The British Dam Society

Understanding the flood risk benefit of small reservoirs and recommendations for maintenance

P WEST, Binnies
D BULLOCK, Binnies
M COOMBS, Binnies
R RAINBOW, Teignbridge District Council
J SHIMELL, Teignbridge District Council
R NEWTON, Environment Agency (EA)

SYNOPSIS Coombe Valley Dam is a 4,500m^3 flood storage reservoir located in Teignmouth, Devon, constructed in the 1980s as compensation for development and subsequently transferred to Teignbridge District Council (TDC). As it is outside of the Reservoirs Act 1975 (HMG, 1075) (the Act), it has not had the stringent maintenance regime required for registered reservoirs that would complement its design function. However, responsibility remained under the Health & Safety at Work Act 1974 (HSWA) (HMG, 1974)and under Rylands v Fletcher 1868 (see in Howarth, 2002). Dam information had no assurance of accuracy, and the flood protection and standard were unknown.

This paper presents the hydrological study and hydraulic modelling employed to understand the dam's standard of protection and assess flood risk benefit provided by simulating a hypothetical dam removal scenario. Details of the model validation are presented to demonstrate how evidence from a recent storm was used to give confidence to the study with otherwise limited data. Assessment of the model outputs is discussed to estimate the number of properties benefiting from the reservoir.

Recommendations were made to allow TDC to operate the reservoir within the spirit of the Act. The paper provides management guidance to similar asset owners with limited experience as reservoir Undertakers (Owners and operators as defined under the Act).

INTRODUCTION

Reservoirs above 25,000m^3 capacity are currently required to be registered under the Act. However, there are significant numbers of flood storage and surface water compensation reservoirs throughout the UK that, whilst falling below the capacity required for the Act, may provide a level of flood protection which warrant assessments of their risk and maintenance within the spirit of the Act. Moreover, an estimated 1,503 additional reservoirs are likely to fall under the Act if the statutory volume is decreased from 25,000 m^3 to 10,000 m^3 (Penman and Golds, 2022). Schedule 4 of the Flood and Water and Water Management Act 2010 (HMG, 2010) makes amendments to the Act. Similar legislation changes in Wales in 2016 approximately doubled the number of statutory reservoirs.

Managing Risks for Dams and Reservoirs

Undertakers may be unaware of legislative requirements of the Act, or if they understand their reservoir to be non-statutory, may not recognise liabilities under common law, or additional duties under HSWA. Many smaller reservoirs are important assets providing a high level of flood protection which have associated risk of failure due to reduced statutory requirements. These assets would therefore benefit from being maintained in the spirit of the Act, regardless of whether they become statutory in the future.

THE SITE AND CONSTRAINTS

Coombe Valley Dam is a 4,500 m^3 capacity flood storage reservoir situated 1.5 km northwest of Teignmouth in the County of Devon along the Bitton Brook. An aerial view of the flood storage reservoir is provided in Figure 1. The embankment slopes are 1 in 3 on both the upstream and downstream faces with a 1m wide crest. A metal walkway with locked security gate provides access from the crest to an outlet tower (the 'spillway').

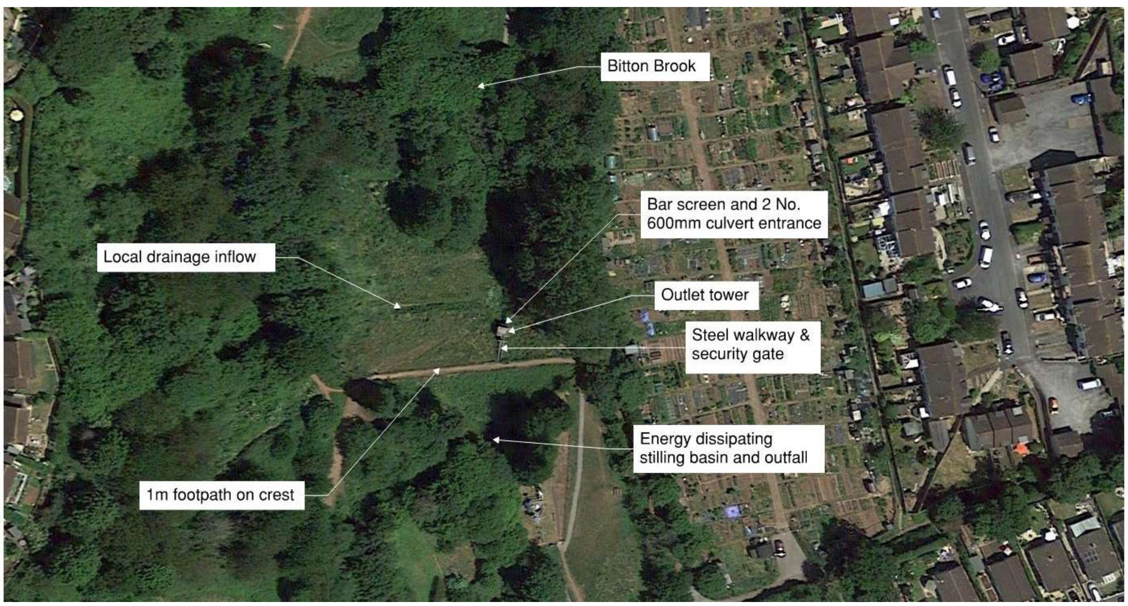

Figure 1. Coombe Valley Dam plan overview

The reservoir was constructed in conjunction with a local housing development in the 1980s with ownership later transferred to TDC. Whilst not a statutory reservoir under the Act, the Undertaker recognised their liabilities and duty under HSWA and therefore commissioned Binnies to undertake a flood study and optioneering report.

