to throat control

Figure B.2 Shaft and culvert spillway

In principle, the following modes of flow are possible for the shaft and culvert form of spillway:

- weir control around the rim of the shaft

- orifice-type control in the throat of shaft (for example, at the tangent between the bellmouth and the uniform shaft)
- entrance control at the upstream end of the culvert (with the culvert running part-full)
- pipe-type flow, with the shaft and culvert running full throughout

These modes would occur in the above sequence with rising water level and increasing flow, but it would be unusual for all 4 modes to occur. Weir control always occurs at low heads, sometimes followed by a direct transition to pipe-type flow. In some cases, the culvert would be designed to be large enough so that weir flow is followed by either throat control or culvert entrance control, with the culvert always running part-full so that pipe-type flow never occurs.

In weir mode, the stage/discharge relationship would be based on the applicable formula for a similar weir profile, using the bellmouth circumference or the perimeter of the shaft rim to represent the width of the weir, perhaps with a slight reduction to allow for the effect of converging flow.

In throat control, the orifice formula would apply:

$$Q = C_C A\sqrt{2g\Delta H} Q = C_C A\sqrt{2g\Delta H}$$

where: C_C = contraction coefficient
A = cross-sectional area (m^2)
ΔH = head difference (m) between upstream water level and the vena contracta

The ‘vena contracta’ is the point at which the area of the flow reaches about $C_C A$. For a bellmouth, the vena contracta would be at the same elevation as the throat and the contraction coefficient would be about 0.95. For an upturned pipe without a bellmouth, the vena contracta would be about half the diameter below the top of the pipe and the coefficient would be about 0.60.

In the case of an overflow box and culvert arrangement, it would be usual for the overflow chamber to be large enough to avoid the equivalent of shaft throat control. The culvert hydraulics would then be determined as in Section A1, taking account of the possibility of entrance control, as well as downstream watercourse control.

If the whole system is running full, then it would be treated in the same manner as a closed pipe system, equating the available headloss to the sum of the formlosses associated with the entrance, the bend at the base of the shaft and any other bends, any changes in flow cross-section and the exit, together with the friction-type losses for the conduits.

Because of the potential for different modes of flow, with some giving rise to possible unstable flow, sub-atmospheric pressures and hence cavitation risks, the design of this form of spillway at large reservoirs, with high heads involved, is a specialist matter. There are generally fewer pitfalls at most flood storage reservoirs, where the maximum heads are generally only a few metres.

The general approach to determining the hydraulic behaviour of a proposed design (which still requires a sound grounding in the hydraulic principles involved) is as follows.

- For each possible flow mode, determine the stage/discharge characteristics.
- Convert all the values of ‘stage’ to the corresponding total energy level.

- Plot all the curves on the same graph, with total energy level on the y-axis and discharge on the x-axis.
- At all discharges, take the mode giving the highest total energy level as the applicable value.
- Identify the flow modes involved and consider changes in the design in order to reduce the number of flow modes that apply and the risks of control flipping between modes.

Figure B.3 shows an example of the rating relationships for the 4 potential flow modes at a shaft and culvert spillway incorporating a 1.8m diameter vertical shaft with a bellmouth discharging to a 30m long culvert, at a 1% gradient, whose upstream invert level is 5m below the bellmouth rim. In this example, there is a progression from weir control to shaft throat control and finally pipe-type control, with culvert entrance control playing no part. In this case, it would probably be best to choose instead an overflow box arrangement, so avoiding the potential region of shaft throat control.

