The Implications of the 2007 Summer Storms for UK Reservoir Safety

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SYNOPSIS. This paper discusses the impact on reservoirs of the storms that affected north-east England and the Gloucestershire region in June and July 2007. The incident at Ulley Reservoir was well publicised and there were a large number of other dams that were overtopped and /or damaged by these storm events. The paper aims to:

- Evaluate the meteorological and statistical significance of the storm events experienced in the two regions;
- Summarise the impacts on reservoirs in both regions;
- Comment on the possible implications for reservoir safety operation, management and legislation; and
- Comment on how current research into extreme rainfall events should improve flood risk assessments for dam safety in the UK.

INTRODUCTION

Two separate storm events in England in the summer of 2007 led to widespread flooding which was widely covered by the national media. This paper aims to evaluate the meteorological and statistical significance of the storm events and to discuss the impacts on reservoirs. The incident at Ulley reservoir near Rotherham was particularly notable, where erosion adjacent to an old masonry spillway channel almost led to the failure of a large reservoir. The impact of a failure of this dam would have been significant both in terms of risk to life and damage and disruption to major infrastructure. However, all of the reservoirs in the two affected areas were affected by the storms to differing extents. It is appropriate, especially in the face of climate change, to review the impact of these floods with respect to current reservoir flood safety provisions in the UK.

Ensuring reservoir safety into the future. Thomas Telford, London, 2008

METEOROLOGICAL SIGNIFICANCE OF THE 2007 STORMS

The late spring and early summer periods in 2007 were exceptionally wet throughout the UK, causing widespread and repeated flooding during June and July. According to Pitt (2007), this was the wettest ever May to July period since national records began in 1766. The most significant flood events followed two particularly extreme storm events, one on 24 to 25 June which affected a band across England from Worcestershire to the North York Moors, and the other on 19 to 20 July which gave rise to flooding in Gloucestershire, the Midlands and south-east England.

Following the first of these storms, the potential threat of the structural damage experienced at Ulley Dam hit the headlines when the M1 was closed for 40 hours and 1000 people were evacuated from their homes. The rainfall event which triggered the alert was caused by a deep area of low pressure moving gradually eastwards. Frontal systems around the northern side of the depression affected a vast swathe of north-east England, the Midlands, Wales and south-west England. Rainfall totals were exceptional, with more than 90 mm of rain in 18 hours being recorded in the Rotherham area (Environment Agency, 2007[1]). The Flood Estimation Handbook's rainfall depth-duration frequency model estimates the return period of such an event to be about 100 years (an annual probability of occurrence of 1%). Thus, while the rainfall event which triggered the damage to the spillway was reasonably rare, it was far from being a very extreme event in itself. However, it followed a remarkably wet spring period, and heavy rainfall had affected much of northern England on 14 to 15 June, leaving many catchments very vulnerable to further rainfall (Marsh and Hannaford, 2008). It has been estimated (Environment Agency, 2007[1]) that the return period of the flood flows at Sheffield and Rotherham was about 200 years.

The second major storm on 19 to 20 July was again caused by a slow-moving depression, this time centred over south-east England. Heavy rainfall moved northward and exceptional storm totals were recorded across the Cotswolds and the lower part of the Warwickshire Avon catchment. The rainfall totals recorded were somewhat higher than those of the June event in northern England, with 142.6 mm being recorded in 24 hours at Pershore College in Worcestershire (Marsh and Hannaford, 2008). The estimated return period of this event from the FEH model is over 800 years and the extreme rainfall was remarkably widespread, although the return period of the resulting fluvial flooding has been estimated to be about 200 years.

It is not unusual for extreme rainfall events to occur in the summer in the UK, but as they are generally caused by convective storms, they tend to be isolated, although their effects can be devastating as demonstrated by the Boscastle floods in August 2004. It is, however, very rare for summer flooding to be experienced on a regional rather than catchment scale. The distinguishing feature of the storms experienced in the summer of 2007 is that, although they were caused by embedded convection, they were associated with a succession of frontal systems which persisted for many weeks. Blackburn *et al.* (2007) attribute the unusual summer weather patterns to a southerly shift in the position of the jet stream steering Atlantic weather systems across the UK. It is interesting to note that current climate change projections point towards drier summers in the UK, associated with a poleward shift of the storm track; that is the opposite of the situation that pertained last summer.

