Risk and Reservoirs in the UK

Mark Morris¹, Henry Hewlett², Craig Elliott³

¹ HR Wallingford, Howbery Park, Wallingford, OX10 8BA.UK.
² RKL-Arup, Raffety House, 2 Sutton Court Rd., Sutton, Surrey SM1 4SS.
³ CIRIA Water Group, 1-2 Castle Lane, Westminster, London, SW1E 6DR.UK.

m.morris@hrwallingford.co.uk
henry.hewlett@arup.com
craig.elliott@ciria.org.uk

Abstract:
Interest in the risk arising from reservoirs has grown during the last 5 years. As a result, a range of risk assessment techniques and methodologies have been developed to assist reservoir owners and managers. However, current methodologies can vary significantly between dam owners and countries around the world as each organisation attempts to create a system suited to their particular perceived needs. This applies equally to the UK dam industry.

During a recent research project, a risk assessment methodology for the safety assessment of UK reservoirs has been developed. The methodology is relatively simple, easy to implement and fits within the current UK approach to reservoir safety; namely that of periodic inspections by registered dam engineers.

This paper describes the background conditions to the research and outlines the study through which the risk assessment procedures were developed - CIRIA¹ Project RP568 Reservoirs and Risk.

The methodology incorporates two clear stages; Stage 1 includes an Impact Assessment and Stage 2 a Failure Mode, Effect and Criticality Analysis (FMECA) type Risk Assessment. The impact assessment considers seven key potential impacts, along with a measure of the potential loss of life resulting from dam failure. Combining all measures of impact allows for a single Impact Score to be calculated, which can be used to determine the requirement for further, more detailed risk assessment.

The Risk Assessment methodology is based on a FMECA approach. This offers a simple framework in which sound engineering judgement may be applied through consideration of the various ‘components’ creating a dam. Components are scored according to their Consequence of failure, Likelihood of failure and Confidence (of the

¹ CIRIA is the Construction Industry Research and Information Association, a not-for-profit scientific research organisation.
two previous scores). Analysis of dam incident records on two UK dam databases provides some guidance on the scoring of various components and is taken in conjunction with site-specific details and engineering judgement.

Once scoring has been undertaken, components may be prioritised according to their need for capital or investigative works. By combining Risk Scores with Impact Scores, components from multiple dam sites may also be prioritised.

The methodology provides a simple, transparent system for identifying and managing reservoir risks. It has been presented to the UK dam industry and will be undergoing initial application during 2000 / 2001. A review of performance, issues and problems is anticipated after 2-5 years to determine the operational effectiveness of the system and to review the weighting parameters used within the scoring system.
1 Introduction
Many reservoirs in the UK lie immediately upstream, or adjacent to, heavily populated areas. The rapid, uncontrolled discharge of water from such reservoirs could have catastrophic consequences in terms of loss of life and damage to property. All reservoirs in the UK holding more than 25,000m³ are subject to regular safety inspections as required by the UK Reservoirs Act (1975). Although no lives have been lost in the UK as a result of a dam failure since the introduction of reservoir safety legislation in 1930, there have been a number of ‘near misses’. There is particular concern about the safety of the large number of embankment dams constructed over 100 years ago, before the development of modern understanding of soil mechanics.

No one responsible for reservoir safety should be complacent about the risk posed by reservoirs. In recent years, public expectation with regard to ‘acceptable’ degrees of risk or hazard (e.g. risk of accidental death from any cause) is much less submissive than in the past. In addition, societal demands for transparency and accountability in dealing with risks to health and property are much greater than before. Recent accidents show that the public is particularly concerned with so-called “societal risks” where exposure is involuntary and a single incident can result in multiple fatalities.

Working as part of a team² on the CIRIA Research Project RP568 (Risk and Reservoirs), HR Wallingford developed a risk assessment methodology for the safety assessment of UK reservoirs. To allow the methodology to be generally applied it needed to be relatively simple and easy to implement, realistically achievable and to fit within the current UK approach to reservoir safety, principally that of periodic inspections by qualified and experienced dam engineers.

This paper outlines the development of the risk assessment methodology. A CIRIA report (CIRIA Report C542, Risk management and UK reservoirs) will be published during 2000 and details the methodology as well as containing additional supporting information on dam safety, risk assessment and risk management.

2 Risk Assessment in the UK
The House of Lords Select Committee on Science & Technology first suggested the application of risk assessment methodology for use on UK reservoirs in 1982. A pilot risk assessment, using a probabilistic approach, was carried out for an earth dam in north-west England as described by Parr and Cullen (1988). A number of difficulties were encountered in this exercise, most notably the fact that there were insufficient statistical data on dam failures and other incidents to enable probabilities to be reliably assigned.

