Reservoir Safety Research Strategy

Evidence Base for the Reservoir Safety Research Strategy

Environment Agency

Date: August 2026

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We’re here to protect homes and habitats – not just to safeguard what exists, but to create places of resilience and renewal, where nature returns and futures can take root.

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But wherever you find us, and whatever we’re doing, we’re one team – all guardians.

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Foreword

This report has been prepared on behalf of the Environment Agency. It presents the evidence collected to update the Reservoir Safety Research Strategy and ensures that research and development continues to support the safe management of reservoirs in England.

Since the publication of the previous strategy in 2016, significant developments have occurred across the reservoir sector. These include:

- new evidence from incident reporting
- advances in technology and data analysis
- increasing understanding of climate change impacts
- the establishment of the Reservoir Safety Reform Programme following the 2019 Toddbrook Reservoir incident

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Throughout the production of the report, many representatives of the UK and international dams and reservoirs sector and individual experts have been consulted. They have provided valuable comments and input. Contributors include:

- the British Dam Society
- the reservoir safety enforcement authorities in England, Wales, Scotland and Northern Ireland
- members of the Reservoir Engineer Panels for England and Wales
- reservoir owners and undertakers
- members of the Reservoir Safety Research Advisory Group (ReSRAG)
- academic researchers and practitioners working in dam engineering, hydrology, geotechnics and infrastructure resilience

Artificial intelligence (AI) tools were used by the authors to support the preparation of this report. All content has been reviewed, verified and approved by the report authors.

Abbreviations

AI	Artificial Intelligence
ALARP	As Low As Reasonably Practicable
ASLL	Average Societal Life Loss
ANCOLD	Australian Commission on Large Dams
BDS	British Dam Society
BNG	Biodiversity Net Gain
CEATI	Centre for Energy Advancement through Technological Innovation
CIRIA	Construction Industry Research and Information Association
CPM	Convection-permitting model
Defra	Department for Environment, Food and Rural Affairs
EA	Environment Agency (England)
EIA	Environmental Impact Assessment
FAS	Flood Alleviation Scheme
FCERM	Flood and Coastal Erosion Risk Management
FMP	Fixed Monetary Penalties
FSR	Flood Storage Reservoir
ICE	Institution of Civil Engineers
ICOLD	International Commission on Large Dams
LLM	Large Language Models
MIOS	Measure in the Interest of Safety
ML	Machine Learning
MROG	Major Reservoir Owners Group
NERC	Natural Environment Research Council
NRW	Natural Resources Wales
PESTLE	Political, Economic, Social, Technological, Legal and Environmental
PMF	Probable Maximum Flood
PMP	Probable Maximum Precipitation
PoF	Probability of Failure

QCE	Qualified Civil Engineer
R&D	Research and Development
RACE	Reservoir Act Compliance Enforcement (Environment Agency database)
RARS	Risk Assessment for Reservoir Safety
RCP	Representative Concentration Pathways
ReSRAG	Reservoir Safety Research Advisory Group
RFM	Reservoir Flood Mapping
RIKbase	Reservoir Incidents Knowledge Base (England and Wales)
RL	Reinforced Learning
RSR	Reservoir Safety Reform
SBM	Statutory Biodiversity Metric
SI	Statutory Instrument
SRO	Strategic Resource Options
SROG	Single Reservoir Owners Group
SRR	Small Raised Reservoir
UAV	Unmanned Aerial Vehicle
UKCP	UK Climate Projections
UKRI	UK Research and Innovation
UKWIR	UK Water Industry research
VMP	Variable Monetary Penalties
WG	Welsh Government

1. Context for a new strategy

1.1. Background

Around 2.6 million people across England and Wales live and work in a location that could be flooded if an upstream reservoir were to fail. The chance of such emergencies varies depending on a range of factors. These include:

- dam type
- dam age
- reservoir infrastructure
- the level of maintenance
- competency of operation

The consequences should failure occur also vary. Given the average reservoir age is over 130 years, we need continued active management to minimise the chance of a catastrophic failure or major incident.

The need for a legal framework to ensure public safety is recognised in the Reservoirs Act 1975. This is the primary instrument governing reservoir safety in England and Wales. Scotland and Northern Ireland have their own Reservoirs Acts.

The responsibility for enforcement in England lies with the Environment Agency. The enforcement authorities not only make sure reservoir owners comply with the legal requirements. They also support research and development (R&D) to ensure the latest and most appropriate science and methods are used to ensure reservoirs remain safe.

The Reservoir Safety Research Strategy was first developed in 2009 and updated in 2016.

1.2. Changes in the reservoir safety industry since 2016

Since the publication of the 2016 Reservoir Safety Research Strategy, the reservoir safety landscape in England has experienced substantial change. This has been caused by:

- major incidents
- evolving regulatory expectations
- technological and environmental shifts

The most significant reason has been the 2019 Toddbrook Reservoir incident, which prompted the Independent Reservoir Safety Review. The subsequent recommendations are changing the status quo for undertakers, panel engineers and regulators. This has led to:

- clearer emphasis on proportionality
- improved guidance
- strengthened oversight

- modernisation of the legislative framework

Alongside regulatory reform, the period since 2016 has seen an expansion of technical guidance and standards. These include:

- new spillway design and examination documents
- updated engineer guidance
- improved flood mapping specifications
- the development of a revised hazard classification methodology

These updates reflect a shift towards more explicit risk-based practice, clearer documentation of safety decisions, and a stronger audit trail.

Incident and Measure in the Interest of Safety (MIOS) reporting have improved markedly, providing data to identify trends in issues affecting reservoir safety. Technological advances are changing monitoring and analysis capabilities. These advances include:

- remote sensing
- unmanned aerial vehicle (UAV) inspection
- high resolution climate modelling
- emerging applications of AI

They both offer opportunities and pose challenges to the industry. Climate change is resulting in more intense rainfall, clustered storm events, droughts and other impacts.

This has heightened focus on:

- Probable Maximum Precipitation (PMP)
- Probable Maximum Flood (PMF) estimation
- extreme precipitation events
- spillway performance
- water security
- the resilience of ageing assets

Workforce pressures are also increasing, which is impacting undertakers, especially smaller owners.

1.3. The case for change

The second Reservoir Safety Research Strategy was published in 2016. It highlighted several reasons for change:

- 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

We established the case for change for the current (2026) strategy by:

- assessing whether the previous reasons still apply
- building on the outcomes of the previous research strategy
- identifying new reasons such as more emphasis on ageing reservoirs / spillway design after the 2019 Toddbrook incident, 2025 Bridgewater and Llangollen canal breaches, dam breach in small raised reservoirs (SRRs) and low height / low erodibility dams, nature-based solutions and the evolution of remote sensing and sensors
- reviewing the independent Reservoir Safety Review into the Toddbrook incident and the wider reservoir safety industry
- reviewing the resultant implementation of the Reservoir Safety Reform Programme in England and Wales
- reviewing existing research outputs, uptake and outcomes
- assessing the process of defining, funding and carrying out the research
- reviewing which project recommendations were taken forward from previous strategies and by whom
- reviewing how previous R&D outputs have impacted outcomes

1.4. Review of progress against the 2016 strategy

The 2016 Reservoir Safety Research Strategy Report (Environment Agency, 2016) contains a prioritised list of research topics. These are based on the outcome of the reviews carried out at that time. From a full list of 76 research topics, a review and consolidation process resulted in a final list of 48 proposals, ranked in order of priority.

As part of this new strategy, we have carried out a review of progress made to date in carrying out the research identified on the consolidated list of proposals from 2016. This review was completed by undertaking an internet search, based on topics identified by ReSRAG in 2024 and reviewing relevant papers from industry conferences and journals

This list was provided to the Environment Agency, to help with developing their next programme of R&D work.

We cannot assess progress against the 2016 strategy solely by the completed research proposals. We also need to assess it by the effectiveness of the delivery routes for the research and whether the most relevant research themes were identified at the outset.

As part of the research for this strategy, we reviewed a list of suggested and prioritised projects from the 2016 Strategy. Progress has been made in completing research relating to the prioritised proposal list. However, there are many areas where research into topics has not started or has only partially been indirectly addressed.

Of the 48 proposals identified, 3 are complete. A further 12 have been partially completed, in some cases accounting for follow-on work that emerged during the initial projects. Research projects were progressed through:

- the R&D joint programme
- Construction Industry Research and Information Association (CIRIA)
- wider working groups
- academia

Projects were also carried out through other routes including the creation of summer placement opportunities for students under the mentorship of ReSRAG members.

These schemes have a two-fold benefit. They speed up research and they also contribute to skills development and access to the industry for prospective professionals

The strategy and the ReSRAG are there to shape and form routes for completing work. This means we should also consider indirect achievement. The industry and ReSRAG do not always have insight into these wider initiatives, or where research external to the reservoir safety industry may be applicable or beneficial. Better visibility of applicable research and developments across relevant industries may help achieve the new strategy.

Our review also highlighted that a record of progress towards achieving the previous strategy is not readily available. As a result, we recommend that on adoption of the new strategy, we implement a monitoring plan so that:

- progress against the strategy is regularly reviewed
- progress and outcomes are recorded and shared on a regular basis with the wider industry

This may also help to improve visibility of wider initiatives if communication channels can involve the capture of the activities.

The 2016 strategy also set out plans for how the strategy would be implemented. The proposed roles and responsibilities have been partly achieved using ReSRAG and Environment Agency support. British Dam Society (BDS) members have at times been approached to join steering groups and working groups. However, broadly, the proposed regular consultation with BDS members has not formally been progressed. The exception to this was a workshop on themes at the 2018 BDS Conference in Swansea.

Project outputs have been presented at BDS conferences and engineering forums, though often via the delivery partners. The links between the BDS and ReSRAG have consisted of:

- the chair of ReSRAG being fulfilled by either the chair or vice-chair of the BDS
- a page on ReSRAG included within the BDS website

Although this provides a useful communication link between the committees, the reservoir community felt that there was opportunity to improve communication across the reservoir safety industry.

The Flood and Coastal Erosion Risk Management (FCERM) R&D Joint Partnership is one avenue available to carry out projects directly, but facilitation by ReSRAG also achieves research outcomes indirectly. Constraints in available funding and human resource have impacted on successful outcomes. At the same time, the plans for promotion of new proposals and alternative delivery routes have on occasion been unable to be actively progressed. Some progress has been made on ongoing engagement and review of research outcomes. However, as reflected in the industry feedback, these are areas where improvements could still be made.

We included consultation with ReSRAG in this review. This is included in the next section. Feedback on how successful the dissemination and delivery of the strategy has been is relevant to the case for change. There was acceptance that ReSRAG is seen within the wider industry as a ‘closed group’ and their progress is not effectively disseminated.

ReSRAG considered that:

- the industry should be involved more to help achieve the themes, provide technical input, review and funding
- improvements in funding sources were required, with a fresh approach to accessing available sources external to the dam safety industry
- ReSRAG should provide expert advice to actively strengthen and justify themes and potential R&D, ensuring research is ready to take forward should funding become available, thereby reducing the perceived delays in research being completed

1.5. Current research outputs gap analysis

Some of the possible shortfalls in knowledge in the industry such as impacts of climate change on floods and reservoir structures are highlighted by the Independent Reservoir Safety Review (Balmforth, 2020).

The review highlighted the requirement for more:

- guidance for panel engineers
- technical guidance and knowledge (such as the spillway design guide)

This may have delayed some of the prioritised research identified in the 2016 strategy due to priorities changing and resources being diverted.

The gaps in the research carried out for priority topics within the previous strategy have been reviewed and remaining topics summarised. We will use them when planning our next R&D programme of works.

1.6. Section summary

The highlights from the feedback collected from reservoir safety professionals show they consider:

- that the previous strategy has partially achieved its objectives through the production and dissemination of relevant research
- there are areas where change in the delivery of the strategy could be of benefit
- that awareness of the strategy could be improved, together with sharing of information about active research across organisations

Respondents agreed that the main reasons for change in the previous strategy remain important. These include climate change and sustainability. However, other reasons have become more important since the strategy was published. These include:

- learning from incidents
- financial and wellbeing impacts of reservoir failures
- emerging technology and resilience in the context of changing environmental and societal pressures

We found that the barriers to research and development remain similar to those identified for the previous strategy. These include:

- funding and procurement routes
- availability of technical expertise
- lack of co-ordination and engagement

2. Review of safety incidents, MIOS and case studies

2.1. Reservoir safety incidents 2016-2024

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. We have administered the national incidents database since 2007. Since 2013 it has been a mandatory requirement for undertakers to report incidents that occur at reservoirs in England and Wales.

We identified trends by assessing reservoir incident data from the Institution of Civil Engineers' Reservoir Incident Knowledge Base (RIKbase) along with data from the English reservoir register. Reservoir incident data may be skewed by incidents that go unreported. Reservoirs with volumes under the threshold for mandatory registration have incidents that, if reported, could provide valuable data. The main trends identified in the data are presented in the next section. Appendix B also includes a full assessment of incident data.

Undertakers in Wales report approximately 250% more incidents per reservoir than those in England. The cause of this trend warrants further investigation, but it suggests there may be improvements to be made in English undertakers' incident reporting. This data is skewed by incident reports on reservoirs between 10,000 m^3 and 25,000 m^3, which make up 29% of the incidents. These reservoirs did not fall under the Reservoirs Act in Wales until 2016. This means they are likely to be in poorer condition and may be more prone to incidents.

Design and construction shortcomings are attributed as the most common cause of reservoir incidents. A shortcoming is defined as "a deficiency, flaw, or inadequacy arising from the original design assumptions, detailing, materials, methods, or construction practices of a reservoir. This compromises - or has the potential to compromise - its safety, performance, or resilience, either at the time of construction or under current and future operating conditions".

From the data, these shortcomings are more common in reservoirs constructed prior to 1900. This is shown in Figure 1. Design shortcomings were attributed twice as often for reservoirs constructed pre-1900 compared to those constructed after 1900. This is partly due to developments in geotechnical engineering since 1900.

Dams constructed prior to 1900 account for 53% of reservoir incidents while making up 41% of the reservoir stock. Reservoirs constructed after 1990 are statistically less prone to incidents making up 10% of the reported incidents and 22% of the reservoirs. This is likely due to the advancement in design and construction methods and the impact of aging on infrastructure. It could also be linked to the size and type of reservoirs being constructed, 70% of the reservoirs constructed after 1990 are non-impounding compared to 28% prior to 1990.

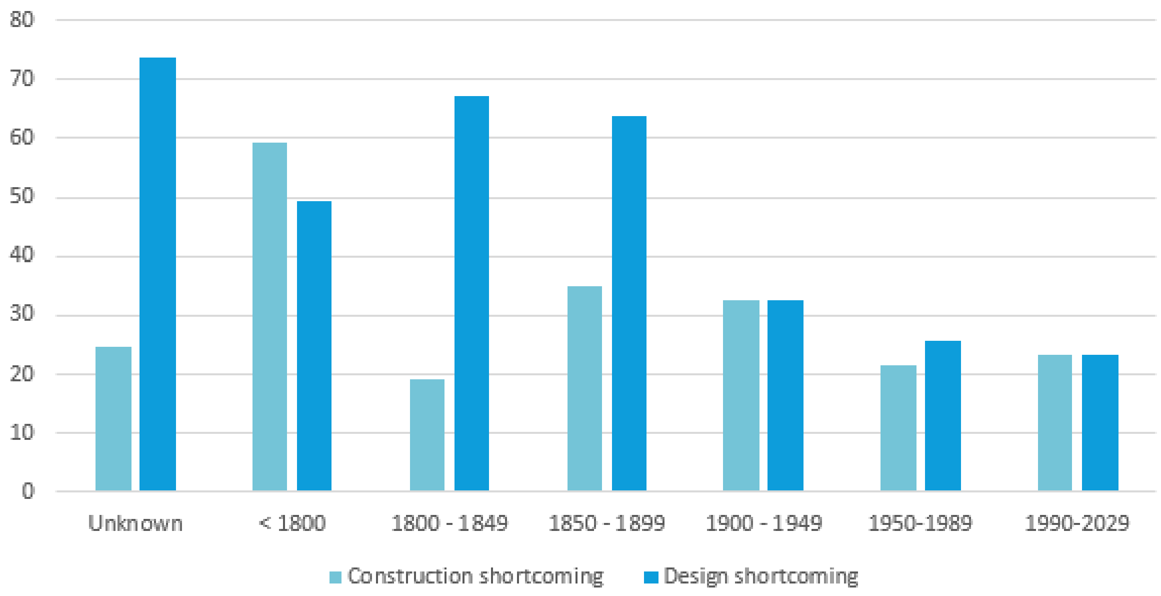


Figure 1 Design and construction shortcomings by reservoir age

In England, the average age of impounding reservoirs is 158 years and non-impounding reservoirs is 57 years. The average height of impounding reservoirs is 9 metres (m) and non-impounding is 6 m.

Impounding reservoirs were disproportionately represented in reports making up 86% of the reports while accounting for 63% of the reservoir stock. This is likely because these structures are more prone to internal and external erosion issues due to difference in:

- operation
- age
- height
- hydrology

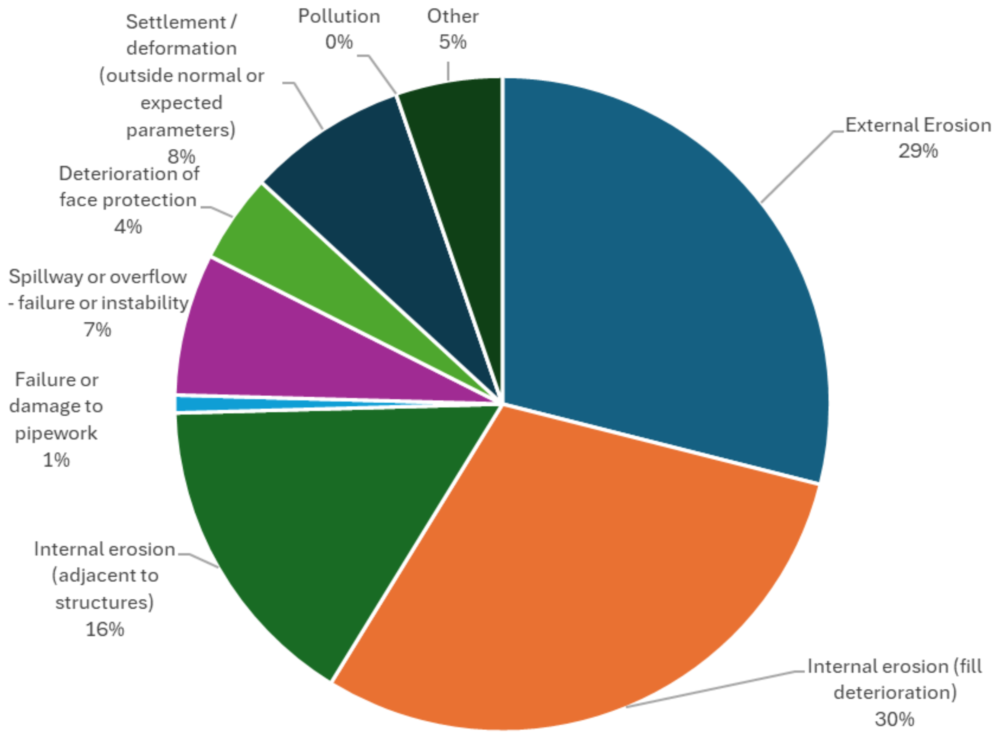
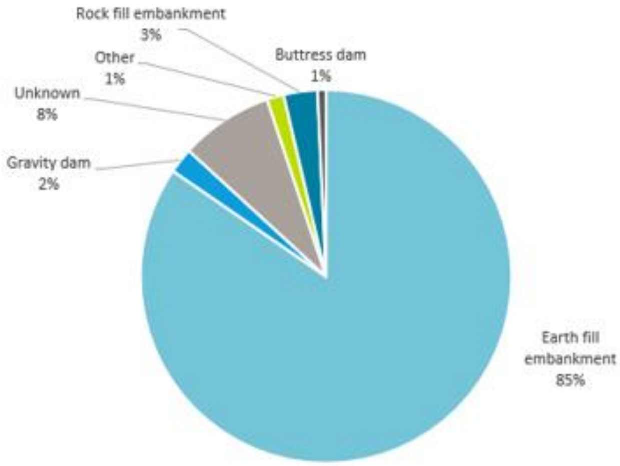


Figure 2 Reservoir incidents by impact 2016-2024

Internal erosion features in nearly half of all reported incidents, with internal and external erosion being a factor in 75% of reported reservoir incidents. This is shown in Figure 2. These are the major failure mechanisms associated with embankment dams. We explore this trend in more detail in Section 2.4.

There is a marginal trend showing embankment dams are disproportionately represented in the incident reporting data. These dams make up 85% of the incidents and 76% of the English reservoir stock. This is shown in Figure 3. This is likely due to embankment dams generally being:

- constructed with more variable material
- susceptible to internal and external erosion
- older structures



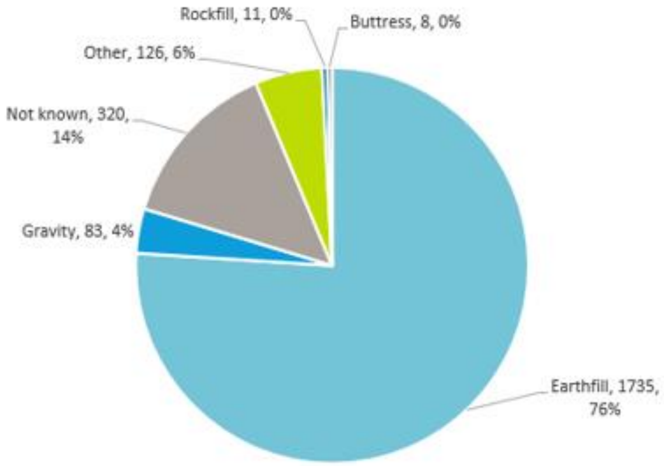


Figure 3 Reservoir incident reports (a) and numbers by dam type (b)

Assessment of reports by undertaker group found public bodies and registered charities reported the most incidents per reservoir (on average). Private individuals reported the least. There is more information on this in Appendix B. This is likely related to the differences within these different groups in reporting culture, knowledge and availability of resources.

Reservoirs with a capacity under 500,000 m^3 were disproportionately represented in reports. They feature in 99% of the reports for reservoirs over 25,000 m^3. They make up 78% of the statutory reservoir stock in England. This could be related to the perceived risk posed by large reservoirs. Larger reservoirs draw more resources from undertakers for surveillance, maintenance and upgrades. Large reservoirs are likely owned by water companies or other major owners. They are knowledgeable and experienced undertakers with significant resources. These resources and expertise are likely focused on larger reservoirs to reduce incidents where financial and reputational risks are greatest.

There has been an increase in reporting year on year, which will, over time, improve the data available and the opportunities for analysis to identify trends

2.2. Statutory reservoir safety measures 2016 to 2024

2.2.1. Sources of information

This review of statutory reservoir safety measures between 2016 and 2024 is based on data we hold. This comprises:

- a MIOS Analysis Report written in 2023
- MIOS Data Analysis Spreadsheets

The MIOS data contained 5 fields:

- undertaker type
- dam construction
- dam age range
- safety measure type
- deadline and implementation timescales

It also contains detailed information on the MIOS. This was likely to be the exact wording from the associated Section 10 reports.

We carried out an analysis of the over 8,000 MIOS recorded across approximately 1,400 reservoirs. While early data (pre-2016) is less reliable, percentage-based analysis and basic statistical testing were used to identify trends across:

- dam types
- ages
- MIOS types
- implementation deadlines

2.2.2. Main findings

Dam type

The data for the dam type field had 6 unique categories:

- Earthfill
- Gravity
- Rockfill
- Buttress
- Other
- Not known

Most reservoirs requiring a MIOS were earthfill embankment dams. These featured in 81% of MIOS. This is shown in Figure 4.

The distribution of MIOS broadly reflects the prevalence of dam types, indicating no significant relationship between dam type and number of MIOS.