The overflow is a vertical 975mm diameter bellmouth culvert within 2.2m stacked concrete precast manhole rings. The top of the bellmouth spillway and top water level (TWL) is at 45.53m AOD according to historic drawings. The footpath crest elevation of the embankment of 46.40m AOD provides 870mm of freeboard. Dual 600mm diameter culverts at invert 40.90m AOD join the 975mm outlet culvert extending through the embankment. Upstream control is provided by two penstocks maintained at 50% open since construction. A near vertical bar screen is provided over the entrance to the culvert. An energy dissipating stilling basin is located on the downstream side which contains a concrete baffle. Historic construction drawings show the core as silty material with embankment fill detailed as gravelly material.

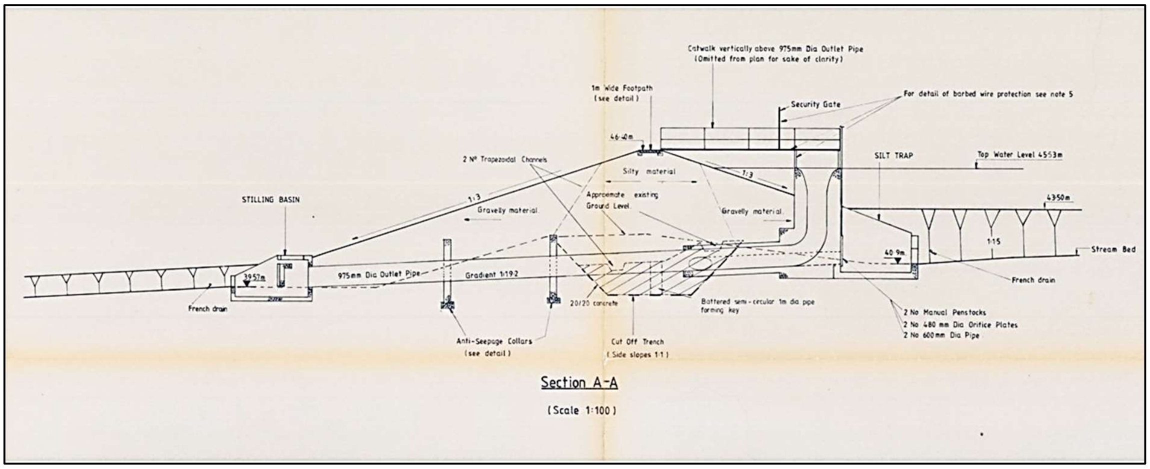

Figure 2. Dam cross section from historic drawing

Current Condition

A site visit was conducted on 4th October 2023 to assess the condition of the reservoir. Figure 3 shows the overgrown state of the upstream face and outlet structure. The vegetation encroaching on the screen above the precast manhole rings housing the 975mm overflow structure presents a blockage risk. The downstream face was similarly overgrown. Figure 4 shows the current condition of the bar screen over the dual 600mm diameter culvert entrance in connection with the overflow. TDC noted that this screen was prone to debris build-up and that cleaning it was a persistent maintenance issue due to the heavily wooded upstream catchment. TDC has a maintenance contract which includes yearly vegetation and mechanical and electrical services. The contract includes reactive grill maintenance but is not sufficient to meet the needs of the dam. TDC has considered installation of a tree catcher within the catchment to improve the issue. Vegetation was also growing in the security fence at the outlet to the downstream energy dissipating chamber, preventing surveillance of the condition within the culvert outlet.

Figure 3. Photo showing overgrown condition of upstream face and overflow structure

Figure 4. Photo of bar screen over inlet works prone to blockage.

METHODOLOGY

Overview

Greater detail regarding the dam's flood protection function needed to be established to be able to evaluate management options. Hydrological analysis and hydraulic modelling were undertaken to understand the current level of flood protection provided by the dam (the 'baseline'), and the potential impact on flood risk from its removal ('dam removal').

The modelling study approach was as follows:

1. **Hydrological analysis** to generate flows in the Bitton Brook for the catchment to the dam (the 'upstream' catchment) and the downstream catchment.
2. Flows were then routed using **hydraulic models**
    i. For the baseline scenario only, the upstream catchment flows were firstly routed through a one-dimensional (1d) model of the dam to a) understand the dam's current standard of flood protection, and b) to create attenuated flows after passing through, and potentially over, the dam control structures.
    ii. For both the baseline and dam removal scenarios, flows downstream of the dam were simulated in a two-dimensional (2d) model of the downstream catchment to understand flooding.