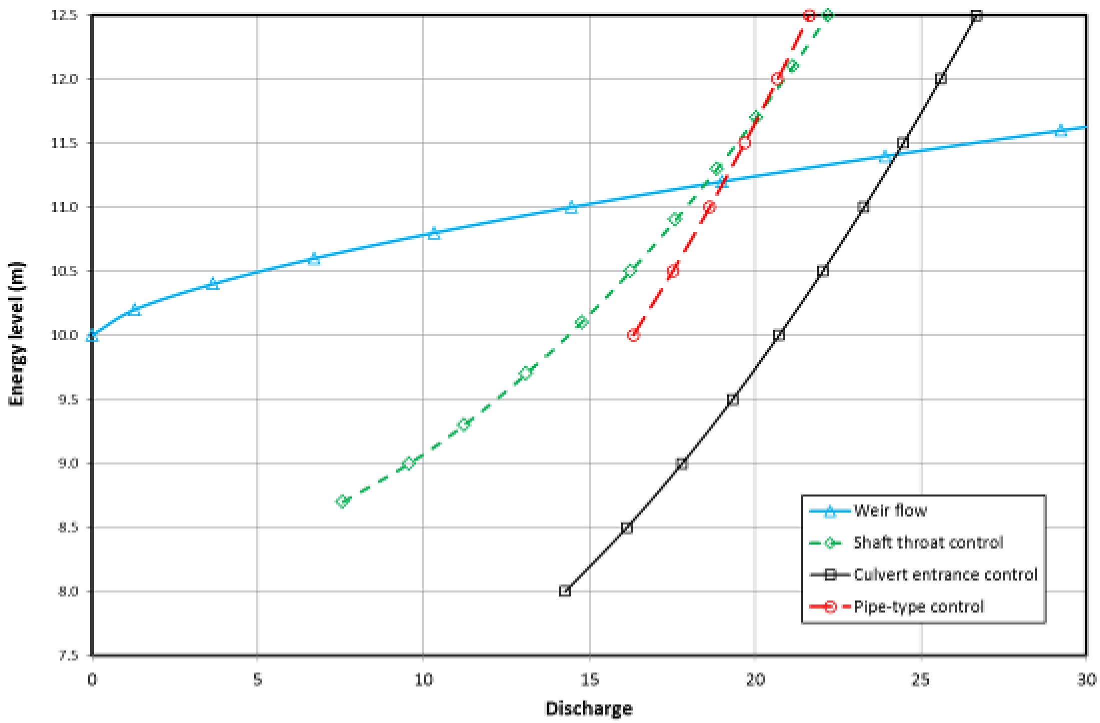


Figure B.3 Example of ratings for a shaft and culvert spillway

B.4 Siphons

It may be occasionally be advantageous to adopt a siphonic overflow structure in cases where only a small rise in flood level can be accepted during an extreme flood, or where it is necessary to accommodate the structure within a space that is too small for a conventional weir and spillway. The discharge equation for a siphon takes the form:

$$Q = C_D A\sqrt{2g\Delta H}$$

where C_D = discharge coefficient, normally around 0.85
A = cross-sectional area of siphon barrel (m^2)
ΔH = head difference between upstream and downstream water levels (m)

The graph in Figure B.4 illustrates the potential advantage of a siphon over a simple weir. However, this advantage can only occur if there is sufficient driving head.

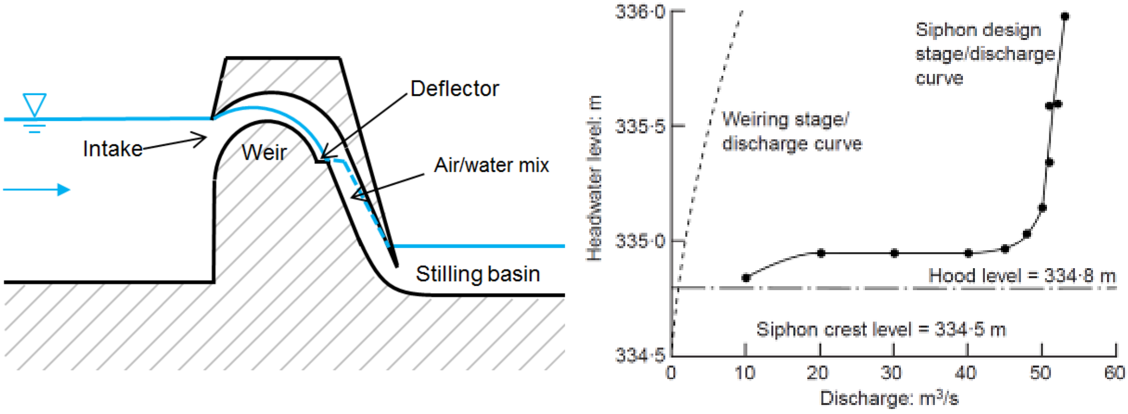


Figure B.4 Cross-section and typical performance curve for air-regulated siphon

A modern air-regulated siphon can normally be designed to pass the full discharge with a flood rise above overflow level of no more than 0.1–0.2m (depending on the barrel height) and without 'hunting', matching the flow passed through the siphon to the inflow to the flood storage reservoir. If, however, the inflow exceeds the full discharge capacity of the siphon, any further increase in siphon discharge requires a disproportionate increase in operating head, following the square of the discharge. Hence, siphon spillways must always be designed with a margin of safety over the maximum design discharge.

