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Floods and Reservoir Safety

Fourth edition

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Floods and Reservoir Safety

Preface

The Floods and Reservoir Safety Working Group was established in March 2013 by the Institution of Civil Engineers (ICE) in order to update the third edition of *Floods and Reservoir Safety*. This followed from a request to ICE from the Department for Environment, Food and Rural Affairs that a fourth edition of the guide be prepared to take account of legislative change, research, and guidance on aspects such as hydrology and risk produced subsequent to the publication of the third edition in 1996.

The working group met seven times under the chairmanship of A Macdonald. The membership consisted of

A Macdonald	
T M Hewitt	
Professor A K Hughes	Atkins Ltd
E J Stewart	Centre for Ecology & Hydrology
Dr P J Mason	Damsolve Ltd
Professor N W H Allsop	HR Wallingford
C A Goff	HR Wallingford
M Chrimes	Institution of Civil Engineers
A Wescott	Institution of Civil Engineers
G Jamieson	ICE Publishing

The working group is pleased to acknowledge the assistance given during the preparation of this edition from a number of other organisations and individuals who have helped in reviewing the guide, undertaking trials of the methodology recommended, or in allowing reservoirs that they own to be used for the purpose of benchmarking against the third edition. These include the Reservoir Safety Consultative Group, the Reservoir Safety Advisory Group of ICE, Bristol Water plc, Dwr Cymru Cyf, Scottish Water, Southern Water Services Ltd, SSE plc, United Utilities Group plc, MWH Global Inc., Jacobs UK Ltd, Mott MacDonald Ltd, and the Environment Agency.

In addition, there have been valuable contributions from many people at technical meetings where the guide has been discussed. The authors of the guide are grateful for this input together with the practical support provided by ICE.

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Chapter 1
Introduction

Background

UK reservoir safety legislation places an obligation on the owners of certain reservoirs, dependent on the capacity of water above the level of the adjacent ground and the hazard posed by that water, to provide for their inspection in the interests of public safety.

A guide relating to flood protection standards, flood magnitude and freeboard for the benefit of engineers exercising personal judgment under UK reservoir safety legislation was first published in its current form in 1978. This was revised in 1989 (minor corrections and additional references) and in 1996 (update taking account of best current research and experience of using the guide).

In the period since 1996 there have been changes to extreme flood estimation in the form of rainfall depth–duration–frequency and rainfall–runoff models, reservoir safety legislation, and adoption of a risk-based approach to that legislation.

In view of this, the UK Department for Environment, Food and Rural Affairs asked the Institution of Civil Engineers (ICE) to bring the publication up to date by preparing a fourth edition of the guide. In order to undertake this task, a small working group was established to operate under the following terms of reference.

> The purpose of the working group is to undertake a review of the third edition of *Floods and Reservoir Safety* and, with the assistance of ICE Publishing, to amend the document such that a fourth edition can be published during 2014. The revised edition should build on the text in the original, only amending those elements where legislative or technical aspects or feedback from the profession have resulted in the need for revision. In particular this will include
> - legislative changes in England, Wales, Scotland and Northern Ireland
> - the *Flood Estimation Handbook* (*FEH*) (IH, 1999)
> - recent research into extreme rainfall
> - guidance on risk assessment for UK reservoirs
> - research on wave overtopping of embankments.
>
> At appropriate events, the working group should also seek the views of owners and panel engineers on the proposed revisions and invite a selection of owners and panel engineers to assess the impact of the proposed changes on a small number of reservoirs prior to publication.

Changes

The flood protection standard required for each dam has historically been based on four categories dependent on the potential hazard to life and damage downstream. There is a general consensus that the existing system is uncomplicated and has been applied in a broadly consistent manner by panel engineers. The categories in Table 2.1 in this guide have therefore been retained from the previous edition, partly because all dams retaining reservoirs that come under existing UK reservoir safety legislation will have been categorised and assessed against those standards.

It is recognised that a small change in hazard can result in a change in category and a step change in protection requirements. Changes in legislation could also result in a large number of existing reservoirs being subject to assessment for the first time.