Catchment and Hydrological Analysis

The following summarises the hydrological approach used to estimate model inflows for the sub-catchments upstream ('catchment 1') and downstream ('catchment 2') of the dam:

1. Delineation of the **catchment boundaries** ('watersheds') for catchments 1 and 2.
2. Retrieval and review of **hydrological catchment descriptors**.
3. Determination of the **critical storm** duration for the whole catchment.
4. Calculation of **peak flow** rates for different flood events ('return periods').
5. Generation of a **hydrograph shape** to create model inflows.

The former 2016 modelling study was reviewed to confirm suitability. The 2016 study performed catchment delineation via the Flood Estimation Handbook (FEH) web-service which is based on coarser resolution data and may be inaccurate for small catchments. The Bitton Brook catchment delineation was therefore revised by performing GIS analysis on LiDAR Digital Terrain Model (DTM) data together with appropriate visual inspection. Figure 5 shows the revised Bitton Brook catchment extent in orange.

The sub-catchment to the dam ('catchment 1 previous') was calculated using the same approach (shown in Figure 5 by the yellow outline). However, following a site visit it was apparent that this calculated area did not include the areas serviced by the local surface water network draining into the upstream storage area. This was confirmed by service plans available from South West Water (SWW) as draining a portion of the area to the west of the dam that was understood in the 2016 study to be within the downstream sub-catchment.

Catchment 1 was adjusted using manual inspection of SWW's plans to include the yellow shaded areas shown in Figure 5. The updated catchment 1 is shown by the red line where

Table 1 compares catchment areas. This analysis shows that the catchment area of the dam is 0.28km^2 larger (13%) than previously estimated by a 2016 study.

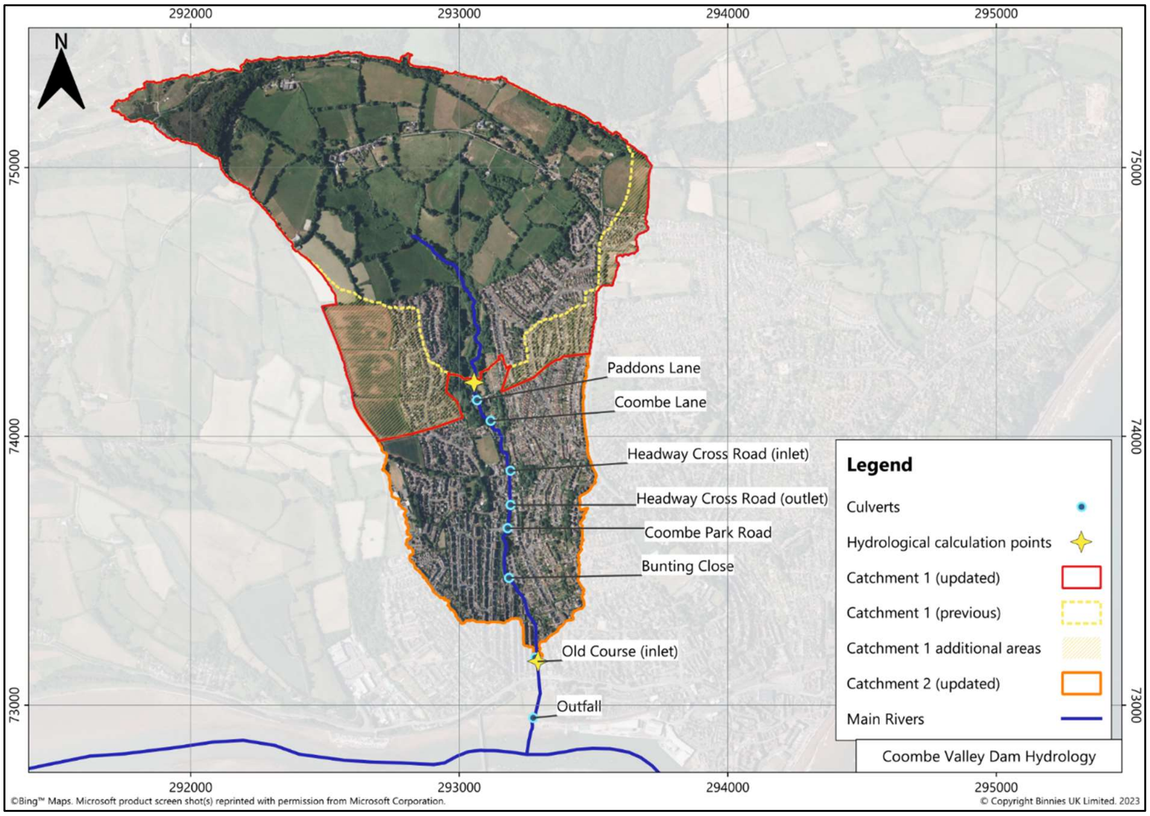

Figure 5. Revised catchment to the dam and the Bitton Brook outfall

Table 1. Catchment areas [km^2]

Catchment	Former Study	FEH	GIS analysis	Updated
Bitton Brook	n/a	1.93	2.15	**2.15**
Catchment 1	1.39	1.39	1.29	**1.57**
Catchment 2*	n/a	0.54	0.86	**0.58**

*Area for catchment 2 is the additional area such that the Bitton Brook is the sum of catchment 1 and catchment 2.

