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Environment Agency

delivering benefits through evidence

Reservoir Safety Research Strategy

Report – SC130003/R

Flood and Coastal Erosion Risk Management Research and Development Programme

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We operate at the place where environmental change has its greatest impact on people's lives. We reduce the risks to people and properties from flooding; make sure there is enough water for people and wildlife; protect and improve air, land and water quality and apply the environmental standards within which industry can operate.

Acting to reduce climate change and helping people and wildlife adapt to its consequences are at the heart of all that we do.

We cannot do this alone. We work closely with a wide range of partners including government, business, local authorities, other agencies, civil society groups and the communities we serve.

This report is the result of research commissioned by the Environment Agency's Evidence Directorate and funded by the joint Flood and Coastal Erosion Risk Management Research and Development Programme.

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- **Delivering information, advice, tools and techniques**, by making appropriate products available.

Doug Wilson

Director of Research, Analysis and Evaluation

Executive summary

The first Reservoir Safety Research Strategy was published in 2009. This report aims to refresh research requirements to reflect current priorities for reservoir safety research in the UK. The research priorities have been revised to reflect:

- new challenges presented to reservoir managers and operators through severe weather events and in the face of climate change
- developments in methods and materials
- changes in reservoir safety legislation
- apparent needs arising from recent research and incidents

The report summarises the progress made against the recommendations of the first strategy.

A baseline review and gap analysis was performed in relation to various reservoir safety themes. An industry-wide consultation was then conducted to determine the outline scope of prospective research topics and to prioritise them. Workshops were held with reservoir safety professionals and academics working in related fields to discuss the various topics and to explore linkages between the needs of the reservoir industry and current/planned university research.

The top ranked topics were developed to provide a preliminary scope for project implementation. Prospective sources of funding for these and other research projects have been identified, with an emphasis on diversifying potential sources of research funding.

Proposals for how the strategy should be delivered are presented. The proposed roles and responsibilities of key personnel, committees and other bodies are described. Consideration is given to how the strategy can be kept ‘live’ by evaluating new research requirements as needs are identified by the reservoir industry and from national and international events.

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This research project was led by a Project Board comprising:

- Tony Deakin, Environment Agency – Chair
- Craig Woolhouse, Environment Agency – Project Sponsor
- Dave Hart, Environment Agency – Project Manager
- Neil Rich, Environment Agency – Business User
- Steve Naylor, Environment Agency – Senior User

The project team was led by:

- Alan Warren, Mott MacDonald
- John Chesterton, Mott MacDonald

The project steering group included:

- James Ashworth, SEPA (corresponding member)
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- David Porter, Rivers Agency Northern Ireland (corresponding member)

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- one-to-one consultees listed in Table 5.1
- participants of the industry workshop listed in Table A.3
- participants of the academic engagement workshop listed in Table A.4

Contents

1 Introduction

1.1 Background

Some 1.2 million people across England and Wales live and work in the flood inundation area of a reservoir,[1] should any one of them fail. The average age of these structures is 120 years and, without intervention, the possibility of a catastrophic failure may increase. The risk of such an emergency varies depending on a range of factors including dam type, dam age, reservoir infrastructure, the level of maintenance and competency of operation.

The need for a legal framework to ensure public safety is recognised in the Reservoirs Act 1975, which is the primary instrument for reservoir safety in England and Wales. The responsibility for its enforcement in England lies with the Environment Agency. In Wales this responsibility sits with Natural Resources Wales. The Scottish Environment Protection Agency (SEPA) fulfils this function for Scotland under the provisions of the Reservoirs (Scotland) Act 2011. The Department for Environment, Food and Rural Affairs (Defra) and these agencies not only ensure reservoir owners comply with the legal requirements, but also support research and development (R&D) to safeguard reservoirs in the future.

Reservoir safety R&D is carried out as part of the Joint Defra, Environment Agency and Natural Resources Wales Flood and Coastal Erosion Risk Management (FCERM) R&D programme. The current Reservoir Safety Research and Development Strategy (RSRDS) (Environment Agency 2009a) is now more than five years old and many projects from the strategy have now been completed.

A number of developments led to the decision to review the RSRDS.

- Recent severe weather events have presented new challenges to reservoir managers and operators.
- There have been developments in methods and materials.
- Priorities for research have changed as a consequence of climate change and revised legislation, both introduced and planned.
- New suggestions have been proposed for research that was not considered at the time of existing strategy.
- Research projects that have been delivered have made new recommendations for research.
- Incidents that have occurred at dams have prompted new calls for research.

In 2014, Mott MacDonald was commissioned to conduct a review of the progress made against the 2009 strategy and to prepare a new strategy to reflect progress and changing needs.

The strength of the RSRDS is that it has been inclusive and transparent in the way that research priorities have been identified. This has proved to be crucial in obtaining 'buy-in' from the reservoir industry. Building on this success, development of the new

[1] A 'large raised reservoir' as defined by the Reservoirs Act 1975

strategy was through consultation with the reservoir safety industry. Priorities for research must be established through consensus of opinion within that group.

1.2 Objectives

The scope of the strategy is to initiate and encourage R&D furthering reservoir safety in the UK over the coming 5-year period (2016–2021) and beyond. This will be achieved through the identification of industry research needs and the development of a strategy to enable the funding of proposals designed to meet these needs. The strategy seeks to make it easier to translate practitioner needs into research projects and to disseminate the results of R&D back to the industry.

Research proposals identified by the strategy and which fall within the remit of the Joint Programme will be delivered by the Environment Agency's Flooding and Communities team and championed by the Environment Agency's Reservoir Safety Manager. Research proposals that fall outside that remit may be delivered by other organisations. The Environment Agency will be assisted in delivering the reservoir safety work by the Institution of Civil Engineers (ICE) Reservoir Safety Advisory Group (RSAG) which draws on experience from government, industry and academia.

The strategy aims to identify steps to improve the linkages between the reservoir community, funding organisations and researchers.

The aim of the current revision is to build on the 2009 RSRDS with the following main objectives:

1. Review and provide an overview of current and recent UK and international reservoir safety research to establish where useful work is already being undertaken to meet gaps in our knowledge.
2. Review the 2009 RSRDS to identify successes and lessons learned from the existing strategy and to establish progress on proposals within that strategy.
3. Consult with the reservoir safety community including reservoir engineers, undertakers, policymakers and academics to establish and then prioritise the research requirements to support reservoir safety for the next five to ten years.
4. Produce a brief research proposal form for each project and a prioritised road map of proposals to address each identified need.
5. Develop an engagement plan covering the lifetime of the strategy. The project will develop an approach for monitoring the progress and benefits of the strategy.
6. Develop a plan for updating the strategy.

The new strategy also seeks improved integration with R&D in other related areas such as the research councils, EU and international programmes, CIRIA and UK Water Industry Research (UKWIR). Alternative sources of funding were seen to be critical to the delivery of proposals that were not strictly R&D as defined by the Joint Programme.

1.3 Process and definitions

While research needs were previously delineated by disciplines, this document takes a modified approach with the reservoir safety field being divided by **area** and **themes** from which research **topics** are taken. Research topics taken forward into the strategy are referred to as **proposals** for development into funded **projects**. This process is represented graphically in Figure 1.1.

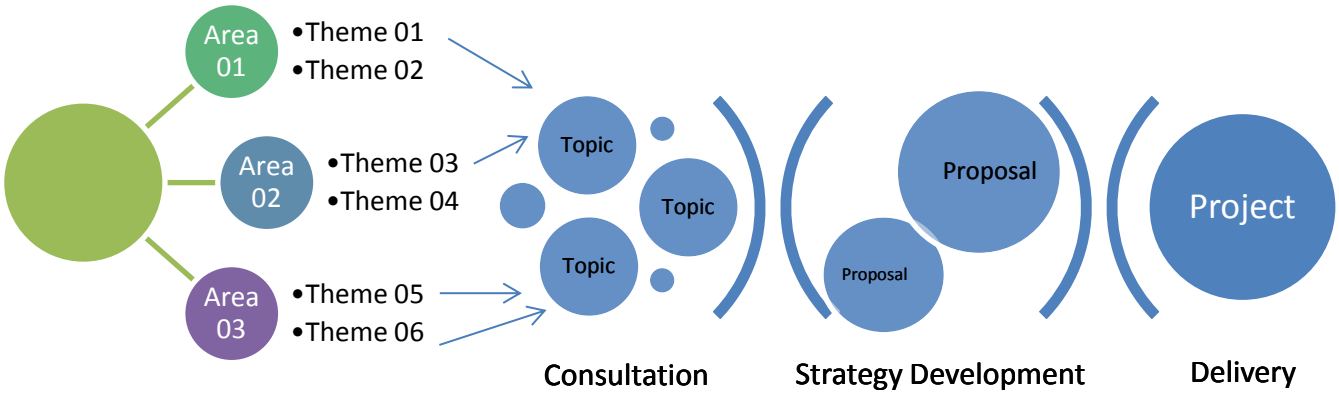


Figure 1.1 Process and definitions

2 R&D context

2.1 Research

R&D can be defined as systematic investigation and work directed toward scientific discovery, innovation and the advancement and synthesis of knowledge, technology or processes.

Research should aim to achieve one or more of the five benefits listed in the UK FCERM Research Strategy (Moores and Rees 2011, Table 1):

- Enabling activities – allowing us to do things we cannot currently do
- Improving efficiency – allowing us to do things more economically
- Improving effectiveness – allowing us to achieve our goals in the right way
- Improving understanding – allowing us to better appreciate the scientific principles needed to address reservoir safety issues
- Providing evidence – allowing us to make and justify better decisions

2.2 Joint Programme

The Joint Programme is a partnership between Defra and the Environment Agency which serves all FCERM operating authorities. It is run by the Environment Agency, Defra, the Welsh Government and Natural Resources Wales. The Joint Programme was set up to ensure the government's investment in FCERM is based on reliable and sound evidence. It develops information and tools to help practitioners to reduce and mitigate the impact of flooding on the UK economy and local communities.

The main objective of the Joint Programme is to develop the timely evidence and innovation required to underpin sustainable FCERM policy, process and delivery through the provision of leading-edge science and development of good practice driven by user needs.

The Joint Programme has three themes:

1. Policy, Strategy and Investment
2. Asset Management
3. Incident Management

And four cross-cutting work areas:

1. Local flood risk
2. Coastal
3. Reservoirs
4. Working with Natural Processes (WWNP) to reduce flooding

The Joint Programme is an end user oriented, applied research programme, steered and peer reviewed by relevant experts. It attempts to bridge the gap between work carried out by others (basic scientific research) and the development of policy and operational guidance and tools.

Research likely to fall within the remit of the FCERM programme should seek to provide and strengthen the evidence needed to improve asset management practice and reduce flood risk. It should develop tools, methods and guidance to ensure all concerned know how to put in place assets that are resilient and adaptable to future change.

The FCERM programme aims to strike an appropriate balance between tactical research to meet immediate needs and strategic research to anticipate and prepare for future and longer term challenges.

2.3 Related research initiatives and links

The following research frameworks are supported by the Environment Agency and may provide linkages or overlapping research projects:

- Coastal Research, Development and Dissemination research framework
- WWNP
- Local Flood Risk Research Framework
- Living with Environmental Change

2.4 Drivers and barriers to reservoir research

To understand the R&D context it is necessary to consider the drivers and barriers to development within the industry.

2.4.1 Drivers

The 2009 strategy detailed the various short-term and long-term factors driving reservoir safety R&D. These included:

- legislative change both in the UK and EU
- climate change
- ageing dams and deterioration
- dam removal or discontinuance
- sustainability and increased demand
- development of renewable energy potential at new and existing sites
- emergency preparedness and communication of risks
- scientific advances and trends
- risk and uncertainty
- specific industry needs such as guidance and tools

Reservoir safety incidents have also spurred research and these, together with safety measures, have been included in the baseline reporting as it is recognised that they are indicative of industry need.

2.4.2 Barriers

It is also important to understand the barriers to research. This enables efforts to be directed during the development of the strategy to find ways around these both in what goes into the strategy and its delivery. Some potential barriers are listed below.

Awareness

Reservoirs often lack visibility and are, by design, low risk and very rarely in the headlines. While incidents at reservoirs have spurred research in the past, reservoir safety research should not be reactive. Awareness of reservoir safety concerns among relevant academics, researchers and agencies may be required to bring this area to the front of people's minds.

Funding

As in all fields, funding is often limited and is typically aimed at addressing specific industry concerns that have measureable outcomes for funders.

Lack of academic involvement

Some academic research is currently being conducted in relation to reservoir safety in the UK. However, few university courses include reservoir engineering and academic attention is focused on matters perceived to be more urgent in areas of flooding and resilience to change. Despite this, these areas are often relevant to and impact on reservoir safety and awareness of this linkage should be encouraged.

Silos

The application of research in other areas to reservoir safety can be missed where those involved in their development are not aware of the needs of the reservoir safety community.

Lack of large new reservoir projects (research focused offshore)

Large civil engineering projects often raise awareness and provide funding for industry R&D.

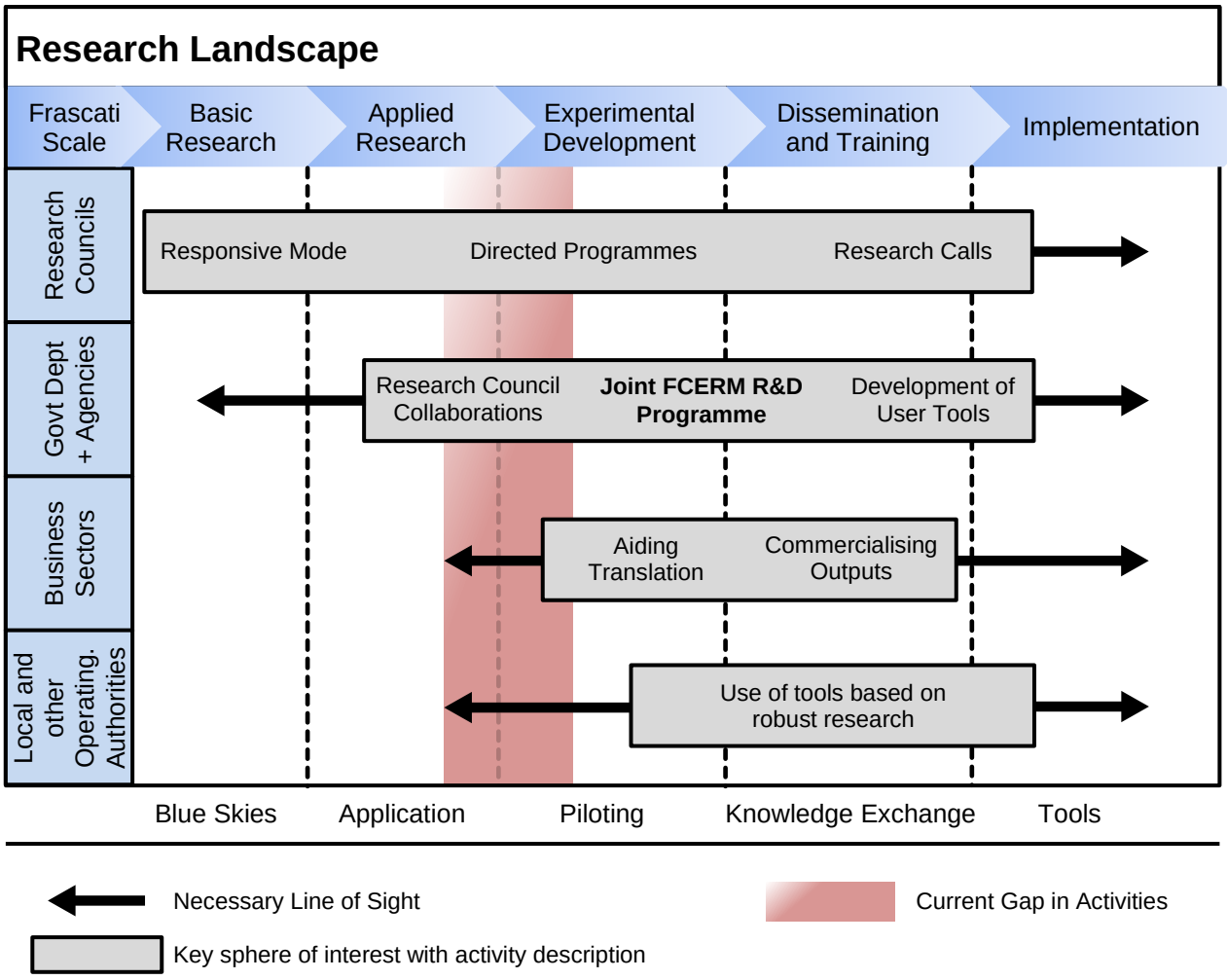
Maturity of research

Reservoir development in the UK has occurred for over 100 years and is a mature field. This also means that many of the fundamental questions have been addressed. Research is often incremental and less likely to result in a step change in the industry and may not be perceived as 'cutting edge'. But despite the extensive research in this area, many questions remain and advances in geotechnics, hydraulics, materials and instrumentation continue to be made.

2.4.3 R&D landscape

To better understand the R&D context as viewed by the Joint Programme, the R&D landscape is summarised in Figure 2.1. The Joint Programme aims to occupy a

position between basic academic-led research and practitioner needs. It thus provides a translator role in the pipeline of research delivery.



Source: Moores and Rees (2011, Figure 3)

Figure 2.1 Research landscape: the relationship between research spectrum and key stakeholder groups

3 Methodology

3.1 Baseline

To develop this strategy, a baseline was first established to determine the state of research in the field and to evaluate how the baseline had moved since the 2009 strategy was published.

Industry needs were evaluated using background information provided by the Environment Agency on reservoir incidents and statutory safety measures to provide insight to the issues faced by the reservoir community.

The previous strategy was reviewed and the progress against its recommendations reported.

A literature review was also carried out. Reservoir safety research encompasses many disciplines and specialties in science and engineering. As such it was not possible to conduct a comprehensive review of all developments in fields relating to reservoir safety. Instead an overview approach was taken that focused on:

- research or guidance published by organisations involved in reservoir safety
- the adequacy/age of existing guidance and tools

3.2 Consultation

A variety of consultation formats were used to identify the perceived needs of the reservoir community and to establish what research is currently being undertaken.

A final list of 76 research topics was developed and prioritised at an industry consultation workshop.

Consultations were also held with research councils and other funders or facilitators to establish links and to explore alternative routes for the delivery of identified projects.

3.3 Proposal development

Following the consultations and the identification of needs and priorities, proposals were written to give detail to the higher priority areas. Where appropriate, research topics addressing similar areas were combined. This resulted in a final list of 42 research proposals of which 7 were developed in detail. These are presented in Appendix B.

3.4 Funding and delivery

With final prioritised proposals in place, routes for their delivery were summarised.

3.5 Driving the strategy

Recommendations are made to carry the strategy forward, keeping the project list current and maintaining engagement with industry and academics.

3.6 Strategy process diagram

The steps used to develop the strategy are summarised in Figure 3.1.

