ARUP

Bristol City Council

Bristol Avon Flood Strategy OBC

Baseline modelling report

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1. Introduction

1.1 Purpose of this report

This report summarises the updates made to the baseline hydraulic model for use in the Bristol Avon Flood Strategy (BAFS) Outline Business Case (OBC) and the associated data reviews and model tests to support this. The baseline model is the model that will be used to represent the existing business as usual 'Do Minium' scenario (rather than the 'Do Nothing' walkaway economic baseline scenario).

This report covers:

- Summary of the modelling inception stage and agreed methodology.
- Summary of updates to hydrology.
- How the 2d model has been converted to single domain GPU model.
- How the model has been extended upstream to Bath and refined in areas downstream of Bristol.
- How the recommendations from the reviews of the existing models have been addressed.
- Model runtime parameters and performance.
- Model quality assurance.
- Model validation.
- List of agreed simulations required for OBC study.
- A selection of baseline model results.

1.2 Background

Bristol is at risk of widespread flooding from the River Avon from high fluvial flows and from tidal events propagating up the river from the Severn Estuary. Bristol City Council (BCC) have worked with the Environment Agency (EA) and other partners to create a long-term Strategy for managing flood risk from the River Avon. In March 2021 the Strategic Outline Case (SOC) was granted approval for progressing to OBC stage.

The preferred option comprises raised defences along the River Avon including new tidal stop gates for the Floating Harbour. The initial phase of construction ('Phase 1') is assumed for the 2020s. The flood defences will be constructed sufficiently high to prevent overtopping until the 2060s based on current climate change allowances. For the purposes of modelling, it is assumed that the 2060s corresponds to the epoch year 2069 – this is because the current climate change guidance[1] applies a step change in fluvial flow allowance between 2069 and 2070. Note in the SOC, the 2060s was represented using the epoch year 2065. A subsequent phase ('Phase 2') of constructing additional defences and raising defences is assumed for the 2060s. The location of raised defences proposed in the SOC is shown in Figure 1. The preferred option will include detriment mitigation measures, such as raised flood defences, to manage impact of the preferred option to acceptable levels.

Phase 1 has been split into:

- Build Stage 1: This comprises the proposed new tidal stop gates for the Floating Harbour and the detriment mitigation measures required for Phase 1.
- Build Stage 2: All other parts of Phase 1.

[1] Flood and coastal risk projects, schemes and strategies: climate change allowances, Environment Agency, May 2022.

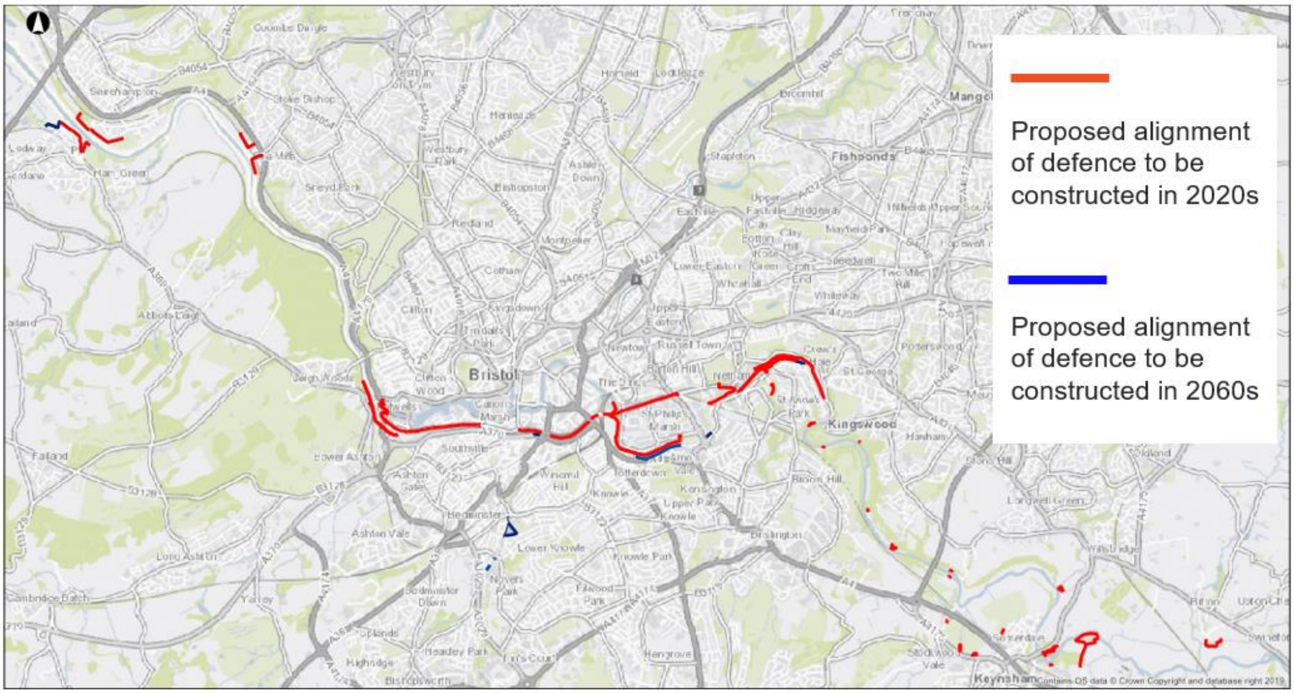

Figure 1: Location of raised defences proposed in the SOC.

1.3 Objectives of new modelling

New hydraulic modelling will be undertaken to support the OBC. The new hydraulic modelling will be used to:

- Assess flood risk for present day and future climates.
- Determine required flood defence alignments, flood defence crest levels and freeboard allowances.
- Assess flood risk for baseline and the Phase 1 preferred option.
- Provide results for use in economic appraisal.
- Assess detriment arising from the proposed raised defences and identify and develop mitigation measures.
- Support consenting and design.

2. Summary of inception stage

A modelling inception stage was undertaken in 2022 to review the relevant existing flood modelling and to develop and agree a methodology for the BAFS OBC modelling with BCC and the EA. The draft modelling methodology report[2], which includes a summary of the model reviews, the recommended updates to the baseline model, the options modelling approach and lists the recommended simulations, can be found in Appendix A.

The most relevant existing models are listed below and described in more detail in the draft modelling methodology report:

- BAFS SOC model (2018): This is based on the Bristol Central Area Flood Risk Assessment (CAFRA) model was developed in 2011 – 2012.
- Bristol SFRA 'defended' scenario model (2019 and updated in 2022): this is based on the BAFS SOC baseline model.
- North Keynsham model (2019): this is based on the EA's Bath to Bristol flood mapping model (2017).

The draft modelling methodology captures specific recommendations for updating the baseline model from:

- Recommendations made during the SOC stage by the project team.
- Recommendation made during an Arup peer review of the Bristol SOC and SFRA modelling and the North Keynsham modelling.
- Recommendation made by Wallingford Hydro Solutions (WHS) during a third-party review of the Bristol SFRA model and the North Keynsham model.

The draft modelling methodology report was reviewed by BCC, the EA and Wallingford Hydro Solutions. Comments on the report generally related to the assumptions relating to epoch years, climate change allowances, simulations to run, and scheme impact assessment. Comments were responded to by Arup and subsequent discussions lead to the agreement of:

- Which model review recommendations should be implemented for the OBC. This is documented in Section 4.2.
- A list of all baseline and options model simulations required, including climate change allowances. This is documented in Chapter 8.

[2] Bristol Avon Flood Strategy OBC, Hydraulic modelling methodology, Arup, May 2022.

3. Summary of hydrology updates

A high-level review of the SOC fluvial hydrology was undertaken during the inception stage to identify high priority updates. The following updates to the hydrology were agreed with BCC and the EA and have been undertaken:

1. Estimated 1:1yr flows for Avon and Frome by extending the existing WINFAP flood growth curves used in deriving the existing model peaks flows.
2. Updated Index Flood (QMED) values for gauged catchments using most recent gauged record and compare against existing QMED values in model. Applied proportional change to all other inflows within the model.
3. Reviewed and updated times to peak, durations and phasing of hydrographs for all inflows upstream of Bristol based on the North Keynsham model.
4. Undertook a Phase 1 non-stationarity assessment on flood flows in consultation with the EA.

In addition to the above, hydrology was undertaken to generate calibration hydrology for the March 2020 tidal event. This used gauged data for the Avon and Frome from the March 2020 event and design event flows based on an estimate of the fluvial return period for the March 2020 event for the other watercourses.

The hydrology work is documented in the hydrology reporting included in Appendix C to this report.

3.1 Additional tributary phasing updates

Following task 3 above and reviewing impacts of phasing and hydraulic model tests, further hydrological assessment was undertaken for the phasing and hydrograph shape for Brislington Brook and the phasing for the Malago. The hydrograph phasing used in the BAFS SOC model was adopted from the CAFRA modelling, which applied a worst-case phasing for tributaries such that all tributary fluvial flood peaks coincided with the Avon flood peak in Bristol.

3.1.1 Brislington Brook

The flood risk and detriment off the left bank of the Avon in the Brislington area are dominated by fluvial flows from the Avon and Brislington Brook. The phasing of the Brislington Brook hydrograph is currently set up in the model to coincide with peak River Avon water levels, and this coincidence of peaks exacerbates flooding and detriment from the proposed scheme defences in the Brislington area. The shape and phasing (timing relative to the Avon hydrograph) of the Brislington Brook hydrograph was therefore reviewed. The review, (Appendix C) identified that the hydrograph shape was acceptable if conservative. However, the review identified that the phasing was not realistic as analysis of river gauge data shows the Brislington Brook peaks consistently and significantly earlier than the Avon; this is expected given the relative catchment sizes and associated responses to rainfall. The hydrograph phasing in the model was therefore updated to be consistent with observed catchment behaviours and then subsequently adjusted slightly such that outflow from the brook coincides with high tide level. The updated phasing results in the Brislington Brook fluvial flows peaking 24hrs before the Avon hydrograph passes. Updating the Brislington Brook phasing is anticipated to reduce complexity and associated risk of detriment mitigation measures in the Brislington area.

3.1.2 Malago

An initial assessment of scheme impacts showed some small areas of detriment of typically 20 to 30mm. Review of model results showed this detriment was due to the model setup being representative of the worst-case scenario of the Malago fluvial flood peak coinciding with the Avon fluvial flood peak and the peak of the highest tide. Having all three sources coinciding at the same time was considered overly conservative. There is not sufficient gauge data for the Malago to review the historic timing of the Malago hydrograph. However, it is considered reasonable to assume the Malago and Brislington Brook systems would have similar response given the below points. Therefore, the phasing of the Malago has been set to be consistent with the updated Brislington Brook phasing (see Section 3.1.1) with a slight adjustment to ensure that peak outflow from the Malago coincides with high tide level.

- Malago and Brislington Brook catchments are adjacent to each other.
- Malago and Brislington Brook catchments are similar in area, length and overall similar gradient.
- Malago and Brislington Brook catchments have similar level of urbanisation, Malago is slightly more urban, which if anything should mean it would peak earlier than Brislington Brook, all else being equal.
- Malago and Brislington Brook catchments have overall similar BFIHOST value.

The Avon water levels at the Malago outfalls are dominated by tidal not fluvial conditions (as with all the catchment downstream of Netham Weir) and adjusting the phasing of the Malago to peak much earlier results in the Malago flows no longer peaking at the peak tidal surge level. Note that the adjusted Malago flows still peak at high tide level but two tides earlier than the main tidal surge peak.

This change could initially be considered to be inconsistent with the Joint Probability Assessment (JPA) applied to date, which specifies a 1:1yr tidal event occurring with a 1:100yr fluvial event and a 1:200yr tidal event occurring with a 1:2yr fluvial event etc. However, the joint probability combinations of fluvial and tidal conditions used to date are based on the dependence measure for river flow and surge, which in turn is based on analysis of daily mean river flow and daily maximum surge. This dependence measure is considered appropriate for fluvial flood durations over 6hrs. The Malago system is a relatively steep, highly urbanised and mostly culverted system so can be considered as more of an urban drainage system than a typical fluvial system. The critical storm duration used in the model hydrology is 2.2hrs and the results show the duration of the outflow hydrograph is about the same. The joint probability guidance[3] includes a case study for an urban drainage system outfalling into the sea.

For the case study, the guidance assumes a 2hr rainfall duration and argues that it is more appropriate to base the joint probability on the dependence measure between for rainfall and sea level rather than river flow and surge given the short duration rainfall event. Therefore, for the Malago, it is considered appropriate to base the joint probability on the dependence measure between for rainfall and sea level. For our study area, Figure 3 in FD2308/TR2[3] shows that there is independence between rainfall and sea level. Therefore, phasing the Malago flows to coincide with the peak of a tidal surge event is considered overly conservative. To add to the above justification:

- Initial model results show that the proposed scheme would increase River Avon water levels above baseline water levels for a period of only about 1.5hrs around the highest peak tide. It is considered overly conservative to phase the Malago such that the peak of the short duration Malago outflow hydrograph coincides with this 1.5hr period.
- The results of the Malago phasing test show that adjusting the phasing of the Malago flows has no material impact on water levels in the River Avon (less than 5mm difference).

It is recommended that future studies that use the model to specifically assess flood risk on the Malago consider the tidal conditions and phasing of Malago flows vs high peak tidal level.

[3] Use of Joint Probability Methods in Flood Management: A Guide to Best Practice, R&D Technical Report FD2308/TR2, Defra/Environment Agency, 2005.

4. Baseline model updates

This chapter summarises all the updates that have been made to the baseline hydraulic model and is broken into the following main sections:

1. Base model and asset assumptions
2. Implementation of agreed recommendations from model reviews
3. General updates
4. Extension to Bath
5. Refinements downstream of Bristol
6. Implementing HPC solver

4.1 Base model and asset assumptions

The Bristol SFRA 'defended' scenario model as opposed to the BAFS SOC model has been used as a basis for the updated model as this includes updates made to the SOC model during the SFRA modelling study.

Inspection of the SFRA 'defended' model showed that the Underfall Yard sluices and Northern Storm Water Interceptor Sewer (NSWI) are included and operational and that the model does include the Cumberland Road raised flood defence. The SFRA model also appears to reference the same riverbank / wall layers as the Bristol SOC model and includes the Junction Lock flood stop gate as being closed. It was agreed with BCC and EA that the BAFS OBC baseline model should assume that the flood risk management assets described above remain operational as per the BAFS SOC and SFRA models.

4.2 Implementation of agreed recommendations from model reviews

The recommended updates to the baseline model in the Bristol area, i.e. excluding those relating to the areas upstream and downstream, that are identified in the draft modelling methodology report, are reproduced in Table 1 below with additional information added as follows:

- Last column flags whether the recommendation was agreed by BCC and EA to be required and included in the scope.
- For items not included, text in red font briefly explains why it was not included.
- For items included, text in blue font briefly explains the implementation where this is not obvious. In some cases, reference is made to a subsequent sub-section of this report that gives more detail.

Further detail on the decision-making process is provided in Appendix B, which includes commentary from WHS, EA, BCC and Arup.

Table 1: Summary of updates to Bristol model (excluding upstream and downstream areas) that were proposed in the draft modelling methodology report.

ID	Description	Priority	Where recommended: SOC	Where recommended: Arup review	Where recommended: 3rd party review	Agreed to be included in scope
1	Incorporate the latest available LIDAR data. The Bristol SFRA modelling report states that the LIDAR in the model was updated but it does not state the source of the LIDAR data used. It is proposed that the DTM data in the model is updated with the latest EA LIDAR composite DTM, which includes the surveys flows in January 2019.	H	Y	Y	Y	Y

			Where recommended			
ID	**Description**	**Priority**	**SOC**	**Arup review**	**3rd party review**	**Agreed to be included in scope**
	This was implemented. See Section 4.3.2.					
2	Remove TUFLOW 'snap tolerance' command and fix any snapping issues. Testing identified that the snap tolerance command was only required for the 1d network layers for the river channels, which are used for the WLL for mapping 1d results. The snapping issues with these layers has been resolved enabling the TUFLOW 'snap tolerance' command to be removed.	H	Y			Y
3	Resolve TUFLOW model warning messages. Some warning messages resolved; others found to have no issues associated with them. There remain some warning messages and these are summarised and justified in Section 5.2.	H	Y			Y
4	Remove or reduce roughness patches in the TUFLOW model if and where model stability allows. The roughness patches used in the Bristol SFRA model were removed and the spatial definition of materials was updated using the current Ordnance Survey MasterMap data (See Section 4.3.4).	H	Y			Y
5	Ensure flow pathways between 2d domains is represented correctly. This has been implemented by converting the model to single domain – see row ID10 (Ref 4A) below.	H	Y			Y
6	Incorporate the new housing estate at Malago Drive. The model will be updated with the latest OS Mastermap and LIDAR data, which include the new housing estate. It is proposed that threshold survey is only collected here if detriment is still predicted here. Threshold survey could be used to refine the detriment assessment. Updated LIDAR, which was flows after the new housing estate was constructed and reflects current ground levels there, was incorporated into the updated model - see Section 4.3.2. Updated OS Mastermap, which incorporates the new housing estate, was also incorporated into the updated model. Property threshold survey was originally specified for areas at flood risk on the Malago, including at and around the new housing estate. However, these were considered low priority given scheme impacts were not predicted here until after the 2060s in the SOC.	H	Y	Y		Y
7	Update tidal boundary conditions using the latest coastal flood boundary conditions The SFRA model was found to incorporate the latest tidal boundary conditions. These were adopted in the updated model but with revised sea level rise allowances – see below.	H	Y	Y		Y
8	Update climate change allowances to reflect current guidance. Sea level rise allowances were updated based on the required epoch years for the BAFS OBC study – see Section 8.4 for sea level rise allowances applied.	H	Y	Y		Y
9	Use TUFLOW HPC to reduce model run times. This was implemented and found to significantly reduce run times. See Section 4.7.	H		Y		Y
10	Convert model to single domain. (**Ref 4A**). This was implemented. See Section 4.3.1.	H		Y	Y	Y
11	Update spatial definition of floodplain roughness using the latest Ordnance Survey MasterMap data. (**Ref 4B**). This was implemented. See Section 4.3.4	H		Y		Y
12	Review operating rules of major movable structures that control flows and water levels, including those in the Floating Harbour and the NSWI and amend where required. (**Ref 4C**). Note this does not include review of the structure geometry – a separate item is provided for this. It was agreed that the structure operating rules should be identified from the existing baseline model and provided to BCC for them to confirm whether the operating rules are appropriate based on their knowledge of how these assets are intended to operate. The operating rules used within the existing baseline model are presented in Appendix E. BCC confirmed these operating rules are appropriate with the exception of the Brislington Brook Boat Screen culvert outfall which has been changed from flapped (represented using operating rules) to unflapped.	H		Y	Partial	Y