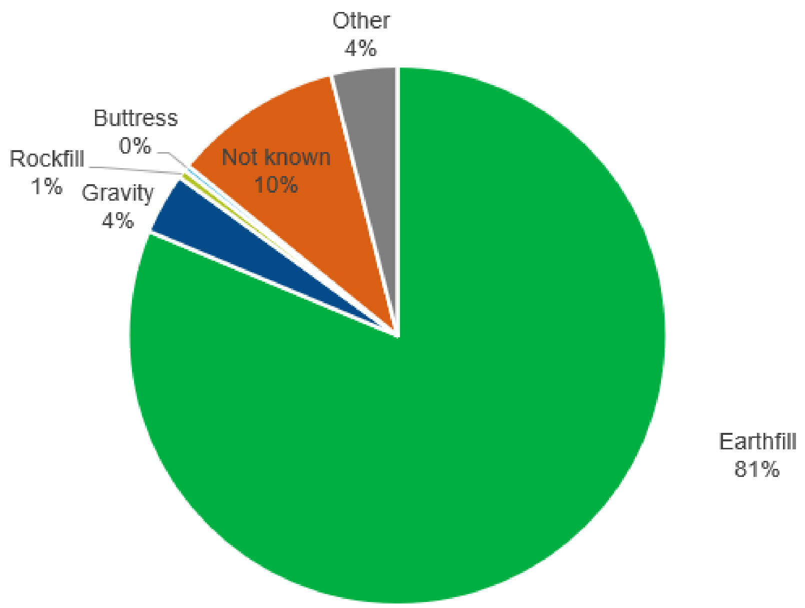


Figure 4 Number of MIOS by Dam Type

MIOS Type

The data for MIOS type contained 7 unique categories:

- physical and construction works
- investigation
- design review
- monitoring procedures
- emergency planning
- records
- other

This is shown in Figure 5.

In summary:

- the most common MIOS type is Physical and Construction Works, representing 58% of all MIOS
- investigations account for around 15 to 17% of MIOS across all dam types
- emergency planning, monitoring, and records MIOS are relatively uncommon, often covered under other statutory requirements
- monitoring and record keeping requirements are usually recommended against Section 11 which means few are expected to feature in MIOS

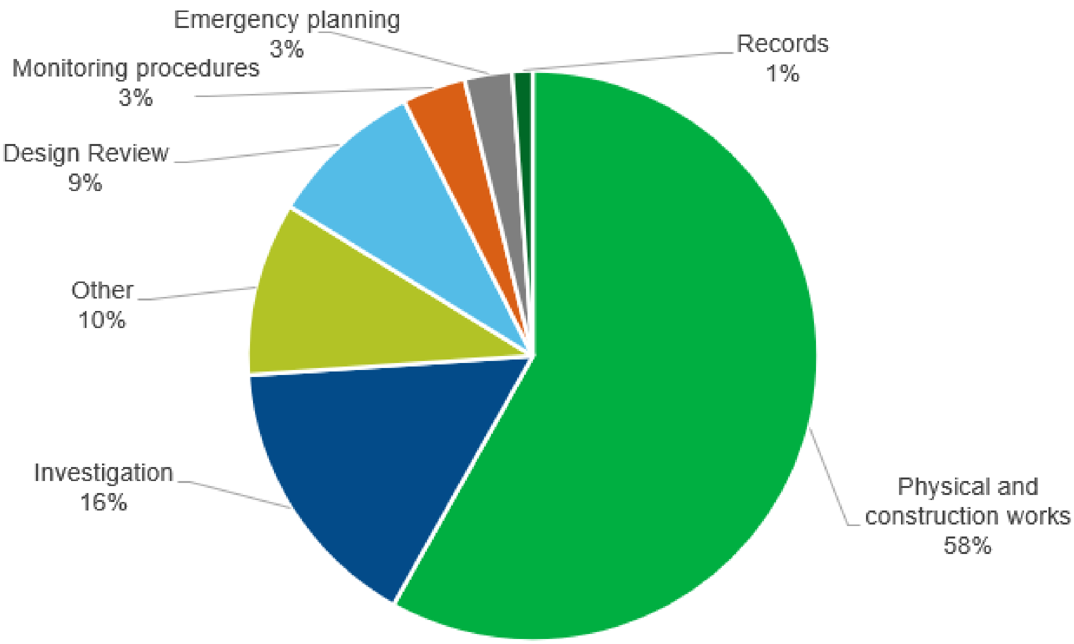


Figure 5 Distribution of MIOS by MIOS category

Age of dams

The year of completion for the dam is provided for each MIOS. There is a clear relationship between dam age and number of MIOS. Figure 6 shows the number of MIOS normalised by the number of reservoirs per age range.

In summary:

- there are more MIOS for older dams, especially those built between 1800–1950 (56% of MIOS vs 40% of total reservoirs)
- newer dams (post-2000) receive proportionally fewer MIOS (3% vs 14% of total reservoirs)

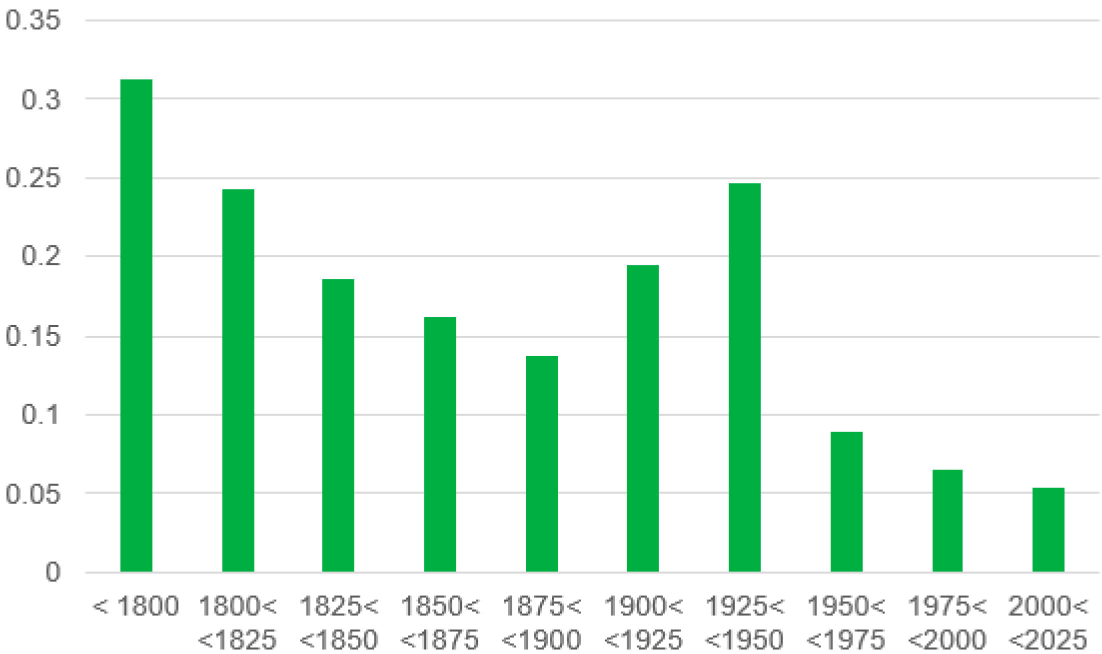


Figure 6 Number of MIOS normalised by number of reservoirs

Deadlines and Implementation timescales

The deadline and implementation time scale range from 15 days to 11 years, with most MIOS having deadlines between 3 and 12 months. This is shown in Figure 7. There is a median of 18 months and a mode of 12 months.

In summary:

- physical works have the longest and most variable timescales, with a median of 18 months and mode of 3 years
- design review, investigation, and 'other' MIOS typically have median deadlines of 18 months
- monitoring, records, and emergency planning have shorter deadlines, with a median of around 12 months

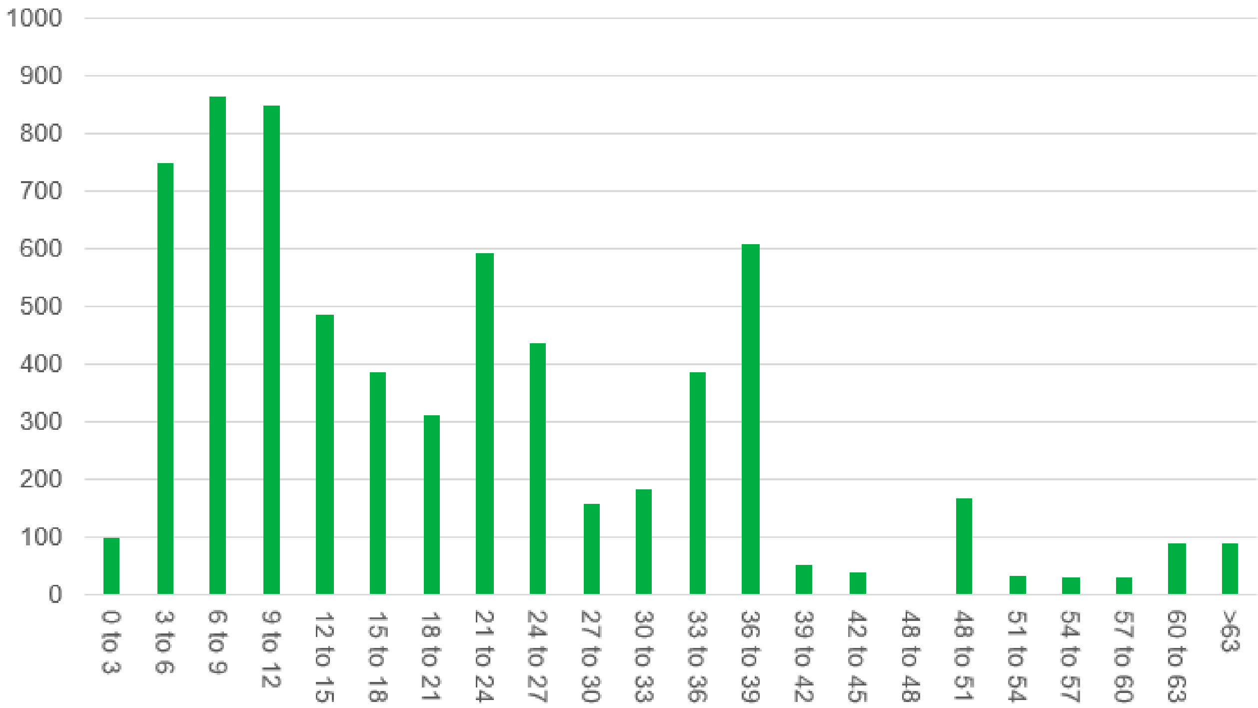


Figure 7 distribution of MIOS timescales

Undertaker type

The distribution of MIOS by undertaker type is presented in Figure 8. This shows that water company reservoirs receive the highest number of MIOS. We would expect this as water companies own the largest number of reservoirs. It is not possible to normalise the data by the number of reservoirs owned by each undertaker type.

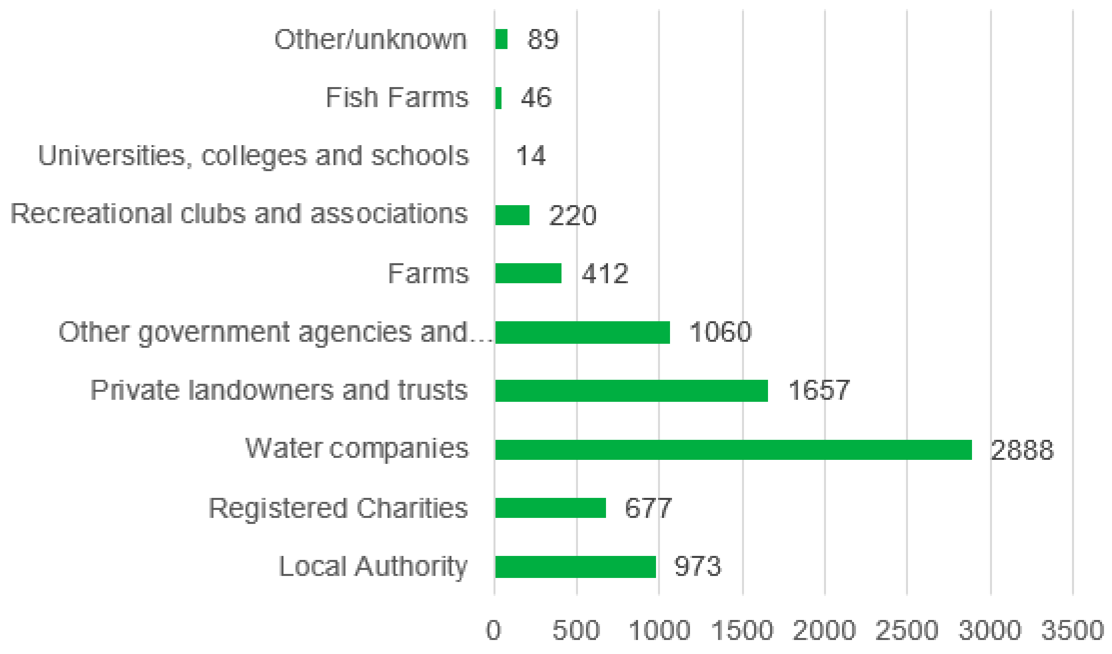


Figure 8 Distribution of MIOS Undertaker Type

2.2.3. Conclusions and implications for the research strategy

MIOS distribution aligns broadly with dam type prevalence, but age-related differences are pronounced. Older reservoirs require:

- greater intervention, likely related to legacy design and construction methods
- longer deadlines potentially due to external factors and complexities, for example working on historic structures, need for environmental surveys and planning permissions
- a larger scale of work required

Physical and construction works dominate MIOS recommendations. This shows an ongoing focus on asset integrity. Short-term MIOS, such as emergency planning and monitoring, appear well embedded within other legislative processes.

2.3. Issues identified from MIOS analysis

Issues emerging from the analysis of MIOS data that may inform future research are summarised in Table 1.

Table 1 Issues identified from analysis of past MIOS

Issue	Possible Research Theme	Output/Progress
Lack of detail in MIOS scope and context in Inspection reports which makes analysis of trends difficult.	Guidance on how to categorise MIOS and to provide more context.	Have a unique code for every MIOS which qualified civil engineers (QCE) use in their Section 8 or 10 reports and S8 or 10(6) certificates. This would allow a MIOS to be easily tracked through various documents using Machine learning (ML)/AI. Capture data to allow direct correlation between MIOS and (for example): • dam type • reservoir risk designation • flood category Actual incidents or near misses.
Lack of detail in incident reports on the root cause.	Guidance on how to categorise and document an incident and identify root cause.	Capture data to allow direct correlation between incident data and (for example): • dam type • reservoir risk designation • flood category Past MIOS.
The Reservoir Act Compliance Enforcement (RACE) system became fully operational in 2016, yet the dataset spans back to 1987. **RACE provides structured data since 2016. Pre-2016 records are available within RACE, and important, but difficult to analyse.**	Further work to improve the quality of pre-2016 MIOS and reservoir incident data	

Issue	Possible Research Theme	Output/Progress
MIOS and incident trend by risk & condition	Effectiveness of MIOS actions	Analyse: • whether MIOS effectively prevented incidents • whether absence of MIOS preceded failures • develop models to: • predict MIOS issuance / incident probability based on dam age, type, and inspection cycle • assess effectiveness by comparing MIOS presence vs absence in past incidents

2.4. Relevant case studies from the reservoir sector 2016-2024

The most significant incident that occurred in the period between 2016 and 2024 was the auxiliary spillway damage at Toddbrook Reservoir in August 2019. The incident resulted in the evacuation of 1,500 residents and significant coverage in the news. Following the incident an independent review was commissioned. The review undertaken by Professor Balmforth was completed in two parts:

- Part A was the review of the Toddbrook incident
- Part B an assessment of the current reservoir safety regime and legislation

The review delivered 15 recommendations for modernising and making the reservoir safety framework and legislation more robust. The recommendations related to:

- adding further proportionality to reservoir safety management based on risk
- updating the undertaker's role and the support and guidance provided to them
- updating the role of panel engineers and supporting supply and their development
- the role of the Institution of Civil Engineers (ICE) and Reservoirs Committee and collaboration with other enforcement agencies
- updating the role of the regulator
- climate change
- changes in legislation

These recommendations have all been accepted by Defra and work has started to implement them. The Reservoir Safety Reform Programme (RSR) has been setup to:

- modernise legislation
- act on the recommendations put forward in the Independent Review

The Independent Review was the reason we published the following guidance documents:

- reservoir owner and operator guidance: inspection information pack guidance, 2021
- reservoir supervising engineers: written statements and site visit reports guidance, 2022
- spillway design guide, 2022
- spillway examination guide, 2022
- spillway failure mechanisms guide, 2022
- reservoir inspecting engineers: safety inspection of reservoirs guidance, 2024
- how to manage your large raised reservoir, 2024
- managing your large raised reservoir in extreme weather, 2025

The Toddbrook case study shows how the reservoir industry had to adapt following a significant incident. Although this incident has resulted in a positive change to the reservoir safety industry, it is a reactionary response. The goal for future change is for proactive adaption driven by research and development. This should be supported by a functioning and auditable reservoir research programme.

2.5. Incident data case studies

The assessment of reservoir incidents in Section 2.1 highlighted factors that were disproportionately linked to the reservoir incidents. This section contains a detailed review of the reservoir incident case study data to provide more information on these trends and causation. We have used the data available from the Institution of Civil Engineer's reservoir incident database to inform this review. We have also used the Environment Agency's Public Register of English Reservoirs to collate dam data to enable the assessment of trends.

The review will focus on the data from 2016 to 2024 to ensure trends in the data are current.

2.5.1. Internal erosion

Internal erosion is the most common underlying reason for an incident occurring noted in the incident data, featuring in 46% of incidents. Of this:

- 30% of incidents of internal erosion were associated with fill deterioration
- 16% of incidents were associated with internal erosion adjacent to structures, such as contact erosion

No significant unexpected trends were identified in the internal erosion case study data. Detection of issues normally resulted from:

- sinkholes (most common)
- new or increased in seepage from the dam
- deposition of fine material
- reduction in water level without an operational reason

Causes noted were:

- poor material used for construction and inadequate compaction
- increase in proportion of granular material within clay from use of poor-quality material during construction
- seepage adjacent to spillway structures
- tree removal creating seepage pathways
- failure of pipework
- mining subsidence
- interface between earthworks and structures
- cavities in bedrock, construction without Construction Engineer oversight
- high flows during remedial works
- lining failure
- inadequate drainage of groundwater
- excavation of dam by a 3rd party
- defects and cracks in structures

Further causes for concern were mentioned, such as:

- geotextiles bridging voids reducing ability to detect defects
- piezometers not identifying increases in pore water pressure
- availability of engineers for incident response

Management of the risk posed commonly involved reduction in reservoir levels. This also aided detection of the elevation seepage was occurring. Remediation commonly involved:

- geotechnical investigations
- grouting or excavation
- reconstruction of embankments and liners

Assessment of internal erosion incident reports by construction age shows that reservoirs constructed after 1929 have a much lower rate of internal erosion incident reports. This is shown in Figure 9. Reservoirs constructed prior to 1800 and between 1850 and 1899 have the most internal erosion incident reports.

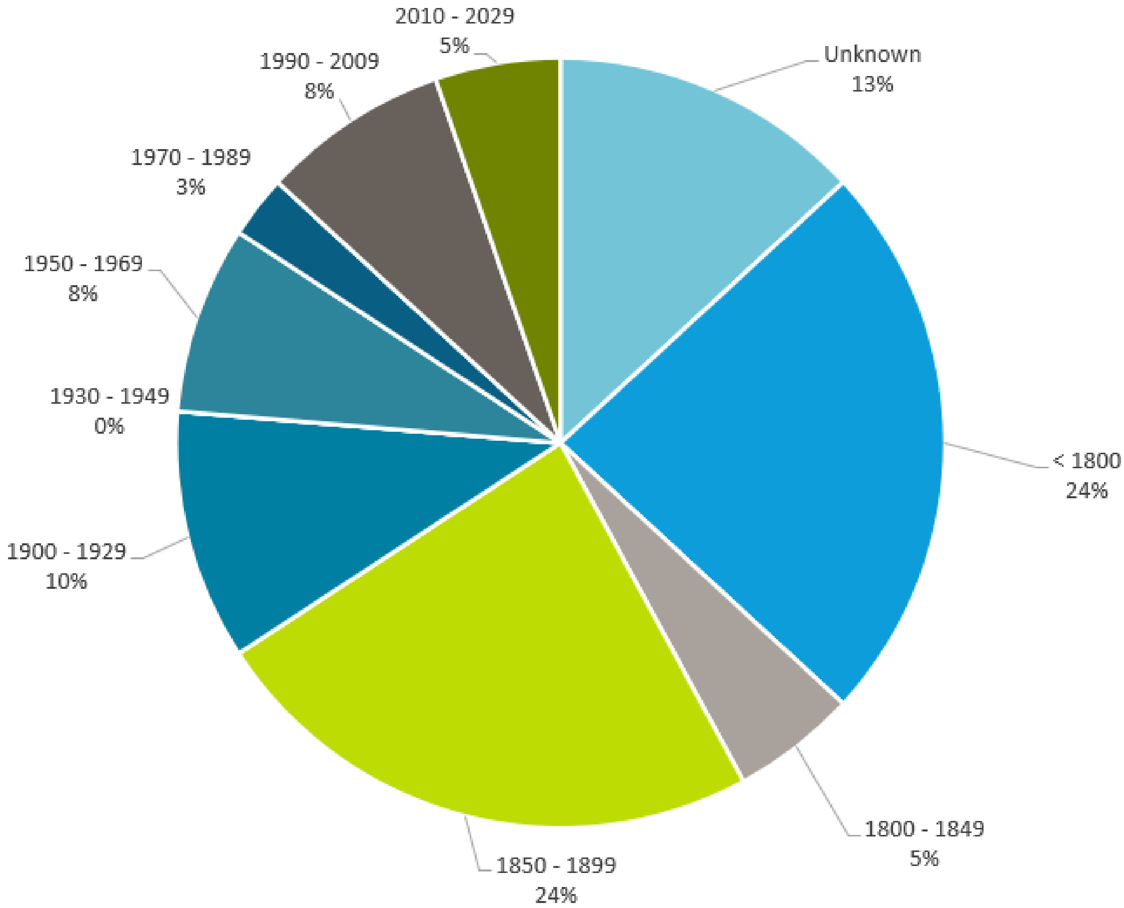


Figure 9 Internal erosion incident reports by construction date

Comparison of internal erosion incident reports by dam height shows that 87% of these reports are at dam heights between 2 and 10m. These dams make up 74% of the reservoir stock which shows a marginal trend between dam height and internal erosion reports.

88% of internal erosion incidents are reported on impounding reservoirs which make up 64% of the reservoir stock. One of the causes for this could be age. This is because, on average, impounding reservoirs are approximately 100 years older than non-impounding reservoirs. Another factor is that impounding reservoirs are storing water more frequently. This means defects and leakage are more identifiable, causing more incidents.

2.5.2. External erosion

External erosion is the second most common cause of incidents, following internal erosion, featuring in 29% of incidents. The most common terms referenced in the incident description of the case studies were:

- interactions with adjacent infrastructure
- damage by a 3rd party
- overflowing
- wet weather, including high flows and high rainfall
- reservoir type as flood storage reservoirs

These are shown in Figure 10.