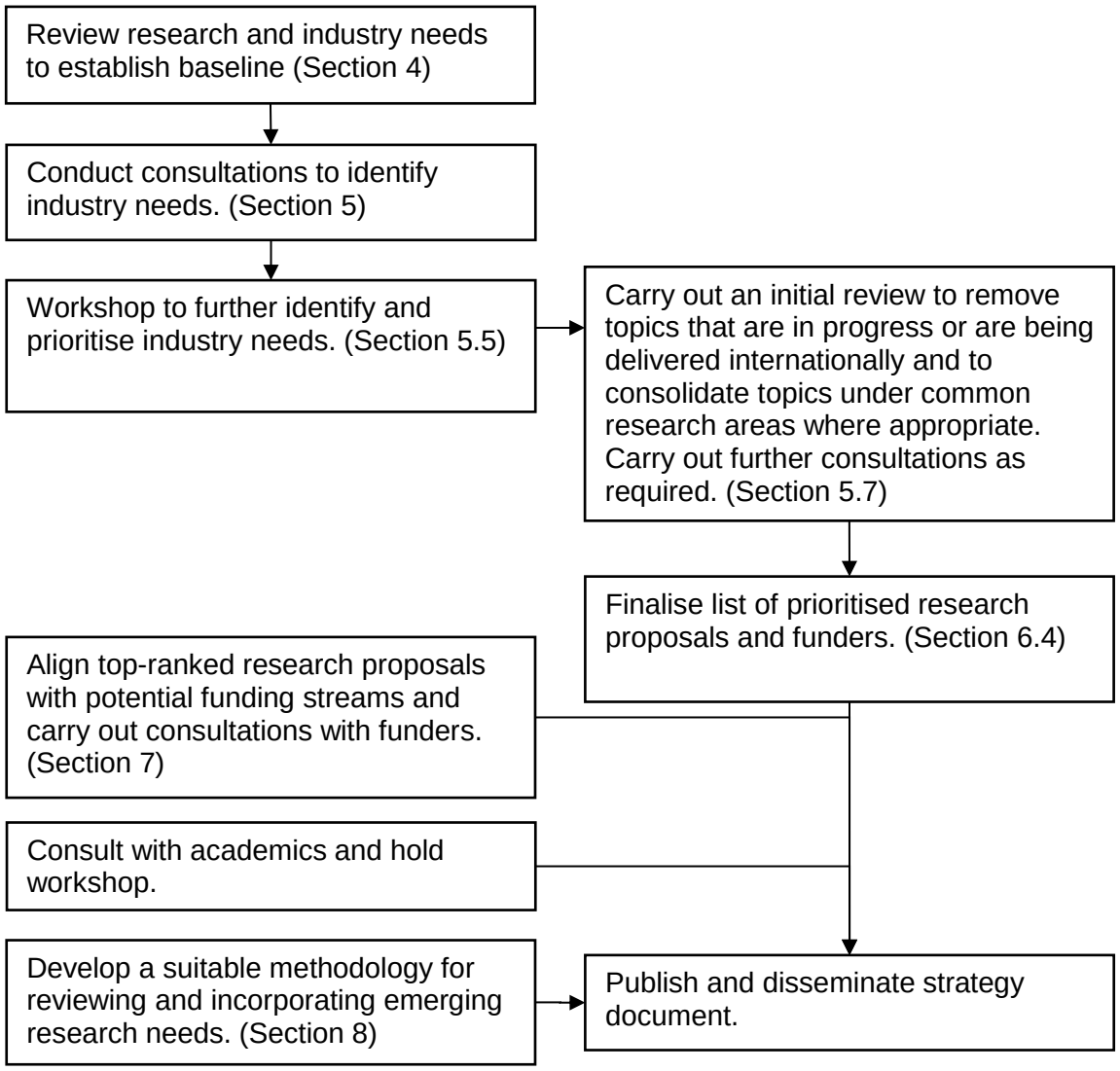


Figure 3.1 Process for research strategy development

4 Background and R&D baseline

4.1 Introduction

The industry and R&D baseline report was produced to inform deliberations on the further development of the Environment Agency's 2016 reservoir safety research strategy. The report provided the output of the review stage of the project and covered:

- a review of the progress made against delivery of the top-ranked research projects recommended in the 2009 RSRDS
- a summary of the reservoir safety incidents reported to the Environment Agency since 2008 (when the first strategy was prepared)
- a summary of the matters instigating statutory recommendations made under Section 10 of the Reservoirs Act 1975 since 2008
- development of a list of reservoir research themes against which to map developments in research
- the results of a review of reservoir safety literature, including all UK and selected international publications since 2008
- a gap analysis (Appendix D) to highlight the subject areas where recent progress has been made and where little information exists to inform guidance for reservoir safety practitioners

The gas analysis aims to ensure that:

- research effort is not duplicated
- new work is focused on areas of greatest perceived need for which more research and guidance are required

Sections of this part of the report were used to brief participants at the industry consultation workshop.

4.2 Background information

4.2.1 Reservoir safety incidents and failures

The purpose of reservoir safety research is to promote best practice in the design, construction, operation, monitoring, surveillance, maintenance and decommissioning of reservoirs. Although there has been no loss of life in the UK due to reservoir failure since 1925, serious incidents and dam failures continue to occur at regular intervals.

The Environment Agency has administered the national incidents database since 2007. A system of voluntary post-incident reporting for the UK was introduced at the same time, and annual reports and bulletins have been published to report on the various types of recorded incidents.

However, a significant proportion of incidents were not reported under this system. With the recent amendments to the Reservoirs Act 1975, it is now a mandatory

requirement for undertakers to report incidents that occur at reservoirs in England and Wales.

Of the 76 incidents recorded for the UK between 2004 and 2013, 49 occurred at statutory reservoirs and 27 at non-statutory reservoirs. From this record, it can be seen that the threats to reservoir safety were near equally distributed between those arising from external threats (principally flooding) and internal threats (principally internal erosion). The related mechanisms of deterioration are shown in Table 4.1.

Table 4.1 Breakdown of the 76 reservoir incidents between 2004 and 2013 by mechanism of deterioration

Mechanism of deterioration	Percentage of total
Erosion by flood overtopping	32
Internal erosion – hydraulic fracture	18
Internal erosion – adjacent to structures	8
Internal erosion – other	7
Pipework/culvert deterioration	7
Damage to safety-critical structures/equipment	3
Settlement	3
Deterioration of dam fill material	3
Deterioration of foundation	3
Deterioration of structures	3
Other/not known	13

Source: Environment Agency research (Environment Agency 2013c)

Note that higher proportions of incidents do not necessarily translate to higher R&D requirements.

Flood overtopping incidents occurred between 2004 and 2013 at both statutory and non-statutory reservoirs. They typically occurred at small dams following intense rainfall over small catchment areas.

Although internal erosion accounts for a third of all of the reported incidents, statutory recommendations relating to internal erosion are very small in number and generally relate to material investigations and seepage studies. The threat from internal erosion tends to be treated in a reactive manner on the basis of monitoring and surveillance information, whereas flood risk is more proactively reduced through freeboard studies and spillway capacity improvements. Some other notable causes of incidents include:

- spillway damage during floods, causing erosion of the downstream shoulder (for example, Ulley and Boltby)
- rapid drawdown (for example, Sutton Bingham)
- leakage at dams where the crest has been raised, either during a flood or during sustained operation with an abnormally high water level
- poor surveillance effectiveness due to surface vegetation
- blockage of low level outlets (for example, Cwm Ebol)
- human error (for example, blocking spillways and incorrect operation of gates or valves)
- leakage due to unknown pipes/structures within or under the dam

- burrowing animals
- poor design

4.2.2 Research on statutory reservoir safety measures

All of the reservoir safety inspection reports submitted to the Environment Agency or Natural Resources Wales for reservoirs in England and Wales between 2004 and 2013 were reviewed to categorise the safety recommendations made by Inspecting Engineers under Section 10 of the Reservoirs Act 1975. A total of 3,155 recommendations in the interests of safety were made from 1,104 reports with safety recommendations made under Section 10 of the Reservoirs Act 1975. These measures were categorised according to subject areas under the following headings:

- monitoring and surveillance
- reservoir operation
- risk assessment and emergency planning
- research, investigations and studies
- measures to improve the intrinsic condition of the reservoir (that is, improvement in design standard, for example, by lengthening a spillway)
- measures to address deterioration of the design condition
- other measures

The percentage breakdown of the measures by these headings is shown in Figure 4.1.

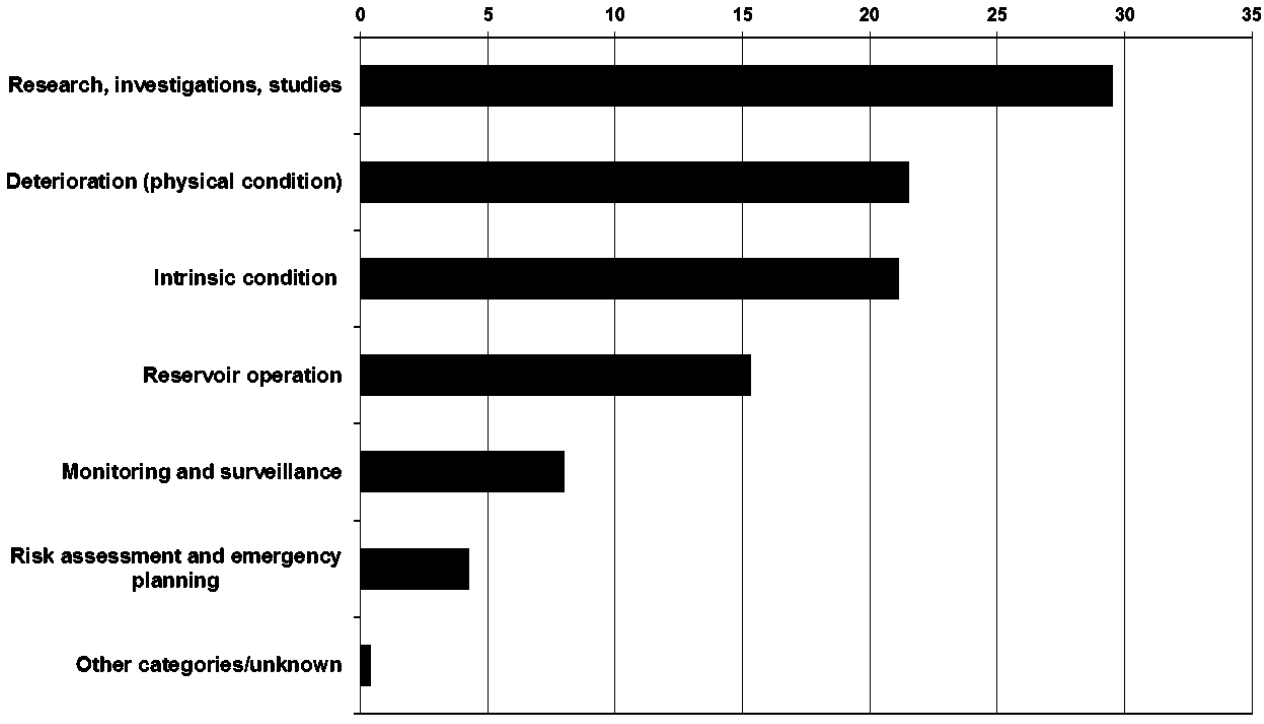


Figure 4.1 Breakdown of statutory reservoir safety measures by type, 2004–2013 (%)

Source: Environment Agency research (Environment Agency 2013c)

The most significant subject areas under each heading are listed in more detail in Table 4.2. This assessment was found to be useful in identifying the research topics (see Section 5).

Table 4.2 Significant areas of concern to Inspecting Engineers at statutory reservoirs

Type of measure	Significant subject areas [1]
Research, investigations, studies	• Reservoir flood study (203) • Hydraulic analysis/modelling (151) • Topographic survey (123) • Stability analysis (81) • Seepage investigation (60) • Condition survey – internal structures (57) • Condition survey – CCTV (45) • Material investigation of dam fill material (43) • Condition survey – other (33) • Condition survey – surface structures (32)
Measures to improve the intrinsic condition	• Spillway capacity improvement (213) • Crest levelling (69) • Crest raising (57) • Erosion protection to the dam crest and/or downstream face (54) • Drainage improvements (49) • Other (46) • Grouting/sealing (except of dam core) (37)
Measures to address deterioration	• Spillway – minor repairs (117) • Gates/valves (100) • Spillway – major repairs (72) • Repairs to the dam upstream face (67) • Repairs to the downstream face (except due to internal erosion) (49) • Dam crest repair (except due to overtopping) (30)
Reservoir operation	• Vegetation (except grass cutting) (148) • Clear/prevent blockage/debris (102) • Water level control (46) • Access/fencing (35)
Monitoring and surveillance	• Reservoir records/documentation (66) • Seepage monitoring (except toe drain monitoring) (42) • Reservoir water level monitoring (32)
Risk assessment and emergency planning	• Emergency drawdown planning (53) • Emergency action planning (50)

Notes: [1] Measures where number is >30 or ~1% of total
Source: Environment Agency research (Environment Agency 2013c)

The review shows that the most common recommendation is for work to be carried out to improve the information available for a subsequent evaluation of acceptability.

Although the standards of flood safety at reservoirs have not changed substantially since the first edition of 'Floods and Reservoir Safety' (ICE, 1978), the assessment methodology has changed. Hence the most common recommendations relate to flood safety – to carry out a flood study, check/increase freeboard, or check/increase spillway capacity. Other possible reasons include changes in the dam category due to downstream development (consequences of dam failure) and reductions in freeboard due to settlement or other factors. Spillway enlargement and crest levelling/raising was the most common type of reservoir design improvement measure.

Where safety-critical repairs have been carried out, these most commonly relate to spillway structures although a significant number also relate to the deterioration of a gate or valve.

The most common operational issue is the management of vegetation, typically dealing with trees or removing vegetation to improve access for monitoring and surveillance. Issues with screen or spillway blockage due to weed, reeds and so on are also common.

The analysis of measures of safety provides interesting evidence to support research priorities.

4.3 Review of progress against the 2009 strategy

4.3.1 Overview

The 2009 strategy report (Environment Agency 2009a) contains a prioritised list of research topics based on a review of perceived needs and the potential for securing appropriate funding. This list of research projects is presented in Table 4.3 where:

- Column 1: Ranked order of priority based on value of the mean score (from highest to lowest)
- Column 2: Project description
- Column 3: Type of output
- Column 4: Mean score: the mean of all scores assigned to the project
- Column 5: Estimated project duration in months
- Column 6: Estimated cost in £k
- Column 7: Difficulty (based on the mean difficulty assigned to the project by voters)
- Column 8: Project type (**H**igh/**L**ow **B**enefit/**D**ifficulty)
- Column 9: Suggested additional sources of funding
- Column 10: Progress with delivery to date

Table 4.3 Summary of progress against 2009 strategy recommendations

Rank	Project description	Output	Score mean	Duration (months)	Estimated cost (£k)	Difficulty	Project type	Additional sources of funding	Progress to date
2009-1	Review latest knowledge on internal erosion leading to updated UK guidance	Guide	8.3	24	125	1.9	HB/LD	Owners	Covered by ICOLD Bulletin 164 (ICOLD 2013)
2009-2	Review of modes of failure of dams and failure of monitoring techniques	Report and guide	8.1	24	150	1.9	HB/LD	Owners	Delivered; SC080048 (Environment Agency 2011a)
2009-3	Research and guidance on the behaviour of masonry spillways	Science, guidance	8.0	36	175	2.0	HB/HD	Owners, EPSRC,FEMA, CIRIA	Delivered; SC080015 (Environment Agency 2010a)
2009-4	Publication – lessons from dam incidents	Report	7.8	12	50	1.3	HB/LD	Owners/CIRIA	Delivered; SC080046 (Environment Agency 2011b)
2009-5	Collect geotechnical and geological data of old dams for Environment Agency database	Research, database	7.7	12/36	100	1.9	HB/LD	Owners	See note 1.
2009-6	Review of direct impacts of climate change on dams and reservoirs	Report	7.2	12	150	3.0	HB/HD	UKWIR/EC/ NERC	Delivered; FD2628 (Defra 2013)
2009-7	Review of existing methods and development of guidelines for dambreak assessment	Science, guidance	7.1	12	85	1.9	HB/LD	EC	Due 2016
2009-8	Extreme flood hydrology: (1) finalise the improved methods for extreme rainfall event predictions; (2) develop a tool for implementing the new method; and (3) develop a rainfall–run-off method appropriate for modelling extreme floods	New method; tool	7.1	42	650	2.3	HB/HD	NERC/EPSRC	Defra. Revised extreme Flood Estimation Handbook rainfall tool delivered in 2015. No development of revised rainfall–run-off model to date.

Rank	Project description	Output	Score mean	Duration (months)	Estimated cost (£k)	Difficulty	Project type	Additional sources of funding	Progress to date
2009-9	Monitoring and measuring methods for embankment dams	Chapter in guide	6.9	12	145	1.5	HB/LD	Owners/FEMA	SC080048 Delivered (with item 2)
2009-10	Publication – a guide to instrumentation and monitoring'	Report and guide	6.8	12	100	1.8	HB/LD	Owners//FEMA/ CIRIA	Delivered – covered by SC080048
2009-11	Training in dambreak analysis and evaluation	Training	6.8	6	20	1.3	HB/LD	Owners	See note 1. Training is now available at HR Wallingford
2009-12	Training for event management	Research, guidance	6.7	9	100	1.9	HB/LD	Owners/NERC/ EPSRC	See note 1.
2009-13	Guide on inspection, monitoring, maintenance and repair of tunnels	Guide	6.7	12	50	1.7	HB/LD	CIRIA	SC080049 (scoping) Delivered under SC110006; published as CIRIA C743 (CIRIA 2015)
2009-14	Compendium of design and assessment of embankment dams – collaboration of work	Research	6.7	12	75	1.6	HB/LD	CIRIA	Covered in part by 'The International Levee Handbook' (CIRIA 2013).
2009-15	Revise guide 'Design of Flood Storage Reservoirs' (CIRIA B14)	Guidance	6.6	9	85	1.5	HB/LD	CIRIA	In progress and includes adaptation of existing reservoirs for flood storage. SC120001 due 2016
2009-16	Methods of raising embankment dams	Guide	6.5	12	60	1.8	HB/LD	EPSRC/NERC/ CIRIA	To be covered in part by ranked item 15. Some techniques for levees covered in 'The International Levee Handbook' (CIRIA 2013).

Rank	Project description	Output	Score mean	Duration (months)	Estimated cost (£k)	Difficulty	Project type	Additional sources of funding	Progress to date
2009-17	Dambreak analysis – structure failure mechanisms	Scope, science, guidance	6.5	36	120	2.0	HB/HD	EPSRC/NERC/ FEMA/DSIG/EC	No progress but failure modes covered by item 2.
2009-18	Update the guide to small embankment dams, CIRIA 161 (CIRIA 1996a)	Updated guide	6.4	9	30	1.3	HB/LD	CIRIA	Covered in part by 'The International Levee Handbook' (CIRIA 2013).
2009-19	Update 'Floods and Reservoir Safety: An Engineering Guide', 3rd edition (ICE 1996)	Update	6.4	12	60	1.5	HB/LD	CIRIA/Owners	4th edition published (ICE 2015)
2009-20	Retrofitting of filters to reduce the risk of internal erosion	Review	6.4	18	45	2.1	HB/HD	EC/DSIG/FEMA	No research but subject is covered in ICOLD Bulletin 164 (internal erosion) (ICOLD 2013)
2009-21	Review alternative materials and techniques for embankment dam auxiliary spillways	Report/guide	6.4	36	320	2.0	HB/HD	FEMA/DSIG/EC	Not progressed
2009-22	A guide to mechanical and electrical equipment in dams	Guide	6.3	12	75	1.9	HB/LD	CIRIA	MEICA equipment project considered by the Joint Programme in 2013. See note 1.
2009-23	Development of UK-based risk assessment methodology	Guide	6.3	18	150	2.3	HB/HD	Owners	Delivered SC090001 (Environment Agency 2013a)
2009-24	Research to identify failure modes and processes	Report or guide	6.3	12	100	1.9	HB/LD	FEMA/DSIG/EC	Covered by items 2 and 23.
2009-25	Manual on the degradation and repair of concrete dams	Report	6.1	30	230	1.5	HB/LD	CIRIA	Partly covered by the 'Cracking of concrete dams' research for CEATI – in progress. Scope of phase 2 to be agreed.