			Where recommended			
ID	**Description**	**Priority**	**SOC**	**Arup review**	**3rd party review**	**Agreed to be included in scope**
13	Obtain threshold survey at Crew's Hall Road and incorporate into model. (**Ref 4D**). This was implemented. See Section 4.6.	H		Y		Y
14	Rationalise model boundary files to facilitate management and update of model files. (**Ref 4E**). This was implemented. The updated baseline model now uses one tidal boundary IED file and one fluvial boundary IED file.	H		Y		Y
15	Collect check survey at key structures and review against model to validate structure data in the model. (**Ref 4F**). It was agreed that the scope of this item should be amended to exclude check survey for Netham Weir given survey used in model is recent. See Section 4.6.	H		Y		Partial
16	Reduce cross-section spacing to less than or equal to 100m in urban areas. Section spacing will be reduced by adding interpolates. The TUFLOW 1d network and 1d-2d links will be updated to accommodate these. Review of section spacing shows that 7 interpolates are required on the Frome and up to 10 are required for the Avon downstream of Bristol. It is assumed that the North Keynsham model will be merged into the Bristol model upstream of the A4174; the cross-section spacing in this model is less than 100m. (**Ref 4G**). Agreed this should be excluded as unlikely to current node spacing is not excessive and updating is unlikely to materially affect stability.	M		Y		N
17	Left/right bank markers will not be updated as this does not impact model results. Agreed bank marker position amendments can be excluded as they do not influence model results.	M		Y		N
18	A full detailed review of bank roughness values will not be undertaken. However, sensitivity testing of channel roughness will be undertaken (included in current scope). Agreed to exclude detailed review given previous work and calibration of models, and the proposed management of uncertainties during option development stage. Note sensitivity testing of channel roughness to be undertaken as part of residual uncertainties assessment.	M		Y		N
19	Enable orifice flow option at bridges identified in review. (**Ref 4H**). This has been implemented at bridge nodes identified in the review, namely, LONG_2151BU, LONG_1608BU, PIGE_0134BU, MALA_2826BU, 01.027bru, 01.025bru, 01.023bru, MALA_2098BU, 01.017bru, 01.012bru, Av5_0737, 031.006, wick_up, W01_0235Bu.	M		Y		Y
20	Attempt to reduce dflood and maxitr runtime parameters to closer to default values. During model development, many tests were undertaken with varying runtime parameters. It was found that maxiter could be reduced to 17 but dflood could not be reduced without leading to model instabilities.	M		Y	Y	Y
21	Turn off 'Mass Balance Corrector == ON' command. This was implemented.	M		Y		Y
22	Totterdown Bridge: Add flow path to represent walkway tunnel on right bank. Topographic survey from 2010 is available. (**Ref 4I**). The flow route through the walkway underpass has been represented using an orifice unit (Av6_4513oru) in parallel with the bridge unit.	M		Y		Y
23	Update Netham Sluice Gates using the available survey data from 2016. (**Ref 4J**). Agreed this is to be excluded given that sensitivity testing undertaken during BAFS SOC study found operation of sluice gates does not materially affect river water levels during flood conditions.	H			Y	N
24	Improve representation of Floating Harbour and assets. (**Ref 4K**). This was implemented. See Section 4.2.1	H			Y	Y
25	Review flows for tributaries that are based on old modelling with no survey.	H			Y	N

ID	Description	Priority	Where recommended: SOC	Where recommended: Arup review	Where recommended: 3rd party review	Agreed to be included in scope
	EA and BCC agreed focus is on River Avon as it contributes vast majority of flood volumes. However, flows for large tributaries upstream of Bristol have been reviewed as part of item 7B and 7C.					
26	Review and address issues where model layers are not picking up correct wall or bank levels. (**Ref 4L**). This was implemented. Zline layers were updated where required to fix snapping issues. Note that additional Zline layers have also been created to incorporate the new (2022) topographic survey of bank levels and wall levels (see Section 4.6.4).	H			Y	Y
27	Fix issue identified with Feeder Canal bed level. (**Ref 4M**). The anomaly, which was causing a large lump in the bed level at grid reference 361221,172689, has been removed using a Zshape layer (2d_zsh_Harbour_Arup_L/P_01.shp).	H			Y	Y
28	Incorporate gap in riverside wall identified in review. It is assumed sufficient information is available from existing topographic surveys to complete this. (**Ref 4N**). Gap identified in the Zline layer 2d_zln_avon_bristol_Arup_P_53 at grid reference 358560, 172066. This Zline layer has been updated (to v54) with the gap filled in.	H			Y	Y
29	Add River Avon railway bridge (next to Cattle Market Road) to model. Topographic survey from 2010 is available for this bridge. (**Ref 4O**). This has been implemented. The newly added rail bridge is at node Av6_3662Bu.	H			Y	Y
30	Add panel markers to improve conveyance curve at cross-sections identified. (**Ref 4P**). This has been implemented for the nodes identified in the model review, namely BRIS_0465, BRIS_0630, BRIS_0632, 1.003, 1.009, 01.009us, 1.013, Pige30, 1.03, COL02_0000, COL02_0121, fr90, FR1342, FR1407, FR1520, FR1586, FR2670, FR2680, TRY1442, 032.006U, 32.007.	M			Y	Y
31	Add two missing structures over Feeder Canal: Railway bridge pier at 360810,172600 and Castle Bridge (the latter requires topo survey). (**Ref 4Q**). It was agreed with BCC and the EA that these structures are unlikely to have a material impact on flood risk given flows are limited along Feeder Canal when Netham Lock gate is closed and given the large opening dimensions of bridges (for navigation). It was agreed that rather than collect new topographic survey of these structures, a visual assessment can be undertaken and presented to justify excluding the structures from the model. This has been implemented – see Section 4.2.2.	M			Y	Partial
32	Add two missing bridges over River Avon: Brock Bridge (grid reference 359944,172243) and footbridge at grid reference 359979,172105. Both require topo survey. (**Ref 4R**). Brocks Bridge has been added to model (node Av6_3792bu) as a Bernoulli loss unit to be able to represent the sloping soffit. Footbridge: almost all of the soffit is above max flood level, so it was agreed it didn't need to be added. See Section 4.6 for more details.	M			Y	Partial
33	Increase or justify the initial water level of Cumberland Basin (set to -0.5m). (**Ref 4S**). It is assumed no further work to close out this item is required. Agreed to exclude from scope. However, note that item 4K now addresses this issue.	M			Y	N
34	Confirm normal water level for Floating Harbour (modelled as 6.2mAOD). BCC confirmed this is appropriate and this is consistent with long term water levels from gauge.	M			Y	N
35	Sensitivity test with a higher initial water level for the Floating Harbour. (**Ref 4T**). This test was run using the updated baseline model following model validation; the results of this test are presented in Section 10.2.	M			Y	Y
36	Confirm whether St Philips footbridge defence has been constructed. If not yet constructed, the BAFS team is to agree whether it should be retained in the model. Footbridge has been constructed and therefore has been retained in model.	M			Y	N
37	Scope new survey and incorporate into model. Please refer to Section 4.6 for details.	M/ H	Y	Y		Partial

4.2.1 Ref 4K: Improved representation of Floating Harbour

The original baseline model did not include Entrance Lock gates, i.e Entrance Lock was assumed to be permanently open, and Junction Lock gate was represented using a Zline, i.e. was assumed to be permanently closed. This meant that the baseline model could not be used or readily adjusted to represent any control of water levels in the Floating Harbour except for the Underfall Sluices which regulate water levels during normal flow conditions. It is necessary to be able to represent control of water levels during flood conditions, including fluvial flood conditions where the River Frome discharges into the Floating Harbour. This is particularly important for the proposed scheme model as the proposed scheme is to allow this control.

The 1d model has therefore been updated to include a simplified representation of Entrance Lock and Junction Lock. For each of these two locks, only one pair or lock gates has been represented; these have been represented using movable sluice units. It is assumed that no navigation is undertaken during extreme events and therefore the many small sluices enabling the locking operation have been excluded. The movable sluice units allow the control of the sluice to be specified, either as permanently open or permanently closed or opening/closing at pre-defined times in the simulation or opening/closing based on logical rules that reference the water levels within the River Avon and Floating Harbour to mimic an operational protocol. For the baseline model, the control rules for the movable sluice units have been specified as follows:

<u>Entrance Lock:</u>

- Lock gate opens if Avon water level is higher than Cumberland Basin water level.
- Lock gate closes if Avon water level is lower than Cumberland Basin water level.

<u>Junction Lock:</u>

- Lock gate fixed in closed position for the duration of the flood event. This is consistent with the BAFS SOC and CAFRA baseline Do Minimum option modelling assumptions.

The initial water level within the Floating Harbour and Cumberland Basin is set to 6.2m AOD.

The model schematic at Entrance Lock and Junction Lock is shown in Figure 2. The 1d model has been linked to the 2d model at either end of each lock via TUFLOW SX links and the locks have been removed from the 2d model to prevent double counting of flows and volumes.

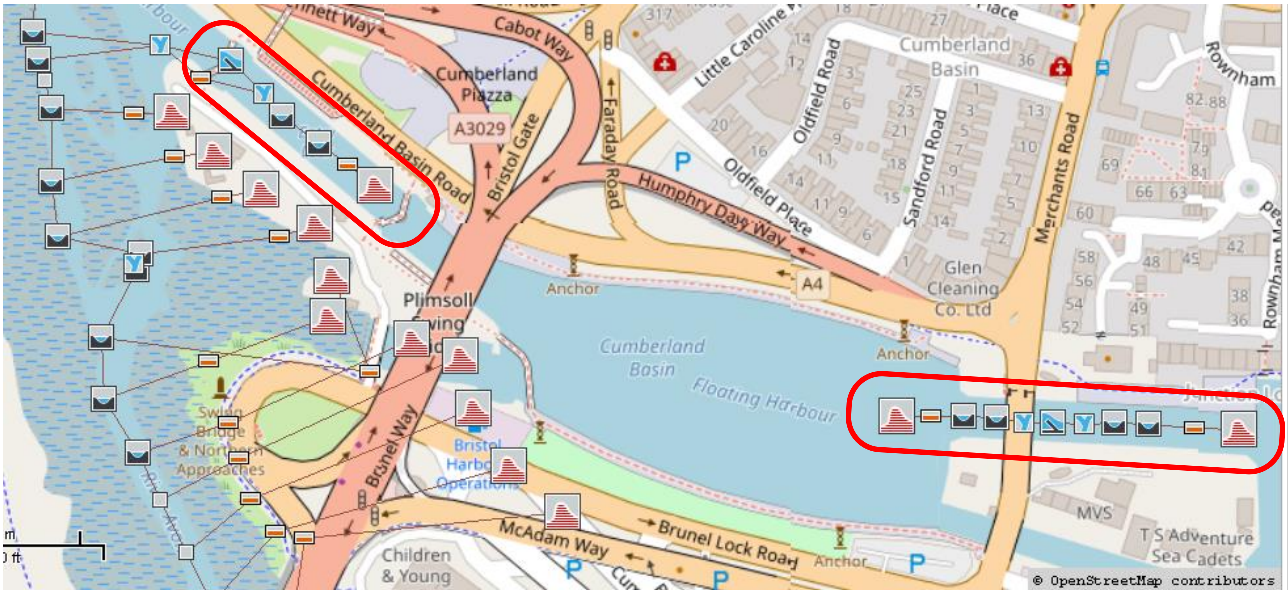

Figure 2: Representation of flow through locks in 1d model.

The updated model configuration has enabled the appropriate water levels within the Cumberland Basin between the two locks to be represented, which addressed recommendation 4S. In the original model the

Cumberland model emptied at each low tide due to the Entrance Lock gate being represented as permanently open.

It was originally intended that the Netham Lock gate be changed from a permanently closed / fixed crest elevation to a sluice gate that could be opened and closed dynamically. However, given model stability issues encountered and the fact that there is no project need to dynamically represent the operation of this lock gate during flood conditions, the original representation has been retained.

The control rules used for the Underfall Yard Sluices have been amended to incorporate a small dead zone to prevent artificial "gate hunting" where the sluices in the original model rapidly closed and opened multiple times in quick succession when trigger levels occurred.

4.2.2 Ref 4Q: Assessment of Feeder Canal missing structures

The 3rd party review of the Bristol SFRA model identified two missing structures over Feeder Canal: (a) railway bridge pier at 360810,172600 and (b) Castle Bridge. Topographic survey for these structures was not available. It was agreed with BCC and the EA that these structures are unlikely to have a material impact on flood risk given flows are limited along Feeder Canal when Netham Lock gate is closed and given the large opening dimensions of bridges (for navigation). It was agreed that rather than collect new topographic survey of these structures, a visual assessment can be undertaken and presented to justify excluding the structures from the model.

The rail bridge pier at 360810,172600 is shown in the Google Streetview photograph in Figure 3. This shows the bridge pier is located on the bank of the Feeder Canal and not within the actual channel. As such, it should not impede flow along the Feeder Canal and therefore does not need to be incorporated into the model.

Figure 3: Rail bridge pier at 360810,172600. © Google.

Castle Bridge is shown in the Google Streetview photograph in Figure 4. This illustrates the blockage ratio of the bridge relative to the channel is very low and is unlikely to significantly influence water levels, particularly when the Netham Lock gate is closed during high flows.

Figure 4: Castle Bridge. © Google.

4.3 General updates

4.3.1 Conversion to single domain

The SFRA model has 8 separate 2d model domains. This resulted in complex file management with duplication and also resulted in some areas where transfer of floodplain flows from one domain to the next was not modelled as accurately as a single domain model. To facilitate model file management and model updates and to reduce duplication and improve representation of flow routes in some areas, the model was converted to single domain. This involved:

1. Creating a single unified 2d model active area without any gaps.
2. Merging some layers, for example 1d-2d connection layers, 1d_nodes, and river channel deactivation polygons.
3. Updated the control files so that only a single TGC and TBC file are used with duplicates layers removed.
4. 2d-2d links removed as no longer needed.
5. The SFRA model included a Zpt layer (5m point spacing) for the Floating Harbour and Feeder Canal bathymetry that was based on a very outdated model file structure that uses row and column numbers from an arbitrary 2d domain origin as opposed to Ordnance Datum and where the file structure is specific to a 5m grid resolution. Thus, when the newly created single domain version of the model was tested, the bathymetry was applied in the wrong location. To facilitate management of the bathymetry data and to facilitate future model updates, including potential adjustments to model resolution, the bathymetry files Zpts layers have been converted to grid files using GIS. The DEM check file elevations were reviewed and found to be consistent with the DEM check file from the SFRA model in the Floating Harbour and Feeder Canal where the bathymetry is applied.
6. Various layers need small adjustments to position to prevent errors during model initialisation. These errors were fixed by specifying the Z flag of some SX connections in the 2d boundary conditions layers for the Brislington, Ashton, Netham and Frome areas; the flag automatically adjusted the elevation of the grid cell(s) at the SX link.

4.3.2 Terrain data

The Floodplain terrain data in the TUFLOW 2d model was updated to use the latest available EA LIDAR at the time of modelling (July 2022), specifically the EA's composite LIDAR Composite DTM 2020 dataset. This is read into the model as grid files. Inspection of the LIDAR catalogue metadata showed that the most recent data available during 2022 is the EA National LIDAR programme DTM data (1m resolution), which was flown in January 2019 for the majority of the study area. This data was incorporated into the EA's LIDAR Composite DTM 2019 published in June 2020. The most recent LIDAR data for Pill, Shirehampton and Sea Mills at the time of modelling is from the EA LIDAR surveys flown in Jan 2019 and these were incorporated into the EA LIDAR Composite DTM 2020 dataset. Prior to the 2018 and 2019 LIDAR surveys, the LIDAR for the study area was from:

- Upstream of Hanham / Broom Hill: 2014
- Between Hanham / Broom Hill and Cannon's Marsh (Osborne Road): 2005
- Downstream of Cannon's Marsh (Osborne Road): 2016

In March 2023, a third-party review of the updates to the BAFS baseline model was undertaken by WHS on behalf of BCC (see Chapter 6). This identified that a new version of the EA LIDAR Composite DTM (LIDAR Composite DTM 2022) published in Feb 2023 was now available and that the ground levels in this new version are different to the 2020 version for the Sea Mills, Shirehampton and Pill areas. Arup subsequently reviewed the DTM 2022 dataset against the DTM 2020 dataset and identified some differences in elevation in the downstream areas as identified by WHS. However, many of these differences were found to be associated with the way that the LIDAR has been processed with the 2022 dataset showing more apparent filtering issues. Given that the 2020 dataset incorporates 2019 LIDAR and exhibits fewer filtering issues, it was agreed that LIDAR currently used in the updated model (from the DTM 2020 dataset) can be retained in the model and the DTM 2022 data did not need to be included.

4.3.3 Terrain data adjustments

A TUFLOW model Zshape layer (2d_zsh_LiDAR_smooth_bristol_Arup_R_47.shp) has been created to smooth out anomalies spotted in the LIDAR data, generally these are at large buildings where filtering issues are apparent.

The SFRA model was found to include a Zshape layer that smoothed out large areas around the Floating Harbour. This layer was reviewed and adjusted to remove Zshape polygons that were no longer deemed necessary based on review of the updated LIDAR data and to incorporate some additional Zshape polygons to smooth out anomalies in the LIDAR data.

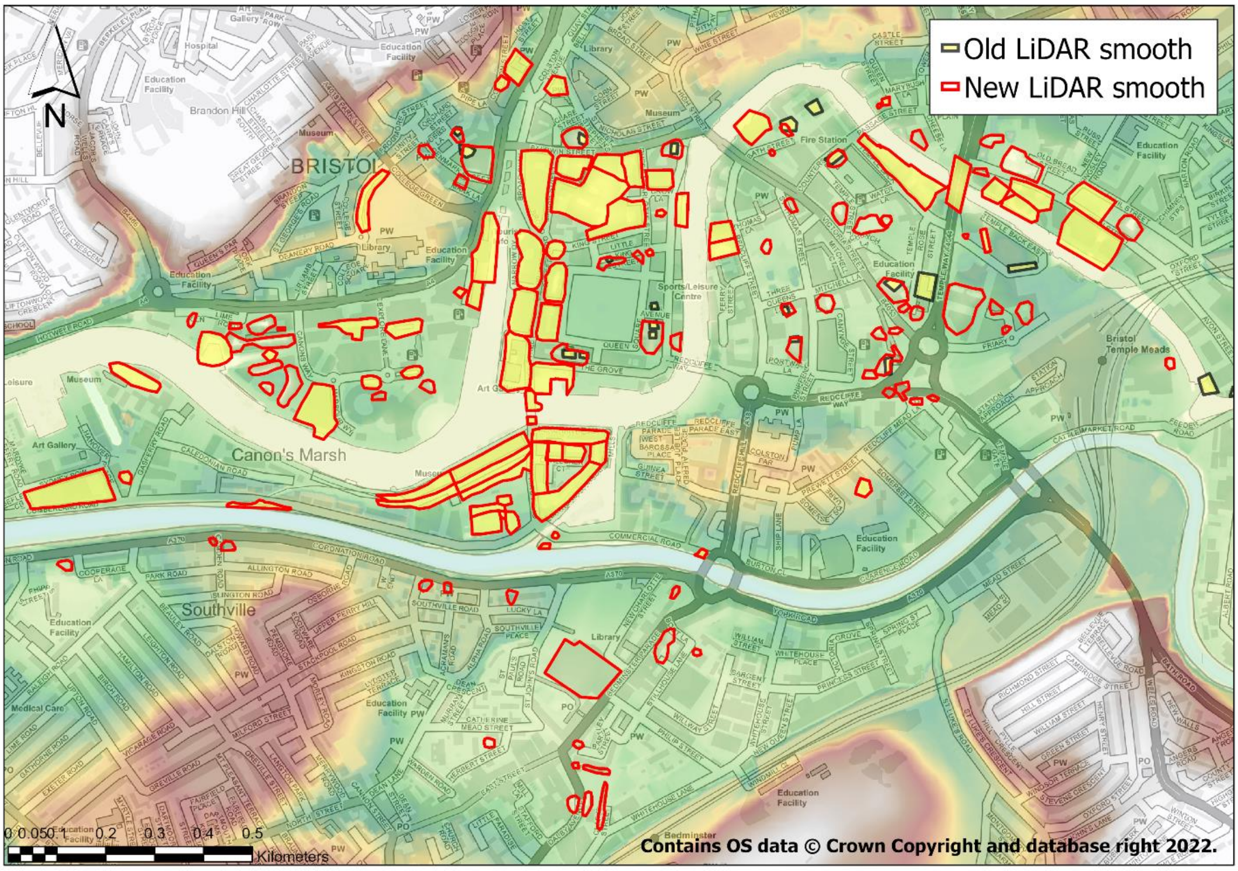

Figure 5: New vs old LIDAR smoothing patch layer.