The Revitalised Flood Hydrograph 2 (ReFH2) rainfall run-off method was used to estimate peak flows. This method generates peak flows for a given flood event by routing rainfall depths for a given storm duration (Depth Duration Frequency [DDF]) through an empirical model controlled by hydrological catchment descriptors.

The storm duration was iteratively adjusted within this model to obtain the maximum peak flow rate for the whole Bitton Brook catchment. The critical duration for both catchments was found to be five hours. The ReFH2 model was also used to generate design storm hydrograph shapes for the 5-hour critical storm to which peak flows were fitted.

Reservoir Model

A 1d hydraulic model of the dam and reservoir was constructed in Flood Modeller software. This approach allowed the capacity of the reservoir and hydraulic controls (i.e. the outlet, spillway, and dam crest) to be simulated for a range of flood magnitudes. The 1d model was also used to generate outflow hydrographs from the dam to apply to the flood routing model.

Managing Risks for Dams and Reservoirs

Figure 6a shows a schematic of the 1d reservoir model 'nodes'. The model consists of an inflow connected to a 1d reservoir unit. The flow routes out of the 1d reservoir are controlled by two 1d-spill units representing the spillway and dam crest, while two orifice units represent the outlet penstocks. A small section of dummy channel with a normal depth boundary was inserted to provide a downstream boundary condition.

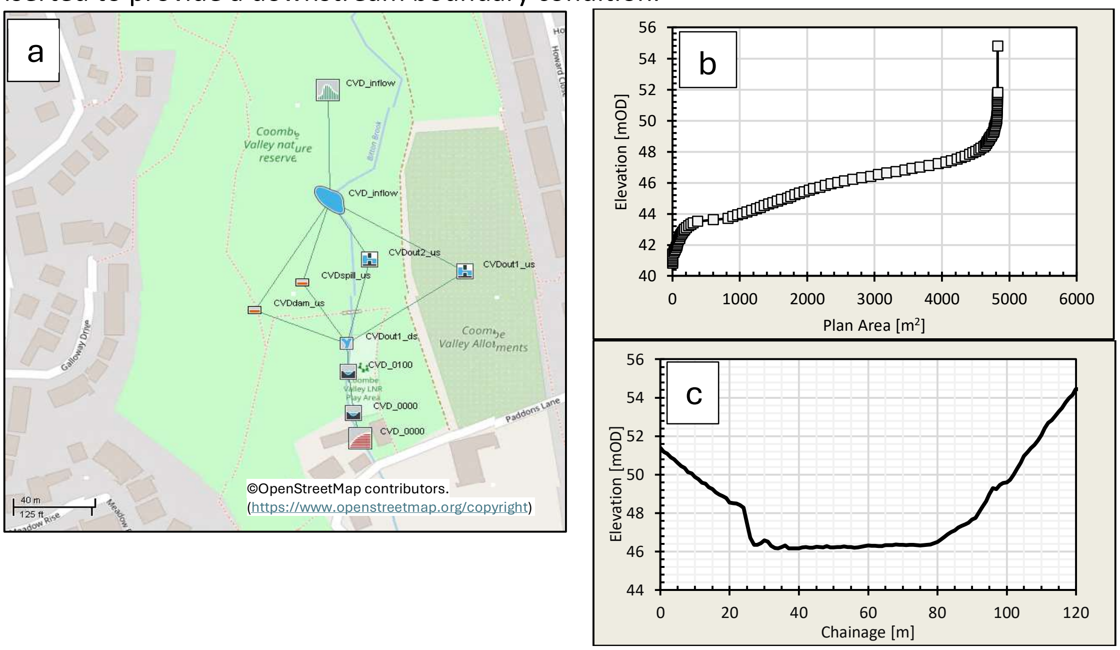

Figure 6. 1d Flood Modeller reservoir model schematisation

The capacity of the reservoir impounded by the dam was calculated using Flood Modeller's in-built 1d-reservoir tool which creates elevation-area relationships for a given input topography. The LiDAR DTM data was analysed to generate this relationship, with results shown in Figure **6**b.

The 1d spill representing the circular concrete spillway (Figure 3) was set to 45.53m AOD at a length of 3.06m as given in the 1984 design drawings. No detailed topographic survey of the dam crest was available. As such, the crest elevations were generated from GIS analysis of the LiDAR DTM, as seen in Figure 6c.

The two penstocks which control flows out of the reservoir were represented as two circular orifice units. The invert levels and bore areas of these units were defined using the 1984 design drawings. The penstocks are operated at 50% closed, as such the bore area was reduced to reflect this.

Only the existing dam conditions were simulated for the reservoir model. This is because it was assumed that, should the dam be removed, the flows passing the former location of the dam would be the same as those arriving upstream and therefore there would be no need to route these inflows through a model without the dam in-place.

Flood Routing Model

A 2d hydraulic model of the catchment downstream of the dam was constructed and simulated using TUFLOW hydraulic modelling software. TUFLOW is an industry standard tool for simulating flood flows for studies of this type.

