The British Dam Society

Risk assessment of existing flood detention (storage) reservoirs

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SYNOPSIS The Environment Agency is carrying out a portfolio risk assessment of their portfolio of around 200 large flood detention reservoirs (FDRs), to inform their reservoir safety management and operation.

The 'Guide to risk assessment for reservoir safety management' (RARS) was published in 2013 and provides a methodology for risk assessing existing reservoirs in the United Kingdom. It was intended primarily for reservoirs which are normally full, where indicators of poor condition can be observed. It was therefore necessary to extend RARS to cover FDRs, and this paper describes the key elements of the extension to the RARS Tier 1 methodology. It is anticipated similar extensions could be applicable to FDRs owned and operated by other agencies. The next step is to extend RARS for Tier 2 and 3.

Washland flood detention reservoirs are in effect partially bunded reservoirs, so some aspects of the approaches adopted here will also be applicable to non-impounding reservoirs.

INTRODUCTION

Modern management of reservoir safety is moving towards a risk-based approach, recognising that risk can never be zero (unless the asset is removed), but that risk can be reduced to as low as reasonably practicable, where the benefits of the asset in reducing damage from operational floods outweigh the consequences and risks of the dam failure and release of the reservoir.

In the UK, the first guide to provide a means of quantifying the risks to the public from reservoir failure was published in 2014 – the Interim Guide to Quantitative Risk Assessment for UK reservoirs (Brown and Gosden, 2004), with this being updated and extended in the Guide to Risk Assessment for Reservoir Safety Management (RARS) in 2013 (EA, 2013).

RARS is intended primarily for reservoirs which are normally full, where indicators of poor condition can be observed. However, flood detention reservoirs (FDRs) are normally empty and only fill during floods to reduce the effects of flooding downstream, hence it was necessary to extend RARS to cover FDRs.

Managing Risks for Dams and Reservoirs

The term "flood detention reservoir" (FDR) is used in this paper, rather than flood storage reservoirs (FSRs), as this more closely follows international practice and emphasises that the purpose is to attenuate, rather than store floods.

This paper describes the key:

a) challenges in applying RARS to FDRs

b) elements of the extension to the RARS Tier 1 methodology to accommodate FDRs

c) comments on the likely extension needed for Tier 2

It is anticipated similar extensions could be applicable to FDRs owned and operated by other agencies.

PROJECT OBJECTIVES

In 2013, the Environment Agency commissioned HR Wallingford to convene a consortium of experts to produce RARS. The aim of the guide was to provide a tool for reservoir safety management and, although not a statutory requirement, it is viewed as best practice for reservoir owners/operators. It takes a three-tiered approach to assessing risk moving from qualitative (Tier 1) to quantitative (Tier 2 & 3).

The overall objective of this project is to provide an improved baseline understanding of risk associated with all the Environment Agency FDRs. Specifically, this involved the completion of Tier 1 assessments for over 200 reservoirs, following RARS guidance and best practice to demonstrate a pro-active and exemplary approach to reservoir safety management.

To help manage and deliver this process, the Environment Agency commissioned HR Wallingford to develop a web application that provides a digital version of the Tier 1 assessment process as documented within the published guidance. The RARS Tier 1 App was designed to allow multiple users at different organisations to undertake the risk assessment work in a structured and auditable manner.

The assessments were carried by teams of experienced reservoir engineers at Jacobs and Binnies, who assessed the reservoirs on the east and west sides of England respectively. The project team included staff who had written the original RARS guide, which facilitated the reviewing and refining the risk assessment process.

RARS METHODOLOGY FOR RISK ASSESSMENT

This was written in 2013, building on the Interim Guide (Brown and Gosden, 2004), with various erratum (Wallis and Brown, 2014 and 2017) incorporated in the 2017 edition, which is on the website at https://www.gov.uk/flood-and-coastal-erosion-risk-management-research-reports/risk-assessment-for-reservoirs. In addition, there were some extensions published in Peters et al (2016), developing key themes.

The process and key stages within the risk assessment methodology follow the process as shown in Figure 1.2 of the RARS guide.