Rank	Project description	Output	Score mean	Duration (months)	Estimated cost (£k)	Difficulty	Project type	Additional sources of funding	Progress to date
2009-26	Review and update of CIRIA guide on valves, pipework and associated equipment, R170 (CIRIA 1997)	Guide	6.0	12	60	1.5	HB/LD	Owners/CIRIA	See note 1
2009-27	Review and update 1996 engineering guide to safety of concrete and masonry dams, R148 (CIRIA 1996b)	Guide	6.0	12	50	1.2	HB/LD	Owners/CIRIA	See note 1
2009-28	Embankment and grout curtains and cutoffs	Research	6.0	48	200	1.5	HB/LD	CIRIA/EPSRC/ NERC	Not progressed
2009-29	Review science and practice supporting emergency planning for dams (including UK, European Commission and US projects)	Scoping review --> R&D needs and best practice	6.0	12	30	1.3	LB/LD	FEMA/DSIG/EC	Not progressed
2009-30	Slip lining of conduits	Research	5.9	12	30	1.3	LB/LD	NERC/	Covered in CIRIA C743 on conduits (CIRIA 2015)
2009-31	Decommissioning of dams	Guide	5.9	15	75	1.7	LB/LD	FEMA/DSIG/ Owners/CIRIA	ICOLD Bulletin 160 due but no specific UK guidance progressed
2009-32	Review methods for predicting return period of events >10,000 years to support risk-based assessments	Scoping review and revised guide	5.8	42	400	2.1	LB/HD	NERC/Owners/ FEMA/DSIG	Some work on estimating the return period of probable maximum precipitation (PMP) has been carried out but not well disseminated to date.
2009-33	Understanding and reducing uncertainty within dambreak analyses	Research, guidance	5.7	12	120	2.5	LB/HD	EC/DSIG/FEMA	Might be progressed in 2016.

Rank	Project description	Output	Score mean	Duration (months)	Estimated cost (£k)	Difficulty	Project type	Additional sources of funding	Progress to date
2009-34	Guide to safety of embankment dams (BRE)	Updated guide	5.5	12	75	1.4	LB/LD	CIRIA	Discussed at RSAG June 2012. Not progressed
2009-35	Guidance on public safety at dams	Guide	5.4	18	35	1.5	LB/LD	EC/DSIG/ Owners	Not progressed
2009-36	Dambreak analysis – data and forensics	Data	5.3	Ongoing	100	2.0	LB/HD	EC/DSIG/FEMA	Not progressed
2009-37	Review and guidance on techniques for installation and operation of drawoff system	Report/guide	5.3	12	75	1.5	LB/LD	Owners/CIRIA	Partly covered by SC13001 on determination of the optimum hydraulic capacity of low level outlets, due 2016.
2009-38	Waves on reservoirs: (1) wave height prediction in shallow water where interference of wave trains occurs; (2) wave impact forces on wave walls – in particular 'dry stone' walls and adequacy of wave walls to withstand waves; and (3) guidance on wave wall protection	Science, guidance	5.1	24/36	150	1.9	LB/LD	EPSRC/NERC/ EC/CIRIA/FEMA / DSIG	Partly covered by item 19 (4th edition ICE's 'Flood and Reservoir Safety' published 2015)
2009-39	Communication strategy for reservoir R&D	Strategy	5.1	12	20	1.0	LB/LD	CIRIA	Not progressed
2009-40	Development of a web-based GIS management system for dams	Tool	4.7	24	200	2.5	LB/HD	Owners	Not progressed
2009-41	Non-linear numerical analysis of concrete dams and their foundations	Report	4.7	18	120	1.7	LB/LD	EPSRC/NERC	Not progressed

Rank	Project description	Output	Score mean	Duration (months)	Estimated cost (£k)	Difficulty	Project type	Additional sources of funding	Progress to date
2009-42	Review tools to reduce operations and maintenance (O&M) costs for extended life of spillways	Report	4.5	12	40	1.6	LB/LD	Owners/CIRIA	Not progressed
2009-43	Review of indirect impacts of climate change on dams and reservoirs	Report	4.5	12	150	3.0	LB/HD	UKWIR/EC	Not progressed
2009-44	Application of reservoir flood forecasting and control to UK reservoirs	Guidance	4.5	18	150	1.5	LB/LD	UKWIR/Owners	Not progressed
2009-45	Procedures for the assessment of intake towers and gates	Report	4.4	12	50	2.0	LB/HD	CIRIA	Not progressed
2009-46	Review management methods, inspection standards and inspection intervals and develop new requirements to take account of climate change	Guidance	4.3	12	50	1.9	LB/LD	UKWIR/EC	Not progressed
2009-47	Investigate methods and technologies to help dams adapt to climate change	Guidance	4.1	12	100	2.4	LB/HD	UKWIR/EC	Not progressed
2009-48	Knowledge optimisation of data (update of UK register of dams with additional information)	Tools	3.3	12	150	2.5	LB/HD	Owners	Not progressed (links with item 5)
2009-49	Guidance on the location, design and maintenance of fish screens	Guide	3.1	12	30	1.2	LB/LD	CIRIA	Partly covered by the Environment Agency's fish pass manual (Environment Agency 2010b)

Notes Based on Table 4.4 of the 2009 strategy document (Environment Agency 2009a)
[1] Projects referred to this note were considered not to be research under the criteria set by the Defra Joint Programme and have not been progressed.
HD = high difficulty; LB = low benefit.

DSIG = Dam Interest Safety Group; EC = European Commission; EPSRC = Engineering and Physical Sciences Research Council; FEMA = Federal Emergency Management Agency (USA); ICOLD = International Commission on Large Dams; MEICA = Mechanical, Electrical, Instrumentation, Control and Automation; NERC = Natural Environment Research Council.

4.3.2 Commentary on progress made

It is clear that at least some progress has been made with the majority of the top 50 ranked research projects from the 2009 strategy report. The vast majority of all the UK-funded reservoir safety research projects carried out since 2009 relate exactly or closely to the list of recommended projects. This indicates that the strategy was successful in scoping projects that funding agencies and sponsors were able to support.

Some of the research areas have been, or will be, covered by international publications. In many cases these do not provide comprehensive guidance for UK conditions, and international research or guidance may have to be framed for the UK context to be useful.

Important areas where significant progress has been made in terms of research and guidance since 2008 include:

- internal erosion (guidance)
- masonry spillways
- incident reporting/dissemination
- reservoir conduits (design/management)
- modes of failure and risk assessment
- extreme rainfall and flood safety (most aspects but not all)
- effects of climate change

Crucial areas of research identified in the 2009 strategy where little or no progress has been made include:

- dambreak analysis
- gates and valves
- emergency planning (a course is now planned)
- decommissioning of dams
- better use of the national reservoir database (such as web-based GIS systems), which could be published and made freely accessible to researchers

4.3.3 Projects carried forward

Projects not progressed between 2009 and 2015 were not automatically listed as projects in this updated strategy. Instead, current industry needs were identified during consultation with the reservoirs community. These needs were then cross-checked with the previous strategy.

A summary of the 2009 projects listed as ‘not progressed’ is given in

Table 4.4 together with the 2016 topic references should they be covered under the new strategy.

Table 4.4 Projects carried forward

Rank	Project description	Covered in new strategy?	2016 topic number(s)
2009-5	Collect geotechnical and geological data of old dams for Environment Agency database	YES	39, 70
2009-8	Extreme flood hydrology: (1) finalise the improved methods for extreme rainfall event predictions; (2) develop a tool for implementing the new method; and (3) develop a rainfall–run-off method appropriate for modelling extreme floods	YES	2
2009-18	Update the guide to small embankment dams (CIRIA 161)	YES	65
2009-21	Review alternative materials and techniques for embankment dam auxiliary spillways	YES	1
2009-22	A guide to mechanical and electrical equipment in dams	YES	6
2009-28	Embankment and grout curtains and cutoffs	YES	39, 52, 56
2009-29	Review science and practice supporting emergency planning for dams (including UK, European Commission and US projects)	YES	20, 48, 60
2009-31	Decommissioning of dams	YES	13, 33
2009-32	Review methods for predicting return period of events >10,000 years to support risk-based assessments.	YES	5
2009-33	Understanding and reducing uncertainty within dambreak analyses	Not taken forward	
2009-34	Guide to safety of embankment dams (BRE)	Covered	
2009-35	Guidance on public safety at dams	YES	66
2009-36	Dambreak analysis – data and forensics	Not taken forward	
2009-37	Review and guidance on techniques for installation and operation of drawoff system	YES	6, 28
2009-38	Waves on reservoirs: (1) Wave height prediction in shallow water where interference of wave trains occurs; (2) wave impact forces on wave walls – in particular ‘dry stone’ walls and adequacy of wave walls to withstand waves; and (3) Guidance on wave wall protection	YES	25, 30, 41, 42, 63, 72
2009-39	Communication strategy for reservoir R&D	Covered in part by this strategy	
2009-40	Development of a web-based GIS management system for dams	Not taken forward	
2009-41	Non-linear numerical analysis of concrete dams and their foundations	Not taken forward	
2009-42	Review tools to reduce O&M costs for extended life of spillways	YES	8, 13, 16
2009-44	Application of reservoir flood forecasting and control to UK reservoirs	YES	2, 28
2009-45	Procedures for the assessment of intake towers and gates.	YES	6
2009-46	Review management methods, inspection standards and inspection intervals and develop new requirements to take account of climate change	YES	8
2009-47	Investigate methods and technologies to help dams adapt to climate change	YES	50, 54
2009-48	Knowledge optimisation of data (update of UK register of dams with additional information)	Not taken forward	

4.4 Literature review

4.4.1 Research topics

The main reservoir safety research areas and themes were developed so as to:

- categorise technical papers and other publications completed since 2009
- provide a framework of themes for discussion of perceived research and guidance needs during the industry workshop
- inform the gap analysis

The table of themes is not exhaustive. It is reproduced as Table 4.5 under the nine general themes summarised in Figure 4.2, together with those themes classed as 'general/miscellaneous'.

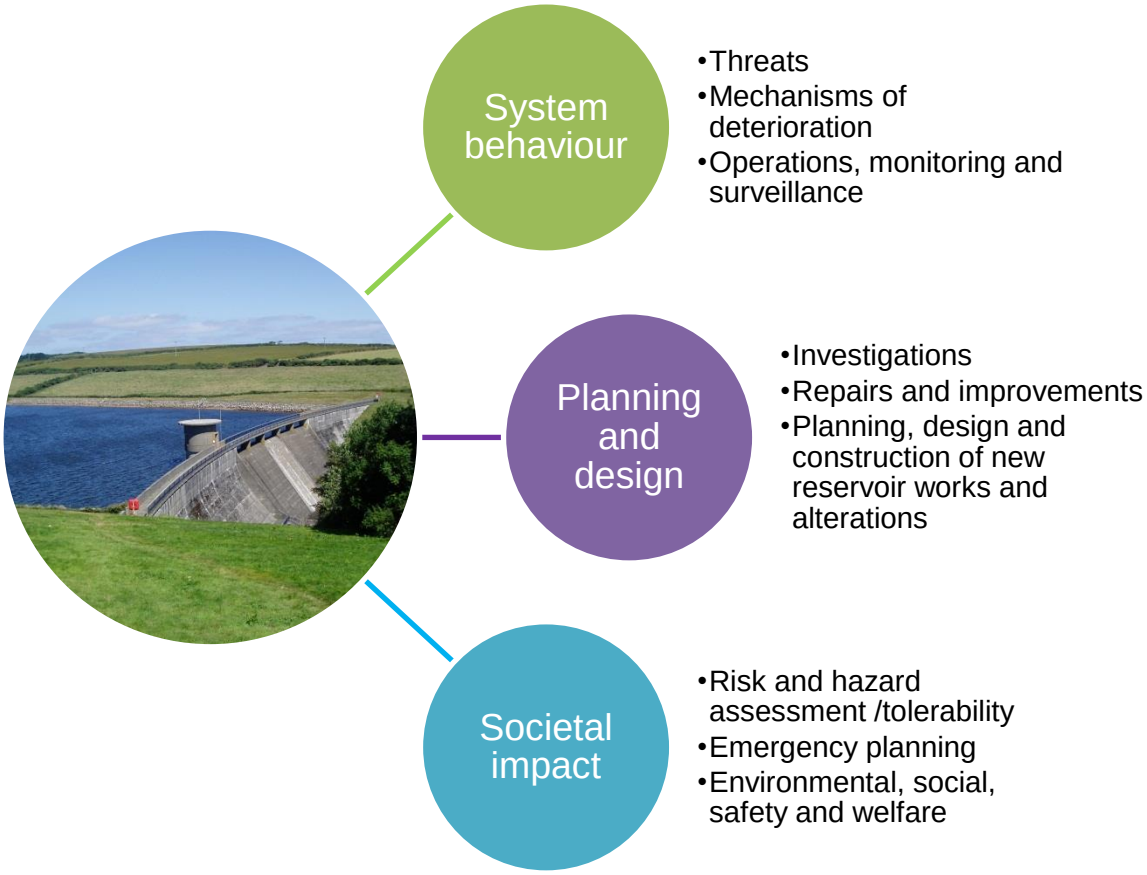


Figure 4.2 Reservoir safety research areas and themes

Note that some topic areas feature under more than one theme. For example 'wind and waves' features both as a threat (assessing the magnitude of the threat at a subject reservoir) and as a mechanism of deterioration (understanding the mechanisms by which wind/wave damage impacts reservoir safety).

Table 4.5 Potential topic areas for research or guidance

Area: System behaviour Theme 1: Threats	Sub-theme
Failure of upstream reservoir	Vulnerability/performance
Floods/direct rainfall	Fluvial, pluvial/groundwater, forecasting, rainfall depth–duration–frequency, rainfall–run-off modelling, inflow design floods, flood diversion strategies
Climate change	Wetting effects, drying effects, thermal effects, wind, increased demand/impact on operations
Seismic events	Accelerations, vulnerabilities (direct, indirect), reactivation of faults
Catchment/rim stability	Induced waves, debris slides within catchment, blockage of spillway channel
Snow/ICE/thermal	Structural loadings, blockage of inlets/outlets, expansion, freeze–thaw
Wind/waves	Wetting of crest and downstream face, wave wall loadings, trees
Vehicle damage	Instability or other damage due to vehicle movements/loadings
Ultraviolet (UV) radiation	Impact on plastics and so on
Unusual water level changes	Spates, rapid drawdown, human error
Animal and vegetation damage	Burrowing animals, external erosion, invasive species, tree fall threat, disease, root penetration/decay, impact from climate change
In situ material deterioration	Corrosion, alkali–silica reaction, carbonation, UV deterioration of linings, desiccation of clay
Reservoir drawdown and hydraulic threats	Instability of upstream shoulder, pressures within structural elements, suction, vortices, cavitation, uplift, vibrations
Sedimentation and debris	Loss of yield, blockage of low level outlets or screens
Human operational errors	Inappropriate gate/valve operations, unauthorised works/operations
Vandalism/terrorism	Data security, access restrictions, alarm systems
Foundation deterioration	Mining, sinkholes, deterioration due to seepage/solution

Area: System behaviour Theme 2: Mechanisms of deterioration	Sub-theme
Settlement	Primary, secondary, monitoring, estimation and design allowance/freeboard
Overtopping	Erosion of downstream face, effect of geometry, grass cover, features, crest design/surfacing performance
Embankment instability due to pore pressure rise in embankment or foundation	Mass stability, hydraulic fracture
Erosion from localised run-off	
Wind-related damage (for example, trees)	Damage by root balls, tree management
Wave erosion due to deterioration of upstream face protection	Performance of protection systems, maintenance, repair, crest damage

Area: System behaviour Theme 2: Mechanisms of deterioration	Sub-theme
Internal erosion: backward erosion (piping); concentrated leaks; contact erosion; suffusion	Indicators, likely failure rate after initiation, prevention
Physical deterioration of fill materials	Mineralogical, drying/wetting, chemical, freeze–thaw
Physical deterioration of foundation materials	Impact of mining, solution cavities, washing out of clay seams and so on, changes in foundation permeability/strength due to reservoir
Deterioration of drawoff towers	Materials, loadings, modifications
Deterioration of conduits/tunnels	Inlets, pipe walls, joints/couplings, restraints/supports/anchors, outfalls
Deterioration of spillways/energy dissipators	Capacity restriction/reduction, deterioration of channels/basins, joints
Deterioration of internal drainage systems	Clogging, calcification, collapse
Deterioration of metalwork – gates/valves/equipment	Gate/valve body deterioration, seals, headstocks, safe operation, actuation, ladders, landings
Deterioration of post-tension anchors	Testing, replacement
Wave damage	Face erosion, wave wall deterioration, undercutting
Blockage of conduits	Dealing with blocked/obstructed conduits or channels due to silt, vegetation and so on

Area: System behaviour Theme 3: Operations, monitoring and surveillance	Sub-theme
Reservoir first filling	Rate of filling, monitoring
Reservoir drawdown	Rates of drawdown, supplementary equipment, flood gate operation
Monitoring – deformation	
Monitoring – water level	
Monitoring – hydraulic pressures	
Monitoring - seepage	Rates, turbidity
Monitoring – real-time	Deformation strain, temperature, porewater pressure and so on
Monitoring – alarms	
Surveillance	
Debris management	Screens, clogging, trash removal
Sediment management	Influx reduction, removal, mitigation
Reservoir safety records	Reservoir specific records, UK national database
Communications	

Area: Planning and design Theme 4: Investigations	Sub-theme
Bathymetric surveys	Techniques, accuracy
Silt within reservoir	Distribution/depth/volume, degree of consolidation
Escapable sediment	Guidance for sediment released in a breach
Seepage paths	Techniques available, development of appropriate strategies, limitations
Pore pressure	Piezometer performance
Underwater surveys	Planning diving operations, unmanned survey methods
Watertightness of core/fill/foundation	Permeability assessment and evaluation Evidence of deterioration
Void detection	Within fill, within foundations/abutments
Conduit surveys	CCTV and so on Deformation, deterioration, shell thickness, residual life, blockage
Residual life testing	For example, pipe shell thickness, reinforced concrete
Hydraulic modelling	Capacity, conveyance, pressures, cavitation, bed shear stress, erosion potential, vortices, optimisation, energy dissipation, vibrations and so on Mathematical versus physical
Settlement/deformation/stability	
Geotechnical characteristics of fill	Shear strength, erodibility, permeability and so on
Geotechnical characteristics of foundations	Strength, joints, fractures, faults, permeability, soluble minerals and so on
Performance of filters	Determining in situ filter performance

Area: Planning and design Theme 5: Repairs and improvements	Sub-theme
Foundation sealing	Grouting, diaphragm walls
Core sealing	Grouting, diaphragm walls, re-coring
Filter layers	Retrofitting measures to reduce the threat of internal erosion, filter blankets
Crest raising/levelling	
Wave walls	Replacement, raising/extending
Surface membrane	Materials, jointing, formation, underdrainage, surface protection, anchorage, inlets/outlet sealing
Geotextiles	Use in construction, rehabilitation
Conduits and drains	Relining, replacement
Concrete repairs	Methods, materials, underwater repairs
Post-tensioning of gravity dams	
Minor repairs to embankments	
Stability improvements	Toe berms, buttressing and so on
Spillway repairs	
Auxiliary spillways	