Because of this shortage of statistical data, the Building Research Establishment (BRE) developed a computerised database containing information on all 2500 or so dams that are subject to the provisions of the Reservoirs Act 1975 (in the UK). This database includes information on matters such as dam construction, problems, investigations and remedial works (Tedd et al, 1992 and Tedd et al, 2000). In parallel with this, similar databases have been developed, for example, by Moffat at the University of Newcastle.

² The Project Team included RKL ARUP, HR Wallingford, EQE International, University of Newcastle and the Building Research Establishment (BRE).
With renewed interest in risk management for dam safety during the late 1990s combined with the added potential of support from the BRE Dams database, CIRIA initiated a research project for the development of an initial approach to risk assessment for UK reservoirs. The study commenced in 1997 and CIRIA appointed a consortium comprising RKLArup, HR Wallingford, EQE International Ltd, the University of Newcastle and BRE to undertake the detailed research for the study. The objective of the project was to produce a guidance document on risk assessment for reservoir owners, panel engineers, regulators, insurance companies and other stakeholders concerned with reservoir safety.

3 The Risk and Reservoirs Project
The project proceeded in four stages:

- Assessment of industry requirements and prioritising of risk assessment and management/maintenance tasks
- Analysis of the hazard and risk posed by UK reservoirs
- Examination of the role of hazard and risk assessment in the management of UK reservoirs
- Preparation of a guide on hazard and risk assessment and their use in the management of UK reservoirs

3.1 Assessment of industry requirements
Industry requirements were primarily determined through consultation with stakeholders and others via a questionnaire and a workshop. Consideration was first given as to why risk assessment methodologies developed for use in other industries had not been applied (so far) to dams and reservoirs. It was concluded that the main reasons were:

- inadequate data
- the fact that all dams are unique
- the complex interactions involved in the behaviour of a dam
- unrealistic or meaningless results
- the fact that the risk of dam failure is perceived to be negligible
- concern about the cost of risk assessment
- scepticism
- problems with terminology (risk, hazard, etc)
- difficulties in understanding or applying the output from any form of risk assessment for a dam.
- lack of knowledge of risk assessment techniques by the dam community.

Considering the above points, the principal conclusions and recommendations from this stage of the project were that:

- The application of risk assessment could help to improve reservoir safety in the UK and it should therefore be welcomed.
- A relatively simple and easily understood risk assessment methodology would be preferred which is cheap to implement. Full probabilistic risk assessments using
fault trees etc were not desired, although a simplified approach may be appropriate in some cases.

- Hazard indexing would be useful in identifying the potential consequence of failure and in the classification of reservoirs.
- There was concern about the availability of data on dam ‘incidents’ including failures and ‘near misses’.
- The UK should take note of approaches to risk analysis in other countries, but should develop its own methods applicable to its own unique stock of dams.
- A consistent approach is needed to the preparation of emergency plans and inundation maps.

### 3.2 Analysis of the hazard and risk posed by UK reservoirs

The perception of risk by society and its acceptability is heavily influenced by the nature of the risk. There is a tendency for accidents involving a single but large number of fatalities to be more unacceptable than frequent, smaller fatality events even though statistically both may cause the same rate of death in the longer term.

The perception of risk is also influenced by whether the risk is undertaken voluntarily (e.g. rock climbing) or is imposed by others (e.g. construction of a nuclear power station).

Consideration may be given to the past safety performance of dams in the UK and how this relates to the safety performance of other industries. Table 1 below provides a summary of British dam failures resulting in loss of life between 1831 and 1930. Note that there has not been a failure leading to the loss of life since 1930.