ENVIRONMENT AGENCY PORTFOLIO OF FLOOD DETENTION RESERVOIRS (FDRS)

The Environment Agency is the undertaker for 217 FDRs, of which around 79 are washland reservoirs, concentrated in the low-lying regions of Yorkshire, East Anglia and the Somerset Levels as shown on Figure 1 of Courtnadge and Brown (2022). Washlands are similar to bunded and non-impounding reservoirs in that there are a number of perimeter banks, and the likely consequences of failure are likely to vary with position around the perimeter.

This project was applicable to both impounding flood detention reservoirs constructed across valleys to impound floodwater, and to washland reservoirs. Courtnadge and Brown (2022) describes some of the key challenges in assessment the safety of washland reservoirs and describes the approach that has been adopted in this project.

EXTENSION OF RARS TO FDRS

General

In practice this occurred in several stages as queries arose both in developing/testing the App and later when applying the App where the standard RARS methodology shown in the software was not always intuitive or directly applicable in certain circumstances to FDRs. There were also refinements after practitioner feedback from the two consultants upon completion of a pilot of ten initial assessments each. It was therefore necessary to both update the App, and to produce supplementary guidance to align the large project team, which included:

a) Guidance produced by HR Wallingford for use of the App

b) FAQs (many of which were clarifying standard RARS terminology in the App, for specific use on FDRs)

c) Supplementary in-house prompt list for completing an assessment, produced and used in-house by each of the companies carrying out the risk assessments

The extensions to RARS are summarised in Table 1 and discussed under each step of the risk assessment in the following text.

The RARS App

This is a cloud-based system. Users undertaking a risk assessment are able to log in and select, from a pre-populated list of EA reservoirs, which reservoir they wish to assess. If the selected reservoir has not previously been assessed, an empty Tier 1 Assessment form is opened. This mirrors all the steps that are defined in the RARS Guide for a Tier 1 assessment. Upon completion, the assessment is 'Submitted' whereupon all the data are posted to the secure cloud server.

Once complete, the App allows the assessment for a reservoir to be reviewed at any time. Upon selecting a reservoir, if already assessed, the latest data are retrieved from the database and loaded into the Tier 1 Assessment form where they can be reviewed, updated and resubmitted. This ensures that the App becomes a valuable resource for reviewing and later updating the latest Tier 1 risk assessment for each reservoir in the EA FDR portfolio.

Table 1. Areas where extensions have been added to RARS to accommodate FDR

Step	Aspect	Need for extension	Extension to RARS Tier 1
Prep.	Define critical dam location	Washland reservoirs have multiple perimeter banks; often not self-evident which is highest risk bank	See Courtnadge & Brown (2022). Default was to assess highest consequence (i.e. location assumed for Reservoir Flood Mapping (RFM))
1b	Potential consequences	National Reservoir flood mapping (RFM) now has two scenarios, dry day and incremental wet day.	Add comparison and decision step (use maximum consequence scenario)
2a	Intrinsic condition	Many FDRs lack information on internal zoning	Extend Table 4.17 of RARS
2a	Current condition score	As not normally full, normally no indicators of performance available while retaining water	Extend Table 4.18 of RARS
2b	Spillway chute	Likelihood of failure due to scour of grass reinforced spillway	Not covered by RARS. Method developed
2b	Slope stability	Phreatic surface in most reservoirs governed by steady seepage from full reservoirs, FDRs subject to periodic overflow but otherwise dry	Extend Table 4.6 of RARS

The Tier 1 Assessment form follows the published guidance very closely. The first part is to enter some key properties of the reservoir, for example, type, capacity, dam crest, width and height, upstream and downstream slopes, PMF value, spillway capacity and so on. Next, in Step 1: Risk Identification, the user identifies the credible failure modes and reviews the potential consequences (pre-loaded from assessment of the RFM mapping by EA). In Step 2: Risk Analysis, for each credible failure mode the form allows the likelihood of failure to be assessed using previously entered data wherever possible. Lastly the risk is calculated using the likelihood and consequence matrix from the RARS Guide.

Finally, in Step 3: Risk Evaluation, the reservoir engineers give judgements on options to reduce the risk, their recommendations and other considerations, before uploading the assessment. Throughout the assessment, there are boxes for entry of supporting information and metadata (e.g. free text reference or weblink to data) that might be useful when reviewing the results and moving on to Tier 2 level assessment.