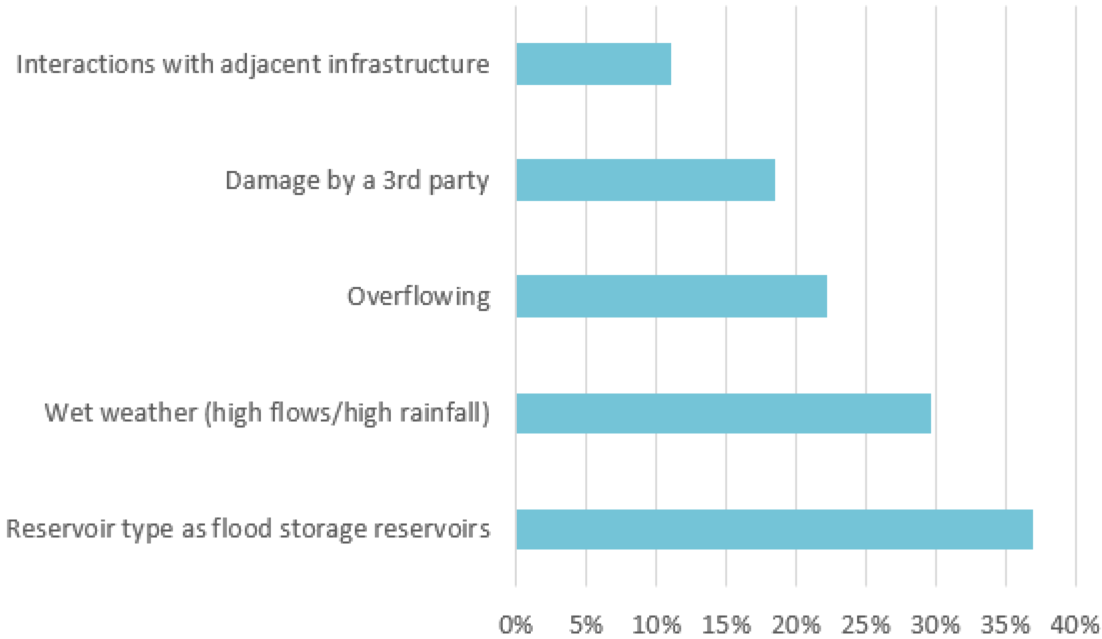


Figure 10 Most frequently mentioned terms in incident case study description for external erosion incidents

Flood storage/attenuation reservoirs (FSR) are mentioned 10 times in 27 case studies. They feature in 37% of the incidents while representing approximately 5% of the reservoir stock. Flood storage reservoir type is not specified in the Public Register of English Reservoirs, as such, all reservoir names referencing Flood Alleviation Scheme, FAS, Flood Storage Reservoir and FSR were summed. The shortcomings (assumed to be the cause of the incident) noted against each of these case studies were:

- process or procedural (30%)
- design (30%)
- maintenance (23%)
- surveillance (15%)

All of the interactions with adjacent infrastructure like river embankments, bridge structures and railway embankments were associated with FSRs.

Wet weather and overflowing are mentioned in 25% and 19% of the case studies respectively. These factors are already known to be an important factor in external erosion. These incidents appear to have been caused by:

- inadequate spillway capacity
- river erosion
- inadequate design of erosion protection

Damage by 3rd parties was mentioned in 16% of case studies. Most of these were developers and utility companies.

2.5.3. Impounding versus non-impounding

Internal erosion incidents feature in 39% of the incidents at impounding reservoirs but in only 19% of the non-impounding reservoir incidents. This is discussed in the previous Section, 2.5.1

Overtopping and external erosion feature in:

- 9% of the impounding incidents
- 25% of the non-impounding incidents

Damage by 3rd parties featured in:

- 19% of the reported incidents on non-impounding reservoirs
- 5% of those related to impounding reservoirs

Construction and design defects are mentioned more in non-impounding reservoirs than impounding reservoirs.

The impounding case studies feature more:

- spillway damage
- blockages
- operational failures
- slope instability

We compared the shortcoming attribute (assumed to relate to the root cause of the incident) for impounding and non-impounding reservoirs in the case study data This showed the following trends:

- the largest cause for both groups is related to design
- non-impounding reservoirs have a high proportion of incidents caused by construction and process or procedural issues
- impounding reservoirs have a high proportion of incidents caused by maintenance and surveillance issues

These are also shown in Figure 11.

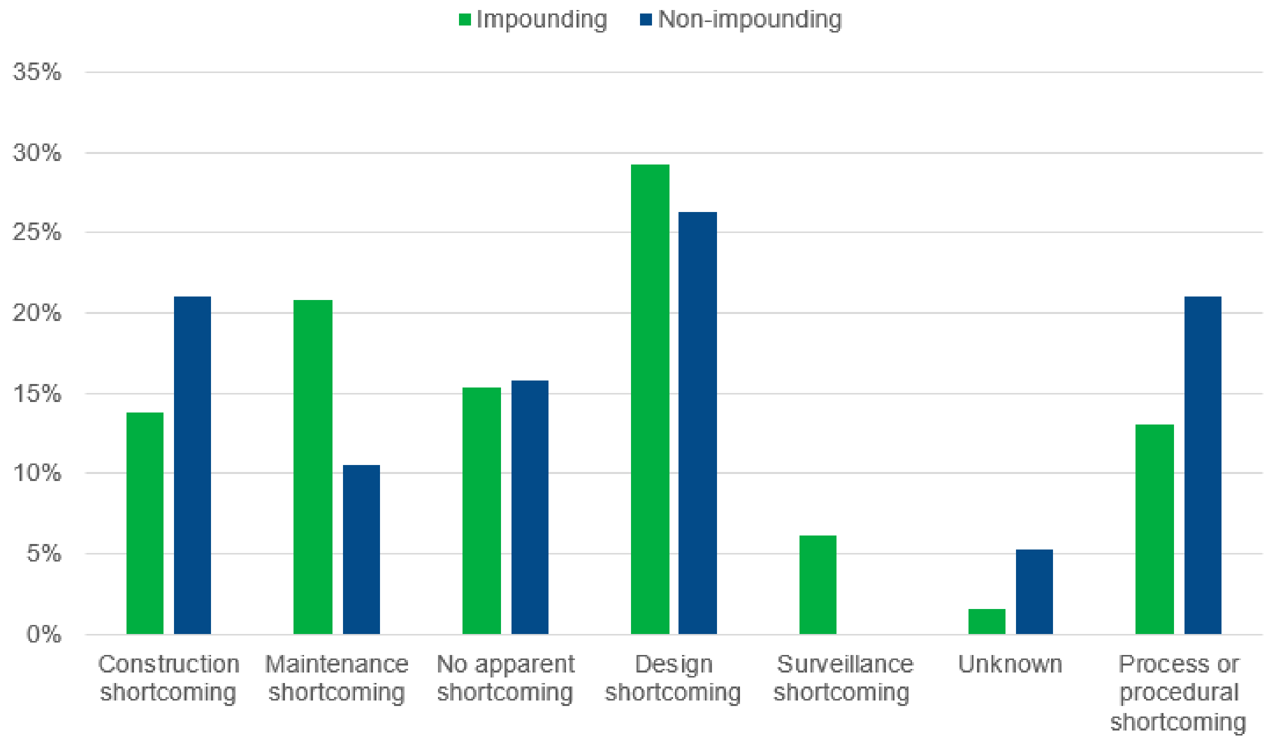


Figure 11 Comparison of incident causes for non-impounding and impounding reservoirs

3. PESTLE analysis to provide a framework for decision making

3.1. Introduction to PESTLE factors

In order to consider the context for the new strategy and the review of triggers of identified gaps, we used a PESTLE (Political, Economic, Social, Technological, Legal and Environmental) framework. This helps determine a range of factors important to the future research strategy and identify any interdependencies.

The PESTLE analysis does not consider the individual research themes or topics. Instead, it evaluates the external factors that can impact on the delivery of the overall reservoir safety research strategy. This helps to:

- understand long term trends
- recognise the context for change
- support planning of the strategy
- identify any future events which may influence its success

Using this approach allows those responsible for implementing the strategy to better plan for any identified factors. Table 3-1 summarises the wider factors that may influence the delivery of reservoir safety research and development. For each PESTLE factor:

- examples of areas to be considered are set out
- factors that are important to future reservoir research and their interdependencies are noted

Table 3-1: PESTLE Factor identification Reservoir Safety

PESTLE Factor	Examples of areas to be considered	Factors important to future research and interdependencies
POLITICAL	• Government policy • Political stability • Tax regulations • Global trade agreements and or restrictions	• RSR Programme and any resulting major changes to reservoir legislation • Potential changes in the wider water sector as a result of the Independent Water Commission (Cunliffe) Review. • Future, as yet unknown, changes in other environmental, sustainability and climate change strategies and legislation which may impact reservoirs • Potential conflict and/or incompatibility between reservoir legislation and other regulated activities • General election and a change

		in political party (and their priorities/ funding) • Desire to have freely available research outputs restricting the delivery of research through more commercial routes • Change in ownership profile of reservoir owners as a result of legislation change • Restrictions placed on previous accessible guidance (e.g. from the USA)
ECONOMIC	• Exchange rates • Globalisation Economic growth/decline • Inflation • Interest rates • Cost of living • Labour costs • Consumer spending habits • Impact of skills shortage within labour market • Taxation and tariff levees	• Level of industry priority given to R&D impacting investment • Lack/ shortage of technical/ professional skills – resilience of the industry • Contract terms and procurement routes • Challenge of prioritising funding for reservoir safety against other priorities in the R&D joint programme • Procurement routes/ directing some research topics towards a restricted number of suppliers • Asset management of aging dams and infrastructure, increasing need for dam removal or discontinuance • Potential increase in number of regulated reservoirs
SOCIAL	• Consumer trends/tastes, Fashions • Consumer buying habits Lifestyle factors • Career attitudes • Work-life balance • Population demographics Willingness to work in certain labour markets • Attitudinal influence • Social Value • Corporate social responsibility	• Lack of industry awareness of research strategy and progress in between major reviews (2016 and 2025/6) • Reservoir safety incidents that impact society altering the research priorities, or diverting funding (e.g. Toddbrook) • Emergency preparedness and communication of risks • Changes in the way that people secure, access and share information • Sustainability and resilience becoming increasingly important to society • Mitigation of climate change impacts on society such as water scarcity, increased flood risk and environmental damage • Demonstrating learning from incidents to gain public (and

		regulatory) trust • Communication and open dialogue with the public on balancing needs, desires and impacts
TECHNOLOGY	• Disruptive technologies • Automation / Robotics • Social networking • AI • Security • Cost of keeping up with technology advance / return on investment	• Fast changing technology. The research programme needs to stay up to date with this – so should be evolving, not set at 2026 priorities • Consider benefits and challenges of emerging technologies, AI, ML • Need for up-to-date guidance and tools to ensure a consistent industry approach • Scientific advances and trends.
LEGAL	• Employment law • Environmental law Common law • Health and safety regulations	• Reservoir Reform Programme and any resulting major changes to reservoir legislation. • Contract terms and procurement routes. • Effects of reservoir safety incidents
ENVIRONMENTAL	• Environmental restrictions imposed by devolved governments • Ethical sourcing • Transportation Procurement Supply chain management Future pandemic • Sustainable resources	• Impact of changing climate on reservoir safety and the research drivers • Mitigation of climate change impacts on society such as water scarcity, food security, increased flood risk and environmental damage • Biodiversity, Heritage, water quality (pollution), water resource all links into key parts of the Governments wider joint approach, • Development of renewable energy potential at new and existing sites • Sustainability throughout the lifecycle of a dam • Resilience in the context of changing environmental pressures • Increased environmental targets (e.g. Biodiversity Net Gain, carbon calculations) • Changing catchment management practices and ensuring sustainability in managing water resources

The scope of ReSRAG is primarily dam safety. However, the interconnected nature of the PESTLE factors and driving forces for research across the wider water industry mean that a more holistic approach to research and evidence synthesis may help to unlock other funding or delivery streams.

Evaluation of the PESTLE driving factors may identify how integration or opportunities could arise. They can be mutually beneficial to other water industry specialisms. This wider consideration could lead to joint initiatives and ideas, such as those identified in Table 2.

Table 2 PESTLE factors across the wider water industry

PESTLE factor	Examples of mutually beneficial integration or opportunities
Political	Clarity on wider UK political drivers for water management, including: water resources; treatment and delivery; and management of too much or too little water (i.e. flooding and droughts). Consider the worldwide political environment for water, linking in with United Nation's Sustainable Development Goals, and global water forums and events.
Economic	Consider where major investments are taking place, for example Strategic Resource Options (SRO) schemes and data centres, and how the strategy can link better into these funding sources, to enable mutually beneficial research.
Social	Linking with other industries on how they calculate and categorise risk and the impact on society. Industries such as nuclear and rail are leaders in risk assessment techniques, providing opportunities to explore co-ordinated research and development.
Technology	Links with real time monitoring specialists. Links with satellite monitoring and space agencies. Improvements in monitoring and data processing using AI (links with technology companies). Considering relevant technological advances from the global dam safety industry through conferences, technical committees and working groups (for example the International Commission on Large Dams [ICOLD]).
Legal	Changes in legislation may result in more funding being available through charging schemes, for example.

Environmental	Explore future environmental challenges and drivers and identify where a joint approach would be beneficial. Requirement for improved drought resilience including increased water storage and connectivity. Increasing desire for multi-use facilities to balance flood or drought resilience with adequate supply and other water uses. This is particularly relevant to the developing renewable energy market in the UK and also any incentives to address impacts of climate change.

The PESTLE framework has also been used to consider the wider UK infrastructure sector and identify likely changes and drivers for change in the next 20 to 50 years. This is discussed further in Section 3.2

3.2. Forecasts of 20 to 50 year future changes and change drivers in the infrastructure sector

3.2.1. Introduction

Significant changes in the reservoir industry are currently being implemented. This follows the Ministerial acceptance of the recommendations of the Independent Review. It also results from advances in understanding reservoir risk profiles. These follow recent research, case studies and incidents. This section highlights the likely areas of change and change drivers for the next 20-50 years with a focus on the reservoir industry.

We recognise that it can be difficult to predict what changes and change drivers may become important in the future. It is imperative that the new strategy allows for the regular review of drivers. Also, for intentional reaction to changes in the drivers so that research priorities are reviewed and maintained where necessary.

Each of the changes and change drivers, presented below, relate to one or more of the PESTLE factors, with them often spanning a number of PESTLE factors. Changes and change drivers have been mapped against PESTLE factors in Table 3.

Table 3 Changes and change factors mapped against PESTLE factors

Change / Change Driver	POLITICAL	ECONOMIC	SOCIAL	TECHNOLOGY	LEGAL	ENVIRONMENTAL
Legislation	x				x	x
Enforcement	x		x		x	x
Definition of a Reservoir					x	
Panel Engineers		x	x		x	
Climate Change		x	x	x		x
Probable Maximum Flood Derivation				x		x
Reservoir Flood Mapping	x	x	x	x	x	x
Hazard Classification and new requirements	x	x	x		x	x
Water Resources and New Large Scale Reservoirs	x	x	x	x		x
Artificial Intelligence and Cyber security				x	x	
Technological Advancement and Data				x		
Aging infrastructure		x	x	x		x
Dam Removal and Discontinuance	x	x	x		x	x
Small Raised Reservoirs	x	x	x		x	x
Probability of Failure		x	x	x		x
Downstream Development and Planning	x	x	x	x	x	x

Change / Change Driver	POLITICAL	ECONOMIC	SOCIAL	TECHNOLOGY	LEGAL	ENVIRONMENTAL
Environmental policy and biodiversity/net-gain drivers	x		x		x	x
Reservoir valves, gates and pipework		x		x		x

3.2.2. Legislation

The Reservoirs Act 1975 and the preceding Reservoirs (Safety Provisions) Act 1930 have been effective at ensuring reservoir safety. There have been no fatalities occurring in the UK from a reservoir breach since 1925.

The Reservoirs Act 1975 has had several amendments. The Water Acts of 1989 and 2003, Flood & Water Management Act 2010 and various Statutory Instruments (SI) have made changes. It also now only applies in England & Wales. Scotland and Northern Ireland have developed their own Reservoir legislation. The Independent Review concluded the 1975 Act lacks the regulatory flexibility found in other infrastructure sectors' legislation. It requires updates to primary and secondary legislation. This would allow legal requirements and duties to evolve with best practice. At times the 1975 Act can be in conflict with other legislation, such as environmental protection.

There have been many cases in recent years which test which legislation takes priority. The current Act does not allow implementation of all the recommendations of the Independent Review. It recommended the development of appropriate legislation and regulations to support the implementation of the recommendations. Following the publication of the Independent Review, the industry has concluded that the existing Act could benefit from modernisation.

The RSR programme is currently considering options. Changing the legislation will drive change in the reservoir industry. New guidance will be required to support the new legislation and to define the role and requirements of the panel engineer, owners and operators.

3.2.3. Enforcement

The powers contained in the Reservoirs Act 1975 (as amended) restrict enforcement in England and Wales. It does not include fixed monetary penalties (FMP) and variable monetary penalties (VMP). If FMP and VMP are added to the powers of the regulator, the consequence of non-compliance would change. This could drive change in the approach to non-compliance. It may change the commercial risk and appetite for private reservoir ownership.

3.2.4. Definition of a Reservoir

The Reservoirs Act 1975 defines a Large Raised Reservoir (one which falls under the ambit of the Act) in Section A1. The minimum capacity is defined in subsection (3). The relevant Ministers in England and Wales have the power to make regulations on calculating capacity. This power is for the purpose of subsection (3). “Natural level” and “surrounding land” are to be construed in accordance with the regulations.

The existing regulations are clear about calculating the capacity in terms of water. Statutory Instrument 2013 No.1677 in England and SI 2016 No.80 (W.37) in Wales) set this out. Judgement is however required by the Panel Engineer on what constitutes the “bed of the reservoir.” The SI states this as including “any silt or other material that is judged by the engineer to be incapable of flowing out of the reservoir over natural ground in the event of an uncontrolled release of water from the reservoir.”

Research could improve consistency by:

- defining what types of bed material could be mobilised in the event of a breach
- how the “escapable” volume can be estimated
- including guidance or a toolbox on how to estimate the bed sediment that could be released during a drawdown

This research could reduce conservatism in the estimate of reservoir capacity under the Act.

3.2.5. Panel Engineers

There is a recognised shortage of panel engineers in the UK, in particular those appointed to the All Reservoirs Panel. This shortage makes it harder for undertakers to procure panel engineers to fulfil their duties. The potential consequence is an increase in non-compliance and reservoir risk. There may be:

- delays to statutory inspections and reports
- non-appointment of engineers, risking reservoirs having limited or no technical supervision
- delays to delivery of MIOS works

Change to the duties of panel engineers, restructuring of the existing panels, a new risk designation system, changes to the minimum reservoir capacity and procurement will drive change within the industry. It also drives the need for updated supporting resources. Training material and appointment criteria will need updating to reflect their changing role. Research is required to understand the impact of the changes in the industry on already stretched panel engineer resources. It needs to identify opportunities to create procurement routes for small owners.

3.2.6. Climate Change

Climate change has caused increasing frequency and intensity of extreme hydrometeorological events. This affects reservoir risk and water security. Section 4 discusses climate change in more detail. The main potential impacts of climate change on reservoir safety relate to:

- **hydrology.** With more frequent and higher rainfall intensity events, conventional methods of hydrological modelling based on historical data could become less reliable. This may lead to the underestimation of flows for design events and increased external erosion risk. Conversely the increase in drought could lead to a greater demand for new reservoirs
- **geotechnical impacts.** Wetter winters and drier summers cause seasonal and long-term changes in moisture regimes. This affects slope stability, embankment permeability, shrink-swell behaviour and foundation interactions. Temperature extremes and freeze thaw cycles may accelerate material deterioration
- **sedimentation.** Altered runoff regimes and land use could intensify sediment delivery. This reduces storage capacity, compromises inlets/outlets and accelerates scour and siltation issues
- **operational complexity.** There is increasing pressure to provide multi-use facilities, such as flood attenuation as well as water supply. This creates competing operational objectives and more complex operating envelopes

Continuing to adapt to climate change impacts and the creation of new methods to predict and manage the risks will drive change in the reservoir industry.

3.2.7. Probable Maximum Flood Derivation

The probable maximum flood (PMF) is used as the safety check event for the design and assessment of Category A reservoirs. Most methods for the derivation of the PMF have not been updated since the issue of the Flood Studies Report in 1975 (NERC, 1975).

Over or under estimation of the PMF affects the risk posed by the reservoir. It could result in costly works for the undertaker to reduce the risk posed by the reservoir. Alternatively, it could result in under-design of the spillway or reservoir freeboard. A more accurate approximation for the PMF would better define the risk profile of the reservoir.

An Environment Agency-led programme to update the PMF estimation method started in 2020. This incorporated advancements in meteorology and hydrology. Phase 1 of the programme reviewed the current method and set out detailed recommendations for improvements. The Phase 1 report was completed 2022 and published in 2025. Phase 2, which would implement the recommendations, has not yet been commissioned.

Any change to the PMF methodology may result in reassessment of the performance of all Category A reservoirs. Changes to PMF (or other design flood estimates) could lead to:

- concluding that the existing overflow capacity remains adequate or accepting that the risk is already As Low as Reasonably Practical (ALARP)
- a need to change reservoir operation
- structural changes more minor than spillway enlarging
- spillway enlarging / additional spillway

3.2.8. Reservoir Flood Mapping

The reservoir flood mapping (RFM) specification has evolved since it was first introduced in 2009. Initially, it was called reservoir inundation mapping. The intent of the mapping was to inform people of flood risk from an uncontrolled release of water from a reservoir. It allows Local Resilience Forums to perform their emergency planning functions. We published the most recent flood risk from reservoir data in 2021. This followed the most recent update to the RFM specification in 2019. Modelling of each reservoir is required to produce the maps. The models help to calculate the Average Societal Life Loss (ASLL) and the economic damage from the modelled worst-case failure.

The guide to risk assessment for reservoir safety (RARS) provides a method for managing the risk posed by reservoirs to society. The two major components forming this assessment are the risk to life and the probability of failure.

The models used for breach flow estimation are largely uncalibrated or verified for dams under 15 metres and for service reservoirs. There is a lack of guidance on how erodibility category can be related to measurable attributes of the dam.

The specification makes conservative assumptions in the modelling of the worst-case failure. This can lead to over estimation of the fatalities cause by a reservoir breach. If the ASLL is overly conservative and used in the RARS assessment it could result in the need for owners to do costly construction works. Reservoir experts have scrutinised its suitability for use in RARS and as a justifying major works. As such, there is a financial reason for the need of further work. We should find a better approach or update the methodology to better define embankment erodibility and geometric characteristics of reservoirs.

Methods for estimating the impacts of flooding on human life have evolved over time. Work to refine this methodology will continue to be a research topic that will drive change. This could include:

- refinement or replacement of how reservoir breaches are modelled
- cascade failure
- calibration with data from real events
- refinement of thresholds for velocity, depth and the product of both
- the assessment of different receptors, such as footpaths, moored boats and caravan parks

There is also a potential need to calibrate thresholds specifically for the output from 2-dimensional as opposed to 1-dimensional hydraulic models.

3.2.9. Hazard classification and new requirements

The Independent Review proposed a new hazard classification system. The RSR programme completed initial research work in 2025 (Defra R&D project FD2739). Any changes in the hazard classification system will change the requirements on existing undertakers and the work of panel engineers.

The new hazard class may change the regulatory requirements for the management of that specific reservoir. This may increase or reduce the requirements compared to the existing scenario. Any new methodology may result in owners wanting to lower the class and regulatory requirements of their reservoirs. They may do further investigations or reservoir alterations to refine the parameters used in the new designation process.

The reservoir industry will need to adapt to any changes to the designation system and requirements under the Act.

3.2.10. Water resources and new large scale reservoirs

There is a need for drought resilience including increased water storage and connectivity. The frequency and severity of droughts in the UK is increasing. Industrial and domestic water demands are increasing. There is tighter regulation of abstraction licenses. It is a challenge to find suitable locations for new reservoirs and safely increase the capacity of existing ones.

Recent large scale reservoir schemes have faced scrutiny in the media. Economic efficiency of the design of new large-scale reservoirs must be optimised. Research into opportunities to maximise the efficiency of design and construction could be useful. It is important to avoid overly conservative design assumptions while maintaining a suitable factor of safety. This will drive change in the design, cost and viability of new reservoirs.

Environmental and social drivers are shaping the development of these large-scale reservoirs. Providing sustainable solutions that bring environmental benefits and amenity value is a goal. This shouldn't come at the cost of reservoir safety. These large-scale projects are also changing the commercial environment. Trying to construct multiple large-scale reservoirs simultaneously is impacting procurement, construction and management of resource constraints.

3.2.11. Artificial Intelligence and cyber security

Every industry is exploring opportunities to use AI including reservoir safety. AI could benefit the reservoir industry in many ways, for example:

- real time monitoring of sensors
- early warnings
- running real time scenario modelling
- checking data for anomalies
- predicting component degradation
- checking defect detection from imagery

AI in its current state is suitable to support the work undertaken by reservoir engineers, operatives and undertakers. It should not be relied upon in isolation. Research to maximise the benefit AI can provide to the reservoir sector will drive change.

As reservoir control systems become more digitised and remotely accessible, cyber-physical risks are rising. Supervisory Control and Data Acquisition and Operational Technology systems are at risk. This exposes gates, sensors, alarms and decision-support tools to hacking, ransomware or insider threats. It could ultimately result in an uncontrolled release of water. Other impacts include disruption of monitoring, operations and emergency response. There is a priority in all industries to adapt cyber security measures. This will help to stay protected against the evolving risk posed by cyber-attacks.