<table>
<thead>
<tr>
<th>Dam</th>
<th>Date Built</th>
<th>Height (m)</th>
<th>Reservoir Volume ($\times 10^3$m$^3$)</th>
<th>Date of Failure</th>
<th>Cause Of Failure</th>
<th>Deaths</th>
</tr>
</thead>
<tbody>
<tr>
<td>Whinhill</td>
<td>1821</td>
<td>12</td>
<td>262</td>
<td>1835</td>
<td>Overtopped</td>
<td>31</td>
</tr>
<tr>
<td>Welsh Harp</td>
<td>1837</td>
<td></td>
<td></td>
<td>1841</td>
<td>Overtopped</td>
<td>2</td>
</tr>
<tr>
<td>Glanderston</td>
<td></td>
<td></td>
<td></td>
<td>1842</td>
<td>Overtopped</td>
<td>8</td>
</tr>
<tr>
<td>Darwen</td>
<td></td>
<td></td>
<td></td>
<td>1848</td>
<td>Overtopped</td>
<td>12</td>
</tr>
<tr>
<td>Bilberry</td>
<td>1845</td>
<td>20</td>
<td>310</td>
<td>1852</td>
<td>Internal erosion</td>
<td>81</td>
</tr>
<tr>
<td>Dale Dyke</td>
<td>1863</td>
<td>29</td>
<td>3240</td>
<td>1864</td>
<td>Internal erosion</td>
<td>244</td>
</tr>
<tr>
<td>Rishoton</td>
<td></td>
<td></td>
<td></td>
<td>1870</td>
<td>?</td>
<td>3</td>
</tr>
<tr>
<td>Cwm Carne</td>
<td>1792</td>
<td>12</td>
<td>90</td>
<td>1875</td>
<td>Internal erosion</td>
<td>12</td>
</tr>
<tr>
<td>Castle Malgwyn</td>
<td></td>
<td></td>
<td></td>
<td>1875</td>
<td>Overtopped</td>
<td>2</td>
</tr>
<tr>
<td>Clydach Vale</td>
<td></td>
<td>5</td>
<td>24</td>
<td>1910</td>
<td>Overtopped</td>
<td>5</td>
</tr>
<tr>
<td>Skelmorlie</td>
<td>1924</td>
<td>11</td>
<td>320</td>
<td>1925</td>
<td>Overtopped</td>
<td>16</td>
</tr>
<tr>
<td>Coedty</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1: British dam failures resulting in loss of life (1831-1930)

A comparison may be made between the FN curve derived for UK Dams between 1831 and 1930 and the FN curve produced in the ACDS report for the total national societal risk from handling dangerous substances in all UK Ports, or the national societal enroute risks for transport of dangerous substances by road and rail (Figure 1). The data for ports, road and rail have been synthesised from representative accident scenarios, assuming dangerous goods transport rates and traffic data from the mid-1980s: it does not therefore represent historical cumulative accident data in the same way as for the
At first sight, the record of dam safety does not appear to be as good as that in the other industries shown on this F-N diagram. It should, however, be remembered that there have been no known deaths due to dam failure in the UK since 1925, while a failure causing one or more deaths occurred on 12 occasions during the period 1831-1930. It therefore appears that there is a direct correlation between the introduction of reservoir safety legislation in the UK in 1930 and improved safety, which is not apparent on the F-N diagram.

It is therefore difficult to set rigid risk criteria for all industries or situations. The approach generally adopted within the UK risk industry comprises a three-tier system:

1. An upper-bound on individual (and possible, societal) risk levels, beyond which risks are deemed unacceptable.
2. A lower-bound on individual (and possible, societal) risk levels, below which risks are deemed not to warrant regulatory concern.
3. An intermediate region between the above bounds, where further risk reduction is required to achieve a level deemed ‘As Low As Reasonably Practicable’ (ALARP).

Target values of maximum risk are published by the HSE (1989, 1996) for various hazardous industries and these are generally in the range of $10^{-5}$ to $10^{-7}$ (one in 100,000 to one in 10,000,000 per year). The most appropriate standard to apply to reservoirs would appear to be that for land-use planning (HSE, 1989) where the target level of individual risk is $10^{-6}$ (one in 1,000,000 per year).
3.3 The role of hazard & risk management

The assessment and quantification of risk in a general sense has been practised for centuries. The benefits of risk assessment (through prioritisation of resources and improvement in health and safety) have been realised in industries in the UK that have a major hazard potential, namely (Harvey, 1976; 1979; 1984):

- power generation (especially nuclear power stations)
- nuclear chemicals reprocessing
- conventional chemical processing involving hazardous materials or processes
- onshore petrochemical processing and refining
- offshore oil and gas exploration and production
- railway and road transportation (especially involving carriage of hazardous goods)
- aerospace
- mining and mineral extraction.

In the UK, legislation has been the principal driver for the protection of both workers and the public from hazards. It includes a requirement for risk assessments to be undertaken and documented, initially in the industrial sector but now from most other sectors (HMSO, 1984; HSE, 1996).

3.3.1 Current practice for dam safety

The risk of failure of existing UK dams is minimised by a combination of factors such as good engineering practice, ongoing surveillance and inspection techniques, including the following:

- Compliance with the Reservoirs Act 1975 and the recommendations of the available guidance documents on floods, seismic safety, etc.
- Routine visits/surveillance.
- Standardisation of surveillance procedures.
- Long-term monitoring and surveillance of the dams via levels, piezometers, etc.
- Undertaking remedial works to correct deficiencies identified and maintain the dam in good condition.
- Maintaining comprehensive records of the reservoir: in addition to the Prescribed Form of Record this could include calculations, drawings, construction records, photographs, monitoring records, remedial works details, Inspecting and Supervising Engineers’ reports, etc.
- Management systems to ensure the communication of problems identified to the correct personnel.
- Training of personnel associated with operation, inspection and maintenance of the reservoir.
- Reporting of incidents which require remedial action (enabling a database to be developed for the overall benefit of reservoir safety).

