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File Note

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Executive Summary

Inspections under the Reservoirs Act 1975 at both Cannop Ponds identified a number of issues with the dams which need to be resolved in order to ensure the safety of the two reservoirs. Four concept options for potential remedial works at the sites were presented at public consultation events held in March 2023. A detailed appraisal of the four options was carried out considering many factors including flood risk.

This technical note has been prepared to inform the options appraisal process and presents the results of the hydraulic modelling undertaken to understand the likely changes to downstream flood risk from each of the four options. To inform the options appraisal process, the results compare the impact of each option to the Baseline, which represents the current situation. This modelling exercise does not cover dam failure and as such, dam breach analysis has not been conducted.

Based on hydraulic modelling of the concept design options presented at public consultation, Option 1 is hydraulically similar to the Baseline and shows negligible detriment to downstream flood risk. Option 2 increases storage in the ponds and therefore shows benefit to downstream flood risk. Option 3 indicates a very small detriment to downstream flood risk which is driven by its slightly smaller storage capacity. If taken forwards this option would be optimised to improve storage and ensure there is no detriment. Finally, Option 4 consists of decommissioning both Cannop Ponds, removing existing flow attenuation and therefore causes a detriment to downstream flood risk.

Once a preferred option is identified, the model(s) presented here will be used during the next phase of design to refine scheme development to ensure that no detriment occurs and, if possible, to provide benefit. A further flood risk assessment will then be produced incorporating refinements brought to the final design.

1. Introduction

Cannop Ponds (Upper Cannop and Lower Cannop) are two man-made reservoirs, both nearly 200 years old. Cannop Ponds are located approximately 3km to the east of Coleford. The location of the reservoirs is rural, with the nearest significant settlement along the Cannop Brook being Parkend, located approximately 2km South-South-East of Lower Cannop. The hydraulic flow path channel from the Upper Cannop inlet to next key tributary (Oakwood Brook) in Parkend measures approximately 4km.

Recent inspections of the reservoirs under the Reservoirs Act 1975 identified a number of issues with the reservoirs which must be resolved in order to ensure the ongoing safety of the reservoirs and the downstream population. Forestry England is currently considering four options for remedial works at the sites. As part of the options development work, Ove Arup & Partners Limited (Arup) was commissioned by Forestry England to undertake flood modelling for the valley in order to assess the existing flooding risks to property downstream, and also to assess the potential flood risk impacts of each of the four remedial options under consideration.

2. Previous Environment Agency flood risk modelling

The Environment Agency (EA) has previously undertaken catchment scale flood mapping for the area. The publicly available mapping shows that there are some residential properties at risk of flooding in Parkend downstream from the Upper Cannop and Lower Cannop Ponds, as shown in Figure 1. The EA flood risk mapping was developed using broadscale modelling, which is unlikely to accurately capture the channel capacity at Cannop Ponds and in Cannop Brook immediately downstream. There was some uncertainty in using the results of the EA broadscale modelling for assessing the direct impacts from potential works at Cannop Ponds. As such, a project-specific flood model was needed to inform the Cannop Ponds project. The sections below provide details of the modelling approach and the results obtained.

3. Model approach

3.1 Software

The Flood Modeller and TUFLOW suite of modelling software and solvers was used for this project. All modelling runs have been conducted using Flood Modeller 6.0 and TUFLOW 2023-03-AA versions of the software.

3.2 Input data

New channel topographical survey data was collected in November 2022, including a total of 90 channel cross-sections and 29 structure cross-sections. These were used to build the 1D element of the bespoke 1D-2D hydraulic model. Bathymetry and topographical survey data for Upper Cannop and Lower Cannop ponds was collected in November 2021. This was used to inform various aspects of the modelling such as the crest elevation of each dam and to generate a level-storage curve for each reservoir. Finally, latest available LiDAR at the start of the study was downloaded from the Defra Data Service Platform and was used to generate elevations in the floodplain, which is the 2D element of the bespoke 1D-2D hydraulic model.