Rather than introducing additional categories to smooth out such impacts, the approach advocated in this guide where an existing reservoir fails to meet the standards required in Table 2.1 is to adopt a risk-based assessment, and to review the benefits that would be gained in meeting the

Table 2.1 standard against the cost of doing so, and also the tolerability of the residual risk. Such an assessment should be viewed as part of the decision-making process when assessing the safety of the dam against floods and reflects the principles outlined in the *Guide to Risk Assessment for Reservoir Safety Management* (EA, 2013) and *Reducing Risks, Protecting People: HSE's Decision-making Process* (HSE, 2001).

Procedures for deriving reservoir flood inflows have been amended since the last edition by the *FEH*, which introduced new estimates for rainfall depth–duration–frequency for inflow floods of certain return periods. Chapter 3 has been updated to reflect this change and to clarify the appropriate model and also where the new *FEH* rainfall model should be used, once it has been released.

In scope and general layout the updated guide follows that of its predecessors with the exception that the chapter on the overflowing and overtopping of dams now follows that describing wave height and the prediction of overtopping rates. To avoid confusion, the guide now uses two distinctive terms: overflowing (relatively steady rates of flow) and overtopping (intermittent flows from waves).

The approach in previous editions of establishing required flood freeboard margins by estimating the wave surcharge height has been replaced by a method for predicting the rate of wave overtopping. This is better able to take account of upstream slope and crest profiles. Benchmark testing has shown that in general the tolerable limit of overtopping rates suggested in the guide results in a slightly less onerous freeboard requirement than the previous edition.

Scope of the guide

This guide is intended to assist those individuals who bear the personal responsibility that comes from being appointed to the statutory panel of engineers qualified to design and also inspect reservoirs.

A desire for brevity and clarity of principle has led to this document being relatively concise. It should be read in conjunction with the latest revision of the *FEH*, in particular those sections that apply to reservoir safety flood inflow estimation.

The working group has updated Chapter 2 on the protection standards to cover all major points of principle, including the use of a 'standards-based' approach and a 'risk-based' approach. It has also sought to give further clarification and guidance to avoid excessive discrepancies in the conclusions reached by different engineers, when reviewing the required level of protection to a dam against the threat of a flood event. A flowchart outlining the process is included in Appendix 3.

The guidance here is not mandatory; however, it is recommended that where an engineer feels it is right to depart from the general principles provided by this guide, or the circumstances are not covered by the principles in this guide, the fact should be recorded, for example in the inspection report or annex to a certificate, with the reasons why.

A glossary of terms used in this guide is included after the appendices, together with a schematic diagram, showing the relationship between the principal terms in the guide.

This edition of the engineering guide supersedes and replaces the 1978 original and the 1989 and 1996 revised guides.

REFERENCES

EA (Environment Agency) (2013) *Guide to Risk Assessment for Reservoir Safety Management*. EA, London, UK.

HSE (Health and Safety Executive) (2001) *Reducing Risks, Protecting People: HSE's Decision-making Process*. HSE, Bootle, UK.

IH (Institute of Hydrology) (1999) *Flood Estimation Handbook*, vols 1–5. IH, Wallingford, UK.

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Chapter 2
Floods and waves protection standards

General

This guide categorises dams in terms of potential hazard to life and damage downstream. Protection standards must resolve acceptably the conflicting claims of safety and economy by giving guidance on the risks associated with these hazards.

Recent research published in the *Guide to Risk Assessment for Reservoir Safety Management* (EA, 2013) (*RARS*) provides guidance on the methodologies that can be adopted to determine the probability of failure due to a number of identified threats, including floods. Using that guide allows an assessor to determine the risk that a reservoir poses to human life, and the tolerability of that risk, together with a means by which the value in terms of cost to save a life can be judged against the reduction in risk that can be achieved by undertaking works. This relates closely to legislative change in the UK, which is moving towards a risk-based approach for reservoir safety. It is therefore appropriate that this edition of the guide acknowledges these changes and makes provision for them to be considered when undertaking an assessment of a reservoir's suitability for passing flood flows safely.

Although it is now considered possible to design a spillway for the almost total protection of a dam against overtopping by waves or overflowing by stillwater, there is the clear possibility that a dam built with a smaller spillway at less expense would survive several generations without any disaster or damage occurring. Equally, risk can never be totally removed, and while it can be reduced to tolerable levels, the risk of failure can never be reduced to zero. Some dams, even if subject to overflowing, may not breach, and increasing experience of erosion resistance makes it possible to introduce this additional factor into present-day assessments.