4.3.4 Materials layer

The SFRA includes multiple materials layers that are used to spatially assign surface roughness values. With the exception of two files (which are only used for the Floating Harbour and Feeder Canal water surface), all materials layers have been replaced with a single new layer created from the latest Ordnance Survey MasterMap data.

4.4 Extension to Bath

The model has been extended upstream from Saltford to Bath by merging in the North Keynsham hydraulic model. The areas upstream of the A4174 main road were represented in 1d only using extended cross-sections in the SFRA model. By merging in the North Keynsham model, all areas from Bristol to Bath are represented in 1d-2d with all major floodplain areas represented in the 2d model.

The two models overlap between the A4174 main road and Netham Weir. In the updated (merged) model, the model data for the reach downstream of node Av5_1931 is taken from the SFRA model and the model data for the reach upstream of this node is taken from the North Keynsham model.

The 2d model domain dimensions were extended to enable the 2d active area to extend to Bath. Given the significant increase in size of the 2d active area and the overall 2d grid size (based on X and Y grid dimensions), the updated (merged) model took approximately 5 days to run using TUFLOW Classic solver. To achieve practical runtimes, the model was set up and run using TUFLOW HPC GPU solver – please refer to Section 4.7 for more details.

Other model amendments undertaken to merge the models and stabilise the merged model:

- To enable the updated (merged) model to initiate, some of the 1d model domain initial conditions were adjusted.
- The ‘orifice flow when surcharged’ option was turned on for the bridge unit at node RC053us.

- The Brislington Brook Boat Screen culvert outlet was connected to the River Avon reach (at node Av5_2536) taken from the North Keynsham model.

The modelled reach between Bath and Bristol includes several control structures (Figure 6); these are listed below with a description of how they are represented. With the exception of Hanham Lock, the modelled representation of these structures has been adopted directly from the North Keynsham model.

- Pulteney Radial Gate, Bath: Represented using a radial sluice unit with control rules to automatically open/close the gate based on flow in the river.
- Twerton Radial Gate, Bath: Represented using a radial sluice unit with control rules to automatically open/close the gate based on the river water level.
- Twerton Vertical Sluice Gate, Bath: Represented using a vertical sluice unit with control rules to automatically open/close the gate based on the river water level.
- Kelston Lock, Saltford: Represented using a single spill unit with elevations representing one pair of lock gates fixed in the closed position.
- Saltford Lock, Saltford: Represented using a single spill unit with elevations representing one pair of lock gates fixed in the closed position.
- Swineford Lock, Swineford: Represented using a single spill unit with elevations representing one pair of lock gates fixed in the closed position.
- Keynsham Lock: Represented using a single spill unit with elevations representing one pair of lock gates fixed in the closed position.
- Hanham Lock: Represented using a single spill unit with elevations representing one pair of lock gates fixed in the closed position. The geometry for this has been refined as part of the current study to be consistent with the available topographic survey[4]. Note the North Keynsham model also represented this lock using a single spill unit to represent one pair of lock gates fixed in the closed position but was based on simplified geometry that was slightly different to the available topographic survey.

[4] Hanham Lock Cross Sections, Drawing No JBA/2010s4046/15, Bristol City Council, May 2010.

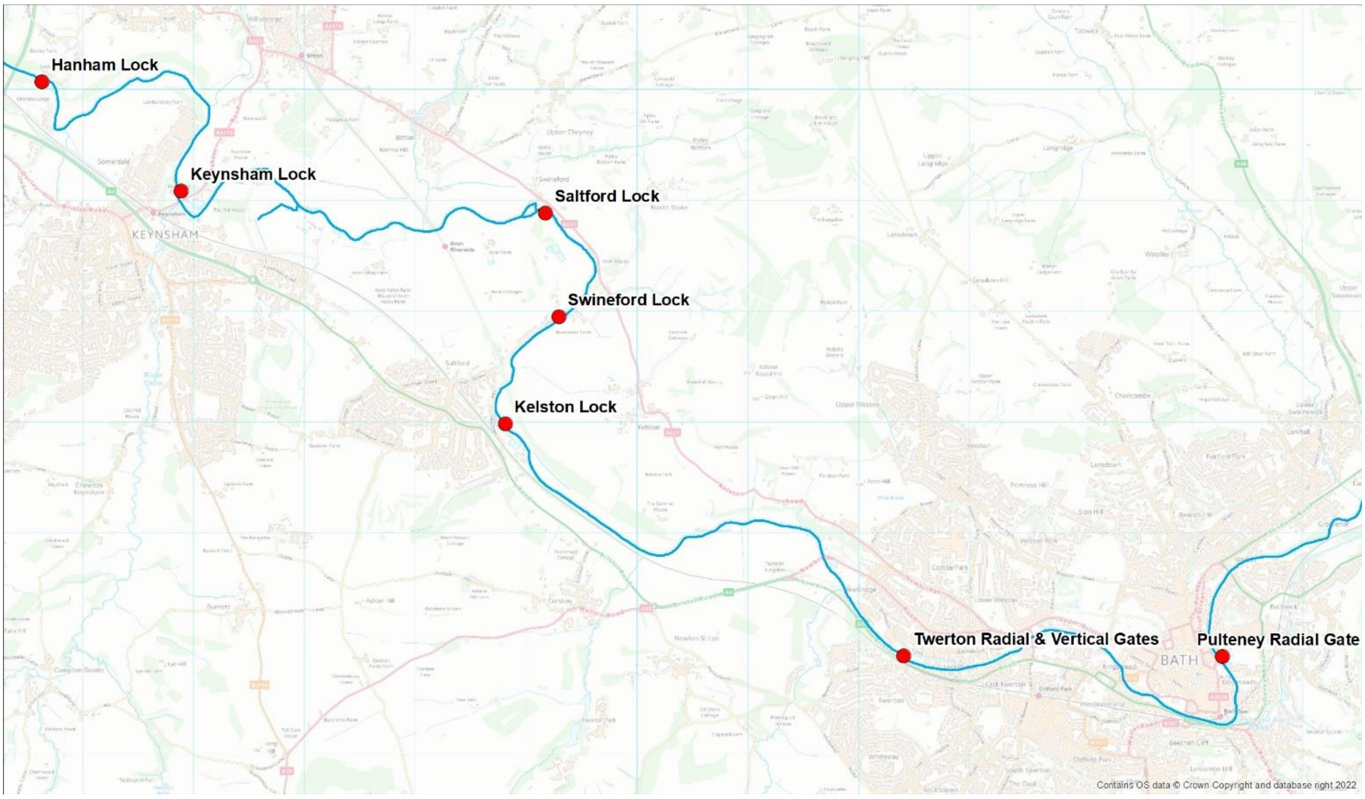

Figure 6: Control structures between Bath and Bristol.

4.5 Refinements downstream of Bristol

The following downstream areas that contain properties and are at flood risk from the River Avon have been refined by converting the model from 1d (extended cross-sections) to 1d-2d:

- Sea Mills
- Pill
- Shirehampton

The interface between the 1d and 2d parts of the model has been aligned along the crest of existing flood defences where present. The 1d model cross-sections have been trimmed to the 1d-2d interface. Floodplain levels have been defined using the latest version of the EA's composite LIDAR DTM. Bank levels and flood defences, where present, have been incorporated into the 2d model using Zlines. The downstream areas that have been converted from 1d to 1d-2d in the model are shown in Figure 7.

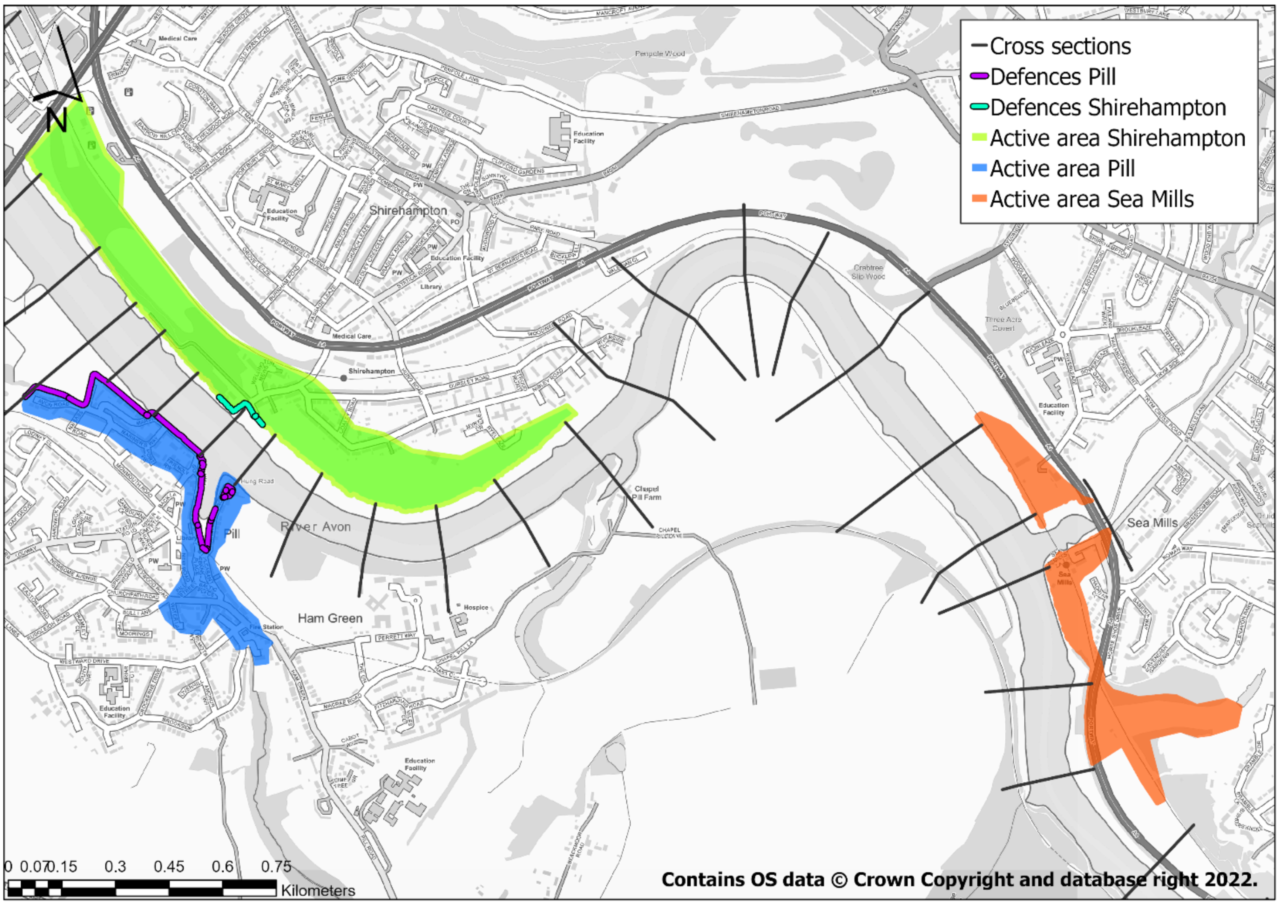

Figure 7: Downstream areas in model converted from 1d to 1d-2d.

Other model layers have been created as described in the sub-sections below.

4.5.1 Sea Mills

- Bank levels: These were defined using a Zline layer with elevations based on LIDAR.
- Flood defence around one building. This has been incorporated into the model as a Zline layer based on crest elevations form the 2022 topographic survey[5], which is included in Appendix E2. See Section 4.6.4.
- Building threshold levels have been incorporated into the model using a Zshape polygon layer representing building footprints with threshold levels taken from the 2022 topographic survey[6], which is included in Appendix E2. See Section 4.6.5.

4.5.2 Shirehampton

- Bank levels: These were defined using a Zline layer with elevations based on LIDAR.
- Flood defence levels obtained from the EA based on spreadsheet data provided by the EA (EA_Pill_Shirehampton_Crest_Level_Extract.xlsx), which is included in Appendix E3. The alignment of the flood defences are shown in Figure 7.

[5] Sea Mills Lane Topographic Survey FW1, Drawing no. 285982_19, Storm Geomatics, 10/01/2023.

[6] Sea Mills Lane THL Location – SM, Drawing no. 285982_20, Storm Geomatics, 20/01/2023.

4.5.3 Pill

Topographic survey from 2022[7] was provided by the EA and used to define bank levels, flood defence levels and threshold levels in the model at Pill.

- Bank levels and defence levels were incorporated into the model using Zline layers. The alignment of the flood defences are shown in Figure 7.
- Building threshold levels were incorporated into the model using a Zshape polygon layer representing the building footprints (Figure 8).

Figure 8: Location of property thresholds in Pill.

4.5.4 Water Level Lines

Water Level Lines (WLL) layers are used in the TUFLOW model to enable mapping of results such as flood water levels and flood extents. across the 1d model domain. In the updated model, WLLs have been refined in various locations, most notably for the River Avon downstream of Bristol where some rural areas continue to be represented purely in the 1d model. Downstream of Bristol, numerous additional WLLs have been added to improve the spatial definition of the mapped outputs. In addition, WLL points have been incorporated to specify the elevation of the topography (extracted from LIDAR data) at increments along each WLL. This approach was found to greatly improve the accuracy of the mapped 1d results downstream of Bristol. This approach was not deemed necessary upstream of Bristol as the 1d domain only represents the river channels here.

4.6 Topographic survey

The modelling methodology recommended that existing topographic survey is sourced, or new topographic survey is collected to either (a) validate data within the model, or (b) refine the model. The modelling methodology provides more detail for each and explains the reasons for the recommendations. The

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[7] Pill Topographic Survey, drawing C21319_3D_SX, Lewis Brown Chartered Land Surveyors, Jan-Apr 2022.

recommended survey items are listed below with summary for each on the BAFS project team decision made during the inception stage.

- **Ref 5A**: River Frome and Frome culverts: Recommended to validate model data. Frome culvert point survey from 2015 was sourced and compared against model data. See Section 4.6.1 for more details.
- **Ref 5B**: NSWI sewer and flow control structures: It was agreed that this could be excluded given the flows from the Frome are not expected to significantly influence water levels in the Avon through Bristol and the SOC showed no detriment along the Frome
- **Ref 5C**: Underfall Yard sluices / culverts: BCC provided various information including old drawings and inspection reports. The data included a cross-section drawing of the culvert showing dimensions. The dimensions were found to exactly match the values used in the model to represent the culverts. The dimensions were also consistent with the modelled sluice dimensions. Given this finding, the modelled representation was retained.
- **Ref 5D**: Levels of Junction Lock gates: Matthew Sugden of BCC confirmed Junction Lock gate level is 8.7m AOD (email, 11/07/2022).
- **Ref 5E**: Nova Dam and Nova sluices: Matthew Sugden of BCC confirmed that the only flow route through Nova Dam is either through the sluices or over the road (email, 11/07/2022). It was agreed with BCC and the EA that the Nova sluices should be assumed to be closed throughout the modelled flood event as per the existing modelling.
- **Ref 5F**: River Avon flood defences at Shirehampton: The EA provided defence levels from topographic survey of the Shirehampton flood defences. These were provided in spreadsheet format[8] and are from a survey undertaken in 2006. This data has been used to define flood defence crest levels in the model – see Section 4.5.2.
- **Ref 5G**: Bridges over Feeder Canal / Floating Harbour: It was agreed that a visual assessment of these structures is undertaken to justify excluding them from the model – see Section 4.2.2.
- **Ref 5H**: Two bridges over River Avon were identified as being missing from the model and these were not included in the CAFRA survey. Survey data for these bridges was sourced and reviewed and one of these bridges was incorporated into the model. Please refer to Section 4.6.2 for more details.
- **Ref 5I**: Keynsham bridges: It was agreed new topographic survey of Keynsham bridges could be excluded given this location is sufficiently remove from the location of proposed flood defences in Bristol and given refinements to bridge representation considered unlikely to materially affect scheme detriment.
- **Ref 5J**: Check survey at key structures: The check survey items originally proposed were:
  - Brislington Brook culverts: culvert under rail line, culvert under St Anne’s Park Road, and culvert between Chapel Way and River Avon. Note Brislington Brook flooding mechanism contributes to detriment at Netham. For the Brislington Brook culvert check survey, please refer to Section 4.6.2.
  - Feeder Road Bridge over River Avon: soffit levels and hard parapet levels. The model data reviewed against the 2010 topo survey collected for the CAFRA study. Modelled parapet level was found to be consistent with the survey. The modelled soffit level (9.83m AOD) corresponds to the surveyed soffit level in centre of channel but the survey was found to include lower soffit levels near the river banks. The soffit level in the model was therefore updated to represent the average of the surveyed soffit levels, calculated as 9.785m AOD.
  - Netham Weir levels (in case of any movement since the 2018 topographic survey). It was agreed new topographic survey of Netham Weir could be excluded as the model is based on recent topographic survey data for the weir and any movement since can be assumed to be minimal.

[8] EA_Pill_Shirehampton_Crest_Level_Extract.xlsx (provided via email by Deborah Steadman, EA on 15/06/2022).

– Brislington Boat Screen culvert. BCC provided several drawings (date unknown) of the boat screen weir, inlet and culvert. These were used to confirm that all modelled levels and dimensions were consistent with the drawings except for (a) culvert height, which has been slightly changed from 2.16 to 2.13m, and (b) bore area of the inlet orifice between the weir and the culvert, which has been changed from 2.65 to 3.73m^2 to match the bore area of the culvert as the drawings provided show no obvious constriction in width at the upstream inlet to the culvert as implied by the bore area of the orifice unit used in the existing model.

- **Ref 5K**: Bank levels: See Section 4.6.4.
- **Ref 5L**: Property threshold levels: See Section 4.6.5.

New topographic survey was collected in 2022. The original scope for the topographic survey is included in Appendix E1 and the final survey deliverables (without the very large background mapping .TIF files) are included in Appendix E2. Note the 505 properties in the original property threshold survey scope were descoped as they were considered low priority. The new topographic survey collected specifically for the BAFS OBC hydraulic modelling comprises the following items, which are described in more detail in the sub-sections below.

- Check survey of Brislington Brook culverts
- Bank levels and wall levels
- Property threshold levels

Data used to check / validate the model can be found in Appendix E3. Topographic survey from 2022 was provided by the EA and used to define bank levels, flood defence levels and threshold levels in the model at Pill (see Section 4.5.3); this survey can be found in Appendix E4.

4.6.1 Frome culverts (Ref 5A)

Point cloud survey[9], including section drawings generated from the point cloud data, was provided for the long Frome Culvert between the upstream open channel and the Floating Harbour (coverage shown in Figure 9). Note this survey doesn't cover the most downstream portion of the Frome culvert (the downstream part has invert level of 5.6 to 5.8m AOD in the model).