The principal form of risk assessment currently practised in the UK is the inspection of reservoirs by experienced engineers in accordance with the Reservoirs Act 1975. These rely heavily on the engineering judgement of such engineers. Fully quantified assessments giving risk values for dams have not been carried out in the UK. The major difficulty is the lack of statistically valid failure data that is required to allow quantification without great uncertainties. This leads to the use of relative risk ranking.
techniques. In most cases, this is sufficient for the purposes of identifying and prioritising areas requiring action, and assessing (in relative terms) the effectiveness of proposed measures.

### 3.3.2 The benefits of risk assessment

The benefits from adopting a structured and systematic risk assessment process have been demonstrated in all industries where these techniques have been used. Similar general benefits may be realised by applying the process to UK reservoirs. These benefits include:

- increased knowledge to the operator about the hazards posed by a particular operation
- identification of risk reduction and risk mitigation options
- compilation of information for the prioritisation of resources
- compilation of information for the selection between technology/process options
- development of contingency planning
- compilation of risk information to communicate risks to the general public
- demonstration of compliance with legislative regimes
- provision of guidance on planning permission applications.

Specific benefits of the application of risk assessment technology to owners, panel engineers, regulators, insurance companies and others concerned with reservoir safety include:

- prioritising the implementation of safety recommendations and remedial works
- prioritising maintenance
- planning a surveillance, monitoring and instrumentation strategy
- identifying possible failure modes requiring detailed investigation and analysis
- checking that all hazards at a reservoir are systematically identified and considered
- preparation of emergency plans for dam operation and interaction with emergency services
- identifying the financial risk associated with the failure of a dam
- providing comparison with hazards in other industries
- avoiding complacency in respect of dam safety.

It should be realised that there are potential drawbacks resulting from the implementation of a risk assessment/risk management system and these include:

- the cost of undertaking the risk assessment - particularly if the system is too complicated
- the cost of implementing measures resulting from the risk assessment (e.g. remedial works, additional surveillance/monitoring, etc. – although this work should be justified if correctly identified as a priority risk issue)
- incomplete knowledge of matters affecting the performance of the dam (although it must be better in terms of safety to be aware of what is and is not understood about the performance of a dam)
- the risk that any assessment procedure becomes routine and encourages a false sense of security through lack of consideration of new and changing risks at a given site (it
is essential that risk assessments are not undertaken simply as a form filling exercise but as a fresh review of potential risk during each assessment.

3.4 The Risk assessment methodology
The two extremes of risk assessment are an engineering judgement approach (fully qualitative) and full probabilistic assessment (fully quantitative). Between these two extremes lie a range of semi-quantitative approaches that build on the strengths of both systems when data and assessment budgets are limited but consistency and reliability are equally important. One of these, the Failure Modes, Effect and Criticality Analysis (FMECA) approach was adopted because it provides the flexibility to deal with varying levels of knowledge regarding the performance and reliability of different dam components. A similar method has been used for UK dams by Scottish Hydro-Electric (Sandilands et al, 1998).

The procedures that have been developed are based on a combination of methodologies linking hydraulics, impact assessment, risk assessment and risk management. The methodology provides a structure for determining the potential impact of failure, considering the possible causes of failure, identifying critical elements leading to failure and identifying and taking appropriate mitigation steps.

Figure 2 provides a flow chart indicating different the components of these four stages and how they contribute to dam safety. It should be clearly recognised that this methodology is a continuously evolving process that should be updated as more information becomes available to support the procedure. Equally, there is more understanding to be gained in doing the assessment rather than in calculating a value for the final score. Risk management is about identifying and understanding risk so that it may then be dealt with in the most effective way. Someone who undertakes a risk assessment without understanding the nature of the risks identified will not be able to effectively manage those risks.

![Flow chart showing the risk management process](image)

3.4.1 Impact Assessment
The aim of the impact assessment is to determine a measure of impact for a site that may be used to determine an appropriate level of risk assessment for the site and also to allow a measure of risk to be calculated for each ‘component’ considered in the risk assessment. By doing this, each component from a specific site may be compared with
components from other sites. This allows an owner of multiple dams to prioritise risks associated with different components from different dams.

The impact assessment may be broken into a number of steps, as shown in Figure 3 below.

**Figure 3 Impact assessment steps**

**Information and Site Visit**
In order to undertake the impact assessment some basic information for the reservoir will be required, along with a site visit. Information required includes:

- 1:25,000 / 1:10000 scale OS plans for the reservoir and the route taken by flood water up to a distance of 30km from the site
- Structure details – type, height
- Reservoir stage discharge relationship and normal / flood operating levels

A site visit to the reservoir and along the first 5km stretch downstream of the site is suggested to assist in assessing the impact scores.