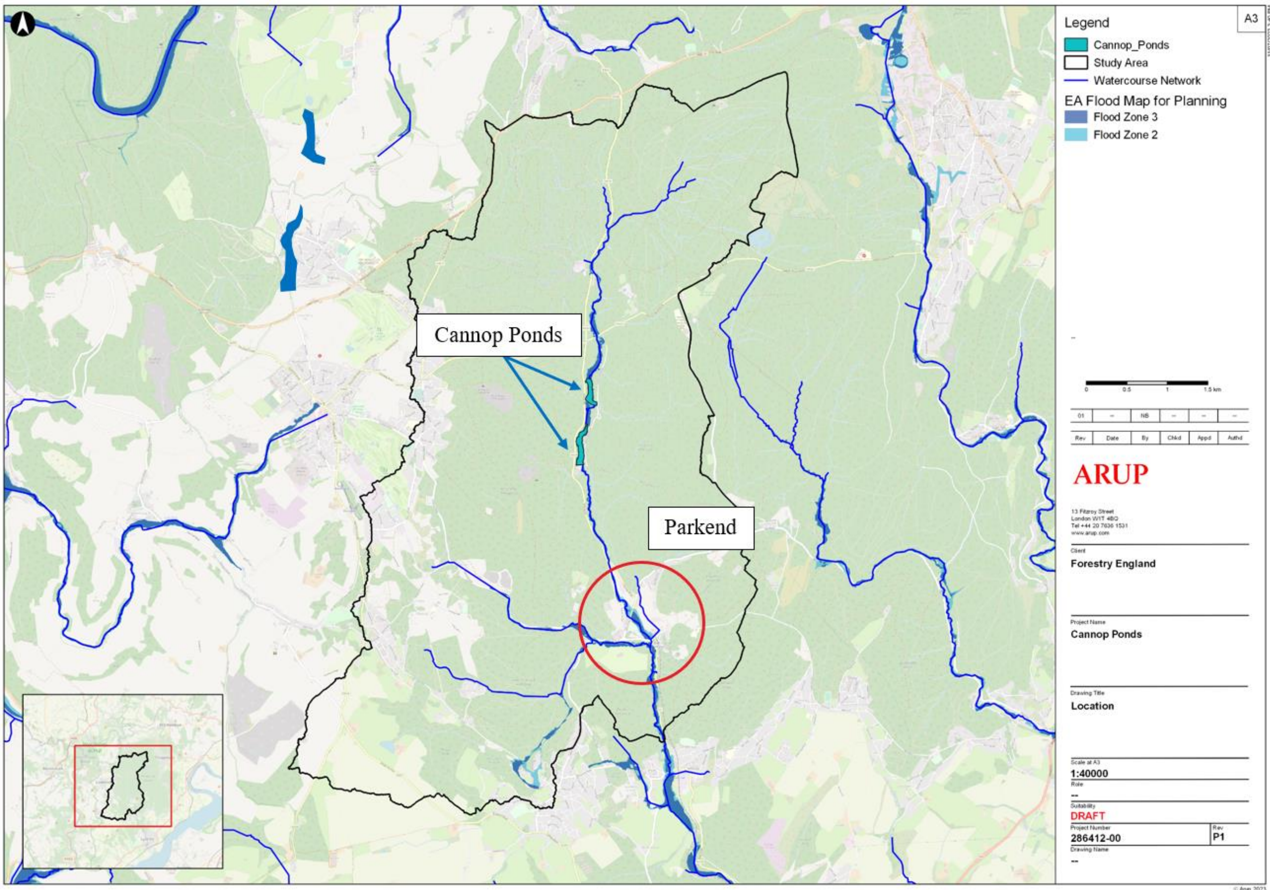

Figure 1: Environment Agency Flood Mapping

3.3 Hydrology

New hydrology was derived for the Cannop Brook catchment as part of this study. The final peak flow estimates at the downstream end of the target catchment boundaries (shown in Figure 2) are provided in Table 1.