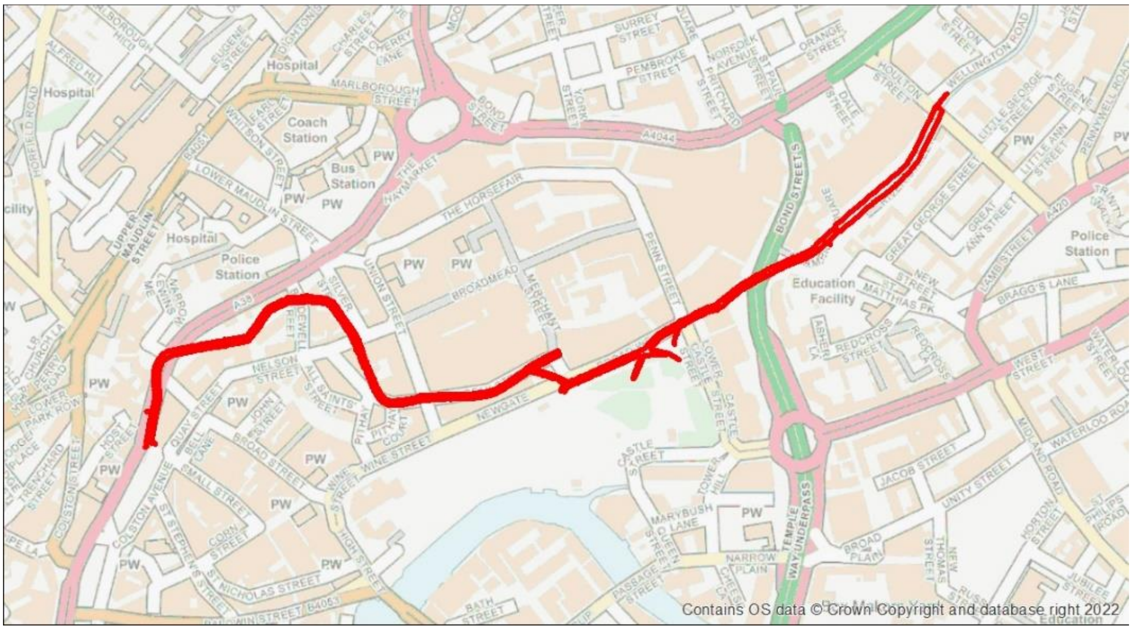


Figure 9: Frome culvert survey coverage.

[9] Bristol Frome Culvert Survey, APLS-0354, AP Land Surveys, Feb 2015.

There is uncertainty associated with the exact spatial location of the culvert data in the model. The model data has been checked against what should be the closest surveyed section data based on chainages (lengths). The culvert changes dimension / shape at various points and it is possible that these locations of change aren't accurately matched in the model – this may contribute to some of the differences identified in the model.

The comparison of model against survey data is summarised in Table 2, which shows:

- Surveyed invert levels are significantly lower than in model for the downstream part of the survey. Not anticipated to have a significant influence of hydraulics given downstream water levels are at least 6.2m AOD and culvert downstream of survey has significantly higher invert level in the model.
- Overall close match in culvert width throughout.
- Good match to both width and height in middle part of culvert.
- Surveyed height at upstream part of culvert is smaller than in model. Model may over-estimate culvert capacity here. However, culvert significantly narrows in both the model and survey downstream of here so the mismatch in height at the upstream end is not anticipated to have a significant impact on the overall flow capacity of the culvert.
- Surveyed height at downstream part of culvert is larger than in model. However, surveyed height is based on maximum height as opposed to average height – survey shows significant silt build-up here that is not replicated in the model – see example survey section copied below (survey ID 180). Model is represented as flat-bottom arch shape here. On balance, modelled bore area of culvert is similar to survey once silt is taken into account.

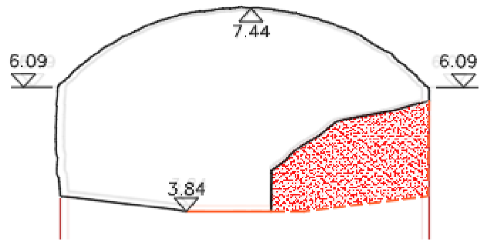


Table 2: Comparison of model against survey data for Frome culvert.

				Invert level			Width (max)			Height (max)			Shape		
Model node	chainage model	Survey ID	Equivalent chainage of survey	Model	Survey	Diff	Model	Survey	Diff	Model	Survey	Diff	Model	Survey	Diff
FC1737	54	1380	40	5.89	5.84	0.05	9.27	9.96	-0.69	4.11	3.35	0.76	Square	Square, irregular	Similar
FC1670	121	1320	100	5.84	5.79	0.05	11.1	9.95	1.15	4.32	3.76	0.56	Square	Square, irregular	Similar
FC1520	272	1120	300	5.56	5.48	0.08	6.7	6.73	-0.03	3.77	3.75	0.02	Arch	Arch	same
FC1296	495	920	500	5.26	5.19	0.07	5.6	5.67	-0.07	3.29	3.19	0.10	Arch irregular	Arch	Similar
FC1175.5	616	780	640	4.98	5.16	-0.18	5.5	5.32	0.18	2.97	2.96	0.01	Arch irregular	Arch	Similar
FC1025.5	766	660	760	4.94	4.82	0.12	5.5	5.54	-0.04	3.58	3.73	-0.15	Arch	Arch	same
FC897	895	520	900	4.96	4.47	0.49	5.8	5.77	0.03	3.26	3.55	-0.29	Arch	Arch irregular	Similar
FC724	1058	380	1040	5.2	4.31	0.89	6.5	6.43	0.07	2.84	3.76	-0.92	Arch	Square irregular	different
FC535.5	1246	180	1240	4.87	3.84	1.03	6.5	6.34	0.16	2.38	3.6	-1.22	Arch	Arch irregular	Similar
FC377U	1404	60	1360	4.2	3.44	0.76	6.1	6.44	-0.34	3.77	3.76	0.01	Arch	Arch	Similar

Based on the results of this check, the overall representation of the Frome culvert is considered acceptable for the current BAFS study. However, it is recommended that updating the culvert representation to better match available topographic survey is considered for future studies where the focus is flood risk from the River Frome.

4.6.2 Missing bridges over the River Avon (Ref 5H)

Two bridges over River Avon were identified as being missing from the model and these were not included in the CAFRA survey. Survey data for these bridges was sourced and reviewed and one of these bridges (Brocks Bridge) was incorporated into the model as described below:

<u>St Philip's Marsh footbridge (grid reference 359979,172105):</u>

BCC provided a survey drawing of this bridge10, which shows the soffit level to be 12m AOD but with a stepped access section (approx 25% of the total span) having soffit reducing from 12m AOD to approx 9.5m AOD at the right bank. For context, maximum water level from the BAFS SOC modelling on Phase 2 Defences in 2125 with FRA climate change is 10.68m AOD here; this level has been estimated to increase to around 11m AOD here based on updated climate change allowances and other considerations. Based on a water level of 11m AOD, water would hit the soffit for about 60% of the stepped section, i.e. for about 15% of the total bridge span. This would not be easy to accurately represent and this is not anticipated to have a significant impact on water levels in 2130 and no material impact in the 2060s. It was therefore agreed that this footbridge did not need to be incorporated into the model.

Brocks Bridge (grid reference 359944,172243):

BCC provided a survey drawing of this bridge[11], which shows the soffit level to slope from 12.33m AOD (left bank) to 9.5m AOD (right bank). Based on the above estimated maximum water level of 11m AOD, it is estimated that the water would hit the soffit for about 50% of the total bridge span in 2130 and 20% of the total bridge span in the 2060s. This is anticipated to have a non-negligible impact on water levels in the 2060s and 2130 and therefore it was agreed that this bridge should be incorporated into the model. The standard bridge units in the modelling software are not able to represent a sloping soffit level and using an average value is not considered appropriate in this case. A Bernoulli loss unit has therefore been used to represent the impact of the bridge based on flow area under the bridge which has been derived using the channel geometry from the CAFRA topographic survey and the bridge soffit levels from the more recent survey drawing. The channel geometry is taken from an adjacent surveyed cross-section 77m upstream of the bridge; as such, there is a degree of uncertainty associated with the representation of the bridge at this location. However, the inclusion of the bridge in the model is considered more appropriate and more accurate than omitting the bridge as per the original model.

4.6.3 Brislington Brook culvert check (Ref 5J)

Topographic information on Brislington Brook culverts was sourced to check the model representation of these. The culverts in question are the culvert under rail line, the culvert under St Anne’s Park Road, and the culvert between Chapel Way and River Avon. This was considered important because the SOC modelling showed that Brislington Brook flooding mechanisms contribute to scheme detriment at Netham. The outcome of this check is described below.

It was originally intended that new topographic survey of the rail culvert would be collected. However, due to restrictions associated with access to Network Rail land, it was agreed that this culvert could be omitted from the survey given that culvert dimensions were available from a Network Rail asset inspection report[12]. The modelled culvert shape and dimensions were consistent with the details given in the Network Rail report with the exception of a concrete encased service pipe running inside the culvert on one side and encroaching by 0.5m into the culvert (see Figure 10 below), which was not represented within the model. To improve the model representation of the culvert capacity, the culvert width has been reduced by 0.25m to represent the approximate reduction in flow area imposed by the service pipe.

[10] Bristol City Council TQEZ RIF, drawing no. 203742-CH-SBRSTPST-DR-ST-0008 Rev, 2ch2m, 22/03/2016.

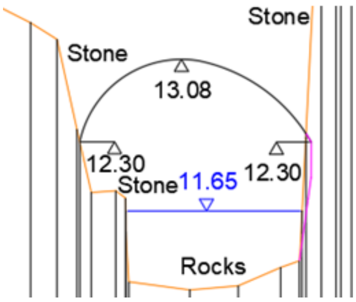
[11] Temple Quay Phase 3, Brocks Bridge Sheet 2 of 2, drawing no. Q80004/S50/A/02 Rev AB3, Pell Frischmann, 06/06/2022.

[12] Structure ref 116 61 B/U, Exam ID 2683406, Network Rail, April 2019

Figure 10: Concrete encased service pipe within the Network Rail culvert (photo taken on 24/04/2019).

The Brislington Brook culvert data in the model against was checked against the new topographic survey received in December 2022 for the culvert under St Anne's Road. The results of the check are summarised in Table 3 below. The largest differences are:

- Culvert under St Anne's Road (model nodes BRIS_0958c to BRIS_0908c): The model over-estimates the capacity of this culvert as the narrowed width below the ledge (see image below) is not represented. It was agreed that this culvert should be updated in the model to better represent the capacity of this culvert. It was also agreed that inlet and outlet loss units should be added to the model for this culvert (if model stability allows) as these are currently missing, which may also cause the model to over-estimate flows through the culvert. The recommended actions have been implemented in the model. The updated model now represents the geometry for this culvert using asymmetrical conduit units to enable accurate representation of the surveyed culvert shape. Culvert inlet and outlet units have also been added.



- The long culvert downstream of Chapel Way (model nodes BRIS_0276c to BRIS_0081c): The check initially shows the model is significantly under-estimating upstream culvert width (by 0.6m); however, accounting for skew angle of 26 degrees provided in the survey (and confirmed in GIS) the adjusted upstream width becomes 2.82m (still 0.26m wider than the modelled width). It was agreed that BRIS_0276c culvert dimensions should be updated to 2.82m wide and 1.65m high. For this culvert, it was also agreed that the representation in the model should be updated to gradually transition from the upstream dimensions to the downstream dimensions as currently the full culvert except the outlet is assigned the upstream dimensions (as replicate units are used instead of interpolate units within he culvert). The recommended actions have been implemented in the model.

Table 3: Comparison of model against survey data for Brislington Brook culverts.

		Invert level			Width			Height			Shape		
Model node	Survey ID	Model	Survey	Diff	Model	Survey	Diff	Model	Survey	Diff	Model	Survey	Diff
BRIS_0958c	BRI01_00956	11.62	11.66	-0.04	2.7	2.6	0.10	2.06	2.28	-0.22	arch	arch	same
BRIS_0908c	BRI01_00905	10.97	10.9	0.07	2.1	1.68 to 2.19	-0.09 to 0.42	2.02	2.18	-0.16	arch	arch irregular	similar
BRIS_0276c	BRI01_00279	7.47	7.47	0.00	2.56	3.16	-0.60	1.78	1.65	0.13	Square	Square	same
BRIS_0081c	BRI01_00062	6.43	6.39	0.04	2.65	2.74	-0.09	1.89	1.93	-0.04	Square	Square irregular	similar
BRIS_0030o	BRI01_00012	6.087	6.09	0.00	2.67	2.6 (approx average)	0.07	1.733	1.75	-0.02	Orifice	Square irregular	different

4.6.4 River bank ground levels and wall levels (Ref 5K)

Topographic survey of ground levels along some of the river banks and crest levels of walls, defences and flood gates was collected (see Figure 11 and Figure 12). This data was used to refine the bank levels, wall levels, defence levels and flood gate levels in the model. New Zlines were created to represent these levels and alignments.

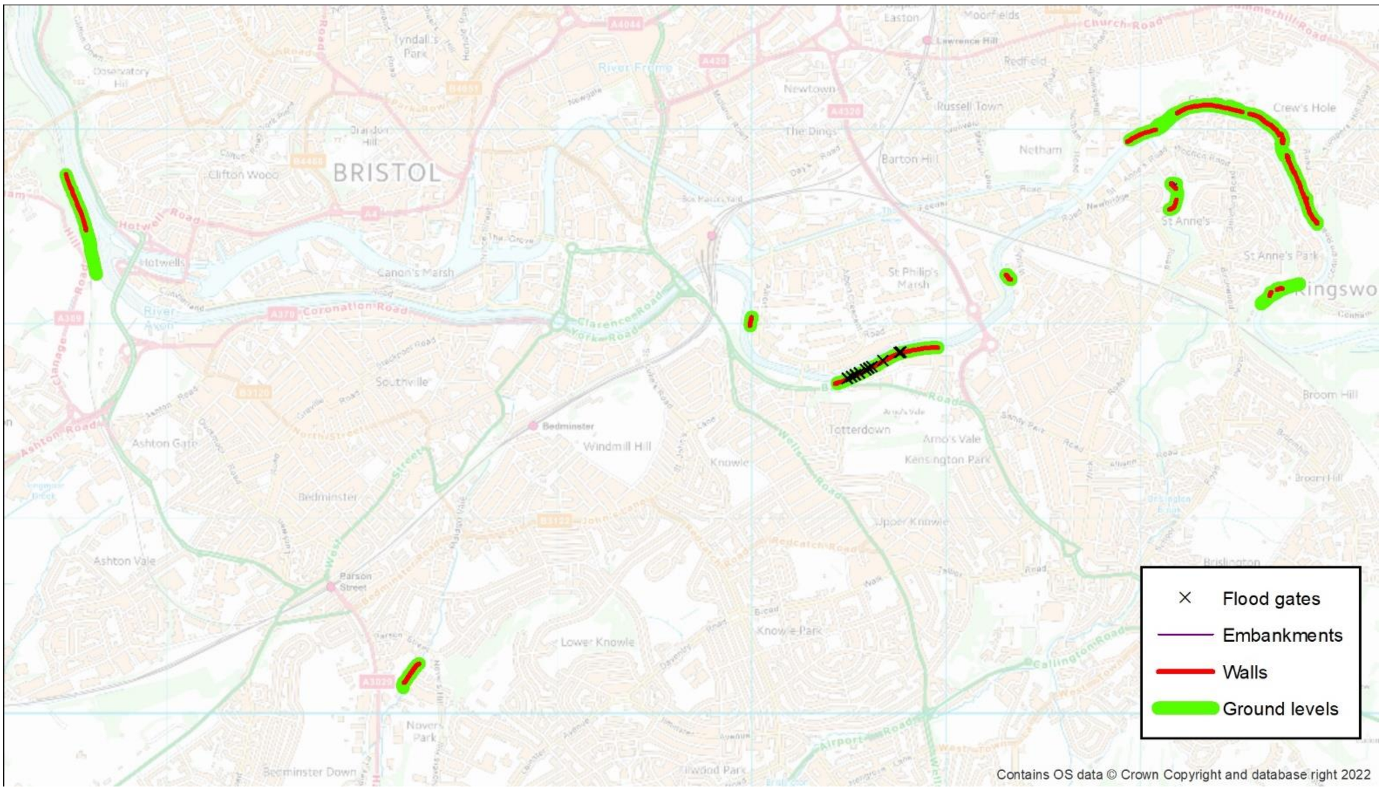


Figure 11: Location of newly surveyed river bank and wall levels (Bristol).

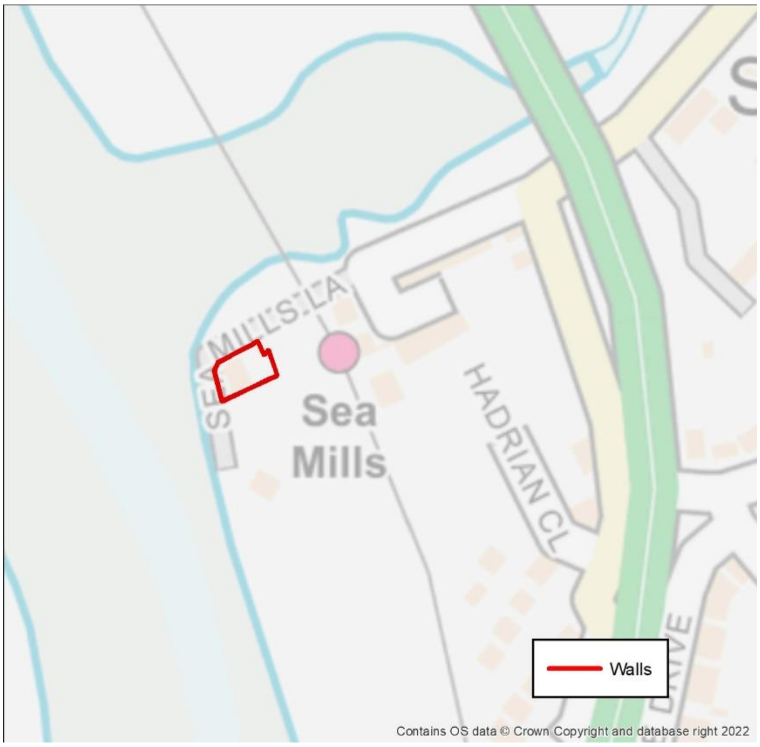


Figure 12: Location of newly surveyed and wall levels (Sea Mills).

4.6.5 Property threshold levels (Ref 5L)

The SOC identified areas where properties were at risk of increased flood risk from the main scheme defences before mitigation measures were included. Topographic survey of the threshold levels of properties in these areas was collected for the OBC. The location of the properties included in the survey are shown in Figure 13 with more detail shown in the Brislington and Crews Hall Road area in Figure 14.

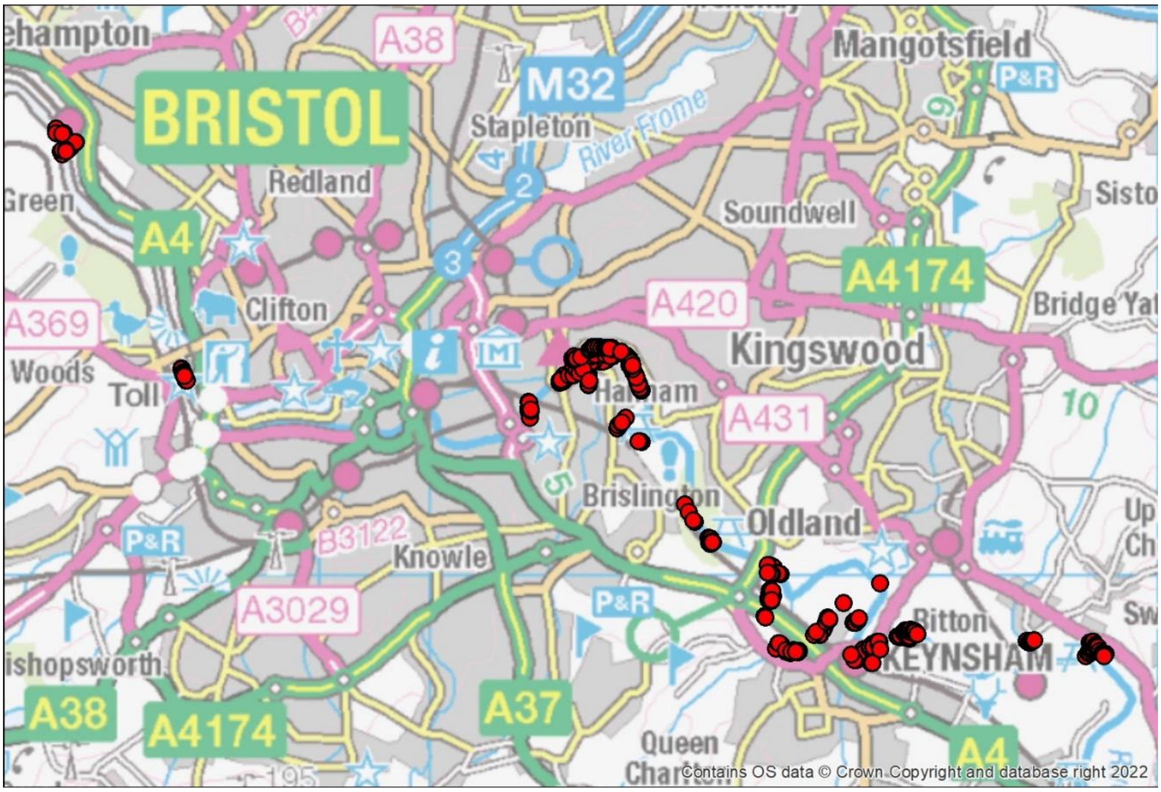


Figure 13: Location of surveyed threshold levels.