Area: Planning and design Theme 6: Planning, design and construction of new reservoirs works and reservoir alterations	Sub-theme
Planning for new reservoir development	
Embankments – impoundments	
Embankments – flood storage	Relatively UK-specific, Environment Agency requirements for operations, maintenance and so on
Concrete/masonry dams	
Hydraulic structures – spillways	
Hydraulic structures – drawoffs and bottom outlets	
'Small dams'	Guidance on design, load cases construction, operation and maintenance of non-statutory reservoirs, legislation
Dam raising, reservoir adoption/adaptation	Increased demand, raising of top water level with or without raising of dam crest, or crest raising to increase freeboard
Redundant reservoirs	Risks, strategies, options
Discontinuance/abandonment/reuse	Planning, investigations, consultations, methods, mitigations
Services	Management of services on/within/over/under dams

Area: Societal impact Theme 7: Risk and hazard assessment/tolerability	
Qualitative risk assessments	
Quantitative risk assessment	Probability of failure, fault trees, portfolio risk assessment, tolerability
Dam breach development modelling	Breach development for different types of dam and failure modes, rates of erosion/failure
Dam breach inundation modelling	Developments in shock capture and two dimensional (2D) modelling techniques Dealing with culverts and obstructions (for example, large buildings), escapable contents
Dam breach mapping	Representation of modelling results to promote effective hazard assessment
Hazard assessment	Endangerment, impact on infrastructure
Tolerability	ALARP (As Low As Reasonably Practical), societal acceptance

Area: Societal impact Theme 8: Emergency planning	Sub-theme
Flood plans – onsite plans	Preparation, exercises, lessons learned, communicating risk, helping communities prepare for the risks associated with reservoir failure
Flood plans – offsite plans	Preparation, exercises, lessons learned Regional collaborations

Area: Societal impact Theme 8: Emergency planning	Sub-theme
Emergency planning	Reservoir operation, gate/valve operation
Dam Safety	

Area: Societal impact Theme 9: Environmental, social, safety and welfare	Sub-theme
Management of fish and so on	Ladders, passage through open conduits (for example, flood detention reservoirs)
Environmental enhancement	Planning and implementing environmental enhancement measures at reservoirs for example, shallows, islands, planting of reservoir rim, treating the reservoir basin of discontinued reservoirs
Social enhancement	Planning and implementing recreational facilities at reservoirs
Public safety and welfare at dams	Access controls, barriers, signage, facilities, disabled access
Disturbance of animals	Identification of issues, relevant legislation, strategies
Property development at dams	Impact of properties on/adjacent/below dams Access issues Conflicts
Environmental releases	Compensation releases
Scour releases to test valves/gates	Planning, implementation
Use of existing structures to generate renewable energy	For example, hydropower, solar

General/miscellaneous	
Skill succession planning	Declining panel engineer numbers
Post-incident reporting	Database, reporting, investigations
Mechanical and electrical equipment in dams	Automated controls, evaluation, improvement, replacement

4.4.2 Literature search

A search was carried out to identify information published in relation to reservoir safety since 2008. More than 500 technical publications, papers and articles were identified to be of relevance or potentially of relevance to UK reservoir safety. This list included references from the following sources:

- ANCOLD Australian National Committee on Large Dams
- ASDSO Association of State Dam Safety Officials [USA]
- BDS British Dam Society conference papers and issues of its *Dams and Reservoirs* journal
- CEATI Centre for Energy Advancement through Technological Innovation

- CIRIA Construction Industry Research and Information Association
- Environment Agency
- FEMA Federal Emergency Management Agency [USA]
- IJHD *International Journal on Hydropower and Dams*
- ICE Institution of Civil Engineers [UK]
- ICOLD International Commission on Large Dams
- USACE United States Army Corps of Engineers
- USBR United States Bureau of Reclamation
- International journals on earthquake, environmental management, flood risk management, fluid mechanics, hydraulic engineering, hydraulic research, hydrodynamics, hydrology, sediment management, river basin management, rock mechanics, sediment research, water resources and so on

The publications reviewed were assigned to one or more of the themes highlighted in Section 4.4.1. The resulting database was applied to assist in the scoping or preparation of new research. A copy of the database is available from the Environment Agency.

The majority of the publications will not have been reviewed and incorporated in UK research since 2008 due to the long lead time in scoping, tendering and delivering research projects. Looking at some examples from recent UK research projects, about a third of the references cited were published within the prior 5-year period:

- 'Guidance for the Design and Maintenance of Stepped Masonry Spillways', SC080015 (Environment Agency 2010a) – 31% of references cited published since 2005
- 'Modes of Failure and Monitoring and Measuring Techniques', SC080048 (Environment Agency 2011a) – 13% of references cited published since 2006
- 'Risk Assessment in Reservoir Safety Management', SC090001 (Environment Agency 2013a) – 34% of references cited published since 2008

This underlines the fact that much of the evidence used in research or guidance for reservoir safety publications is drawn from papers published over a considerable period of time. Reservoir safety publications typically draw from many decades of R&D and their inputs necessarily reflect the long history of reservoir research in the UK.

Considerable activity in any particular field might highlight strong progress in a particular area and the need for new guidance or research relevant to UK reservoirs.

5 Consultation

5.1 Approach

The perceived needs of the UK reservoir industry for future research were determined through a series of consultation exercises as described below. Prospective research topics were identified through the consultations which were then collated and reviewed during the workshop.

5.2 One-to-one consultations

A series of consultations were made with a short list of specific individuals to discuss current/emerging needs for future research. The individuals consulted are listed in Table 5.1.

Table 5.1 List of consultees for one-to-one consultations

Name, affiliation	Specialist field
Mr Rodney Bridle, Dam Safety Ltd	Internal erosion
Dr Catherine O'Sullivan, Imperial College	Internal erosion
Mrs Lisa Stewart, Centre for Ecology and Hydrology	Extreme rainfall and flood estimation
Mr Tony Morison, CH2M Hill	Concrete dams and dam engineering
Dr Mark Morris, Samui	Dambreak modelling
Mrs Ljiljana Spasic-Gril, Arup	Seismicity
Mr Russ Digby, KGAL Consulting Engineers	Gates and valves
Mr Phil Deebank, Health and Safety Executive	Societal risk and public safety
Mr Craig Goff and Dr William Allsop, HR Wallingford	Hydraulic research

5.3 One-to-few consultations

One-to-few consultations were carried on three occasions. Research needs and prospective topics were discussed and recorded during the following events:

- a meeting of the reservoir safety managers in Darlington in November 2014
- the morning session of the workshop described in Section 5.5.
- the workshop with academics held in December 2015

5.4 One-to-many consultations

Proposals for research topics to inform the strategy were invited through:

- an informal request held during the BDS biennial conference in Belfast in September 2014
- a questionnaire emailed to BDS members in November 2014

The output was incorporated in the planning for the workshop.

5.5 Workshop

An industry workshop was held at the Environment Agency's office in Solihull in December 2014. Its objectives were to:

- draw on the gap analysis and brainstorm ideas with members of the reservoir community
- prioritise the final list of research topics

5.5.1 Attendance

The workshop was open to all those who expressed an interest in attending. However, particular efforts were made to ensure there was a diverse representation of the reservoir industry at the event. A list of the attendees is given in Table A.3. A total of 33 delegates attended in addition to the project team.

5.6 Scoring of nominated research topics

During the workshop, attendees participated in the scoring of the research topics.

The consultation phase had led to the proposal of a total of 76 potential research topics. A small number of these topics were raised during the consultations prior to the workshop (described above). In scoring the full list of topics, some very similar or identical topics were either therefore scored twice or the attendees were directed not to score a topic where there was clear duplicity.

The scoring criteria used to score the topics are shown in Table 5.2. Each topic was assigned a score between 1 and 5 against each of the criteria shown and the 3 scores were summed to give a total score between 3 and 15. These scores were used to directly rank the research topics without weighting.

Table 5.2 Scoring criteria

Score	Benefit/impact	Needs/drivers	Risk of not doing the work over the next 5–10 years
5	Well-defined benefits Benefits would apply to a large section of the reservoir industry.	The needs for the research are clear from the evidence available. There are strong drivers (for example, changes in legislation).	There is an urgent need to carry out the research to inform best practice and guidance.
3	Some benefits/impacts anticipated	There are some evident needs/drivers.	The research is reasonably urgent.
1	Benefits unclear or the research would only benefit a small part of the reservoir industry.	There is little evidence of any need or clear drivers for the research.	The research is not urgent.

A full list of the topics scored is shown in Table A.1, together with the outline aims/scope of each topic and its prioritisation scores. The topics that were raised at the conference or workshop, for example, were not scoped as fully as those raised through detailed individual consultations. A number of the topics proposed are not suitable for funded research activities but nevertheless represent genuine industry needs. These topics are discussed in Appendix A.4.

The first 25 items in Table A.1 provide a representation of the projected needs of the reservoir industry over the next 5–10 years. This is notwithstanding the fact that there are likely to be emerging needs as a consequence of, for example, legislative changes and incidents at reservoir sites.

5.7 Academic consultation

Notwithstanding the consultations undertaken to develop and prioritise the research topics, it was felt by those involved that the strategy would benefit from further consultation with academic researchers. A workshop for this group was therefore held at the Environment Agency's Birmingham offices in December 2015 to discuss the strategy and to discover what research was being undertaken. The workshop aimed to:

- raise awareness of the strategy and the need and potential for academic engagement and linkages
- present themes and current projects lists
- learn about current research being carried out or investigated by organisations or key individuals
- collate research ideas and potential projects
- enquire about funding universities might have available
- promote links with organisations through the strategy

5.7.1 Attendance

An invitation list was developed by enquiring within the reservoir community for the names of researchers and by evaluating recent publications for relevance to reservoirs and dam safety. Once circulated, the invitation was extended to others where requested and resulted in a final workshop attendance of 23 academics from 18 universities. A list of the attendees is shown in Table A.3.

5.7.2 Activities and outputs

The workshop included short discussions on:

- the importance of reservoir safety
- the roles of the Environment Agency and panel engineers
- the functions of the Reservoir Safety Advisory Group and the British Dam Society

Researchers were then invited to present a synopsis covering their relevant research areas and the areas their institutions covered. This highlighted the broad range of topics covered by those present.

Following these presentations, workshops were held to:

- discuss what research might be relevant and able to be supported
- brainstorm new research ideas

Finally, a general question and answers session was held to address any issues that had arisen during the event. This mainly revolved around the level of support the Environment Agency could provide and how to maintain engagement in the future.

A summary of the research ideas discussed during the workshop is given in Appendix C.

5.8 Alternative funding and delivery partner consultation

How industry needs would be delivered was reviewed in the light of some of the topics identified falling outside of the criteria for R&D within the Joint Programme.

Where topics do not qualify for funding under the Joint Programme, other key partners will be sought such as the research councils (NERC and EPSRC), CIRIA and UKWIR. If it was thought these organisations could be a key partner, they were contacted to establish better links and to seek their support. The consultation was intended to:

- make them aware of the updated strategy and the need and potential for academic engagement and linkages
- present themes and current proposal lists
- learn about current research they were carrying out
- collate research ideas and potential projects
- enquire about funding that might be available
- promote links with them through the strategy

6 Proposal development

6.1 Introduction

Following the consultations and the identification of needs and priorities, proposals were prepared to give detail to the higher priority areas. Where appropriate, research topics addressing similar areas were combined. This resulted in a final list of 42 research proposals of which 7 were developed in detail and are set out in Appendix B.

6.2 Initial review

The ranked research topics developed during the baseline review and consultation were first reviewed to remove those already underway in the UK or internationally. This resulted in the removal of two projects:

- *'*Effective reinforcement of grassed surfaces for overtopping flows' – due to be delivered in the near future
- *'*Reservoir monitoring and surveillance' – met by CEATI project T082700-0210 (2012)

Another request arising from the consultation was for guidance on legislative conflicts. It is considered that this could be covered by direct guidance from Defra on how to approach conflicts and therefore can be excluded from the strategy proposals.

6.3 Consolidation

Following the initial review, research topics that included duplicates or that could form section of a single research proposal were consolidated. The consolidation process involved three steps:

1. Each topic was categorised under the areas, themes and sub-themes developed during the baseline review. This allowed themes with multiple topics to be readily identified.
2. Once all topics under a given theme had been found, their general scope was evaluated to determine if the topics could be grouped and delivered under a common research proposal.
3. Research proposals that comprised several topics were prioritised according to the highest ranking topic included.

The grouped topics then formed the basis for the developed research proposals taken forward in the strategy. This resulted in some low ranking topics being included within the scope of higher priority proposals.

Figure 6.1 summarises the identification, ranking and consolidation process.

Identified	Ranked	Categorised by theme	Consolidated by rank & theme	Proposal Definition
#	A	A	A	PR 1
#	B	B	D	
#	C	C	K	
#	D	D	B	PR 2
#	E	E	F	
#	F	F	M	
#	G	G	C	PR 3
#	H	H	H	
#	I	I	L	
#	J	J	N	
#	K	K	E	PR 4
#	L	L	O	
#	M	M	G	PR 5
#	N	N	I	
#	O	O	J	

Figure 6.1 Identification, ranking and consolidation

From a full list of 76 research topics, the initial review and consolidation process resulted in a final list of 48 proposals. The top seven proposals are listed in Table 6.1. The full list is provided in Table A.1.

Table 6.1 Top-ranked research proposals

Proposal number	Main topic		Proposal name	Included topics	
	Reference	Rank		Reference	Rank
2015-01	7	2	Extreme flood estimation: rainfall–run-off modelling	7	2
2015-02	10	4	Management of trees and vegetation on embankment dams	10	4
2015-03	8	5	Extreme flood estimation: probable maximum precipitation (PMP)/ probable maximum flood (PMF) estimation	8	5
2015-04	30	6	New guidance on the selection, operation, evaluation, repair, maintenance and replacement of gates and valves for dam structures	30	6
2015-05	44	7	Managing reservoir leakage and seepage	44	7
2015-06	26	9	Geophysical methods for reservoir safety investigations	71	52
				72	56
2015-07	15	10	Tolerability to wave and sustained overtopping	4	12

Note: Proposals 2015-8 to 2015-42 are listed in Table A.2.

6.4 Finalised research proposals

Once the review and consolidation process was complete, the top research proposals were developed in more detail. A proposal proforma was drafted following the FCERM R&D Programme Research Proposal Form to allow easy transfer of information from this strategy to FCERM submissions.

The top seven developed research proposals are shown in Appendix B.

6.5 Summary of proposals

The final proposals were classified against the themes and sub-themes to understand industry needs and priorities, and how the proposals address these.

Figure 6.2 shows the distribution of research proposed during the consultation process sorted by theme and overlaid with the areas of research addressed by the top seven prioritised projects developed in Appendix B. This shows that, while mechanisms of deterioration is likely to require the most research in the coming years, industry considers improvements in operations, monitoring and surveillance to be the most pressing need.

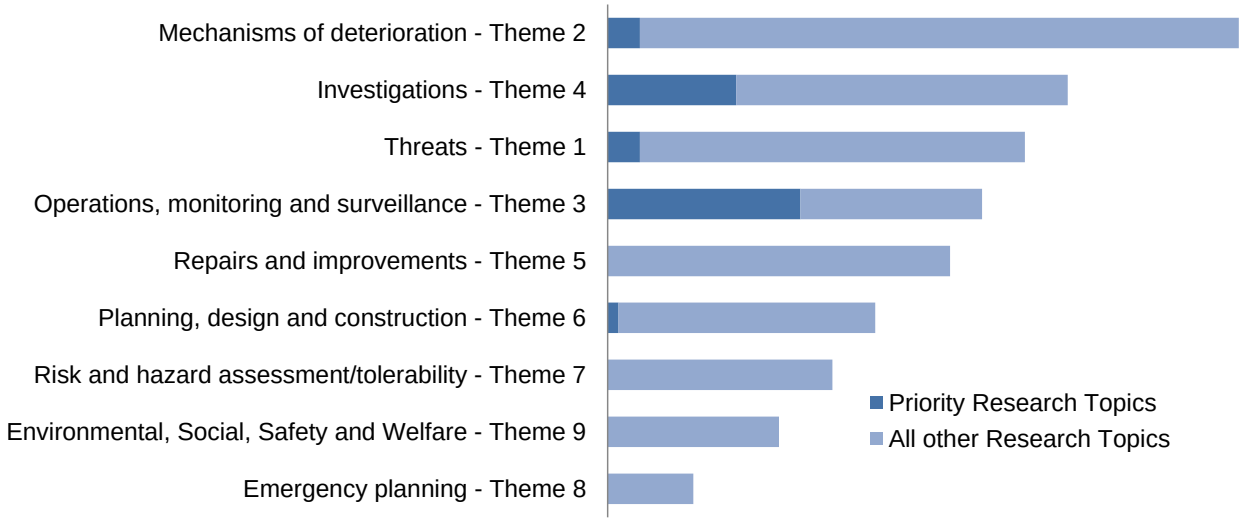


Figure 6.2 All research and priority research (top seven projects) by theme

7 Project funding and delivery

7.1 Introduction

A large portion of reservoir research in the UK is currently funded through the Joint FCERM R&D Programme, which identifies reservoir safety as an important cross-cutting area of research. The proposals in this new strategy will first be considered for submission to the Joint Programme.

Where projects are not progressed by the Joint Programme or their delivery is better suited to other routes, alternative funding and delivery partners should be identified and encouraged to progress.

This section briefly discusses each of these routes and recommended actions to improve engagement and the potential for delivery.

7.2 Joint FCERM R&D Programme

Proposals submitted through this programme are prioritised and submitted for review to the Joint Programme Board, which considers funding of approximately £4 million per year across its three themes and their cross-cutting groups (see Section 2.2). Because it is one of the cross-cutting groups, funds are not dedicated to reservoir safety research and the case for research needs to be made clearly so as to compete with other programme themes.

In each of the four cross-cutting areas, the programme aims to conduct, manage and promote FCERM R&D. This includes:

- influencing and steering the content and direction of FCERM research undertaken by research councils, the EU and beyond
- conducting practitioner-led research to inform policy and operations
- developing user tools, methods and guidance to aid delivery of FCERM

A prioritised programme of proposals is developed and submitted to the RSAG, which advises on proposals to be taken forward. These are then submitted to the Joint Programme Board, which decides on the project portfolio for the following year.

To procure work on these projects, the programme currently relies on its framework partners where practicable. This is followed by competitive open tender and, where warranted and justifiable, single tender awards. The programme is also open to requests for research and applications for support or partnership.

Actions recommended for funding under the Joint FCERM R&D Programme must comply with the following three criteria.

- A clear case for each proposal should be made using the programmes scoring methodology outlined in Section 5.6.
- The Joint Programme Proposals should be written emphasising research to improve the evidence base for reservoir safety.
- Proposed guidance documents should focus on delivering research outputs to practitioners through evidence-based tools.

7.3 Research councils

The research councils are non-departmental government bodies that invest around £3 billion in annual funding from the Department for Business, Innovation and Skills (BIS) of research grants and training at universities. There are seven research councils covering the full range academic disciplines, with those of most relevance to reservoir safety research being EPSRC, NERC and the Economics and Social Research Council (ESRC).

Proposals progressed with funding from the Research Councils would be delivered by UK Universities or Research Institutes.

7.3.1 EPSRC

EPSRC is the main UK government agency for funding research and training in engineering and the physical sciences, investing around £500 million per year in a broad range of subjects – from mathematics to materials science, and from information technology to structural engineering. EPSRC operates to meet the needs of industry and society by working in partnership with universities to invest in people, scientific discovery and innovation. Its work complements other research investors including other research councils, government agencies, industry and the EU. EPSRC actively encourages a range of partnerships and collaborations across disciplines and boundaries. Its current themes are:

- digital economy
- energy
- engineering
- global uncertainties
- healthcare technologies
- information and communication technologies (ICT)
- living with environmental change (LWEC)
- manufacturing the future
- mathematical sciences
- physical sciences
- quantum technologies

A range of grant funding, interdisciplinary research collaborations and strategic packages, external partnership funding, collaborative R&D and fellowships are used. These are discussed and may be applied for through the forms available from the EPSRC website.