The 2d model simulates both the channel and floodplain in 2d. Culverts were embedded in the 2d domain as 1d channel features, however the open channel sections of the Bitton Brook were not modelled as 1d elements (as is often customary) given the absence of suitable survey data. Figure 7 shows the extent of the 2d model, extending from the downstream face of the dam in the north, and ending at the frontage with the River Teign estuary in the south.

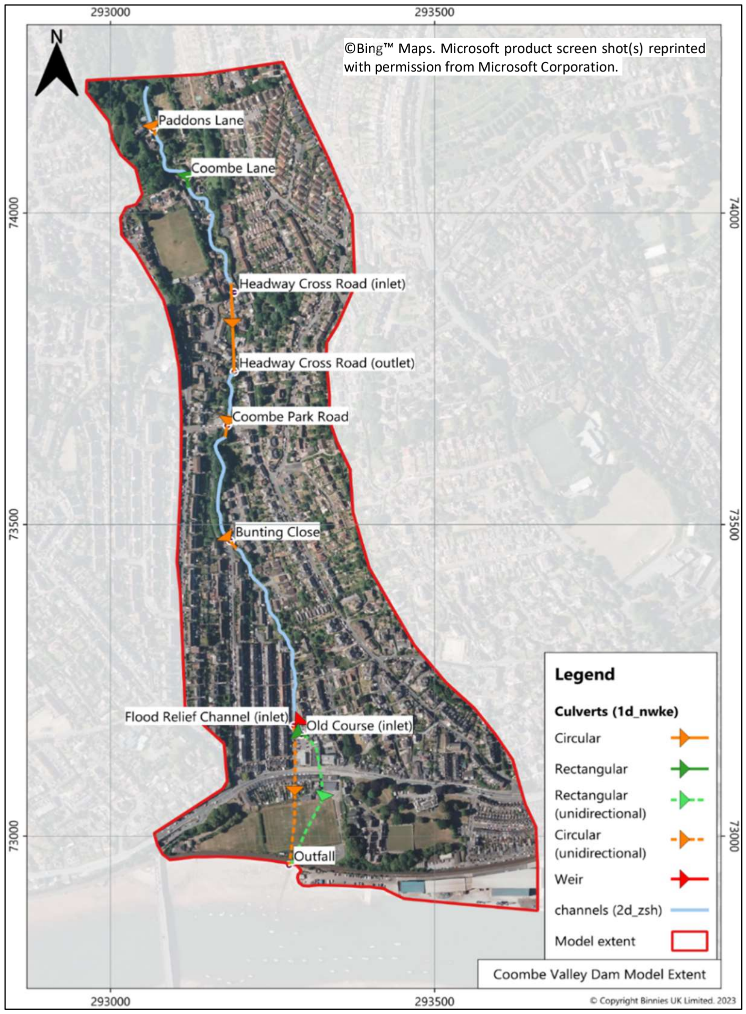

Figure 7. 2d model extent downstream of the dam

The model topography was based on the 1m LiDAR DTM. However, the narrowness of the Bitton Brook combined with high vegetation coverage meant that its representation within the raw LiDAR DTM was limited. As such, to ensure a reasonable representation of in-channel flows the Bitton Brook open channel sections were enforced within the DTM using additional model features (2d_zsh layers in TUFLOW as shown by the blue lines in Figure 7).

Flood extents in the catchment are strongly influenced by the various culverts and bridges that lie within the Bitton Brook. In addition, the LiDAR DTM did not have any culverts or bridges filtered from the raw elevation model data and therefore the elevation model represents ground level above these structures. The example in Figure 8 at Bunting Close shows how the recording of ground surface levels above the culvert creates an artificial dam across the watercourse. Therefore, the representation of these structures along the Bitton Brook was an important component of the model.

