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THE TODDBROOK RESERVOIR SPILLWAY INCIDENT AND EMERGENCY RESPONSE

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ABSTRACT

In August 2019, Toddbrook Reservoir in north-west England was affected by two storm events in quick succession, resulting in damage to the auxiliary spillway, located on the main earth embankment dam. The concrete lining to the auxiliary spillway was damaged in passing the flood event and water erosion of the underlying dam shoulder material occurred, prompting fears of a dam breach and the emergency evacuation of approximately 1500 persons from the downstream town of Whaley Bridge. Emergency services were mobilised and the scour hole was infilled with the assistance of a helicopter. Stream diversion and pumping works were initiated to empty the reservoir. One week following the incident, the downstream residents were allowed to return to their homes.

This paper will provide some insight to the history of the reservoir, the events leading up to the incident and the effectiveness of the emergency response.

1. INTRODUCTION

The UK has an excellent record in dam safety. There has been no loss of life from dam failure since 1925. However, there have been many serious incidents requiring emergency response activities to avert potentially dangerous escapes of water from reservoirs. Legislation was first introduced in 1930 to introduce regulatory controls for the design, construction, periodic inspection and removal of reservoirs. The current legislation for England and Wales is the Reservoirs Act 1975 (the Act). The Act sets out the responsibilities of reservoir owners and operators in maintaining records, carrying out monitoring and surveillance activities, appointing a Supervising Engineer to oversee the safety management of the reservoir and Inspecting Engineers to carry out periodic independent safety reviews. For England, the government regulatory body is the Environment Agency (EA). Over 2000 reservoirs in England are currently regulated under the Act. It is widely considered that the regulatory controls imposed in the UK brought a marked improvement in reservoir safety standards. Under current UK spillway design guidelines (ICE, 2015), all reservoirs that pose a risk to persons living in a community should have design provisions to accommodate a 1 in 10,000 year flood event without significant damage and should not fail under the Probable Maximum Flood (PMF) event. Hence, the risk of a community being at risk of a dam failing due to a flood event should theoretically be close to zero.

The EA have operated a system of post-incident reporting since 2007 (Hamilton-King et al, 2008). Through an amendment to the Act in 2013, it became a mandatory requirement to report any serious incident. The EA publishes annual reports on all reported incidents. Typically, there are a few serious incidents each year requiring urgent intervention activities. The dam failures that have occurred in recent times have occurred at small non-statutory reservoirs of less than 25,000m^3 capacity. No regulated reservoir in the UK has failed since 1970 when the Warmwithens dam failed due to internal erosion (CIRIA, 2014). There have however been three incidents in the present century involving flood events which gave rise to population evacuations and an emergency response to preserve dam safety, namely the incidents at Ulley (2007, England), Cwm Ebol (2012, Wales) and Toddbrook (2019, England). This paper describes the incident at Toddbrook Reservoir which gave rise to the largest civilian evacuation in the UK since World War II.

2. TODDBROOK RESERVOIR

2.1 Original Construction

Toddbrook Reservoir was constructed in 1931, providing a feed to the Peak Forest Canal. It is owned and managed by the Canal & River Trust (the 'Trust'). It is a Category A dam (ICE, 2015), meaning that it poses a risk to lives in

a community downstream of the reservoir, and holds 1.3 million m^3 of water behind a 24m high earthfill dam, with a central puddle clay core. The reservoir features a bywash on the northern bank of the reservoir which can be used to pass a proportion of the reservoir inflow around the reservoir and into the primary spillway channel down the left mitre of the dam embankment. A gated inlet to the bywash channel is provided at the inlet weir located at the head of the reservoir. The main features of the reservoir are shown in Figure 1.