However, it is not simply a matter of economic judgement. As the Institution of Civil Engineers' (ICE) Rules for Professional Conduct state, all members shall have full regard for the public interest, particularly in relation to matters of public safety, and in relation to the well-being of future generations and shall show due regard for the environment and for the sustainable management of natural resources.

Thus, there are now two methods of approach to reservoir safety with regard to floods: a 'standards-based' approach, where the required level of protection is arrived at based on a broad categorisation of downstream damage, including the potential to endanger life, for example as detailed in the previous version of this guide (third edition, 1996), and a 'risk-based' approach, where the risk of failure of the dam due to floods is assessed together with downstream damage, including the likely loss of life, and the tolerability of that risk evaluated to arrive at the required level of protection, for example as described in the *RARS* and *Reducing Risks, Protecting People: HSE's Decision-making Process* (HSE, 2001).

A key difference is acceptance criteria. The third edition of this guide required a dam to be able to pass the inflow flood with sufficient freeboard as defined in Table 1 of that edition – with an explicit statement regarding the need to correct any deficiency.

In the risk-based approach, the dam is assessed with regard to reducing the risk of failure due to floods to 'as low as reasonably practicable' (ALARP). The ALARP principle is met when it is deemed grossly disproportionate in terms of expending resources to gain any further reduction in risk.

The approach adopted in this guide is to retain the previous 'standards-based' approach and categorisation but where an existing reservoir fails to meet these standards it is recommended that an engineer carry out a 'risk-based' assessment to review the benefit that would be gained to reduce risk to life when compared with the costs incurred in meeting the 'standards' in this guide. Once more experience in the use of the risk assessment guide has been achieved, a further revision of this guide may occur. For new reservoirs, it is recommended that provision for floods is reviewed against both a 'standards-based' and 'risk-based' approach.

The main factors

A crucial question when considering flood protection is the combination of circumstances that may arise in progressively rarer events. Three main factors have to be defined:

- the initial reservoir level
- the flood inflow
- the concurrent wind speed.

Despite continually improving techniques for defining flood hydrographs, wave overtopping and flood routing, the currently available methodologies permit only the independent assessment of each factor and then their combination to estimate maximum reservoir flood levels. This traditional approach ignores the dependence amongst hydrometeorological variables and the complex 'joint probability' problem; that is, choosing a coherent set of inputs to yield a maximum reservoir water level of stated rarity. In the early 1990s, prior to the third edition of this guide, the UK Department for Environment funded joint probability studies for reservoir flood safety which explored the application of multivariate extreme value analysis techniques to the problem of choosing design inputs for reservoir flood safety appraisal. A weak dependence between extreme wind and extreme rainfall events was found.

A consultative process has been followed in this and previous versions of this guide in order to ensure that the values recommended for the assumptions adopted in this guide are generally acceptable within the profession. Although the general framework may have relevance abroad, the values published in Table 2.1 refer strictly to dams in the UK. Panel engineers must satisfy themselves that the application of values published is valid in particular cases.

Standards-based approach

Initial reservoir level

When investigating reservoir safety, it is important to consider at what level the stored water could be when the flood inflow commences. It is recommended that the flood routing calculation should commence from a stable storage situation as shown in Table 2.1 prior to the commencement of flood inflow. The alternative of postulating an antecedent flood that creates a starting water level would only be appropriate for individual complex cases, for example where additional flood storage is created by a narrow slot within an overflow. Further comment is given in Chapter 4.

As discussed later in this chapter, flood attenuation embankments are a special case requiring individual consideration, and the 'just full' criteria shown in Table 2.1 at the start of the flood inflow may not be appropriate.

Reservoir flood inflow

It is necessary to determine the flood, in combination with wave action, that the dam must be capable of withstanding. The passage of this flood through the reservoir should cause no fundamental structural damage to the dam. However, it is normally uneconomic to provide a waterway below the dam that is sufficiently large to contain all flood outflow within its banks. Damage associated with rare overbank flows below or alongside spillway stilling basins may well be tolerated without risk to the integrity of the dam, but this needs to be confirmed. Similarly, there are situations where it is essential that the spillway channel should be hydraulically designed to carry all the dam flood outflow, for example where the spillway follows the line of the mitre of an embankment dam and out-of-channel flow may lead to failure of the downstream slope. Some engineers prefer a clear distinction between the flood inflow for which the reservoir is designed and the spillway design flood, but by definition only the former is essential to reservoir safety.