The design of siphons is a specialist subject, because of the subtleties of priming, air regulation and de-priming, together with the potential effects of wave action and the cavitation risks. Indeed, the geometrical design – primarily the crest radius – of even a small siphon spillway is usually governed by cavitation considerations. Technical papers by Head (1971, 1975), Ackers and Thomas (1975) and Ackers and Ashraf Akhtar (2000) provide more information, together with further references.

Precast modular siphon units may be available as an alternative to the relatively complex in situ construction that would otherwise be required.

B.5 Spillway chutes

The spillway chute conveys the flow from the emergency overflow weir to the receiving watercourse, often via an energy dissipater which would usually be a hydraulic jump stilling basin.

Whereas the spillway in a modern conventional impounding reservoir is normally built of reinforced concrete, the low head involved in the spillways at many flood storage reservoirs allows the use of 'softer' structures, principally various systems of reinforced grass, many of which form part of the impounding embankment. These are covered in the next subsection, but the following design principles usually apply whatever structural form the spillway takes.

For the spillway chute to perform as required, it is normally designed at a supercritical gradient, meaning that it slopes sufficiently steeply to ensure that the flow is supercritical rather than subcritical. This is necessary to ensure that the overflow weir remains 'modular', meaning that the flow over the weir is unimpaired by conditions downstream of the weir. Figure B.5 shows the primary hydraulic features of a spillway chute that terminates in a hydraulic jump stilling basin.

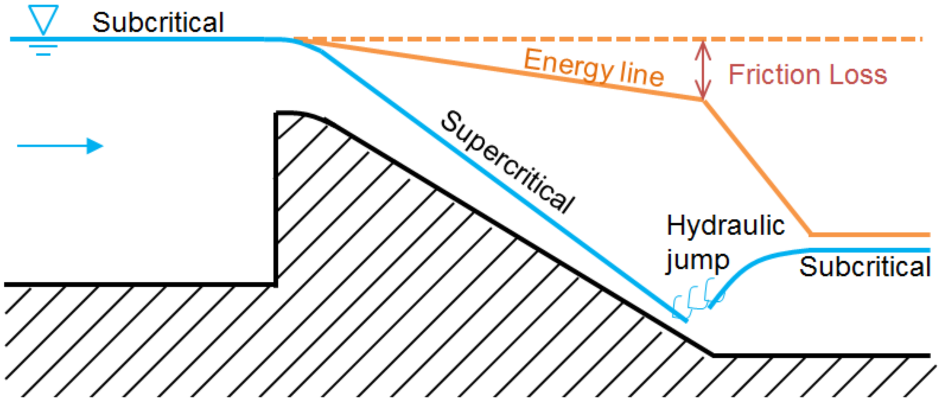


Figure B.5 Spillway chute hydraulic behaviour

Ideally, the spillway chute should be straight, directly aligned with the flow passing over the weir and having the same width as the crest length of the weir, so that the flow behaves predictably according to simple one-dimensional analyses. This is normally practicable for a spillway that forms part of the impounding embankment, but not if the spillway is separate from the embankment.

There are 2 features commonly found in spillway chutes that require further analysis of the flow behaviour, namely tapering and bends.

If the spillway tapers approximately symmetrically, the flow conditions can be largely solved by the one-dimensional analyses, although there is a tendency for cross-waves to form, meaning that the flow depths at the walls vary above and below the values predicted by the one-dimensional analysis. A key point to note is that the gradient through the taper must be sufficient to ensure that, at no point, does the taper form a hydraulic control that results in drowning of the overflow weir. Although the one-dimensional analysis should demonstrate whether or not the weir is drowned, it is better to perform a separate check, by dividing the taper into (say) 10 intervals and at each intermediate cross-section determining the value of the minimum energy level, E_{min}, which is given by:

$$E_{\min} = z + 1.5\sqrt[3]{\frac{Q^2}{B^2 g}}$$

where: z = elevation of chute invert (m OD)
Q = design discharge (m^3/s)
B = width of chute (m)
g = gravitational acceleration (9.807m/s^2)

The values of minimum energy level are plotted against distance downstream of the weir crest, together with the calculated water level in the flood storage reservoir for the same discharge. Provided that the minimum energy levels all plot below the reservoir level by an amount that appears sufficient to allow for the intermediate friction losses, the overflow weir should remain undrowned.