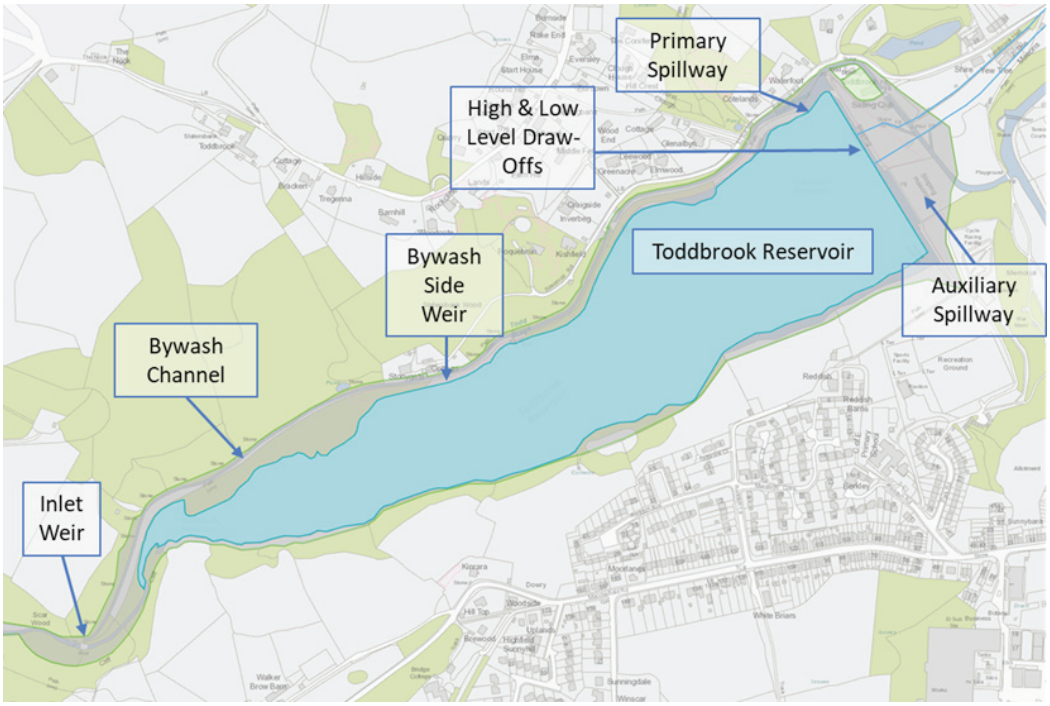

Figure 1 : Features of Toddbrook Reservoir

2.2 Reservoir characteristics

The main characteristics of the reservoir are given in Table 1.

Table 1 : Toddbrook Reservoir characteristics

Characteristic	Value
Dam category	A
Full supply level (primary weir level)	185.690mAD
Auxiliary weir level	185.854mAD
Capacity	1,238,200m^3
Surface area	0.158km^2
Catchment area	17.3km^2
Dam height	23.8m
Dam length	310m
Crest width	4 to 5m

2.3 Auxiliary spillway works

In 1964, Toddbrook Reservoir experienced a severe flood and the level in the reservoir basin was above full supply level (FSL) for a number of days, with spill flows being conveyed by the original masonry spillway. This resulted in damage to the lower section of the spillway chute, with sections of the side walls being washed out and erosion of the right bank adjacent to the downstream toe of the dam. The channel was repaired in 1966 and, in the 1968 report of an Inspection under section 2 of the Reservoirs (Safety Provisions) Act 1930, the Inspecting Engineer commented:

'*Following certain recommendations made by me in a letter on 9th December 1966, the Owner has undertaken to prepare a scheme and invite tenders for a new emergency spillweir near the centre of the dam.*'

Between May 1969 and March 1970, construction of a new concrete auxiliary spillway was completed, located on the dam embankment. This supplemented the original primary masonry spillway weir located at the left abutment. The auxiliary spillway is 76.2 m long and was originally constructed 0.26 m above the level of the original weir, according

to the safety records. However, recent surveys have shown the level difference between the two weirs to be only 164mm (Table 1).

During 1982 the side walls of the auxiliary spillway were raised to contain extreme flood flows, following recommendations by an Inspecting Engineer. In the 2006 safety inspection report, under section 10 of the Act, the Inspecting engineer, made the following recommendation;

'*Modifications are required to improve the hydraulic performance of the auxiliary spillway and to guard against potential overtopping of the channel during flood discharges*'.

Works were completed in 2008, to again raise the spillway side walls and a 'bus shelter' style overhang was added to the lower section of the left-hand spillway wall, in order to return spill flows into the channel.

3. INCIDENT OF AUGUST 2019

3.1 Storm event

The catchment area was affected by two storm events over the period 27th-31st July 2019, the first having a return period of approximately 40 years followed two days later by a second event with a return period of approximately 90 years. Neither of the storm events could be considered severe, but the combined flow volume that impacted the reservoir was moderately rare. The rainfall and catchment flow data are shown in Figure 2.