The standards-based approach in this guide concentrates on the requirements for the reservoir flood inflow, with two criteria referred to as the 'design flood' and the 'safety check flood' in Table 2.1, for each dam category:

Table 2.1 Flood, wind and wave protection standards by dam category

Dam category	Potential effect of a dam breach	Initial reservoir condition standard	Safety check flood conditions		Design flood conditions	
			Reservoir flood inflow	Concurrent wind speed for assessing wave overtopping	Reservoir flood inflow	Concurrent wind speed for assessing the freeboard required to contain wave overtopping, or minimum flood freeboard provision (whichever is the greater)
A	Where a breach could endanger lives in a community	Just full (i.e. no spill)	Probable Maximum Flood (PMF)	Mean annual maximum hourly wind speed	10 000-year flood	Mean annual maximum hourly wind speed, with minimum flood freeboard of 0.6 m
B	Where a breach (i) could endanger lives not in a community or (ii) could result in extensive damage	Just full (i.e. no spill)	10 000-year flood	Mean annual maximum hourly wind speed	1000-year flood	Mean annual maximum hourly wind speed, with minimum flood freeboard of 0.6 m
C	Where a breach would pose negligible risk to life and cause limited damage	Just full (i.e. no spill)	1000-year flood	Mean annual maximum hourly wind speed	150-year flood	Mean annual maximum hourly wind speed, with minimum flood freeboard of 0.4 m
D	Special cases where no loss of life can be foreseen as a result of a breach and very limited additional flood damage would be caused	Just full (i.e. no spill)	150-year flood	Mean annual maximum hourly wind speed	150-year flood	Mean annual maximum hourly wind speed, with minimum flood freeboard of 0.3 m

- design flood – the inflow that must be discharged under normal conditions with a safety margin provided by an accepted freeboard limit
- safety check flood – the inflow beyond which the safety of the dam cannot be assured (i.e. key components exhibit marginally safe performance for this flood condition).

(After ICOLD, 1992)

However, it is acknowledged that at the 'safety check' level of flood, some damage may occur to the dam due, for example, to overtopping by wave action, or by overflowing.

For the case of embankment dams not specifically intended and designed to withstand overflowing or overtopping, the design flood in Table 2.1 is the flood at which no significant wave overtopping of the crest or wave wall should be allowed to occur. An overtopping flow of 0.001 l/s/m, or less, is taken as being no overtopping.

For the case of a concrete or masonry dam, wave overtopping would be acceptable at the design flood in Table 2.1, assuming that it is founded on rock, although stillwater level should be below the dam crest or wave wall level unless a rigorous assessment of the founding conditions at the toe of the dam is undertaken to demonstrate resistance to erosion by overtopping flows.

Concurrent wind speed

In the British climate, major rainfalls of several hours' duration can result from very different storm systems. Intense depressions can be expected to have relatively steady high winds over large areas, whereas thunderstorm clusters can exhibit very different wind patterns within a few kilometres. Sometimes, storms may become stationary over an area, with low-level air rushing in; other storm cells can move in a line, possibly up or down a valley, with consequent wind veering. Waves generated on lakes during a storm, and more particularly at the time of peak flood surcharge at the dam, vary widely as a result. There is some evidence that steep-sided valleys often direct winds close to the valley axis even when winds at higher levels are at significant obliquity to the valley axis. The wind-generated waves on reservoirs and lakes should not be underestimated on the basis that the direction of the valley axis does not align with the predominant wind direction. Chapters 5 and 6 provide guidance on the methodology for assessing waves, wave overtopping, dam freeboard and allowable rates of wave overtopping. Records of past extremes suggest that a wave allowance should always be made and that it should be a more cautious one, particularly where there is a potential risk to human life. This allowance will provide a further margin of safety in many (but not all) rare floods.

There is no clear evidence that rare floods will be accompanied by outstandingly rare winds. Balancing a precautionary approach with the need for the justification of capital spending on additional safety, it seems only necessary to test each dam against overtopping from the waves generated by the highest hour's wind in a year (taken as an average from a series of annual peak hourly wind statistics). Even with valley wind steering there is frequently as much chance that the wind will blow waves away from the dam rather than to it.