The RARS App has brought several advantages over a more traditional (e.g. spreadsheet based) approach:

- There is consistency across all assessments, including those entered by different engineers and organisations
- The app has enabled the assessments to be undertaken more efficiently
- There is a documented sign-off process and means for storing additional supporting information
- Being an online form, updates to the RARS App are instantaneous across all 217 assessments, with no need to update individual computers or any risk of people having old versions of software

- The results are stored securely in the cloud; many users can input and review data concurrently and it is possible to make global updates to the data such as those described in this paper.
- The data can be updated and resubmitted and an audit trail produced tracking progress of the understanding of the risk at each site over time. It will be possible to determine changes in risk across the portfolio of reservoirs over time

A dashboard viewer has been created to show the headline summaries for all reservoirs with a map, graphs and tables being available to look for trends and outliers

Review and validation of output

The output of each consultant was revised and validated in-house, with further reviews of the completed assessments by HR Wallingford and the EA. The data and principals in Section 15.2 (Basis of a tiered set of tools) of RARS were used in this review.

PREPARATION

As with any risk assessment of an existing reservoir, a key stage is collating the available data needed for the assessments. This had to be provided by the reservoir manager and was similar to the information needed for a periodic inspection under Section 10 of the Reservoirs Act. This was recommendation 4 from the Balmforth report Part A (2020). The first step of the App was to populate key data on physical attributes of the reservoir, and the App was extended in use to provide space to comment on the provenance of the data.

Dam location to be used in risk assessment

A significant challenge for washland reservoirs was identifying which dam section was to be assessed, with options shown in Table 2. At Tier 1 level, it was assumed that if a reservoir is retained by multiple dams then the assessment would be for the highest consequence dam (e.g. for a washland this would normally be the barrier bank, or where no barrier bank the highest part of the riverside bank).

Table 2. Considerations at washland reservoirs to define location of bank subject to risk assessment

Location	Factors which may make highest risk
River bank	Likely to be lower than barrier bank so overflows first. Sometimes varying construction, and some may have originally been transportation embankments e.g. old railways
Transverse banks (across flood plain)	May be housing, or other receptors, present remote from reservoir
Barrier bank	Housing present below crest of barrier bank, which would be inundated if barrier bank failed during a flood

Key dimensions of dam on which risk assessment carried out

Some of the features present at washland reservoirs, and how they were assessed are shown in Table 3.

Table 3. Approach adopted in defining features of dam to be analysed

Aspect	Adopted in the Tier 1 PRA
Number of spillways	Include option for two spillways in the app, so that a check can be made on the spillway and main river bank (in terms of operating as an overflow).
Absence of spillway	Assume river bank acts as a spillway
Catchment area	Direct catchment of the reservoir, which for washlands reservoirs is the reservoir area and any direct catchment on the adjacent valley side, rather than the indirect catchment for the adjacent main river (Courtnadge and Brown, 2022).
Spillway crest length	As FDRs often have earth spillways with no well-defined "weir crest" and depths of overflow are modest and similar to irregularities in crest level, the effective length of the spillway was reduced to provide a more realistic estimate of the length likely to overflow (e.g. for riverbanks 10% of the length)

STEP 1 RISK IDENTIFICATION

Step 1a Failure mode identification

Threats, failure modes and breach types (for Tier 1) of RARS was amended such that the failure modes shown in Table 4 were analysed for FDRs.

Table 4. Failure modes considered in Tier 1 assessments

Threat	Failure mode		Comment
Internal	FM1	Internal erosion in embankment	
	FM2	Internal erosion in foundation	
	FM3	Internal erosion along interface between structure and embankment	
External	FM4	Flood – crest overflow	
	FM5	Floods – overflow of sides of chute	Not often considered credible at FDR
	FM6	Slope Instability of downstream slope	
	FM7	Floods - scour of downstream slope	Not covered by RARS. Method developed

Step 1b Potential Consequences of dam failure and release of reservoir

This was pre-populated from the national Reservoir Flood Mapping (RFM) data held by the Environment Agency. However, this was also expanded by the EA Geomatics team to include the other measures of consequences not included within RFM data, namely community health assets, economic activity, environment and cultural heritage.