Table 1: Flood peaks for a range of flood events

Flood peak (m^3/s) for the following flood events (likelihood of occurence per year, 1 in X)														
Catchment code	**2**	**5**	**10**	**20**	**25**	**30**	**50**	**75**	**100**	**150**	**200**	**500**	**1000**	**10000**
Cannop Brook 1	4.0	5.5	6.7	7.9	8.3	8.6	9.6	10.5	11.1	12.2	13.1	16.3	19.2	30.2
Cannop Brook 2	5.9	8.2	9.9	11.6	12.2	12.7	14.2	15.5	16.4	18.0	19.2	23.9	27.9	43.4
Cannop Brook 3	6.1	8.5	10.2	12.0	12.7	13.2	14.7	16.0	16.9	18.6	19.9	24.7	28.8	44.9
The Lyd DS	13.1	17.9	21.0	24.0	24.9	25.7	27.8	29.4	30.6	33.4	35.6	43.7	50.7	77.8
Oakwood Brook DS	4.4	6.1	7.3	8.6	9.1	9.4	10.5	11.5	12.2	13.4	14.4	18.2	21.5	34.7

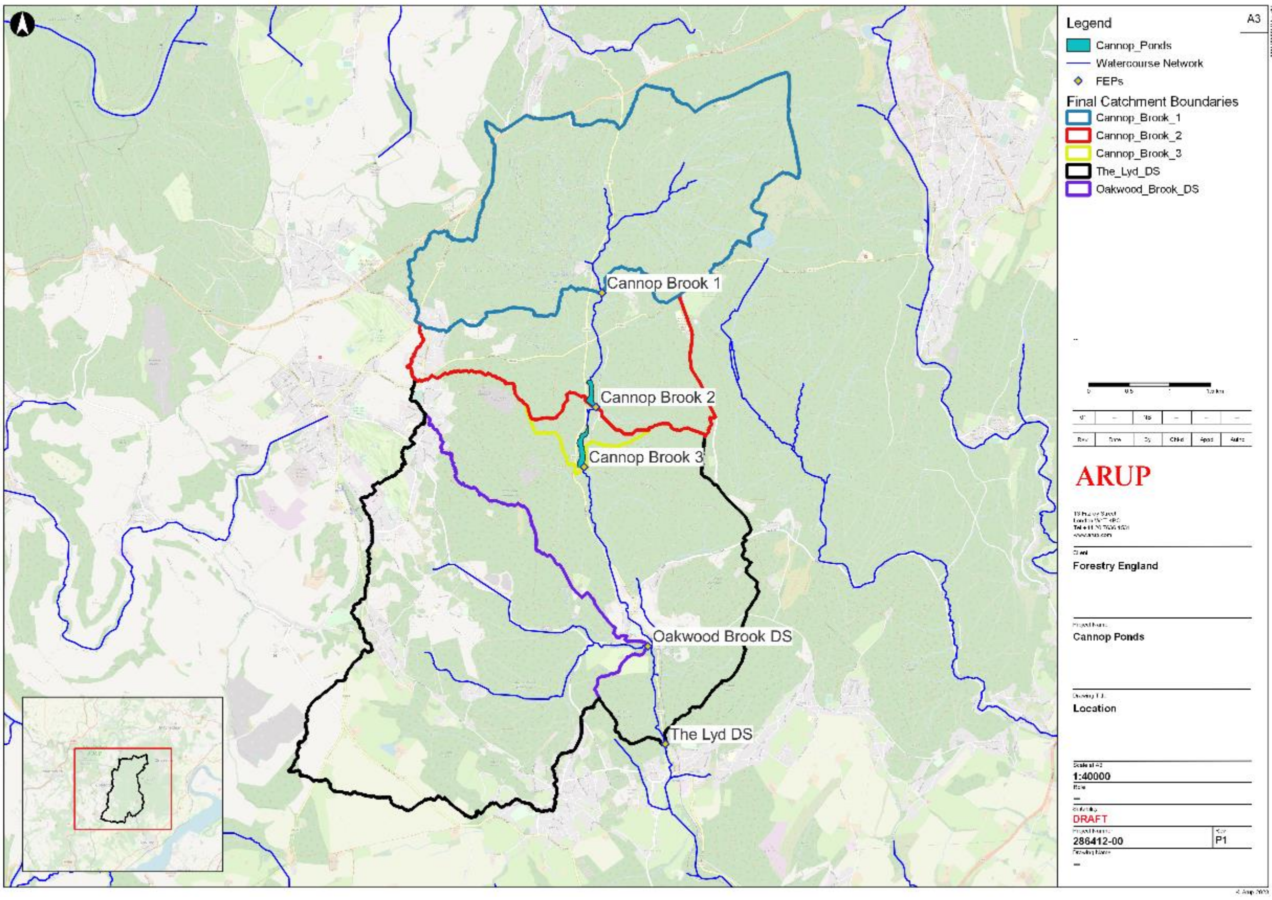

Figure 2: Hydrology flood estimation points

3.4 Baseline model (Existing Conditions)

In the Baseline model, the watercourse was represented in the 1D domain using surveyed cross-sections. Structures were added into the 1D element of the hydraulic model to represent bridges, culverts and weirs. Bridges generally used 1D spill units to represent the flow overtopping the bridge. However, for larger structures, these were instead linked to an area of 2D domain spanning the channel. 2D levels were updated using survey and LiDAR levels to ensure decks over the structures were accurately represented.

The Upper Cannop and Lower Cannop ponds were modelled in Flood Modeller as reservoir units. For Upper Cannop, the existing spillway was represented using a spill unit with a crest elevation of 69.04mAOD, a spillway width of 8.65m and with a weir coefficient of 1.7. The dam was also represented using a spill unit with an irregular crest elevation based on surveyed bathymetry (lowest crest elevation of 69.55mAOD), a length of 147m, and with a weir coefficient of 0.45.

