A Note on Reservoir Safety

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16th August 2019

Abstract

On 1st August 2019, the dam at Toddbrook Reservoir, Whaley Bridge in Derbyshire, was severely damaged by a period of extreme rainfall. This damage was so serious that part of the town was evacuated by the authorities owing to the real risk of dam failure leading to loss of life. The serious incident at Toddbrook Reservoir is not a one-off as there have been several other near-misses in recent years. The aim of this note is to provide a brief review of reservoir and dam regulation and the supporting science in the UK in the context of extreme rainfall events. The operation of large reservoirs is regulated by the Reservoir Act (1975). This describes a system whereby large reservoirs are inspected by suitably qualified so-called 'panel engineers' at least once every ten years. Despite this system, serious near-misses at reservoirs keep occurring. Two key aspects of reservoir safety are the probable maximum precipitation (PMP) and the probable maximum flood (PMF). Panel engineers must use estimates of the PMP to calculate what a PMF would be for the reservoir they are assessing. If their calculations show that the reservoir could not safely cope with this extreme flow of water, they must call for changes in the structure of the reservoir. However, the science of the PMP and the PMF is constantly evolving and serious questions have been raised by some members of the scientific community. This has shown that the PMP values across Britain may in some instances underestimate the actual values. There have been instances when monitoring has recorded rainfall totals greater than the PMP. Also, there are several methods for calculating the PMF and some aspects of these have not changed since the mid' 1970s. One scientist concluded that UK engineering design flood hydrology is 'stuck' – it is resistant to substantial improvement because it is too-heavily invested in unrealistic concepts dating from 1975, 1999 and 2005.

Introduction

On 1st August 2019, the dam at Toddbrook Reservoir, Whaley Bridge in Derbyshire, was severely damaged by a period of extreme rainfall. This damage was so serious that part of the town was evacuated by the authorities owing to the real risk of dam failure leading to loss of life. The Environment Agency issued a Severe Flood Alert. This level of alert is issued when there is a substantial risk possibly leading to a loss of life. As reservoirs are designed, operated and regulated on the basis that they should be able to withstand even the most severe rainfall (often referred to as a '1 in 10,000' event), it is considered unacceptable that the dam was not able to withstand the rainfall event without suffering such severe damage that dam failure was regarded by the authorities as a real possibility. It should also be noted that the emergency at Toddbrook was not without precedence as there have been others such as at Boltby Dam (N. Yorks) in 2005; Ulley Reservoir (S. Yorks) in 2007; Cwm Ebol (N. Wales) in 2012 and Rhymney Bridge (S. Wales) in 2013. The Chair of the British Dam Society recently said that there have been 'many recent near misses' [1]. Additionally, Storm Desmond in December 2015 caused significant damage to Thirlmere Reservoir in the Lake District which led to substantial repairs and strengthening.

The aim of this note is to provide a brief review of reservoir and dam regulation and the supporting science in the UK in the context of extreme rainfall events. This note has a roughly chronological structure commencing with the Reservoirs Act of 1975, the Defra guidance of 2004, Environment Agency guidelines of 2013, a paper by Faulkner and Benn in 2016 and finally a very recent joint meeting of the British Hydrological Society and the British Dam Society in 2019.

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The Reservoirs Act 1975

The operation of reservoirs is regulated by the Reservoirs Act 1975. This sets out the system of safety regulation. Statements relevant to reservoir safety in the context of severe rainfall events include:

- There must be a panel of independent, suitably-qualified engineers ('the inspecting engineer') who will periodically examine reservoirs to ensure that they are safe.
- A large, raised reservoir shall be inspected within ten years at most from the last inspection.
- Where an inspecting engineer includes in his report any recommendation as to measures to be taken in the interests of safety, then the undertakers shall as soon as practicable carry the recommendation into effect.
- At all times when a large raised reservoir is not under the supervision of a construction engineer, a qualified civil engineer ('the supervising engineer') shall be employed to supervise the reservoir and keep the undertakers advised of its behaviour in any respect that might affect safety.