VULNERABILITY OF DAMS TO EXTREME FLOODS

Flood-related damage to dams in the UK

The overtopping of dams in flood events is a major cause of dam damage and failure in many parts of the world. ICOLD (1995) report that, globally, floods account for 51% of dam failures. The Machhu II failure in India was attributed to the overtopping of a 26m high dam that failed resulting in the death of 2000 people (Charles, 2005). In the UK, many of the most notable dam failures have also been due wholly or partly to overtopping, whereby the hydraulic capacity of the spillway facilities and the available freeboard to the lowest point on the dam crest was insufficient to prevent the uncontrolled flow of water onto the downstream face of the dam. Significant flood-related failures include Darwen (12 lives lost in 1848), Cwm Carne (12 lives lost in 1875) and Skelmorlie (5 lives lost in 1925). There have been no lives lost due to dam failure in the UK since the introduction of reservoir safety legislation in 1930, but many dams have been overtopped. White (1994) lists four dam failures for the period 1960-71.

The failure of an embankment dam when overtopped is not assured and depends on various factors including the duration of the overtopping event, the nature of the ground cover on the downstream face and the velocity (erosive power) of the water flow. Hughes and Hoskins (1994) provide a useful summary on the wide range of factors that can contribute to the risk of damage to an embankment during an overtopping event and guidance on mitigating the risk. Erosion of the downstream face is not the only means by which dam integrity is threatened during floods. An embankment dam under flood conditions is at increased risk of damage due to:

- internal erosion during or at some time long after the flood event (refer to Defra, 2003);
- wave damage;
- unnatural flood inflows, for example due to the failure of an upstream dam.

ENSURING RESERVOIR SAFETY

Charles (2002) provides a summary of historical dam failure events in the UK. The Environment Agency intends to publish reports on reservoir incidents annually and an update on the progress of the voluntary reporting system has been provided (Hamilton-King *et al.*, 2008). Analysis of the national incident database administered by the Environment Agency was carried out for incidents at dams arising from flood inflow. Incidents were grouped as pre- and post-1985; 1985 being the year when the current UK reservoir legislation and safety regime came into force.

Table 1. Incidents where flood inflow was the primary threat to the dam

Incident Severity*	**1799-1985**	**Post-1985**
Level 1	10	1
Level 2	14	5
Level 3	1	7

*Level 1: Dam failure; Level 2: Emergency actions taken; Level 3: Precautionary actions taken.

Table 2. Incidents where the dam was overtopped

Incident Severity	**1799-1985**	**Post-1985**
Level 1	10	1
Level 2	11	4
Level 3	1	5

It should be noted that the incident statistics in Tables 1 and 2 do not accurately reflect the frequency of occurrence (particularly for Level 3 incidents) as the database has historically only captured well-publicized incidents. Recent developments in incident reporting have improved the level of reporting but reporting currently remains on a voluntary basis and hence the level of reporting is less than complete.

Guidance on reservoir flood safety provisions

When the Reservoirs (Safety Provisions) Act 1930 came into force, there was a diversity of opinion on appropriate levels of reservoir flood safety. In 1933, the Council of the ICE published guidance entitled *Interim report of the Committee on Floods in Relation to Reservoir Practice.* This guidance was updated in 1960 following the Lynmouth disaster of 1952. The publication of the *Flood Studies Report* (FSR) (NERC, 1975) and *Floods and Reservoir Safety* (ICE, 1978) provided new guidance on appropriate levels of flood safety and contributed to the large increase in spillway-related improvement works in Great Britain in the 1980's and 1990's. The ICE guidance on flood safety provisions was primarily aimed at panel engineers in relation to statutory reservoirs. Specific guidance for the design and maintenance of small reservoirs has since been provided (CIRIA, 1996) which draws from the ICE guidance. The Flood Estimation Handbook

(FEH) (Institute of Hydrology, 1999) did not aim to specifically address the estimation of very extreme flood events and as such was of limited relevance to the design of spillway facilities for reservoirs that pose a high degree of risk to downstream persons and property. Over recent years Defra has issued guidance notes for panel engineers in the use of the FSR and FEH in relation to spillway design and the Cox report (2003) reviewed the use of the FEH in the estimation of extreme rainfall. A revised model of rainfall frequency estimation and updated guidance are currently in preparation by the CEH and this is covered below.

Best practice in relation to spillway design or improvement is generally applied to large reservoirs through the provisions of the Reservoirs Act 1975. Qualified engineers who are familiar with the various flood safety guidelines are required to certify the adequacy of spillway provisions for statutory reservoirs. There are no such provisions for smaller, non-statutory reservoirs and the risk of small dam embankments being overtopped during floods is believed to be far greater than that for statutory reservoir embankments (Goff and Warren, 2008).