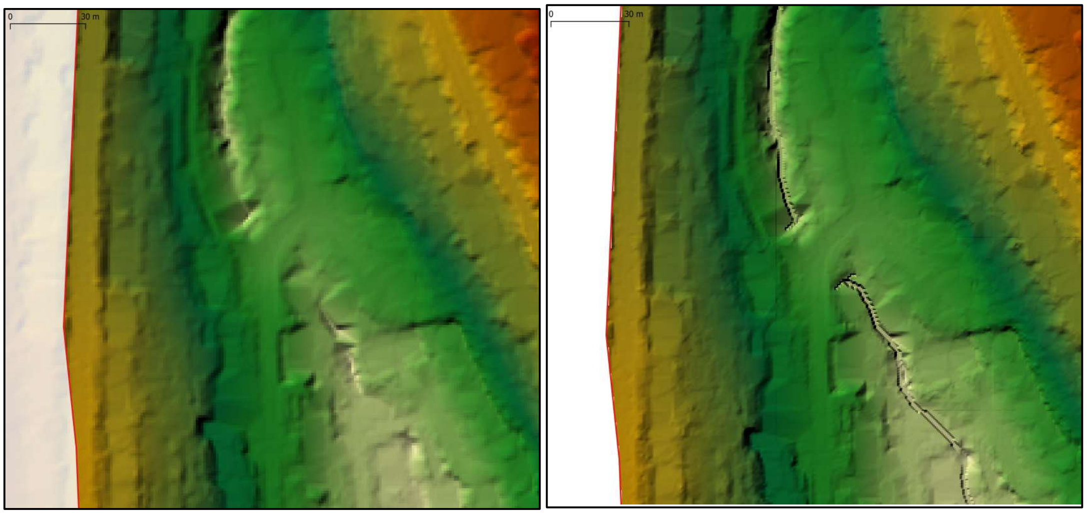

Figure 8. Bitton Brook channel enforcement in the DTM

Eight 1d culverts were embedded into the model to represent the in-channel features shown by the arrows in Figure 7. The dimensions and invert levels of the culverts were supplemented with site measurements provided by TDC or estimated where necessary. Survey data of these culverts and the open channel sections would provide more accurate information, however the absence of this data does not limit the conclusions of this study. One weir has been included to represent the side spill from the Bitton Brook into the flood relief culvert. The flood relief culvert and the old course (dotted green line in Figure 7) were both assumed to have tide flaps at their outfalls into the River Teign estuary.

The outlets of the flood relief culvert and old culvert course were connected to a 1d boundary condition which simulates tidal variations in the River Teign estuary. A Mean High Water Spring (MHWS) tide level and profile was applied such that the peak of the tide occurred at the peak of the flood giving conservative conditions. The MHWS level was taken from the EA Coastal Flood Boundary dataset while a representative profile was extracted from Admiralty Total Tide for the estuary side of Teignmouth.

The 2d model was simulated for the 2, 5, 10, 50, 100, 200, and 1000-year floods for the baseline and dam removed scenarios. The impact of climate change was also tested using the 1 in 100-year flood by uplifting peak flows by 46% in accordance with EA guidance.

RESULTS

Reservoir attenuation

Prior to a site visit in October 2023, the catchment experienced intense rainfall on 17 September 2023, resulting in the reservoir filling and almost reaching the spillway. Wrack marks and debris from the event were evident during the visit and allowed the peak water level in the reservoir to be estimated (at approximately 0.08m below the level of the overflow, at 45.45m AOD). The model was validated against this event to see if a similar water level was achieved.

The recorded rainfall on 17 September 2023 from the nearest rain gauge (4km away at Ashcombe) was retrieved and processed through the ReFH2 model to generate an estimated inflow hydrograph. This gauge recorded 66mm of rainfall over five hours which, according to the FEH DDF model, equates to a 1 in 140-year event. The 17 September 2023 estimated inflows were run in the reservoir model and compared to the estimated maximum water level recorded from the site visit. Figure 9 compares the model water level (block line) in the reservoir to the estimated flood level of 45.45m AOD (dotted blue line). The modelled water level is within 0.2m of the estimated flood level giving reasonable confidence in the modelling approach.

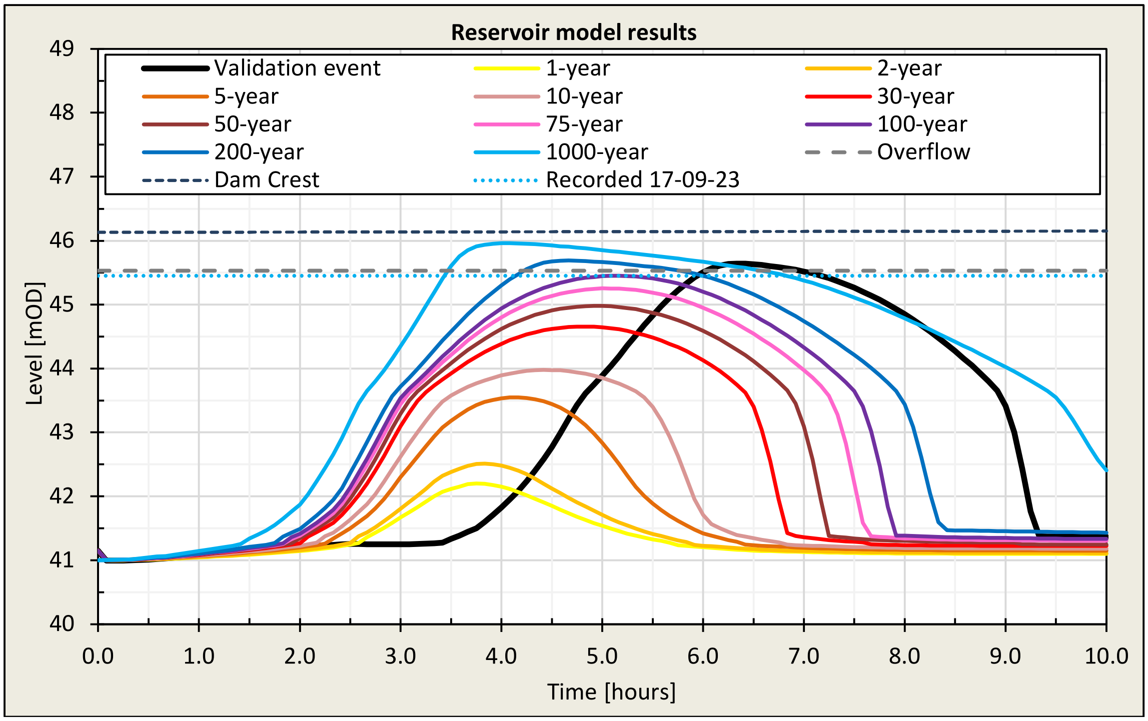

Figure 9. Validation event water level profile upstream of the dam

Current Flood Protection

The results from the 1d reservoir model are also plotted in Figure 9 below showing how water levels vary with time for the 5-hour storm design events. The dam spillway (45.53m AOD) and crest (46.2m AOD) are shown by the dashed and dotted lines, respectively, indicating when the levels would exceed each threshold.

