10 Flood storage works

10.1 Why provide flood storage?

There are two main reasons for providing temporary detention of floodwater:

- to compensate for the effects of catchment urbanisation;
- to reduce flows passed downriver and mitigate downstream flooding.

Although these may be separate drivers for a flood storage scheme, they are in essence identical. The flood storage works are designed to reduce the peak flood flow passed downstream, spreading the overall volume passed downstream over a longer period. Alternative methods of providing this flood protection would be to:

- enlarge the river channel;
- raise the riverbanks;
- construct floodbanks set back from the river;
- provide specific protection around flood-prone buildings or groups of buildings.

Providing flood storage is thus one of a portfolio of options for managing and controlling the risk of flooding. In some cases it can provide sufficient flood protection on its own; in other cases it may be chosen in conjunction with other measures.

The advantage of flood storage is that the flood alleviation benefit generally extends further downstream, whereas the other methods benefit only the local area, and may increase the flood risk downstream.

If the primary driver for flood storage is to compensate for the effects of urbanisation (see Box 10.1), the objective is normally to detain the additional and faster runoff that results from an increase in the impermeable area. This is then released downstream at a slower rate, designed to mimic the natural runoff from the non-urbanised catchment, avoiding any increase in flood depths and frequencies being propagated downstream.

Box 10.1 The effects of urbanisation

The five major effects of urbanisation on the hydrological behaviour of a catchment are:

- the increased proportion of impervious ground cover leads to a larger proportion of runoff from the rain falling upon it;
- the provision of stormwater drains and culverted or ‘improved’ watercourses which increase the flow velocities and thereby shorten the response time of the catchment;
- the discharge of a larger volume of runoff within a shorter time leads to greater peak flows downstream;
- the infilling or obstruction of the natural floodplain reduces the available flood storage in the valley, further increasing peak flows passed downriver;
- the increased impervious area prevents soil moisture recharge, leading to lowered groundwater levels and reduced dry weather streamflows (though this effect can be offset by leakage from water mains).

Source: Hall *et al* (1993)

If the primary driver is reducing the downstream flood risk, this normally involves throttling the flow passed downriver to an amount that has been estimated to avoid property flooding in events up to a particular return period.

Increasing attention has been given in the last decade to the opportunities to mitigate the effects of urbanisation through controlling runoff at, or close to, the place where the rain falls on the surface. The various measures that have been developed are collectively known as SUDS (sustainable drainage systems) (see Box 10.2). Some of these measures involve the temporary detention of floodwater and thus could be considered to come within the scope of this chapter, while others involve the use of surfaces that inhibit runoff or enhance infiltration and the recharge of groundwater.

Box 10.2 More about SUDS

All SUDS measures involve either infiltration or storage, or a combination of these methods. The typical SUDS components that involve flood storage comprise:

Swales	Broad, shallow channels covered by grass or other suitable vegetation. They are designed to convey or store runoff (or both), and can infiltrate the water into the ground (if ground conditions allow).
Infiltration basins	Depressions in the surface that are designed to store runoff and infiltrate the water to the ground. They may also be landscaped to provide aesthetic and amenity value.
Wet ponds	Basins that have a permanent pool of water that may be designed for treatment to improve water quality. They provide temporary storage for additional storm runoff above the permanent water level. Wet ponds may provide amenity and wildlife benefits.
Extended detention basins	Normally dry, though they may have small permanent pools at the inlet and outlet. They are designed to detain a certain volume of runoff as well as providing water quality treatment.
Constructed wetlands	Ponds with shallow areas and wetland vegetation to improve pollutant removal and enhance wildlife habitat.

These descriptions are taken from Table 1.1 of *The SUDS manual* (Woods-Ballard *et al*, 2007) – a comprehensive manual for the promotion, design and future management of works that come within its scope. The remainder of this chapter therefore covers only the use of flood storage in a context that either lies clearly beyond the scope of *The SUDS manual* or is subject to the provisions of the Reservoirs Act 1975 (see Section 10.3.5).

10.1.1 The role of flood storage

According to *Design of flood storage reservoirs* (Hall *et al,* 1993), the provision of flood storage:

> 'has much in its favour. The capacity of the reservoir both attenuates the incoming flood peak to a flow that can be accepted within banks by the downstream channel and delays the timing of the flood so that its volume is discharged over a longer time interval'.

Hall *et al* (1993) go on to point out that, where several flood storage reservoirs are deployed in a river basin, their overall effect has to be considered carefully. For example, a flood storage reservoir on a minor tributary could delay the peak of the tributary flood so that it coincides with the peak flood coming down the main stream, thereby making matters worse. It is normally obvious if there is a risk of this occurring, but the application of appropriate hydrological and flood modelling approaches can demonstrate if this is indeed a problem. Such studies need to cover a range of rainstorm and flood scenarios – including the effect of rainstorms moving across the catchment – to ensure that the provision of flood storage at a site is a robust solution that does not have detrimental effects at other locations downstream.

10.1.2 Adaptability

Flood storage works sometimes lend themselves to adaptability to changed circumstances such as:

- increased upstream catchment runoff;
- a change in the vulnerability of downstream communities to flooding.

Increases in catchment runoff may be due to progressive urbanisation or a change in climate, while the downstream vulnerability might change with increased urban development or the implementation of a flood alleviation scheme.

Adaptability of the flood storage works could include such features as:

- the ability to raise the impounding embankment to increase the flood storage capacity;
- adjusting the settings of gates or orifices that control downstream releases;
- if applicable, changing the setting of weirs and gates that admit flows to the reservoir.

At the time when flood storage works are proposed and designed, it is vital to consider:

- whether it may be desirable to adapt the design of the scheme in the future;
- whether any such flexibility should be incorporated into the design.

10.2 Types of flood storage

Flood storage works can usually be described as one of the following:

- ***online*** – in which the water is temporarily stored within the river channel and its floodplain;
- ***offline*** – in which the water is diverted from the river channel, stored in a separate area (which may be part of the floodplain) and subsequently released back to the river or to another watercourse.

In general, online storage works are normally located in the upper catchment (where the catchment area is modest) while offline storage works are more common on larger rivers with wide floodplains. Some complex flood storage schemes include a combination of online and offline components, designed to act in conjunction. Table 10.1 gives a more detailed classification of flood storage works.

Table 10.1 Classification of flood storage areas

Type of reservoir	Description
Online	Dry-weather flows pass through the flood storage area
Offline	Dry-weather flows bypass the flood storage area
Dry	Flood storage area is kept essentially empty under dry-weather flow conditions
Wet	Most of flood storage area contains water under dry-weather flow conditions
Wet/dry	Part of flood storage area contains water and part is essentially empty under dry-weather flow conditions

Floodplains that are modified to augment their natural flood storage and attenuation characteristics are often described as washlands – a term that can be used in the context of either online or offline flood storage.

10.2.1 Online flood storage

The components of online storage works normally include:

- an impounding structure – generally comprises an earth or concrete structure across the river and floodplain, behind which the water is stored;
- a flow control structure – normally located within the impounding structure to control the outflow from the storage area;
- a spillway – to pass floods that are more extreme than those that the reservoir is designed to attenuate.

Figure 10.1 shows the basic components of an online flood storage area. The flow control structure can be a fixed throttle (such as an orifice, pipe or flume) sized to have little effect on normal flows, but requiring a significant rise in upstream water level to pass larger flows. Sometimes, the control structure incorporates gates, which are normally left open, but are operated during floods to ensure that downstream flows do not overtop the downstream flood defences.

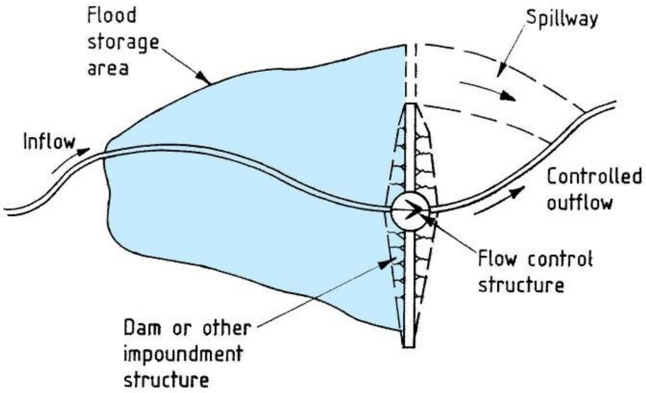


Figure 10.1 Online flood storage area

As noted above, an online flood storage reservoir must also be designed to deal safely with more extreme floods than it is designed to attenuate; these could otherwise lead to the water level upstream of the impounding structure rising above safe levels or unacceptable damage to the impounding structure or surrounding land. This normally involves the provision of an overflow weir or spillway to convey the extreme floods. Sometimes the entire impounding embankment – or a major part of it – provides the overflow route for floods, having been designed to withstand the flow velocities involved. In other cases, the flow control structure incorporates the necessary arrangements for passing flood flows, either through gates or over fixed weirs and other structures.