Dam categories

The accidental, uncontrolled escape of water from an impounding or other reservoir can threaten life and property. Greater security is required against dam failure where there is a severe threat of loss of life and extensive damage and a lower security where the threat is less severe. All dams should be assessed for the consequences of failure during a flood event, and the categories shown in Table 2.1 indicate the degree of security required of a dam and the likely effects of the failure of the main dam (or if applicable, any other dam) by which the reservoir is retained. It is possible in some circumstances for a reservoir to be retained by dams of different categories. In assessing the consequence of failure, it is the additional damage that would occur if the dam failed under flood conditions compared with the damage caused by the flood were the dam not to fail.

The potential effects of dam failure for each of the categories A–D in Table 2.1 are given below. It is recognised, however, that some dams may lie between the stated categories. For instance, a periodically used camp below a dam may not justify a full category A rating: in such cases the judgement of the panel engineer is required to determine the appropriate reservoir flood inflow.

In assessing the damage that may be caused as a result of a breach, the panel engineer should take account not only of normal property damage but also damage that may be caused to critical infrastructure, scheduled monuments, protected environmental habitats and the like, where such information is readily available.

Published dam breach inundation maps can assist the panel engineer in making an assessment of the risk to life and the extent of the damage that may result from a dam failure. However, for some maps, the limitations of the underlying assumptions and accuracy of the methods used to produce them should be carefully considered.

Category A dams

Category A relates to endangering the lives of inhabitants of communities. A community in this context is considered to be not less than about 10 persons who could be affected; it is considered that inspection of any valley will soon reveal whether the presence of a hamlet, school or other social group means that a dam at its head should be in category A. Road and rail traffic caught in a valley flood would only accidentally be involved and would not by itself justify category A. A more difficult situation exists where an occasional camp site exists in the holiday season alongside a reservoired river. If, for example, this is in regular use by school parties it could well justify a community rating, but if it is frequented by a few unrelated short-stay individuals, it need not.

Category B dams

Category B(i) is intended to refer to inhabitants of isolated houses and, for example, to operatives in treatment works immediately below a dam and in other places of work in the flood path. (These situations lend themselves to taking measures to buy out the property or to arrange flood escape routes where appropriate.) Category B(ii) refers to extensive damage, including erosion of agricultural soils and the severing of main road or rail communications or other critical infrastructure such as gas mains or transformers.

Category C dams

Category C covers situations with negligible risk to human life and so includes flood-threatened areas that are 'inhabited' only spasmodically, such as footpaths across the flood plain and playing fields. In addition, this category also covers damage to scheduled monuments and loss of livestock and crops and protected natural habitats.

Category D dams

Many small reservoirs with low earth dams may cause no real problem, except that of replacement, if they wash out. These special cases, many of which are ornamental lakes kept full for aesthetic reasons, are given a separate category where they pose no significant threat to life or property. A flood intense enough to cause failure of a dam would create some damage even if the valley were still in its natural state; the additional damage caused by the release of stored water may well be insignificant if the lake is small. So, where the amount stored would add no more than 10% to the volume or peak of the flood, it is recommended that the reservoir flood inflow should be that from the 150-year flood. The point of reference for assessing whether the damage is significant or not can be taken as the first site below the dam at which some feature of value exists (e.g. a mill or road bridge). The 1000-year flood hydrograph applicable to the catchment prior to dam construction can be used for making this 10% sensitivity test.

Recommended standards

Table 2.1 sets out the standards that are appropriate for the wide variety and scale of dams in the UK. To apply them, it is necessary to route the appropriate reservoir flood inflow using the corresponding initial reservoir condition to obtain the flood surcharge level. The wind speed given in Table 2.1 is then used with the flood surcharge level to determine the wave overtopping discharge, if any, taking account of the geometry and protection standards of the upstream face and crest.

For the safety check scenario, the wave overtopping discharge must be less than the allowable wave overtopping discharge as indicated in Chapter 6. These allowable wave overtopping discharges will be sufficient to prevent quantities of flow arising from overtopping causing unacceptable damage to the top of the dam or downstream face, which would otherwise place the dam at risk of a breach. In addition, any wave wall must be able to withstand the loading from the waves generated by the concurrent wind speed indicated in Table 2.1.