7.3.2 NERC

NERC funds and manages research and training in earth system sciences, and covers the full range of atmospheric, earth, terrestrial and aquatic sciences. NERC invests about £220 million a year to fund scientific research in universities and at its own sites. Applicants for grants must be employed by an eligible UK research organisation (higher education institution, NERC research or collaborative centre) or other NERC recognised research organisation. Its current research areas are:

- archaeology
- atmospheric physics and chemistry
- climate and climate change
- ecology, biodiversity and systematics
- genetics and development
- geosciences
- marine environments
- medical and health interface
- microbial sciences
- omic sciences and technologies
- planetary science
- plant and crop science
- pollution, waste and resources
- terrestrial and freshwater environments
- tools, technology and methods

7.3.3 ESRC

ESRC is the UK's largest funding agency for social and economic research. It focuses on 7 research areas:

- economy and business
- environment
- health and well-being
- international
- public services
- politics
- governance and society

It supports independent, high quality research relevant to business, the public sector and voluntary organisations. ESRC invests around £193 million annually to support research in academic institutions and research policy institutes.

Awards ranging from £350,000 up to £1 million can be made to eligible institutions to enable individuals or research teams to undertake research from small projects through to large-scale surveys. Eligible institutions include universities, colleges of higher education and independent research institutes in the UK. There is considerable flexibility when it comes to subject area, as long as the suggested topic falls within ESRC’s remit. Applications may be submitted at any time.

7.3.4 Actions recommended for funding by research councils

Defra and the Environment Agency should consider exploring the development of a strategic partnership with EPSRC and other partners to fund a collaborative centre for multidisciplinary reservoir safety research and training in UK universities. A strategic partnership would increase the available funding for the Defra and Environment Agency portfolio of recommended research. To cover the cross-disciplinary nature of the research, partners could include dam owners, engineering consultancies specialising in reservoir safety, and the sister research councils NERC and ESRC. The aim of the centre should be two-fold:

- to bring university researchers together to apply their knowledge to reservoir safety research
- to train graduates on the research in associated specialist areas, thus contributing in part to the succession training of reservoir safety experts

Defra and the Environment Agency should also consider identifying/employing/ procuring a champion to proactively encourage the development of joint proposals for research council funding for research collaborations and networks between universities and other organisations. By stimulating research in the universities, the available funding for the recommended reservoir safety research projects would be increased.

7.4 Industry-supported research

7.4.1 CIRIA

CIRIA is a member-based research and information organisation dedicated to improvement in the construction industry. Members include representatives from all parts of the supply chains of the modern built environment, covering building and civil engineering as well as transport and utilities infrastructure. CIRIA's work is recognised as being independent, objective and authoritative.

CIRIA's research is member and industry driven. The themes of work cover wide remits topical to construction such as technical issues, legislation and regulation, training, management and economics. While much of the work benefits from competitively-won public sector funding, CIRIA maintains its provision of 'club-funded' projects aimed at building understanding between contributors in key areas of concern, such as knowledge management and performance indicators of design.

In addition to design guides, training manuals and so on, CIRIA provides training seminars and workshops based on the results of its project work. Typically, each project is funded by a number of stakeholders, which often includes core members and government departments, as well as other private sector companies.

CIRIA has funded many of the guides relating to dams and reservoirs, and should be examined as a source for further funding, particularly for updating some of the guides.

7.4.2 UKWIR

Set up by the UK water industry in 1993, UKWIR provides a framework for the procurement of a common research programme for UK water operators on 'one voice' issues. UKWIR's members comprise 24 water and sewerage undertakers in England and Wales, Scotland and Northern Ireland. Its objectives are to:

- identify research requirements to meet the water industry's strategic business needs
- procure the research competitively
- work with the water industry regulators
- provide value for money for the contributors
- transfer the research outputs to contributors

Over the past 15 years, UKWIR subscribers have contributed some £50 million, with a further £30 million of research coming from UKWIR collaborators. This has resulted in over 750 reports delivered to members. Work is often carried out in collaboration with government departments and regulators including Defra, the Drinking Water Inspectorate and the Environment Agency. Some work is also done in collaboration with research organisations internationally. The majority of work is put out to open tender to a wide range of companies, academic institutions and other organisations in the UK and overseas. Project management is undertaken by the water industry's R&D departments and by individuals employed by UKWIR.

7.4.3 Dam Safety Interest Group (CEATI International)

DSIG manages a programme of research addressing reservoir safety issues and is facilitated by CEATI International, based in Canada. Group members are all dam owning or operating companies. Research needs are identified by members and research funds established through member contributions. Research results are shared between group members and later sold to industry via CEATI. DSIG's current list of topics and issues include:

- investigation
- instrumentation and monitoring
- analysis
- performance assessments
- risk assessment and management

As an owner and regulator of dams, the Environment Agency qualifies as a potential member of DSIG. Scottish and Southern Energy (SSE) has been a member for a number of years and participated successfully in a range of projects.

7.4.4 Actions recommended for funding under industry supported research

Defra and the Environment Agency should:

- continue to work with CIRIA to identify funding opportunities on appropriate projects
- identify research projects that cut across both dam safety and water resources issues and approach UKWIR with the view to jointly funding and project managing research in these areas
- continue to support DSIG activities and take an active role in contributing to and disseminating research output of interest and relevance to the UK reservoir industry

8 Driving the strategy

8.1 Ongoing activities

The strategy will require active involvement to promote implementation and to maintain the list of proposals. The following activities will require input throughout the year to drive the strategy forward and to promote reservoir safety research.

- submission of proposals to the Joint Programme
- promotion of proposals for alternative delivery
- incorporation of new proposals and emerging topics
- ongoing engagement activities for industry and academia
- review of project delivery
- periodic review of progress on strategy actions

8.2 Roles and responsibilities

To manage these activities, the following roles and responsibilities are proposed.

8.2.1 Project Manager: Environment Agency nominee

It is envisaged that the Environment Agency will assign an individual to work as the contact person and project manager.

8.2.2 Committee: RSAG

The committee to support and steer delivery of the strategy will be RSAG. RSAG members represent a cross-section of the reservoirs community and are capable of providing a balanced view of the priorities of the reservoirs industry. The committee would be expected to review/revisit the proposal prioritisation annually, and score and incorporate new proposals that emerge.

To ensure its sustainability and effectiveness, the time and costs of committee members' duties may need to be reimbursed.

8.2.3 Knowledge and networking: BDS

BDS is the body responsible for sharing reservoir safety knowledge and ideas. It is proposed that:

- ideas for new research requirements are gathered from its membership on a 3-year basis by questionnaire
- the findings are forwarded to the project manager for discussion with RSAG

It is envisaged that the BDS website would be able to host a collection of current knowledge and research, plus a list of researchers and industry representatives, accessible to those interested in reservoir safety research.

8.3 Promotion of proposals for alternative delivery

The programme of proposals will be circulated by the project manager to other delivery partners via the programme website, through the BDS, regular engagement activities or through direct contact.

The project manager will be the point of contact for these proposals and will connect appropriate individuals within the reservoir industry, delivery partners and researchers to enable research to be delivered.

Where required, the project manager will make possible the provision of support either directly through the Environment Agency or by contact with industry.

8.4 New proposals

The RSRDS is intended to be a live document, actively managed through its expected 5–10 year life. However, even within this time frame, research needs can be expected to change in response to industry needs. Emerging topics will need to be incorporated in the strategy, and prioritised and funded before existing proposals where appropriate.

New research projects will be encouraged during regular engagement events and directly through the project manager. These may arise as specific needs from industry or practitioners, from researchers or through the proposed BDS membership questionnaires.

A three-stage methodology is proposed for the incorporation of new research proposals:

1. **Origination.** The committee will review the topic submissions with respect to the wider industry needs and recent/ongoing international research/guidance and any other relevant factors.
2. **Scoring and prioritisation.** The committee will then score each proposal using the same parameters of impact, driver and risk. These scores should be averaged and the project included within the list of proposals to identify its position and priority. Weightings have not been applied to date and would only be applied should the committee consider it necessary.
3. **Proposal scope.** Once scored, and should the proposal rank within those to be submitted for implementation that year, a summary scope should be developed by a relevant committee member similar to those found in Appendix B.

8.5 Ongoing engagement

To move the strategy forward through implementation and encourage continuing awareness of reservoir safety, an engagement plan should be implemented through the programme outlined in Section 8.5.1.

To enable these engagement activities, the list of researchers and industry partners should be updated and kept live by the Environment Agency and hosted on the BDS website or similar. This would provide a focus for the reservoir R&D community.

8.5.1 Engagement activities programme

Reservoir safety research updates: biannual

Updates should include information on projects being carried out by the Joint Programme and others in the research community. To inform this, the project manager will contact the industry and researchers on the project list to canvas for updates on ongoing research to be included.

Reservoir safety R&D workshops: Biennial

Reservoir safety workshops should be held biennially and possibly in conjunction with the BDS biennial conference. These workshops would be a place for researchers and industry representatives to:

- network and gain insight into industry needs and priorities
- communicate R&D developments that may have application to the reservoirs industry

Such workshops would provide a common forum for academics and reservoir practitioners.

Reservoir safety promotional events: ongoing

The BDS currently offers technical or awareness talks at universities around the country with the aim of encouraging young engineers into a career involving reservoirs. This approach is endorsed and may benefit from more regular contact with researchers through the R&D workshops.

Reservoir safety research presentation: annual

Researchers working in fields with direct application to reservoirs would share an evening presentation on current academic research. This could involve the presentation of a single research project or an evening shared by up to four researchers who would present their work in a forum such as the BDS's evening meetings.

8.6 Review of project delivery

As projects are delivered, the RSAG will formally review their success to evaluate the process and provide lessons for application to following projects. The development of an annual scorecard will help this evaluation. This should be prepared by the project manager and agreed with the committee.

Criteria for successful projects may include:

- delivery of the project scope within the funding provided
- successful communication or dissemination of the results
- adoption of the work by the reservoir community

Research projects should be reviewed both immediately post-completion to assist in the selection of researchers and facilities, and five years after delivery to evaluate the adoption of the research outputs in further research or guidance documents.

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List of abbreviations

ASDSO	Association of State Dam Safety Officials [USA]
BDS	British Dam Society
CEATI	Centre for Energy Advancement through Technological Innovation
CEH	Centre for Ecology and Hydrology
CFD	computational fluid dynamics
DSIG	Dam Safety Interest Group
EPSRC	Engineering and Physical Sciences Research Council
ESRC	Economics and Social Research Council
FCERM	Flood and Coastal Erosion Risk Management
FEH	Flood Estimation Handbook
FEMA	Federal Emergency Management Agency [USA]
ICE	Institution of Civil Engineers
ICOLD	International Commission on Large Dams
IEC	International Electrotechnical Commission
NERC	Natural Environment Research Council
PMF	probable maximum flood
PMP	probable maximum precipitation
R&D	research and development
RARS	risk assessment for reservoir safety
ROV	remotely operated vehicle
RSAG	Reservoir Safety Advisory Group [ICE]
RSRDS	Reservoir Safety Research and Development Strategy
UKWIR	UK Water Industry Research Limited
UV	ultraviolet
USACE	United States Army Corps of Engineers
USBR	United States Bureau of Reclamation
WWNP	Working with Natural Processes

Appendix A Full list of research topics, proposals and industry needs

A.1 Introduction

This appendix includes details of all the topics identified through the consultation phase as industry needs. Table A.1 lists all of the 76 topics identified. This list is in ranked order but is not consolidated.

It was considered important to capture all the perceived needs of the reservoir industry, regardless of whether the needs could be addressed through funded research. This then allows the industry to consider how such additional needs might be addressed. Some discussion of these wider industry needs is provided in Appendix A.4.

A.2 Research topics

Table A.1 Full list of ranked research topics and prioritisation scores

Rank	Title	Prioritisation				Outline aims/scope
		Impacts	Drivers	Risks	Total score	
1	Effective reinforcement of grassed surfaces for overtopping flows	4.5	4.3	4.2	12.9	Research on the effectiveness of reinforced grass and concrete block systems for protecting surfaces against overtopping flows. This should cover the sensitivity of the level of protection to construction tolerances (depth of soil cover, lap joints and so on) as well as design details (soil type being protected, presence of underdrainage systems and so on). Consideration of long-term effectiveness.
2	Development of methods for estimating extreme floods	4.7	4.2	4.0	12.8	This could be design event rainfall–run-off approach – as currently, probably involving the Revitalised Flood Hydrograph (ReFH) model rather than the Flood Studies Report/Flood Estimation Handbook (FSR/FEH) rainfall–run-off method – or could be based on explicit simulation of the flow regime (continuous simulation) using existing models such as the Probability Distributed Model (PDM) (catchment based) or Grid-to-Grid (UK-wide applicability). Another alternative could be statistical joint probability modelling to determine the frequency of extreme rainfall combined with high degree of catchment wetness, thus providing probability of extreme floods (this has so far been applied to modelling spatially extreme events by JBA Consulting). The method should take account of climate change and hydrological parameter uncertainty and revisit areal reduction factors and storm profiles. Investigate catchment response times during extreme events. There is an indication that hydrograph time-to-peak can be shorter during relatively frequent events (that is, not only for the PMF).
3	Guidance on legislative conflicts	4.4	4.3	3.9	12.5	Guidance on what reservoir owners should do where there is legislative conflict.
4	Management of trees and vegetation on embankment dams	4.5	4.0	3.8	12.3	Common issues, risk assessment, mitigation, debris management, dealing with invasive species
5	Probable maximum flood estimation	4.3	4.0	3.8	12.1	Revision of PMP values and use of PMPs with the revised rainfall–run-off methodology. It would be appropriate to also include in this scope a review of snowmelt provisions. Study of areal reduction factors and design rainfall profiles is also needed as these have not been revisited since the research for the Flood Studies Report (NERC, 1975).

Rank	Title	Prioritisation				Outline aims/scope
		Impacts	Drivers	Risks	Total score	
6	New guidance on the selection, operation, evaluation, repair, maintenance and replacement of gates and valves for dam structures	4.3	3.9	3.8	12.0	The guidance will seek to define best practice in maintaining gate and valve equipment in good condition, evaluating likely residual life through surveys, identification of problems and trends in operational behaviour, checking related electrical or hydraulic equipment, and carrying out a review of programmable logic controllers. Reference will be made to the latest International Electrotechnical Commission (IEC) standards to be maintained for the control of safety-critical equipment. Through description of a variety of case studies in evaluating and replacing equipment, the guide will seek to assist in decision-making on the replacement or refurbishment of equipment and the planning of the works. The guide will make reference to environmental guidelines in operating low level gates and valves and in carrying out replacement works. Include examples of failures and lessons learned.
7	Leakage guidance	4.3	4.0	3.6	11.9	Investigation into different types of leakage. What systems are available to find/measure leakage? What type is appropriate and when. Case studies – what worked and why? How do we deal with leakage?
8	Reservoir monitoring and surveillance	4.2	3.9	3.6	11.7	Provide guidance and some spreadsheet tools to assist reservoir owners in monitoring reservoir safety condition. The aim is to promote a consistent approach in how data are gathered, recorded and presented to assist in data interpretation. The guide would also cover new developments in monitoring and surveillance techniques such as fibre optics and the use of remotely operated vehicles (ROVs).
9	Guide on the use of geophysical methods for reservoir safety investigations	4.0	3.9	3.6	11.5	Provide a summary of the techniques used in reservoir safety applications including seepage path detection and void detection, and provide guidance on the requirements and limitations for the application of each technique.
10	Tolerability of wave overtopping	4.2	3.8	3.5	11.5	Allowable discharges onto embankment slopes from wave overtopping.
11	Acceptable ‘rapid’ drawdown rates	4.1	3.8	3.5	11.5	Provide comprehensive guidance on the rates of drawdown which could initiate upstream instability under various embankment fill characteristics and embankment geometry.
12	Quantifying cascade reservoir risk	4.0	3.8	3.5	11.3	Guidance on the evaluation of cascade reservoir risk.
13	Flood management for reservoir repairs, alterations and discontinuance works	3.9	3.7	3.5	11.2	Provide advice on setting appropriate flood protection standards and protocols for managing the flood risk at dams during periods of increased vulnerability.

Rank	Title	Prioritisation				Outline aims/scope
		Impacts	Drivers	Risks	Total score	
14	Masonry spillways – guidance	3.8	3.7	3.5	11.0	A 'CIRIA 116 approach' to flows on masonry spillways – a 'single graph' displaying what is acceptable and what is unacceptable. Correlation of physical model, CFD and so on. Use of case studies.
15	Sediment management in reservoir operations	4.0	3.6	3.4	11.0	Provide guidance to reservoir operators on effective means of managing reservoir sediment in carrying out various operations or alterations including: draining of reservoirs to carry out works; scour valve testing; dredging and discontinuance works. Develop guidance on planning and carrying out scour conduit testing.
16	Maintenance recommendations	4.2	3.4	3.4	11.0	Guidance on optimum maintenance regimes. Correct approach for different types of dams.
17	Standards for spillway remedial works	4.0	3.7	3.3	10.9	Guidance for the standard of protection required at reservoirs during works at spillways.
18	Workshops on the use of RARS and ICOLD Bulletin 164 on internal erosion to provide probabilities of failure from internal erosion	3.8	3.6	3.5	10.9	Funding would be provided to host a series of workshops aimed at providing best practice in assessing the threat of failure from the various types of internal erosion and how this information can be used to assess the value of improvement works in the context of societal risk.
19	Application of particle-scale soil modelling to assess the vulnerability of UK dams to internal erosion	3.9	3.5	3.5	10.9	Use of new techniques to assess the vulnerability of typical UK soils to particle movement. Application of latest techniques – developed at Imperial College – to assess the likelihood of particle movement.
20	Emergency plans for reservoir breach	3.8	3.5	3.4	10.8	Provide guidance on preparing and exercising onsite emergency plans.
21	Estimation of the escapable contents from reservoirs	3.8	3.7	3.3	10.7	Estimation of the release of silt with water discharged from reservoirs either due to an emergency drawdown or due to dam failure.
22	Industry expertise and succession planning	3.7	3.7	3.1	10.6	Analysis of where dam engineering knowledge and skills lie with respect to the age profile of the UK pool of dam engineers. Is the situation manageable? What steps can be taken to promote succession planning and transfer skills and knowledge?
23	Improving local surveillance of dams.	3.9	3.5	3.1	10.5	Guidance on local surveillance of dams through community engagement.
24	Design life of materials in the UK.	3.7	3.5	3.2	10.4	What is the true design life for reinforced concrete structures? How can we prolong the design life? What is the expected design life of existing structures? How do we design for a 200 year design life? Research into the degradation of materials in the UK. Causes of concrete deterioration and that of other materials (soil, steel).