10.2.2 Offline flood storage

Offline flood storage works generally consist of:

- an intake structure to divert water to the storage area when the river flow or level exceeds a pre-determined value;
- a storage area that comprises a reservoir separated from the river, formed either by low ground levels (natural or excavated) or by retaining structures (embankments, walls, or a combination of the two);
- an outlet structure that returns water from the storage area to the river after the flood peak has passed;
- a spillway to pass floods that are more extreme than those that the reservoir is designed to attenuate.

As illustrated in Figure 10.2, the intake structure (which is of course an ‘offtake’ from the perspective of the river) often includes two components that may be located separately:

- a device designed to control flows passed downriver;

- an inflow structure to the storage area.

The device controlling downstream flow can take most of the forms used for the control of online flood storage works. Rather than building a new control structure, a ‘natural’ control may be used on the river in some cases, or a pre-existing control such as an existing weir in others. In these cases, the offline storage works are designed to make use of the existing stage/discharge characteristics of the river.

Weirs (Rickard *et al*, 2003) are often favoured for the inflow structure, sometimes in the form of a sideweir (May *et al*, 2003) along the riverbank. They have the advantage of beginning to operate whenever river levels rise above a given value, but need to be long to limit the rise in river level needed to pass greater flows into the storage area. For this reason, a gated arrangement is often used.

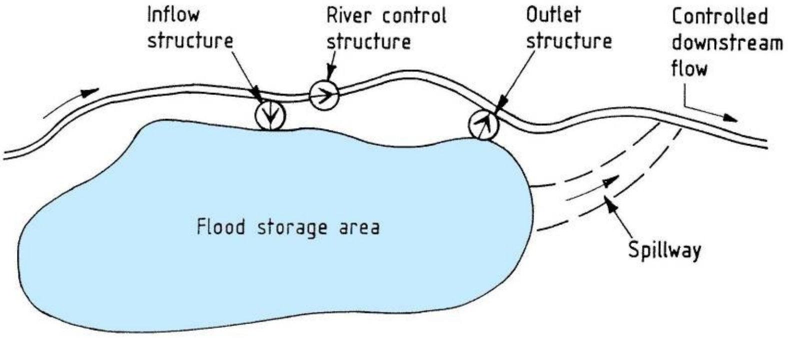


Figure 10.2 Offline flood storage area

The offline flood storage area generally lies within the floodplain, but isolated by purpose-built walls or embankments (see Chapter 9). The volume available for storage in the reservoir depends on the water depth that can be obtained, which is controlled by existing ground levels, and the peak flood level that can be accommodated. This depth is often limited, making it necessary for the reservoir to cover a large area. Choosing a site where the ground is low – either naturally or as a result of excavations (for example, for gravel pits) – increases the depth available, but may mean that pumps are needed to empty the reservoir after the flood has passed.

The outlet may be by gravity (generally using gates), pumped or by a combination of the two (with gravity flow initially, then pumping to drain the lowest sections). The outlet capacity required depends on the volume stored and the time allowed for the system to be fully drained. Whenever the reservoir contains water – and so has less capacity to accommodate another flood – the standard of protection provided will be temporarily compromised. If the outfall is to a tidal river, it may only be possible to complete the emptying the reservoir at low tide, perhaps via a flapgate.

As for online flood storage works, arrangements for the safe passage of extreme floods are again needed to protect the reservoir and its associated structures. These may form a major part of the facility, particularly if the inlet to the storage area is uncontrolled.

10.2.3 Washland development

On some of the larger rivers in the UK, flood alleviation schemes have been developed which build on the natural behaviour of floodplains in alleviating the magnitude of floods that are passed downriver. They do this in a manner that goes beyond the simple concept of a single online or offline flood storage reservoir.

Such washland development schemes normally include most of the following features:

- raised banks that separate the river from most of the floodplain;
- subdivision of the floodplain into ‘cells’ separated from each other by dividing embankments;

- weirs (which normally form parts of the riverbank) that admit flows into the washlands at a defined river stage, often when the river has virtually reached its maximum in-bank capacity;
- high-level weirs that allow some flow between washland cells as they fill;
- gates (sometimes flapped) to allow flows back from the washland to the river when the flood recedes.

Washland development schemes typically include no direct means of controlling river flows. Instead they rely on passing sufficient flows into the washland when the river level reaches a particular threshold.

An important feature of most such schemes is the presence of the banks between the washland cells. This maximises the retention of water in the floodplain, thereby reducing the degree to which the floodplain provides a supplementary flood conveyance route parallel to the river.

On many rivers, the natural processes of sediment deposition during floods have often resulted in that part of the floodplain adjacent to the river being a little higher than the swathe of floodplain lying further from the river. In addition, the farmers working the land have often traditionally raised the riverbanks to protect the farmland behind from such frequent inundation. Further raising and strengthening of these banks is usually part of a washland development scheme.

Examples of washland development include the ‘ings’ on the Yorkshire Ouse and its tributaries and many of the Fen river system washlands.

10.3 Planning for flood storage

This section covers the key issues to be considered early in the design process. More detailed coverage of most of the topics, including a 20-step design procedure illustrated by a flowchart, is given in Chapter 2 of *Design of flood storage reservoirs* (Hall *et al*, 1993). Box 10.3 highlights some of the factors that make a good flood storage site.

Box 10.3 What makes a good flood storage site?

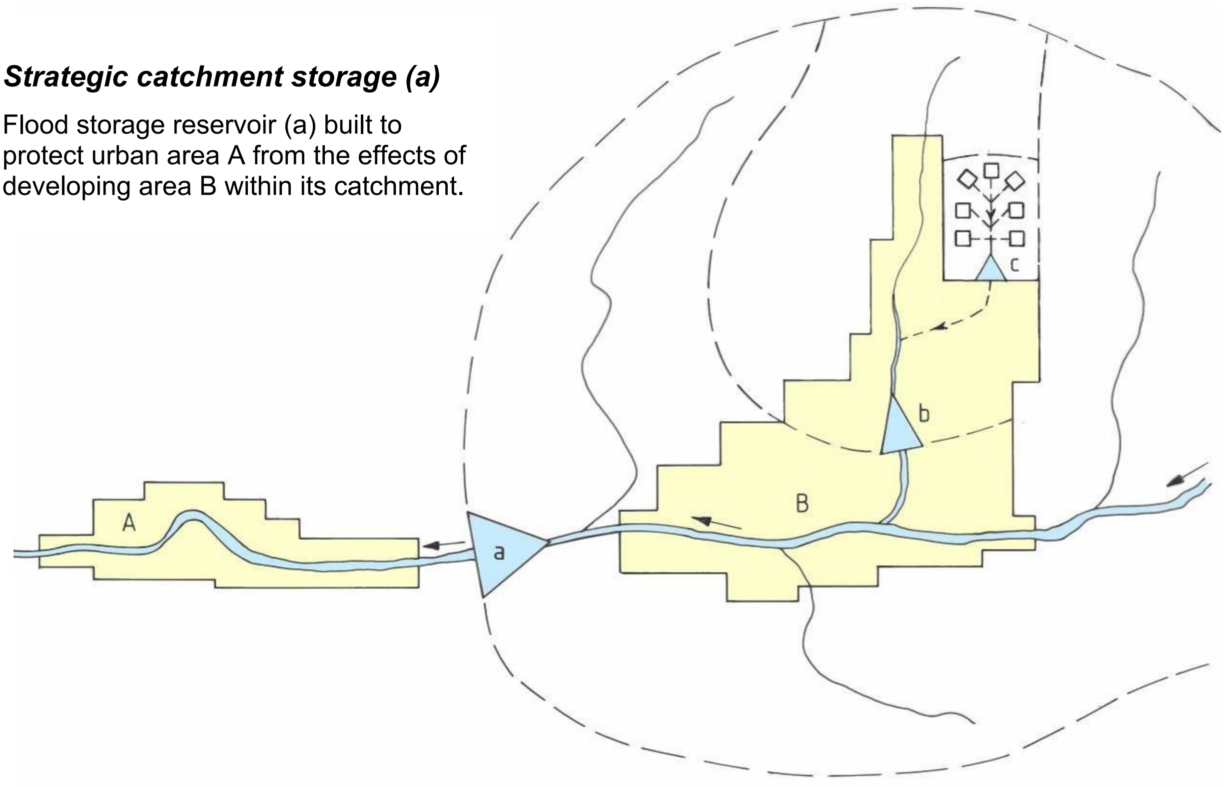
- A suitable location within the catchment for the purpose intended – controlling flows from a large enough proportion of the catchment upstream of the location where protection is needed.
- Sufficient storage volume.
- A suitable site for the impoundment structure – for example taking advantage of a narrower part of the valley to allow the dam to be shorter.
- A wide floodplain that allows a low dam height to be deployed.
- A relatively impermeable foundation.
- Suitable foundation conditions for supporting the dam and control structures.
- Suitable access for construction, operation and maintenance.
- The availability of suitable construction materials on or near the site.
- Minimum adverse impacts on landowners, land-use and local residents.
- Minimum adverse impacts on the environment.
- Opportunities for environmental enhancement.