Figure 14: Location of surveyed threshold levels at Brislington and Crews Hall Road.

The surveyed threshold levels have been used in the model to set elevations of building footprints using a Zshape layer. A total of 355 buildings are included in the survey and a total of 801 threshold points were surveyed (as multiple points were surveyed for some buildings, generally large buildings containing multiple properties). For buildings where multiple threshold elevations have been surveyed, the modelling approach used is:

- Where threshold elevation points are recorded at the same location, the minimum elevation has been taken as it is considered the most conservative value.
- Where threshold elevation points vary around a building perimeter, the threshold levels and associated locations were carefully reviewed to identify whether (a) the minimum threshold level should be taken, or whether (b) multiple threshold levels should be incorporated. The outcome of this review was that approach (a) was taken for all but one building as either threshold levels for a particular building were very close in elevation (within 50mm) and/or were located on the same side of the building. The one building where this was not the case was the large P&H building on St Anne's Road (Figure 15). Review of LIDAR and Google Streetview and aerial photography showed the south-western side of the building to be a loading area with the lower threshold while the rest of the building has the higher threshold with stairs from ground level to access level evident in the photography. This building was therefore represented using two Zshape polygons with the different threshold levels.

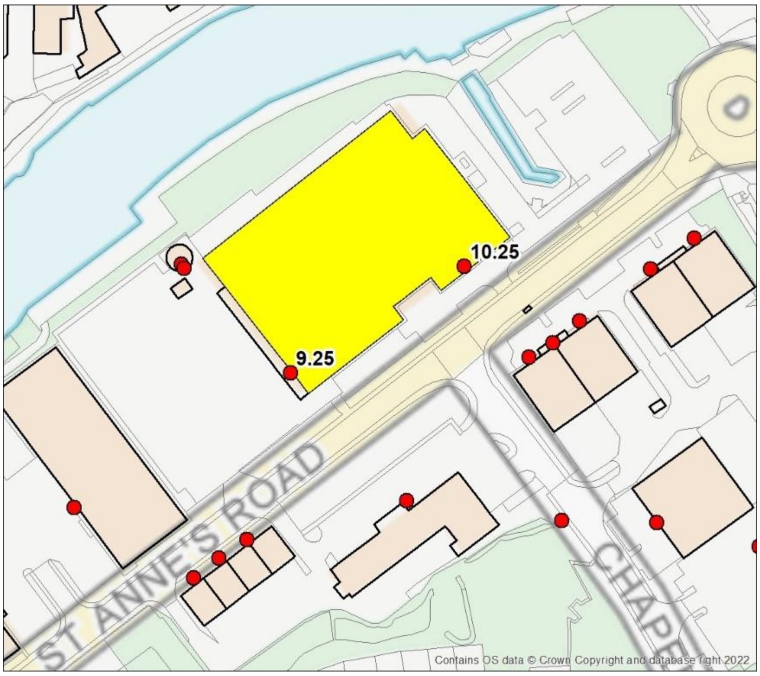


Figure 15: Large P&H building on St Anne's Road (threshold survey shown as red dots).

4.7 Implementing HPC solver

The SFRA model took over 30hrs to simulate a large flood event. Once the 1d and 2d components of the model were extended upstream and downstream, the run time of the model increased to approximately 5 days, which was not considered practical given the numerous model simulation required and programme constraints. Reducing the grid resolution from 5m to 10m may have enabled more practical run times but would result in a significant loss of detail and greater risk of model instability. It was therefore considered necessary to attempt to test and use the TUFLOW HPC solver using a computer with a modern GPU card rather than the TUFLOW Classic solver, which uses the computer's CPU.

To enable use of the HPC solver, two Flow Constriction Shape layers had to be converted to Layered Flow Constriction Shape layers as the former type of layer was not compatible with the HPC solver. The Bed Resistance Cell Sides parameter was also changed from 'AVERAGE M' to the default 'INTERROGATE'.

4.8 Model stability improvements

Using the GPU solver was found to result in unexpected stability issues in some locations in the 1d model where no flooding in the 2d model was occurring, particularly for the lower Malago system. Extensive testing was undertaken to try and diagnose the cause of the instability, which typically occurred during relatively low flows, and it was concluded that the cause was likely due to the 1d solver using a slightly different number of iterations at particular points within the simulation when the GPU solver was used. This suggested that the 1d model was inherently quite unstable and that minor changes in runtime state could lead to unexpected and unexplained failures. It should be noted that the SFRA model uses non-default runtime parameters, including high number of maximum iterations and a high dflood value. It is also noted that the SFRA model includes various stability edits such as high manually defined top slots in symmetrical conduit units, including those on the Malago system. After extensive testing and trialling many potential fixes (both runtime parameters and model stability edits and combinations of these), a solution was reached that enabled the model to complete to the end of the simulation without significant stability issues. The edits that were made are as follows to the lower Malago system:

- Bed drop for replicate unit MI_LTR62R1 changed from 0.067 to 0.052.
- Max movement rate reduced from 0.5m/s to 0.01m/s for Underfall sluices ufs1b and ufs2b. Underfall sluice rules modified to prevent gate hunting - see 'Underfall Sluice Rules' sheet.
- Lower Malago (between 01.006 and Avon and between 01.002 and Avon) moved to ESTRY (see Figure 16). Dummy nodal storage has been included to maintain model stability at the long culverts at the downstream end of this reach. A 1d-1d link (type X1DQ) was used to link the upstream FMP Malago reach to the downstream ESTRY Malago reach. Two 1d-1d links (type X1DH) were used to link the downstream two ESTRY Malago reaches to the FMP Avon reach.
- Dummy weir inserted at MI_LTR50 to stabilise model.
- Adjusted top slot geometry for d/s part of twin culvert (from MI_LTR50U to MI_LTD and MI_RTR50U to MI_RTD).

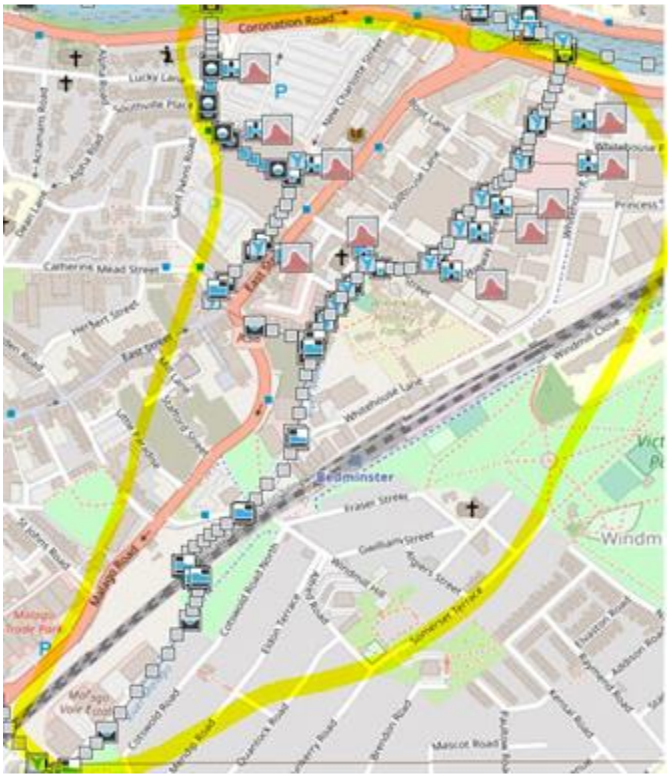


Figure 16: Part of the Lower Malago moved to ESTRY.

Intermittent stability issues were found to occur within Mylnes culvert, which links the Frome to the Avon and discharges approximately 1m^3/s during low tides. These issues resulted in failure of simulations and did not appear to be associated with extreme flow conditions. After testing and trialling potential fixes (both runtime parameters and model stability edits and combinations of these), the only solution that was found to enable the model simulations to reliably complete without stability issue here was to move the Mylnes culvert from FMP to ESTRY. A 1d-1d link (type X1DQ) was used to link the upstream inlet weir in FMP to the ESTRY Mylnes culvert. A 1d-1d link (type X1DH) was used to link the downstream ESTRY Mylnes culvert to the FMP Avon reach.

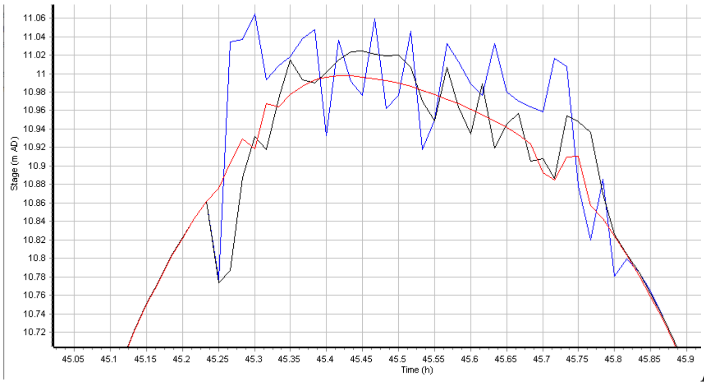
During the largest flood events, oscillations in water level vs time were found to occur on the Brislington Brook from St Anne's Wood to the Avon confluence; the oscillations were large in the Chapel Way area. Given this is an area where detriment mitigation is proposed and that the proposed detriment mitigation at Chapel Way could worsen stability here, a decision was taken to investigate and resolve the stability issues. The stability issues were found to be mainly associated with (a) the narrow width of Brislington Brook in the 1d model relative to the 2d cell size, and (b) large depths of flow over the 1d-2d link cells upstream of Chapel Way. The stability issues were resolved by extending cross-sections for a 336m reach of Brislington Brook within St Anne's Wood in the 1d model (nodes BRIS_0799 to BRIS_0465) such that all flows are contained within the 1d model here. The TUFLOW layers were adjusted here accordingly. The cross-section geometry for the extension was taken from the existing model by moving the deactivation markers in the model. This amendment is considered acceptable given it results in improved stability and the reach adjusted is in a steep sided valley with no receptors. One interpolate in the 1d model (BRIS_0414) was replaced with a river cross-section based on manually interpolated geometry (in-channel) and LIDAR data (banks) to better represent the narrowing in flow width when the channel gets to Chapel Way.

5. Model runtime and performance

5.1 Model runtime parameters

Table 4 summarises the non-default runtime parameters that have been used. Note the model uses TUFLOW HPC which automatically adjusts the 2d timestep as required to maintain model stability.

Table 4: Non-default runtime parameters

Parameter	Default value	Value used	Comment / justification
FMP model:			
1d timestep	-	0.5s	This value has been adopted from the Bristol SFRA model and has been retained to maintain model stability. Attempts were made increase this to 1.0s but the model proved too unstable.
Minitr	3	5	Greater than default value to maintain stability. Note the Bristol SFRA model used a value of 13 and this has been reduced to closer to default value.
Maxitr	11	17	Greater than default value to maintain stability. Note the Bristol SFRA model used a value of 27 and this has been reduced to closer to default value.
Matrix Dummy Coefficient	0	1E-6	This value has been adopted from the Bristol SFRA model and has been retained to maintain model stability. This is not anticipated to materially affect model results.
Alpha	0.7	0.6	This value has been adopted from the Bristol SFRA model and has been retained to maintain model stability. Attempts were made to set this closer to the default value, but the model proved too unstable.
Theta	0.7	0.8	This has been increased to improve model stability on tributaries. Testing of runtime parameters during model development showed that increasing the theta value had no impact on River Avon water levels but did significantly reduce anomalous oscillations in water levels and flows on the Malago – see example results on the Malago below showing theta = 0.7 (blue), theta = 0.75 (black) and theta = 0.8 (red).  A sensitivity test has been undertaken using a near final version of the baseline model (June 2023) for the 2065 fluvial 1:100yr event (before the 2060s epoch year was updated to 2069). The results of this test show that the maximum difference in peak water level is 1mm for 98% of the nodes in the model including all River Avon nodes. There are 23 nodes where the difference exceeds 10mm but these nodes are all associated with two sections of culvert (one on the Colliters Brook and one on the NSWI).
dflood		15	This value has been adopted from the Bristol SFRA model and has been retained to maintain model stability. Attempts were made to set this closer to the default value, but the model proved too unstable.
TUFLOW-ESRTY model:			
ESTRY 1d timestep	-	1.0s	This is appropriate given the 5m cell size of the model.
Manholes at All Culvert Junctions	ON	OFF	Turned off to prevent manholes being automatically created at ESTRY culvert junctions.

5.2 Runtime messages and warnings

Table 5 summarises the FMP model runtime messages.

Table 5: FMP runtime messages.

ID	Message	Comment / justification
2000	Poor model convergence	This occurs at several time periods during most simulations; in most cases the duration of non-convergence is very brief. Please see Section 5.3 for more information.
2010	Poor interpolation u/s of current node	This warning is due to a large change in cross-section geometry between adjacent nodes. This only occurs at 20 nodes. Additional cross-section survey could be collected and incorporated into the model in future studies to prevent this warning, but this is unlikely to materially affect model results.
2044	Different values (+/- 20 %) for Mannings n encountered in same panel	This occurs at 12 nodes, all of which are bridge units – no impact on model results.
2238	Panel has very small width	This occurs at two nodes and is due to the cross-section geometry and panel marker placement.
2262 2263 3006 3007	Warnings / notification regarding backflow at culvert inlet and outlets	Backflow of the culverts where this occurs is expected and is due to elevated River Avon water levels causing water to flow back up the culverts during high tides.
2267	No supercritical depth could be found – flow = 0, setting critical depth to bed level.	This occurs at 5 locations in the model. The model results were inspected, and no apparent anomalies were identified in the timeseries results at these locations.
2294	Crump/Flat-V weir is not connected at u/s [d/s] node to a river section	This occurs at Netham Weir unit and is due to the unit being connected via junction units without remote nodes specified – this is intentional and is used to force the weir unit to determine the upstream flow area from the channel breadth (W) and depth of weir above bed (P1) from the weir unit, which are derived from more recent topographic survey than that used in the adjacent cross-sections.
3028	Data points omitted from deactivated section areas	Occurs at many nodes and is due to cross-section deactivation markers being used as intended.

Table 6 summarises the TUFLOW model runtime messages.

Table 6: TUFLOW runtime messages.

ID	Message	Comment / justification
1037	Channel xxxx interpolated from XS xxxx and XS xxxx.	Occurs on the Malago ESTRY channel. This has been checked and is appropriate.
1044	Upstream / downstream invert levels interpolated for culvert xxxx	Occurs on the St George FAS on the Frome system. This occurs in the SFRA and SOC models; no changes have been made here for the current study. These have been spot-checked and found to be acceptable.
1100	Structure xxxx crest/invert is below bed of primary upstream channel	Occurs on the St George FAS on the Frome system. This occurs in the SFRA and SOC models; no changes have been made here for the current study. These have been spot-checked and found to be acceptable.
1152	For channel xxxx, using centre cross-section and ignoring end cross-section(s).	Occurs on the Malago ESTRY channel culverts where culvert geometry is used as intended. This has been checked and is appropriate.
1206	CHECK 1206 - Node occurs at the same location as manhole, pit or	This occurs because the western Malago outfall and the Mylnes culvert outfall in the ESTRY model are connected to the same river cross-section node in the FMP model – this is appropriate.

ID	Message	Comment / justification
	another node [IDs: "Mal_Avon" and "MYL_Avon"].	
1393	Node xxxx linked to external 1D scheme.	Occurs where the Malago and Mylnes ESTRY models have been linked to the FMP model. This has been checked and found to be appropriate.
2099	Ignored repeat application of boundary to 2D cell.	This occurs where two HX lines cover the same grid cell. This will not impact results.
2117	Inactive 2D cell made active by 2D SX link.	This also occurs in the SFRA and SOC models. This has been investigated and no issues have been identified. This warning occurs at grid cells where SX boundaries have been digitised but where the grid cell initially slightly fell outside the 2d domain as it was at the edge of the domain. As an SX is specified at the cell TUFLOW automatically activates the cell, which extends the 2d domain by one grid cell at these locations. Most of the occurrences of this warning message are associated with the SX connections used on the left bank of the Avon near Brunel Lock. A slight modification has been made to the 2d_code_ESTRY_netham_v35.mif layer at Cattlemarket Rd to align better with SX connection line (minor issue inherited from CAFRA model).
2118	Lowered SX ZC Zpt by xxxx to 1D node bed level.	This also occurs in the SFRA and SOC models. This occurs where the 2d cell elevation has bene automatically lowered to match the bed level of the 1d node connected to it. This has been spot-checked and found to be appropriate.
2210	Top of first FC Layer is below ground level.	This also occurs in the SFRA and SOC models. This has been checked and no issues have been identified
2370	Ignoring coincident point found in ORIGINAL layer.	This occurs due to duplicate elevation points in the topographic survey data used to create this layer. This will not impact results.
2468	Active cell has no active faces.	This was found to occur on high ground outside of the flooded area. No changes to model required.
2550	1 or 2 instability timestep corrections recorded at cell	This shows that timestep corrections were recorded at the 2d grid cells in the Floating Harbour and in all cases, only 1 or 2 timestep corrections were applied. Model results show no obvious instability or anomaly in the floating harbour.

5.3 Convergence

Model convergence gives an indication of model health and how well the solver is able to converge the flows and water levels to the modelling tolerances. The baseline FMP model convergence bitmaps are presented for the following events:

- 2030 fluvial 1:100yr event: Figure 17
- 2030 tidal 1:200yr event: Figure 18
- 2130 fluvial 1:100yr event: Figure 19
- 2130 tidal 1:200yr event: Figure 20

These figures show good overall convergence across fluvial and tidal events with and without climate change, particularly given the size and complexity of the model. With the exception of the 2130 tidal 1:200yr event, non-convergence is limited to isolated instances or very short duration periods.

For the 2130 tidal 1:200yr event, there is intermittent non-convergence for approximately 1.3hrs around the peak (46 – 47hrs). Inspection of the diagnostics file shows this occurs at a culvert on Horfield Brook on the Frome system, which is considerably distant from the focus of the current study. On the River Avon there is a very brief occurrence of non-convergence at node Av6_1281 (New Cut) at 47.4hrs and at node Av5_0100 (immediately upstream of Netham Weir) at 63.6hrs – model results show no apparent instability or anomalies here.