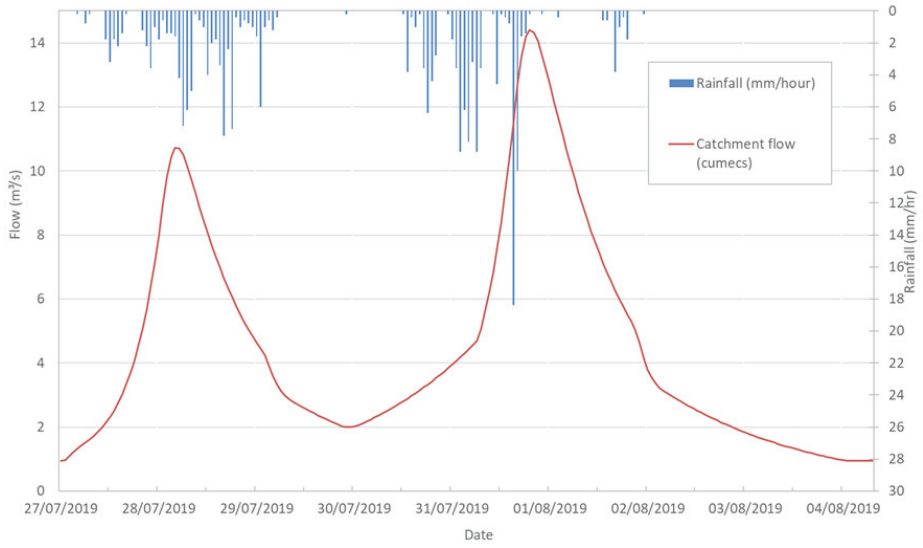

Figure 2 : Toddbrook Reservoir rainfall and catchment run-off

3.2 Days before the incident

Toddbrook Reservoir is visited twice weekly by one of the Trust's trained Reservoir Surveillance Inspectors.

The last water level reading before the incident were taken on Monday 29th July. The water level at the time was recorded at 340mm above FSL and was spilling over both the primary and auxiliary spillways. Due to the level difference between the primary and auxiliary weir crests (164mm), the auxiliary spillway operates only infrequently.

The last reservoir inspection before the incident took place on Wednesday 31st July, the day before the section of spillway failed, at which time the feed along the compensation channel was reported as being normal. Table 2 gives a timeline of the events over the days leading up to the incident.

Table 2 : Timeline of events leading up to the incident

Characteristic	Value
Sat 27th July	94mm rain fell on the catchment (equates to ~40 year return period)
Sun 28th July	Sailing club report a large increase in the level of the reservoir
Mon 29th July	Reservoir surveillance inspection Water level recorded as FSL+ 340mm
Tues 30th July	Reservoir spillways continued to operate 114mm rain fell on the catchment (equates to ~90 year return period)
Wed 31st July	Reservoir surveillance inspection
Thurs 1st Aug	Failure of a section of the auxiliary spillway

3.3 Incident development

The storm event caused substantial overflow down the auxiliary spillway as well as the primary spillway. As this was an unusual occurrence, the spill over the auxiliary spillway was filmed by a number of local people. On the morning of 1st August 2019, several of the reinforced concrete slabs protecting the downstream face of the dam collapsed. The exact mechanism of deterioration is unknown and became the subject of an ongoing government investigation following the incident. In the following few hours, the scope of the collapse increased with adjoining slabs falling into the void. Through the slab collapse, water flowing over the auxiliary weir was able to directly flow onto and erode the void, enlarging it further. The void extended under the slabs forming the downstream side of the spillway weir, eroding the fill on the downstream side of the puddle clay core.

3.4 Implementation of the emergency plan

The first report of a problem was received by Whaley Bridge Town Council office just before 9am on 1st August, reporting 'muddy water' coming out of the slabs at the base of the spillway. Another local resident also called in to report that a large section of concrete had broken away from the spillway, exposing the earth embankment below it.

The Reservoir Surveillance Inspector attended site soon after and immediately reported the severity of the situation. A decision was taken to implement the reservoir emergency drawdown plan, and the Supervising Engineer was contacted.

Both the upper and lower draw-off valves were fully opened in an attempt to begin to lower the reservoir water level.

Under normal operation, there are removable weir boards installed at a side weir halfway along the bywash channel. These divert flows back over a side weir into the reservoir. These boards were removed to allow full flow down the bywash channel and boards were installed across the overflow weir to prevent the channel overflowing back into the reservoir (Figure 3).

Figure 3 : Bywash side weir

At the head of the reservoir, a penstock controls flow into the bywash channel. Under normal operation this is left substantially closed to maintain a compensation flow down the bywash channel and to direct the majority of inflow over the inlet weir into the reservoir. This penstock was fully opened during the initial response to maximise flow into the bywash channel.