The maximum water levels upstream of the dam show that the spillway would not become activated until the 1 in 200 year ('Q200') flood, and that the crest would not be exceeded even during the 1 in 1000 year flood. The standard of protection of the dam is therefore at least a 1 in 1000 year.

Dam Removal Scenario

Table 2 summarises the impacts of removing the dam in terms the estimated properties added to the flood outline for the range of modelled floods demonstrating the flood risk benefit provided by the dam. Figure 10 shows an example of the impact of flood extent for the 1 in 10-year flood. It is evident that the dam provides protection to a significant number of properties (between 11 and 18 depending on the flood) when compared to the absolute number of properties at risk in the baseline.

Table 2. Dam removal summary in terms of estimated flooded properties

Flood event [year]	Baseline	Dam Removed	Change
2	0	0	0 (none flooded)
5	0	0	0 (none flooded)
10	3	21	18
50	10	27	17
100	12	29	17
200	29	40	11
1000	60	71	11
100+46% climate change*	43	54	11

*The upper allowance for peak river flow for the 2050s has been used from the South Devon Management Catchment.

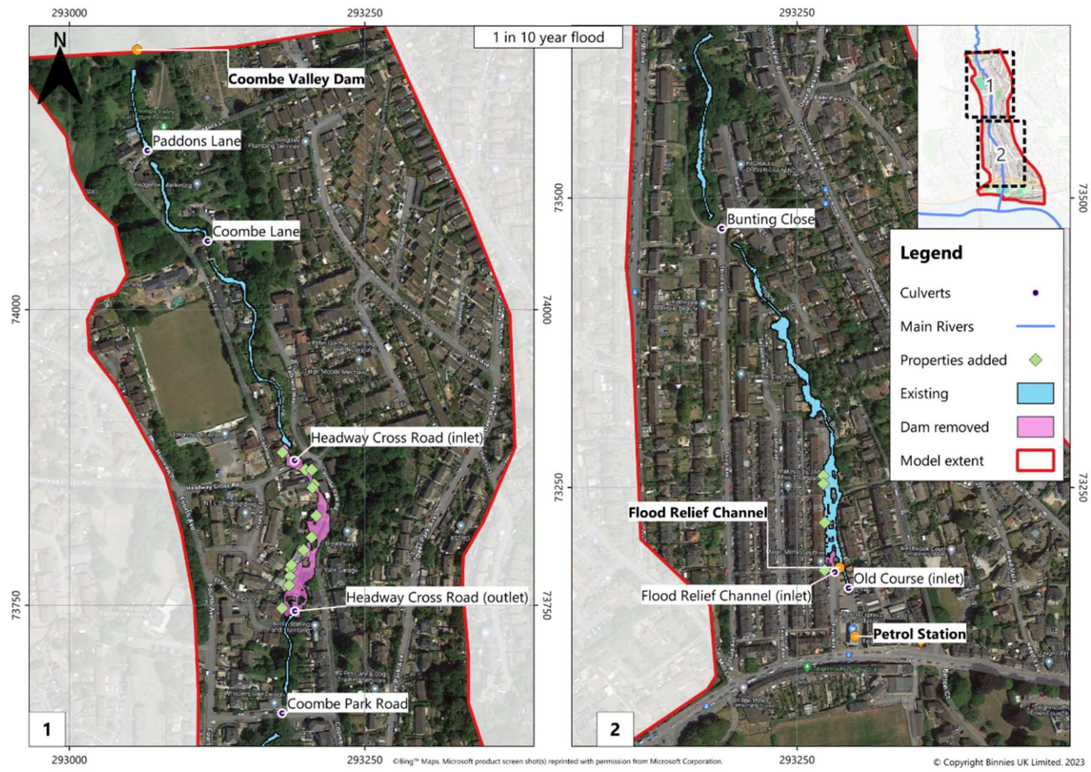

Figure 10. Example change in flood outline by removing the dam – 1 in 10 year flood

ANALYSIS OF IMPLICATIONS ON MANAGEMENT

With confirmation of the level of protection offered by the dam, an options appraisal was carried out. Scenarios considered included (1) do nothing, (2) remove dam, (3) retain dam at reduced capacity, (4) retain dam at current capacity and bring up to standard, and (5) retain the dam at increased capacity. Given the high standard of protection provided by the dam and the increase in properties impacted by the dam removal scenario, the option to retain the dam at its current capacity and treat it within the spirit of the Act, was identified as the preferred option. This option balanced capital costs with flood protection benefits whilst ensuring the Undertaker's duties under relevant legislation were met.