Essentially, in the context of safety, the Reservoirs Act prescribes that there is a panel of suitably qualified inspecting engineers who must inspect the reservoirs at least once every ten years. The Act does not detail what aspects of the reservoir should be inspected or how it should be inspected. This is provided by Government in the form of guidance to inspecting engineers.

DEFRA Guidance on Floods and Reservoir Safety – Revised Guidance for Panel Engineers

In March, 2004, DEFRA issued guidance to Panel Engineers on floods and reservoir safety. This refers to several important concepts and reports including long return period rainfall; the Probable Maximum Precipitation (PMP), the Flood Studies Report (FSR) and the Flood Estimation Handbook (FEH). Long return period rainfall is the extreme rainfall that is regarded as rare or occurs very infrequently. For example, the most extreme rainfall is often referred to as the 1 in 10,000-year rainfall. It is called this because statistical analysis of rainfall records can identify a depth of rainfall (in millimetres) that has a probability of occurring once every 10,000 years at a given location. This does not mean that once a 1 in 10,000-year rainfall has occurred it will not occur anywhere in the UK in the next 10,000 years. This is because it is location-specific. Also, there is substantial uncertainty around the 10,000-year value because such values are extrapolated from the statistical analysis of rainfall records of only tens of years or perhaps up to around 100-300 years at most. Additionally, the statistical analysis must make some assumptions and these cannot always be rigorously met. One example is that it is assumed that the processes relating to rainfall are stationary. However, it is known that climate and weather patterns are cyclical and can change. This can lead to periods when there are more instances of severe rainfall and flooding. These are often called 'flood rich periods' and in these periods, the 'normal' processes around rainfall and the related statistics may apply less well or not at all.

The FSR was a large and significant report produced by the Institute of Hydrology in the 1970s and formed the basis of the modern understanding of the science of flooding in the UK. The Flood Estimation Handbook was produced by the Centre for Hydrology and Ecology in the 1990s and updated the FSR with improvements in understanding and introduced new and revised techniques.

The Probable Maximum Precipitation (PMP) is a very important concept in reservoir safety as it is the maximum rainfall that is presently envisaged. The PMP varies around the UK owing to the spatial variability of rainfall characteristics. Reservoir Inspecting Engineers use the estimates of the PMP as one of the factors in their decisions on whether or not reservoirs are safe. In simple terms, a PMP value can be looked up for the catchments feeding the reservoir in question and then hydrological and hydraulic calculations should be made to determine that the reservoir can cope with the Probable Maximum Flood (PMF) resulting from the PMP without compromising safety. It is important to understand that Toddbrook Reservoir had in recent years been inspected and signed off as safe and yet it was not able to cope with the rainfall that led to the spillway being damaged in August 2019. This raises the question 'is the effect of a PMP event on reservoirs being adequately assessed?'. There have also been incidents in recent years when the PMP for a given area has been exceeded. For example, this occurred during Storm Desmond when the recorded rainfall at Honister Pass and at Thirlmere Reservoir exceeded the one-day PMP (the PMP for a period of 1 day). This then raises a second

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question ‘has the probable maximum precipitation been calculated with a sufficient level of accuracy for safety purposes?’. Is it possible that it has been underestimated and that reservoirs should be re-examined on the basis of even higher rainfalls?

DEFRA guidance of 2004 (three pages) noted that the FEH (1999) contained a new methodology for the estimation of return period floods in the UK and this included the estimation of rainfall with a return period of 2,000 years which could, with caution, be used to extrapolate estimates up to 10,000 years. However, it was found that this method identified 1 in 10,000-year rainfalls greater than the PMP assessed in the earlier FSR of 1975. Following some additional investigation, DEFRA issued interim guidance which was prepared by the Reservoir Safety Working Group (RSWG) of the Institution of Civil Engineers (ICE). Defra stated that this interim guidance ‘should give clearer direction to Panel Engineers when considering floods and reservoir safety’. The interim guidance stated that the FEH should not be used for the assessment of 1 in 10,000 rear return period rainfall. Instead, design rainfalls provided by the earlier FSR of 1975 should be used while further research was carried out.