The Trust's framework contractor was contacted and works began to contact pump suppliers and mobilise pumps to the site.

Sand bags were brought to site by Derbyshire County Council (DCC) and were used at various locations around the reservoir to begin to turn flows out of the reservoir and protect the damaged section of spillway (Figure 4). The emergency services also began to arrive on site to support the incident response.

Figure 4 : Photo of sandbagging the auxiliary weir crest

When the Supervising Engineer arrived on site early afternoon, he advised the police that there was a very real risk of collapse, and that evacuation of the downstream town of Whaley Bridge was necessary. An Inspecting Engineer was also contacted at this time and a police escort was provided to bring him to site immediately.

3.5 Incident management and support

A Gold-Silver-Bronze command system was established to manage the incident. The Gold command team was set up at a Derbyshire County Council office and reported directly to a UK government committee. The Silver command team was set up on site at a football clubhouse close to the dam to provide strategic support. The Bronze command team was also based on site to provide direct support and direction. The police led the emergency response at the site until the residents were permitted to return to their homes. Regular multi-agency meetings were held throughout the first 72 hours. A rota was set up to provide 24-hour support by Trust employees, external dam specialists and a Trust reservoir engineer.

A large number of organisations provided their support through these first few days and worked together to manage the incident. In addition to Trust staff, this included:

- Kier (the Trust's framework contractor);
- Mott MacDonald (reservoir engineers);
- The Fire Service;
- The Environment Agency;
- The Royal Engineers;
- The Royal Air Force;
- Derbyshire County Council Emergency Planning Team;
- Mountain Rescue;
- Yorkshire Water;
- The Police Task Force;
- The Royal National Lifeboat Institution and Water Safe Organisation; and
- Many volunteers.

3.6 Monitoring and Surveillance

During the initial incident response and the ongoing management of the reservoir, a range of monitoring and surveillance techniques were used to supplement the on-site observations and to monitor any further movement or damage to the auxiliary spillway. Techniques used included:

- drone camera used to carry out surveillance of the void, including thermal imaging
- deformation monitoring of the damaged slabs
- monitoring of piezometers to determine any deterioration in the seepage performance of the core.

3.7 Primary spillway modifications

The primary overflow spillway is located at the left abutment of the dam and comprises a 41m long broad-crested weir discharging directly into the bywash channel. With the bywash channel in operation, flow over the weir was not modular. A crump weir had been installed a short distance downstream of the spillway weir within the bywash/spillway channel for flow measurement purposes. It was decided to remove this weir using an excavator to lower the water profile in the bywash channel and thereby increase the flow passing over the spillway weir. Once the reservoir had reduced to the point that little flow was passing over the spillway, an excavator was used to remove the sill of the spillway to further augment reservoir outflow. Care was taken not to damage the structure to a point where bywash water could flow into the reservoir.

3.8 Reservoir dewatering

In common with the majority of reservoir emergencies, the primary response action was to reduce the reservoir water level to relieve the pressure on the damaged section of dam and to reduce the volume of water that would be released in an uncontrolled manner if the dam failed. Pumps were made available by the fire services, the EA and commercial suppliers. Pump pipelines were laid at both abutments and over the dam crest. The greatest contribution to reservoir drawdown was from the commercial pumps, supplied by the Trust's framework contractor, on the right side of the reservoir, where eleven 12-inch (300mm) pipelines were deployed. This was supplemented by numerous smaller pumps provided by the fire service. The right side of the valley sloped off steeply from the edge of the reservoir so that less frequent work was needed to reposition the pumps as the reservoir water level dropped. In addition, these pump pipelines were well away from the separate activities to fill the damaged section of the dam. Little progress was made in the first day of the incident in reducing the water level as floodwater was still entering the reservoir and only a few pumps had been deployed. By the second day, all of the natural inflow was able to be diverted into the bywash channel such that the permanent outlets and pumps could more effectively draw the reservoir level down. The reservoir was substantially reduced, to 12m below FSL (less than 5% of the total volume) over the course of six days.

3.9 Inlet weir and bywash channel works

Many of the older reservoirs in the UK were constructed by first constructing a contour canal around the reservoir area to bypass the dam construction area. These are known as bywash channels. Many such channels were subsequently infilled to improve access to the edge of the reservoir. However, there are many examples of where these channels were retained to provide supply when the reservoir is substantially full. Fortunately, Toddbrook featured a functioning diversion weir at the head of the reservoir and bywash channel on the left bank. This was to prove valuable in limiting the inflow to the reservoir and to maximise the effectiveness of the permanent and auxiliary drawdown provisions.