For washlands the dry day normally has higher consequences and is used to assess risk. This is because in the wet day scenario if the washland is at capacity or spilling, it is likely that the adjacent watercourse is at the same raised level, and fluvial flooding is likely have occurred downstream due to runoff from the adjacent main river catchment and warning/ provisions made.

STEP 2 RISK ANALYSIS

Step 2A likelihood of failure due to internal threats

As FDRs are normally dry, indicators of poor condition may often not be observed. It was therefore necessary to extend RARS Tables 4.17 and 4.18 to cover FDRs, as shown by the red text in Tables 5 and 6.

Table 5. Extensions to RARS Table 4.17: Supplementary guidance on assigning intrinsic condition score for embankment dams (Tier 1)

Intrinsic condition score	**Extent to which feature means dam is vulnerable to failure, that is, criticality in failure modes analysis**		
	Embankment		**Foundation**
	Features present at site	**Fallback for section of flood detention reservoir being assessed where no information (Note 2)**	
5 – Body of dam/foundation vulnerable to failure	Embankment shoulder does not act as a filter to core Hydraulic gradient across core > 5	Historic transportation, or flood defence, embankment forms part of section of embankment being assessed	a) Erodible or compressible foundation b) No foundation treatment such as slush grout/dental concrete on open jointed hard rock foundation
4	Erodible core material (silt or dispersive)	a) Embankments built by developer before 2000 b) embankments built with colliery spoil	
3	a) Downstream slope steeper than 2H:1V b) Abutment slopes > 1V:1H or steps > 0.1H c) No filtered drainage in downstream shoulder		No foundation cut-off
2	Core material low plasticity clay	Modern dam built since 2000 (i.e. likely to have been designed after Environment agency founded in 1996)	
1 – Design/ construction inherently resistant to failure	Filtered core		On in situ rock, which is low permeability/been adequately treated to reduce risk of internal erosion

Notes:

1. Selection of score is judgement by user. Either take highest score (worst case) across both columns as giving condition (not average or minimum), or where several vulnerable features combine to give higher score. Where unsure (for example, no drawings) then do not score zero, but score most likely condition (for example based on typical construction practice at time the dam was built or upgraded).
2. Amended following the same approach as set out for Tier 2 in Table 8.17 of RARS

Table 6. Extensions to RARS Table 4.18 Supplementary guidance on assigning current condition score for embankment dams (Tier 1). 'Current condition scoring' system for probability of failure due to internal threats

Current condition score	Extent to which feature is symptomatic of performance and thus likelihood of failure		
	Surveillance and Monitoring	**Reservoir operation/ability to lower reservoir**	**Extended guidance for FDR**
3	• Surveillance <2 per week in dams which are vulnerable to rapid failure (Note 2) • No surveillance (dam not vulnerable to rapid failure) • For flood detention reservoirs the surveillance during impounding events is applicable, which is normally daily, so this is not normally the governing consideration		Normal for washlands, which are more difficult to check every metre length
2	• No instruments at dam, or readings not evaluated within one week of reading • Poor ability to inspect (that is, large leak would not be detected	• Never been filled - for example flood detention reservoir • No fixed bottom outlet/means of lowering reservoir in an emergency • Annual refill is rapid (>10% of dam height/week) • Rate of lowering with fixed bottom outlet < Hinks formula	Normal for impounding reservoirs

Notes:

1. No change to features for seepage quantity or deformation, or Current condition scores 1, 4 and 5.
2. Selection of score is judgement by user. Take highest score (worst case) across all columns as giving condition (not average or minimum). Where unsure (for example if no settlement or seepage monitoring) then do not score zero but score most likely condition.
3. Dams which include one or more of the following are vulnerable to rapid failure – (i) non-cohesive core, (ii) sandy foundation, (iii) outlet pipe in cut and cover trench with no sand collar filter

Step 2B Likelihood of failure due to external threats

FM7 Erosion of surface protection to spillway

It was recognised at the onset of the project that a key failure mode, erosion of a grass spillway, was not included in RARS, so the matrix shown in Figure 1 was developed to provide a Tier 1 assessment of the likelihood of failure.