For Lower Cannop, the existing spillway was represented using a spill unit with a crest elevation of 64.44mAOD, a spillway width of 4.60m and a weir coefficient of 1.7. The dam was also represented using a spill unit with an irregular crest elevation based on surveyed bathymetry (lowest crest elevation of 65.96mAOD), a length of 75m and a weir coefficient of 0.45 to account for the roughness of the dam crest.

In each simulation the ponds were assumed to be entirely full at the beginning of an event, so the initial water level in each pond was set to the crest elevation of each spillway respectively.

3.5 Options representation

3.5.1 Option 1

In Option 1, the following modifications were made to the ponds' spillways and dams:

- Upper Cannop pond: The original spillway was replaced by a two-stage spillway. The lower spillway retained the crest elevation and width of the original spillway i.e., a crest elevation of 69.04mAOD and a width of 8.65m. The upper spillway crest elevation was set at 69.90mAOD with a width of 33m. The dam crest was set to an elevation of 70.60mAOD with the same length as the existing dam of 147m.
- Lower Cannop pond: The original spillway was replaced by a two-stage spillway. The lower spillway retained the crest elevation and width of the original spillway i.e., a crest elevation of 64.44mAOD and a width of 4.60m. The upper spillway crest elevation was set at 65.60mAOD with a width of 16.50m. The dam crest was set to an elevation of 66.60mAOD with the same length as the existing dam of 75m.

3.5.2 Option 2

In Option 2, the following modifications were applied to the model:

- Upper Cannop pond: the spillway crest elevation was lowered to 67.3mAOD and the dam was represented using a spill unit with a crest elevation of 69.55mAOD and a length of 122m. The spillway weir is a "flat v" section with 1:2 side slopes.