For fill embankment dams, the elevation of the top of the dam will be governed by one of three conditions, the first being that the safety check flood surcharge level should not exceed the top of the dam, normally the crest level. If the flood peak is particularly prolonged, the safety check flood surcharge level may have to be lower still to avoid harmful leakage through the crest materials above the dam core. The second condition is that the safety check flood surcharge combined with wave action must not lead to a wave overtopping discharge in excess of the allowable wave overtopping discharge indicated in Chapter 6 (unless the dam has been designed to be capable of withstanding overtopping in excess of the recommended standards set out in Chapter 6). The third condition is that the design event flood surcharge combined with wave action must not lead to any overtopping discharge unless the dam has been specifically designed to permit wave overtopping at this level of flood. (A mean wave overtopping discharge rate of 0.001 l/s/m may be taken as zero, when calculated using the method described in Chapter 5.)

Where an existing dam is checked against the recommended standards given in Table 2.1, and is found to be lacking in spillway capacity or freeboard, it will be necessary to provide for the safe passage of the safety check flood, unless it can be shown using a risk-based approach that the probability of failure has already been reduced to ALARP. It will also be necessary to check the stability of the dam, and wave wall, particularly if the improvement involves a raising of the flood stillwater level.

For concrete or masonry dams that typically have a spillway over most of their crest length and no fill embankments at the abutments, the concept of freeboard may not be relevant provided that they are constructed on non-erodible foundations, and that there is no chance of erosion caused by overflowing or flow around the abutments. For these dams, it is necessary to be certain that the loading derived from the Table 2.1 safety check flood does not go beyond structural design limits.

Where concrete or masonry dams have fill embankments incorporated in the composite structure, the recommended standards for embankment dams will normally govern, as defined by Table 2.1.

The above points relating to the application of Table 2.1 are summarised by way of flowcharts in Appendix 3.

Table 2.1 is designed to take account of those factors that are weighed together by panel engineers both for the design of new dams and when undertaking inspections of existing dams. Its main intentions are to ensure that, where a community could be endangered by the breach of a dam, the risk of any breach caused by a flood is virtually eliminated. However, expenditure on safety works should be kept to a scale justified by the risk. In this respect, judgement and the rules associated with disproportionality as defined by the UK Health and Safety Executive can be used as an aid to making such assessments. Reference should be made to the publication *Reducing Risks, Protecting People: HSE's Decision-making Process* (HSE, 2001).

Risk-based approach

General

The risk-based approach using appropriate tools and methods seeks to provide an approach that allows an owner and their advisors to better understand and evaluate reservoir safety risks in a structured way. This then allows for risk-based decisions to be made to reduce risks to people, the environment and the economy but still maintain an important reference to accepted best practice. Where expenditure on remedial works will be significant to meet the standards-based approach to dealing with floods as set out in the previous sections, a risk-based approach could be adopted to assessing the value (cost versus reduction in risk) of undertaking remedial works. This can form part of an overall options appraisal.

The process of examining and assessing the significance of estimated risks is tiered risk evaluation, and the UK Health and Safety Executive has a well-established framework for risk evaluations called the tolerability of risk, which splits risk into areas of unacceptable risk, tolerable risk, and broadly acceptable risks.

The *RARS* guide uses a tiered approach to enable a user to move from essentially a qualitative assessment to a detailed quantitative assessment, depending on the levels of uncertainty, the complexity of the problem and the importance of the decisions to be made.

In each tier, the 'loads' or events which could lead to failure and flooding are considered as well as the consequence of these dam failure scenarios. In each case, failure mode identification forms an important element. In terms of floods, the analyses provide a numerical estimate of failure probability and risk.

In assessing the vulnerability of a dam to floods, judgement will need to be exercised. The *RARS* guide encourages the use of the two-staged phased approach to floods whereby if a reservoir did not meet the requirements of the standards-based approach then the use of the ALARP test can be used to help determine the extent of the works required.

In looking at the criteria for Category A and B dams as defined by Table 2.1, which are loosely based on the population at risk (PAR), it can be seen by plotting the values indicated in Table 2.2 on an f–N chart – which relates the estimated annual probability of failure f against the average societal loss of life, N (LLoL) (see *RARS* Vol. 2, Figure 9.2, for an example of a simple f–N chart) – that most existing Category A and B dams lie within the 'broadly acceptable' range (see page 12 for definitions of PAR and LLoL). This illustrates that the standards-based approach can, at least in the short term, sit alongside a risk-based approach.