10.3.1 Scale and location of storage

Flood storage not only comes in various types, but also in a wide range of sizes. These are primarily related to its strategic purpose or its place in the catchment. This is illustrated in Figure 10.3, which focuses on successively smaller areas.

As noted in Section 10.1.1, the location where flood storage is provided can be crucial. Flood storage works have the potential – in some locations and for some types of storm event – to aggravate downstream flooding, so their effects need to be investigated rigorously at the design stage by appropriate flood modelling studies.

Figure 10.3 Examples of storage scale, location and purpose



Strategic catchment storage (a)

Flood storage reservoir (a) built to protect urban area A from the effects of developing area B within its catchment.

Subcatchment storage (b)

Flood storage pond (b) built to alleviate the effects of urbanisation within a subcatchment and provide protection in the lower reaches of the watercourse in urban area B.

Local on-site storage (c)

A flood storage pond or tank (perhaps of the SUDS type) installed within or close to the source of increased runoff from a new development at the edge of urban area B.

10.3.2 Design objectives

Before design can begin, it is necessary to understand what it is intended to achieve through the provision of flood storage – either on its own or as part of a portfolio of measures – and the design return period (standard of service) that it is expected to provide. The design objectives may depend on the strategic purpose of the flood storage (see above), but would typically include at least one of the following:

- controlling the flow hydrograph passed downriver, for example to mimic the natural or pre-development runoff from its catchment up to the design return period;
- controlling the maximum flow passed downstream to a pre-determined fixed amount related to the estimated ability of the downstream watercourse to accommodate it;
- controlling the flow released in response to flood levels being experienced a short distance downstream;

- controlling the downstream flows as part of a strategy (for example, in conjunction with other flood storage reservoirs) to control the flows and water levels at some remote location(s) downstream.

In the last of these cases, there is increasing scope for operating a series of flood storage reservoirs in a manner that is guided by a real-time flood forecasting model.

10.3.3 Storage capacity

An early estimate of the storage capacity needed – together with an estimate of the storage capacity available at the potential site – is the key to discovering whether a scheme based solely on flood storage is likely to be suitable, or whether it needs to be combined with other measures. Figures 10.4 and 10.5 illustrate this for a simple online flood storage pond, where the primary purpose is to limit the flow passed downstream to a particular threshold.

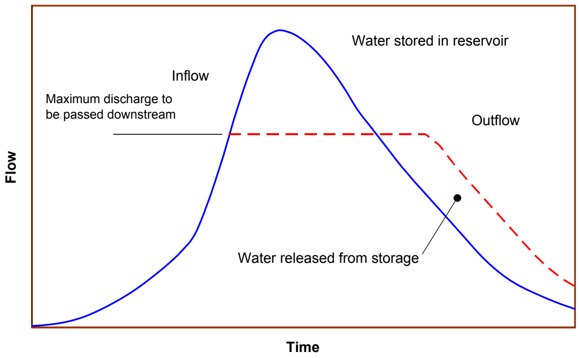


Figure 10.4 Ideal utilisation of storage

In this case, the pond is designed to pass downstream the full flood up to threshold, storing all the water in excess of the threshold. In theory, this ideal performance can be achieved through the use of gates but, in practice, it is impossible to achieve this ideal utilisation of flood storage.

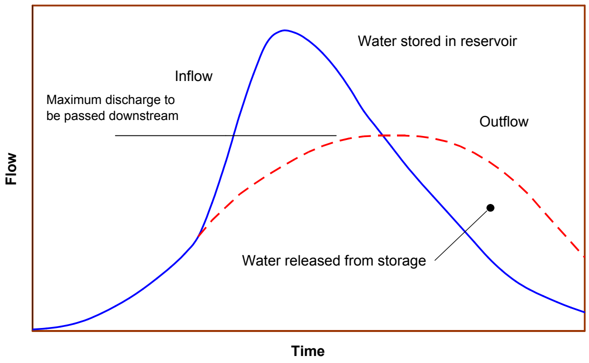


Figure 10.5 Practical utilisation of storage

In a practical scheme, the control device starts to affect the flow passed downstream well before the threshold is reached. A greater volume of flood storage is therefore required.

Examination of the available mapping for the proposed site should give an early indication of the average inundation depth needed over the chosen area to provide the flood storage needed, and therefore whether the flood storage scheme is potentially feasible.

In practice, the site may not yet be selected and it may be necessary to consider alternative sites, or the provision of a number of flood storage areas that are designed to act in conjunction.

10.3.4 Construction issues

Early consideration needs to be given to the practical issues associated with the construction of flood storage works. These include:

- the need for a site investigation to inform the design of the works and establish the suitability of materials for reuse;
- the availability of suitable construction materials on site;

- the potential for balancing cut and fill and thus minimising the earthmoving (especially by public highway) associated with the scheme;
- sources of imported materials and the disposal of waste materials;
- whether the site involves contaminated land that might require remediation or special precautions and design features;
- the presence of services – especially overhead power lines and buried pipelines – or other constraints, and the implications for the types of construction plant that can be safely deployed;
- access to the site for site investigation and surveys, construction work, and subsequent maintenance and operation;
- the impacts of the scheme – including construction work – on the environment, landowners, local residents and others, which would normally be the subject of an environmental impact assessment (EIA).

10.3.5 Reservoirs Act 1975

The Reservoirs Act 1975 applies to all reservoirs ‘designed to hold, or capable of holding’ more than 25 000 m^3 of water ‘above the natural level of any part of the land adjoining the reservoir’. The reference in Section 16 of the Act to protecting ‘persons or property against an escape of water’ makes it clear that its primary purpose is public safety. The Act imposes a number of duties concerned with the design, construction and ongoing ownership of such reservoirs. Box 10.4 gives further information. The Institution of Civil Engineers (ICE) has produced a useful guide to the Reservoirs Act (ICE, 2000).

Box 10.4 Statutory control over reservoir and dam safety

Regulations are adopted in many countries to ensure that reservoirs and dams are inspected regularly and constructed or altered only under the charge of properly qualified engineers.

Reservoir safety in the UK is governed primarily by the Reservoirs Act 1975, which was brought into effect in 1986, replacing the earlier Reservoirs (Safety Provisions) Act 1930.

The 1975 Act applies to ‘large raised reservoirs’ which are defined as having a capacity of 25 000 m^3 or more above the level of any part of the adjacent land. Specifically excluded from the 1975 Act are:

- lagoons covered by the Mines and Quarries (Tips) Act 1969 (together with the corresponding 1971 Regulations and the Quarries Regulations 1999);
- navigation canals.

The Act includes roles for the Secretary of State, for the ‘undertaker’ (the owner and/or operator of the reservoir), for the ‘enforcement authority’ and for ‘qualified civil engineers’. A series of ‘panels’ of such engineers have been set up to perform the particular functions under the Act, namely:

- construction engineer – responsible for supervising the design and construction or the enlargement of a reservoir;
- inspecting engineer – carries out periodic inspections, normally at intervals of ten years, supervises and certifies remedial works affecting reservoir safety;
- supervising engineer – has a continuous appointment to ‘supervise’ the reservoir, watching out for problems and keeping the undertaker informed.

It is the undertaker’s duty to ensure that the relevant engineering appointments are in place and the requisite duties undertaken during the design, construction, operation and decommissioning of a reservoir. There are significant cost implications involved in compliance with the Reservoirs Act 1975.

Three panels have been set up to cover the duties of construction engineer and inspecting engineer. These panels are defined according to the type of reservoir on which the engineer is qualified to exercise their duties and are as follows:

- all reservoirs panel – all reservoirs covered by the Act;

- non-impounding reservoirs panel – all reservoirs, except impounding reservoirs;
- service reservoirs panel – service reservoirs only.

All engineers on these panels are also entitled to act as supervising engineer for all reservoirs covered by the Act. In addition, the supervising engineers panel covers those qualified to act only as supervising engineers. Panel appointments are made for a period of five years and are renewable.

The 1975 Act contains provisions for the registration of reservoirs and for the enforcement of the Act, both of which functions were transferred to the Environment Agency in October 2004.

The enforcement of the Act is facilitated by requirements for the issue of certificates by the qualified civil engineers under specific circumstances, in particular in association with:

- the construction or enlargement of a reservoir;
- the issue of inspection reports;
- the implementation of 'measures taken in the interests of safety'.

Appointments of qualified civil engineers by the undertakers also have to be notified to the enforcement authority.