THE IMPACT OF THE 2007 FLOODS ON RESERVOIRS

Of the twelve reportable incidents held on the national database for incidents in 2007, eight were attributable to flood inflow.

Ulley Reservoir

A stepped masonry spillway failed at Ulley Dam near Rotherham on 25 June 2007 and was very similar to the failure of the stepped masonry at Boltby dam near Thirsk on 19 June 2005. The masonry spillway had been supplemented by a larger concrete spillway in 1943. However, the arrangement of the design meant that the older, stepped masonry spillway always operated preferentially. It appears that the masonry had lost much of its pointing and had little bedding mortar between the blocks. The unusually high flow conditions in the stepped channel might have led to the development of high hydrodynamic pressures within the walling, leading to the collapse of the wall and the subsequent erosion of the embankment fill material. The resulting loss of support to the dam core, and fear for the stability of the dam led to the closure of the M1 motorway and a widespread evacuation downstream of the dam. This particular incident has led many to question the performance of masonry stepped spillways and it seems clear that research is warranted.

Other reservoirs in the north-east

Reporting of the impact of the storms in the north-east is mostly anecdotal as not all the incidents would have been judged as reportable, and others were not formally reported to the Environment Agency for various other reasons. It is believed that more than 20 reservoirs were in some way damaged or endangered by the storm event in this region. The industry is also aware that there were several other examples of where masonry spillway channels were damaged by spillwater, but no details are currently available. This further underlines the need for research.

At two separate incidents, embankments were overtopped that featured sheet piles that had been installed to raise the crest level. Both suffered damage by erosion to the crest and downstream face.

A further incident arose at a reservoir which is located in a catchment area where the geology is predominantly chalk. The overflow spillway system was overwhelmed by the amount of groundwater issuing from a chalk escarpment and the dam embankment was overtopped.

Reservoirs in the Gloucestershire region

The number of reservoirs affected by the storms in the Gloucestershire area was far fewer than the number in the north-east, largely due to the fact that the areal density of reservoirs in this area is less than that in the north-east. It appears that the statutory reservoirs in the region were not seriously affected by the storms. This may be in part due to the fact that most of the larger reservoirs would have had available storage at this time of the year such that the flood runoff volume was partly or wholly absorbed. In addition, statutory reservoirs generally have well sized and designed spillway facilities capable of dealing with large floods. However, there were several non-statutory reservoirs that did not fare so well. Non-statutory reservoirs are often kept full or near full to serve some amenity function and therefore only the effectiveness of the spillway facilities can prevent overtopping in such circumstances when floods arise. To compound the threat to non-statutory reservoirs, these generally have spillway design capacities well below that of statutory reservoirs and are generally not so well maintained.

We are aware of two reservoir incidents in the Gloucestershire area that caused alarm, both at non-statutory reservoirs. In the first case (Incident 313) the dam crest had not been maintained at a uniform elevation and this led to overtopping of the embankment at the low spot and erosion steps to form on the downstream face. Monitoring of a seepage point at the toe over the following three months led to concern that internal erosion was occurring and the embankment was grouted in addition to repairs to the downstream face.

In the second case (Incident 321), a statutory reservoir had been discontinued but left with inadequate spillway provision. The dam was very nearly overtopped during the flood event. A panel engineer was called to the scene but was initially unable to reach the reservoir due to the transport disruption.

IMPLICATIONS FOR RESERVOIR OPERATION, SURVEILLANCE AND LEGISLATION

Flood events represent one of the principal threats to reservoir safety and this is widely acknowledged in the guidance and training given to reservoir operators and engineers. The great majority of statutory reservoirs are provided with spillway facilities able to withstand floods of return period far greater than that experienced in either the north-east or the Gloucestershire areas in 2007. It is therefore surprising perhaps that we continue to be able to learn so much about the safety of reservoirs when moderately severe flood events occur.

Operation

Ideally, where reservoirs have poor provisions for dealing with floods, operators should be encouraged to either address the problem or to maintain some flood storage below the spill level. Currently, there are many problems in promoting or enforcing such behaviour:

- the problem generally only arises at a proportion of non-statutory reservoirs;
- there is currently no comprehensive database of non-statutory reservoirs that pose a significant risk were they to fail and hence no database of reservoir owners from which to impart good advice;
- non-statutory reservoirs are often kept full to meet some amenity purpose such as fishing;
- non-statutory reservoirs often do not have operable draw-offs by which the reservoir level could be effectively maintained below the spill level.