DEFRA noted that the research project into ‘Integration of Floods and Reservoir Safety’ recommended that in the long term, estimation of floods should move away from the concept of PMP and probable maximum flood (PMF) towards a fully probabilistic approach. It appears that this has yet to happen.

Specifically, in relation to risk assessment for dams, DEFRA stated ‘By following a risk assessment approach, it is possible that Panel Engineers may find that additional expenditure on spillway upgrading is not justified in terms of the benefits it will give in reducing potential loss of life in the event of a dam breach’.

The DEFRA Revised Guidance for Panel Engineers was written by the Institution of Civil Engineers Reservoir Safety Group in March 2004.

Environment Agency Guidelines on Flood Estimation 2013

While this EA report covers the broad topic of flood estimation, it includes a section on ‘flood estimation for reservoir safety’. Essentially this is about calculating the amount of water likely to move through a reservoir as a result of extreme rainfall in order to determine how this would affect the reservoir. This contributes to the key question ‘can the reservoir cope with an extreme flood event?’.

The report states that reservoir spillway capacities are usually assessed as part of a detailed inspection that is carried out by Panel Engineers under Section 12 of the Reservoirs Act 1975 every 10 years. The final water level of the reservoir during a design storm is assessed to ensure there is adequate freeboard in the reservoir. The final water level includes a wave assessment, which is not covered in these flood estimation guidelines. Design floods at reservoirs are also needed for the preparation of reservoir flood plans.

The report ‘gives a brief overview of the methods available and the latest current guidance (at July 2009)’.

The design flood of the required return period is derived for the catchment flowing into the reservoir and then routed through the reservoir, allowing for the reservoir lag effect in the storm duration.

For long return periods, particularly 10,000 years, users should be aware that the FEH rainfall frequency statistics were not derived with such extreme events in mind. When extrapolated to a return period of 10,000 years, they give some contradictions with estimates of the probable maximum precipitation (see MacDonald, D.E. and Scott, C.W., 2000) [2].

After reviews by Babtie Group and Sir David Cox, DEFRA commissioned a project starting in 2005 to investigate alternative methods of extreme rainfall estimation for return periods up to 10,000 years and, if appropriate, to amend the FEH methodology for extreme rainfall. This research is complete, see Stewart, et al. [3]. This was completed in 2010 but not published until 2013.

The method for estimating the PMF was revised with the following changes:

- the design rainfall event is the probable maximum precipitation, PMP; this is estimated from a rather involved procedure based on information from maps and tables;

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- both summer and winter PMPs should be applied to see which gives the larger flood;
- the time to peak of the unit hydrograph is reduced by one third to account for the more rapid response of an exceptional flood;
- when applying the winter PMP, the standard percentage runoff is set to a minimum of 53% to account for frozen ground;
- when applying the winter PMP snowmelt should be considered;
- the catchment wetness index is increased to allow for greater antecedent rainfall.

Recent Near-Misses

Dams which threaten lives in a community must be assessed using the PMF. The incidence of near-misses and severe floods in the last two decades raises a number of questions, i.e. (i) have all category A dams been assessed against the current estimates of the PMP and PMF? and (ii) are the current estimates of the PMP/PMF sufficiently accurate; has the frequency of the PMP been underestimated. The experience of Thirlmere during Storm Desmond in December 2015 suggests that some and maybe many of the Category A reservoirs have not been assessed against current estimates of the PMP. After Storm Desmond, United Utilities commissioned studies utilising the current estimates of the PMP to identify the PMF for this reservoir. Why was this not done before Storm Desmond? After all, the latest estimates of the PMP were published in 2013 [3]. When this question was put to an Environment Agency employee involved in reservoir safety, they said they were not aware of this publication.

Guidance (2015)

The most recent guidance comes in the form of a book written by the ICE Working Party on Floods and Reservoir Safety [4]. This was published in 2015 and is the fourth edition. This has not been reviewed here.