3.2.12. Technological advancement and data

Advances in technology are supporting the reservoir safety industry. There is improving quality and availability of data. Examples of this are:

- dense Internet of Things sensors and telemetry
- distributed fibre-optic sensing
- high-revisit satellite and small-sat constellations
- unmanned aerial vehicle
- light detection, ranging and thermal imaging
- geophysical methods
- jet erosion testing
- cloud/edge platforms
- AI and ML analytics and with digital twins are enabling near-real-time, spatially detailed detection of seepage, deformation and internal erosion

Advancements in technology will continue to drive change and improve the quality and availability of data.

3.2.13. Aging infrastructure

England has an aging reservoir stock. The average reservoir age is over 130 years. Assessment and adaption of this infrastructure to keep the risk of dam failure ALARP, combined with new regulatory requirements, is a challenge to the reservoir industry. This challenge will drive change. Data provision is needed to inform assessments, enhance monitoring and deliver remedial works.

There is a driver for undertakers to better understand the remaining asset life of their structures. The industry must improve asset management, so reservoir lifecycles can be better understood. This will allow more effective investment to ensure sufficient storage capacity is available.

3.2.14. Dam Removal and Discontinuance

A significant number of reservoirs have been discontinued in England and Wales. This is normally done to remove or reduce the undertaker’s financial liability associated with the reservoir. In Wales, there has been an upward trend in discontinuance since the lowering of the regulatory threshold to 10,000 m^3 in 2016. A similar pattern could be expected if the threshold is lowered in England. An increase in discontinuance schemes would further stretch ARPE resources.

The Environment Agency published guidance in 2022 on discontinuing, abandoning or repurposing UK reservoirs. The document refers to international experience, but it does not systematically benchmark UK practice against established international guidance. The document is process-led and legal-led, but not explicitly risk-led. Optioneering is framed largely in terms of cost, legal compliance and impacts. It would be useful to understand the probability–consequence risk reduction.

3.2.15. Small Raised Reservoirs

There is the potential for the regulatory threshold in England to be reduced to 10,000 m^3. This could result in more regulated reservoirs. It would create a significant amount of work to identify sites and their owners. Inspections, flood mapping and hazard classification would be required. In this scenario, there will likely be a significant number of undertakers new to reservoir safety regulation. There will be a need to innovate. The workload for processing the new reservoirs and educating the new undertakers will need to be efficient.

Although reservoirs under the 25,000 m^3 threshold have failed, to date there have been no reported fatalities.

3.2.16. Probability of Failure (PoF)

The risk posed by an uncontrolled release of water from a reservoir is the product of the PoF and the impacts. At present there are methods for estimating the impact, but no reliable methods for estimating the PoF. Improving methods to estimate PoF could drive change in the reservoir industry. It would provide a better understanding of the risk posed. This would allow reservoirs to be managed in a manner that is proportional to this risk.

3.2.17. Downstream Development and Planning

The development of land downstream of reservoirs can affect a reservoir's category and risk designation. This results in the need for further assessments and physical works. The risk should be reduced to ALARP. In the present regime, the presence of downstream development is only identified during periodic inspections and following revision of reservoir flood mapping. As such, a reservoir can pose an unacceptable risk for years before it is identified. This could be picked up during the planning process and flagged to the regulator for consideration.

Updating existing planning process and the further development of technology, procedures and systems to automatically flag changes in downstream receptors could drive change.

3.2.18. Environmental policy and biodiversity/net-gain drivers

Reservoirs create non-standard habitat mosaics. These can be:

- drawdown zones
- fluctuating littoral margins
- off-channel wetlands
- riparian transitions

The future strategy should include research that translates reservoir ecology into something regulators can use for accounting and securement.

In England there is a legally mandatory 10% Biodiversity Net Gain (BNG) for most Town and Country Planning Act major developments (from February 2024) using the Statutory Biodiversity Metric (SBM). Updated BNG regulations in 2026 amended the application of these policies.

Future changes in environmental policy will impact the manner and drivers for infrastructure schemes. This will include their interaction with other policies. They should not create a barrier to the effectiveness of each other.

3.2.19. Reservoir valves, gates and pipework

Most reservoirs have valves and gates. They are either to allow the control of water being taken into supply, for infilling or for drawdown. There has been recent updated guidance produced (Williamson, et al., 2020) which covers the specification, installation. operation, maintenance and replacement/removal of these safety-critical assets.

Reservoir safety critical valves need to be periodically tested and operated. At present, routine valve testing can be time consuming to facilitate. Undertakers must obtain the required environmental consent. This can also contradict with environmental legislation. Reservoir valves, gates and pipework are key to reservoir safety. Any advancements in this area could drive change in the reservoir industry.

3.3. Conclusions

The review of reservoir safety incidents, statutory safety measures and associated case studies between 2016 and 2024 highlights several trends that are directly relevant to shaping the future research strategy. Across both incident and MIOS datasets, internal and external erosion remain the dominant failure mechanisms. They account for around three-quarters of reported incidents. These mechanisms disproportionately affect older embankment dams. In particular, those constructed before 1900. This reflects the legacy of historic design and construction practices.

Impounding reservoirs continue to feature prominently in incident data. Their age, height, hydrological loading and more frequent storage cycles contribute to this. Trends also show some over reporting in smaller reservoirs (25,000-500,000 m^3) and structures owned by organisations with stronger reporting cultures, such as public bodies and charities. Improved national reporting has strengthened visibility of these trends. However, Pre-2016 data contains inconsistencies. There is also potential under-reporting among smaller private undertakers. This remains a barrier to robust long-term analysis.

The MIOS review reinforces these themes. Older dams require more frequent and extensive physical interventions. Most MIOS relate to construction works or investigations. This reflects the ongoing need to address ageing infrastructure and better understand deterioration pathways. Deadlines for implementing MIOS highlight the practical and logistical pressures on owners and engineers.

Case studies highlight recurring issues in:

- internal erosion
- spillway performance
- interactions with adjacent infrastructure
- overtopping in flood storage reservoirs
- damage caused by third parties

They also highlight knowledge gaps in erosion protection, spillway design robustness, and performance under clustered or extreme loading events.

There are a significant number of changes and change drivers that are shaping the reservoir industry. This section has summarised the main known changes and drivers for change. The research strategy needs to remain flexible to account for unknown unknowns that drive change in the future. Further research on the change drivers discussed in this section will help drive the reservoir industry forward. It will enable:

- improved assessment of reservoir risk
- reservoir safety
- proportionality in reservoir risk management

Taken together, this evidence provides a foundation for research priorities focused on:

- ageing assets
- erosion mechanisms
- spillway performance
- risk assessment methods
- climate-related loading
- inspection quality
- data consistency

These findings directly inform the strategic themes and problem statements developed in later sections of the strategy.

4. Updated review of climate change research in the reservoir sector

4.1. Context

This chapter records the findings of a quick scoping review of climate change in the reservoir sector. This follows the definition of (Collins, et al., 2015). It will assist in developing the case for a new research theme of climate change.

4.2. Purpose

The principal objective is to identify gaps in knowledge of the effect of climate change on reservoir safety. In particular, any progress towards filling knowledge gaps since the 2016 research strategy. This includes any new gaps that may have arisen since then.

The project scope refers to recommendation 13b of the Independent Reservoir Safety Review. That recommendation states:

"The Environment Agency should review recent and ongoing research on the impact of climate change on constructed embankments and determine if further research is needed to better understand the implications for earth embankment dams and other reservoir structures."

While the recommendation is quite specific to embankment dams, the quick scoping review has included all dam types. In terms of dam use, it covers flood storage areas and washlands as well as water supply reservoirs. It does not cover impacts of climate change on aspects of reservoirs other than dam safety.

4.3. Summary of earlier strategies

We first published our Reservoir Safety Research Strategy in 2009 (Environment Agency, 2009) The 2009 strategy made four recommendations focused on climate change:

1. "review of direct impacts of climate change on dams and reservoirs"
2. "review of indirect impacts of climate change on dams and reservoirs"
3. "investigate methods and technologies to help dams adapt to climate change"
4. "review management methods, inspection standards and inspection intervals and develop new requirements to take account of climate change"

Our update to the strategy in 2016 Reservoir Safety Research Strategy (Environment Agency, 2016) stated that all but the first had not progressed. It recommended to carry all of them forwards. This assessment seems difficult to reconcile with the fact that the 2016 strategy was preceded by Atkins (2013) Impact of Climate Change on Dams & Reservoirs (report FD2628). That report provided a comprehensive assessment, covering both direct and indirect impacts of climate change. This fulfilled recommendations 1 and 2 above. Atkins, (2013) identifies some specific knowledge gaps. Section 4.5.2 discusses these further. The primary focus of this literature review is to review progress towards filling the gaps since 2013.

4.4. Details of review

See Appendix A for a description of the method used to undertake this literature review and systematic map of the findings. The remaining parts of this chapter summarise the knowledge gaps identified by Atkins (2013) (Section 4.6) in light of more recent research. This report then comments on the relevance of developments in AI and ML (Section 4.7). It concludes with a current assessment of knowledge gaps (Section 4.8).

4.5. Summary of Atkins (2013) Impact of Climate Change on Dams & Reservoirs

4.5.1. Summary

Atkins (2013) distinguishes between impacts of climate change on the form and function of reservoirs. The form is the physical makeup of the dam and ancillaries. the function is their operational uses. Atkins (2013) states the impacts on the function to be more likely. The report is comprehensive and broader in scope than reservoir safety. It also covers aspects such as yield assessment, demand and water quality, invasive species, plant diseases and fish parasites. In this section we focus only on reservoir safety aspects.

It divides impacts of climate change on reservoir form or function into three classes:

1. impact on policy and planning
2. impact on design and construction
3. impact on operation and maintenance

Some important points made are on the following issues:

- the long operational lives of dams. This means that it cannot be assumed that current climatic conditions will prevail. In particular, for functions or attributes that require vegetation types or hydrology to remain stable
- the impact of climate change on the frequency of floods. This potentially increases the stress on flood storage reservoirs

- the impact on reservoir catchments, such as changes in land use. This is mainly driven by policy in response to climate change, drainage or erosion
- the potential for changes in the suitability of building materials or vegetation. This is relevant for embankment dams and some types of spillway in a hotter or drier climate

The report emphasises the importance of lateral thinking. Impacts are often not related to a single issue. There can be feedback between form and function. Many of the identified vulnerabilities related to mechanisms not caused by climate change. Instead, they manifest or are exacerbated by climate change.

It provides wide-ranging checklists of questions relevant to the impact of climate change on dam safety. It covers aspects well beyond the direct impacts on flood-producing weather conditions such as:

- landslides
- catchwaters
- spillway blockage
- spillway scour
- rusting
- metal fatigue
- algae growing over gauge boards

It suggests that checks of the impact of climate change on spillway capacity are only needed for floods below the probable maximum flood (PMF) because "... allowing for the PMF is a very stringent standard and it is unlikely that the overall level of risk will change significantly in relation to the experimental error that already exists within the calculations." The suggestion that the PMF will not be significantly impacted by climate change is called into question by more recent work, as discussed below.

4.5.2. Gaps identified in 2013

The introduction to Atkins (2013) states that its chapter on conclusions and recommendations "identifies the key areas of uncertainty and future work that may be required as policy and understanding of climate change progress." This does not appear to be the case. However, there are some places throughout the report where they identify knowledge gaps. The clearest gaps relevant to reservoir safety are:

- impact of climate change on estimation of the PMF – relevant for the safety check flood at Category A dams
- limited ability for climate models to simulate extreme rainfall. Therefore, impact of climate change on design floods for reservoir safety

- uncertain changes in summertime extreme rainfall. This is relevant for some reservoir spillways for which the critical storm event is a short-duration summer downpour
- uncertainty over impact on the frequency at which floods occur. This may affect spillway operation and the filling of flood storage reservoirs. For example, if climate change leads to more closely-spaced sequences of floods

4.6. Findings

This section synthesises the findings from the quick scoping review. It first summarises the findings of the Atkins (2013) review, including the knowledge gaps that it identified. Subsequent sections are structured using the headings applied in the systematic map, i.e.:

- climate modelling and translation into impacts on local meteorology or hydrology
- reservoir safety - floods
- reservoir safety - structural aspects
- reservoir safety - impact on demand or operations
- reservoir safety – other aspects

4.6.1. Climate modelling and translation into impacts on local meteorology

Aspects of climate change impacts

The relationship between rising global average temperature and the more localised impacts of climate change is highly complex and potentially a very big topic. Here we focus mainly on aspects with specific relevance to dam safety, i.e. the most extreme events.

Impacts of climate change are relevant looking in two directions. Firstly, to the future, where current design parameters may no longer be applicable. Secondly, to the past, where designs based on past measurements of weather or hydrological data may not be directly applicable to present-day conditions. (Ho, et al., 2024) quantified this latter issue for a sample of 18 dams in Australia. The authors found that extreme floods have a current occurrence probability more than twice as high as previously thought. This is due to the approximate 1ºC increase in global temperature from the 1961-1990 baseline that has already been observed.

Climate change is expected to affect (and already be affecting) several aspects of flood generation (Environment Agency, 2025a) (Environment Agency, 2026 (due date)) (Wasko, et al., 2024).This includes:

- rainfall intensity
- spatial and temporal storm profiles

- snowmelt
- runoff processes

Several sources emphasise the deep uncertainty associated with impacts of climate change on storm rainfall. Reasons for this include the fact that intense rainfall often occurs over small spatial and temporal scales that are not well resolved by many climate models. The uncertainty is all the greater for the extreme events of relevance to dam safety. Publications typically advocate adaptive design or management as a result (International Commission on Large Dams, 2025) (World Bank, 2021).

Current UK practice

There is currently no formal guidance in the UK on how to account for climate change impacts on design floods for reservoir safety. While Floods and Reservoir Safety (Institution of Civil Engineers, 2015) mentions the possibility of adjusting inflows, it does not definitively state how to do so.

Design rainfalls for return periods up to 10,000 years are estimated using the FEH22 methodology. This assumes stationarity over the period of record. It takes no account of past climate change (Vesuviano, 2022). Alternative approaches to rainfall frequency estimation that allow for non-stationarity are reviewed, in a UK context, in Environment Agency (2026). While rainfall depths can be adjusted for projected future climate change (for example (Environment Agency, 2022), these adjustments are provided for return periods of 30 years and 100 years. No information is available on what adjustments might apply for more extreme events, typically relevant to dam safety.

Similarly, the method for estimating PMP (and hence PMF) does not include any allowance for climate change impacts, as noted in Atkins (2013). Phase 1 of the review of PMP and PMF estimation developed a plan for the research needed to address this knowledge gap (Environment Agency, 2025a).

Scaling factors for extreme rainfall

One response to the uncertainty mentioned earlier has been to introduce relatively simple scaling factors for extreme rainfall depths in dam safety assessments. In Colorado there is a recommendation to increase rainfall depth estimates used in dam safety work (up to the PMP) by 7%. This is to account for expected increases in temperature and associated increases in atmospheric moisture availability over 2020 to 2070 (McCormick and others, 2020). See further discussion in subsection “Physical understanding and modelling of extreme precipitation events” below.

In Australia, Ho, O'Shea, Wasko, Nathan, & Sharma (2024) recommend increasing design storm depths across the whole range of probabilities, up to the PMP. They specify change factors as 8% per °C increase in global temperature relative to a 1961-1990 baseline. This is for rainfall durations longer than 24 hours. For shorter durations, higher changes are recommended. In the current edition of Australian Rainfall and Runoff, Ball, et al. (2024) also recommend the same change factors for applications outside dam safety.

One advantage of the Australian approach is that it can easily be adjusted to apply to any baseline period. This means that the change factor can be tailored to the baseline period spanned by the observed rainfall data on which the frequency analysis has been based. It allows for past as well as future change in rainfall.

Physical understanding and modelling of extreme precipitation events

The scaling factors mentioned above are based on well-established physical principles. An increase in precipitation extremes of approximately 7% per 1°C increase in near-surface atmospheric temperatures is consistent with a physical law known as the Clausius–Clapeyron relation. This is a thermodynamic relationship where a warmer atmosphere can hold more moisture.

An important finding in the scientific literature over recent years is that the intensification of rainfall extremes in the mid-latitudes and tropics appears to be stronger than this so-called “Clausius–Clapeyron scaling”. Da Silva & Haerter (2025) found that this is largely due to changes in the structure and behaviour of storm systems over Europe. A combination of the intensification of both convective and stratiform types of precipitation within the meso-scale storm systems that dominate the generation of extreme rainfall over Europe explain this apparent “super-Clausius–Clapeyron scaling.” Plainly, both intense local downpours and broader areas of sustained rainfall are becoming stronger within the weather systems that produce the most severe rainfall events. Together, these changes increased some short-duration extreme rainfall events at almost twice the rate that would be expected from temperature increases alone. The combined effect was found to have produced intensification of 5-year return period rainfalls at nearly double the Clausius–Clapeyron scaling for durations between 15 and 60 minutes and dew point temperatures of 10-15 °C.

Although this work examined rainfall at less extreme levels than required for dam safety, the findings point to a general recommendation to focus attention on understanding the spatial organisation of storms and the partitioning of extreme rainfalls into convective and stratiform contributions. The partitioning differs between seasons, and so intensification with climate change can be expected to occur at different rates in different seasons. Such seasonal changes have been a source of uncertainty even in recent climate models (Kendon, et al., 2020).

Potential of high-resolution climate modelling in the UK

There has been progress towards reducing the uncertainty of the impacts of climate change on extreme rainfall in the UK. This is thanks to the UKCP Local climate model outputs (Environment Agency, 2026 (due date)). These come from a very high resolution (2.2km) climate model. It can resolve the effect of atmospheric convection, known as a convection-permitting model, (CPM). When released, this was the first time that a climate model at a spatial resolution on a par with operational weather forecast models was made for national climate scenarios. It provides hourly outputs.

The UKCP Local dataset consists of a set or ‘ensemble’ of 12 CPM simulations representing climate conditions during the period 1980-2080. Each simulation represents a plausible realisation of the past, present, and future climate. The ensemble members differ due to natural climate variability and uncertainty in the physics of the driving global model. An additional four simulations were made available in 2024, which use the same CPM but driven by four different global climate models. This allows for the estimation of uncertainty due to differences in the driving models. Ensemble results are valuable for enabling adaptive planning of dam design and management. Quantification of risk and uncertainty is vital for this (International Commission on Large Dams, 2025) (World Bank, 2021).

Outputs from UKCP Local have been used to develop uplifts for rainfall depths. This has been used for flood management and drainage design in all four UK nations. For example, in Environment Agency (2022). Some are still in the process of being released to practitioners (Environment Agency, 2026 (due date)). The translation to uplifts was carried out within the FUTURE-DRAINAGE project. This used a coarser 5km gridded version of the UKCP Local results (Chan, et al., 2023).

Moving beyond the ‘design event’ and ‘uplift’ concepts

Uplifts to rainfall depths do not consider the impact of climate change on the temporal sequencing or spatial pattern of rainfall. This is expected to be relevant to some reservoirs. Especially, flood storage reservoirs which may not have emptied from one event before the next arrives. Some UK reservoirs with large catchments or small outlet capacities can be sensitive to rainfall over multi-day periods. The temporal pattern of the rainfall can significantly influence the magnitude of peak water levels. UKCP Local contains information that could be mined to help address this knowledge gap.

The concept of the ‘design event’ or ‘design flood’, is widespread in flood management and infrastructure design. It has long been criticised for its overly narrow focus. A recent research briefing, in the context of nuclear regulation (Sayers, 2024), points out that a focus on single extreme events may not provide a robust safety case. It promotes a broader understanding that focuses on the outcome performance rather than input loads. It suggests considering sequences (uncorrelated) or clusters (correlated) of storms. Individual occurrences may not be particularly large, but they may pose the most significant safety risk.

A recent update to Australian Rainfall and Runoff (Ball, et al., 2024) acknowledged the impact of climate change on temporal and spatial rainfall patterns. However, it did not recommend any universal changes to design practice. See also ANCOLD (Ho, et al., 2024), which found that changes in rainfall depth have a larger impact on dam safety than changes in profiles.

The continuing advances in scientific understanding of extreme weather events mean that model outputs applied for dam safety hazard assessment are effectively part of a wider experimental framework. It points to a need for scientific “scaffolding” to support the use and evolution of models in practice. This point has been raised about applications of numerical weather prediction for dam safety by (Mahoney, et al., (2022). They explored the benefits of moving beyond the simple “uplift” approach. Instead, suggested moving towards modelling plausible extrapolations of storm events. They concluded that “going forward, dynamical model approaches to simulating historical storms for applications such as PMP should establish”, in advance, “a more structured and exhaustive experimental design, which includes clear standards for the governance of possible application of model results”.

A current research project, FUTURE-FLOOD, is aiming to provide a more comprehensive picture of the impact of climate change on flood hazard. It moves beyond the confines of the uplift approach. It is introduced in the following section.

Remaining knowledge gaps

There are some remaining knowledge gaps which the rainfall uplifts provided to practitioners in the UK do not address. These include:

- potential variation of uplifts with event severity, of obvious relevance to dam safety
- in the extreme, what uplifts to apply, if any, for the PMP (Environment Agency, 2025a)
- variation of uplifts with rainfall event duration. The FUTURE DRAINAGE project only considered durations up to 24 hours, since its primary focus was urban drainage
- seasonal variation of uplifts
- impact of climate change on the temporal sequencing or spatial pattern of rainfall, not captured by the uplifts approach. Assessing the effect of such changes on dam safety would require a move beyond the limitations of the current ‘design event’ methods for hydrological assessment
- lack of UKCP Local outputs for greenhouse gas emission scenarios other than the high-end pathway, RCP8.5. This creates a gap in the knowledge of impacts of less extreme scenarios. This is relevant given uncertainty over future emissions and the description by some authors of RCP8.5 as implausibly high (Burgess, et al., 2021)
- guidance on how to understand and allow for uncertainty when investigating climate change impacts. This is particularly important for high-hazard infrastructure, like some dams. Testing the 'median' scenario may not give an adequate understanding of the critical loading conditions
- unknown aspects of model uncertainty. For example, all UKCP Local ensembles are from the same CPM
- the presence of some unrealistic artefacts that have been detected in the UKCP Local simulations (MET Office Hadley Centre, 2024). They typically appear as linear rainfall features aligned with the climate model grid. These can affect estimates of present-day extreme rainfall and future changes. The Met Office has advised using the re-gridded 5km data, which is less affected by the issue, in preference to the

2km data. A drawback of the 5km data is that it tends to smooth out local extreme rainfalls. This issue is most likely to affect assessments for reservoirs with small catchments
- the need to account for the impacts of climate change that have already occurred, as well as future change
- impacts of climate change on snow accumulation and snowmelt. Particularly of relevance to PMF estimation (briefly reviewed in Environment Agency (2025a).

4.6.2. Reservoir safety - floods

Overview of issues

Impacts of climate change on extreme rainfall (and, where relevant, snowmelt) need to be translated into impacts on reservoirs during flood conditions. This requires consideration of other impact pathways such as changes in:

- catchment soil moisture (for example caused by increased evaporation at higher temperatures)
- runoff processes (for example if climate change impacts vegetation or decisions on land management)
- wave overtopping (for example due to increases in wind strength)
- blockage of outlet structures by debris (for example trees)
- slope stability in the dam embankment
- slope stability in the catchment of the reservoir, where slope failures could lead to diversion of watercourses into the catchment
- slope stability directly above the reservoir, where slope failures could lead to material falling into the reservoir and displacing water so that it overtops the dam (Fluixá-Sanmartín, et al., 2018). This was the cause of the Vajont Dam incident, Italy, in 1963, in which 50 million m3 of water overtopped the dam

Most of these topics are covered in Atkins (2013). It is possible that some will be secondary issues compared with the impact of climate change on rainfall depths. Ho, O'Shea, Wasko, Nathan, & Sharma (2024) found that, for a sample of 18 dams in Australia, changes in soil moisture (and hence rainfall losses) often resulted in a slight decrease in the risk of dam overtopping. This was swamped by the large increase due to increased storm depths.