The Water Act 2003 contained a number of changes to the Reservoirs Act 1975, including transferring the role of the enforcement authority to the Environment Agency and creating a new power to direct an undertaker to prepare a 'flood plan' (see Box 10.5) for a large raised reservoir.

The ICE's *A guide to the Reservoirs Act 1975* (issued in 2000) contains the full text of the Act, together with the relevant regulations up to that date, a commentary on the application of the Act and flowcharts to illustrate the duties of the various parties. Anyone engaged on work involving reservoirs in the UK is advised to refer to this guide and to guidance on the Environment Agency website (http://www.environment-agency.gov.uk/business/sectors/32427.aspx).

Particular points worth noting with regard to the Reservoirs Act 1975 are:

- responsibility for the construction or enlargement of a reservoir remains with the construction engineer for between three and five years from first filling;
- a supervising engineer is not required until the end of the construction engineer's involvement, upon issue of their final certificate;
- the first inspection under Section 10 of the Reservoirs Act 1975 is required within two years of the issue of the final certificate;
- the inspecting engineer must be 'independent' of the construction engineer and undertaker.

The provisions of this Act and the earlier Act of 1930 have worked well, in that they have assisted in preventing any dam failures involving a loss of life in the UK for three-quarters of a century. A particular feature of the 1975 Act is that it imposes a personal responsibility on the engineer who issues a certificate. Such responsibility can only be effectively exercised by an engineer having adequate experience of dam design and construction, and who has access to the specialist services frequently required in making a proper inspection.

Consideration is currently being given to further legislative changes that would lead to a risk-based approach to the statutory registration and control of reservoirs and encompass smaller reservoirs (down to 10 000 m^3). For further information see: http://www.defra.gov.uk/environment/water/flooding/flow/index.htm.

Box 10.5 Reservoir flood plans

The Water Act 2003 contained a number of changes to the Reservoirs Act 1975, including creating a new power allowing the enforcement authority to direct an undertaker to prepare a 'flood plan' for a large raised reservoir. The flood plan is intended to improve emergency preparedness and covers:

- any escape of water from the reservoir in terms of the predicted extent and depths of inundation;
- the risks to life and property;
- arrangements for issuing warnings.

The proposed arrangements for reservoir flood plans are currently being reviewed by the Environment Agency, Defra and their consultants. The detailed requirements have not yet been fully formulated, but it is expected that a five-year programme of directions to prepare flood plans for selected reservoirs will commence in 2009–2010. In the meantime, it would be prudent to assume that a flood plan will be required for any flood reservoir that is currently being planned. For current guidance, see the Environment Agency website (http://www.environment-agency.gov.uk/business/sectors/32427.aspx).

There has been concern in recent years that many small British reservoirs that do not come within the scope of the Reservoirs Act 1975 may nevertheless represent a significant hazard to some communities by virtue of issues such as their particular location, steepness of the valley, height of the structures and state of repair. The principles embodied in the Reservoirs Act 1975, and the guidance associated with it (ICE, 2000), are also applicable to reservoirs that do not come within its scope. Regardless of whether their reservoir comes under the Reservoirs Act 1975, owners and undertakers also need to be aware that anyone who stores water is responsible under common law (based on the historic case of *Rylands v. Fletcher*) for any damage that may be caused to any other party arising from the release of that water.

Nothing in this guide should be taken as overriding or diminishing the responsibilities resulting from the Reservoirs Act 1975; nor the responsibilities resulting from the design, construction or ownership of bodies of water which, whether or not they come within the scope of the Act, could represent a significant hazard to people and property situated downstream.

10.3.6 Land acquisition and compensation

Land acquisition can take many years – either in protracted negotiation or need for compulsory purchase. If there is a risk that compulsory purchase will indeed be required, the process should be started as soon as possible. Specialists in land negotiations need to be brought into the team at an early stage to advise on the implications for the feasibility of the scheme and its implementation programme.

In some cases, the entire area of the flood storage works may be acquired. In other cases, it may be possible for the impoundment area to serve other purposes (such as agriculture or playing fields), in which case the promoter may not need to acquire it but would instead acquire a ‘right to flood’. In this case, the owner would receive compensation, either as a commuted sum based on the anticipated detriment to its future use, or upon each occasion that the land floods more deeply than it would have done naturally. The loss of development potential could be a significant element of compensation payable.

10.3.7 Planning consent

Most flood storage works require planning permission. If flood storage is being promoted as an integral part of a development, which requires the flood storage works in order to proceed, then the application may be incorporated within that for the development proposal. If the implementation of flood storage works is imposed as a condition of a development proceeding, a separate application may be made.

For a scheme designed to alleviate an existing flooding problem, the scheme would normally be the subject of a planning application in its own right. Even if planning permission is not strictly required (for example, if the scheme comes within the scope of an organisation’s permitted development rights), it is often considered good policy to seek permission in order to give legitimacy to the scheme.

Appropriate planning advice needs to be obtained at an early stage to ensure major pitfalls are avoided.

10.3.8 Environmental impacts and opportunities

It is often assumed that the provision of a flood storage reservoir will automatically result in environmental benefits. This may be the case, but there are often also disbenefits. One of these is the loss of productive agricultural land. With an increasing population and the demand for crops for both food and energy, this issue needs careful consideration to get the balance right.

In common with most works involving construction, flood storage works are likely to have a number of environmental impacts. These have to be addressed through an assessment that may be required as part of the planning process, or that may be undertaken under the Environment Agency's role as the 'competent authority'. The impacts are likely to be associated with construction itself, including access to and from the site, as well as the residual impacts of the works.

This assessment takes account of impacts on the different receptors (that is on people, property, infrastructure and land affected) and attributes a level of significance to each impact. The assessment includes all aspects of the environment from the natural environment, species and habitats through to the community and its health and wellbeing. Every project is screened to determine whether it requires an environmental impact assessment.

Some of the permanent impacts are usually beneficial to various flora and fauna, while some of the adverse impacts can be mitigated through the inclusion of appropriate design features and operational practices. Where opportunities to enhance the environment exist, every effort should be taken to adopt them. But it should not be assumed that all flood storage basins can offer environmental benefits, as their impact could be negative.

Chapter 6 of *Design of flood storage reservoirs* (Hall *et al,* 1993) describes the potential for flood storage works to offer environmental benefits, focussing on the impacts of detention on water quality.

10.3.9 Landscaping

Appropriate integration of landscape design (see Chapter 5) during the design development for flood storage works is often an essential element in reducing their impact and making the scheme acceptable. It is important, however, to give proper regard the following issues, some of which are related to reservoir safety.

- Floodbanks and floodwalls need to be inspected from time to time and should not be hidden from view. The planting design should ensure that adequate inspections can be made.
- Flood storage works should be designed and maintained so that colonisation by burrowing animals is discouraged.
- The root systems of trees and bushes can be detrimental to various components of flood storage works, but especially to embankments.
- Embankments should be covered with grass (or some other form of sympathetic erosion protection) and suitably maintained to aid inspection and prevent colonisation.
- In planning landscaping and planting schemes within the impoundment area, due account should be taken of the risks that vegetation debris can pose to the proper hydraulic operation of the flood storage works. (Similarly, the design of the flow conveyance structures needs to take into account the potential impacts associated with the agreed landscaping plans, for example in terms of the anticipated debris load on trash screens.)

10.3.10 Multiple uses

Flood storage works can often provide opportunities for multiple uses. Section 7.4 of *Design of flood storage reservoirs* (Hall *et al,* 1993) covers this at some length and gives the following examples:

- amenity – such as public open space and parkland;

- car parking – though this is generally not to be recommended because of the risks associated with cars remaining when the flood arrives and floating away, adding to the downstream risks;
- recreation – fishing, sports fields and the like;
- agriculture – livestock and crops (subject to the availability of a livestock escape route, avoiding livestock damage to the works and crop tolerance to inundation);
- water quality – sediment control and removal of biological oxygen demand (BOD);
- nature conservation and ecology – wetland habitat and nature reserves.

These opportunities need to be considered carefully as there can be implications for public safety and the proper functioning of the works in their flood storage role.

In some situations, an existing reservoir may be modified – or its operational practices modified – so that it provides a flood storage and attenuation function.

10.3.11 Safety

The particular issues associated with the safety of flood storage works are listed in Table 10.2. Some of these are common to other fluvial works.