Review of the Strategy for Reservoir Safety Research (2016)

A review of the strategy for reservoir safety research in 2016 made the following statements:

'Extreme flooding remains one of the main threats to reservoir safety. Flood safety studies, investigations and improvements in spillway capacity commonly feature in reports by panel engineers. Flood overtopping is the most common type of recorded incident at reservoirs nationally and internationally. Following interim advice from Defra in 2004 in relation to the application of available methodologies to reservoir flood safety evaluations, work has continued to improve estimates of extreme rainfall estimation (Stewart et al. 2010). The new rainfall estimates for return periods up to 10,000-year return period (excluding PMP) developed by the Centre for Ecology and Hydrology (CEH) were made available in 2015. The next step will be to review the rainfall–runoff methodology for developing flood hydrographs from the rainfall data and catchment characteristics. There are a number of possible techniques covered in the literature which could inform this research'.

The Need to Update Methods

Faulkner and Benn (2016) [6] have stated that there have been instances of both PMP and PMF being exceeded. Faulkner and Benn stated that:

'Design floods for reservoirs in the UK and Ireland are currently estimated using a method that in many respects has not changed since the Flood Studies Report of 1975. Although estimates of design rainfall for reservoirs in the UK have recently been updated, other aspects of the design method and the estimation of probable maximum precipitation (PMP) are dated.'

The paper by Faulkner and Benn gives an overview of aspects of the design flood estimation procedure that are in need of an update. Discrepancies are identified between the different methods used to calculate percentage runoff and time to peak for the 10,000-year flood and the probable maximum flood. The pros and cons of adopting the newer Revitalised Flood Hydrograph rainfall-runoff method for reservoir safety work are discussed and suggestions offered for development of an up-to-date method for reservoir flood estimation that builds on existing methods, with the aim of improving understanding

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of the liabilities associated with dams and reducing the risk of dam failures. Together with the work of Stewart et al. [3] the paper by Faulkner and Benn [6] shows that the science of reservoir safety is developing but the methods of safety assessment require revision.

A Recent Conference

A joint meeting of the British Hydrological Society and the British Dam Society on UK Reservoir Spillway Hydrology was held in March 2019. Several of the presentations from the meeting are available on the website of the British Hydrological Society and have been reviewed.

In a presentation titled ‘Flood Estimation for Reservoir Safety: An Inspecting Engineer’s Perspective’, Alan Warren of Mott MacDonald Ltd provided the following illustration (**Table 1**) of how changes in guidance could affect a hypothetical reservoir.

Table 1: Hypothetical impact on flood safety at a reservoir over time.

Inspection	Inspection flood review outcome	Consequence on flood safety design
1940	First inspection by panel engineer	Spillway weir lengthened
1950	New estimate of catchment data	Dam embankment core raised
1960	Catchwater included	Wave wall added
1970	New rainfall DDF or rainfall-runoff model	Spillway weir changed to ogee type
1980	New guidance on application of research	Dam crest raising
1990	Change in reservoir consequence class	Auxiliary spillway added
2000	New rainfall DDF or rainfall-runoff model	Wave wall strengthened
2010	New guidance on application of research	Main spillway relined
2020	??	??Any plausible further improvements??

The presentation made the following conclusions:

- Flood estimation is one of the most critical factors in determining whether a dam is adequately safe.
- Despite improvements in flood estimation methods and guidance, flood-related issues dominate incident statistics, accounting for approximately one third of UK dam failures and near-misses.
- Flood estimation is relevant to engineers/operators throughout the ‘life cycle’ of a reservoir.
- Changes in flood estimation techniques/guidance mean that flood safety reviews and flood safety improvement measures are common outcomes from the 10-year reservoir safety review cycle in the UK.