**Prediction of Potential Flood Water Levels**
A key objective of the project was to develop a simple and practicable procedure for the initial risk assessment that could be refined subsequently as necessary. This meant that the initial analysis had to be simple and relatively quick to undertake. As such, carrying out a dambreak analysis using a numerical model was not appropriate for the prediction of flood water levels within this risk assessment procedure. However, where a dambreak analysis has already been carried out prior to the application of this risk assessment procedure, then the results derived should be used in preference to the less robust technique described below.

In the absence of outputs from a dambreak analysis the only apparent alternative was to use peak discharge equations to estimate flow from the failed dam combined with some form of flow equation (such as Manning’s equation) to translate the discharge into a flood level. In this limited form, however, it was felt that the accuracy of the predictions would be too crude so a technique was developed to allow a measure of flood wave attenuation to be taken into consideration. This was achieved through the procedure shown in Figure 4 below.
The main feature of this quick calculation process is the estimation of flood attenuation as the flood passes down the valley based upon an approximate analytic solution of the St. Venant equations. This calculation is undertaken assuming geometrically uniform conditions, hence the division of the downstream valley into similar zones. Having initially estimated the triangular flood hydrograph at the dam (Figure 5), attenuation effects are considered using the following equations:

\[ Q_p(x) = Q_p(0) \exp\left[-\frac{X}{L_a}\right] \]

where

- \( Q_p(x) \): Discharge at a location Xm downstream of \( Q_p(0) \) location (m\(^3\)/s)
- \( Q_p(0) \): Discharge calculated at upstream location (m\(^3\)/s)
- \( X \): Distance between zone intersections (i.e. length of the zone across which the calculation is being made, not the chainage downstream of the dam) (m)

and

\[ L_a = k B^{0.2} S_0^{1.9} n^{-1.8} Q_p(0)^{0.2} T_h^2 \]

where

- \( k \): Factor, with a possible range of 1 to 10. The suggested value is 2.5. (Further research is required to validate this value within the given range)
- \( B \): Estimated surface width of valley at estimated water depth (m)
- \( S_0 \): Valley slope (m/m)
- \( n \): Manning’s n
- \( Q_p(0) \): Discharge calculated at upstream location (m\(^3\)/s)

and
Time period at half discharge:

\[ T_h \]

Following calculation of an attenuated value of \( Q_p \) the associated new value of \( T_h \) may be found using the equation below. These new values of \( Q_p \) and \( T_h \) may then be used for subsequent attenuation calculations.

\[ T_h(\text{new}) = T_h(\text{original}) \times Q_p(\text{original})/Q_p(\text{new}) \]

The value of \( T_h \) therefore grows in proportion to the reduction in peak discharge. Maximum flood levels may then be estimated at each calculation point by applying Manning’s equation with the peak discharge value:

\[ Q_p = \left( \frac{A^{5/3} S_o^{1/2}}{(nP^{2/3})} \right) \]

where:

- \( Q_p \) Peak discharge at the calculation point (m\(^3\)/s)
- \( A \) Flow cross sectional area (m\(^2\))
- \( S_o \) Slope along the river valley
- \( n \) Manning’s roughness coefficient
- \( P \) Wetted perimeter of valley section (m)

Assessment of Impacts due to Flooding

Having now estimated flood water levels, a measure of potential flood impact may be made. This can be done by considering different types of potential impact in relation to the different flood zones. The following seven impact categories have been identified and are used in the calculation process:

- residential properties (housing etc.)
- non residential properties (factories, schools, hospitals etc.)
- transportation infrastructure (roads, railways etc.)
- recreational sites (camp sites, sports fields, lakes etc.)
- industrial sites (chemical works etc.)
- utilities (power, water etc.)
- agriculture / habitats (crops, historic sites etc.)

The assessor is asked to consider the impact category in relation to the predicted dambreak conditions and rate the severity on a scale of 0 - 4. Guidance is given on the
level of impact associated with each score. Table 2 shows, as an example, guidance offered for Impact No. 2 – Non residential properties.

<table>
<thead>
<tr>
<th>Disruption</th>
<th>Number of People Affected</th>
<th>Score</th>
<th>PAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Minor</td>
<td>0 to 150</td>
<td>1</td>
<td>150</td>
</tr>
<tr>
<td>Appreciable</td>
<td>150 to 500</td>
<td>2</td>
<td>500</td>
</tr>
<tr>
<td>Significant</td>
<td>500 to 1000</td>
<td>3</td>
<td>1000</td>
</tr>
<tr>
<td>Major</td>
<td>Estimate (&gt; 1000)</td>
<td>4</td>
<td>Estimate</td>
</tr>
</tbody>
</table>

Table 2  Impact table for Non Residential Properties

Potential loss of life from the first four impact categories is also considered. For these categories, an estimate of the number of people at risk (PAR) is also given in the table. The PAR value may then be used to estimate the potential loss of life using the following equations:

\[
\text{Near Valley (0-5km) potential loss of life} = 0.5 \times \text{PAR}
\]

\[
\text{Far Valley (5-30km) potential loss of life} = \text{PAR}^{0.6}
\]

These equations are based on work undertaken in the US (Graham, 1998).