  To improve model stability for this configuration, the existing causeway and weir (located at the upstream end of Upper Cannop pond) were explicitly represented in the 1D model using a spill unit with a weir crest elevation of 68.98mAOD and a dam crest elevation of 69.8mAOD. The width of the weir is 2.4m and the width of the dam is 51m for a total combined width of 53.4m.
- Lower Cannop pond: Option 2 assumes the dam was set to an elevation of 66.60mAOD with the same length as the existing dam of 75m (same as Option 1). The original spillway was replaced by a notched three-stage spillway. The lowest elevation of 62.40mAOD allowed the water to spill over a width of 1m; the intermediate elevation of 64.90mAOD allowed the water to spill over a width of 4.5m and the highest elevation of 65.60mAOD allowed the water to spill over a width of 22m.

3.5.3 Option 3

In Option 3, the following modifications were applied to the model:

- Upper Cannop pond: the pond was replaced by a series of four smaller cascading ponds. The most upstream of the four cascading ponds retained the spillway and dam crest elevations of the original Upper Cannop pond. The spillway and dam crest elevations for the remaining three cascading ponds were derived assuming a constant slope.

The surface area profile for each cascading pond is the same. The calculation of the surface area profile was based on the total surface area of all four cascading ponds being approximately equal to half the surface area of the original Upper Cannop pond.

- Pond 1 (furthest upstream) has a spillway width of 7.04m and a dam length of 34m.
- Pond 2 has a spillway width of 7.04m and a dam length of 55m.
- Pond 3 has a spillway width of 7.04m and a dam length of 115m with two crest levels (30m long crest with an elevation of 68.45mAOD and 85m long crest with an elevation of 69.88mAOD).
- Pond 4 (furthest downstream) has a spillway width of 16.64m and a dam length of 25m.

All spillway weirs have a “flat v” section with 1:2 side slopes.

- Lower Cannop pond: the most upstream of the four cascading ponds retained the spillway and dam crest elevations of the original Lower Cannop pond. The spillway and dam crest elevations for the remaining three cascading ponds were derived assuming a constant slope.

  A fifth pond was added downstream of the four cascading ponds, with a spillway crest elevation of 59.6mAOD and a spillway width of 26.72m. A dam crest elevation of 65.96mAOD and a dam length of 48m were adopted. The spillway weir has a “flat v” section with 1:2 side slopes.

The surface area profile for each cascading pond is the same. The calculation of the surface area profile was based on the total surface area of all four cascading ponds being approximately equal to half the surface area of the original Lower Cannop pond. As such, all dams have a spillway width of 1.2m and a dam length of 63m.

3.5.4 Option 4

In Option 4, the Upper Cannop and Lower Cannop Ponds were removed and replaced by cross-sections to simulate the re-naturalisation of the watercourse. Cross-sections within the area originally covered by the extent of the ponds were taken from the bathymetry survey and amended where necessary (for instance in areas close to the dam embankment where siltation affected the cross-sectional profile). In the Baseline model, the ponds were represented as 1D reservoir units and the spillways as weir units therefore the length of those components is not accounted for. In Option 4, the length of the centreline of the watercourse was increased.

3.6 Model scenarios

Simulations were performed for the Baseline scenario and Options 1, 2, 3 and 4. The final model design events completed included the 1 in 2YR, 5YR, 10YR, 20YR, 25YR, 30YR, 50YR, 75YR, 100YR, 150YR, 200YR and 1000YR events, corresponding to 50%, 20%, 10%, 5%, 4%, 3.33%, 2%, 1.33%, 1%, 0.66%, 0.5% and 0.1% AEP (Annual Exceedance Probability).

The hydrological analysis identified two critical storm durations (13 hours and 45 minutes and 22 hours and 45 minutes); the storm duration of 22 hours and 45 minutes was found to maximise flooding in the study area and was therefore selected as the default storm duration (results of the 13 hours and 45 minutes storm duration were included as a sensitivity test).