Table 10.2 Safety issues for flood storage works

Feature	Nature of hazard	Scope for mitigation
Culverts and operating equipment	Public entry to culverts, risk of drowning or injury by operating mechanical equipment.	Exclude public from hazardous areas.
Trashscreens	Tendency to block during floods, requiring clearance in hazardous conditions, sometimes at night.	Provide safe access to remove collected debris (including lighting, safety harness facilities). Dispense with trash screens where possible. Otherwise use sound and conservative trash screen design.
Gates (manual or remote operation)	Need to attend during floods, either to operate or deal with failure of gates to operate correctly.	Automatic gate operation. Adopt non-mechanical control devices where practicable. Otherwise provide safe access and appropriate operating rules.
	Gates fail to operate correctly, for example due to power failure.	Provide back-up power and operating systems.
	Danger to public during operation.	Provide warning signs and klaxons, information boards. Or exclude public access.
Embankment maintenance	Grass cutting on slopes and maintaining access to adjoining structures	Adopt mild slopes, preferably no steeper than 1 in 4, with gentle curves.
Public footpaths etc	Normally negotiable route becomes impassable during operation of flood storage scheme.	Provide clear signage (with lighting where appropriate), including alternative routes. Display public information about the scheme.

Water body	Falling in and drowning or suffering hypothermia.	Have shallow margins with reeds and use planting to discourage access to the water's edge.
Large drops	Falling into deep or swiftly flowing water, especially if a drop is obscured below rising water.	Fit handrails and warning signs. Provide escape ladders. Provide lighting; lifebelts and rescue lines.
Steep slopes adjoining impoundment	Slipping down waterlogged slope and unable to gain a foot-hold to escape.	Use gentler slopes (no steeper than 1:3). Restrict water depth at toe of slope to no more than 0.5m where practicable.
General	Children using the works for various recreational purposes and being subjected to any of these hazards.	Make sure the mitigation measures referred to above are suitable for children and not just for adults.

10.4 Hydrological and hydraulic design

10.4.1 Design procedure

The detailed hydrological and hydraulic design procedure set out in Chapter 2 of *Design of flood storage reservoirs* (Hall *et al,* 1993) has much to commend it in terms of thoroughness, even if parts of it are out-of-date with regard to the analysis methods recommended. The key parts (assuming that the site has already been selected) are summarised in Table 10.3.

Table 10.3 Main steps of design procedure

Element	Procedure
Design standard and objectives	Define the design standard (return period, etc) and the objectives of the scheme (for example, to limit the flow to a threshold or mimic the natural flow regime).
Preliminary analysis (assuming the primary purpose is to provide 'compensation' for catchment development)	Assess the hydrological significance of urbanisation, determining pre-development and post-development flood frequency relationships. Assess downstream impacts and whether flood storage is likely to be the appropriate measure (compared, for example, with downstream channel enlargement works).
Flood hydrographs and storage requirements	Survey the site and plan the approximate layout of the storage area. Estimate the stage/storage relationship for the site. Derive the pre-development and post-development flood hydrographs for a range of return periods. By using trial routings (with estimated stage/storage and tentative stage/discharge relationships), estimate the volume of storage required to meet the downstream flow criteria. Confirm that the scheme is potentially feasible within the space and depth available at the site.

Design of flood storage works	Refine the plans for the flood storage area and confirm the stage/storage relationship. Refine the proposed control structure designs and their associated stage/discharge relationships. Carry out detailed flood routings (see Section 10.4.4) and make adjustments to arrive at: ▪ the requisite downstream flood levels and/or flows; ▪ the peak storage level in the design flood; ▪ the crest level and flow capacity for the emergency spillway; ▪ the confirmed stage/discharge relationships for all hydraulic structures.
Checking the design	Route a range of other floods (different profiles and severities) through the flood storage works to confirm that the behaviour is suitable. Undertake flood modelling including the wider catchment to confirm that conditions elsewhere are acceptable. Make any adjustments needed.

10.4.2 Design criteria

The design criteria (including the design standard) should emerge from the objectives (see Section 10.3.2). These typically involve controlling the flow passed downriver, either in a predetermined manner or proactively in response to conditions being monitored at some point downstream. A checklist of wider design criteria – including environmental, operational and legal – is given by Hall *et al* (1993, Table 2.1) but needs to treated with caution

In cases where the flood storage works are designed to limit the downstream flow to a particular threshold value (above which flooding would be expected), the most important issue is in establishing that threshold. This is commonly undertaken using a hydraulic model, although the designer needs to be aware of the limitations of such models (for example, in terms of the accuracy of the various roughness and headloss parameters used, the realism with which the topography and the structures are represented, and the reliability of the simulation methods used in the hydraulic model) (see Chapter 7).

10.4.3 Hydrological design standard

Flood storage works are normally designed to provide full mitigation up to a particular annual exceedance probability (AEP) or return period. This is termed the ‘design flood’. In this event, the impoundment would either fill completely, or it would fill up to within a defined freeboard of the bank tops or the emergency spillway crest.

Ideally the choice of design standard for a scheme should be based on an economic justification, so that the benefits of the scheme in terms of damages avoided are optimised in relation to the whole-life costs of its implementation. Even for schemes designed on the basis of ‘no detriment’ (for example, avoiding any aggravation of downstream flood risks), it is normal to limit that requirement to a range of return periods up to a ceiling rather than requiring the scheme to protect fully against all events, however extreme.

A flood storage scheme must be resilient to flows in excess of the design flood, and under no circumstances should an extreme flood result in more severe damages to downstream interests than would have been the case had the flood storage scheme not been implemented. In most cases, this means that the storage dam must not be significantly damaged if overtopped. In addition, the scheme would normally continue to provide some flood mitigation in more severe events.

Figures 10.6 to 10.8 illustrate how a given online scheme – designed to just contain a flood of a given return period – may perform when faced with floods of increasing severity.

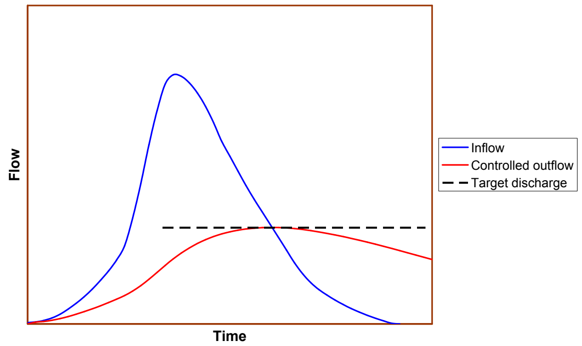


Figure 10.6 Design flood hydrograph

The online flood storage pond contains the flood and mitigates the peak to the target flow (in this example, about 40% of the peak inflow).

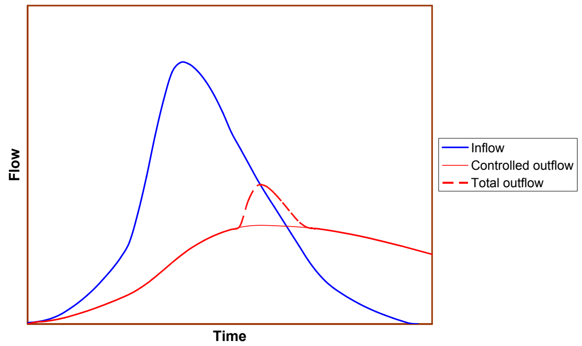


Figure 10.7 Flood volume about 10% greater than design flood

The flood storage pond does not quite contain the flood, so overflows, but still provides significant mitigation to the peak flow passed downstream.

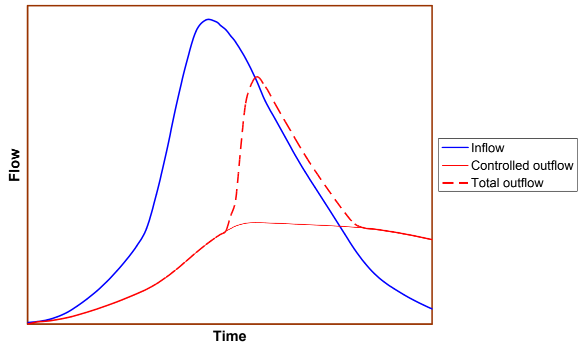


Figure 10.8 Flood volume about 50% greater than design flood

The flood storage pond fills at about the time of the peak inflow and attenuates the peak flow passed downstream by a limited amount (only about 20% in this example).

The derivation of the appropriate inflow hydrographs to use in the design of flood storage works is covered in Chapter 2. Following the provision of flood storage, the critical rainstorm duration is normally longer than it would be without the flood storage. This needs to be taken into account when such schemes are designed.

Current climate change guidance for the UK is outlined in Section 2.8.1. For the design of flood storage reservoirs, primary consideration should be given to guidance on climate change effects that is specifically related to flood volumes rather than to peak flood flows.

10.4.4 Flood routing

By ‘flood routing’, we mean the step-by-step calculations undertaken to analyse how a flood storage pond or reservoir responds to an incoming flood. The flood inflow causes the water level to rise and this generally causes increasing rates of flow through the control device. After the peak of the incoming flood has passed, the analyses show how the storage area stops filling and the water is released downriver as the level falls.

In the past, graphical approaches were sometimes adopted to assist in flood routing calculations, but now computer programs or spreadsheets can be used much more conveniently. In most practical circumstances, the reservoir water surface can be treated as horizontal at each timestep and the flood routing approach is therefore described as ‘level pond’ (see Box 10.6).