An important aspect of the impact assessment is the completion of impact score justification records. The reason behind the allocation of each score in each zone is noted in a summary table so that there is a clear record of how the assessment has been undertaken. This then allows consistency between different assessors and assists in updating the assessment during periodic reviews.

Combining Impact Scores

Having calculated potential flood water levels, identified and scored possible impacts and estimated the potential loss of life due to flooding, it is now possible to combine these conditions into a single measure of impact. This is undertaken by combining the impact scores with weighting values that were derived to represent the relative importance of the various different impacts. These weightings were developed through discussion during a risk workshop and are based on engineering judgement and expertise. Table 3 shows an example summary table for recording and combining the impact scores leading to the calculation of a single impact score.
3.4.2 FMECA Assessment

LCI Diagrams
A risk assessment follows on from completion of the initial impact assessment. The complexity of this risk assessment may be determined by the magnitude of the impact score. For example, a low impact site may not warrant a detailed risk assessment whereas a site with potentially catastrophic impacts would benefit from a detailed analysis.

An FMECA (failure modes, effect and criticality analysis) approach has been adopted for the risk assessment procedure. This approach:

- offers a balance between engineering judgement and full probabilistic analysis
- avoids the use of specific probabilities; adopting instead a descriptive system
- uses a common calculation system enabling risks from all components and all sites to be compared
- encourages the use of risk registers
- provides systematic identification and management of risks
- provides a mechanism for recording all risks at a site
- has been successfully applied to UK reservoirs

The analysis is structured around an ‘LCI Diagram’ - so called after the areas of the tree diagram relating to location of a component at the dam, cause of failure and indications of failure. Part of an LCI diagram is shown in Figure 6.

The aim of the diagram is to offer an outline structure around which the assessment may be undertaken. The assessor considers elements within the tree and allocates scores to a level of complexity that is realistic for the particular element and site. Additional boxes may be added for elements that the assessor considers appropriate for any particular site.
The LCI diagram score categories may be defined as:

Consequence: How directly is failure of this element related to complete (or partial) failure of the dam? (Score 1 to 5: 1 low, 5 high)

Likelihood: What is the likelihood of failure of this element? (Score 1 to 5: 1 low, 5 high)

Confidence: What is the assessor’s confidence in their estimates of consequence and likelihood? (Score 1 to 5: 5 low, 1 high). This is to take into account uncertainty in knowledge of the dam and its components.

Figure 6 Part of an LCI diagram

For each element considered, the assessor is required to allocate three scores relating to consequence, likelihood and confidence. Guidance on scoring the consequence values for some elements is also provided (colour coded and indicated H, M or L). This
guidance is based upon an analysis of incident records from two UK dam databases, which were analysed in relation to dam type. Different LCI diagrams are offered according to age (pre 1840, 1840-1960 and post 1960), height (less than 15m, 15-30m and greater than 30m) and type (embankment, concrete/masonry and service). The diagram structure for each dam type remains the same however score guidance differs according to age and height. Additional branches may be added to the diagram to cover site specific items, while some of those shown may be omitted if they are not relevant to a particular dam.

The LCI diagrams play a central part in the risk assessment process and offer four key roles:

- to provide guidance as to the importance of various ‘indicators’ and ‘causes’
- to demonstrate that ALL key elements have been considered
- to provide structure and traceability to the reporting of an inspection
- to provide an aide memoire for the Inspecting Engineer

An important part of this procedure is the completion of an LCI score justification table. This provides a record of the LCI scores and the reasoning behind their allocation. This record is essential to allow the assessor to later review high-risk elements and to confirm and understand the particular risk they pose.