At this time, it is considered that the Probable Maximum Flood (PMF) should be retained as the most onerous inflow flood for UK dams.

Table 2.2 Relationship between 'risk' parameters and category

	Category A	Category B
Population at risk (PAR)	>10	<10
Likely loss of life (LLOL)	>1	1 to <10
(1) Safety check flood Annual probability of occurrence	PMF 2.5×10^{-6}	10 000 year 1×10^{-4}
(2) Likelihood of failure during a safety check flood very low, say 1% (0.01) chance	0.01	0.01
Annual probability of failure from a safety check flood (1) × (2)	$<2.5 \times 10^{-8}$	$<1 \times 10^{-6}$

Until further research is available, it is recommended that the PMF is assigned an annual exceedance probability of 1 in 400 000 (2.5×10^{-6} per year).

Other criteria

Dam break wave

Assessment of the physical effect of a potential dam failure and the consequent flood wave is far from straightforward. However, Figure 2.1 indicates that the flow immediately downstream is influenced mainly by the dam height. Differences between dam types are not strongly marked where storage is substantial. Extrapolation of the curve for a lower dam demands caution because individual circumstances at the site are likely to be more significant. The *RARS* guide includes methods for estimating peak breach flow, taking account of dam type, height and reservoir volume. Computer programs are available to estimate flood levels as the wave passes downstream, and the models have improved dramatically over the years. Either depth or the velocity of flow or their combination may pose a threat. Although results cannot be precise, such a calculation can help in the assessment of the hazard posed by the possible failure of a dam, and hence its category. Inundation maps generated by others should be treated with caution unless the input parameters are clearly understood. In addition, breach modelling software should be used with care, and analysts should make themselves aware of the inconsistencies, uncertainties and assumptions made in the analyses, whether undertaken by themselves or by others.

Economic considerations

In general, determining the capacity of a spillway for a new dam is an economic balance between the cost of the provision of the spillway (or the raising of the dam crest) and the protection it affords to life and property downstream. The effect of the recommendations in this guide is to impose safety criteria that effectively constrain the range over which an economic solution is applicable. However, in certain cases the use of a risk-based approach may assist in analysing the additional benefit to be gained. For example, would a spillway capable of passing the design flood without a breach of the dam mean that there would be an improved situation in respect of likely loss when compared with a smaller spillway that would increase the probability of failure of the structure? Normally, a dam breach would be expected to result in a higher loss of life when compared with the natural flood event, but that might not always be the case.

For existing dams that do not meet the standards based approach in Table 2.1, it is recommended that the *RARS* guide is used to assess the value to be gained in undertaking works in order to reduce the probability of failure and downstream impact. A quantitative (Tier 2 risk assessment) approach is likely to be required.

A risk-based approach can also be used to support a panel engineer's judgement where dams are assessed as being between the categories in Table 2.1.