In the most extreme form of taper, the head of the spillway forms a ‘side-channel’ into which the flow enters over (usually) one sidewall. The flow in the side-channel is characterised primarily by conservation of momentum, which is accompanied by a rate of energy loss that is substantially greater than would be needed to overcome friction alone. The theoretical treatment of the flow in the side-channel is given in standard textbooks, such as Henderson (1966).

In some cases, the upstream end of a spillway chute tapers down to an access crossing, such as a bridge or culvert, where it may prove more economical to allow a hydraulic control point to be created, subject to the overall hydraulic performance of the overflow weir spillway being found acceptable.

If a spillway chute includes bends, then its behaviour is further complicated by both cross-waves and by a tendency for super-elevation of the water surface. Although there are means of estimating super-elevation in the textbooks (for example, Henderson 1966), they are subject to a substantial degree of uncertainty and it is common practice to clarify the issue through the use of physical model testing or CFD (Figure B.6).

The issue of how much freeboard to provide on spillway chutes above the predicted water surface is the subject of divergent guidance. In the case of flood storage reservoirs that involve head differences of no more than about 5m, a freeboard of 0.3m above the greatest depth predicted in a physical or CFD model is probably more than sufficient.

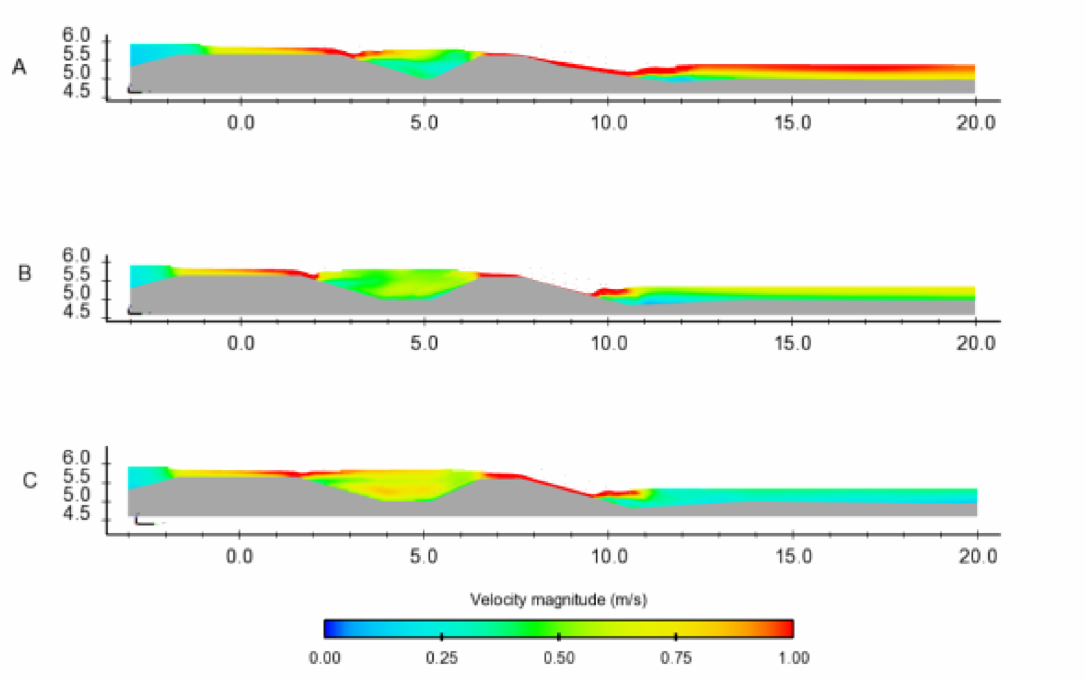


Figure B.6 Example of a CFD model of a spillway chute (Finchetts Gutter flood storage reservoir) to assess the effect of a downstream buried utility embankment on spillway flows and reservoir levels

B.6 Stepped and baffled spillways

This section covers 2 forms of spillway chute:

- spillways with steps in the floor, usually at regular intervals
- spillways that include regularly spaced blocks or ‘baffles’ protruding from the floor

The purpose of using steps or baffles in the spillway chute is to dissipate as much as possible of the kinetic energy resulting from the drop in water level on the spillway itself. This will reduce the amount of energy remaining at the toe of the spillway, thereby allowing the use of a more economical stilling basin or other energy dissipator at the toe.