The FUTURE-FLOOD project is investigating the combined impact of changes in rainfall characteristics and soil moisture. This project led by the University of Bristol and funded by NERC. It aims to increase our understanding of future flood risk and provide new flood estimates across the UK that improve current uplift approaches. This reflects earlier work funded by NERC on the importance of changing spatial structures and seasonality (Sayers, et al., 2024). It focuses on fluvial, surface water and coastal flooding, not reservoir safety. The approach is to use the full space-time varying precipitation fields from the UKCP Local simulations to drive hydrological and flood models. This produces flood projections continuously over 100 years. This allows for the effects of more complex changes to be captured. It accounts for the effect of changes in storm sequencing and temporal clustering. Results will be compared to those using the standard uplift approach. A pilot study showed a markedly larger increase in future surface water flood hazard, when compared to the uplift approach (Archer, et al., 2024). Results from AquaCAT are already published and those from FUTURE-FLOOD are expected to become available in 2026-27. It will take some time to translate the findings into operational tools or guidance suitable for practitioners to apply.

It is important to assess the combined effect of climate change on reservoir safety by integrating all aspects. Their interdependencies should be considered. It is not simply an accumulation of separate impacts (Fluixá-Sanmartín, et al., 2018)

Remaining knowledge gaps

Knowledge gaps associated with the impact pathways listed above should be understood in the context of a general lack of knowledge about flood generation processes in extreme conditions. Even in the absence of climate change. The review of PMP and PMF estimation (Environment Agency, 2025a) sets out proposals to improve our ability to model how flood generation processes alter in extreme conditions.

The likelihood and consequence of some of the impacts listed above are difficult to quantify. Screening and sensitivity tests (for example, of catchment topography and land use) may help to assess risk qualitatively. Atkins (2013) suggests some questions to ask as part of screening.

Little information was found in the literature on the impacts of climate change on wave overtopping. This could be quantified using the UKCP Local model results, which include wind strength.

4.6.3. Reservoir safety - structural aspects

This section deals with research on the impacts of climate change on aspects of the structural safety of dams. This includes slope stability, the condition of concrete and the operation of outlets. All of these were covered in Atkins (2013) and none was identified as a particular knowledge gap. However, the scope of this report is to review research on the implications of climate change for earth embankment dams.

As well as the Toddbrook Reservoir incident, other international incidents have focused attention on a possible increased risk of embankment dam failure due to climate change. These include the overflowing of the Steinbach Reservoir in North Rhine-Westphalia following the storm of July 2021 (Aufleger & Kafashan, 2025). Actual inflows significantly exceeded design assumptions. Overflowing of the dam crest led to severe erosion on the downstream slope, bringing the structure to the brink of failure. A failure occurred at the

Derna Dam in Libya, September 2023 (Aufleger & Kafashan, 2025). It led to thousands of deaths. Some spillway types are inherently more vulnerable to increases in hazard loading. For example, closed conduits such as bell-mouth spillways. These were at the Derna dams (Aufleger & Kafashan, 2025).

(Fluixá-Sanmartín, et al., 2018) reviewed the impacts of climate change on structural aspects of reservoir safety. Most of the references they cite pre-date 2013 and so were available at the time of the Atkins (2013) review. Examples of issues they cover include:

- reductions in soil moisture, both directly due to weather at the dam site and indirectly due to reduction in stored water levels
- consequent increase in the coefficient of piping erosion
- consequent changes in vegetation on downstream face of dam. This leads to changes in both internal and overtopping erodibility
- greater erosion leading to more abrasion of spillway gates
- increased risk of blockage by debris
- extreme temperatures, or fluctuations in temperature, affecting gate operation
- concrete structural behaviour being sensitive to changes in temperature or solar radiation

Preziosi & Micic (2014) present a methodology for risk classification of small homogeneous earthfill embankment dams integrating climate change projections. Rainfall rates for UK conditions were fed into a probabilistic slope stability model. The model considers only changes in slope failure due to changes in infiltration. it does not consider the influence of overtopping or piping erosion. The paper focuses on the methodology rather than its application or results.

Ongoing research into the impacts of climate change on the stability of long linear embankment assets may provide insights into asset performance and deterioration that are relevant to UK reservoirs. Assets like railway and highway embankments. An example is the ACHILLES Programme. However, consideration must be given to the material composition of the embankments studied. These may not be representative for many dams, for example studies of highway embankments constructed from sands or silts (Baninajarian, et al., 2019).

It seems likely that climate change is impacting the structural safety of dams, including earth embankment dams, by increasing the probability of overtopping or overflowing. This is via the changes in flood conditions reviewed in the preceding sections. Beyond this, the review did not identify additional knowledge gaps in the impact of climate change on the safety of reservoir structures. However, it is worth quoting this important acknowledgement of the limits of our knowledge. "The assignation of probabilities to uncertain future conditions and scenarios remains a major challenge and thus the management of dam safety based on climate change impacts must take into account these limitations" (Fluixá-Sanmartín, et al., 2018)

4.6.4. Reservoir safety - impact on demand or operations

Climate change is increasing the demand for water on hotter days, for purposes such as domestic supply, irrigation and cooling. It is also changing the distribution and timing of rainfall, with drier summers. These climate impacts are a factor that has led to the current programme of strategic water resource development in England (Environment Agency, 2025b). This includes development of 10 new reservoirs and 1 enlarged reservoir through the 2020s and 2030s. There is also an increasing demand for farm reservoir construction. This will help smooth out the increased seasonal extremes of weather.

This major programme of reservoir construction creates an opportunity to address reservoir safety at the design stage. Use of contemporary approaches would allow for the current and projected future impacts of climate change on all aspects of dam safety. Most of the planned strategic water supply reservoirs (listed in Environment Agency (2024)) are offline. This means water is diverted or pumped into them from rivers or spring sources. Similarly, farm reservoirs for irrigation are often offline. This configuration changes the focus of dam safety, with little or no need to provide capacity for conveyance of floods. However, the structural integrity of the dam embankment remains paramount. They may be very long embankments.

Climate change is also affecting typical reservoir water levels (Fluixá-Sanmartín, et al., 2018) due to changes in:

- precipitation and evaporation
- agricultural land use
- irrigation water demand
- demographic, socioeconomic, and technological changes

Some such changes are more likely to reduce levels in water supply reservoirs. this might benefit dam safety. Others may work in the opposite direction, for example if higher typical water levels precede an extreme flood inflow. This may be more likely to be an issue for dams which are subject to prolonged spillway overflowing. For example, Thirlmere in Cumbria spilled continually for several months in winter 2015-16. Dam safety is already assessed using conservative assumptions of initial water level. It does not seem likely that safety of most dams will be compromised by such impacts.

The way in which FSRs operate appears to be changing. In the UK, FSRs have been found to be filling and spilling more often than their design standard (Mergen, et al., 2021). The change is said to be consistent with guidance indicating a typical 30% increase in peak flows and flood volumes. However, the 30% change factor quoted in the paper is for the 2080s. More frequent filling of FSRs could impact dam safety. For instance by increasing the chance of an extreme flood arriving while a FSR has not yet emptied from a previous event. It may impact the stability of earth embankments.

4.6.5. Reservoir safety – other aspects

We identified other aspects of climate change impacts on reservoir safety during the review.

A publication from Sweden, (Brandesten, 2023) mentions the impact of forest fires. It cites an example that caused problems with access to the dam and power being cut off. This could be relevant in the UK situation with increasing prevalence of wildfires. Atkins (2013) covered other aspects of wildfire risk. The ongoing project on climate change impacts by CEATI, mentioned earlier, is also considering wildfire risk.

Preziosi & Micic (2014) mention increasing interest from UK insurers on impact of extreme weather on dam failure. It also highlights importance of understanding impacts on small reservoirs that were previously outside the provisions of the Reservoirs Act.

4.7. Future directions

4.7.1. Artificial Intelligence

The Atkins (2013) report does not contain any reference to the terms “artificial intelligence” or “machine learning”. The past few years have seen an acceleration in the capabilities, uses, impact and societal awareness of AI and related technologies. Although not identified in 2013 as a research gap, it is now reasonable to consider AI in almost any research context, including in reservoir safety.

AI is not one thing, rather it refers to a diversity of systems, tools and techniques. Engineers may be familiar with the underlying techniques of regression models, neural networks or statistical inference. For many people, the most familiar interaction with modern AI systems may be through chatbots that rely on Large Language Models (LLM). These services, such as ChatGPT or Gemini, comprise of a foundation layer for generating text. It is built into a pipeline designed to shape outputs to meet design aims such as:

- relevance
- ethical alignment
- accuracy

- computational efficiency

Most aspects of the pipeline are effectively invisible to most users. The underlying LLM is, in effect, a highly compressed, although still huge, representation of even greater volumes of natural language data. It was originally sourced from human-authored content.

The process of modelling the data is called Machine Learning (ML). Underpinning ML are the fundamentals of statistical learning and mathematics. Large Language Models are not the only use of ML. Many ML-based models are appearing in scientific and engineering fields, including in prediction of climate and weather extremes (Camps-Valls, et al., 2025).

In scoping future research, there are three areas in which AI should be considered, as set out in the following sections.

4.7.2. Machine learning for hazard analysis

Machine learning models of climate and weather are now available and can be used for weather forecasts (Price, et al., 2025). They can generate large ensembles of regional weather sequences ((Mahesh, et al., 2025) for flood risk analysis (Ashcroft, et al., 2025). Models like this are capable of generating realistic simulations over the sub-seasonal to seasonal time scales (3-12 months) (Karlbauer, et al., 2024). This highlights the potential to use them to test resilience against the cumulative effects of sequences of storm events. ML can also be applied to climate downscaling, where Kendon and others (2025) found it has promise in the next 5-10 years for use in the production of local climate projection information.

ML models have great flexibility to learn patterns from large quantities of data. This enables them to reproduce those patterns convincingly. This is like when a chatbot responds to a prompt with a coherent natural language response. However, this statistical learning comes with no automatic guarantees that the model embodies physical relationships. For example, with the Clausius-Clapeyron relation mentioned earlier. Even in basic physical principles like conservation of mass and energy. Hence, there is a risk that ML models may perform well when used within the range of variability seen in their training data, but fail, and fail unpredictably, when extrapolated to more extreme scenarios. This is an obvious concern with respect to the use of ML for very extreme events considered in reservoir safety. It motivates research into the development of physics-informed ML (Raissi, et al., 2019) (Sharma, et al., 2023). Several approaches have been proposed to embed knowledge of the physics of dynamical systems into ML which aim to produce more robust models. Machine learning relies on data. The ownership, accessibility, long-term retention and updating of training data are issues to be considered in relation to the potential adoption of ML-based hazard modelling.

4.7.3. Machine Learning for dam health monitoring and modelling

A second area of research in ML concerns the monitoring and modelling of physical assets, including dams. Deng, et al. (2025) reviewed applications of ML in dam health monitoring. They found 13 studies published between 2019 and 2024 on dam deformation monitoring, and 26 on dam seepage. Cited applications involved a wide range of ML techniques. Recommendations for research included:

- recovery of missing data from sensor networks
- better detection and interpretation of outliers in monitoring data
- relationships between temperature changes and seepage
- integration of multi-modal data sets
- explainability of neural network models
- automated damage identification.

The applications of ML for dam safety research include its use to assess changes or trends in hydro-climatological parameters. It enables ML to be used for the assessment of climate impacts on dam seepage. Ishfaque, et al. (2023) demonstrated this at the Tarbela dam in Pakistan.

As with applications for weather and climate modelling, any ML model is defined by the data it was trained on. This raises similar questions about robustness if models are generalised to conditions unseen during training. This applies to ML models of dams, as discussed by (Liu, et al., 2025). They developed an effective ML model for predicting displacement of a concrete gravity dam and noted sensitivity to temperature. They concluded that ML models should be tested for robustness across varied temperature scenarios.

4.7.4. Machine Learning for operational rules

Reinforcement learning (RL) (Bishop, 2006) is a key paradigm in ML that is suited to the discovery of operational rules. In RL, an “agent” acts as a decision-maker, learning an optimal policy that determines which actions to take in an environment. The environment can be either a real, monitored system, or a simulation. A classic example of RL is training an agent to learn how to play a video game. As such, it has attracted considerable attention for applications in water resources management. This includes the regulation of reservoirs.

A recent review (Kage, et al., 2025) found that RL is a viable approach to learn optimal sequential decision-making policies in water management. Most applications have trained the RL algorithms in simulated environments. The authors recommended a focus on improving the explainability of the decision-making process. This is particularly important for safety-critical applications.

As before, the caveats about extrapolation beyond training data are relevant. There is a research need to test the robustness of RL in the context of simulated climate scenarios.

4.8. Conclusions

4.8.1. Updated assessment of knowledge gaps identified in 2013

Section 4.5.2 mentioned four knowledge gaps identified by Atkins (2013):

- impact of climate change on estimation of the PMF
- limited ability for climate models to simulate extreme rainfall, hence impact of climate change on design floods for reservoir safety
- uncertain changes in summertime extreme rainfall
- uncertainty over impact on frequency of floods (affecting spillway operation and the filling of flood storage reservoirs)

From the material in Appendix A we can conclude that:

- (1) remains a knowledge gap although Phase 1 of the review of PMP and PMF estimation has developed a plan for the research needed to address this knowledge gap
- (2) and (3) have seen major steps forward since 2013 thanks to the release of the UKCP Local rainfall scenarios. While there has been some work to translate these into hydrological impacts, there are opportunities to do more, as identified in section 3.3.2, to align with advances in scientific understanding of the physical processes that influence extreme weather events
- (4) is being addressed by the current FUTURE-FLOOD project

4.8.2. Summary of remaining knowledge gaps

Combining the above with additional gaps identified during this review, we summarise remaining gaps in knowledge of the impact of climate change on reservoir safety:

- variation of climate change impacts on rainfall with event severity (including up to the PMF); rainfall duration or seasonality
- impact of climate change on the temporal sequencing or spatial pattern of rainfall, not captured by the uplifts approach. Assessing the effect of such changes on dam safety would require a move beyond the limitations of the current 'design event' methods for hydrological assessment
- impacts on snow accumulation and snowmelt, of relevance to PMF estimation

- translation of the above meteorological effects into hydrological impacts on extreme flood inflows to reservoirs. This should include potential changes in runoff generation processes
- impacts on wave overtopping at dams via changes in wind strength or direction
- the need to account for the impacts of climate change that have already occurred, as well as future change
- limitations of the UKCP Local climate model. This underpins both the currently-applied uplifts for rainfall and flood flows, and current research such as FUTURE-FLOOD. These include:
- limitation to a single greenhouse gas emission scenario, with very high emissions (RCP8.5)
- lack of information about uncertainty associated with the structure and parameterisation of the convection-permitting model
- presence of some unrealistic rainfall artefacts in the output
- guidance on how to understand and allow for uncertainty when investigating climate change impacts on dams and other high-hazard infrastructure. This includes the impacts of changes to operation and the impacts of structures operating beyond their design standards or design life.

These knowledge gaps should be understood in the context of a general lack of knowledge about flood generation processes in extreme conditions. This concept applies even without climate change. While some of the gaps could be addressed using model outputs that are readily available, others may require more in-depth research. It would then need follow-up translation into policies and guidance that meet the needs of industry.

Some relevant research is already underway. In particular, the FUTURE-FLOOD project. This aims to provide new flood estimates across the UK that improve upon current uplift approaches. It allows for changes in storm sequencing and temporal clustering. The scope of FUTURE-FLOOD does not include reservoir safety. Its simulation length is limited to 100 years. Nevertheless, its outputs may provide some useful information on extreme events of relevance to dam safety.

5. Consultation

5.1. Approach

We consulted with those working within the reservoir industry. This was to ensure that the priorities within the new strategy reflect those of the industry. The aim of consulting was to establish topics that are a priority for future research. We also wanted to facilitate improved collaboration between industry, academic institutions and specialists.

We conducted a survey and ran a series of workshops. They included:

- academia
- supervising panel engineers
- owners and undertakers
- inspecting engineers
- ReSRAG

Common themes identified throughout the consultation process include:

- funding constraints
- climate change
- monitoring and measurement
- grass embankments
- skills shortages
- communication and relationships
- technology
- policy
- regulation and standards
- risk management

The following sections summarise the key findings from each of these consultations. Detailed workshop summaries are available on request.

5.2. Industry feedback on previous strategy

As part of the development of the strategy, we issued a survey to gather feedback on:

- the previous (2016) strategy
- perceptions of research delivery and dissemination
- views on future research priorities

We issued the Microsoft Forms survey via email on 29 July 2025 and it closed on 15 August 2025. We received a total of 21 responses. They came from a broad cross-section of professionals working within the reservoir safety sector. This included:

- academics
- consultants
- enforcement authority representatives
- government officials
- ICOLD (International Commission on Large dams) representatives
- panel engineers
- reservoir undertakers

The survey formed one element of the wider consultation process. It intended to provide high-level insight to help set the context for the new strategy, rather than to capture a comprehensive range of views. The key findings are summarised below.

5.2.1. Awareness and Understanding of the 2016 Strategy

Levels of familiarity with the 2016 Strategy (Environment Agency, 2016) varied considerably. While a small number were involved in its original development, or were broadly aware of its purpose, others reported limited or no familiarity. The 2016 strategy was developed as a supporting document for ReSRAG. This may explain why the awareness of the strategy's objectives and intended outcomes is currently limited across the sector. Awareness will also be affected by a decline in interest over time. It may also be that awareness was not widely established at the outset. This indicates a need for greater sector-wide visibility for future strategies.

5.2.2. Delivery against objectives

Most respondents felt that the 2016 strategy (Environment Agency, 2016) had partially delivered against its objectives. Comments reflected a general sense that progress had been made, but that the full extent of delivery was difficult to gauge. This was due to the lack of clear reporting and communication of outcomes. Some expressed uncertainty over whether the objectives were ever fully measurable.

5.2.3. Research outputs and dissemination

Respondents were predominantly panel engineers. They generally agreed that the 2016 strategy (Environment Agency, 2016) had contributed to the production of relevant research. Examples cited included work on valves, conduits, and grouting. However, there was inconsistency in awareness. Several participants stated they were unaware of any specific outputs.

Views on dissemination were mixed:

- some respondents felt that research had been shared effectively. This was through the BDS, conferences, and publications
- others noted poor visibility. They suggested that existing outputs had not reached the wider practitioner community
- many suggested improved communication, particularly in accessible formats. Open and public publication should be encouraged where possible. This allows accessible outputs for all stakeholders

5.2.4. Drivers for future reservoir safety research

Respondents identified several key drivers for research and development over the next 30 years:

- the **financial and wellbeing impacts** of reservoir failures. Likely due to lack of expert availability and resources. 90% of respondents mentioned funding as a key driver
- **climate change**. For example, the increasing frequency of extreme weather and its implications for reservoir design and operation
- **learning from incidents**. Particularly following Toddbrook, and embedding those lessons into ongoing practice
- the need for **resilience and sustainability** in the context of changing environmental and societal pressures. This is due to legislation change and skills shortage

5.2.5. Barriers to research and development

The most significant barriers identified were:

- limited funding and financial constraints
- availability of technical expertise and time from specialists
- a perceived lack of industry-wide coordination and engagement in research activities

Respondents noted that while enthusiasm exists within the sector, there is limited resources and financial incentives to participate. Feedback on these barriers was consistent across the range of respondent types. It did not appear to be specific to any single group, organisation or role within the reservoir safety sector.

5.2.6. Priority research areas and themes

Commonly suggested areas for future focus included:

- risk assessment, internal erosion, and unexpected failure mechanisms
- climate resilience and adaptation to changing conditions
- operational and maintenance guidance, particularly for smaller reservoirs and owners with fewer resources
- simplification of risk analysis approaches, making tools and methodologies more accessible and proportionate
- improved surveillance and emergency planning for small dam owners

These themes reflect a desire for both technical innovation and practical guidance.

5.2.7. Awareness of ongoing or planned research

Awareness of current or planned research activity is limited.

A few respondents referenced ongoing Environment Agency projects. In particular, the PMF estimation work (Environment Agency, 2025a). Most were unaware of specific initiatives. This indicates a need for a clearer mechanism to share information about active research across organisations.

5.2.8. Willingness to engage further

Most respondents expressed a willingness to contribute to further discussions or collaborative activities related to the development of the new strategy. This indicates a strong appetite within the sector for more coordinated and transparent research planning and delivery.

5.3. Workshop 1 - research community

5.3.1. Workshop format

We held 2 identical workshop sessions for academics specialising in reservoir topics. These were online via MS Teams on Tuesday 7th October 2025. Each followed the same format with the same objectives:

- highlight current and desired research topics
- establish priority topics for future reservoir research
- discuss research problems and challenges
- identify opportunities to improve collaboration between the reservoir industry and academia

5.3.2. Attendance

Stakeholders invited to the workshop included 33 academics and members of ReSRAG. 10 delegates, of the 33 invited, attended the workshop, in addition to the project team.

5.3.3. Workshop structure

The workshops included the following elements:

- an introduction to the project
- three virtual breakout rooms to explore the following key areas reflecting the objectives set out above, along with priorities and timescales:
    - what are the future research priorities and who needs to be involved?
    - name current reservoir research topics that are being undertaken and who is involved in the research? Are there additional parties who are needed to support research progress?

    - what are the current challenges and problems being experienced in reservoir research? Who needs to be involved to help address these challenges?

- post breakout room feedback covering:
    - what are the consistent topics identified?
    - what are the key links between different organisations and groups to support research efforts?
    - is there anything else that has been missed?

5.3.4. Workshop outputs

Future research: short-term priorities (0 to 5 years)

Short term priorities should focus on addressing immediate gaps in:

- risk management
- consequence assessments
- operational practice

A particular priority should be to better understand risks relating to ageing and deteriorating reservoir structures. Enhancements to consequence assessments are required. These include the incorporation of non-life loss impacts. For example:

- effects on the environment and heritage assets
- recognising the benefits reservoirs provide

Monitoring and measurement emerged as a key theme. There was an emphasis on identifying visual indicators of stress on dams. There are opportunities to use technology and citizen science to widen monitoring and data capture techniques. Stronger relationships and improved communication are required across the industry. In particular, with non-technical audiences and small and single reservoir owners.

A priority area for technology development is to improve ML and to use advanced technology. Future research must be:

- UK relevant
- problem led
- better coordinated

Particular focus should be on:

- erosion protection
- grass embankments
- climate change
- ageing assets

Future research: medium-term priorities (5 to 10 years)

Priorities include:

- wider application of machine learning
- improved threshold triggers
- new monitoring techniques

Research should focus on predicting and understanding asset condition, dam deterioration rates, erodibility, breach, and associated costs. Continued upskilling of those working in the reservoir industry remains essential.

Future research long-term priorities (10+ years)

Long-term priorities focus on adapting to climate change and monitoring how assets respond to these evolving conditions. There is a need to review whether current policies, standards and regulations remain fit for purpose. Research should explore opportunities for reoperation, repurposing, or removal of dams. It should also consider social, environmental, and recreational factors.

Collaboration between technical experts, commercial organisations and key industry sectors will be essential. Consulting with stakeholders including local communities, farmers, asset owners and operators is important.

Current research – key priorities

Current research activity covers a wide range of technical, operational, and strategic themes. A significant focus is on erosion. In particular soil performance, erosion testing and modelling. Also, the role of vegetation and environmental stressors such as wildfire.

Research relating to design and operation includes:

- ICOLD bulletins
- pumped storage hydropower design
- dynamic loading assessments
- dam modification strategies
- improved data management and training for engineers
- Investment planning and asset management research aims to improve understanding and prediction of asset condition

Climate related triggers and catchment management research includes the development of an asset management tool for owners. We are leading risk management research and several international collaborations. Themes include breach prediction, wave wall research, and the use of AI.

Those involved in current research include reservoir panel engineers, subject specialists, universities and infrastructure operators.

Short-term challenges (0 to 5 years)

In the short term, funding is known to be a major challenge. Public funding is limited and stronger collaboration between industry, government, and research councils is required.

Translating research into clear, actionable guidance is essential. This will inform future policy, regulation, and standards. Early and consistent engagement with regulators is critical. This will ensure research outputs meet user needs and are embedded into policy and practice. Short term planning cycles also present challenges over a long period of time.

Data and information management practices are inconsistent across the sector. Challenges include:

- restrictions on sharing commercially sensitive data
- limited UK-specific data
- fragmented data ownership

These issues present opportunities to improve efficiency and coordination.

- Risk management challenges include:
- uncertainty associated with ageing dams
- the concentration of risk among major owners
- the need to effectively communicate risks to all those affected
- The complexity of reservoir ownership can result in engagement and communication challenges

Additional challenges relate to:

- climate change and the impact of extreme events
- skills shortages
- the importance of the right skills sets
- making the best use of technology

Medium-term challenges (5 to 10 years)

Funding remains the main challenge for reservoir research in the medium term.