Rank	Title	Prioritisation				Outline aims/scope
		Impacts	Drivers	Risks	Total score	
25	Estimating wave loadings on wave walls for structural design	3.7	3.4	3.3	10.4	Develop a standard methodology for estimating loadings on wave walls of various shapes.
26	Guidance on use of geotextiles in reservoirs.	3.7	3.5	3.2	10.3	When should geotextiles be used? What is their durability? When is it appropriate to use them in dams? Partially covered by the USBR's reclamation design standard for geotextiles (USBR 2014).
27	Updated breach inundation methodology	3.8	3.4	3.1	10.3	Better quality LiDAR, better estimation of flood peaks and so on.
28	The operation of reservoir gates	3.6	3.6	3.0	10.2	Development of guidelines for the responsible use of reservoir gates such as spillway gates and flood gates.
29	Erodibility of soils research	3.6	3.5	3.2	10.2	Participate in current USACE research on soil erodibility to inform any need for UK research.
30	Performance of masonry wave walls	3.6	3.3	3.3	10.2	Carry out research to assess the performance of masonry walls of various construction and geometry.
31	Sealing of dam cores and foundations	3.7	3.2	3.1	10.0	Research and guidance on the techniques available for improving dam watertightness through various repair techniques.
32	Applicability of Eurocode to Reservoirs	3.5	3.3	3.2	10.0	
33	Options for obsolete reservoirs	3.7	3.4	2.9	9.9	Provide guidance to owners in considering options for dealing with reservoirs which are no longer required. Carry out a review of reservoirs rendered obsolete to inform the guidance and provide case studies. Guidance on the discontinuance of reservoirs, including option studies, technical and environmental constraints, consultation and funding.
34	Tool to predict the minimum time to failure	3.5	3.3	3.1	9.9	Develop guidance for the estimation of the time to failure of homogeneous and zoned dam embankments.
35	Drawdown capacity	3.8	3.3	2.8	9.8	What are the allowable rates of drawdown for different types of dam (links to environmental constraints)?
36	Guidance on design of debris screens.	3.5	3.1	3.1	9.7	Use of tree blockers, coarse trash screens and so on.
37	Dam safety management - guidance for major owners	3.6	3.2	3.0	9.7	How should a company structure itself to manage dams safely in terms of reporting, structure, operation, risk assessment, maintenance programmes, accountability and independent scrutiny? Case studies: (post Taum Sauk) Amer, United Utilities, Thames Water, Dwr Cymru Welsh Water, DCWW, Severn Trent Water and so on.
38	Applying modern safety standards to old dams	3.6	3.2	2.9	9.7	Guidance on how to safely access, operate, monitor or repair old dams that were not designed to modern safety standards.

Rank	Title	Prioritisation				Outline aims/scope
		Impacts	Drivers	Risks	Total score	
39	Forensic opportunities at discontinued dams	3.6	3.2	2.8	9.7	Characterising geotechnical parameters for a wider range of dams. Consider both overtopping and internal erosion failure. Carry out forensic tests on discontinued and other dams. Collation of geotechnical data, bottom outlets, data from remedial works and so on. Could be split into different aspects (for example, geotechnical, pipework).
40	Operation of ancillary equipment in extreme events.	3.3	3.4	2.8	9.6	Guidance for owners on operating gates and turbines to limit downstream flooding in the event of a storm.
41	Research into joint probabilities of wave and reservoir rise at reservoirs	3.5	3.1	2.9	9.5	
42	Threat of overtopping from wave action	3.5	3.0	3.0	9.5	Joint probability analysis of high reservoir water levels with high wind speeds (critical event might not be during a PMF).
43	Effect of rapid drawdown on upstream erosion protection under rapid drawdown of flood storage reservoirs	3.3	3.3	2.9	9.4	Investigation into the upstream erosion protection under rapid drawdown of flood storage areas.
44	Research to support the risk assessment for reservoir safety (RARS) tier 3 probabilistic risk assessment	3.4	3.2	2.9	9.4	Further work on probability of failure mechanisms and sensitivity analysis. Develop examples of good application. Modify the USBR Toolbox for use in estimating the probability of failure.
45	Guidance on use of computational fluid dynamic (CFD) analysis for spillways	3.3	3.2	2.8	9.4	
46	Research on grass varieties for various applications and maintenance	3.3	3.1	2.8	9.3	
47	Training of operatives to identify issues, and how they are reported and followed up	3.4	3.1	2.8	9.2	
48	Guide for emergency planners	3.3	3.0	2.9	9.2	
49	RARS updates in 5–10 years	3.3	3.1	2.8	9.1	

Rank	Title	Prioritisation				Outline aims/scope
		Impacts	Drivers	Risks	Total score	
50	Climate change impact on spillway design	3.4	2.9	2.8	9.1	
51	Site supervision of reservoir construction	3.1	3.1	2.9	9.1	
52	Investigation of voids in masonry dams	3.2	2.9	2.9	9.0	Investigation of voids and loss of grout between blockwork in masonry dams.
53	Revised guidance for the seismic risk to dams in the UK	3.3	3.1	2.6	8.9	Harmonise the UK guidance with ICOLD Bulletin 148 (ICOLD 2016) and Eurocode 8 (Bisch et al. 2011), especially for the auxiliary structures design. Need to review/update the 1996 Musson and Winter UK seismic hazard map (Musson and Winter 1996) with more recent information from the British Geological Society. Need to expand the scope of the UK guidance to: address reservoir triggered earthquakes and construction design for earthquakes; and define design earthquakes for auxiliary structures.
54	Effect of climate change on operation of reservoirs	3.3	3.0	2.5	8.9	Research into climate change effects at embankment dams and mitigations (for example, detailing of the crest for extreme heat, gate operation in icy conditions).
55	Guidance on underwater surveys	3.3	2.9	2.7	8.8	
56	Development of non-destructive testing methods into clay core.	3.3	2.9	2.6	8.8	Testing to determine presence of clay core.
57	Use of fragility curves to inform probability of dam failure	3.0	2.8	2.8	8.6	Make use of recent research on coastal and flood defence structures to inform risk assessment of dam embankments.
58	Bathymetry of reservoirs and lakes, and the determination of reservoir volume	3.1	2.9	2.5	8.5	Revise ISO/TR 11330:1997: Determination of volume of water in lakes and reservoirs
59	Seasonal vegetation changes at flood storage reservoirs	3.0	2.9	2.6	8.5	Guidance on vegetation changes at flood storage reservoirs during the year (for example, tree planting). How to carry out appropriate respective surveillance.
60	Behaviour of populations in a dambreak scenario	2.9	2.8	2.7	8.5	Guidance on the use of predicative tools to assess the impact of population concentrations, transport routes and refuge locations on the loss of life and the effectiveness of emergency plans in the event of dam failure. Inform a deeper understanding of the response of a population to warnings and emergencies.
61	Determination of the residual life of grouted post-tensioned anchors in dams	2.9	3.0	2.6	8.4	Research on the rate of deterioration in cable anchors used to post-tension dams. Provide guidance to undertakers on the assessment of likely residual life.

Rank	Title	Prioritisation				Outline aims/scope
		Impacts	Drivers	Risks	Total score	
62	Development of regional flood coefficients (for example, Francou–Rodier or Creager values)	3.2	2.6	2.6	8.4	Regional flood coefficients can provide a rapid assessment of flood safety. Make use of updated PMF methodology to produce a map of coefficients for the UK.
63	Wave wall stability	3.0	2.7	2.7	8.3	Develop a definitive methodology for determining the stability of dry stone wave walls.
64	Structural performance of morning glory spillways	2.8	2.7	2.8	8.3	Evaluation of the vulnerability of morning glory spillways to cavitation and/or vibrational effects during extreme flood events leading to structural damage.
65	Guidance on design and construction of homogenous fill dams	2.9	2.9	2.5	8.3	
66	Community engagement in reservoir safety	3.0	2.7	2.5	8.2	Advice on how reservoir owners can engage with their local community to explain how reservoir risk is managed and the role that the community can have in helping to keep dams safe.
67	Specification for dams	3.0	2.6	2.5	8.2	
68	Vehicle loadings on dam embankments	3.1	2.6	2.4	8.1	Provide guidance on permissible axle loads on the crest of embankment dams.
69	Ice loading on dam structures	2.8	2.9	2.3	8.0	Guidance on the estimation and mitigation of ice loadings on spillway structures, drawoff towers and other sensitive structures. Covered by: ICOLD Bulletin 105 (ICOLD 106); USACE ice engineering manual EM 1110-2-1612 (USACE 2002), The International Levee Handbook (ILH) section 8.4.5 (armorstone only) (CIRIA 2013).
70	Data mining to collect and store information on reservoirs	2.9	2.7	2.2	7.8	
71	Dealing with snow and ice at reservoirs	2.8	2.5	2.3	7.5	Carry out research on the loadings that can be applied to dam structures under UK conditions for consideration in stability reviews. Provide guidance on how ice risk can be mitigated (bent valve spindles, gaugeboards and so on).
72	Quantification of valley funnelling effects on wave augmentation	2.7	2.7	2.1	7.5	Research into the effects of steep valley sides and reservoir plan valley shape/orientation on wave magnitude and risk of wave overtopping.
73	Security against terrorism	2.5	2.4	2.6	7.5	Pragmatic advice for improving security at reservoirs against terrorist attack.
74	Guidance on anchoring systems for floating islands	2.5	2.4	2.0	6.8	Floating islands can become dislodged during floods and block spillways/outlets. Provide guidance on suitable anchoring systems.

Rank	Title	Prioritisation				Outline aims/scope
		Impacts	Drivers	Risks	Total score	
75	Reservoir rim stability	2.4	2.5	1.8	6.8	Guidance on the evaluation, identification and stabilisation of reservoir rims
76	Dealing with vegetation in the basins of new reservoirs	1.8	1.9	1.7	5.4	Guidance on the removal of vegetation from the basins of new reservoirs to limit methane generation, blockage of outlets and so on.

A.3 Research proposals

Table A.2 Full list of prioritised research proposals (consolidated research topics)

Proposal number	Main topic	Proposal name	Included topics
2015-1	2	Extreme flood estimation – rainfall–run-off modelling	2
2015-2	4	Management of trees and vegetation on embankment dams	4
2015-3	5	Extreme flood estimation – PMP/PMF estimation	5
2015-4	6	Investigate the selection, operation, evaluation, repair, maintenance and replacement of gates and valves for dam structures	6
2015-5	7	Managing reservoir leakage and seepage	7
2015-6	8	Reservoir monitoring and surveillance	8
			23
			66
2015-7	9	Geophysical methods for reservoir safety investigations	9
			52
			56
2015-8	10	Tolerability to wave and sustained overtopping	10
			12
2015-9	11	Acceptable drawdown rates	11
			35
			43
2015-10	13	Flood management and other considerations for reservoir discontinuance	13
			33
2015-11	14	Spillway protection and remedial works	14
			17
			45
			50
			64
2015-12	15	Sediment management in reservoir operations	15
			21
			58
2015-13	16	Maintenance regime best practices	16
2015-14	19	Particle-scale soil research and modelling to assess the vulnerability of UK dams to internal erosion and time to failure	19
			29
			34
2015-15	20	Guidance on preparing and exercising onsite emergency plans	20
2015-16	24	Research into the degradation of reservoir related materials in the UK	24
2015-17	25	Research and development of a standard methodology for estimating loadings on wave walls of various shapes	25
			30
			63
2015-18	26	Guidance on use of geotextiles in reservoirs	26
2015-19	27	Updated breach inundation methodology	27
2015-20	28	Research and development of guidelines for the responsible use of reservoir gates such as spillway gates and flood gates	28
			40

Proposal number	Main topic	Proposal name	Included topics
2015-21	31	Research and guidance on the techniques available for improving dam water tightness through various repair techniques	31
2015-22	59	Research and development into vegetation in reservoir basins, seasonal variation and management	59 76
2015-23	36	Guidance on design of debris screens	36
2015-24	37	Research and development of guidance on effective management structures for reservoir safety	37
2015-25	38	Application of modern safety standards to old dams	38
2015-26	39	Forensic opportunities at discontinued dams	39 70
2015-27	41	Research into joint probabilities of wave and reservoir rise at reservoirs	41 42 72
2015-28	44	Research to support the RARS Tier 3 probabilistic risk assessment	44 57
2015-29	46	Research on grass varieties for various applications and maintenance	46
2015-30	53	Revised guidance for the seismic risk to dams in the UK	53
2015-31	54	Effect of climate change on operation of reservoirs	54
2015-32	55	Guidance on underwater surveys	55
2015-33	60	Behaviour of populations in a dambreak scenario	60
2015-34	61	Determination of the residual life of grouted post-tensioned anchors in dams	61
2015-35	62	Development of regional flood coefficients (for example, Francou–Rodier or Creager values)	62
2015-36	65	Guidance on design and construction of homogenous fill dams	65
2015-37	67	Specification for dams	67
2015-38	68	Vehicle loadings on dam embankments	68
2015-39	69	Research and development of methodologies for estimating ice loading on dam structures in the UK	69 71
2015-40	73	Security against terrorism	73
2015-41	74	Guidance on anchoring systems for floating islands	74
2015-42	75	Reservoir rim stability	75

A.4 Wider industry needs

Among the topics listed in Table A.1, a number were not considered suitable for funded research though they reflected a genuine need of the UK reservoir industry.

Consultees indicated a need for guidance on a wide range of matters including:

- how companies responsible for reservoirs should structure themselves to best coordinate matters of reservoir operation, maintenance, monitoring and surveillance, portfolio risk reviews and independent review (#23 and #51)
- how companies responsible for reservoirs should deal with reservoirs which are no longer required for their primary purpose (typically, water supply) given that they become a corporate liability yet often provide a wide range of secondary benefits such as recreation and environmental (#31)
- provision of workshops/training to assist reservoir owners and practitioners in:
  - applying new tools (such as the RARS methodology) (#35)
  - application of advanced modelling techniques (#76)
  - planning underwater surveys (#46)
  - preparing/exercising emergency plans (#39 and #76)
  - site supervision of reservoir construction (#66)
  - use of spillway gates to preserve reservoir safety during severe flood conditions (#54)
  - community engagement in reservoir safety matters (#40 and #55)
- knowledge capture and succession planning (#42)
- dealing with conflicts in primary legislation (#50)

There is a perceived need to assist reservoir owners in developing strategies for managing reservoir safety issues in the broadest sense. Within the UK there is already some degree of collaboration through informal meetings of reservoir safety managers. This collaboration might usefully be extended to include workshops to discuss and inform best practice. There may be a role for UKWIR in sponsoring and facilitating such events. Topics could include organisational structuring, community engagement and dealing with unwanted reservoirs.

Where technical tools are already available to the industry (for example, RARS risk methodology, modelling techniques), there appears to be a need for workshops or presentations to help practitioners apply them. This could be addressed by BDS sponsored workshops. Note that some consultants offer training of this nature.

Defra can be expected to provide direction in relation to legal matters.

The ICE can be expected to play a lead role in directing actions to address knowledge capture and succession planning issues. The ICE president is also the chair of the Reservoirs Committee and has a formal role under the provisions of the Reservoirs Act 1975 in relation to panel engineer appointments.

A.5 Industry workshop attendees

Table A.3 List of industry workshop attendees

Name	Affiliation
Project team	
Dave Hart	Environment Agency
Andrew Moores	Environment Agency
John Chesterton	Mott MacDonald
Tim Hill	Mott MacDonald
Jen Swetman	Mott MacDonald
Alan Warren	Mott MacDonald
Delegates	
William Allsop	HR Wallingford
Matthew Atyeo	Bristol Water
Alan Brown	Stillwater Associates
David Brown	Canal and River Trust
Quinton Campbell	Rivers Agency (Northern Ireland)
Andrew Courtnadge	Jacobs
Peter Down	Mott MacDonald
Malcolm Eddleston	MWH
Robert Elledge	Stillwater Associates
Craig Goff	HR Wallingford
Neil Harding	NHTB Consultancy
Robin Hawley	Independent
Jonathan Hinks	HR Wallingford
Colin Hunt	Bristol Water
Stuart King	Scottish and Southern Energy
Ian Kirkpatrick	Anglian Water
Peter Kite	Independent
Jasvir Malia	Scottish Water
Jack McCarey	South West Water
Jim Claydon	Independent
Dominic Molyneux	Black and Veatch
Steve Morris	Natural Resources Wales
Mohammed Nanekely	University of Salford
Stephen Naylor	Environment Agency
David Neeve	Arup
James Penman	CH2M Hill
Andrew Pepper	Independent
Anthea Peters	Arup
Neil Rich	Environment Agency
Joao Santa-Clara	JBA Consulting
Alex Topple	HR Wallingford
Neil Williams	Stillwater Associates

Name	Affiliation
Tracey Williamson	Dwr Cymru Welsh Water

Table A.4 List of academic workshop attendees

Name	Affiliation	Research areas
Project team		
Tony Deakin	Environment Agency	
Stephen Naylor	Environment Agency	
Daniel Hine	Environment Agency	
Alan Warren	Mott MacDonald	
John Chesterton	Mott MacDonald	
Jen Swetman	Mott MacDonald	
Project Steering Group members		
David Brown	Canals and Rivers Trust	
Ian Hope	Severn Trent Water	
Andy Hughes	Atkins	
Delegates		
Dr Jun Zang	University of Bath	Hydraulics, natural hazards
Dr Kevin Briggs	University of Bath	Deterioration of structures
Professor Colin Taylor	University of Bristol	Seismic and natural hazards
Dr Andrew Brennan	University of Dundee	Physical modelling, liquefaction
Dr Raziyeh Farmani	University of Exeter	Water resources management
Dr Manousos Valyrakis	University of Glasgow	Hydraulics
Dr Catherine O'Sullivan	Imperial College London	Internal erosion
Dr Kenneth Pye	Kenneth Pye Associates	Embankment stability, rim stability
Dr Simon Maher	University of Liverpool	Instrumentation, monitoring, water quality
Professor Jim Chandler	Loughborough University	Image-based modelling
Dr Ksenia Chmutna	Loughborough University	Sustainability and resilience
Dr Andrea Bittachin Busolin	The University of Manchester	Hydraulics and sedimentation, monitoring and decision-making
Professor Quihua Liang	Newcastle University	Hydraulic modelling
Professor Paul Taylor	University of Oxford	Image processing, wave interactions and loading
Dr Andrew Fox	Plymouth University	Risk, disaster management
Dr Elisabeth Bowman	The University of Sheffield	Internal erosion – clay filly, masonry
Dr Margarida Pinho Lopes	University of Southampton	Geomechanics – scour, ageing embankments
Dr Phillippe Sentenac	The University of Strathclyde	Monitoring using geophysics
Dr Colin Booth	University of the West of England	Flood and drought risk
Professor Ian Guymer	The University of Warwick	Pollutant transport in water
Dr Alaa Hamood	The University of Wolverhampton	Sustainable construction materials

Appendix B Research proposals

B.1 Introduction

This appendix contains the final research proposals developed from the topics identified and prioritised during the consultation process.

Each proposal sheet contains the following information and is drawn, in part, from the FCERM R&D Programme Research Proposal Form.

Proposal number:	The proposals are numbered in the rank order of their main topic.
Proposal title:	The title summarises the included research topics.
Main and included topics:	The main topic and included topics are listed.
Context:	A background outlines the state of research in this area.
Overall objective/scope:	The purpose of the proposed project and the main activities to be undertaken
Key outcomes:	Main outcomes of the project and what type of product is expected
Expected impact:	How the work will change reservoir safety and what may be needed to deliver the project
Drivers for the work:	Why the work is required including industry, legislative or other requirements and dependencies
Risks if not carried out:	Impacts if the work is not carried out
Links or dependencies:	Underpinning work or research this builds on – this could include research included in this strategy or currently ongoing that would need to be completed beforehand.
End users or beneficiaries:	Beneficiaries and those who would be expected to utilise the products produced
Delivery partners and funders:	Organisations other than Environment Agency/Defra that may be willing to play a part in delivering the research either by facilitating the project or providing funding or both.
Expected cost:	Costs are a best guess based on the scope and expected timeframes needed to deliver the project.
Expected duration:	The expected time frame is an estimate only.

PR.2015-1: Extreme flood estimation – rainfall–run-off modelling

Context *Main topic: 7. Included topic: 9*

Extreme flooding remains one of the main threats to reservoir safety. Flood safety studies, investigations and improvements in spillway capacity commonly feature in reports by panel engineers. Flood overtopping is the most common type of recorded incident at reservoirs nationally and internationally.