Figure 1 Likelihood of failure for grass spillways

velocity in safety check flood) / CIRIA 116 allowable velocity (% overstress)	Quality of information on design and construction (note 2)			Source/ comment
	Poor e.g. no construction records	Good i.e. drawings include anchor/ overlap details	Excellent e.g. trial excavations to confirm depth of topsoil	
>175%	Extreme	Extreme	Very High	
150%	Extreme	Very High	High	
125%	Very High	High	Moderate	
100%	High	Moderate	Low	This is allowable velocity, so would not expect failure if properly designed i.e. these values selected on basis of RARS table 15.3. This also reflects that the values of v calculated by the app will be peak values, not the full 10 hour duration
75%	Moderate	Low	Very low	
50%	Low	Very low	Very low	

Notes

1. For reinforced grass systems the above assumes average quality grass (for plain grass systems the grass quality should be compared to the design/ S10 requirements). Where grass is poor (based on most recent S12 or S10, whichever is most recent) then increase level of risk by one class
2. As well as the quality of grass cover, the effectiveness of grass spillways also depends on the depth of reinforcement below the surface, the detailing of laps and anchors trenches, and the presence of granular layers beneath concrete systems. We suggest the input data includes assessment of quality of the grass reinforcement

FM6 Slope stability

The methodology given in RARS for assessment of the likelihood of slope instability of an embankment dam was developed for a normal reservoir which is full most of the time, so the downstream slope is dry with a phreatic surface governed by seepage through the dam core/ foundation.

This is inappropriate for flood detention reservoirs, where the downstream slope is normally also the downstream side of the spillway, and thus subject to periodic overflow when the spillway is operating, when the slope is likely to saturate and thus be subject to a different pore pressure regime from the above. Tables 4.6 and 4.8 of RARS were therefore amended for use in checking the stability of a spillway slope under overflow as shown in Table 7. Table 8 gives an updated example illustrative of output for RARS Box 4.4. The App includes a switch to select whether the slope stability is being assessed for the spillway slope, subject to overflow, or a non-overflow section of the perimeter bund.

Table 7 Extension to Table 4.6 of RARS Indicative modern slope design

Soil type	Downstream face (no overflow)		Downstream face of spillway (subject to overflow) (Note 2)
	Modern design slope (Note 1)	Source	
Sand, gravel	2.5H:1V	Section 9.2.3 of CIRIA Report 161 (Kennard 1996a)	3.6H:1V
Low plasticity clays	3.0H:1V		4.3 H:1V
High plasticity clays	4H:1V	Figure 10 of Vaughan et al. (1979). For more detailed assessment where slope angle is related to geological origin of the construction material reference can be made to Table 4 of Parsons and Perry (1985).	5.7H:1V

Notes

1. Downstream slope on good foundation. Where pre-existing shear surfaces are present at the ground surface (for example, due to periglacial action), then much flatter slopes would be required. For example, the redesign of Carsington dam adopted flatter slopes (Johnston et al. 1999) and overall slopes of around 10H:1V have been required on some dams to ensure foundation stability.
2. Equal to 70% of the slope in column 2. This value of 70% has been derived using spencer stability charts (Spencer, 1967), and assuming that RARS Table 4.6 refers to slope with c' of zero and ru of 0.25.
3. Table 4.8R Likelihood of release of reservoir given slope instability. Add note 1. Reduce output likelihood score by one increment where spillway to flood detention reservoir

Table 8. Extension of RARS Box 4.4R. Example for illustrative purposes of instability of embankment slope.