Long-term challenges (10+ years)

In the long term, funding continues to be identified as a significant challenge alongside climate change and associated water resource implications.

Developing a pipeline of new engineers, supported by training and experienced professionals, will be critical. Organisations central to addressing these challenges include research bodies, water industry, Government and European working groups.

5.4. Workshop 2 – practitioners, owners and undertakers

We held 2 workshops online via MS Teams on Tuesday 9th December 2025. One for reservoir supervising panel engineers and one for reservoir owners and undertakers. Both workshops had the same objectives:

- identify specific design, inspection and operational issues currently being experienced
- highlight specific problems anticipated in the future
- establish underlying causes of these challenges
- highlight potential ways to address the challenges
- understand how future research could better support practitioners working in the field

5.4.1. Attendance

All members of the supervising engineers panel for reservoirs were invited to take part in the morning workshop. 41 supervising engineers (27% of total panel membership) attended, in addition to the project team.

Reservoir owners and undertakers were invited to take part in the afternoon workshop. Members of the Major reservoir owners group (MROG) and the Single Reservoirs Owners Group (SROG) were invited. 12 delegates (8 SROG, 1 SROG facilitator, 2 MROG and 1 local authority member) and attended in addition to the project team.

5.4.2. Workshop structure

The workshops included the following elements to align with project objectives:

- an introduction to the project
- virtual breakout rooms to explore current and future challenges relating to reservoir design, inspection and operational issues
- post breakout room feedback to identify key themes
- share key themes identified at the academic workshop and inspecting engineers forum

5.4.3. Workshop outputs - reservoir supervising panel engineers

Reservoir design, inspection, and operation - current challenges

Responders identified a wide range of challenges relating to reservoir design, inspection and operation. Climate change is placing increased pressure on existing reservoirs. There is more frequent extreme weather, higher water levels, and increased use beyond original design assumptions. There is an urgent need to update outdated guidance, models, and specifications to ensure future resilience.

Grass embankments is an area of significant concern. In particular:

- repairs
- maintenance
- grass management

Additional dam design challenges include:

- outdated standards for embankment design and fill materials;
- a lack of clarity around wave overtopping limits
- the carbon impact of reservoir construction

Further guidance is required to address issues such as vandalism at remote sites, grass cover, masonry spillways and internal erosion.

- challenges associated with flood storage reservoirs include:
- understanding the impact of multiple storm events
- ensuring risk management and handover requirements
- the growing importance of ecology, invasive species, and biodiversity
- opportunities to develop guidance

Funding remains a key challenge. There is limited grant support for private owners. There are challenges with inherited or orphaned assets. Procurement and investment cycles is currently inefficient. Many owners, particularly private or small owners, lack sufficient funding, resources or expertise. They may not be fully aware of their obligations.

Data gaps and outdated assumptions reduce confidence in existing datasets. This is often due to non-bespoke risk models and inappropriate mapping methods.

Challenges persist in relation to skills, communication, research, and technology. There are clear gaps with a lack of:

- supervising engineer availability
- training and recruitment for new engineers

There are opportunities to improve engagement. In particular, with reservoir owners and operators, regulators and the public. New technologies offer potential efficiencies, however there is currently a lack of guidance on how to utilise them.

Reservoir design, inspection, and operation – future challenges

Climate change will continue to be a major challenge. It will place increasing strain on ageing infrastructure. Uncertainty around future conditions may further reduce confidence in existing data, models and standards. This highlights the need for:

- more resilient and adaptive design guidance
- agile research approaches

Future dam design should increasingly focus on controlling how a dam would fail, rather than whether it would fail. Clarification is required regarding acceptable construction materials. Clear guidance is needed on ecological and biodiversity considerations in relation to reservoir testing and monitoring.

Pressures on inspection and maintenance requirements are expected to increase. This is due to:

- shortages of qualified engineers
- the reclassification of reservoir size
- greater reliance on private owners with limited technical capability

Policy, regulatory and standards frameworks may face growing strain. If legislation becomes more risk-based, additional guidance will be needed. It will need to manage conflicting statutory, contractual, planning, and environmental requirements. This highlights the need for clearer, more flexible guidance that can adapt to future legislative change without a reform of the Reservoirs Act.

Effective relationships and communication will become increasingly important. Public access, social value, and social media influence will grow. This creates challenges around misinformation, public safety, and risk perception. We will need better approaches to public engagement, societal risk assessment, and learning from other engineering sectors.

There are significant risk management issues. These include:

- assessing ageing earthworks
- researching fatality rates
- planning permission requirements
- vandalism and terrorism
- lowering thresholds
- orphaned reservoirs
- breach modelling equations
- internal erosion

- standards guidance

Emerging technologies may support remote monitoring and inspection. Future water resilience will require balancing water availability with owners intentions to discontinue reservoirs.

5.4.4. Workshop outputs - reservoir owners and undertakers

Reservoir design, inspection, and operation – current challenges

Funding was identified as a major challenge. Lengthy timescales for dam safety reports delay funding decisions.

Annual inspection requirements place a disproportionate burden on small owners. They often struggle to access affordable contractors, suppliers, and engineers. Limited availability of contractors and panel engineers, combined with high costs for minor works, adds to this challenge.

The re-categorisation of reservoirs has significant risk management consequences. Participants expressed concern that current thresholds capture many low-risk reservoirs. They don't feel there are sufficient resources to support inspection and enforcement. A more proportionate approach that recognises the different risk profiles of small and large reservoirs is required. This will in turn help with resource to cover inspection requirements.

Respondents highlighted differences between non-impounding and impounding reservoir risk management. This included the need to manage their risk differently. Communication and support for single reservoir owners were identified as key gaps. In particular, in relation to clarity of duties and access to guidance. An increasing shortage of supervising panel engineers continues to impact inspection capacity.

Reservoir design, inspection, and operation – future challenges

Future challenges include:

- the impact of climate change on ageing infrastructure
- the need for more agricultural reservoirs to ensure water security

Several issues relating to dam design were highlighted. For example, increased headroom requirements resulting in increased costs, plastic specifications, and spillway sizing.

Inspection and maintenance requirements may become increasingly difficult to achieve. This may be due to changes in the regulatory threshold. That would require greater flexibility to ensure inspections remain effective and proportionate.

Most existing policy and legislation were developed when there were more engineers. There is a need to future proof regulation, improve risk management transparency and enable engineers to use professional judgement rather than reliance on overly prescriptive requirements.

Research gaps include the implications of the 10,000 m^3 threshold reduction and differences in regulatory approaches across the UK.

The supply of engineers is declining due to a reduced number of university courses and increasing retirement rates. Demand for engineers is expected to increase due to new reservoir construction. It is essential to:

- address succession planning
- broaden panel participation
- upskill owners
- re-focus engineering effort on the most significant risks

5.5. Consultation – reservoir inspecting engineers forum

5.5.1. Consultation format

We asked attendees at the Inspecting Engineers Forum held on Monday 17th November 2025 to share their views on:

- the problems they are currently facing which future research might help to address
- whether they are aware of any ongoing research into fields that would benefit the reservoir safety industry

5.5.2. Consultation outputs

Inspecting engineers highlighted several current challenges and opportunities where future research may help improve reservoir safety. This included the need to update guidance for grass spillway design. It should include updating hydraulic performance of reinforced grass spillway systems.

Risk management concerns include risk designation processes, particularly in relation to critical infrastructure. Additional issues relate to reliance on:

- flood mapping outputs
- erodibility
- seismic guidance
- drawdown guidance.

There are opportunities to review guidance and standards, including the erodibility statements in Section 10 reports and the RFM standard. Inspection and maintenance challenges include:

- the identification of mobile silt in bathymetric surveys
- using this information when determining reservoir capacity

Current research taking place that would benefit reservoir safety includes:

- fatigue induced degradation of cores and shoulders
- the development of UK-specific pumped storage hydropower design guidance

5.6. Consultation – ReSRAG

5.6.1. Consultation format

ReSRAG discussed the delivery of the 2016 strategy at their January 2026 meeting. Specifically, the approach taken and communication back to the industry.

5.6.2. Consultation outputs

ReSRAG agreed that it can feel like a 'closed group' to the wider reservoir industry. There is a requirement to be more transparent about:

- the progress of the strategy
- the themes
- any changing priorities over the strategy delivery programme

They felt that the industry should be challenged more to help deliver the themes within the strategy. Industry experts should support with technical input, review and funding. It was also not widely known that industry professionals can submit potential research ideas for consideration. In this way, changing priorities in the industry can be efficiently captured and included.

A dashboard providing a live update on current projects, trending issues and a portal for new suggestions could be a useful development. They suggested it could be hosted on the BDS website. It would need to be updated after each ReSRAG meeting to ensure that the wider industry is kept up to date with developing themes. This would require resourcing and better cross-industry communication to ensure the list is up to date. Otherwise, it would add little value.

It was agreed that a workshop at each BDS conference (bi-annual) would be valuable. This could review the priorities and consider new drivers. The BDS conference, Supervising Engineer Forum, Inspecting Engineer Forum and BDS annual report should be used to disseminate progress on delivery of the strategy.

ReSRAG could be used to help strengthen the priority and justification of themes. For example:

- scoping the top three themes in detail so they are ready for implementation
- aiding consideration for funding sources
- ensuring no delays when funding became available

It was discussed whether a list of projects could be developed which could be directed towards Ph.D. students. Confirmation of a resource could attract more funding. The academia within ReSRAG reported that Ph.D.'s are now typically funded by industry. A very specific need is usually required. 'Blue sky' Ph.D. programmes are now relatively rare. They also commented that it was becoming increasingly hard to secure Ph.D. students, even when funding is available.

A main problem with successful delivery of projects under the strategy was considered to be the lack of available funding. The strategy allowed proposals to be justified. However, funding and resources required for delivery are not available in time to deliver the need. It was felt that funding is the core issue which needs to be addressed to allow successful delivery of the strategy. A repeated task of prioritising or 'ranking' projects was not considered a beneficial use of the expertise ReSRAG can provide. Instead, the new strategy will focus on identifying priority themes, where projects can be identified and attributed to. It should consider the most significant drivers and opportunities relevant to the specific project.

5.6.3. Funding sources

ReSRAG discussed potential alternative funding sources. They highlighted opportunities for future improvements were highlighted.

1. UK Water Industry Research (UKWIR)
    a. Major water companies invest in UKWIR. However, they are dominated by research into the downstream end of the water cycle. this tends to focus on pipelines and treatment, rather than reservoirs and their safety. There was agreement that ReSRAG need to better understand the way UKWIR prioritise and rank their research proposals. Also, whether they fund Ph. D. students. It was agreed that there need to be stronger links between UKWIR and ReSRAG. Reservoir community representation on UKWIR could be beneficial.
    b. UKWIR have a series of 'big questions'. ReSRAG agreed that the group need to aim to get at least one 'big question' on this list
2. Major Owners Group. There was agreement that ReSRAG need to liaise and link closer to this group. The Major Owners Group have tried to support CIRIA projects in the past when they see the benefit to their group. It was noted that water companies currently have a drive and investment on Environmental Impact Assessment (EIA), so there is significant investment in this area. There is an

opportunity to explore whether this could be opened up to include reservoir research proposals

3. OFWAT innovation fund. This is restricted to innovative research. ReSRAG agreed that the priority list should be reviewed to determine if any of the research priorities identified in the strategy could be relevant

4. CEATI. The organisation is made up of mostly operators of hydropower facilities, not researchers. It currently includes the Environment Agency as a member, noting that this is a paid membership and that only member staff can access the research at the current time. It was agreed that a larger UK membership could help drive some research priorities forwards

5. Horizon Europe. The European strategy includes a new ‘member state liaison group’ to help steer innovation and research in Europe. The committee are considering research and innovation into hydropower. This will feed into Horizon funding source priorities and there may be some research themes identified in the UK which may feed into or strengthen this.

5.7. Summary

The consultation process involved:

- a survey
- academic workshop
- supervising engineer workshop
- owner/undertaker workshop
- discussions with ReSRAG

It provided clear and consistent evidence on the priorities, barriers and needs of the reservoir safety community. Stakeholders across all groups emphasised:

- funding constraints
- skills shortages
- climate change impacts
- monitoring and measurement challenges
- the need for clearer, more accessible guidance

These issues reflect growing pressure on the sector’s capacity to:

- manage ageing assets
- implement new regulatory expectations
- adapt to environmental change

Feedback highlighted that many research needs identified in 2016 remain relevant. New priorities emerged around:

- erosion protection
- grass embankments
- machine learning
- consequence assessment
- asset deterioration
- practical tools for small and resource-limited owners.

Stakeholders stressed the importance of:

- risk-based approaches
- better definition of failure mechanisms
- improved consequence modelling (including non-life loss impacts)
- greater support for monitoring technologies and data interpretation

A strong theme across consultations was the need for better coordination, visibility and communication of research activities. Many participants were unaware of ongoing or completed research. ReSRAG was perceived as distant from the wider industry. Stakeholders called for clearer mechanisms to track progress, share outputs and capture emerging issues. This could include dashboards, regular updates at industry events and more transparent prioritisation processes.

Collectively, these insights underline the need for a research strategy that is practical, transparent, responsive and well-communicated. The focus should be on implementable tools, accessible guidance and effective engagement across the reservoir community. They directly inform the strategic themes and problem statements.

6. Conclusion

This review refreshes the evidence base for reservoir safety research. It has been informed by:

- reviews of safety incidents
- statutory measures
- case studies
- updated scientific evidence about climate change
- stakeholder engagement

The new strategy points to a consistent set of technical and systemic priorities. Priority issues are:

- erosion mechanisms
- spillway performance
- risk assessment methods
- data quality
- the capabilities of the reservoir safety sector

Implementing the strategy will require sustained collaboration across regulators, owners, practitioners and academia. It recommends:

- improved coordination
- clear communication of research progress and outcomes
- a focus on turning research into usable guidance and tools

The strategy has 5 sections, which are summarised below:

Section 1 – The context for the new strategy describes the reservoir safety landscape, the regulatory framework and the rationale for continued R&D. It reviews progress since the 2016 strategy and identifies gaps and barriers (funding, expertise, coordination, visibility of outputs). It concludes that a refreshed, more transparent and adaptable strategy is required to reflect new drivers such as reform programme activity, technology change and climate impacts.

Section 2 – Review of trends from safety incidents, MIOS and case studies. This section analyses incident and MIOS data (2016–2024). It looks into case studies to identify dominant failure mechanisms and where intervention is most frequently required. The evidence shows erosion-related mechanisms remain the leading causes of incidents. Older embankment and impounding reservoirs seem disproportionately represented. It highlights practical data and reporting issues that affect learning.

Section 3 - PESTLE analysis and change drivers. This section undertakes PESTLE analysis to look at external factors which are influencing the need for research. It frames future drivers in legislation, skills, climate, technology and societal expectations. These must all be considered in research planning.

Section 4 – Updated review of climate change research in the reservoir sector. This section provides a targeted synthesis of UK and international evidence on climate change impacts on reservoir safety. It focusses on research since the 2013 review.

It identifies what has progressed and where major gaps remain. It highlights advances in high-resolution rainfall scenarios, storm sequencing research and emerging AI/ML applications, but notes continuing uncertainty around translating climate signals into extreme inflows and PMF/PMP. The section concludes with a clear set of remaining knowledge gaps to guide future research and guidance development.

Section 5 – Consultation summarises feedback from surveys, workshops and discussions. These included a range of stakeholders across academia, panel engineers, owners and ReSRAG. Stakeholders were found to consistently prioritise:

- climate change
- monitoring and measurement
- erosion
- grass embankment performance
- proportionate approaches for small owners,

They identified funding and skills shortages as critical constraints. The consultation also reinforces the need for better coordination and visibility of research activity and outputs, and informs the strategic themes developed later in the report.

Bibliography

Archer, L. et al., 2024. Future change in urban flooding using new convection-permitting climate projections. *Water resources research,* p. 60.

Ashcroft, J., Poulson, A. & Koch, M., 2025. *AI weather forecasting: Can it reveal unseen flood risks?,* s.l.: JBA Risk Management.

Atkins, 2013. *Impact of Climate Change on Dams & Reservoirs,* s.l.: gov.uk.

Aufleger, M. & Kafashan, N., 2025. Auswirkungen des Klimawandels auf die Sicherheit von Staudämmen und mögliche Vorsorgemaßnahmen. *Wasserwirtsch,* Volume 115, pp. 26-29.

Ball, J. et al., 2024. *Australian Rainfall and Runoff: A Guide to Flood Estimation.* s.l.:Commonwealth of Australia.

Balmforth, P. D., 2020. *Independent Reservoir Safety Review Report,* s.l.: Gov.uk.

Baninajarian, L. et al., 2019. *Effect of climate change on soil embankment stability.* St Johns, s.n.

Bartsch, M. & Engstrom-Meyer, A., 2025. *Dam Safety in Sweden in Times of Energy Transition and Climate Change.* Chengdu, CRC Press, pp. 17-32.

Biesta, M., Mann, R. & Judge, T., 2022. Ice loading at Scottish Water's reservoirs. *Dams and Reservoirs,* 32(4), pp. 140-148.

Bishop, C. M., 2006. *Pattern recognition and machine learning (information science and statistics).* New York: Springer-Verlag.

Brandesten, C., 2023. *Impact of climate change on dam safety - Literature review and initial analysis. Report no. 2023:947.,* s.l.: Energieforsk.

Burgess, M. et al., 2021. IPCC baseline scenarios have over-projected CO2 emissions and economic growth. *Environment Research Letters,* p. 16 014016.

Camps-Valls, G. et al., 2025. Artificial intelligence for modeling and understanding extreme weather and climate events. *Nature Communications,* Volume 16.

Chan, S. C. et al., 2023. New extreme rainfall projections for improved climate resilience of urban drainage systems. *Climate Services,* p. 100375.

Collins, A. M., Coughlin, D., Miller, J. & Kirk, S., 2015. *The Production of Quick Scoping Reviews and Rapid Evidence Assessments: A How to Guide Department for Environment & Rural Affairs.* s.l.:Joint Water Evidence Group.

Da Silva, N. A. & Haerter, J. O., 2025. Super-Clausius–Clapeyron scaling of extreme precipitation explained by shift from stratiform to convective rain type. *Nature Geosciences,* Issue 18, pp. 382-388.

Deng, Z. et al., 2025. From data processing to behavior monitoring: A comprehensive overview of dam health monitoring technology. *Structures,* p. 108094.

Environment Agency, 2009. *Reservoir Safety Research and Development Strategy,* s.l.: Environment Agency.

Environment Agency, 2016. *Reservoir Safety Research and Development Strategy: Report SC130003/R,* Bristol: Environment Agency.

Environment Agency, 2016. *Reservoir Safety Research Strategy Report – SC130003/R,* s.l.: s.n.

Environment Agency, 2022. *Flood risk assessments: climate change allowances. Peak rainfall intensity allowance,* Bristol: Environment Agency.

Environment Agency, 2024. *A review of England's revised draft regional and water resources management plans,* Bristol: Environment Agency.

Environment Agency, 2025a. *Improving PMP and PMF estimation for UK reservoir safety Report FRS19222/R1.,* Bristol: Environment Agency.

Environment Agency, 2025b. *National Framework for Water Resources 2025: water for growth, nature and a resilient future,* s.l.: Environment Agency.

Environment Agency, 2026 (due date). *Extreme rainfall estimation improvements,* Bristol: Environment Agency.

Fluixá-Sanmartín, J., Altarejos-Garcia, L., Morales-Torres, A. & Escuder-Bueno, I., 2018. Review article: Climate change impacts on dam safety. *Natural Hazards and Earth System Sciences,* Volume 18, pp. 2471-2488.

Ho, M. et al., 2024. *The Impact of Climate Change on Overtopping Risk,* s.l.: ANCOLD.

Institution of Civil Engineers, 2015. *Floods and Reservoir Safety.* 4th ed. London: s.n.

International Commission on Large Dams, 2025. *Draft Bulletin on Extreme flood estimation and associated uncertainty.* s.l.:s.n.

International Commission on Large Dams, 2025. *ICOLD Bulletin 169: Global Climate Change, Dams, Reservoirs and related Water Resources.* s.l.:s.n.

Ishfaque, M. et al., 2023. Trend analysis of hydro-climatological parameters and assessment of climate impact on dam seepage using statistical and machine learning models. *Environmental Earth Sciences,* Issue 82, p. 542.

Kage, L., Milic, V., Andersson, M. & Wallen, M., 2025. Reinforcement learning applications in water resource management: a systematic literature review. *Frontiers in Water,* Volume 7.

Karlbauer, M. et al., 2024. Advancing Parsimonious Deep Learning Weather Prediction Using the HEALPix Mesh. *Journal of Advances in Modeling Earth Systems,* Volume 16.

Kendon, E. J. et al., 2020. Greater future U.K. winter precipitation increase in new convection-permitting scenarios.. *Journal of Climate,* p. 7303–7318.

Liu, H. et al., 2025. Attention-enhanced spatiotemporal deep learning-based automatic warning model with uncertainty estimation in dam safety. *Structural health Monitoring.*

Mahesh, A. et al., 2025. Huge ensembles – Part 1: Design of ensemble weather forecasts using spherical Fourier neural operators.. *Geoscientific Model Development,* Volume 18, pp. 5575-5603.

Mahoney, K. et al., 2022. Blasts from the Past: Reimagining Historical Storms with Model Simulations to Modernize Dam Safety and Flood Risk Assessment.. *Bulletin of the American Meteorological Society,* Volume 103, pp. 266-280.

McCormick, B., Lukas, J. & Mahoney, K., 2020. 21st-Century Dam Safety Rules for Extreme Precipitation in a Changing Climate. *Journal of Dam Safety,* 17(3), pp. 1944-9836.

Mergen, S., Courtnadge, A. P., Torenga, E. K. & Brown, A. J., 2021. Reliability and resilience of flood detention (storage) reservoirs. *Dams and Reservoirs,* 31(3), pp. 115-122.

MET Office Hadley Centre, 2024. *UKCP Guidance: Extreme rainfall features in UKCP Local,* Exeter: Met Office.

NERC, 1975. *Flood Studies Report.* London: Natural Environment Research Council.

Preziosi, M. C. & Micic, T., 2014. An adaptive methodology for risk classification of small homogeneous earthfill embankment dams integrating climate change projections. *Civil Engineering and Environmental Systems,* 31(2), pp. 111-124.

Price, I. et al., 2025. Probabilistic weather forecasting with machine learning. *Nature,* Volume 637, pp. 84-90.

Raissi, M., Perdikaris, P. & Karniadakis, G. E., 2019. Physics-informed neural networks: A deep learning framework for solving forward and inverse problems involving nonlinear partial differential equations. *Journal of Computational Physics,* Volume 378, p. 686–707.

Sayers, P., 2024. *Compound Hazards Events Exploring their influence on flood protection and risk. Research Review,* s.l.: Office of Nuclear Regulation.

Sayers, P. et al., 2024. Beyond the local climate change uplift – The importance of changes in spatial structure on future fluvial flood risk in Great Britain. *Natural Hazards,* Volume 120, pp. 3773-3798.

Sharma, P., Chung, W. T., Akoush, B. & Ihme, M., 2023. A Review of Physics-Informed Machine Learning in Fluid Mechanics. *Energies,* Volume 16.

Vesuviano, G., 2022. *The FEH22 rainfall depth-duration-frequency (DDF) model,* s.l.: UK Centre for Ecology & Hydrology.

Wasko, C. et al., 2024. A systematic review of climate change science relevant to Australian design flood estimation. *Hydrology and Earth System Sciences,* Volume 28, pp. 1251-1285.

Williamson, T., Kelham, P., Lopes, S. & Loftus, B., 2020. *Pipework, valves and associated equipment in dams,* s.l.: CIRIA.

World Bank, 2021. *Hydrological Risk. Good Practice Note on Dam Safety; Technical Note 1,* s.l.: World Bank.

Appendix A - Detailed summary of scoping review on climate change and

reservoir safety research

Method

Literature search

Literature was identified using a combination of structured searching and expert knowledge. Searches were conducted using Google Scholar, with the following criteria:

- date range: 2013-2025
- words or phrases in title:
    - "climate change" and "dam safety"
    - "climate change" and "reservoir safety"
    - "climate change" and "embankment"
    - "climate change" and "frequency of floods"
    - "climate change" and "sequencing of floods"

The latter 2 terms were included in attempt to discover any material of specific relevance to flood storage reservoirs and washlands. These types of reservoirs could become less effective if climate change were to lead to more sequences of closely-spaced floods. These 2 search terms did not effectively identify such literature. Some other relevant publications were included from the knowledge of the project team.