In a stepped spillway, the treads of the steps may be horizontal, inclined (with or against the overall spillway slope) or ‘pooled’, if they include an upstand at the downstream end of each tread. The hydraulic behaviour of stepped spillways at the range of gradients likely to be encountered at the chute spillways of UK reservoirs is covered in CIRIA Report 33 (CIRIA 1978). This may be used to predict the performance of existing or proposed stepped spillways with overall gradients of between 11° and 45° and tread angles between horizontal and 20° against the flow. The guidance is presented in graphical form, using dimensionless parameters to characterise the behaviour of the flow, which may be classified as ‘nappe flow’ or ‘skimming flow’, and to estimate the energy dissipation requirements at the spillway toe.

Where stepped spillways are formed in masonry or similar materials, they can present particular problems concerned with the integrity of the structure when subject to the penetration of hydraulic pressures into the joints (Environment Agency 2010d).

A particular form of stepped spillway, initially developed in the former USSR, is the stepped-block or wedge-block spillway, in which a series of specially shaped overlapping precast blocks are laid down the slope, with the resulting top surface being about horizontal or having a gentler gradient than the overall gradient of the spillway (as shown in Figure B.7). Guidance on the design of this form of spillway construction is provided by CIRIA R116 (CIRIA 1997). Discharge intensities of 10m^3/s per metre and higher have been reported in the former USSR, with the largest to date in the UK having a design unit discharge of 5m^3/s per metre.

Figure B.7 Examples of wedge-block spillways

An alternative form of energy-dissipating spillway is the baffle-chute spillway, as illustrated in Figure B.8. Design guidance is well established and is given in USBR Engineering Monograph 25 (Peterka 1978) and other USBR publications concerned with dams and irrigation canal structures. The baffle-chute spillway can be designed for unit discharges up to about 5m^3/s per metre without recourse to model testing. There is no particular virtue in the standard part-circle crest profile and a simpler alternative, such a broad-crested weir, can be adopted instead. The baffle-chute spillway has not been adopted to any significant degree in the UK.

Figure B.8 Example of baffle-chute spillway at Walverden Reservoir

Photograph courtesy of United Utilities and Tim Dyke

B.7 Reinforced grass and similar forms of spillway

Where a non-structural form of spillway is adopted – including where the crest and downstream face of the dam provide the emergency flood route – the surfaces must be suitably protected against erosion damage from the flowing water. Well-established turf is reputed to provide protection against velocities up to 3m/s for up to 9 hours, but for higher velocities and longer durations, a number of systems have been developed to reinforce the surface. These range between various geotextile products and the use of cellular concrete blockwork, supplied by a number of manufacturers.

Hydraulic design guidance is available in 'Design of Reinforced Grass Waterways' CIRIA R116 (CIRIA 1987). The 4 key aspects to the design of reinforced grass spillways covered in R116 are:

- **Hydraulic design**
  - velocity
  - duration of flow
  - erosion resistance of surface
- **Geotechnical considerations**
  - soil sampling (to identify the soil type)
  - testing (for appropriate soil parameters to use in design)
- **Botanical** – choice of the grass mixture to suit the site and management arrangements

- **Detailing and specification –** including such issues as joints, anchorages for the reinforcement edges and crest and toe details

Given the length of time since the publication of this design guidance, it would appear timely for that to be updated in the light of changes in the products that are now available, the performance claims made for the products and any additional research that has been undertaken, together with the longer experience in the use of the products. Such an update is, however, beyond the scope of this guide. Further research on this matter is planned by the Environment Agency.

Experience indicates that cellular concrete systems are normally able to support a healthy cover of grass. In some cases, there has been evidence of the cells heating due to sunlight exposure and drying out the soil and killing the grass. Good quality soil and relatively large cells can help to mitigate this effect. Once the grass cover is established over the concrete, this risk is reduced.

Appendix C Energy dissipation

Information about energy dissipation is given in various hydraulics textbooks such as Chow (1973a), Henderson (1966) and Bos (1989), and in a US Federal Highway Administration publication (Federal Highway Administration 1983a). Figure C.1 shows the USBR impact-type basin, which has been widely adopted in the UK. It can be sized according to guidance given in USBR Engineering Monograph 25 (Peterka 1978) to suit a wide range of discharges. Engineering Monograph 25 includes a standard set of dimensions to suit discharges between about 0.3 and 11m^3/s and velocities up to about m/s, but individual designs can generally be derived, without physical model testing or CFD, according to Froude scaling.