Box 10.6 Level-pond flood routing

For a simple online flood storage pond, without gates, the principal data required to carry out a reservoir flood routing are:

- the inflow hydrograph, at a suitable timestep (preferably no longer than about a tenth of the time to the peak of the incoming flood);
- the control structure and emergency spillway rating curves (that is, the relationship between flow and reservoir level);
- the relationship between the water level and surface area in the reservoir.

In cases where gates are involved – and for offline flood storage ponds – the simulation becomes more complex, for example including the operating rules for the gates. In cases where there is a permanent impoundment, the flood routing starts with the pond at its normal water level.

Flood routing is undertaken by a step-by-step procedure, over each timestep equating the difference between the inflow and outflow to the change in the volume of water contained in the reservoir basin. The calculations continue until the outflow has reduced to close to the antecedent flow.

For large online flood storage reservoirs that extend over several kilometres of a valley, a more sophisticated approach than level-pond flood routing may be appropriate, to take account of the backwater that extends upstream from the downstream end of the impoundment. This also has the potential advantage of retaining an appropriate floodwave speed through the flood storage area.

There are two main approaches for undertaking flood routings of this sort:

- using one-dimensional (1D) river modelling software (such as HEC-RAS or ISIS; see Chapter 7), with the river sections extending across the floodplain to encompass the full range of storage levels;
- using two-dimensional (2D) modelling software (such as Tuflow; see Chapter 7) or a composite 1D–2D model.

In both approaches, it is vital for the hydraulic characteristics of the flow control device(s) and spillway(s) to be properly represented. This may sometimes require the use of non-standard components in the model. The flood routing model would normally be incorporated as an integral part of a wider model of the river system, extending both upstream and downstream of the flood storage works. Such modelling is described further in Chapter 7.

If a 1D model is used, care is needed as to how the geometry of the storage area is represented. If the river is sinuous, for example, there is a risk that the integration of the total watercourse length and the respective cross sections contains more storage than actually exists. In such cases, the volumes implied in the 1D model at a range of fixed water levels should be compared with the true capacity relationship (calculated by integrating the surface area with respect to water level). If the volumes implicit in the 1D model are slightly too great, minor adjustments to the valley width in the cross sections or to the river chainages could probably be used to obtain an adequate match without prejudicing the methodology. If major adjustments are required, this is an indication that the one-dimensional approach is unsuitable.

Flood routings normally need to be undertaken for a variety of floods:

- small floods – that do not mobilise all the available storage;

- the 'design flood' – that is, the event in which the impoundment would either completely fill, or would fill up to within a defined freeboard of the bank tops or the emergency spillway crest;
- more severe floods – to show how the efficacy of the flood storage works progressively diminishes;
- extreme floods – appropriate for the design of the emergency spillway.

In the last of these, there is normally little or no attenuation of the flood peak because the majority of the available storage fills well before the peak of the incoming flood arrives.

10.4.5 Flood storage capacity

It is vital to determine the storage capacity provided by flood storage works (existing or proposed) with a reasonable degree of precision.

For the preliminary planning of a large reservoir, the contours on the 1:25 000 Ordnance Survey maps are a good starting point.

For smaller reservoirs and for the detailed planning of all flood storage works, it is normal to obtain a detailed topographic survey of the site. Various alternative mapping products are available that may suit this purpose, including LiDAR. The user needs to ensure that the mapping is:

- of an appropriate accuracy;
- correctly referenced to the same datum as is being used for the scheme design or analysis.

In order to undertake the routing of the flood through the storage provided, it is necessary to know the relationship between the water level in the reservoir and either the water surface area or the volume stored. The surface area represents the rate of change of volume with level; alternatively the volume is derived from the integration of the surface area with respect to the stage. Flood storage capacity calculations are summarised in Box 10.7.

Box 10.7 Flood storage capacity calculations

The basic approach to calculating the storage/area/capacity relationship – albeit largely superseded by technological advances – is still worth stating clearly and is as follows.

- For successive water levels, starting with the pond just on the point of impounding, determine the water surface area (for example, using a planimeter around each contour).
- Continue tabulating the water level against the surface area until the pond overflow level is reached. Continue until the water level is high enough to pass the most extreme flood being considered in the designs.
- Plot a graph of level (on the y-axis) against surface area (on the x-axis).
- For each level increment, calculate the incremental pond volume and sum these starting from the bottom to obtain a table of water level against volume.

Modern mapping techniques normally result in the site for the flood storage area being incorporated into a digital terrain model (DTM), within which the finished profiles (including embankments and excavation within the pond) can also be modelled. The DTM can usually provide the stage/storage relationship by either of the following alternative approaches:

- automatically contouring the surfaces, following which the above approach can be applied;
- automatically dividing the ground surface into a series of polygons of known area and average elevation, and calculating the volume of volume of water by adding together the volumes sitting above each polygon.

Whichever approach is employed, it is a sensible precaution to convert the relationship back to a stage/area curve that can be readily checked against the design team's knowledge of the site.

10.4.6 Control devices

Chapter 7 of *Design of flood storage reservoirs* (Hall *et al*, 1993) contains a comprehensive account of the types of control structures that may be deployed for the outlet structures of online and offline flood storage reservoirs. Figure 7.10 of that manual summarises the hydraulic properties, but the following errors should be noted:

- the discharge equation for a vee-notch weir (item 5) is incorrect;
- item 13 is an air-regulated siphon (not a gate); the discharge equation, which is indistinct, should be confirmed from other sources.

This remains a key source of preliminary information for flood storage ponds and reservoirs, whether or not they are covered by the Reservoirs Act 1975. The exception is for smaller ponds and basins that come within the scope of *The SUDS manual* (Woods-Ballard *et al*, 2007). Many of the devices used in control structures for flood storage works are covered in Chapter 11 of the present guide.

An important step is to identify:

- the duties that the structure must perform;
- the hydraulic characteristics of the components that need to be included.

Table 10.4 lists the normal range of choices for online and offline flood storage ponds. A number of important issues affecting the choice and design of appropriate control structures are highlighted below.

Table 10.4 Control devices

Type of flood storage pond and component	Fixed devices	Mechanical devices (powered, normally electrically, or float-operated)
Online pond		
Outflow control device:	Orifice Throttle pipe or culvert Flume or notch Weir Passive device*	Vertical lift gate Radial gate Tilting gate or weir
Offline pond		
Downstream flow controlled by:	Existing river rating or control structure Orifice Throttle pipe or culvert Flume or notch Weir Passive device*	Vertical lift gate Radial gate Tilting gate or weir
Flow into flood storage area controlled by:	Sideweir Siphon	Vertical lift gate Tilting gate or weir
Flood storage area evacuated via:	Throttle pipe Flapped outfall (including mitre gates)	Vertical lift gate Pumps

* Passive devices include Hydro-Brake®, Mosbaek and baffled orifice devices.

Gates and other mechanical devices

In theory, gates and other mechanical devices can offer 'ideal' performance for the control device. Such an ideal device would allow 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. Such behaviour can be achieved only by a fully automated gated system.

Undershot gates, such as vertical lift and radial gates, can be adversely affected by floating debris accumulating against the upstream face above the opening. 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.

By their nature, flood storage ponds need to function automatically; this normally precludes manual gate operation, even for the smallest ponds. In practice, gates are normally used only in larger flood storage reservoirs, and are then of a size for which routine manual operation would be ruled out.

The following forms or operation and control may be adopted:

- float or displacer;
- hydraulic;
- 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 and 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 ponds.

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.

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. The Leigh flood barrier (Case study 10.1) is one such example.

Orifices, pipes and culverts

The control devices for most small flood storage reservoirs fall into this category (see Figure 10.9).

In the typical case of an impoundment created by an embankment dam, throttled flows are normally conveyed under or through the base of the embankment via a pipe or culvert. Sometimes the pipe or culvert itself is the throttle but, in other cases, a restricted orifice is placed across its entrance.

Sometimes the orifice is adjustable, so that the setting can be trimmed in the light of experience. In some cases the adjustable orifice actually consists of a gate, which is intended to be adjusted in the same circumstances rather than to be operated actively during a flood. Indeed, at most small flood storage reservoirs, there are no headworks associated with the entrance to the pipe or culvert, which is therefore inaccessible during a flood, precluding any active intervention.

Figure 10.9 Orifice and pipe

The control device at this small flood storage reservoir in Dorset consists of an adjustable orifice plate protected by the screen (in the foreground).

Note the lack of access during impoundment and also the standpipe (behind the left side of the structure) venting the top of the chamber downstream of the orifice.

The orifice discharges to a 1200mm pipe that passes under the dam to a US Bureau of Reclamation (USBR) impact-type basin.

The horizontal component of the screen gives additional flow area, but makes raking the main screen hazardous. This screen is to be the subject of safety improvements in 2009.