The above searches led to 49 hits in total.

The following types of publications were excluded based on their title or abstract:

- university dissertations
- most publications specific to individual dams or reservoirs
- publications specific to regions outside the UK, unless they had clear wider messages
- publications specific to gated spillway dams (which are rare in the UK)
- results for which Google Scholar provided only a title rather than full publication details

After applying the exclusion criteria, there were just 6 publications remaining.

Additional literature was sought from the websites and / or hard copy publications of the following organisations or publishers:

- International Commission On Large Dams (ICOLD)
- Australian National Committee On Large Dams (ANCOLD)
- Association of State Dam Safety Officials (ASDSO) (USA)
- Federal Emergency Management Agency (FEMA) (USA)
- US Army Corps of Engineers (USACE)

- US Bureau of Reclamation (USBR)
- CEATI (Centre for Energy Advancement through Technological Innovation: a network of power industry professionals)
- British Dams Society Dams & Reservoirs journal
- Institution of Civil Engineers
- Environment Agency Flood and Coastal Erosion Risk Management R&D reports, including 1 due for publication in 2026

The Environment Agency provided abstracts from potentially relevant reports by CEATI. This included a summary of an ongoing project, Impact of Climate Change on the Operation of Dams and Reservoirs. This is due for completion in December 2026. Material from ASDSO was not available to non-members. 6 potentially relevant articles were found from the other publishers listed above.

The search process led to 19 documents identified for review. 9 were journal papers, five were reports, 4 were guidance documents and 1 was a conference paper. They are listed in Table A-1.

The geographical coverage of the documents is deliberately mixed. 9 are UK-specific. 6 are specific to other countries with relevance to UK conditions.4 are global in scope.

We refer to other sources as well in this review, primarily where the documents listed here draw heavily on material from earlier sources.

Synthesis method

Relevant material from each document was summarised into a systematic map. A systematic map is a structured database of information extracted from literature, as defined in the Collins and others (2015) guidance on rapid evidence assessments.

The study was undertaken using the following headings:

- climate modelling and translation into impacts on local meteorology or hydrology
- reservoir safety - floods
- reservoir safety - structural aspects
- reservoir safety - impact on demand or operations
- reservoir safety – other aspects
- any remaining knowledge gaps identified in the publication

After all papers had been read, the material in the systematic map on each of the above topics was synthesised, aiming to pick out common themes among the sources.

Table A- 1 List of documents

Title	Type of publication	Location
ANCOLD (2024) The Impact of Climate Change on Overtopping Risk.	Report	Other country
Archer, L., Hatchard, S., Devitt, L., Neal, J. C., Coxon, G., Bates, P. D., Kendon, E.J. and Savage, J. (2024). Future change in urban flooding using new convection-permitting climate projections. Water Resources Research, 60, e2023WR035533. https://doi.org/10.1029/2023WR035533	Journal paper	UK
Atkins (2013) FD2628 Impact of Climate Change on Dams & Reservoirs	Report	UK
Aufleger, M., Kafashan, N. Auswirkungen des Klimawandels auf die Sicherheit von Staudämmen und mögliche Vorsorgemaßnahmen. Wasserwirtsch 115, 26–29 (2025). https://doi.org/10.1007/s35147-025-2452-y	Journal paper	Other country
Baninajarian, L., Ghassemi, A., Sangiuliano, T., DeSira, A., & Bashir, R. (2019). Effect of climate change on soil embankment stability. Proceedings of the GeoSt. John's. Available via researchgate.net.	Conference paper	Other country
Bartsch and Meyer (2025). Dam Safety in Sweden in Times of Energy Transition and Climate Change. Twenty-Eighth International Congress on Large Dams / Vingt-Huitième Congrès International des Grands Barrages, Chengdu, May 2025. CRC Press.	Journal paper	Other country
Chrissy Mitchell, Alan Brown, Mark Morris; Overflow erosion of levees and dams – UK practice and research needs. Dams and Reservoirs 1 June 2019; 29 (2): 59–66. https://doi.org/10.1680/jdare.18.00060	Journal paper	UK
Environment Agency (2024) A review of England's revised draft regional and water resources management plans. Available from: A review of England's revised draft regional and water resources management plans - GOV.UK [Accessed 10 February 2026]	Report	UK
Environment Agency (2025a) Improving PMP and PMF estimation for UK reservoir safety. Phase 1. Report FRS19222/R1.	Report	UK
Environment Agency (2025b). National Framework for Water Resources 2025: water for growth, nature and a resilient future. Available from: National Framework for Water Resources 2025: water for growth, nature and a resilient future - GOV.UK [Accessed 10 February 2026]	Report	UK
Environment Agency (2026) (due date) Extreme rainfall estimation improvements, Phase 1.	Report	UK

ENERGIFORSK (2023). Brandesten, C.-O. Impact of climate change on dam safety - Literature review and initial analysis. Report no. 2023:947. https://energiforsk.se/media/32530/2023-947-impact-of-climate-change-on-dam-safety.pdf	Report	Other country
Fluixá-Sanmartín, J., Altarejos-García, L., Morales-Torres, A., and Escuder-Bueno, I.: Review article: Climate change impacts on dam safety, Nat. Hazards Earth Syst. Sci., 18, 2471–2488, https://doi.org/10.5194/nhess-18-2471-2018, 2018.	Journal paper	Global
ICE (2015) Floods and Reservoir Safety. 4th edition. Institution of Civil Engineers.	Guidance	UK
ICOLD (2025) Bulletin 169, Global Climate Change, Dams, Reservoirs and related Water Resources.	Guidance	Global
ICOLD (2025) Draft of Bulletin on Extreme flood estimation and associated uncertainty.	Guidance	Global
Mark Biesta, Robert Mann, Tony Judge; Ice loading at Scottish Water's reservoirs. Dams and Reservoirs 1 December 2022; 32 (4): 140-148. https://doi.org/10.1680/jdare.22.00092	Journal paper	UK
Preziosi, M. C., & Micic, T. (2014). An adaptive methodology for risk classification of small homogeneous earthfill embankment dams integrating climate change projections. Civil Engineering and Environmental Systems, 31(2), 111–124. https://doi.org/10.1080/10286608.2014.912639	Journal paper	UK
Stephanie Mergen, Andrew Peter Courtnadge, Elmar Kees Torenga, Alan John Brown; Reliability and resilience of flood detention (storage) reservoirs. Dams and Reservoirs 1 September 2021; 31 (3): 115–122. https://doi.org/10.1680/jdare.21.00019	Journal paper	UK
Wasko, C., Westra, S., Nathan, R., Pepler, A., Raupach, T. H., Dowdy, A., Johnson, F., Ho, M., McInnes, K. L., Jakob, D., Evans, J., Villarini, G., and Fowler, H. J.: A systematic review of climate change science relevant to Australian design flood estimation, Hydrol. Earth Syst. Sci., 28, 1251–1285, https://doi.org/10.5194/hess-28-1251-2024, 2024.	Journal paper	Other country
World Bank. 2021. Hydrological Risk. Good Practice Note on Dam Safety; Technical Note 1. © World Bank. http://hdl.handle.net/10986/35488 License: CC BY 3.0 IGO.	Guidance	Global

Appendix B - Reservoir Incident Data Analysis

Background

This review of reported reservoir incidents informs the Reservoir Safety Research Strategy. The aim of the review is to identify trends in the data. This will highlight factors that have a high representation in reservoir incidents.

A greater understanding of these factors could improve risk identification, assessment and mitigation. This could lead to a reduction in reservoir incidents and increased reservoir safety. The data is available from the Institution of Civil Engineer's reservoir incident database (https://www.rikbase.org.uk/).

The review focuses on the data from 2016 to 2024 to ensure trends in the data are current. Data from before 2016 is ignored.

Number of reported reservoir incidents and geographic distribution

Number of Incidents

The number of incidents reported has generally increased since mandatory reporting started in 2013 (Figure B-1, Figure B-2). This trend is attributed to:

- increased engagement about incident reporting
- reassurance from regulators that undertakers will not be penalised for reporting incidents

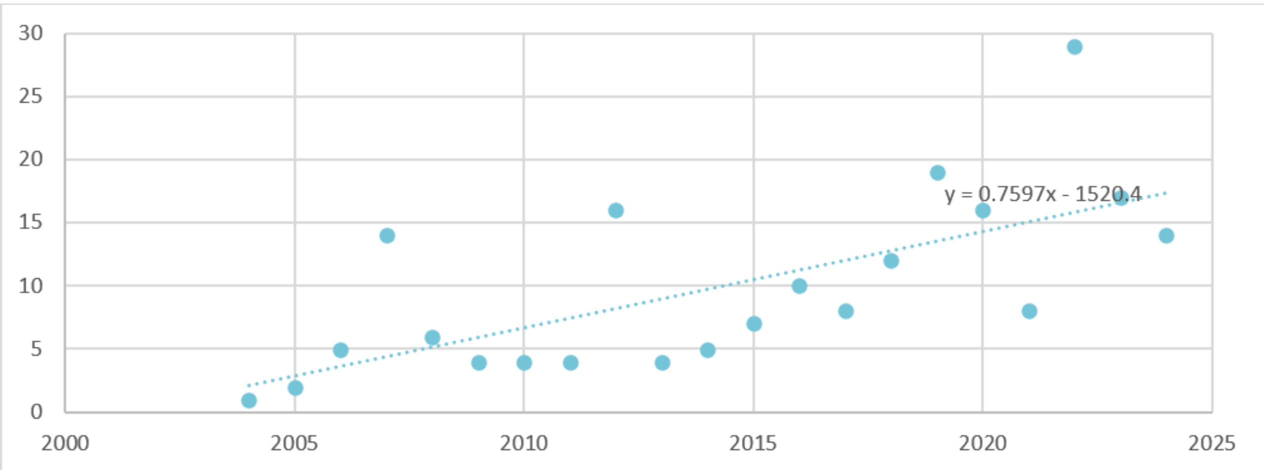


Figure B - 1 Reservoir Incidents reported between 2004 and 2024

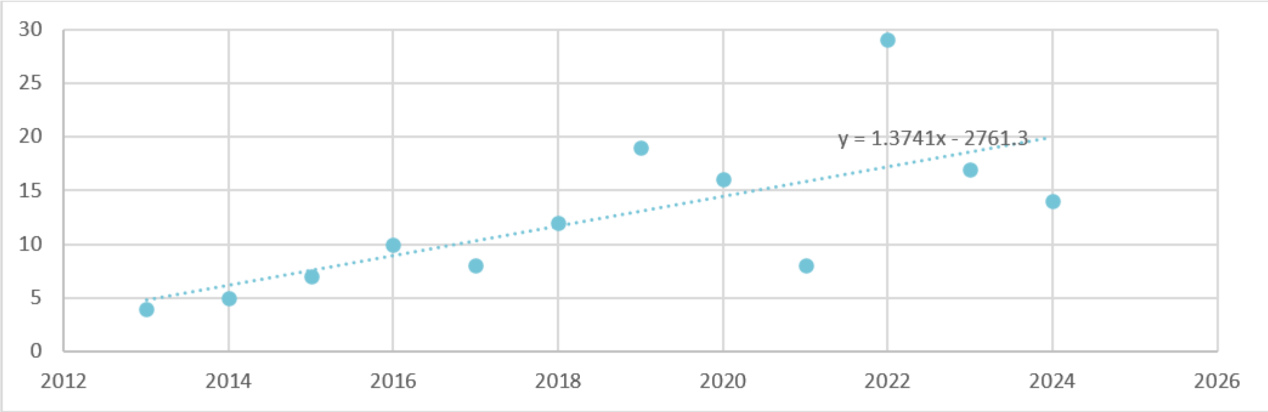


Figure B - 2 Reservoir incidents reported 2013-2024

Distribution of incidents

The absolute number of incidents reported in Wales is consistently lower than those reported in England. See Figure B-3 for details. However, England has approximately 5.7 times the number of statutory reservoirs as Wales. Adjusting the incident reports to take account of the number of reservoirs shows that Welsh undertakers provide 2.5 times the number of incident reports per reservoir than English undertakers. As such, Welsh reservoirs are either more prone to incidents or Welsh undertakers are more likely to report a reservoir incident. The latter is more likely. This data could be skewed by incident reports on reservoirs between 10,000 m^3 and 25,000 m^3 in Wales.

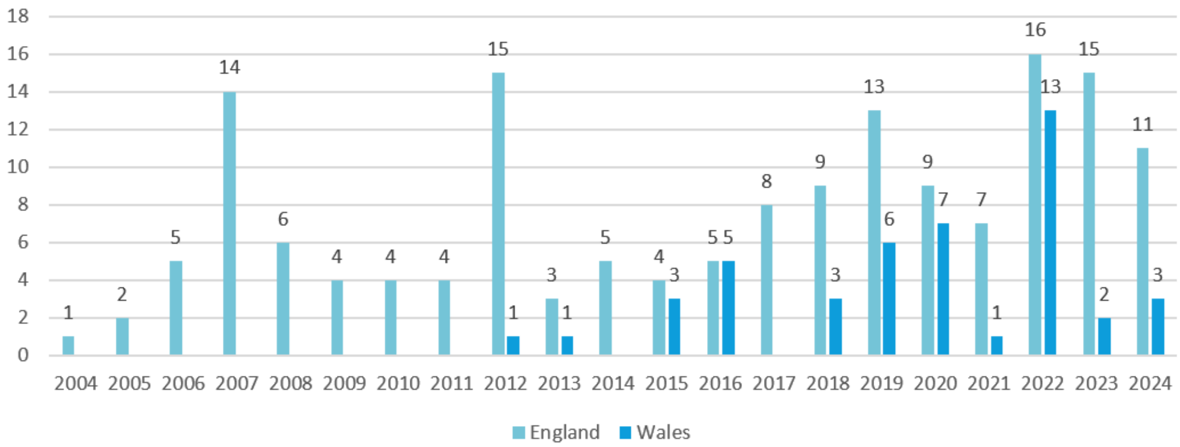


Figure B - 3 Reservoir incidents in England and Wales by year

Reported reservoir incidents by potential failure mechanism

The reservoir incident database contains data on the impact of the incident. This aligns with potential failure mechanisms. The 2016-2024 impact data is presented in Figure B-4. Some incidents record multiple impacts. The data shows that the majority of incidents are related to internal erosion (46%) and external erosion (29%).

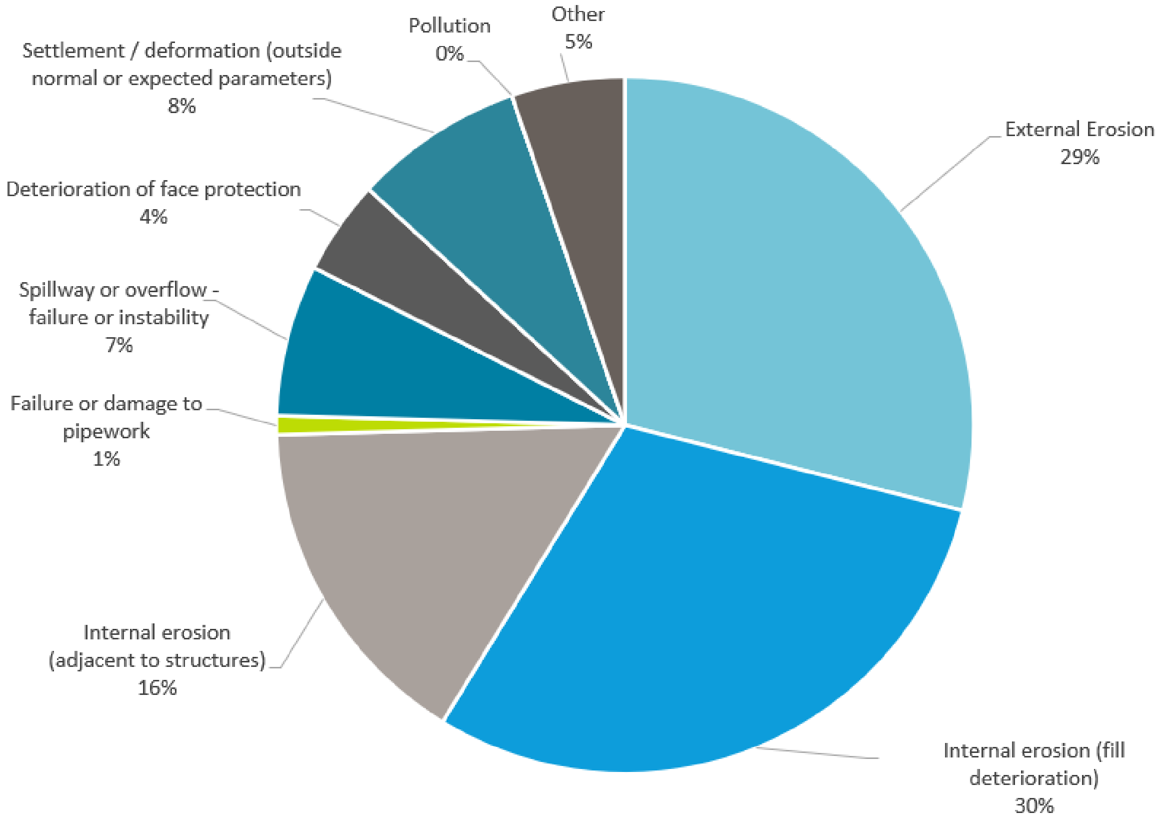


Figure B - 4 Reported reservoir incidents by impact 2016-2024

Incidents by shortcoming (root cause)

The data contains a shortcoming field that has been interpreted as the perceived cause of the incident. The largest shortcomings are poor design (30%), construction (20%), no apparent (17%) and process or procedural (16%), see Figure B-5.

England and Wales have an aging reservoir stock with the average age being approximately 130 years old. It could be assumed that a large proportion of the design and construction shortcomings are due to outdated design and construction practices. As such, a more detailed assessment of the design and construction shortcomings has been undertaken, through comparison with construction year, see Figure B-6. There are a higher proportion of design and construction shortcomings attributed to reservoirs pre-1900, after 1900 the distribution remains relatively flat. Design shortcomings pre-1900 are approximately twice those of reservoirs post-1900.

The data contains a 'shortcomings' field. This is the perceived root cause of the incident. The most frequent shortcomings are:

- poor design (30%)
- construction (20%)
- no apparent (17%)
- process or procedural (16%)

See Figure B-5 for details.

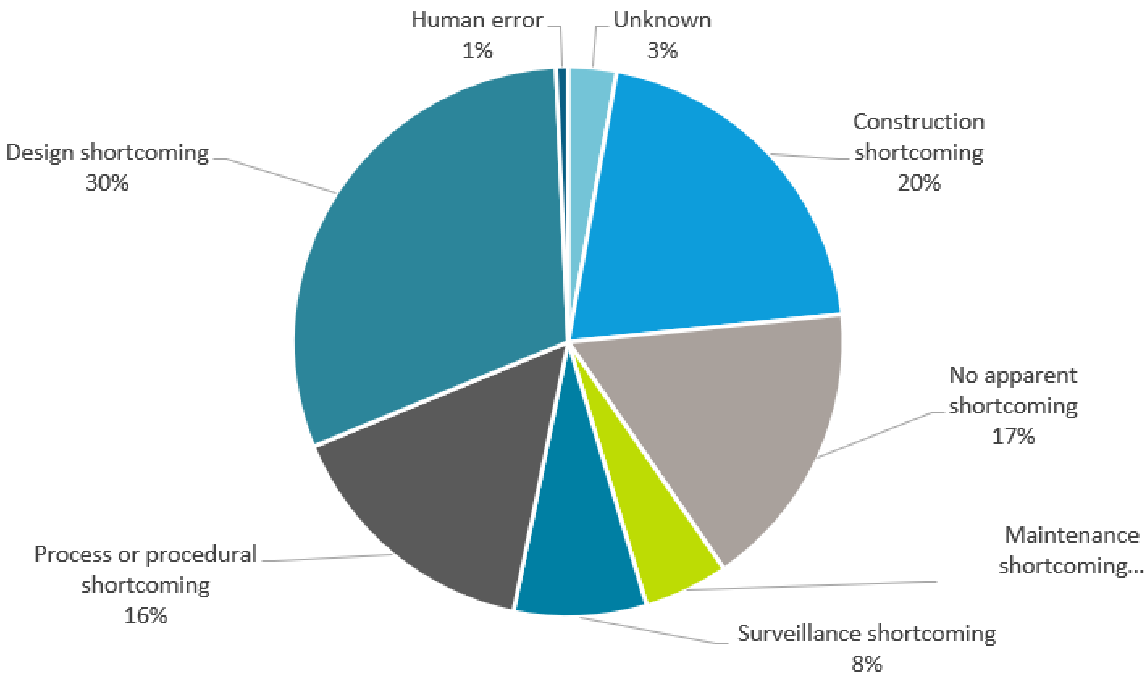


Figure B - 5 Reported reservoir incidents by shortcoming 2016-2024

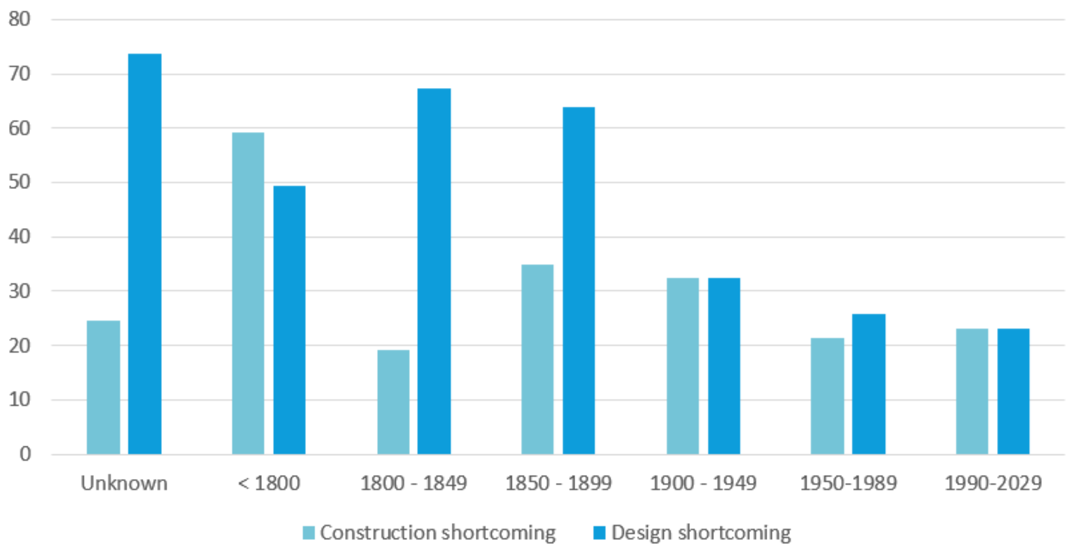


Figure B - 6 Design and construction shortcomings by construction date scaled by number of reservoirs

Reported reservoir incidents by owner type

The highest number of incidents reported are from public bodies. They are undertakers for 20% of the reservoirs and make up 39% of the incident reports. See Table B-1 and Figure B-7. The largest difference in incidents reported compared to percentage of reservoirs owned is private individuals. They own 31.7% of the reservoirs but only account for 14% of the incident reports. Data on owner types from the incident database and English reservoir register don't align exactly. Some assumptions have been made to align categories, see Table B-1.