Following interim advice from Defra in 2004 in relation to the application of available methodologies to reservoir flood safety evaluations, work has continued to improve estimates of extreme rainfall estimation (Stewart et al. 2010). The new rainfall estimates for return periods up to 10,000 year return period (excluding PMP) developed by the Centre for Ecology and Hydrology (CEH) were made available in 2015. The next step will be to review the rainfall–run-off methodology for developing flood hydrographs from the rainfall data and catchment characteristics. There are a number of possible techniques covered in the literature which could inform this research.

Overall objective/scope

Research to improve flood hydrograph estimation for return periods of 1,000 years and greater:

- Review the application of the current UK rainfall–run-off methodology in light of recent research developments and international practice.
- Develop a suitable improved method or methods for rainfall–run-off modelling of extreme flood events.
- Consider how the use of local data might be applied to refine rainfall–run-off modelling parameters.
- Evaluate and refine provisions for snow melt.
- Evaluate the likely impact of improved flood hydrograph assessments on reservoir flood safety assessments from trials and production of worked examples.
- Produce documentation and guidance.

Key outcomes

A revised method or methodologies for evaluating extreme event flood hydrographs based on available rainfall estimates for return periods of 1,000 years and greater.

Expected impact	4.7

The accuracy of flood estimations from available extreme rainfall estimates will be improved such that the application of either deterministic or risk-based approaches to spillway capacity/freeboard evaluations will be more robust.

Revised rainfall–run-off estimates for reservoirs based on the most recent data may increase spillway requirements for some reservoirs.

Drivers for this work	4.2

Flood safety is a critical aspect of the safety evaluation of impounding reservoirs.

Flood overtopping is one of the most common causes of reservoir incidents and failures.

The gains from recent research on extreme UK rainfall can only be maximised through new research to translate rainfall into flood hydrographs based on catchment characteristics and local data where available.

Risk(s) associated with not carrying out this work	4.0
Hydrologists will continue to use outdated methodologies in evaluating extreme floods. Reservoir freeboard and spillway capacity in some areas may be inappropriate.	

Total score	**12.9**

Links or dependencies

This work will need to consider ICOLD Bulletin 142 (ICOLD 2012), recent research by CEATI (2014) on the passage of extreme floods and the latest edition of 'Floods and Reservoir Safety' (ICE 2015) to ensure that the output is of direct application to reservoir safety.

Business end users/beneficiaries		Reservoir owners, panel engineers and industry practitioners	
Delivery partners/alternative funders		NERC, CEH	
Cost	£ 150,000	**Duration**	1 year

PR.2015-2: Management of trees and vegetation on embankment dams

Context *Main topic: 10*

Management of vegetation is a major concern to panel engineers in consideration of safe reservoir operation. Typical issues include:

- risk of tree fall (especially during storms) reducing freeboard to an extent that the embankment is overtopped and fails by erosion
- removal of saplings and so on to reduce the risks associated with root systems (internal erosion, deterioration of the upstream face protection)
- undesirable shading of slopes designed to rely on grass cover for erosion resistance
- removal of trees from slopes designed for overtopping
- desiccation and cracking of earth fill
- specifications for grass seed mixes and maintenance of grass cover
- removal of trees that hinder access for operations, surveillance or maintenance
- clogging of spillway screens or other outlets
- reinstatement of hydraulic capacity in channels
- dealing with vegetation located on the reservoir rim

In addition there can be operational issues associated with unwanted vegetation (for example, invasive species) and management costs associated with the removal of tree litter, weeds, algae and so on.

Research and guidance are currently available on managing the hazards associated with trees but not in the context of trees on dam embankments.

Overall objective/scope

To research information on vegetation management and develop specific guidance for reservoir owners in how to restrict or manage vegetation in a manner that promotes reservoir safety

- Stage 1: Collate information on the range of vegetation issues that can impact UK reservoir safety and scope research required to inform guidance.
- Stage 2: Carry out research and draft guidance.

Key outcomes

Research into the impact of vegetation and its removal from embankment dams

Guidance document for practitioners

Expected impact	4.5

Better knowledge about the impact of vegetation on embankment dams leading to improved decision-making where vegetation is a concern

Standardised risk-based guidance and information

Drivers for this work	4.0

Reservoir owners and panel engineers lack information and guidance on vegetation with respect to embankment performance.

This project would build on the work of others internationally

Risk(s) associated with not carrying out this work	3.8

Lack of guidance and knowledge of vegetation and its impacts on dams may lead to inappropriate use, management or removal of vegetation.

Lack of guidelines will lead to differing practice and advice.

Total score	**12.3**

Links or dependencies

This project would have strong links with ongoing research into the resistance of grass revetments.

International publications should be referenced and built on such as:

- 'The International Levee Handbook' (CIRIA 2013)
- 'Guidelines for Landscape Planting and Vegetation Management at Levees, Floodwalls, Embankment Dams, and Appurtenant Structures' (USACE 2014)
- 'Technical Manual for Sam Owners: Impacts of Plants on Earthen Dams' (FEMA 2005)
- Dutch guidance published by the Foundation for Applied Water Research (De Stichting Toegepast Onderzoek Waterbeheer, STOWA)
- 'Design, Operation and Adaptation of Reservoirs for Flood Storage' (Environment Agency 2016)

Business end users/beneficiaries		Reservoir owners	
Delivery partners/potential funders			
Cost	Stage 1: £25,000 Stage 2: £50,000	**Duration**	1 year

PR.2015-3: Extreme flood estimation – PMP/PMF estimation

Context *Main topic: 8.*

Many dams have been assessed for safety under probable maximum flood (PMF) conditions which draw from information on probable maximum precipitation (PMP) estimates published in the Flood Studies Report (NERC 1975). The PMP estimates are intended to represent the likely maximum rainfall intensities that are physically possible. However, there is some evidence to suggest that the PMP values have been exceeded in some parts of the country since the maps were published. PMF estimation is within the scope of 'Floods and Reservoir Safety' (ICE 2015) and will therefore remain of relevance to the UK reservoir industry for the foreseeable future. With climate change, there may be new types of storm that develop over the UK that result in much increased storm rainfall.

Overall objective/scope

Stage 1

- Review available data on extreme rainfall and define options for methods for assigning annual exceedance probability to such estimates. If appropriate, recommend annual data collection or other works to enable future improvements in estimating the annual likelihood of extreme rainfall.
- Review potential impacts of climate change on extreme rainfall (>1 in 1,000 chance per year) and options for methods of estimation.
- Strategy for future updates (to 2100) to methodology for estimation of extreme rainfall.

Stage 2

- Implement strategy for improving estimates of extreme rainfall.

Key outcomes

Stage 1

- Revised maps (digital interface) for PMP depth-duration
- Revised methodology for PMF estimation
- Strategy for future updates to PMF estimation methodology (to 2100)

Stage 2

- Define in Stage 1

Expected impact	4.3

The accuracy of extreme rainfall and flood estimates will be improved.

Revised PMF estimates for reservoirs based on the most recent data may increase spillway requirements for some reservoirs.

PMF estimates will be required for some new reservoir construction projects, although there are relatively few new reservoirs requiring assessment each year. Where spillways fail to meet PMF requirements at existing reservoirs, a risk-based approach is recommended in 'Floods and Reservoir Safety' (ICE 2015). Hence, PMF estimates might not commonly be used to inform spillway capacity in the future.

Drivers for this work	4.0

Flood safety is one of the most important components of the safety evaluation of impounding reservoirs. Extreme flood estimation is relevant to high consequence reservoirs. The available estimates of PMP are in need of review and revision.

Risk-based approaches may consider rainfall return periods in excess of 100,000 years. An appreciation of the likely return period of PMP can assist in applying such methods without unnecessary expenditure on capital works.

Risk(s) associated with not carrying out this work	3.8

Hydrologists will continue to use outdated information for PMF estimation.

Reservoir freeboard and spillway capacity in some areas may be inappropriate.

Total score	**12.1**

Links or dependencies

This work will need to consider ICOLD Bulletin 142 (ICOLD 2012) on the passage of extreme floods, CEATI research (2014) and 'Floods and Reservoir Safety' (ICE 2015) to ensure the output is of direct application to reservoir safety. This work should follow PR 2015-1 on rainfall–run-off modelling to avoid duplicative effort.

Business end users/beneficiaries		Reservoir owners, panel engineers and industry practitioners	
Delivery partners/alternative funders		NERC, CEH	
Cost	£ 50,000	**Duration**	1 year

PR.2015-4: Investigate the selection, operation, evaluation, repair, maintenance and replacement of gates and valves for dam structures

Context	*Main topic: 30*
Previous guidance, published in 1997, covers condition assessment and repair. However, there are gaps in available guidance with respect to selection and operation that demonstrate evidence for a need within the industry.	
Overall objective/scope	
The research will seek to define best practice in maintaining gate and valve equipment in good condition, evaluating likely residual life through surveys, identifying problems and trends in operational behaviour, checking related electrical or hydraulic equipment, and carrying out a review of programmable logic controllers. Reference will be made to the latest IEC standards to be maintained for the control of safety-critical equipment. Through description of a variety of case studies in evaluating and replacing equipment, the research will seek to assist in decision-making on the replacement or refurbishment of equipment and the planning of the works. The research will, as far as practicable, include the study of gates and valves that have been removed from dams to inform modes and rates of deterioration. The work will reference environmental guidelines in operating low level gates and valves, and in carrying out replacement works. Examples of failures and lessons learned will be included. The project will cover gates and valves commonly used at UK dams.	
Key outcomes	
A comprehensive guidance document that covers valve and gate selection, operation, maintenance, repair and replacement.	
Expected impact	4.3
This guide would have use across the UK reservoir portfolio, giving consistent guidance to engineers and owners. The recommendation of proper standards for operation and maintenance will help serve to reduce incidents.	
Drivers for this work	3.9
There is no consistent recent UK guidance for selection of gates and valves for UK reservoir work apart from the 1997 publication. This work would also draw on the outputs from the ongoing reservoir drawdown work, which may result in the upgrading of many reservoir gates and low level outlet valves.	
Risk(s) associated with not carrying out this work	3.8
Inappropriate valve selection or operation and variation in guidance provided within the reservoir community could occur. Failure of gates or valves in emergency situations such as overtopping can lead to increased risk to the dam.	
Total score	**12.0**
Links or dependencies	
‘Valves, Pipework and Associated Equipment in Dams: Guide to Condition Assessment’, Report 170 (CIRIA 1997)	

Ongoing work into safe reservoir drawdown guidance might be referenced once complete.			
Business end users/beneficiaries		Reservoir owners including water companies	
Delivery partners/potential funders		CIRIA, EPSRC	
Cost	£60,000	**Duration**	1.5 years

PR.2015-5: Managing reservoir leakage and seepage

Context *Main topic: 44*

A large proportion of UK dams and service reservoirs exhibit some perceptible degree of seepage. Seepage can be benign, or can develop into leakage and cause failure through internal erosion. Reservoir owners and panel engineers routinely seek to identify, review, keep under surveillance and monitor seepages. In some cases it will be appropriate to carry out investigations to identify the likely seepage pathway and to carry out remedial works to seal the leakage.

Guidance exists on the common modes of failure through internal erosion (for example, ICOLD Bulletin 164), but research is needed to promote a consistent approach to managing the risk associated with seepage through UK dam embankments or their foundations while recognising that every case will warrant specific evaluations to be made to inform the appropriate actions.

Depending on the circumstances, some types of actions can increase the probability of failure. Other actions may have a significant cost impact or impact on reservoir operation, but not be warranted without additional monitoring or surveillance. Reservoir operators, in consultation in many cases with panel engineers, may need to make decisions that can impact operation (reliability of supply/amenity), cost, the environment and reservoir safety in managing the potential threat posed by seepage.

Technologies are being developed to provide early warning of seepage. There is a need to draw on international experiences in remote sensing and consider this in the UK context.

Overall objective/scope

- Carry out review of methodologies available and applicable to managing reservoir leakage and seepage.
- Research to inform risk-based decision-making on seepage management.
- Develop guidance on the assessment, evaluations and management techniques including the applicability of modern sensing technology to provide early warning or monitoring.
- Enhance (or provide) training of reservoir operatives, owners and engineers in reservoir leakage and decision-making.

Key outcomes

Guidance on seepage management

Training for reservoir operatives and owners on leakage detection, interventions and management

Expected impact	4.3

The project will assist reservoir operational staff, owners and panel engineers in effectively and safely managing the risk of leakage to reservoirs.

It will improve knowledge of leakage and its problems among operational staff to reduce dam safety incidents.

Drivers for this work	3.9

Seepage investigations form a substantial portion of the safety measures required on UK reservoirs and work to promote consistent approaches to investigation and management are required.

Better management of seepage will reduce the number of serious incidents	
Risk(s) associated with not carrying out this work	3.6
Continued largely reactive approach to seepage management Slow adoption of new technologies for early warning Continued high incidence of safety measures to investigate seepage	
Total score	**11.9**

Links or dependencies

The research and guidance should draw from any research gaps identified in the ICOLD bulletin currently in preparation and draw from international experience in remote sensing of seepage.

Business end users/beneficiaries		Operatives, owners and panel engineers	
Delivery partners/potential funders		EPSRC, CIRIA	
Cost	£80,000	**Duration**	6.5 years

PR.2015-6: Reservoir monitoring and surveillance

Context *Main topic: 24. Included topics: 55 and 40*

Reservoir monitoring and surveillance information is crucial to assessing the health of a dam. Where information is not properly gathered or presented, review of the data may be delayed or inadequate. As a result, important trends that indicate changes to dam safety can be missed.

Guidance is needed, together with tools, to assist reservoir owners in monitoring reservoir safety condition and how the level of monitoring relates to the level of risk of failure. The aim is to promote a consistent approach in how data are gathered, recorded and presented to assist in data interpretation. The guide will incorporate new developments in monitoring and surveillance: techniques such as fibre optics, remote monitoring and the use of ROVs.

Advice is also needed on how reservoir owners can engage with their local community to explain how reservoir risk is managed and the role that the community can have in helping to keep dams safe.

Overall objective/scope

- Develop guidance on monitoring and surveillance of dams and reservoirs, and how the effort should reflect the consequence and likelihood of failure.
- Develop guidance on quantifying how increasing the frequency of monitoring and surveillance would reduce the risk to the public.
- Review UK reservoir requirements and common practice through consultation and develop industry tools for appropriate monitoring and surveillance.
- Develop a pictorial training guide for monitoring and surveillance staff similar in style to that produced by Severn Trent Water, with references to the main guide.
- Develop a toolbox for community engagement.

Key outcomes

Risk-based guidance document including spreadsheet tools and training

Expected impact	4.2

Improved quality of monitoring and surveillance leading to improved reservoir safety through improved decision-making and early intervention

Better data interpretation resulting in earlier identification of problems

Drivers for this work	3.9

Improved monitoring and surveillance make up a significant proportion of the safety measures recommended under the Reservoirs Act 1975.

To provide a consistent approach across the industry and ensure new developments in monitoring and surveillance are incorporated.

Risk(s) associated with not carrying out this work	3.6

Poor data collection and interpretation leading to safety measures or reservoir safety incidents

Total score	**11.7**

Links or dependencies

This guidance will draw on documents produced internationally including ICOLD Bulletin 158, ‘Dam Surveillance Guide’, but provide UK specific context			
Business end users/beneficiaries		Smaller asset owners and operatives	
Delivery partners/potential funders		–	
Cost	£80,000	**Duration**	1.5 years

PR.2015-7: Geophysical methods for reservoir safety investigations

Context *Main topic: 26. Included topics: 71 and 72*

Given the age of many dams and reservoirs in the UK (average age is 120 years), subsurface information is often limited. Investigations at or around reservoirs to gather this information often call for non-invasive techniques so as to avoid compromising the water-retaining properties of structures. Commonly, there may be requirements to determine the location of seepage paths, voids or the presence of a clay core in an embankment dam. For masonry dams, void detection and the loss of grout may need to be evaluated.

Geophysics is a field that shows increasing promise, but is a developing applied science that can be challenging for practitioners to apply. There is a case for research and new guidance into its effectiveness and application to reservoirs in the UK.

Overall objective/scope

Stage 1

- Review the current geophysical methods and their history of application to reservoirs in the UK and internationally.

Stage 2

- Research promising techniques for the evaluation of seepage paths and detection of clay cores and their integrity in embankment dams.
- Research techniques for investigation of voids and loss of grout between blockwork in masonry dams and for service reservoirs.
- Carry out trials or detailed analysis of case studies.

Stage 3

- Provide a summary of the techniques used in reservoir safety applications including seepage path detection and void detection and provide guidance on the requirements and limitations for the application of each technique.

Key outcomes

Research into the effectiveness of various geophysical techniques for leakage path detection and subsurface properties

Guidance summarising the application of geophysical techniques to reservoirs in the UK

Expected impact	4.0

Improved understanding of the effectiveness of various geophysical techniques on UK reservoir structures

Drivers for this work	3.9

Use of appropriate technologies to identify seepage paths can save time in identifying and remediating dam structures thereby reducing risk.

Risk(s) associated with not carrying out this work	3.6

The use and dependence on the interpretation of geophysical techniques where they may not be expected to provide satisfactory answers.

Inappropriate or lack of utilisation of modern techniques due to lack of guidance and understanding.			
Total score			**11.5**
Links or dependencies			
Various papers published in the ICE's journal, *Dams and Reservoirs*, and by the British Dam Society should be referenced and built on. Relevant information from recent CEATI research should also be drawn on.			
Business end users/beneficiaries		Asset owners	
Delivery partners/potential funders		EPSRC, CIRIA, water companies	
Cost	Stage 1: £20,000 Stage 2: £200,000 Stage 3: £60,000	**Duration**	3 years

Appendix C Academic workshop session outputs

This appendix summarises the outputs of the academic workshop sessions. The first section outlines what relevant research is currently taking place while the second section discusses what research may be needed or could be beneficial. The two sections are subdivided into their respective themes.

C.1 What ongoing research is relevant to reservoir safety?

C.1.1 Threats

- Internal erosion – stress level effects, particulate modelling and testing
- Climate change – flood hydrology, rainfall clustering, flood memory, understanding material response
- Waves and wave-induced erosion; wind/wave overtopping
- Flood frequency, flood-induced floating debris
- Changes in soil response under intense rainfall conditions
- Catchment stability (landslide modelling)

C.1.2 Mechanisms of deterioration

- Embankment construction (unknown) monitoring
- Age
- Erosion resistance of grass mixes
- Examination of decommissioned dams for clay performance

C.1.3 Operations, monitoring and surveillance

- Geophysics – time lapse monitoring
- Image-based assessment of embankments for wave measurement
- Burrowing animals
- Sediment transport sensors
- Use of fibre optics for monitoring
- Optimisation of operations for flood risk assessment

C.1.4 Investigations

- Sedimentation

- Acoustic measurement for signs of interior failure
- Resistivity
- Slope movement from imagery information
- Impact of trees on embankments

C.1.5 Repairs/improvements

- Hydraulics – design of new element
- Life extension of infrastructure – adding value to justify investment

C.1.6 Planning, design and construction of new reservoirs

- Geomembranes on embankment dams
- Investment planning using multi-objective risk assessment optimisation
- Systems optimisation of reservoir filling

C.1.7 Risk and hazard assessment/tolerability

- Risk – perception of and mathematical risk
- Working with construction industry (Construction Industry Board) to increase competencies
- Flood risk assessment – computational modelling using simple/cheap tools

C.1.8 Emergency planning

- Engaging with communities – social networks
- Onsite and offsite plan testing
- Managing flood risk
- What people need to do to become ‘resilient’
- GIS identification of vulnerability, crowd sourcing tools

C.1.9 Environmental, social, safety and welfare

- Digital story telling – social history, how events were managed
- Effect of public perception on discontinuance
- Drought

C.2 What research is needed?