A range of hydraulic behaviour can apply to orifices, pipes and culverts. The design therefore needs to be tailored to achieve reliable predictable hydraulic behaviour that meets the design requirements of the scheme. In general, the following forms of hydraulic ‘control’ can apply:

- a restricted orifice at the entrance providing the control, which discharges into an oversized pipe or culvert that has minimal impact on the hydraulic behaviour;
- pipe or culvert inlet control (which is similar to orifice control in that the inlet acts as the hydraulic control, not the culvert), with the conduit downstream running part-full;
- the pipe or culvert running full, with the hydraulic resistance provided by the roughness along the conduit length and by the hydraulic headlosses at the entrance and exit.

Changes in flow mode can occur as the discharge increases and the headwater level rises. The flow mode may also change as the tailwater rises and submerges the outlet of the conduit, and this can result in undesirable instabilities and uncertainties in the hydraulic behaviour. Because the design of the control device needs to avoid uncertainty over the hydraulic behaviour, this sometimes requires the use of the following features:

- a vent pipe joined to the crown of the culvert immediately downstream of the entrance orifice;
- rounding of the pipe or culvert entrance, so that orifice-type inlet control does not apply under any conditions.

Further information on the hydraulic design and analysis of culverts is given in *Culvert design guide* (Ramsbottom *et al*, 1997).

Passive devices

A number of devices are available whose objective is to improve on the hydraulic characteristics of the simple orifice. With an orifice, the flow is approximately proportional to the square root of the operating head, which is defined as follows:

- for a freely discharging orifice – the height of the upstream water level (strictly the energy level) above the centre of the orifice or the top of the jet, depending on the circumstances;
- for a submerged orifice – the difference between the upstream and downstream water levels.

In most applications of orifice flow control to flood storage ponds, the result is a significant increase in outflow as the flood storage level rises. Although there are many cases where the behaviour of a standard orifice is acceptable (or even desirable), 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 10.10 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.

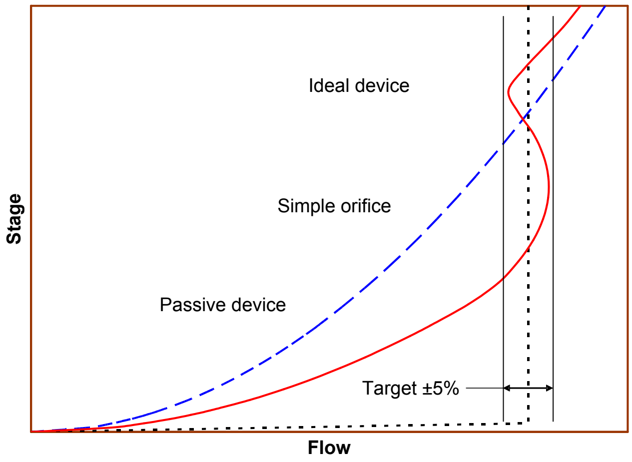


Figure 10.10 Comparison of hydraulic performance for various devices

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.

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.

Vortex devices rely on generating an air-filled vortex in the outlet tube. Various different configurations are available and the following advantages are claimed.

- The total flood storage requirement can be reduced by up to 30% due to the reduced utilisation of flood storage during the rising flood.
- 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.
- 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.

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. The largest such device installed to date (January 2009) is understood to have a maximum flow capacity of 12 m^3/s and is illustrated in Case study 10.2.

Figure 10.11 Hydro-Brake®

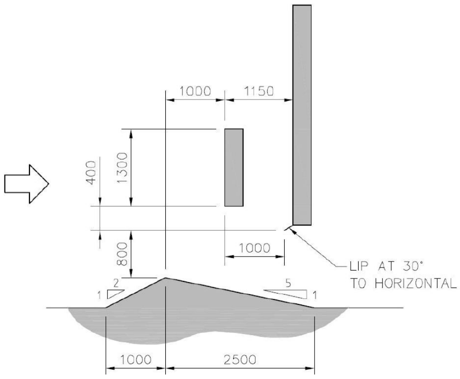
This Hydro-Brake is fitted at a small online flood storage reservoir in Warminster. In this case the dam is low, so the control device and spillway can be combined in a single open structure without the need for a conduit to pass beneath the dam. In an extreme flood, some of the floodwater

would pass over the dam crest.

An uninstalled Hydro-Brake
(photograph courtesy of
Hydro-International)

Baffled orifice devices (see Figure 10.12) 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, which can now be applied with confidence to meet a wide range of stage/discharge requirements (Ackers *et al*, 2004).

Figure 10.12 Baffled orifice control device



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.

The diagram on the left shows the design developed with the aid of model tests to pass an almost uniform flow of ~9 m^3/s per opening over a head range of ~2.5–4.5m above the crest of the Crump-type weir. The photographs below illustrate the key flow modes involved.

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

Flow and level measurement

Because their hydraulic characteristics are broadly predictable, many devices used to control flows and levels at flood storage works also provide a means of estimating the flows that pass – provided that water levels and gate openings (if applicable) are monitored or observed. Subject to not being obstructed by debris, a typical accuracy of ±10% might be expected with most devices.

If better accuracy for either controlling a flow or measuring a flow is required in the control device, this can sometimes be achieved through the choice of flow control device, together with an appropriate water level measurement location. Box 11.1 gives further guidance.

10.4.7 Trash screens and security screens

The normal reasons for providing a screen at a flood storage reservoir are to:

- exclude debris that might otherwise block or damage the conduit or control structure;
- capture that debris at a location where its removal can be facilitated;
- protect against accidental or unauthorised access to particularly hazardous spaces.

Unfortunately, screens can often be the cause of problems at flood storage reservoirs, with trapped debris allowed to accumulate, impairing the flow capacity of the control device and causing premature impounding. *Trash and security screen: a guide for flood risk management* (Environment Agency, 2009) contains guidance on the assessment, design and use of screens appropriate to UK conditions.

Notwithstanding these concerns, it is generally appropriate to deploy an entrance screen to the culvert or other flow control structure at a flood storage reservoir in circumstances where there is:

- easy public access to a hazardous location;
- a supply of leaf and other debris liable to block a restricted flow control device (such as a small orifice).

The screen aperture should be chosen to exclude debris liable to cause a problem, while allowing through smaller debris that is unlikely to cause a blockage of the control device.

It is good practice to install water level monitoring equipment at flood storage reservoir screens, both upstream and downstream of the screen, so that the headloss across the screen can be monitored. Once the headloss exceeds a certain threshold or is increasing beyond a particular rate, an operations team should be sent to clear the screen and avoid premature impounding.

10.4.8 Energy dissipation

Energy dissipation measures are usually needed at outlet structures from flood storage ponds and reservoirs.

In cases where the heads involved are small and the flows are conveyed in pipes or culverts, the energy can often be satisfactorily dissipated within those durable structures, though there are some situations where a specific energy dissipator is required. The most common case is where a pipe or culvert downstream of an outlet structure flows at high velocity directly to a natural watercourse or an earth-lined channel.

Options for energy dissipation include:

- hydraulic jump stilling basin – USBR, St Anthony Falls (SAF), etc;
- USBR impact-type outlet basin;
- Contra Costa outlet basin;
- straight-drop stilling basin;
- tee-fitting on a pipe outlet;
- riprap or gabion apron (and similar).

In some instances, generally associated with larger flood storage reservoirs, energy dissipation is provided as part of an overall structure that includes gates or an overflow weir. Advice on a limited range of energy dissipation devices is given in Section 7.11.6 of *Design of flood storage reservoirs* (Hall *et al,* 1993) and information about most of the above is given in a US Federal Highway Administration publication (1983).

In many cases, the greatest energy dissipation requirements occur with modest 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.

10.4.9 Emergency spillway

The function of an emergency spillway is 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 emergency spillway normally starts operating once the storage capacity has been exhausted by the incoming flood. But overtopping of an embankment could be caused by blockage or some other form of failure of the control structures, so the emergency spillway could be called upon to act under flow conditions much less severe than those for which it is primarily provided. Because the onset of spillway flows would normally result in an unexpected increase in flow passed downriver, consideration should be given to providing some form of public warning when this is imminent.

For ponds and reservoirs that come within the scope of the Reservoirs Act 1975, there is recognised guidance (ICE, 1996) on the appropriate severity for the design flood for the emergency spillway. This guidance is also relevant for smaller ponds and basins (not covered by the Act) that would represent a significant hazard if flood overtopping were to cause the embankment to fail.

The design flood for the emergency spillway is an extreme flood, which for medium sized reservoirs would be expected to have a return period in excess of 1000 years and, for a major flood storage reservoir located upstream of an urban area, would normally be the probable maximum flood (PMF). It is not the same as the design flood that is used for the design of the other features of the flood storage works, including the storage capacity and the control structures, which would normally have a return period of between 50 and 200 years.