Sensitivity testing was conducted in order to improve confidence in the 1D-2D hydraulic model in the absence of gauged data to calibrate the model. Model parameters tested for sensitivity included model fluvial inflows, 1D and 2D model Manning's n roughness coefficient, downstream boundary conditions, building representation, grid cell size and storm duration.

3.7 Model stability

Model stability was checked for the 1D and 2D components of the hydraulic model.

1D model stability is good across all events and runs. Flow and level results remained within tolerance levels and the number of iterations required by the model to find a solution remained below the default software limit, indicating an overall stable 1D model.

For the 2D model, HPC/QPC solution is a volume conservative solution, meaning in 2D there is no mass error. Mass error can still occur within the 1D-2D links and therefore it was checked that all model runs have a mass error within ±1% (as in a classic model).

4. Model results

The number of flooded properties in the Baseline modelled scenario was compared against Options 1 to 4 for a range of flood events, as shown in Table 2. Properties were considered as flooded if the maximum flood depth was above 15cm which is the typical property threshold level corresponding to a doorstep. Threshold levels have not yet been verified by survey.

During initial model runs, it was found that Option 4 causes a measurable detriment to flood risk downstream. This is because the decommissioning of the reservoirs would remove all available flow attenuation. It was clear that Option 4 would not meet one of the key project objectives and would therefore be discounted as a viable option. As such, no further modelling was undertaken. In the table below only the results for the 1 in 100yr flood event (1% AEP) are presented for Option 4.

Table 2: Number of flooded properties

Number of flooded properties for each flood event (return periods 1 in X year (AEP))												
Scenario	**2** (50%)	**5** (20%)	**10** (10%)	**20** (5%)	**25** (4%)	**30** (3.33%)	**50** (2%)	**75** (1.67%)	**100** (1%)	**150** (0.67%)	**200** (0.5%)	**1000** (0.1%)
Baseline	6	9	14	15	15	15	18	18	18	21	21	29
Option 1	6	9	14	15	15	15	18	18	19	21	21	29
Option 2	6	6	11	14	14	15	16	18	18	19	19	28
Option 3	6	9	14	15	16	17	18	18	19	21	21	29
Option 4									22			

* Green shading shows where fewer properties are flooded when compared to the Baseline. Red shading shows where there would be an increase in the number of properties flooded.

With reference to Table 2, the results show that:

- For Option 1:
  - The number of properties likely to be affected by flooding in Option 1 is similar to the number of properties likely to be affected in the existing Baseline scenario.
  - During the 1 in 100yr flood event (1% AEP), there is one additional property which is likely to flood. Maximum flood depths at the property are predicted to increase marginally by 2.2cm - from 13.6cm in the Baseline to 15.8cm in Option 1. This is 0.8cm above the nominal threshold of the property.
  - From a hydraulic point of view, Option 1 is comparable to the Baseline and will therefore not increase flood risk downstream of the ponds.

- For Option 2:
  - The number of properties likely to be affected by flooding in Option 2 is predicted to decrease when compared to the Baseline. Option 2 increases flow attenuation with the use of a notched spillway at Lower Cannop which conveys less flow, thereby maximising the storage in the pond with the potential to decrease downstream flood risk.

- For Option 3
  - The number of properties likely to be affected by flooding in Option 3 is slightly higher when compared to the Baseline:
  - During the 1 in 25yr flood event (4% AEP), there is one additional property likely to flood with maximum flood depths predicted to increase by 2.3cm from 14.5cm in the Baseline to 16.8cm in Option 3. This is 1.8cm above the nominal threshold of the property.
  - During the 1 in 30yr flood event (3.33% AEP), there are two additional properties likely to flood with maximum flood depth predicted to increase from 14.2cm to 16.0cm (+1.8cm) and from 13.8cm to 16.7cm (+2.9cm). This is 1.0cm and 1.7cm respectively above the nominal threshold of the properties.
  - During the 1 in 100yr flood event (1% AEP), there is one additional property likely to flood with maximum flood depths predicted to increase by 3.6cm from 13.6cm in the Baseline to 17.2cm in Option 3. This is 2.2cm above the nominal threshold of the property.