C.2.10 Threats

- Rainfall frequency – climate change impacts
- Animal activity
- Understanding stress state and susceptibility interplay – particle geometry effects
- Wind stress effects and setting up of internal wave effects

C.2.11 Mechanisms of deterioration

- Age/construction of dams/embankments – investigate decommissioned dams or dams being notched through
- Computed tomography (CT) scanning of soil structure
- Real-life filter performance
- Extending fragility curve research to dams
- Effects of tree felling on embankments
- Vulnerability to high intensity rainfall – direct impacts on dam and effect of trees
- Progressive failure from rapid drawdown

C.2.12 Operations, monitoring and surveillance

- Monitoring techniques – built-in/retrofit
- How to link modelling to monitoring
- Film-printed sensor
- Three-dimensional, high density camera scanners
- Smart monitoring of slopes

C.2.13 Investigations

- Reservoir incidents – better sharing of details to identify patterns and mechanisms
- Non-invasive investigation of embankments
- Investigating design of aging structures
- Secure a ‘test dam’ for trialling investigation methods.

C.2.14 Repairs/improvements

- Interaction between waves and structures and downstream impacts

C.2.15 Planning, design and construction of new reservoirs

- Drones for wavelengths of light/vegetation
- ‘Joined up’ research
- Systematic review of critical uncertainties relating to dam safety decisions, leading to specific research topics.

C.2.16 Risk and hazard assessment/tolerability

- Public engagement
- Human activities relating to risk assessment
- Connecting Building Information Modelling (BIM) to numerical analysis to assess impacts on buildings
- Improve current hydrodynamic tools to represent individual buildings and so on
- Multi-hazard assessment

C.2.17 Emergency planning

- Human behaviour for emergency planning linking to modelling to assess loss in dambreak
- Decision-making/education.

Appendix D Gap analysis

D.1 Introduction

A gap analysis was carried out to identify:

- areas of research that have progressed nationally or internationally
- where gaps may remain that could inform or limit the scope of proposals raised through the consultation process

This process was informed by the review of progress against the previous strategy and the literature review.

D.2 Threats

D.2.1 Floods

The primary threat to reservoir safety in the UK is that of erosion by flood overtopping. Although flood standards and design flood estimation methods have not changed considerably over the past 30 years, concerns over spillway capacity often feature in statutory inspections and many reported incidents involve dam overtopping. The 2007 summer storms (Warren and Stewart 2008) led to a number of reservoir incidents, including the significant incident at Ulley Reservoir (Hinks et al. 2008).

Publication of 'The Flood Estimation Handbook' (CEH 1999) gave rise to difficulties in extreme flood estimation, as rainfall estimates for the 10,000-year event were in some cases significantly greater than previous estimates using the Flood Studies Report (NERC 1975). Following interim advice from Defra in 2004, work has continued to improve the estimates of extreme rainfall estimation (Stewart et al. 2010). The new estimates developed by CEH were made available in 2015.

The next step in improving flood estimation will be to review the rainfall–run-off methodology. There are a number of possible techniques covered in the literature which could inform this research. This work, if funded, will need to consider ICOLD Bulletin 142 (ICOLD 2012) and recent CEATI research (2014) on the passage of extreme floods and the latest edition of 'Floods and Reservoir Safety' (ICE 2015) to ensure the output is of direct application to reservoir safety.

D.2.2 Winds and waves

The threat from winds and waves on dam structures was revisited during the preparation of the recently published fourth edition of 'Floods and Reservoir Safety' (ICE 2015). The prediction of wave overtopping, drawing on the EurOtop manual (EurOtop 2007) is covered in Allsop et al. (2010). No recent UK-specific publications have addressed the question of the joint probability of high reservoir levels (floods) and high wind speeds or wider questions about the impact of reservoir valley effects on wind speeds. The research funded by the then Department of Environment as described by Anderson et al. (1994) was not published, but there may be useful information from this source to inform further research.

D.2.3 Climate change

Climate change has been accounted for in the recent extreme rainfall estimation work by CEH. The wider impacts of climate change on reservoir safety and operation were addressed in Defra-funded research. In a paper summarising this research, Hughes and Hunt (2012) concluded that:

- dams and reservoirs are relatively resilient to climate change
- the impacts most likely to occur are through mechanisms that practitioners will be already familiar with

Brekke et al. (2009) considered the impacts of climate change on reservoir operations (for example, flood control rules) in the US context.

D.2.4 Seismicity

The UK annex to Eurocode 8 (BSI, 2008) defines the UK as an area of very low seismicity. However, there can be circumstances where seismic reviews or designs are warranted for reservoir structures (Booth et al. 2008). The current guidance on the seismic assessment of reservoir structures (Charles et al. 1991, ICE 1998) do not align with the approach set out in ICOLD Bulletin 148 'Selecting Seismic Parameters for Large Dams' (ICOLD 2016). ICOLD Bulletin 137 (ICOLD 2011) on reservoirs and seismicity provides an international review of seismicity and reservoir safety. Seismic hazard and risk assessments have further developed internationally.

Some work has been done in the USA to evaluate the impacts of hydrofracking on dam safety, investigating increased seismicity among other issues. A recently published UK-focused review and risk assessment called for research into parameters to be used in warning systems and into potential failure modes (Brown and Claydon 2015).

D.2.5 Animals and vegetation

There is very little published information on the threat posed by animals and vegetation. In recent years, ASDSO has published research on tree root penetration into levees and Bruggemann (2012) addressed the damage caused by badgers.

There is a gap in published guidance on the various threats that animals and vegetation can pose to UK reservoir safety. 'The International Levee Handbook' (CIRIA 2011) covers these subjects but not in depth.

There is little guidance on the treatment of invasive species in relation to reservoirs.

D.3 Mechanisms of deterioration

D.3.1 Internal erosion

Internal erosion remains one of the primary mechanisms of deterioration in embankment dams.

ICOLD Bulletin 174 on internal erosion (ICOLD 2013) provides engineers with guidance on the various types of internal erosion, including references to methods to assess the vulnerability of new and existing dams to internal erosion.

Bridle (2008) illustrated how various methods can be employed to assess the vulnerability of a typical British embankment dam to internal erosion and how a phased approach can be used to inform decision-making.

Tedd et al. (2011) presented examples of investigations of hydraulic fracture at a number of UK puddle clay core dams, which demonstrated that detailed intrusive investigations provide valuable insight into the behaviour of dams whereas the results of instrumentation do not always allow definitive conclusions to be reached.

The current BRE guide on investigating embankment dams (Charles et al. 1996) does not cover, for example, advances in instrumentation and seepage detection methodologies.

Although Dahlin et al. (2008) covers seepage evaluation from resistivity monitoring data, the technologies are constantly evolving in this field.

The associated monitoring of embankment dams for indications of internal erosion was recently covered in Report SC080048 (Environment Agency 2011a).

Although there has been an improved position in terms of general guidance on the subject of internal erosion, there remains much scope for further research to understand the processes involved. Internal erosion research is continuing at several European universities including Imperial College, London (Shire et al. 2013).

D.3.2 Settlement

The long-term deformation of embankment dams is an important dam safety issue that can lead to loss of freeboard and increased risk of flood overtopping. The behaviour of many Greek dam embankments, recently reported on by Dounias et al. (2012), indicates a wide range of factors influencing vertical and horizontal deformation.

There are many UK incidents associated with settlement. The subject is covered in some existing guides (for example, Charles et al. 1996), but no comprehensive research or guidance is available.

Improvements in the estimation of settlement through consolidation and reservoir operations would assist in the interpretation of deformation monitoring results and the detection of possible ongoing deterioration. Most UK dam embankments are of considerable age and therefore any significant settlement is likely to be a symptom of some form of deterioration rather than consolidation.

D.3.3 Instability

Dam instability is a broad subject which reflects the wide range of mechanisms associated with it such as:

- rapid drawdown
- erosion of the upstream face
- erosion of the downstream face
- increases in porewater pressure within the dam fill
- erosion due to animals, water erosion or unauthorised human excavations

For embankments, the subject is covered in ‘The Engineering Guide to the Safety of Embankment Dams’ (Johnston 1999) and is also covered to some extent in ‘The International Levee Handbook’ (CIRIA 2013).

There has been no recent update of the guidance on planning, design and repair of upstream face protection systems despite a number of new systems and material becoming available, such as the use of open stone asphalt and various membrane materials. Messerklinger (2014) describes the recent failure of a geomembrane on the upstream face of an embankment in Switzerland and Amos et al. (2010) describe the problem at the lining for the Tekapo Canal in New Zealand.

Instability due to rapid drawdown (that is, the rate of reservoir drawdown that can be tolerated under a precautionary drawdown situation for dams of different construction) is an area where there is very little research and guidance. The scoping of any research in this field will need to await the completion of the current research on drawdown rates (Project SC120001: Design, Operation and Adaptation of Reservoirs for Flood Storage; Environment Agency 2016).

The stability of concrete dams is currently being partly covered by CEATI research as phase 2 of its 'Investigating cracking in concrete dams' project.

Although there is little recent literature on concrete dam stability, Arslan and Rosassanchez (2008) presented an example of the recent advances made in the techniques available to evaluate the stability of rock foundations for concrete dams.

D.3.4 Overtopping erosion

Overtopping erosion is principally of interest for dams that are designed to overtop (typically flood storage reservoir embankments) and in consideration of the tolerability of erosion due to wave overtopping. Many incidents have occurred where small embankments (usually for non-statutory reservoirs) have been overtopped and either washed out or significantly damaged.

CIRIA 116 'Design of Reinforced Grass Spillways' (CIRIA 1987) is scheduled to be updated in the near future.

Research on wave overtopping of coastal defences has been carried out by the Dutch, but the results of this work have not been well disseminated. In any case, the conditions may not closely represent typical UK dam embankment conditions where the downstream face is typically more irregular and have numerous surface features which could accentuate erosion.

Recent amendments to the guidance on reservoir freeboard in the fourth edition of 'Floods and Reservoir Safety' (ICE 2015) take account of advice in the EurOtop *wave* overtopping assessment manual (EurOtop 2007).

Considerable research has been carried out in the USA on overtopping erosion in the aftermath of the Hurricane Katrina disaster.

D.3.5 Deterioration of structures and equipment

The average age of UK dam structures is well over a hundred years, so research related to condition and residual life assessment, material protection and structural replacement/improvement techniques are all very relevant to the needs of the UK reservoir industry.

Deterioration of conduits and tunnels through dams is a critical issue and this has been recently covered in research projects SC110006 (CIRIA 2015) and more generally in CIRIA Report C671 (CIRIA 2010).

In consideration of surface structures, the vulnerability of stepped masonry spillways was covered in project SC080015 (Environment Agency 2010a). However, a gap

remains in the guidance available for the inspection, repair or replacement of spillway structures. Research indicates that spillway repairs are a very common subject of statutory inspection recommendations. This may indicate that undertakers are not sufficiently aware of the issues that impact the structural and hydraulic performance of spillways or ignore them until required to remediate.

Hydraulic design of spillways is well covered in the literature, but mechanisms of deterioration and planning spillway repair works for UK conditions is not well represented. For example, there is less than a page on the subject in the embankment dam safety guide (Johnston 1999).

Similarly there is little advice in the literature on drawoff tower deterioration aspects, although this subject area is less commonly an issue beyond consideration of seismic safety.

D.4 Operations, monitoring and surveillance

Reservoir operations, monitoring and surveillance is not a topic greatly represented in the literature despite being critical to reservoir safety. Reservoir operations are planned and carried out by the reservoir owner to maximise the benefits of the reservoir asset.

Water level control is one area in particular where reservoir operation decisions can impact reservoir safety. For example, allowing a reservoir to retain water at unusually high levels for prolonged periods can give rise to problems, for example, at reservoirs where the crest has been raised in the past. The degree of control available to owners is dependent on the reservoir characteristics and available controls.

Water level controls and reservoir control rules are of particular relevance to reservoirs that provide a flood control function. Gated spillways can prove challenging during flood events where decisions have to be made to weigh reservoir safety risk (dam overtopping) with the risk of flooding downstream areas through gate operation. There have been a number of cases internationally where gate operations – or the failure to operate gates – have given rise to problems and conflicts. Morison and King (2010) discuss the difficulties experienced in the emergency planning for a dam with a gated spillway.

The monitoring of embankment dams was covered in project SC080048 (Environment Agency 2011a). Advances in web-based ‘smart’ sensors are being made and have been trialled at a number of embankments in the UK and other European countries (Morris et al. 2012). A good example of where poor monitoring and operation led to the failure of a reservoir is that of Taum Sauk in the USA (summarised in CIRIA 2014).

The monitoring of concrete and masonry dams is likely to be covered by, or informed by, the ongoing CEATI-led research on the cracking of concrete dams.

An important area of reservoir operations that is commonly a cause of concern in the UK is that of debris management and blockages, leading to restricted operation or an increased risk of flood overtopping. Where a screen is present, problems can arise if the screen is of poor design or is not routinely cleaned. Spillways can become blocked if not maintained and kept free of debris. It is an area that is not well represented in the literature.

The ‘Trash and Security Screen Guide’ (Environment Agency 2009b) covers debris risk assessment and the design of new screens, particularly for flood defence and flood storage reservoir application. This guide is of value to the UK reservoir community, but does not provide comprehensive guidance to reservoir owners. For example, the subject of blockage of low level outlets by animals (for example, zebra mussels) or vegetation control at spillways is not covered.

Sediment management is not generally a major issue for UK reservoirs except at a relatively small number of reservoirs (Yeoh and Warren 2010). There has been no significant UK-specific guidance in this area for nearly 15 years, indicating it has not been a significant problem. Changes to how sediment is treated in considering the volume of statutory reservoirs have recently been introduced through the Flood and Water Management Act 2010.

D.5 Investigations

Reservoir investigations is a very wide subject and includes reservoir surveys, deformation surveys, stability assessments, seepage assessments, hydraulic modelling internal erosion studies, structural assessments and incident investigations. The subject is extensively covered in the available literature which reflects the breadth of the subject. 'Investigating Embankment Dams' (Charles et al. 1996) remains an important guide for the industry, but the tools and techniques available to the industry have increased since this was published.

Techniques continue to be refined in the field of void and seepage detection. For example, Willowstick Technologies in the USA has used its experience from investigations at many UK reservoirs to refine its techniques and methods of interpretation to find leaks and trace. Similarly, GTC Kappelmeyer has continued to refine its methods for temperature sensing of seepage paths. The British Geological Survey has further developed electrical resistivity tomography techniques that can be applied at reservoir embankments. Operators needing to scope and limit the extent of possible remedial works could make use of guidance on the most appropriate technique(s) for their particular requirement.

D.6 Repairs and improvements

There is very significant literature on repairs and improvements at UK reservoirs. Some notable recent examples include:

- Sutton Bingham (Welbank et al. 2008)
- Llyn Morwinion (Hickman et al. 2008)
- Queen Mary and King George V (Philpott et al. 2008)
- Ulley (Crook et al. 2010)
- Coldwell Lower (Eddleston et al. 2012)
- Wimbleball (Penman et al. 2014)

A description of many historical incidents and related repair and improvement work is given in CIRIA SP167 'Lessons from Incidents at Dams and Reservoirs (CIRIA 2014).

These publications cover a very wide range of technical subject areas which draw on international research and guidance. Areas where research and guidance might be improved for UK practitioners given their aging stock of dams and varied construction techniques include:

- crest raising techniques
- spillway repairs
- grouting of dam cores and foundations

- post-tensioning of gravity dams

Conduit repair and improvements was covered in project SC110006 (CIRIA 2015).

D.7 Planning, design and construction

Most reservoir planning, design and construction is associated with flood storage reservoirs or discontinuance works. The planning of major new reservoirs is no longer common. The planning of Cheddar Reservoir Two is covered by Kelham et al. (2014) and provides a recent example of the investigations and measures required to develop reservoir proposals to the planning stage. The Abingdon Reservoir proposals also provide an example of large reservoir planning in the UK.

Guidance on the planning, design, operation and maintenance of flood storage reservoirs and the adaptation of existing reservoirs for flood storage has been developed in project SC120001 (Environment Agency 2016). The design and planning for a notable new flood storage reservoir for Banbury is described by Ackers et al. (2012).

The planning and design of discontinuance works is a subject of increasing relevance in the UK as discussed by McCulloch (2008) and Hughes et al. (2008). The subject is also very topical in North America. Several specific UK examples of discontinuance have been described in recent years including:

- Hameldon (Edmonds et al. 2010)
- Baystone Bank (Bailes et al. 2012)
- Beaver Dyke (Pickles and Rebollo 2014)

There appears to be no general UK guidance on the planning and design of discontinuance and abandonment works, although there are many case studies from which to draw.

D.8 Risk and hazard assessment

There has been considerable development of UK reservoir risk assessment methodology since the previous strategy study. The ‘Guide to Risk Assessment for Reservoir Safety Management’ (project SC090001, Environment Agency 2013a) draws on international best practice and provides a three-tier approach to risk assessment to assist in understanding asset condition and the benefits of investments in improvements or repairs.

The societal acceptability of risk in the UK, as covered in the HSE’s ‘Reducing Risks Protecting People’ (2001) remains current.

Smith et al. (2014) describe the potential advantages of integrating spatiotemporal population estimates with established flood modelling techniques. Advances in the prediction of human behaviour could improve hazard assessment in the future and is an area of continuing research.

D.9 Environmental, social, safety and welfare

There have been no significant developments in environmental legislation since the previous strategy report. There is improved guidance for any reservoir owner planning

a reservoir release that could result in environmental damage (EPR 7.01; Environment Agency 2012).

Actions to preserve reservoir safety could potentially be contrary to wildlife legislation such as the Conservation (Natural Habitats) Regulations 2012, as well as earlier legislation including the Protection of Badgers Act 1992.

It appears that there is no definitive and up-to-date guide on environmental reservoir management for panel engineers and owners. Although CIRIA R161 'Small Embankment Reservoirs' (CIRIA 1996) covers environmental considerations, environmental legislation and guidance have evolved considerably over the past 20 years.

There is no recent literature covering the safety and welfare of operatives and the public at reservoirs in the UK.

There is a growing interest in the use of existing dams and weirs to generate hydroelectricity. The Environment Agency issued 'Guidance for Run-of-river Hydropower Development' (Environment Agency 2013b) which was subsequently withdrawn, but there is no guidance for reservoir owners and engineers on the potential reservoir safety aspects of such developments.

D.10 Emergency planning

There has been little further development in the guidance available to reservoir owners in preparing emergency plans. Provisions in the modified Reservoirs Act 1975 for owners to prepare 'flood plans' have yet to be enacted. Nevertheless, many owners have prepared emergency plans and some have carried out exercises and shared their experiences, for example, at Pebley Reservoir (Windsor 2012).

Reservoir flood maps are now available to the public from the Environment Agency's website.[2]

D.11 General/miscellaneous

The reporting of incidents at dams and reservoirs in England is now a mandatory requirement under the Reservoirs Act 1975. The Environment Agency issues an annual report describing the incidents from the previous year and the associated lessons learned. Information from this process (see Section 4.2.1) has informed this research strategy review alongside specific reservoir safety research requirements.

There is concern that there is a succession planning issue with reservoir panel engineers. There may be a case for developing a 'good practice guide' for major reservoir owners and engineering consultancies to plan for the succession of skills and knowledge required to develop panel engineers and retain experienced staff for reservoir monitoring and surveillance work. Hope (2012) describes, in the context of a major water utility, the planning and training of staff to ensure that the company retains the capacity or sufficiently skilled staff to promote good practice in reservoir safety management.

[2] http://watermaps.environment-agency.gov.uk/wiyby/wiyby.aspx?topic=reservoir

D.12 Use of the gap analysis

The gap analysis was circulated to attendees ahead of the workshop held in December 2014. It was used to inform the workshop discussions from which proposals for future research were developed and scored (see Section 5.5).

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