Parameter	Units	Embankment face with no overflow		Downstream face of grass spillway (subject to overflow)	
		Value/ Score	Remarks	Value/ Score	Remarks
Slope angle SA	H;V	2.5		4.0	Typical on grass spillways
Crest width	m	11	36 feet (11m)	5	
Dam height	m	12		8	
C/H		0.9		0.63	
Modern design standard slope angle (Table 4.6) SM	H:V	3.0	Using Table 4.6 – Assume low plasticity clay. Slope = 3.0H:1V based on Kennard (1996)	4.3	Assume low plasticity clay
Difference to modern slope design (SM-SA)/SM	%	17%		7%	steeper
Likelihood of slope failure (Table 4.7)		High	Slope is up to 25% steeper	Moderate	
Likelihood of release of reservoir given slope instability (table 4.8)		Reduce by two increments	as example at base of Table 4.8	Reduce by one increment	as new Note to table 4.8
Overall likelihood of reservoir failure		Low		Low	

Steps 2D and 2E Consequence analyses and level of risk

These are prepopulated in the App, but with provision for the user to make manual corrections.

Steps 2F Review outputs

The App includes the suggested checks in RARS with the user to populate whether they consider the assessment's output complete, credible and are confident in the output, together with any comments on data gaps etc.

Step 3 Risk evaluation

The App includes the suggested checks in RARS under Steps 3d and 3e (earlier steps not applicable to Tier 1, or for 3b not in project scope) with the user to populate whether they are satisfied, together with any comments.

DISCUSSION

Challenges/ lessons learnt

The main challenges were achieving consistency between assessors, and in achieving a common understanding of headings/ terminology in the App. The exact terminology used in the RARS Guide was reproduced in the App but this was not always easily understood by the users in relation to FDRs, particularly where terms varied for different reservoir types. This was resolved by production of supplementary "guides" and in-App prompts. The project intends that these assessments would then be used by Environment Agency asset managers, so these guides and training will be critical if the asset managers are to understand, and use, the risk assessments in managing their assets.

Another challenge was the project programme, as the App was updated several times, both to clarify headings and/or to add the extensions needed for FDRs, and update it with the consequence data from the latest national RFM outputs as these became available.

Validation of Tier 1

The outputs were reviewed against each other, and against the indicative range of likelihood of failure of UK dams given in Figures 15.3 and 15.4 of RARS (using the implied ranges of quantitative values in Table 15.3 of RARS).

The main anomaly discovered was that by including economic activity and environmental designations at Tier 1, this often resulted in the highest (i.e. a class 4) consequence even when there is no population at risk. Thus it is implied, for example, that a single SSSI is equivalent to multiple fatalities. As these receptors cannot easily be monetised at Tier 2, RARS plots them separately from the property damage and life loss when assessing risk, as shown in Figure 9.3 of RARS, and it may be worthwhile doing the same at Tier 1.

Implications for Tier 2 and 3

The extensions listed in Table 2 will also be necessary for Tier 2, as FDRs have fundamental differences from reservoirs which are normally full of water. In addition, it will be necessary to consider how to treat dry and wet day failure scenarios. This is not straightforward as the "dry day" for FDRs is when the reservoir is full in an operational flood, but not spilling, so it may be appropriate to derive two separate probabilities for internal threats, relating to dry and wet day failures.

Managing Risks for Dams and Reservoirs

Another challenge will be developing methodology to ensure consistency in identifying failure modes at flood detention reservoirs, as these vary from normal dams. Although the principals in sections 16 ('Guidance on failure mode identification') and 7 ('Tier 2 – Step 1 Risk Identification') of RARS can be used, it is likely that a framework will need to be developed, trialled and then reviewed against actual performance. Useful data to validate the output would involve collecting data on:

- Annual failure rates of flood embankments (fluvial and coastal) as these have many similarities to FDRs
- Incidents and failure of control systems on active flow control systems.

It is also noted that internationally good practice in carrying out risk assessment has developed significantly since 2013 and some aspects of these may be of value in extending the Tier 2 analysis to FDRs.

CONCLUSIONS

The Environment Agency has carried out a Tier 1 risk assessment on their portfolio of 217 flood detention reservoirs (FDRs), which allowed screening of reservoirs where risk is tolerable, and those where more detailed study is necessary. This has necessitated various extensions to the Tier 1 methodology in RARS and this paper describes these extensions and refinements relevant to FDRs. Similar extensions could be applicable to FDRs owned and operated by other agencies. The updated methods have been encoded within a web-based application that has been used by multiple staff at multiple consultant organisations to undertake the consistent risk assessments, and this has produced a live database of Tier 1 assessments for all EA's FDRs.-

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