Surveillance

Flood events can highlight deficiencies in surveillance, especially when ‘near miss’ incidents arise. Experience shows that surveillance at non-statutory reservoirs varies from excellent to none and usually the personnel involved in the surveillance have no formal training in dam safety. In contrast, statutory reservoirs are provided with a suitably trained Supervising Engineer that is able to check on the condition of the dam following a flood event and to take appropriate steps to rectify defects and monitor performance.

The Ulley incident has caused some concern for the owners of masonry-lined spillway channels who will need to take account of the findings of any future research to ensure that such channels are maintained appropriately and kept under surveillance to ensure adequate performance under flood conditions.

Legislation

It seems very likely that many reportable reservoir incidents arose during the 2007 floods that were not reported by major reservoir owners. We will never know whether the implementation of a mandatory system of incident reporting some years ago might possibly have prevented the Boltby and Ulley incidents. However it now seems very likely that mandatory incident reporting will be introduced in Great Britain (Environment Agency, 2007[2]). The Ulley incident also underlined the need for effective emergency planning and measures were already in preparation for the production of inundation maps and response procedures. These provisions are due to be implemented for statutory reservoirs from 2009 (Environment Agency, 2007[2]).

The flood events have also served to remind us that non-statutory reservoirs are far more likely to be adversely affected by flood events than statutory reservoirs (Goff and Warren, 2008). While the hazard that such reservoirs pose is generally small, many pose a significant risk to life and there is currently no effective legislation to assess the risk and make adequate provision for design, monitoring and surveillance as might be appropriate.

CURRENT RESEARCH ON EXTREME RAINFALL FOR RESERVOIR FLOOD SAFETY

An ongoing research project funded by Defra is reconsidering the basis of the rainfall frequency model developed as part of the FEH (Institute of Hydrology, 1999) with particular reference to the estimation of very long return period rainfall. The project aims to develop an alternative depth-duration-frequency model that is specifically designed to deliver frequency estimates for return periods of between 100 and 10,000 years with applications in reservoir flood safety assessment. A number of aspects of the current model are being examined, notably the way in which information from different sites is pooled together and the importance of spatial dependence in the estimation of rainfall extremes across the range of return periods. In addition, recommendations will be made about the applicability of the estimates of probable maximum precipitation (PMP) for the UK which, although not revisited since 1975, still forms part of the ICE guidance for reservoir flood assessment (ICE, 1996).

Although the study will deliver a revised procedure for the estimation of design rainfall depths for return periods of 100 years and above, the research does not include an evaluation of rainfall-runoff modelling for reservoir safety.

CONCLUSIONS

The summer 2007 floods served to highlight a diverse range of reservoir safety issues:

Response

- the benefits of formal emergency planning and inundation mapping;
- the difficulties of reaching reservoirs to provide advice or to undertake emergency measures during severe floods.

Robustness of intrinsic dam design

- there appears to be a need for further research into the performance of masonry-lined spillway channels;
- crest-raising works using sheet piles must take into account the impact of overtopping events;
- spillway systems for reservoirs in catchment areas with well developed groundwater systems should be checked to ensure an appropriate level of protection against overtopping;
- effective draw-off or bottom outlet works enable operators to effectively provide flood storage but many small reservoirs have no such facility and inadequate spillway/freeboard provisions.

Monitoring and surveillance

- the floods served to highlight the fact that the provision of monitoring and surveillance at non-statutory reservoirs varies greatly, and is not carried out at some reservoirs. The dams forming many non-statutory reservoirs would pose a risk to life were they to fail.
- Where unusually high reservoir levels have been experienced (with or without overtopping of the crest) the monitoring and surveillance frequency should be increased for embankment dams over the months following any severe flood events to check for signs of internal erosion.

Industry issues and legislation

- the flood events have served to support the need for legislation in relation to both emergency planning and mandatory incident reporting;
- there appears to be a need to appraise the risk posed by non-statutory reservoirs and to provide appropriate legislation and guidelines for panel engineers. It would appear reasonable that a person living downstream of a small reservoir is equally deserving of an

appropriate level of statutory protection as that for a person downstream of a large reservoir.

- there is current research being carried out to re-evaluate the risk of extreme rainfall events for application to reservoir safety;
- flood events do not always occur in a traditional manner according to the season and may not conform to postulated climate change trends.

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