The difference between the percentage ownership and reporting of incidents is likely to be due to:

- differences in resources

- understanding of reporting requirements
- procedures and culture within the different types of undertaker groups

Table B- 1 Ownership of English statutory reservoirs

Owner Type as per incident data base	Owner Type*	Percentage of reservoir stock owned (number of reservoirs)*		Percentage of incidents
Public Body	Environment Agency	10.3% (219)	20.4	39%
	Local authority	8.2% (173)		
	Other government agencies and departments	1.9% (40)		
Limited companies	Water companies	31.4% (664)	36.8	26%
	Industrial and commercial	5.4% (114)		
Private individuals	Private landowners and trusts	16.3% (346)	31.7	14%
	Farms	15.4% (327)		
Registered charities	Registered charities	7.4% (156)	7.4	12%
Clubs and associations	Recreational clubs and associations	2.0% (42)		2%
***Note: this data is for England only and from 2022**				

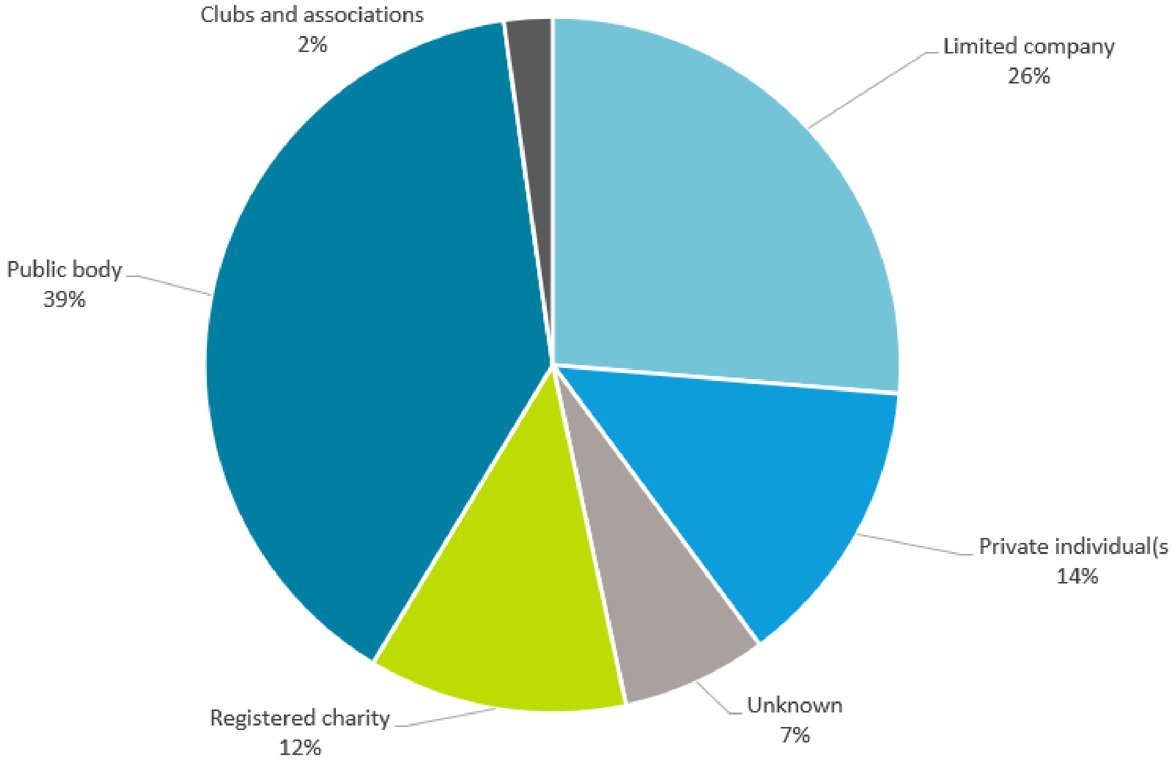


Figure B - 7 Reported reservoir incidents by owner type 2016-2024

Incidents by reservoir type

Most reported reservoir incidents are related to impounding reservoirs (86%), see Figure B-8.. This is likely due to the age, dam construction, dam height and hydrology. They lead to these structures being more prone to internal and external erosion issues. Impounding reservoirs make up 63% of the reservoir stock in England. As such, impounding reservoirs are more prone to incidents.

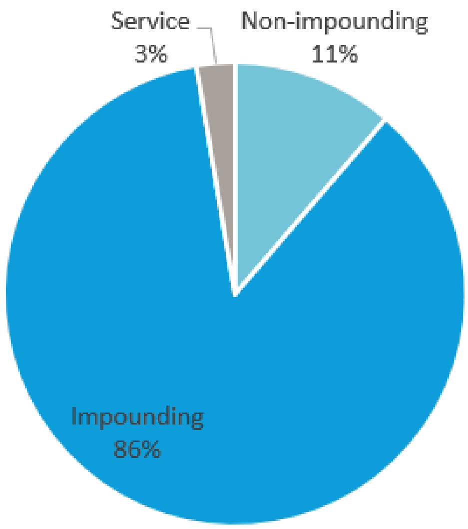


Figure B - 8 Reported reservoir incidents by reservoir type 2016-2024

Incidents by reservoir capacity

Incident data by reservoir capacity is presented in Figure B-9. This shows the comparison of incidents at reservoirs larger than 25,000 m^3 (Figure B-10) with the number of reservoirs over 25,000 m^3 (Figure B-11). Incident data disproportionately represents reservoirs between 25,000 m^3 and 500,000 m^3. They are likely more prone to incidents. This could be related to reservoirs with larger capacities receiving more investment and operational attention due to the significant risk posed by breach.

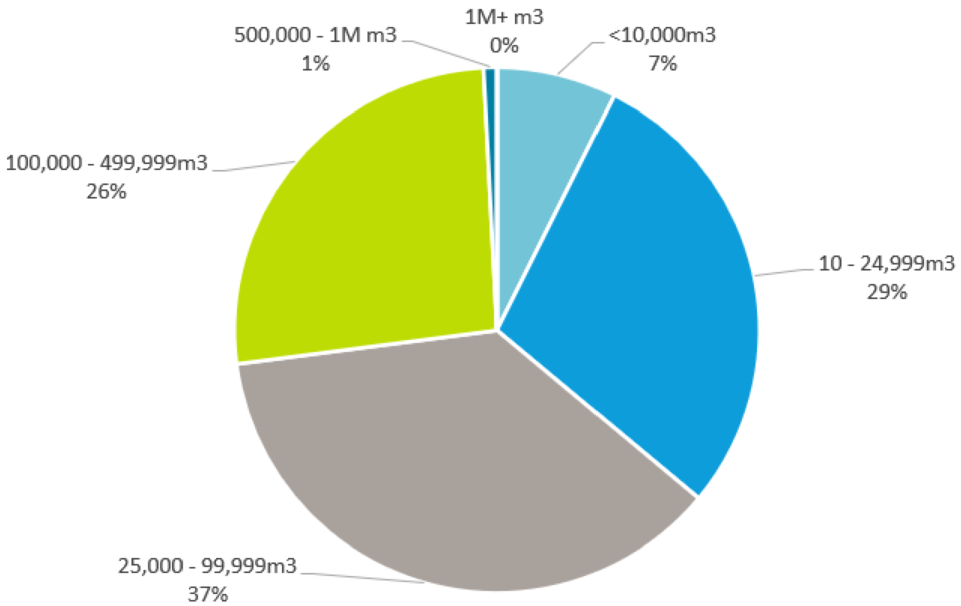


Figure B - 9 Reported reservoir incidents by reservoir capacity

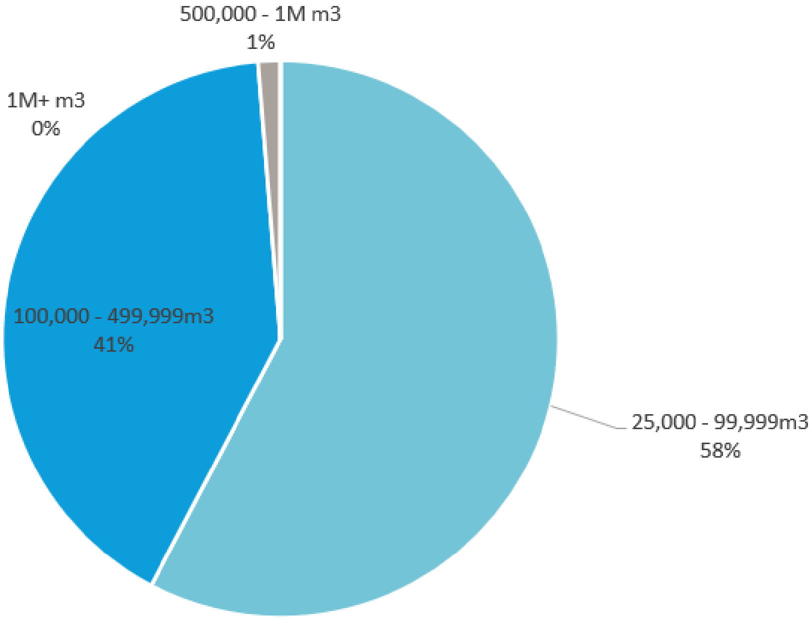


Figure B - 10 Reported reservoir incidents by reservoir capacity 25,000 m^3+

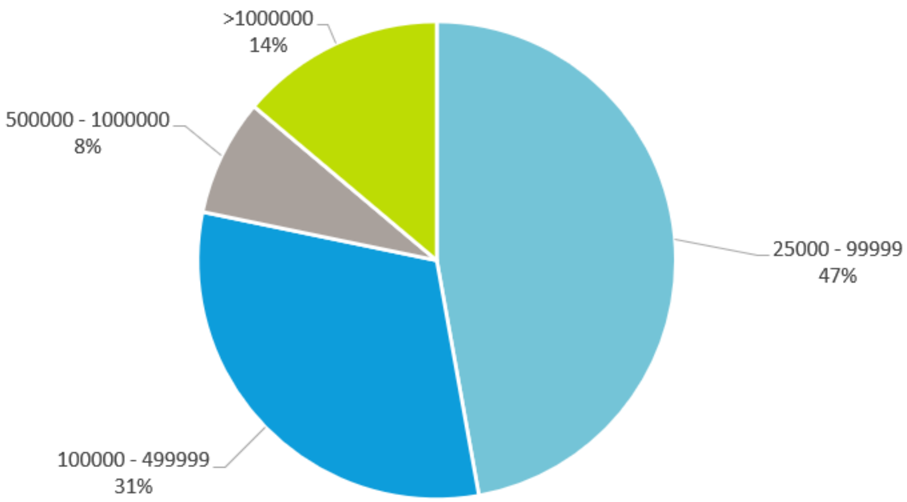


Figure B - 11 Number of English statutory reservoirs by capacity

Incidents by year of construction

The largest proportion of reservoir incidents occur at dams constructed prior to 1900. They account for 53% of the total reservoir incidents. See Figure B-12. These reservoirs make up 37% of the total number of reservoirs, see Figure B-13. As such, reservoirs built before 1900 are more prone to incidents. Reservoirs constructed after 1990 are less prone to incidents. They make up 22% of reservoirs, but only 10% of reported incidents. This is likely due to the advancement in design and construction methods and the impact of aging on infrastructure. It may also be linked to the size and type of reservoirs constructed after 1990. 70% of the reservoirs constructed after 1990 are non-impounding. 28% of reservoirs constructed before 1990 are non-impounding.

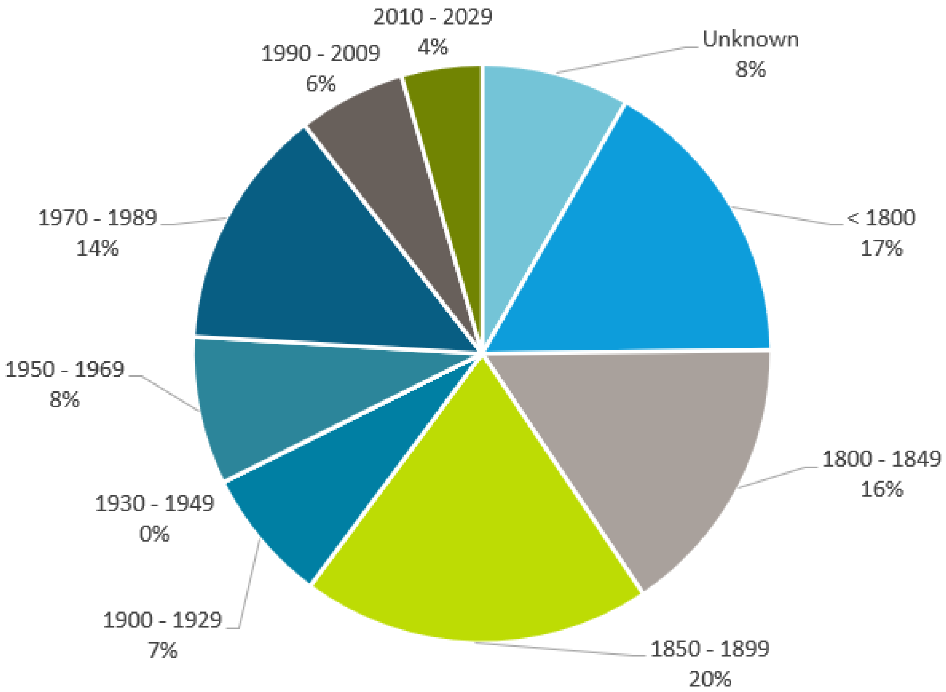


Figure B - 12 Reported reservoir incidents by reservoir age

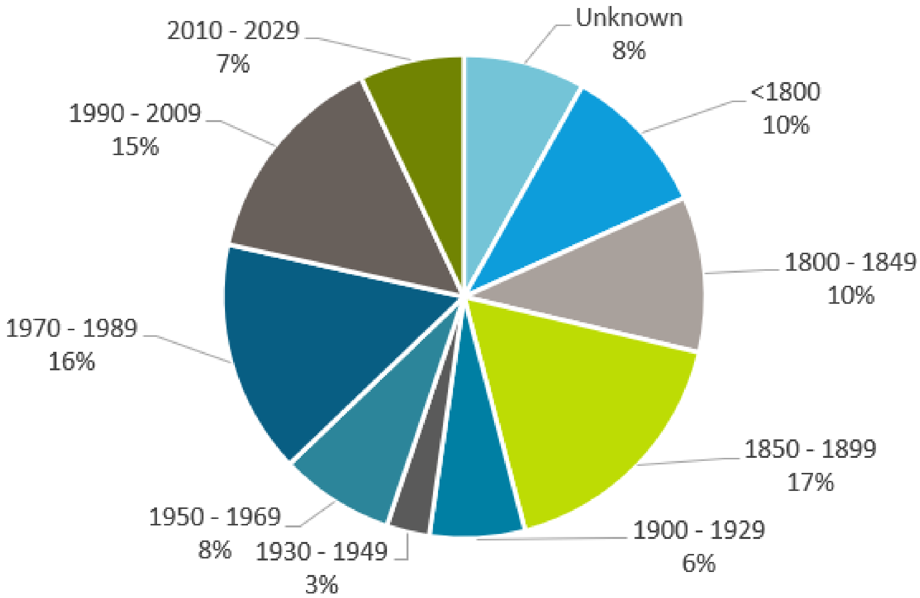


Figure B - 13 Number of English reservoirs by completion date

Incidents by dam height

Incidents by dam height show that dams between 2 m and 10 m make up the majority of reported incidents. See figure B-14. When compared to the English distribution of dam heights (Figure B-15) it can be seen that reported incidents are proportionate to dam heights.

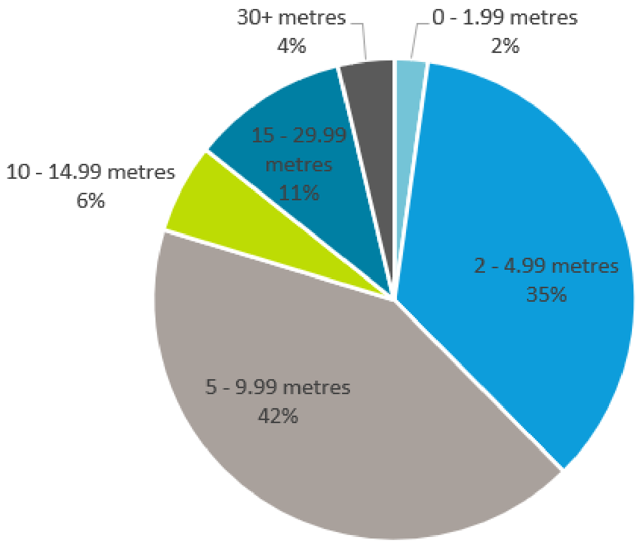


Figure B - 14 Reported incidents by dam height 2016-2024

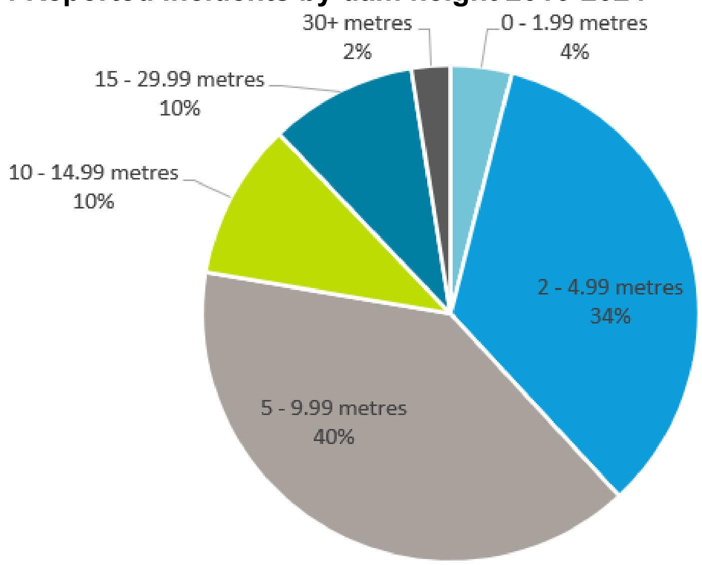


Figure B - 15 Distribution of English dam heights

Incidents by dam type

Incidents by dam type show that most incident reports (85%) and reservoir stock (76%) are earthfill embankments. See Figure B-16 and Figure B-17. Embankment and buttress dams have disproportionately more incidents reported. Only 1 incident report has been made for a buttress dam.

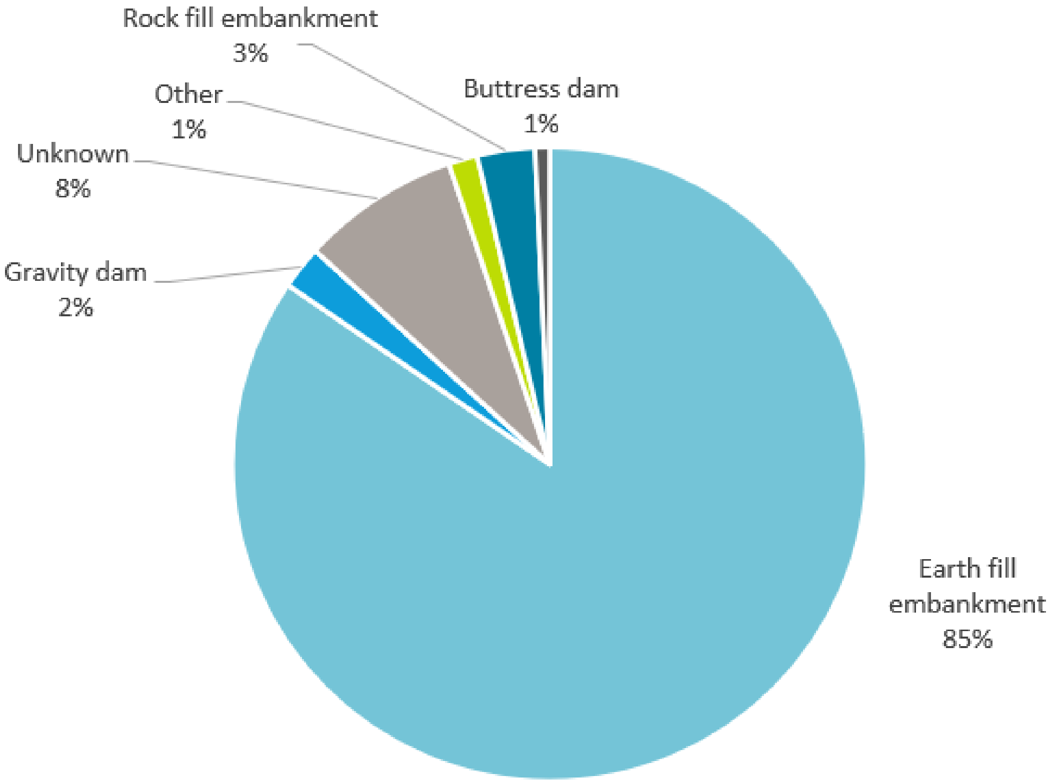


Figure B - 16 Incident reports by dam type 2016-2024

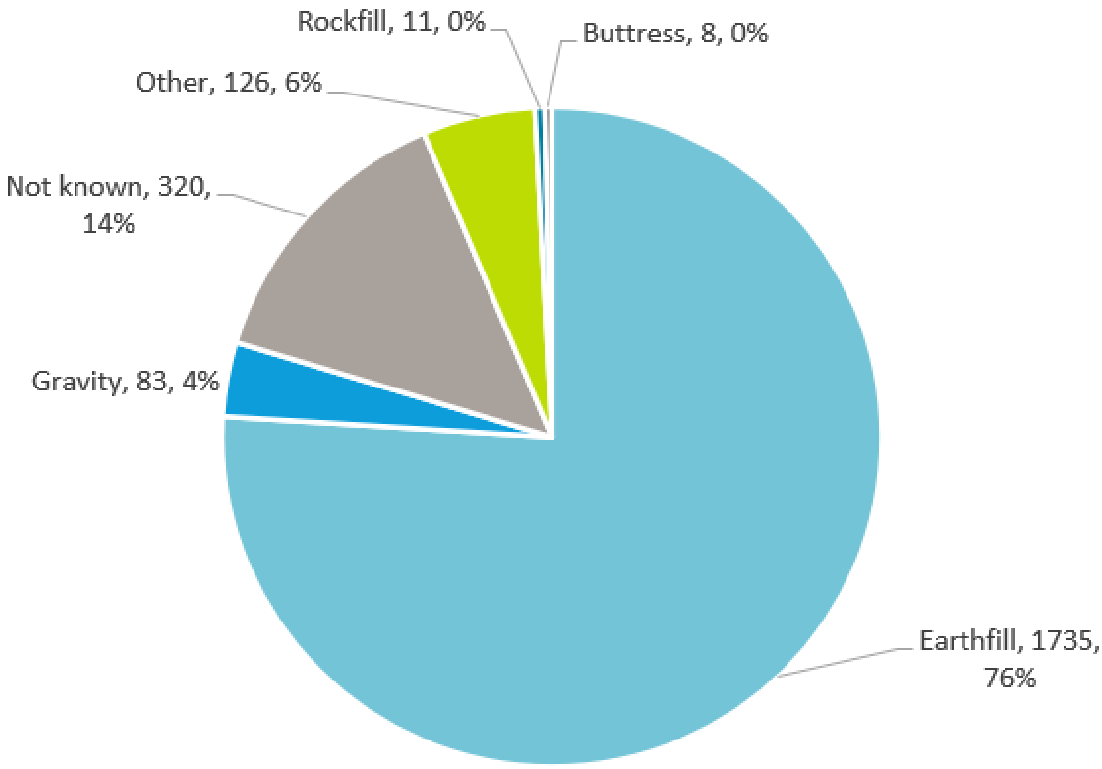


Figure B - 17 Number of English reservoirs by dam type

Conclusion

This review identified trends in the incident data assessed from:

- the ICE's reservoir incident database
- the English reservoir register

Reservoir incident data is likely skewed by incidents going unreported. Data shows an increase in reporting year on year. Over time, this will improve the data available and the opportunities to analyse the data to identify trends.

The key trends identified in the data are:

- Welsh undertakers report more incidents per reservoir (approx. 250% more) than in England. This suggests English undertaker's incident reporting could be improved
- design and construction shortcomings are the most common cause of reservoir incidents. From the data these shortcomings are more common in reservoirs constructed before 1900. Design shortcomings were attributed twice as often for reservoirs constructed before 1900 than after 1900
- dams constructed before 1900 account for 53% of reservoir incidents while making up 37% of the reservoir stock. Reservoirs constructed after 1990 are less prone to incidents making up 10% of the reported incidents and 22% of the reservoir stock
- internal and external erosion are a factor in 75% of reported reservoir incidents
- assessment of reports by undertaker group found private individuals reported the least incidents. Proportionally, public bodies and registered charities reported the most
- impounding reservoirs were disproportionately represented in reports. They made up 86% of the reports while accounting for 63% of the reservoir stock
- reservoirs with a capacity under 500,000 m^3 were disproportionately represented in reports. They featured in 99% of the reports for reservoirs over 25,000 m^3. They make up 78% of the reservoir stock in England
- earth fill embankments are disproportionately represented in the reported reservoir incidents

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