At the head of the reservoir, a penstock controls flow into the bywash channel and the majority of flow from the upstream Todd Brook watercourse passes into the reservoir over the inlet weir and down a masonry cascade. Following the damage to the spillway, it was crucial to turn as much flow as possible out of the reservoir down the bywash channel. To this end, the inlet weir crest was raised by the construction of gabion baskets filled with sandbags, which were subsequently wrapped in plastic sheeting (Figure 5). Construction of this weir modification presented a significant challenge as access to the inlet weir is via a footpath, over a kilometre in length, which required all the materials for construction of the weir works to be transported by wheelbarrow.

Figure 5 : Inlet weir modifications

It was also necessary to reinforce low spots on the embankment dividing the bywash from the reservoir to ensure that the increased flows did not overtop and erode the dividing embankment. Sandbags were used to reinforce the dividing embankment.

3.10 Scour hole temporary repair

The stability of the upper part of the dam could not be determined due to the nature of the damage. Although the reservoir dewatering plan was in place to reduce the pressure on the damaged section of the embankment, it was recognised that any further storm event could cause the reservoir to again spill over the auxiliary spillway and cause further damage to the scour hole, potentially leading to failure of the dam.

Access to the scour hole area to transport, place and compact fill material was poor. There was no suitable location at the toe of the embankment to erect a crane. It was therefore decided to commence filling the scour hole with bags of aggregate transported by helicopter. The Royal Air Force provided a Chinook helicopter for the purpose which was capable to transporting six 1t bags at a time. By stockpiling the material close to the reservoir, the helicopter could complete its run at 10-minute intervals. A second helicopter was discussed but dismissed as two helicopters flying over the dam would be difficult to manage and would be unlikely to bring efficiencies. The helicopter was able to place the bags with high precision.

A necessary limitation of the void-filling process was that the lowermost part of the hole had to be filled first to provide support to the bags above. This meant that stability to the back of the dam core could not be provided until the hole filling was substantially complete. Fortunately, further storms which had been predicted to affect the catchment did not materialise and the dewatering plan was effective in preventing the auxiliary spillway from operating while the scour hole was being repaired.

To maximise the support to the upper part of the scour hole, grout was specified to infill the interstices of the aggregate bags. A sufficient quantity of bentonite grout could not be delivered to the site in a short time. Therefore, a cementitious grout was adopted.

The uppermost part of the scour hole could not be filled with grout as the aggregate bags could not be installed high enough to form an effective back shutter for the grout. Therefore, a structural grade polyurethane expandable foam was used to seal this part of the void by injecting the foam through holes drilled through the concrete slabs at the rear of the spillway crest. The foam was also used locally to help retain the grout at locations where otherwise the grout would escape the scour hole area e.g. under the base of the damaged left side wall of the auxiliary spillway. The works to the scour hole are shown in Figure 6.

Figure 6 : Scour hole infilling

3.11 Incident closure

The Reservoir Draw Down Plan requires 50% of the water to be removed from the reservoir in 5 days. This level was achieved after just 3.5 days.

As the reservoir was dropped to a level of -12m, projections for the reservoir water level in the days ahead were made using a spreadsheet tool which estimated the pumping rates and capacity of the scour facilities under the falling head of the reservoir and the stage-storage characteristics for the reservoir.

It was initially planned to close out the incident when the reservoir was approximately 8m below full supply level, i.e. below the elevation of the lowest part of the damaged area. This strategy was subsequently modified to the following criteria:

- the reservoir be substantially emptied to provide a storage greater than the estimated volume of flood water experienced during the recent storm event (ignoring the bywash facility);
- the dam void be filled and protected and that there are no indications of instability of the embankment; and
- pumping equipment is to remain in place.

These criteria were achieved six days after the incident was declared and the residents were permitted to return to their properties.

4. POST INCIDENT ACTIVITIES

4.1 Management activities

A comprehensive site level water management plan is now in place for Toddbrook Reservoir, in addition to a high-level management plan with the Environment Agency.

The reservoir will be maintained at a drawn down level, with the supplementary pumping in place, until such time as the repair works to the spillway can be completed. Extensive hydraulic modelling and surveying of the bywash channel has been completed to allow the reservoir to be managed at the reduced level and the impact of a range of storm events to be fully understood. To ensure the ongoing safety of the reservoir, a range of surveillance and monitoring has been implemented, including:

- regular weather forecasting;
- CCTV footage and live feeds for the inlet weir and reservoir basin;
- pump automation and alarming;
- flow gauges and level sensors in the by-wash channel and reservoir basin;
- ongoing piezometer measurement and analysis; and
- ongoing settlement monitoring and analysis.