**Criticality and Risk Score**

Having completed the appropriate LCI diagram for a site, criticality and risk scores for each dam element may be calculated. These scores may be defined as:

- Criticality score: $\text{Consequence} \times \text{Likelihood} \times \text{Confidence}$
- Risk score: $\text{Criticality} \times \text{Impact}$

**3.4.3 Risk Management**

Having reviewed and scored all appropriate elements for a site, the next stage is to prioritise these elements so that the risk they pose may be considered in detail. Prioritisation is undertaken through a twin approach. Consider the product of $\text{Consequence} \times \text{Likelihood}$ and the also the value of $\text{Confidence}$ alone. The $\text{Confidence}$ value may be related to the need for investigative works whilst the product of $\text{Consequence} \times \text{Likelihood}$ may be related to remedial works. All of the elements scored are therefore prioritised through the following steps:

1. Initial ranking of all elements according to their *Criticality* score
2. Rank elements primarily according to their *Consequence* $\times$ *Likelihood* product and secondly by their *Criticality* score
3. Rank elements primarily according to their *Confidence* score and secondly by their *Criticality* score

This then identifies the high-risk elements according to their potential need for remedial works and also the need for investigative works. Combining their criticality score with the impact score also allows for a comparison of these elements against the risks posed by elements at other sites. Table 4 below shows an example summary table for the risk prioritisation procedure.
Having prioritised and identified the key risk elements it is then essential that the assessor reviews the scoring and justification behind each high risk element to ensure that the risk is justified. Only by reviewing the score justification tables and understanding the nature of the risk posed will the assessor be in a position to manage those risks through appropriate measures.

Table 4 – Example risk summary table

<table>
<thead>
<tr>
<th>Element Ref.</th>
<th>Cause / Indicator</th>
<th>Criticality Score</th>
<th>Criticality Rank</th>
<th>Cons. X Like. Rank</th>
<th>C x S Rank</th>
<th>Conf. Score</th>
<th>Conf. Rank</th>
<th>Impact Score (Impact x Criticality)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spillway and Components</td>
<td>Seepage / leakage</td>
<td>48</td>
<td>1</td>
<td>3 x 4 = 12</td>
<td>1</td>
<td>4</td>
<td>1</td>
<td>58,320</td>
</tr>
<tr>
<td>Dam body</td>
<td>Internal erosion</td>
<td>40</td>
<td>2</td>
<td>2 x 5 = 10</td>
<td>2</td>
<td>4</td>
<td>2</td>
<td>48,600</td>
</tr>
<tr>
<td>Inlet / outlet works</td>
<td>Pipework damaged Seepage / leakage</td>
<td>30</td>
<td>3</td>
<td>2 x 5 = 10</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>36,450</td>
</tr>
<tr>
<td>Dam body</td>
<td>Settlement Cracking</td>
<td>24</td>
<td>4</td>
<td>2 x 3 = 6</td>
<td>4</td>
<td>3</td>
<td>29,160</td>
<td></td>
</tr>
<tr>
<td>Dam body</td>
<td>Settlement Internal erosion</td>
<td>24</td>
<td>4</td>
<td>4 x 2 = 8</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dam body</td>
<td>Internal erosion Piping</td>
<td>24</td>
<td>4</td>
<td>4 x 2 = 8</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dam body</td>
<td>Settlement Seepage / leakage</td>
<td>18</td>
<td>5</td>
<td>3 x 3 = 9</td>
<td>4</td>
<td>2</td>
<td></td>
<td>21,870</td>
</tr>
</tbody>
</table>

Table 4  Example risk summary table

4  Database analysis (supporting the proposed risk assessment methodology)

Information on the historic performance of UK dams was analysed to provide guidance on allocation of ‘Consequence’ scores on the LCI Diagrams. Data was analysed from three sources:

- The BRE database of UK dams. This was prepared under a DETR project and contains information on some 2700 dams in the UK that come within the ambit of the Reservoirs Act 1975; details are given in Tedd et al (1992). Basic details such as name, location, capacity and type of construction are recorded together with information on problems, investigations and remedial works at a proportion of the dams.
- A database held by A I B Moffat at the University of Newcastle. This database contains over 800 entries associated with incidents at dams in the UK which are, or would have been, subject to reservoir safety legislation. The classification includes information relating to whether there was failure or an incident. Data on the general dimensions of the dams and their performance history including significant remedial/upgrading works, where known, are also included.
- A database held by Dr A K Hughes at RKL-Arup. This database contains more than 700 occurrences of overtopping to dams world-wide. A subset of UK dams details those which have overtopped causing damage and in some cases failure. The database gives data on the general dimensions of the dam, date of construction, etc, as well as notes detailing information relating to the overtopping event.
In order that consistent conclusions were reached using the three databases, a common approach was developed to describe incidents that were reported: four types of incident were defined:

- ‘Failure’ involving a major uncontrolled release of a significant proportion of retained water.
- ‘Category 1 incident’ which involved immediate emergency action or drawdown.
- ‘Category 2 incident’ which caused serious concern and/or involved significant investigation/remedial action.
- ‘Category 3 incident’ which involved the observation of indicators causing serious concern.

Information was sub-divided into various categories based on year of construction, as given in Table 5.