Figure C.1 Example of USBR impact-type basin

Photograph courtesy of ATPEC Ltd

Spillway flows almost invariably involve supercritical flows, whereas the flow conditions in the watercourse or flooded valley downstream are generally subcritical. Energy dissipation measures are usually required to manage the transition from supercritical to subcritical flow, normally in the form of a hydraulic jump.

The principle of the hydraulic jump, which is based on the conservation of momentum at the transition from supercritical to subcritical flow, is covered well in standard hydraulic textbooks. The following equation applies to a hydraulic jump:

$$y_2 = \frac{y_1}{2}\left(\sqrt{1 + 8Fr_1^2} - 1\right)$$

where: y_1 = supercritical flow depth entering hydraulic jump (m)
y_2 = conjugate depth downstream of hydraulic jump (m)
Fr_1 = Froude number of supercritical flow entering hydraulic jump.

It is important to note that the successful deployment of a hydraulic jump depends on the tailwater depth being large enough to force the occurrence of a hydraulic jump at the desired location: essentially, the tailwater depth must be equal to or greater than the conjugate (or sequent) depth that corresponds to the incoming supercritical flow.

If the spillway comprises a concrete chute, then the hydraulic jump is normally contained in a stilling basin that follows one of the standard USBR or St Anthony Falls designs that are widely quoted in textbooks; for the standard USBR designs, see also Peterka 1978). The tailwater depth is created by the flow conditions that exist downstream and the stilling basin must be designed to suit the available tailwater conditions. If the tailwater depth is not large enough, the stilling basin will not function correctly and the high velocity flow will be liable to sweep through the basin. Some designs of stilling basin provide greater resilience against sweep-out, so allow the conjugate depth to slightly exceed the tailwater depth. In other cases, a factor of safety is adopted, with the available tailwater depth therefore being required to exceed the conjugate depth by up to 10%.

Appendix D Specific protected species surveys

Table D.1 Protected species survey guidance available in the UK

Protected species	Guidance details
Badgers	Harris, S., Cresswell, P. and Jefferies. D., 1989. *Surveying badgers*. Occasional Publication of the Mammal Society No. 9. London: The Mammal Society.
Bats	Collins, J. (ed.), 2016. *Bat surveys for professional ecologists: good practice guidelines* (3rd edition). London: Bat Conservation Trust.
Birds	Gilbert, G., Gibbons, D.W. and Evans, J., 1998. *Bird monitoring methods: a manual of techniques for key UK species.* Bedfordshire: RSPB.
Dormice	Bright, P., Morris, P. and Mitchell-Jones, T., 2006. *The dormouse conservation handbook* (2nd edition). Peterborough: English Nature.
Great crested newts	Langton, T.E.S., Beckett, C.L. and Foster, J.P., 2001. *Great crested newt conservation handbook.* Halesworth, Suffolk: Frog Life. English Nature, 2001. *Great crested newt mitigation guidelines.* Peterborough: English Nature.
Otters	JNCC, 2004. *Common standards monitoring guidance for mammals.* Peterborough: Joint Nature Conservation Committee.
Reptiles	JNCC, 2004. *Common standards monitoring guidance for reptiles and amphibians*. Peterborough: Joint Nature Conservation Committee.
Water vole	CIEEM, 2013. *Competencies for species survey: water vole.* Technical Guidance Series. Winchester: Chartered Institute of Ecology and Environmental Management.
White-clawed crayfish	CIEEM, 2013. *Competencies for species survey: white-clawed crayfish.* Technical Guidance Series. Winchester: Chartered Institute of Ecology and Environmental Management.
Macroinvertebrates	Sampling methods should follow BS EN ISO 10870:2012 (BSI 2012a)
Macrophytes	BSI, 2014. *BS EN 14184: 2014. Water quality – Guidance standard for the surveying of aquatic macrophytes in running waters*. London: British Standards Institution.
Fish	Specific monitoring guidance and methodologies relating to fish species of international conservation importance has been produced as part of the project, Life in the UK rivers. This includes methods for: • 'Monitoring the Atlantic salmon, Salmo salar' (Cowx and Fraser 2003) • 'Monitoring the bullhead, *Cottus gobio*' (Cowx and Harvey 2003) • 'Monitoring the river, brook and sea lamprey' (Harvey and Cowx 2003) • 'Monitoring Allis and Twaid Shad' (Hillman et al. 2003)

Note: See www.cieem.net/sources-of-survey-methods-sosm- for guidance on other species.

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