Recommendations for maintenance and surveillance

To bring the reservoir up to standard in the spirit of the Act, a series of recommendations were made. To better inform the Undertaker how deterioration of the dam could lead to risk of failure, several potential hazards at the dam were provided based on EA guidance (EA, 2016). A Risk Assessment for Reservoir Safety (RARS) following EA guidance (EA, 2013) has not been carried out at this stage. Risks to the embankment included vegetation overgrowth, potential animal activity, mitre runoff, seepage, settlement, crest fissuring, and internal erosion along the culvert. Other external threats included blockage of screens and overtopping. A list of recommendation made to bring the reservoir up to standard in the spirit of the Act were provided and are listed in **Table 3**.

Table 3. Recommendations to bring the reservoir up to standard of the Act

Feature	Recommendations
Embankments and Crest	• Clear small vegetation and establish good grass cover • Check for animal burrows. Engineer/ecologist to advise on removal • Check for signs of cracking, movement, or creep
Outlet culvert and Overflow	• Carry out CCTV survey to establish condition of assets • Reseal joints as needed • Clear any debris blocking screens or culvert entrance/outlets
Instrumentation	• Install telemetry system similar to 'Meteor' used at EA reservoirs • Install gauge board for water level monitoring telemetry calibration
Emergency Planning	• Develop a plan similar to an 'On-Site Plan'. Include emergency response contacts, drawdown rate analysis, and valve information

Additional recommendations made to improve maintenance and surveillance in the future are listed in Table 4. These were established based on common industry practice as well as EA and CIRIA guidance (EA, 2011a, 2011b; CIRIA, 1996, 2003, 2015, 2019, 2020)

Table 4. Recommendations for future surveillance and maintenance

Recommendations for future surveillance	Recommendations for future maintenance
• Monthly visits by an appointed 'reservoir surveillance engineer' to visually inspect dam and remove debris from screen • Inspect dam following flood events for blockages, seepage, or settlement • Carry out annual inspection and report similar to Section 12 • Maintain a document similar to Prescribed Form of Record to document maintenance and record water levels • Five yearly asset survey similar to T98	• Maintain grass below 150mm • Regular operation of penstocks and valves • Clear any debris around overflow screen or upstream debris screen • Check condition of safety equipment • Monitor silt buildup in upstream channel • Consider installation of tree catcher upstream in catchment

CONCLUSION

Modelling and optioneering at Coombe Valley Dam supported the Undertaker in understanding their roles and responsibilities under relevant legislation and in the spirit of the Act. Recommendations made helped establish suitable inspection and maintenance regimes. This helped secure revenue expenditure to ensure compliance and flood risk benefits are maintained in the future. TDC is considering similar studies for other non-statutory reservoirs.

As has been demonstrated by the recent experience following the enactment of >10,000m^3 capacity reservoirs in Wales in 2016, there are numerous dam structures which have a capacity below 25,000m^3 but still, due to location and/or height, could cause damage to property or life is they failed. This is not just limited to >10,000m^3, but structures below that capacity, particularly where they have been constructed for flood alleviation purposes such as Coombe Valley Dam.

It is important that these structures are recognised as dams, with the same issues, liabilities and maintenance requirements as registered dams under the Act, whilst providing additional benefits such as flood alleviation. This paper aims provide an example of how similar structures can be analysed to subsequently inform the Undertaker of benefits provided, limitations, and best ways to operate and maintain the structure going forward to minimise risks, using existing guidance, methods and standards that are available within the industry.

REFERENCES

CIRIA (1996). *Report 161: Small embankment reservoirs.* CIRIA, London, UK.

CIRIA (2003). *Report 116: Design of reinforced grass waterways*. CIRIA, London, UK.

CIRIA (2015). *Report 743: Dams and reservoir conduits*. CIRIA, London, UK.

CIRIA (2019). *Report 786: Culvert, screen and outfall manual*. CIRIA, London, UK.

CIRIA (2020). *Report 789: Pipework, valves & associated equipment in dams*. CIRIA, London UK.

EA (2011a). *Lessons from historic dam incidents. SC080046/R1.* Environment Agency, Bristol, UK.

EA (2011b). *Modes of dam failure and monitoring and measuring techniques. SC080048/R1.* Environment Agency, Bristol, UK.

EA (2013). *Guide to risk assessment for reservoir safety management. Volume 2: Methodology and supporting information. SC090001/R2 (RARS).* Environment Agency, Bristol, UK.

EA (2016). *Design, operation and adaptation of reservoirs for flood storage. SC120001/R.* Environment Agency, Bristol, UK.

HMG (Her Majesty's Government) (1974). *Health & Safety at Work etc Act 1974.* Her Majesty's Stationary Office, London, UK.

HMG (Her Majesty's Government) (1975). *The Reservoir's Act 1975.* Her Majesty's Stationary Office, London, UK.

HMG (Her Majesty's Government) (2010). *Flood and Water Management Act 2010.* Her Majesty's Stationary Office, London, UK.

Howarth (2002). *Flood Defence Law*. Shaw and Sons, Crayford, Kent, UK

Penman and Golds (2022). Research on risk designation and small raised reservoirs. *Dams and Reservoirs* **32(2)** 62-69.