- For Option 4
  - The number of properties likely to be affected by flooding in Option 4 is significantly increased when compared to the Baseline. Option 4 will therefore increase downstream flood risk.

5. Assumptions and limitations

There are a number of limitations with the hydrological analysis and the hydraulic modelling, summarised below with recommendations provided where appropriate:

- The options which have been modelled have only been developed to a concept-level of design. Once a preferred option is selected, further design development will be undertaken to enable construction. Flood modelling will need to be repeated as part of the design process. Detriment will be mitigated for the final solution and therefore the modelling results may differ from those presented above.
- Properties predicted to flood during the modelled events are based on an estimated threshold level of 15cm above ground level being exceeded. This estimate is not based on topographic survey and it is recommended that threshold levels of any properties predicted to flood are surveyed for use in further modelling stages.
- Within the area of this study, there are no gauging stations which can accurately record the most extreme flood events. The flow gauging station at Parkend is bypassed at high flows and therefore does not accurately record peak flow for the past flood events which have caused out of bank flooding. This increases the uncertainty around the value of QMED used within the hydrological analysis however recommended best practises (donor transfer from adjacent gauging stations) have been carried out to reduce that uncertainty.
- There are no operational records for the Upper Cannop and Lower Cannop ponds which would allow a better understanding of how much flow was passed forward by the reservoirs’ spillways and over the dam crest respectively, during past flood events. The representation of both reservoirs’ spillways and dams was based on latest available survey data and weir coefficients were assigned based on photographic evidence and best practice within the industry.
- Similarly, calibration data available for this study was limited. No observed flood extents or wrack mark levels have been recorded for previous flood events, making it impossible to calibrate the hydraulic model against known events. A series of sensitivity tests have therefore been conducted to understand the model’s sensitivity to various critical parameters, parameters whose values have been based on photographic evidence or chosen following available guidance and best practice within the industry.
- In the most extreme events, the model demonstrated a number of stability issues, which required the usage of stability patches to assist with model running. The general cause of these stability issues was the extreme volume of flow in a relatively small channel. A thorough review of the usage of these patches and of the overall model was undertaken and concluded that these issues and patches have limited impact on the results or reliability of the overall hydraulic model.

6. Conclusions

The main findings of this study can be summarised as follows:

- A bespoke 1D-2D hydraulic model was developed for the study area and a new hydrology was derived for the Cannop Brook catchment to inform fluvial inflows to the hydraulic model. The Baseline model includes the Upper and Lower Cannop ponds as reservoirs and approximately 6km of open channel watercourse as well as the surveyed hydraulic structures in the catchment.
- Options 1 to 4 were represented in the 1D-2D hydraulic model by amending elements of the reservoirs such as the spillways' crest elevations and widths, the dams' crest elevations, replacing existing reservoirs by smaller cascading ponds or by open channel sections.
- Model results suggest that:
  - Option 1 is hydraulically similar to the Baseline and as such shows negligible detriment to downstream flood risk.
  - Option 2 increases storage in the ponds and as such shows benefit to downstream flood risk.
  - Option 3 offers less storage than the Baseline and as such the modelling is currently showing a slight detriment to downstream flood risk. However, there is only a slight increase in flood depths at the properties at risk. If this option is developed further it will be optimised to ensure that there is no detriment.
  - Option 4 consists of the decommissioning of both Cannop Ponds removing existing flow attenuation, and as such it causes a detriment to downstream flood risk.

These results will be used during the next phase of design to maximise the downstream flood risk benefit of the proposed design. A further flood risk assessment will then be produced incorporating refinements brought to the final design.