<table>
<thead>
<tr>
<th>Dam/reservoir type</th>
<th>Age categories</th>
</tr>
</thead>
<tbody>
<tr>
<td>Embankment dams</td>
<td>Pre-1840</td>
</tr>
<tr>
<td></td>
<td>1840-1960</td>
</tr>
<tr>
<td></td>
<td>Post 1960</td>
</tr>
<tr>
<td>Concrete/masonry</td>
<td>Pre-1960</td>
</tr>
<tr>
<td></td>
<td>Post 1960</td>
</tr>
<tr>
<td>Service reservoirs</td>
<td>No age category</td>
</tr>
</tbody>
</table>

Table 5 Sub-divisions of dams/reservoirs by age

The dates of the embankment dam categories were based on significant changes in construction techniques, for example the 1840-1960 period covering the central puddle clay core era. The embankment and concrete/masonry dams were also split into three height categories:

- less than 15m
- 15m-30m
- greater than 30m

Although this categorisation is somewhat arbitrary, it was considered that different height categories were appropriate because certain types of incident varied with height: a particular example is settlement and loss of freeboard, which becomes more significant as height increases.

The numbers of each type of incident (e.g. settlement) for each dam age/height category were established and this enabled guidance to be given on the relationship between the type of incident and dam failure. This was done using a consistent rules-based decision matrix to allocate ‘low’, ‘medium’ and ‘high’ consequence estimates.

The databases were also used to identify the critical issues associated with each dam type. A typical list is given in Table 6, for embankment dams constructed between 1840 and 1960.
<table>
<thead>
<tr>
<th>Incident type</th>
<th>% of all recorded incidents</th>
</tr>
</thead>
<tbody>
<tr>
<td>Settlement</td>
<td>18%</td>
</tr>
<tr>
<td>Slope instability</td>
<td>10%</td>
</tr>
<tr>
<td>Seepage/Leakage/Internal erosion</td>
<td>30%</td>
</tr>
<tr>
<td>External erosion</td>
<td>6%</td>
</tr>
<tr>
<td>Overtopping/breaching</td>
<td>4%</td>
</tr>
<tr>
<td>Obstruction of flow</td>
<td>1%</td>
</tr>
<tr>
<td>Valve/gate failure</td>
<td>3%</td>
</tr>
<tr>
<td>Inadequate overflow capacity</td>
<td>24%</td>
</tr>
<tr>
<td>Ancillary damage</td>
<td>3%</td>
</tr>
<tr>
<td>Other causes</td>
<td>1%</td>
</tr>
</tbody>
</table>

Table 6 Incidents at Embankment Dams constructed between 1840-1960

5 Intended Application
A number of guides have been prepared in recent years to assist engineers carrying out inspections and safety works associated with the Reservoirs Act 1975 (e.g. for floods, seismic risk etc). The risk assessment techniques developed are designed to highlight areas where current engineering standards may not be sufficient to ensure safety and/or issues that current engineering approaches may not have addressed adequately. The CIRIA report (CIRIA, 2000) provides a method that may be applied to any reservoir falling within the provisions of the Reservoirs Act 1975, including non-impounding and service reservoirs.

It is anticipated that risk assessments are likely to be used as a tool for owners of several reservoirs to rank the reservoirs in order of risk and hazard, and possibly assist them in prioritising any works needed. Risk assessments are only likely to be carried out for safety reasons on individual reservoirs that pose a significant hazard to life and property downstream. It is not anticipated that risk assessments will be carried out on many small reservoirs where the existing inspection and reporting procedures under the Reservoirs Act 1975 should be sufficient to maintain an acceptable level of reservoir safety. It is not considered likely that an Inspecting Engineer will automatically require a risk assessment to be carried out as part of, or following, his inspection.

6 Conclusions
This paper has offered a brief overview of the risk assessment procedure developed under the CIRIA Risk and reservoirs Project (RP568) for application to UK reservoirs. The procedure offers a ‘simple’ method for determining a measure of potential flood impact for application where more robust assessments are unavailable or impracticable, followed by a method for undertaking a ‘quick’ risk assessment of a dam site. The assessment permits the identification of high risk ‘elements’ and may be used to prioritise risk from elements for single or multiple dam sites. The procedure adopts an FMECA approach which attempts to draw on ‘engineering judgement’ rather than using probabilistic values for which there is often little supporting data.

The methodology has only been tested on a small number of reservoirs to date. It is anticipated that the methodology will be reviewed following more widespread use, and
it may be appropriate to publish an additional guidance note. It is anticipated that the score weighting system in particular may be updated and also that further research and validation of the attenuation method for predicting flood levels along a valley will be undertaken during 2000.

The updating of databases to include information on dam incidents is an ongoing process, and personnel involved in reservoir safety are encouraged to provide information (confidentially if desired) on incidents wherever possible.

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References