In a presentation titled ‘Precision and accuracy of Unit Hydrograph parameters for gauged and ungauged basins: Can we do better?’, Dr Ian Littlewood concluded that:

- Improved techniques for identifying UHs (e.g. IHACRES) have not been acknowledged by, or evaluated for, UK engineering flood hydrology.
- UK engineering design flood hydrology is ‘stuck’ – it is resistant to substantial improvement because it is too-heavily invested in conceptually unrealistic unit hydrograph shapes (dating from 1975/1999, 2005).
- The ‘flood hydrology road map’ (EA) acknowledges that “Many of the methods we use are dated and based on approaches developed in the 1970s - 1990s” and aims to “develop a vision of flood hydrology 10-20 years from now”.

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In a presentation titled "Reflections on UK Reservoir Design Flood Estimation", David MacDonald stated that there are some perceived problems with FEH version of UH rainfall-runoff model, i.e.

- Some PMP estimates may be too small.
- Nested bell-shaped storm profile is overly conservative for long durations.

He asked if we need a new rainfall-runoff model for reservoir design flood estimation and his answer was 'Yes'.

Colin Clark and James Dent in their presentation examine the accuracy of the estimates of the PMP. They present several examples from around the world including the UK where the PMP is underestimated.

They say that the Long Return Period Rainfall Report [3] gives a depth of 200 mm for 1 in 100,000-year 24-hour rainfall for St Mawgan. This suggests a 1 in a million-year rainfall of 245 mm but this value has been exceeded in several places in SW England.

Clark and Dent give an example of where the PMF has been determined at 50 cumecs using established methods only for the same location to experience a PMF of 140 cumecs a short time later.

Clark and Dent also examined the return period of the 2009 flood in Cockermouth and Workington and found that established methods put the return period at 700-2,100 years while their method puts it at 130-600 years. This suggests that established methods say that extreme floods are rarer than they actually area. Put another way, extreme floods are more common than established methods suggest. More importantly, this also suggests that an extreme flood of a given return period (e.g. the 10,000-year event that reservoirs are supposed to cope with) could have a greater peak flow than established methods suggest. Therefore, if established methods are used to identify the peak flow of a 1 in 10,000-year flood, it will be smaller than the flow that could actually occur. That is, established methods underestimate the risk.

Conclusions

The operation of large reservoirs is regulated by the Reservoir Act (1975). This describes a system whereby large reservoirs are inspected by suitably qualified so-called 'panel engineers' at least once every ten years. Despite the existence of this system, there have been several near-misses with reservoir safety in recent years. This review has identified five between 2005 and 2019. Some of these have been so serious that there has been a real possibility of loss of life. In addition to these incidents, there have been other incidents where reservoirs have suffered severe structural damage during a flood. Thirlmere reservoir during Storm Desmond is one of these. It is also informative to note that Toddbrook Reservoir was signed off as safe in 2018 only to almost fail in 2019.

Over the years, DEFRA has issued updated guidance to panel engineers is response to scientific developments. This has highlighted difficulties in defining the Probable Maximum Precipitation that reservoirs must be able to cope with. This led to further research and amendments to the method of calculating the Probable Maximum Flood. These amendments were introduced by the EA in 2013. A review of the current strategy for reservoir safety research (2016) stated that '*The next step will be to review the rainfall–runoff methodology for developing flood hydrographs from the rainfall data and catchment characteristics. There are a number of possible techniques covered in the literature which could inform this research'*. In the meantime, serious incidents threatening loss of life such as that at Toddbrook Reservoir continue to happen.

Perhaps the most important finding is that there have been several instances of the PMP being exceeded in Britain in recent years. This raises the possibility that the values of the PMP across Britain have been underestimated. This could mean that reservoirs have been signed off as safe against a flood that is not the most serious that could happen. Several published papers and presentations at meeting of leaned societies have stated that aspects of the safety assessment process are dated and that revision is required. One states that UK engineering design flood hydrology is 'stuck' – it is resistant to substantial improvement because it is too-heavily invested in unrealistic concepts dating from 1975, 1999 and 2005.

Examples of where flood frequencies have been overestimated and PMPs underestimated raises the possibility that reservoirs are being certified as safe against flows that are too small and occur too often. This increases the risk to life in communities close to these reservoirs.

References

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