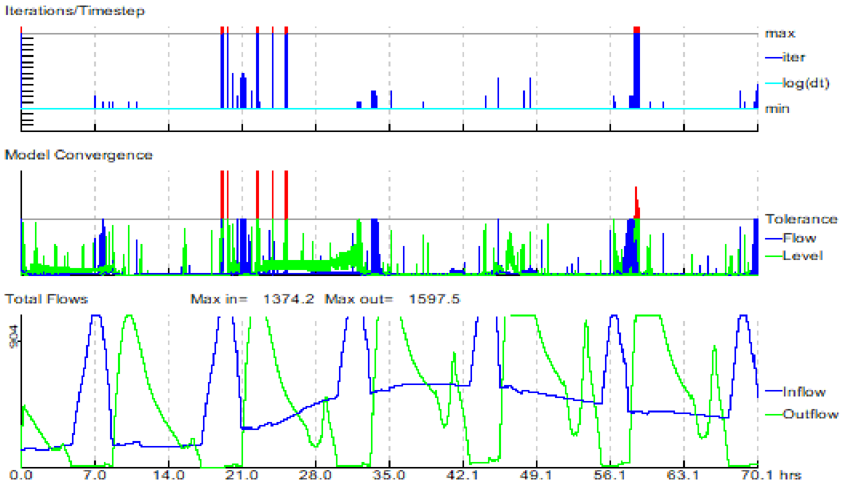


Figure 17: FMP convergence graphic for 2030 fluvial 1:100yr event.

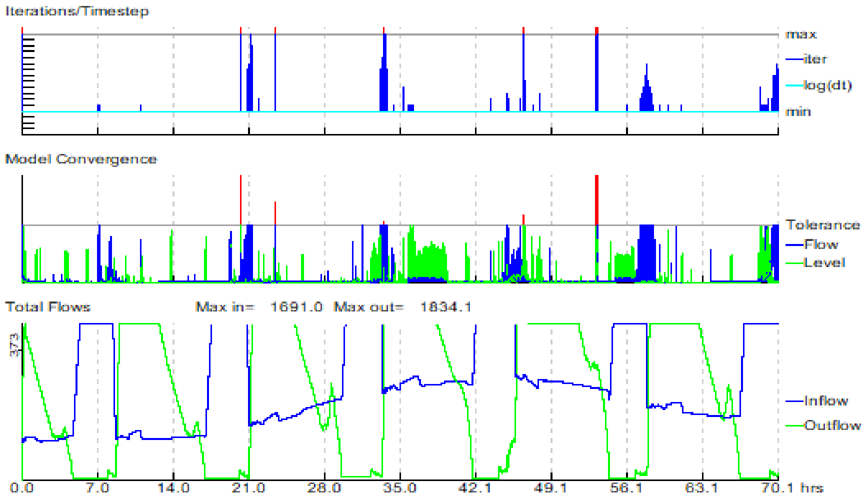


Figure 18: FMP convergence graphic for 2030 tidal 1:200yr event.

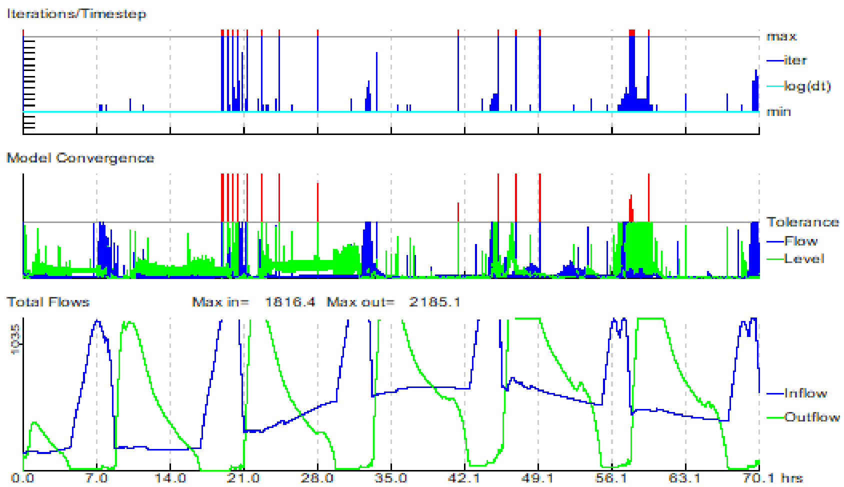


Figure 19: FMP convergence graphic for 2130 fluvial 1:100yr event.

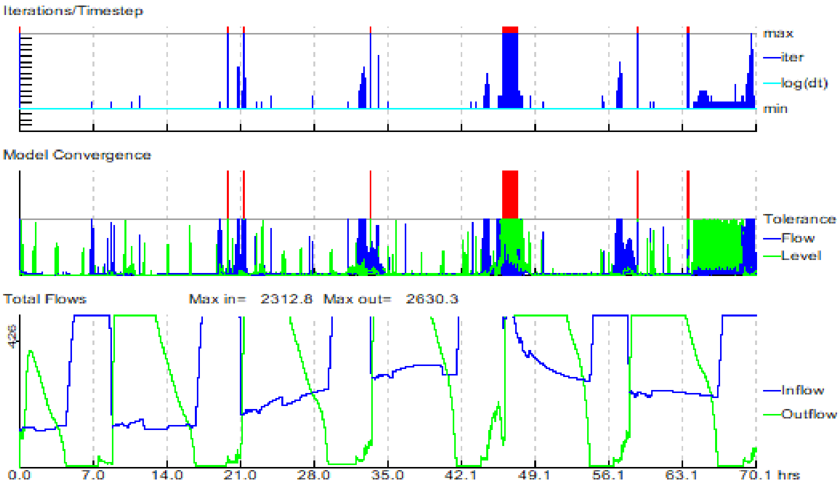


Figure 20: FMP convergence graphic for 2130 tidal 1:200yr event.

5.4 Mass balance

Mass balance gives an indication of model health and how well the model is able to conserve mass. The TUFLOW component of the model uses the HPC solver, which is an explicit mass conserving solver so mass error is practically zero – the TUFLOW mass balance outputs inspected show peak cumulative mass error is less than 0.01%. The dVol results (Figure 21) shows how the volume in the TUFLOW model changes over time; this shows a smooth variation over time, which indicates good model stability, and has the expected characteristics given the fluvial and tidal inflows.

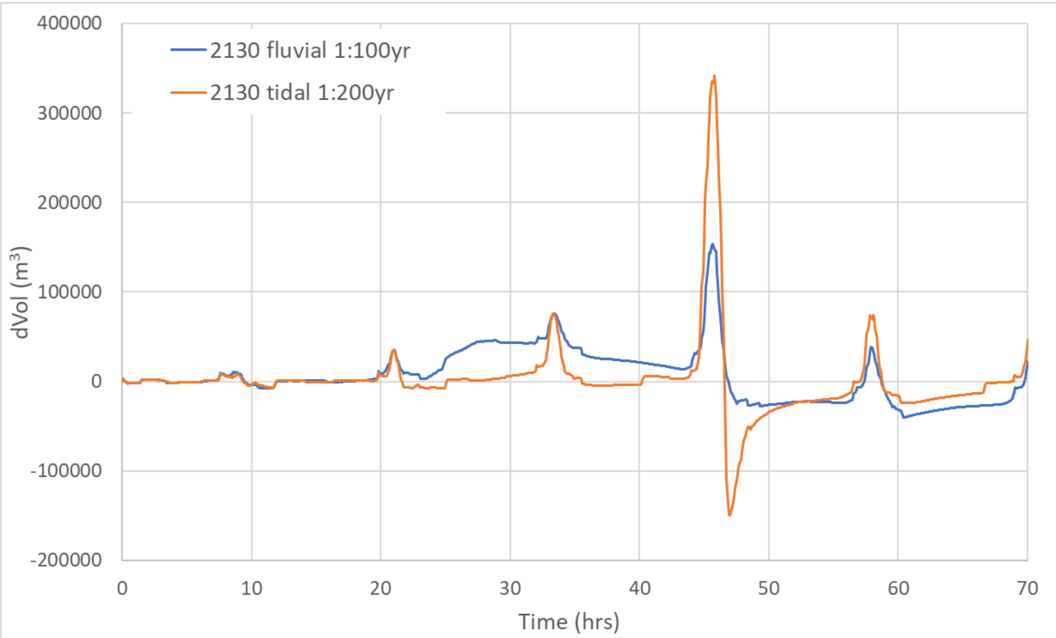


Figure 21: TUFLOW dVol vs time.

The FMP model mass error as reported in the FMP diagnostics files is summarised in Table 7. Note two different metrics are given. For a tidal model simulation that includes multiple tidal cycles, it can be argued that "*the percentage error is better expressed as a proportion of the volume passing through the boundaries*"[13], which corresponds to the lower of the two values in Table 7. These mass error values are considered acceptable, particularly given the size and complexity of the model.

[13] Improving 1D mass balance in Flood Modeller, Jacobs, 2020.

Table 7: FMP mass error.

	Mass error (%)	
Event	**As a % of peak system volume**	**As a % of boundary inflow volume**
2030 fluvial 1:100	-2.24	-0.14
2030 tidal 1:200	-2.24	-0.39
2130 fluvial 1:100	-1.98	-0.11
2130 tidal 1:200	-2.11	-0.30

6. Model quality assurance

The updated hydrological assessment and non-stationarity assessment undertaken for this project (see Chapter 4) has been reviewed by the EA and their comments have been addressed.

The updates to the baseline model have been peer reviewed by a senior modeller. The updates to the baseline model have also been reviewed by the EA and by WHS on behalf of BCC. Arup have provided responses to all review comments, including explaining actions taken to address the review comments, where appropriate. Both the EA and BCC confirmed they accepted Arup's responses. The actions undertaken include further updates to the baseline model and updates to the baseline modelling report (this report).

The model review documentation, including Arup responses / actions to the review comments is included as Appendix F.

The following updates have been made to the baseline model to address the review comments:

- Sea Mills Zlines corrected (elevation points are now ready in).
- 2D model extended at Shirehampton to prevent glass-walling near the rail line.
- All snapping issues fixed enabling the TUFLOW 'snap tolerance' command to be removed.
- Materials layer extended to cover full extent of Shirehampton 2d modelled area.
- Projection for 2d_zsh_TheGalleries_v01_L.shp has been corrected.
- Water Level Lines (WLL) layer refined. See Section 4.5.4.
- Null objects removed.
- Elevation points added to end of 3d breaklines to prevent ambiguity.

The following additional modifications were made to further improve the model:

- Deactivation markers slightly adjusted to improve width 1d consistency with HX lines for some cross-section on the Avon.
- Panel markers added to 1d cross-sections at changes in roughness (where missing).
- Brislington Brook Chapel Way culvert changes: inlet trash screen parameters adjusted to be more consistent with the 2022 topographic survey; culvert inlet and outlet headloss type set to TOTAL and culvert top slot removed as no longer required for stability.

7. Model validation

7.1 Scope

Given the calibration investigation previously undertaken and associated findings, it was considered unlikely that re-calibration of the model would significantly improve confidence in the model. However, it was agreed with BCC and the EA that a verification event should be simulated using the updated baseline model to help provide confidence in the model. The validation event selected in the 11th - 12th March 2020 tidal event which resulted in flooding in several areas across Bristol as reported by BCC[14]. The peak recorded water level at Avonmouth was 8.63m AOD for this event. This is between a 1:20yr and 1:25yr tidal event based on the Coastal flood boundary conditions for the UK: update 2018.

7.2 Model boundary conditions

The March 2020 event was modelled by applying the Avonmouth gauged water level vs time data at the downstream boundary of the model. The fluvial inflows in the model were set as follows:

- River Avon and River Frome: the fluvial inflows for these two watercourses were derived using the gauged data from gauging stations on the Avon at Bathford (53018)[15] and Frome (Bristol) at Frenchay (53006)[16] as identified from the National River Flow Archive (NRFA).
- Tributaries: the fluvial inflows for the remaining ungauged inflows are based on the nearest return period event to the estimated return period of the March 2020 event, which was assessed from review of the Chew at Compton Dando (53004)[17] and Boyd at Bitton (53017)[18] river gauge records. This identified the 1:1yr return period as being the nearest return period.

The modelled validation event covers the 120hr period from 00:00hrs 09/03/2020 to 00:00hrs 14/03/2020.

7.3 River water levels

The model results have been compared against observed river levels at the following gauges:

- Avon at Bath Ultrasonic
- Avon at Saltford: Note this is located upstream of Kelston Weir near Saltford Marina.
- Avon at Keynsham ADCP
- Avon at Keynsham d/s of weir
- Avon at Netham Weir
- Floating Harbour

Figure 22 compares the modelled river water level results for the Avon and Floating Harbour to the gauge data during the validation event. Table 8 compares the peak modelled water levels to the peak gauged water levels.

The river water level results show:

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[14] Flood Investigation: March 2020 Tidal Flooding, Bristol City Council, 2020.

[15] https://nrfa.ceh.ac.uk/data/station/peakflow/53018

[16] https://nrfa.ceh.ac.uk/data/station/peakflow/53006

[17] https://nrfa.ceh.ac.uk/data/station/peakflow/53004

[18] https://nrfa.ceh.ac.uk/data/station/peakflow/53017

- Good match with shape.
- Jumpy profile for Avon at Bath Ultrasonic is due to the operation of the radial sluice gate in Bath.
- Modelled peak water levels under-estimated at the two Keynsham gauges but difference is within the EA's recommended 0.15m.
- Model over-estimates peak water levels at Netham Weir by 0.16m, which is only just beyond the EA's recommended 0.15m.
- Model over-estimates peak water level at Saltford by 0.26m. This is discussed in Section 7.3.1.

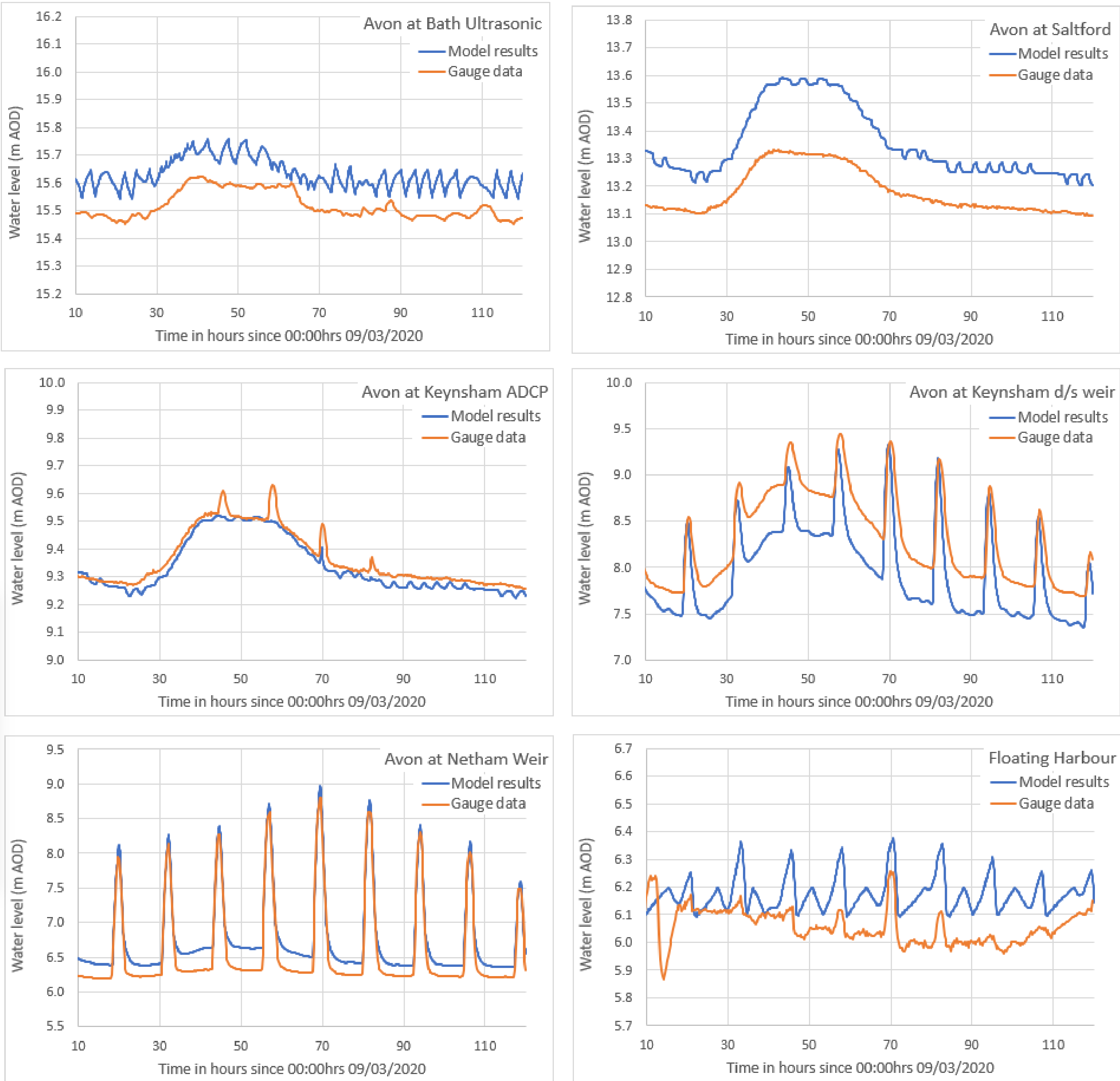

Figure 22: River water levels (model vs gauge)

Table 8: Peak water levels (model vs gauge).

Watercourse	Gauge	Peak water level (m AOD) Model	Peak water level (m AOD) Gauge	Difference (m)
Avon	Bath Ultrasonic	15.76	15.62	0.14
Avon	Saltford	13.59	13.33	0.26
Avon	Keynsham ADCP	9.52	9.63	-0.11
Avon	Keynsham d/s weir	9.33	9.45	-0.12
Avon	Netham Weir	8.97	8.81	0.16
Harbour	Floating Harbour	6.38	6.26	0.12

Measured high tide levels for the March 2020 events are also provided in the BCC Flood Investigation report19. Table 5 in this report included measured peak river water levels at Avonmouth and Bedminster Bridge and estimated peak water levels at other locations. This is reproduced below in Table 9 with two additional columns to compare these values to the peak water levels from the model – this shows a good match.

Table 9: Peak water levels (model vs gauge).

From Table 5 in 'Flood Investigation for the March 2020 Tidal Flood Events' report (BCC)				
Location	Measured high tide level (m AOD)	Estimated high tide level * (mAOD)	Modelled peak water level (m AOD)	Difference (m)
Avonmouth	8.63		8.63	0.00
Sea Mills Lane (Sea Mills)		8.72	8.78	0.06
The Portway, under Clifton Suspension Bridge		8.77	8.83	0.06
Cumberland Basin Road		8.77	8.83	0.06
Junction Lock		8.78	8.84	0.06
Bathurst Basin Dam		8.78	8.86	0.08
Bedminster Bridge	8.81		8.85	0.04
Clarence Road		8.81	8.86	0.05
Cattle Market Road		8.82	8.86	0.04

* (Based on distance upstream of Avonmouth and change in tide level measured between Avonmouth and Bedminster Bridge).

7.3.1 Kelston weir, Saltford

The Bath to Bristol modelling study (2017) model has been incorporated into the updated BAFS model. The 2017 study undertook calibration of the Bath to Bristol model for fluvially dominant flood events; as part of calibration the weir coefficient for Kelston Weir at Saltford was lowered to 0.7 to achieve an overall better calibration during flood flows. The 2017 study report shows the model tends to over-estimate water levels at this weir during smaller fluvial events and under-estimates during larger fluvial events. As such, it was agreed with the EA that the weir coefficient (or other parameters here) is not adjusted to improve calibration during tidally dominated events as that would likely result in under-estimation of water levels during large fluvial events. However, as the weir coefficient of 0.7 is considered low, the representation of the weir has been reviewed to provide confidence in the model here.

[19] Flood Investigation for the March 2020 Tidal Flood Events, Bristol City Council.