4.2 Interim physical measures

In early 2020, works will start to construct a new temporary raised concrete weir across the full length of the auxiliary weir crest. The new weir will be approximately 1.2 high, with a lowered central 'slot' which will feed into a protected channel down the centre of the auxiliary spillway apron (Figure 7). In conjunction with the reservoir's permanent draw-off facilities and the supplementary pumping, this will allow the reservoir basin to safely pass a 1 in 10,000 year event, with the provision for flows from a higher return period event to be safely conveyed down the protected section of channel and away from the damaged area of spillway. These works will remain in place until the final spillway repair works are undertaken.

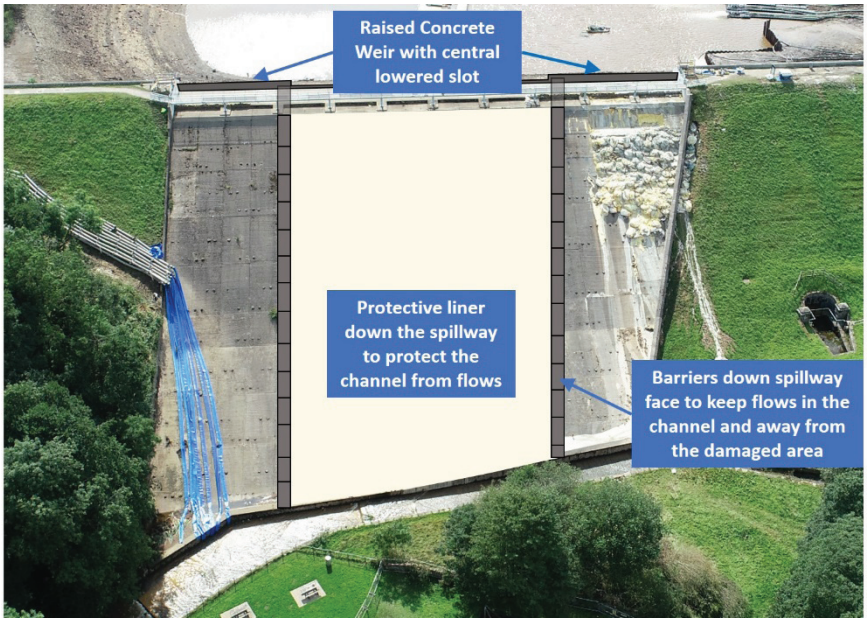

Figure 7 : Temporary weir raising works

4.3 Proposals for permanent repairs

The reservoir has been re-inspected under the Act. Once the report is issued and the ongoing temporary works are completed, options will be developed for reinstating or replacing the spillway.

4.4 Government investigation

The Trust initiated an independent investigation into the cause of the incident. In addition, the UK government instigated an independent investigation of the incident. Provision was made to review the relevant reservoir safety legislation if considered appropriate. As part of the investigation, a survey was conducted of all statutory reservoirs in England and

Wales regarding spillway construction details and the application of emergency plans. The investigation is scheduled to be completed in early 2020.

4.5 Learning from the incident

The British Dam Society are planning a seminar on the incident in early 2020 to bring together all stakeholders and to share the points of learning from the history of the reservoir, the incident development and response and the findings of the independent investigations.

5. CONCLUSIONS

The two independent investigations have yet to declare their findings and the technical details of the design, construction, operation and maintenance of the spillway structure will be the subject of future communications. The incident shares a number of commonalities with the Oroville dam incident of 2017 in the USA (Rigbey and Hartford, 2019). Auxiliary spillway structures require considerable care in their planning, design and construction, particularly where founded on erodible foundations. The incident occurred at an auxiliary spillway structure which had been constructed fifty years ago, had only rarely operated and had received numerous safety inspections.

The incident underlines the importance of maintaining suitable scour facilities to lower reservoir water level in an emergency and demonstrates the value of diversion facilities to limit reservoir inflow when attempting to manage an incident under flood conditions, particularly given the practical challenges associated with the quick deployment of supplementary pumping equipment. In planning new reservoirs or changes to existing reservoirs, consideration should be given to how access is provided to supplement drawdown facilities with pumps, siphons etc (Environment Agency, 2017).

The multi-agency incident response proved effective in managing the incident and enabling the residents of Whaley Bridge to return to their homes as quickly as possible.

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