The emergency spillway provided with flood storage works normally consists of an open weir and channel. These have the following advantages:

- a minimal risk of spillway failure through incorrect or poor operation, or blockage by debris;
- the flow increases in proportion to about the 1.5 power of the height of the impounded water level above the crest level of the weir.

Other types of spillway may be appropriate in some circumstances (for example, a bellmouth spillway discharging to a closed conduit, a labyrinth weir or a siphon), but spillways that rely on gates or other moving parts are unlikely to be appropriate. Further information on spillways is given in Section 7.11 of *Design of flood storage reservoirs* (Hall *et al,* 1993) and in *Small embankment reservoirs* (Kennard *et al,* 1996). There is also good coverage of the hydraulic behaviour of spillways in a number of textbooks and specialist reservoir design guides.

For flood storage works that involve impoundment up to a few metres only above the downstream watercourse, an attractive option is often to use a major part of the impounding embankment as the emergency spillway. For very low embankments, a good covering of grass may be sufficient; for moderate embankment heights, reinforced grass (using a variety of geotextile or cellular blockwork products) may suffice (Hewlett *et al*, 1987).

Figures 10.13 and 10.14 show examples of a plain grass spillway and a reinforced grass spillway respectively.

Figure 10.13 Plain grass spillway

The spillway at this small flood storage reservoir in Dorset was excavated through ground at the abutment. Because the gradient is gentle and the flows modest, grass protection was considered to be adequate.

Figure 10.14 Reinforced grass spillway

The spillway at this small flood storage reservoir near Taunton is located on the highest part of the impounding embankment, directly above the culverted outlet works.

Because of the limited height, the crest and downstream face (on the left) are protected with cable-tied cellular concrete blockwork, covered with topsoil.

The concrete strip along the crest provides a definite line that can be monitored for line and level.

The conditions under which reinforced grass provides sufficient protection against erosion need to be properly understood. There are a number of reservoirs (used for flood storage or otherwise) where the discharge intensity, dam height and hence velocity reached near the toe of the reinforced grass spillway are greater than what is generally recognised as 'safe'. A protection method that can be deployed on embankment spillways beyond the scope of reinforced grass solutions is the 'stepped block' or 'wedge block' (Hewlett *et al*, 1997), an example of which is illustrated in Case study 10.3.

Spillway design is not just about the overflow structure itself. It also needs to include the design of the downstream channel in a manner that successfully carries away the overflowing water. If the downstream channel is too small or the gradient is too gentle, it may impair the hydraulic performance of the overflow weir.

Spillway flows almost invariably involve supercritical flows, while 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. If the spillway comprises a concrete chute, then the hydraulic jump is normally contained in a specially designed stilling basin. 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 flood storage works.

An energy dissipation structure as such 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.

10.4.10 Design against wave action

It is standard practice in reservoir engineering – as in flood defence works generally – to include a freeboard. In the case of a reservoir, the freeboard is designed to accommodate the runup of wind-generated waves on top of the peak design water level when designing the crest level of the impounding embankment. A suitable approach to wave freeboard, which applies to reservoirs that come within the scope of the Reservoirs Act 1975, is given in *Floods and reservoir safety* (ICE, 1996). Other standard guidance documents, including Hall *et al* (1993) and Kennard *et al* (1996), may also be consulted, though both cite an earlier edition of *Floods and reservoir safety.*

Although *Floods and reservoir safety* (ICE, 1996) is generally the appropriate starting point for designing against wave action, its application to flood storage reservoirs needs to take account of the following particular circumstances:

- the possible use of all or part of the impounding embankment as the emergency spillway;

- the presence of protection on the outer face of the embankment and its resistance to wave overtopping as well as to the passage of floodwater;
- the uniformity of the embankment crest level and how this may vary during the design life, bearing in mind the inclusion of settlement allowances and the amounts of settlement likely;
- the very short fetch over which waves may be generated at many small reservoirs, for which the standard wave freeboard allowances may be considered excessive;
- whether rising tailwater levels in the more extreme floods (approaching the PMF) mean that there is very little difference between upstream and downstream water levels, thereby reducing the risk of significant damage from wave overtopping.

The guidance in *Floods and reservoir safety* specifically covers the freeboard allowance to be provided when designing the crest level of the embankment based on considerations of wave runup and the potential for wave overtopping to inflict damage on the downstream face and toe of an embankment. In addition, consideration should be given to protecting the inner face of the embankment against the erosive effects of waves breaking or plunging against it. This may involve the consideration of waves of a greater return period than those considered for the design of its freeboard.

For reservoirs covered by the Reservoirs Act 1975, the engineer overseeing its design and construction (the ‘construction engineer’) must agree the design criteria covering wave action.

10.5 Other design considerations

The design, operation, maintenance and rehabilitation of flood storage works involve a number of features that are common to other works in the fluvial environment.

Further guidance on the design of embankments and walls to retain water can be found in Chapter 9, including protection against erosion, maintenance requirements, stability, and design for overtopping. Guidance on the landscaping of embankments and floodwalls and suitable construction materials can be found in Chapter 5. Hydraulic structures are covered in more detail in Chapter 11 and there is guidance on trash screen design in Chapter 8.

Key references

Hall, M J, Hockin D L and Ellis, J B (1993). *Design of flood storage reservoirs*, B014. CIRIA and Butterworth-Heinemann.

This book is essential reading for the design of all forms of flood storage works except for those that come within the remit of The SUDS manual (see below) and those which do not involve the storage of water above natural ground levels. Some parts of the book are out-of-date, particularly those associated with hydrological and flood modelling methods; in these cases, reference should be made initially to the relevant sections of this guide.

Institution of Civil Engineers (1996). *Floods and reservoir safety*, 3rd edition. Thomas Telford.

This is the key reference by which the ability of existing reservoirs to withstand extreme floods is judged by reservoir engineers. It applies specifically to reservoirs covered by the Reservoirs Act 1975, but contains guidance also likely to be relevant for smaller reservoirs. It includes a method for determining the freeboard required for wave action and for estimating the amount of overtopping of embankments under wave action.

Institution of Civil Engineers (2000). *A guide to the Reservoirs Act 1975.* Thomas Telford.

This is an essential guide for those concerned with proposals for flood storage works possibly subject to the Act. It includes a commentary, flowcharts on its application to various circumstances (including promotion and construction), guidance on reservoir safety, checklists and a comprehensive bibliography. The guide is being revised to take account of subsequent experiences and the provisions for flood plans introduced under the Water Act 2003.

Kennard, M F, Hoskins, C G and Fletcher, M (1996). *Small embankment reservoirs*, Report R161. CIRIA.

This report is subtitled 'a comprehensive guide to the planning, design, construction and maintenance of small embankment reservoirs for water supply and amenity use'. Although not specifically including flood storage reservoirs, the book covers most of the engineering and other issues involved in their promotion and design.

Woods-Ballard, B, Kellagher, R, Martin, P, Jefferies, C, Bray, R and Shaffer, P (2007). *The SUDS manual*, Report C697. CIRIA.

This report provides comprehensive advice on the implementation of SUDS in the UK. It provides information for all aspects of the lifecycle of SUDS from initial planning, design through to construction and management of SUDS in the context of the current regulatory framework. It also provides information about landscaping, waste management and costs, as well as maximising opportunities for community engagement.

Other references

Ackers, J C, Harding, R and Hollinrake, P (2004). A passive flow-control device for the Banbury flood storage reservoir, *Long-term benefits and performance of dams* (H Hewlett, ed). Proceedings of the 13th conference of British Dam Society, Canterbury (June), pp 327–338. Thomas Telford.

Environment Agency (2009). *Trash and security screens: a guide for flood risk management.* Environment Agency.

Federal Highway Administration (1983) *Hydraulic design for energy dissipators for culverts and channels*, HEC14 metric version. US Department of Transportation. Available from: http://www.fhwa.dot.gov/engineering/hydraulics/pubs/hec/hec14SI.pdf.

Hewlett, H W M, Boorman, L A and Bramley, M E (1987). *Design of reinforced grass waterways*, Report R116. CIRIA.

Hewlett, H W M, Baker, R, May, R W P and Pravdivets, Y P (1997). *Design of stepped-block spillways*, Special Publication 142. CIRIA.

May, R W P, Bromwich, B C, Gawowski, Y and Rickard, C E (2003). *Hydraulic design of side weirs.* HR Wallingford.

Ramsbottom, D, Day, R and Rickard, C E (1997). *Culvert design guide,* Report R168, CIRIA. [Due to be superseded by the *Culvert design and operation guide* in late 2009.]

Rickard, C E, Day, R and Purseglove, J (2003). *River weirs – good practice guide*, R&D Publication W5B-023/HQP. Environment Agency. Available from: http://publications.environment-agency.gov.uk/pdf/SW5B-023-HQP-e-e.pdf.