The mapping and aerial photos show 3 possible flow paths at Kelston Weir as shown in Figure 23 and described below:

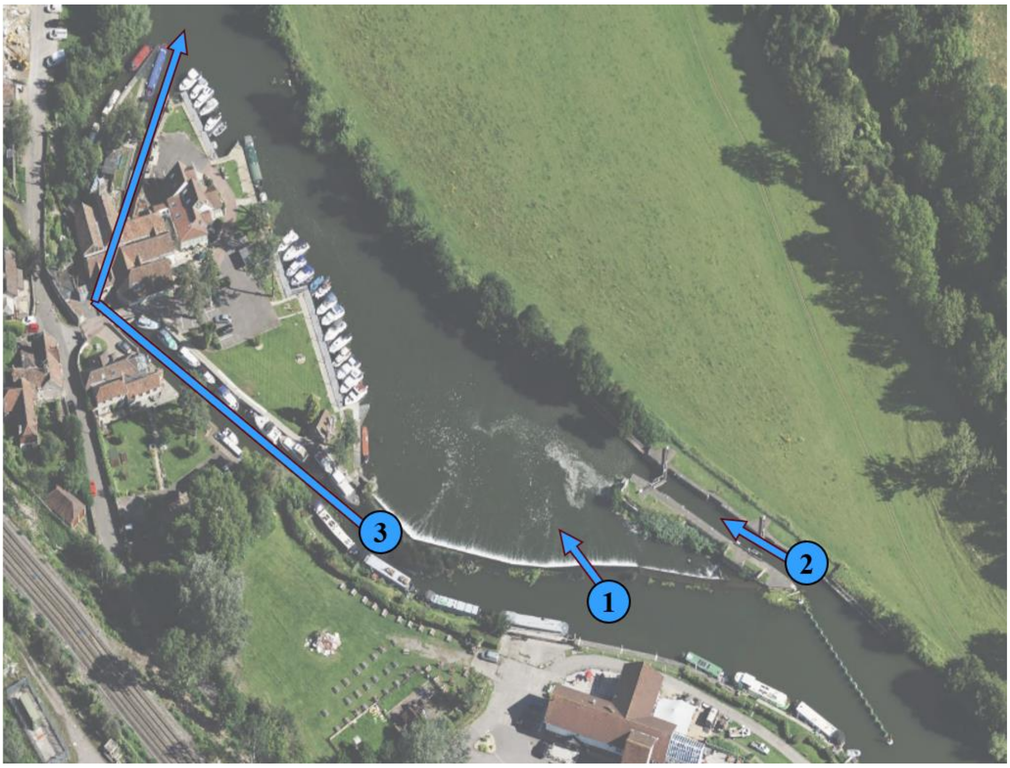

Figure 23: Flow paths at Kelston Weir. (c) Microsoft.

1. Over the weir: Represented in the model using a spill unit. The length of the spill unit is the full length of the weir. During flood conditions, the flow will generally be in the direction of the main channel and so the effective width of the weir would be reduced, particularly with the bend towards the western end of the weir. This may explain why Capita AECOM found that lowering the spill coefficient to 0.7 improved calibration for fluvial flood events in the Bath to Bristol modelling study (2017). An alternative approach would have been to retain a higher spill coefficient but reduce the effective width of the weir, e.g. scale to match the perpendicular flow width, to better represent the effective flow width during flood conditions. From review of flow widths in GIS, this alternative approach would result in virtually the same results. When fluvial flows are relatively low, the effective flow width is the full length of the weir, and therefore either of these two possible approaches would likely result in over-estimation of upstream water levels.

2. Through the lock: Represented in the model using a spill unit representing the lock gate in the closed position, i.e. the spill unit is used to represent the top of the lock gates, which are assumed to be at 13.59m AOD. The model includes the following comment here: "*Lock level estimated from photo to be 30 cm below bank and 60cm above water level*.". The model results show the water level gets to within 1cm of overtopping the lock gate in the March 2020 event. It is possible that the lock gate was open during the March 2020 event, but no evidence has been made available to confirm this. The Environment Agency and the Canal & River Trust do not hold records of how this lock is operated.

3. Through Saltford Brass Mill channel: This is not explicitly represented in the model, but this area is included in the 2d TUFLOW component of the model. Review of the 2d model elevations here shows upstream water levels would need to exceed approx 13.8m AOD before water can flow through this area. The Mill Building itself is represented as a high roughness area (Manning's n of 0.3) as opposed to physically blocking out the area – consistent with the approach taken for all buildings in the model.

Based on the above review, it was agreed with the EA that the representation of Kelston Weir is considered appropriate for the current study.

In addition to the above review of the model representation at Kelston Weir, the modelled water levels for the validation event are compared against those for two design events to provide context – this is shown in Figure 24.

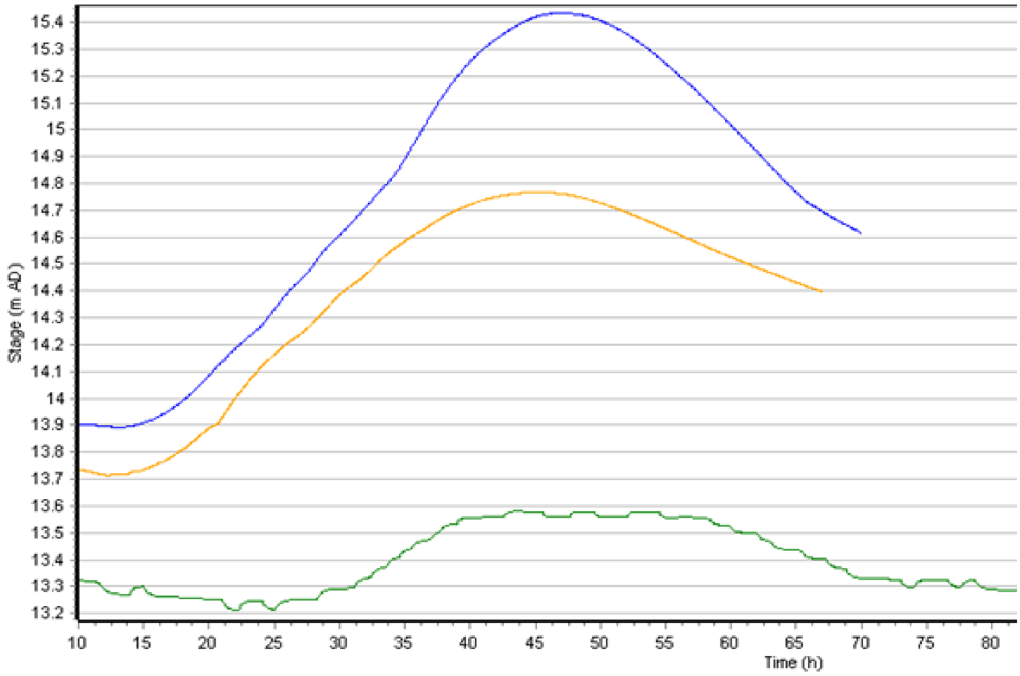

Figure 24: Modelled water levels for March 2020 event (green) vs 2030 fluvial 1:100yr event based on central allowance (yellow) vs 2130 fluvial 1:200yr event based on higher central allowance (blue).

7.4 Flood extents and depths

Maps showing the modelled flood outline and flood depths is provided in AppendixI.1. This has been reviewed against locations identified as having flooded during the event.

The BCC Flood Investigation report includes a map showing locations where flooding was observed in March 2020 – this is reproduced in Figure 25 below. There are also 5 photos in Chapter 2 in the Flood Investigation report. Reviewing the reported locations and photos shows general agreement in locations flooded except:

- Model predicts outflanking at Junction Lock but only on southern bank whereas outflanking was observed to occur on both the northern and southern banks. The model was therefore reviewed and refined to represent the flooding mechanisms on the southern bank here.
- Model predicts significant extent of flooding at Albert Road but only minor flooding was observed in this area. BCC reviewed this area and concluded that this difference is acceptable because:
  - *"Model does overpredict lower order real world events in St Phillips because the model does not represent existing third-party structures, broadly continuous around St Phillips although many 'weak spots'. However we note third-party structures are a variety of forms and all outside EA/BCC or other RMA control, and have not been formally designated. BCC investigations concluded the structures would pose a risk of breach during more severe events and so cannot be formally relied upon or included in the flood model.*
  - *2020 records including a surcharging manhole off Victor Street.*
  - *It was within 100mm of overtopping Victor Street EA flood defence wall, which was leaking."*

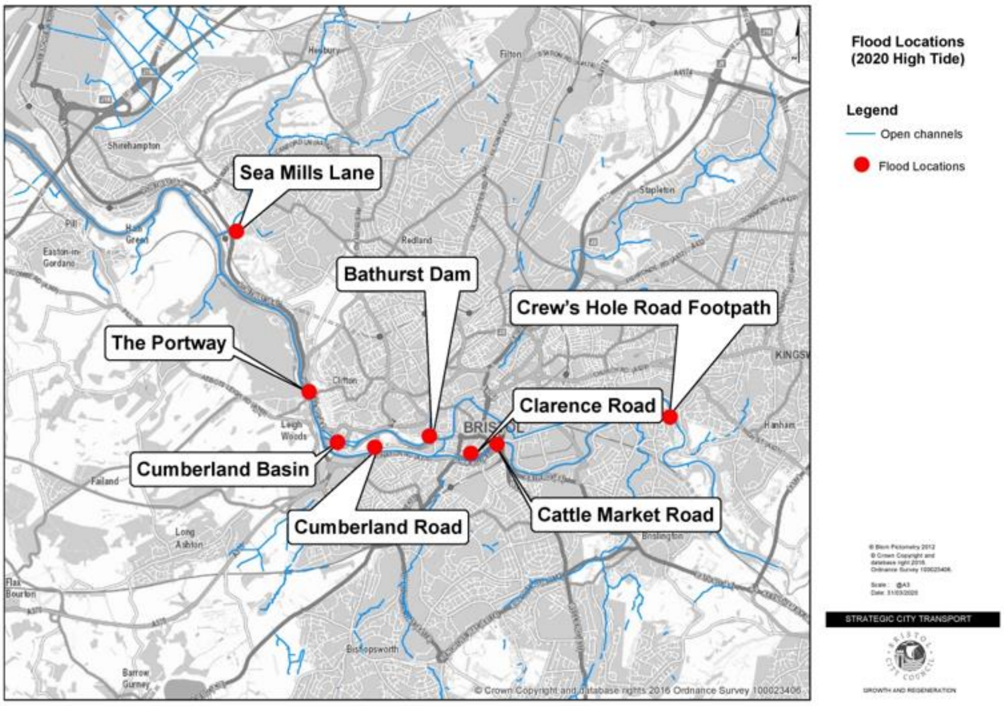

***Figure 1**: Bristol 'watercourses map' showing areas affected by flooding from the tidal River Avon on 11th March 2020*

Figure 25: Locations where flooding was observed in March 2020 (reproduced from the March 2020 Flood Investigation report.

8. Simulations

8.1 Joint probability of tide and flow conditions

The modelling methodology proposed that the same joint probability assessment (JPA) pairs of tide and flow conditions as used in the BAFS SOC are adopted for the OBC with the exception of the 1:20yr, 1:75yr and 1:100yr return period tidally dominated events. For these events, the 1:1yr flow conditions will be used as opposed to baseflow conditions. The 1:1yr flow conditions have been derived as part of the current study (see Chapter 3).

During the inception stage, it was agreed that sensitivity testing should be undertaken using the BAFS SOC models to understand the impact of uncertainty in JPA on flood outlines and river water levels. Tests were therefore set up with a more conservative JPA pairing of fluvial and tidal return period for the selected events. The JPA tests use the closest component return periods derived using a Chi dependency measure of 0.18 (90% confidence interval upper bound from FD2308[20]) compared to a dependency measure of 0.11 used in the base case. Therefore, the tests represent a reasonable upper bound based on FD2308. The following sensitivity test simulations were undertaken:

<u>BAFS SOC baseline Do Minimum option:</u>

1. 2030 1:100yr fluvially dominated event with more conservative JPA (uses a 1:3yr tidal event instead of a 1:1yr tidal event).
2. 2030 1:200yr tidally dominated event with more conservative JPA (usus a 1:7yr fluvial event instead of a 1:2yr fluvial event).
3. 2065 1:100yr fluvially dominated event with more conservative JPA (uses a 1:3yr tidal event instead of a 1:1yr tidal event).
4. 2065 1:200yr tidally dominated event with more conservative JPA (usus a 1:7yr fluvial event instead of a 1:2yr fluvial event).

<u>BAFS SOC Do Something “glass wall” model (proposed flood defences set very high to prevent any overtopping):</u>

5. 2065 1:100yr fluvially dominated event with more conservative JPA (uses a 1:3yr tidal event instead of a 1:1yr tidal event).
6. 2065 1:200yr fluvially dominated event with more conservative JPA (uses a 1:7yr tidal event instead of a 1:2yr tidal event).
7. 2065 1:200yr tidally dominated event with more conservative JPA (usus a 1:7yr fluvial event instead of a 1:2yr fluvial event).

Note in the SOC modelling, 2065 was used as the epoch year for the 2060s.

The tests undertaken for the baseline Do Minimum option were used to assess impact of JPA on flood extent. Appendix I.2 presents figures comparing flood extents against the base case (default JPA). The first four figures compare individual flood outlines (either fluvial or tidal) and the last two figures compare the ‘fluvial 1:100yr merged with tidal 1:200yr’ outlines. These figures show that there is not a city-wide sensitivity to JPA and that the main area of sensitivity to JPA is the St Thomas Street / Victoria Street area for tidally dominated events in 2030. Implications for this are that there may be some additional economic benefits – this is only if a more rigorous JPA assessment actually shows significantly greater fluvial-tidal dependency than has been used to date.

The tests undertaken for the Do Something model were used to assess impact of JPA on peak river water level and hence impact on required flood defence level. The River Avon water level results from the JPA

[20] Joint Probability: Dependence Mapping and Best Practice: Technical report on dependence mapping. R&D Technical Report FD2308/TR1. Environment Agency, 2005.

tests have been compared against the base case (default JPA) to assess potential impact on Phase 1 defence crest levels (2065). This is presented in Figure 26 and Figure 27. Impact on defence levels is less than 0.10m for majority of defence lengths. There is a strange dip at about chainage 12.5km, which appears to be due to an anomaly in the base SOC results where water levels appear to be over-estimated by 0.05 to 0.10m for a 1km reach upstream of Bedminster Bridge (this anomaly doesn't appear in the JPA test results. If the uncertainty associated with JPA is assumed to be 0.1m then applying this value into the freeboard calculation would result in freeboard to increase by 10 to 20mm (the freeboard calculation is based on root mean square of component uncertainty values rather simply adding them up).

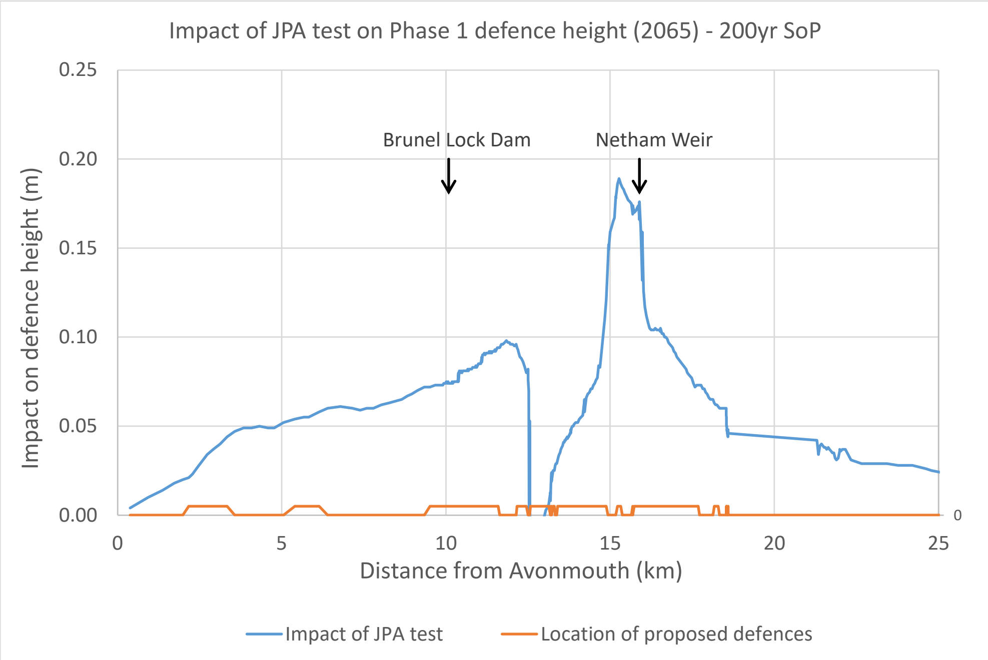

Figure 26: Impact of JPA on Phase 1 defence height (2065) for 1:200yr SoP for both fluvial and tidal.

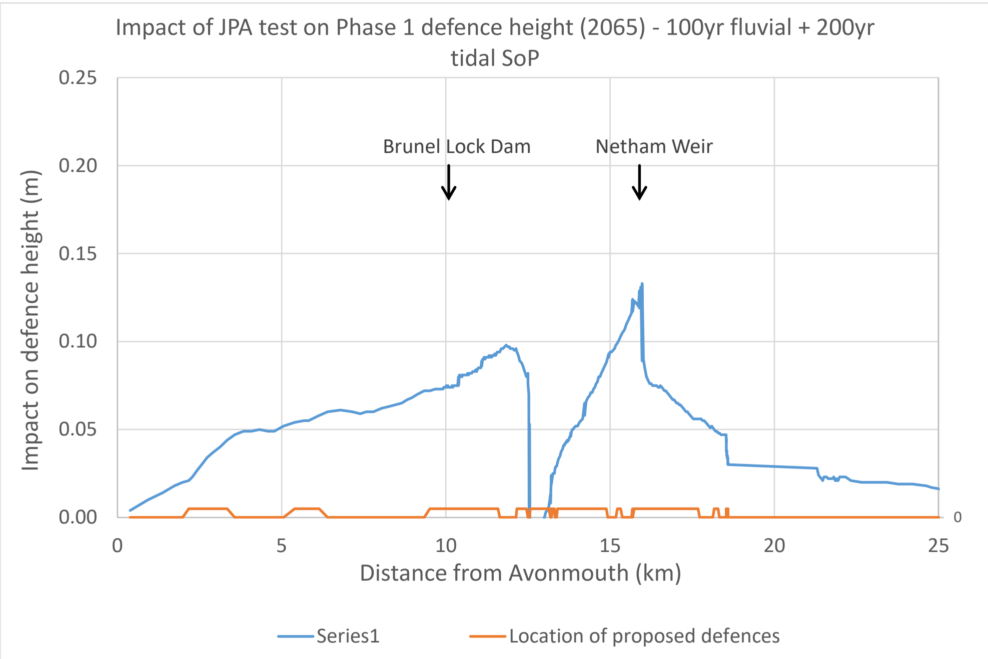

Figure 27: Impact of JPA on Phase 1 defence height (2065) for 1:100yr fluvial and 1:200yr tidal.

There are two main approaches that can be taken to manage uncertainty in water levels due to JPA:

1. Retain the JPA used to date in the BAFS SOC and then account for uncertainty in this JPA using freeboard.
2. Undertake an updated JPA using a more rigorous method to reduce (but not eliminate) uncertainty in JPA and then account for residual uncertainty in the revised JPA using freeboard. An updated JPA assessment could be undertaken using the new EA Multivariate Event Modeller (MEM) tool; however, at the time of this work (2022), there was no formal guidance for the MEM tool.

Given the above, it was agreed that the JPA used to date should be retained for the OBC modelling and that uncertainty in JPA should be managed in the freeboard allowance.

8.2 Return periods:

The model has been used to simulate a range of flood event probabilities for (a) fluvially dominated events; and (b) tidally dominated events. The combined return periods (and the constituent tidal and fluvial return periods) presented within Table 10 have been simulated using the updated model. Note that the BAFS SOC identified that intermediate combinations of fluvial and tidal did not result in higher water levels along the River Avon than the worst-case water level from the fluvially and tidally dominated events. The 1:1000yr return period is only required for the economic assessment.