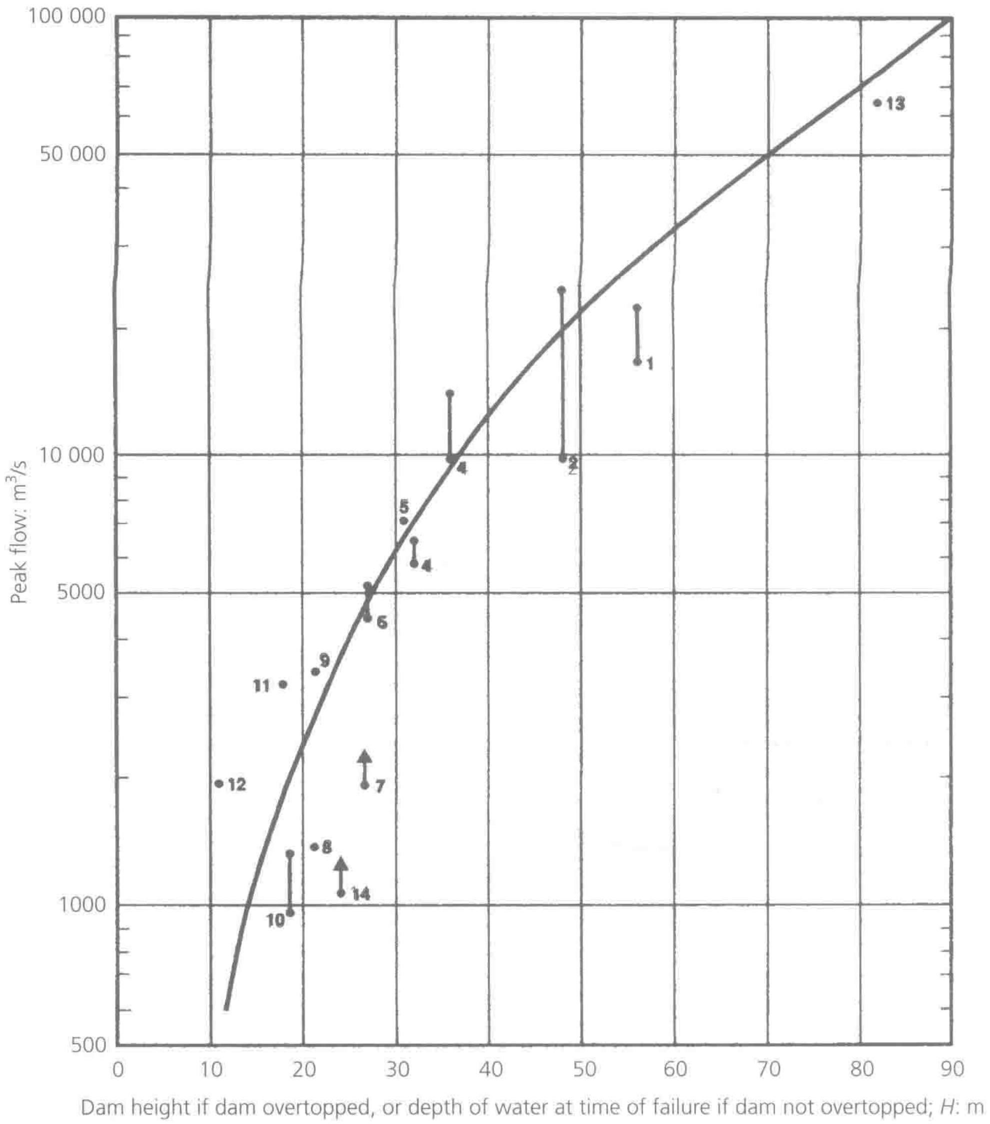
Spillway systems

Due consideration should be given to the performance of a spillway as a system and its ability to cater for the safety check flood outflow, to ensure that the passage of such a flow will not threaten the safety of the dam. The behaviour of the spillway throughout its full extent should be reviewed.

Reservoir cascades

Different categories can exist where reservoirs are in a cascade. In determining the flood category, it is important to consider the effect of a flood-induced failure of an upper reservoir on a lower one, taking account of the likely concurrent water level, as well as the impact of the dam-break flood wave on the intermediate downstream valley.

Figure 2.1 Dam failure flood flow versus dam height. (Source: Kirkpatrick, 1977.)



Estimated flood peaks from dam failures. The numbers indicate the name of the dam, its location, type of dam where known, and the year of failure.

1. St. Francis, California, concrete gravity, 1928
2. Swift, Montana, rock fill, 1960
3. Oros, Brazil, earth and rock fill, 1960
4. Apishapa, Colorado, earth fill, 1923
5. Hell Hole, California, rock fill, 1964
6. Schaeffer, Colorado, earth fill, 1921
7. Granite Greek, Alaska, 1971, discharge at 8 km downstream
8. Little Deer Creek, Utah, earth fill, 1963
9. Castlewood, Colorado, rock fill, 1933
10. Baldwin Hills, California, earth fill, 1963
11. Hatchwood, Utah, earth fill, 1914
12. Lower Two Medicine, Montana, 1964
13. Teton dam, Idaho, earth, 1976
14. Dale Dyke, Sheffield, England, earth fill, 1864, discharge at 10 km downstream

Failure to meet recommended standards

Early action is required where the dam freeboard is inadequate to contain the stillwater flood surcharge of the appropriate standard: this normally takes the form of a temporary lowering of the top water level prior to remedial works being carried out. However, if a dam is found to be adequate to contain the flood surcharge but unable to cope with the associated waves required by Table 2.1, the action to be taken and the timing thereof will depend on local circumstances. Remedial measures such as a wall or rip-rap protection may be feasible. In some cases, the observation of wave patterns and movements during a storm may show that the dam is sheltered, and enable the panel engineer to review the assessment of wave action on the structure.