Table 10: Combined return periods and constituent tidal and fluvial return periods.

Type of event	Combined return period (years)	Fluvial return period (years)	Tidal return period (years)
Fluvially dominated	1:20yr	1:20yr	1:1yr
	1:75yr	1:75yr	1:1yr
	1:100yr	1:100yr	1:1yr
	1:200yr	1:200yr	1:2yr
	1:1000yr	1:1000yr	1:12yr
Tidally dominated	1:20yr	1:1yr *	1:20yr
	1:75yr	1:1yr *	1:75yr
	1:100yr	1:1yr *	1:100yr
	1:200yr	1:2yr	1:200yr
	1:1000yr	1:12yr	1:1000yr

* Baseflow was used in the BAFS SOC, which is lower than the 1:1yr flow.

8.3 Epochs

It was agreed with BCC and the EA that the following epochs should be assessed:

- **2030:** This epoch year has been selected as the construction of the proposed phase 1 flood defences is expected to be complete between 2025 and 2030.
- **2069:** This epoch year has been selected to represent the last year before construction of the phase 2 flood defences is completed (construction in the “2060s”). Note this has been updated since the SOC, which used 2065.
- **2070:** This epoch year has been selected to represent the first year after completion of the phase 2 flood defences. The model results for this epoch year are to be used in the economic assessment to represent the step change between pre and post construction of phase 2, which also coincides with the step change in fluvial flow allowance based on the current climate change guidance.
- **2130:** This epoch has been included to represent the end of the appraisal period. Note the BAFS SOC used 2125.

8.4 Climate change allowances

The latest EA guidance on climate change allowances at the time of writing are:

- Flood and coastal risk projects, schemes and strategies: climate change allowances, EA, May 2022. This guidance is for risk management authorities seeking flood and coastal erosion risk management (FCERM) grant-in-aid (GIA) for FCERM projects, schemes and strategies.
- Flood risk assessments: climate change allowances, EA, May 2022. This guidance is to be used for strategic flood risk assessments and flood risk assessments (FRAs) for planning applications, and development consent orders for nationally significant infrastructure projects. This includes FCERM schemes that need planning permission.

Review of the above guidance documents showed there is no difference in the fluvial flow allowances between the two guidance documents (see Table 11).

There is a small difference in the sea level rise allowances between the two guidance documents. The sea level rise allowances were found to be slightly different – for 2030 and 2069 epochs the maximum difference was only 10mm and for the 2130 epoch the difference was 24mm for the higher central allowance and 92mm for the upper allowance (see Table 11). In all cases, the FRA CC allowances were slightly higher than the FCERM allowances. Given this result, it was agreed that the sea level rise allowances specified in the FRA CC guidance as opposed to the FCERM CC guidance could be used for all modelling to be undertaken in the BAFS OBC.

The EA specified that for all model simulations except those used to assess residual flood risk, the central fluvial flow allowance and the higher central sea level rise allowance should be used. The EA specified that for simulations undertaken to assess residual flood risk, the higher central fluvial flow allowance and the upper sea level rise allowance should be used.

Table 11: Climate change allowances.

	Fluvial flow allowance (%)		Sea level rise allowance (m) based on 2017 baseline year			
Epoch year	FCERM+FRA central	FCERM+FRA higher central	FCERM higher central (not used)	FCERM upper (not used)	FRA higher central	FRA upper
2030	10	15	0.074	0.090	0.075	0.091
2065 **	12	19	0.364	0.466	0.368	0.468
2069	12	19	0.405	0.522	0.415	0.532
2070	26	39	0.416	0.536	0.427	0.548
2125 **	26	39	1.089	1.419	1.111	1.498
2130 *	26	39	1.153	1.498	1.177	1.590

* Allowances calculated based on method agreed with EA (see Section 8.4.1).
** 2065 and 2125 used in SOC but not in OBC: included in table for comparison.

8.4.1 Allowances for 2130

As the above guidance documents only provide allowances up to year 2125, allowances for 2130 needed to be agreed with the EA given the need for modelling this epoch. The EA agreed the following:

Fluvial flows:

Use the same allowance as for 2125 given there are only 5 years between 2125 and 2130. Note the allowance for 2125 is taken from the '2080s' category which represents the period 2070 to 2125.

Sea level rise:

The current FCERM climate change guidance for sea levels states "*To perform an extra assessment for the lifetime of the scheme after 2125, use the sea level rise projections to 2300 for RCP 8.5. You can get sea level rise projections for the appropriate location and year from the UKCP18 user interface.*" This is referring to the 'extended projections' dataset, which go up to 2300 but are slightly different from the '21st century projections' dataset where they overlap.

Four methods were considered to determine sea level allowances for 2130:

- Method 1: Take the FRA allowance for 2125 and then add on 5 years of sea level rise calculated using the millimetres per year value given in the guidance for the last epoch (2096 to 2125).
- Method 2: Based on method proposed in the FCERM climate change guidance (uses the 'extended projections' data).
- Method 3: Based on an alternative interpretation of the method proposed in the FCERM climate change guidance where the 'extended projections' data is only used to calculate the increase between 2125 and 2130. This is then added to the 2025 FCERM allowance previously calculated.
- Method 4: Based on the same average incremental increase as used to calculate the 2125 FCERM values.

Table 12 presents the results from applying each of the above methods, expressed in terms of total sea level rise between the base year (2017) and 2130. Method 2 gives a noticeably lower 'Higher Central' value than the other methods and is actually lower than the 2125 allowances in Table 11, which is not considered realistic so method 2 is not appropriate. It was agreed that Method 1 is used as it results in the greatest amount of sea level rise, though all 3 methods are very close for the Higher Central allowance.

Table 12: Comparison of 2130 sea level rise based on different methods tested.

	Sea level rise (m) to 2130 assuming base year of 2017	
Method	**Higher Central**	**Upper**
1	1.177	1.590
2	1.093	1.478
3	1.148	1.504
4	1.153	1.498

8.5 Fluvial boundary conditions

The peak fluvial inflows excluding climate change allowance uplift are shown in Table 13 below for key watercourses.

Table 13: Peak fluvial inflows (m^3/s) for key watercourses.

Watercourse / location	1yr	20yr	75yr	100yr	200yr	1000yr
Avon @ Bath (Pulteney Bridge)	173.13	280.75	340.24	353.26	390.44	485.27
River Chew	19.58	62.00	104.86	117.83	156.86	306.32
River Boyd	12.74	27.51	35.59	37.57	42.68	56.71
River Bitton	0.56	1.26	1.76	1.89	2.25	3.36
Corston Brook	1.32	2.90	3.93	4.20	4.89	6.97
Newton Brook	5.65	12.39	16.79	17.92	20.88	29.74
Frome @ Frenchay	28.16	52.22	64.84	67.79	75.31	95.14
River Trym	6.76	15.59	21.05	22.41	25.97	36.16

8.6 Tidal boundary conditions

The downstream boundary of the model represents tidal water levels vs time at Avonmouth. The tidal water level boundary data from the existing SFRA model was checked and found to be appropriate and consistent with the methodology and peak tidal values given in the current guidance[21]. The tidal boundary conditions

[21] Coastal Flood Boundary Conditions 2018 update, Environment Agency, 2019.

for the 2069 and 2070 epoch were not available from the SFRA so these were generated by applying the correct amount of sea level rise (from Table 11) to the existing water level boundaries.

While the peak tidal levels were confirmed as being consistent with the current guidance, it was noted that the shape of the tidal curves from the SFRA model differed to those from the SOC model. The profile used in the BAFS SOC study has higher water levels for the low and high tides that precede the highest (design) tidal peak. This is because the surge residual in the SOC tidal curve is timed to peak at the preceding low tide, which is more representative of a worst case compared to the SFRA tidal curve, which assumes the surge residual peaks at the same time as the highest (design) tidal peak. The difference is illustrated by comparing Figure 28 with Figure 29.

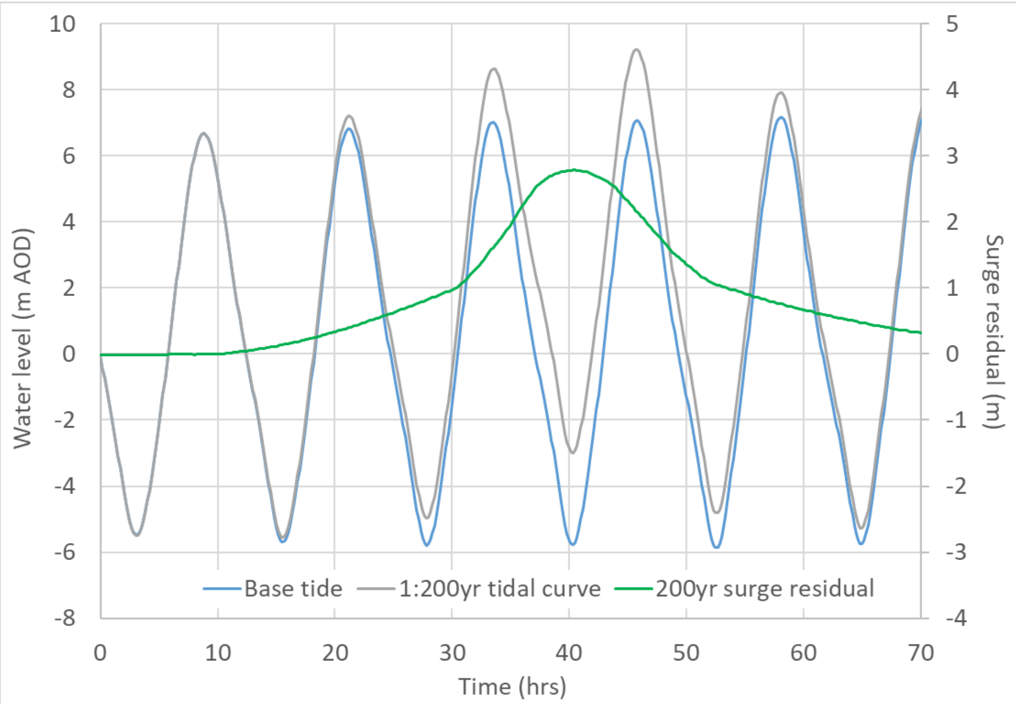

Figure 28: 2030 HC 1:200yr tidal curve from SOC.

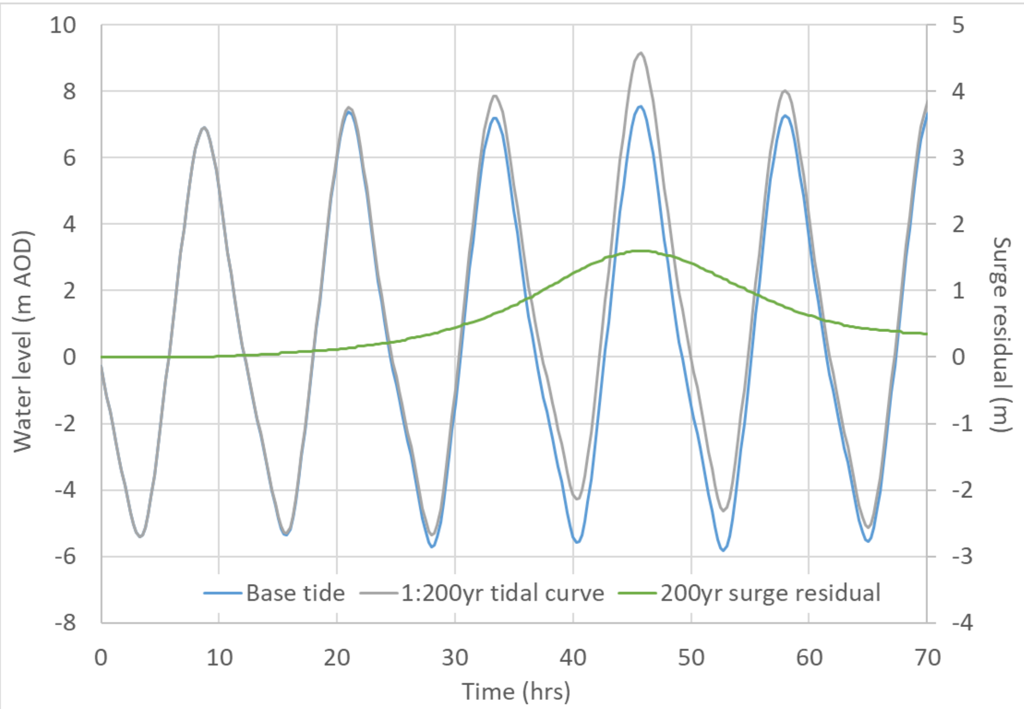

Figure 29: 2030 HC 1:200yr tidal curve from SFRA.

While the SFRA tidal curve adopts the standard approach given in the Coastal Flood Boundary Conditions guidance, Section 6.3.4 of the guidance does state "*Sensitivity tests for the peak surge occurring before or after the base of the peak astronomical tide may be appropriate depending on the purpose of the study or assessment*". To understand the impact of the difference in tidal curve on model results, a sensitivity test was run using the scheme "glass-wall" version of the model to determine impact on the required flood defence levels. In the sensitivity test, the tidal curve was adjusted to be consistent with the profile used in the SOC study (but with correct peak water level). The sensitivity test results showed very marginal impact on the peak River Avon water levels – the maximum impact at key locations was +/-0.02m but generally less than this and in some locations the test resulted in a slight decrease in River Avon water levels. However, the results did show a significant increase in peak water level in the Floating Harbour and Feeder Canal of 0.138m - this occurs in the 2069 fluvial 1:100yr event and appears to be due to the increased length of time that the harbour is tide locked leading up to the flood peak which causes a higher initial water level in the harbour immediately before the peak of the flood event due to the preceding low tide being higher in the sensitivity test. It was agreed with the EA and BCC that the SFRA tidal curves should continue to be used in the modelling but an allowance should be added to the Feeder Road defence to take into account the uncertainty in the timing of the surge residual – this is documented in the residual uncertainty assessment[22].

The peak tidal water levels at Avonmouth are given in Table 14 below.

Table 14: Peak tidal water levels (m AOD) at Avonmouth.

	Higher central allowance			Upper end allowance		
Return period (years)	**2030**	**2069**	**2130**	**2030**	**2069**	**2130**
1	8.185	8.525	9.287	8.201	8.642	9.700
2	8.295	8.635	9.397	8.311	8.752	9.810
5	8.445	8.785	9.547	8.461	8.902	9.960
10	8.565	8.905	9.667	8.581	9.022	10.080
12	8.597	8.937	9.699	8.613	9.054	10.112
20	8.685	9.025	9.787	8.701	9.142	10.200
25	8.725	9.065	9.827	8.741	9.182	10.240
50	8.865	9.205	9.967	8.881	9.322	10.380
75	8.935	9.275	10.037	8.951	9.392	10.450
100	8.995	9.335	10.097	9.011	9.452	10.510
200	9.145	9.485	10.247	9.161	9.602	10.660
1000	9.505	9.845	10.607	9.521	9.962	11.020

8.7 Simulation list

A total of 107 simulations (not including interim baseline model development test simulations) were agreed during the scoping stage with BCC and the EA for the following purposes:

1. JPA sensitivity tests
2. Validation
3. Baseline assessment
4. Initial assessment of defence alignment
5. Freeboard assessment

[22] Bristol Avon Flood Strategy OBC, Technical Note: Residual uncertainty assessment, August 2023.

6. Refined assessment of defence alignment
7. Initial detriment assessment
8. Develop detriment mitigation
9. Final detriment assessment and identify defence levels without freeboard
10. Identify the increase in defence height required to cope with severe climate change
11. Assess residual flood risk
12. Assess residual flood risk

A full list of the simulations agreed during the scoping stage can be found in Appendix G. Additional simulations were subsequently scoped to support an updated economic assessment of flood damages, including the addition of the 1:1000yr return period. All model simulations undertaken to support the economic assessment will be documented within the options modelling report.

In addition to the above, it was agreed that sensitivity test should be undertaken on the baseline model to test the impact of higher initial water level for the Floating Harbour (**Ref 4T**). The results of this baseline sensitivity test and other standard sensitivity tests are documented in Chapter 10.

8.8 File naming convention

The file naming convention for the modelling files can be found in Appendix H.

9. Baseline model results

9.1 Flood outlines comparison against Bristol SFRA model

The updated baseline model for the BAFS OBC has been run for the flood events shown in Table 15 using the central climate change allowance for fluvial flows and higher central allowance for sea level rise.

Table 15: Baseline flood events simulated.

Type of event	Combined return period (years)	2030	2069	2070	2130
Fluvially dominated	1:20yr	✓	✓	✓	✓
	1:75yr	✓	✓	✓	✓
	1:100yr	✓	✓	✓	✓
	1:200yr	✓	✓	✓	✓
	1:1000yr	✓	✓	✓	✓
Tidally dominated	1:1yr	✓	✓	✓	✓
	1:2yr	✓	✓	✓	✓
	1:12yr	✓	✓	✓	✓
	1:20yr	✓	✓	✓	✓
	1:75yr	✓	✓	✓	✓
	1:100yr	✓	✓	✓	✓
	1:200yr	✓	✓	✓	✓
	1:1000yr	✓	✓	✓	✓

The 2030 and 2130 fluvial 1:100yr and tidal 1:200yr flood extent results are compared to the closest equivalent Bristol SFRA defended flood outline results in Appendix I.3. The SFRA outlines are based on the same fluvial flow climate change allowances as the OBC model but the epoch years differ, which results in slightly lower peak tide levels being applied at Avonmouth compared to the OBC model. There is 0.046m difference between the SFRA 2022 tide and the OBC 2030 tide and 0.103m difference between the SFRA 2122 tide and the OBC 2130 tide.

The comparison of flood outlines shows:

- 2030 fluvial 1:100yr: Generally very similar. OBC has flooding removed at Unicorn Business, St Annes, possibly due to updates to Brislington Brook culverts. OBC also has flooding removed at Paintworks where new defence has been constructed. OBC shows less flooding in Malago area, which is likely due to the updated phasing applied for the Malago.
- 2030 tidal 1:200yr: Generally very similar. OBC has more flooding around Underfall Yard. OBC shows no flooding in Malago area, which is likely due to the updated phasing applied for the Malago. OBC also has flooding removed at Paintworks.
- 2130 fluvial 1:100yr: Very similar. Slightly less flooding on the Malago and Unicorn Business Park.
- 2130 tidal 1:200yr: Generally very similar. Less flooding on the Malago but slightly more on the Frome.

9.2 Flood outlines comparison against Bristol SOC model

The flood extent results from the updated baseline model are compared to the closest equivalent Bristol SOC baseline (Do Minimum option) flood outline results in Appendix I.4. The SOC outlines are based on the ‘FCERM’ results as opposed to the ‘FRA’ results as the climate allowances are closest to those used in the OBC modelling. The fluvial flow allowance is the same for 2030 and only 1% different for 2130. The peak tidal level is very similar for 2030. The SOC used an epoch year of 2125 instead of 2130 and older sea level rise allowance and older design tide levels; the net effect is that the SOC 2125 peak tide level is about 0.14m lower than the 2130 OBC peak tide level.

The comparison of flood outlines shows:

- 2030 fluvial 1:100yr: Generally very similar. OBC has flooding removed at Unicorn Business, St Annes, possibly due to updates to Brislington Brook culverts. OBC also has flooding removed at Paintworks where a flood defence has been constructed in recent years, which has been incorporated into the OBC model. OBC shows less flooding in Malago area, which is likely due to the updated phasing applied for the Malago. Also, slightly less flooding on the Frome, likely due to updated LIDAR data for the floodplain.
- 2030 tidal 1:200yr: Generally very similar. OBC shows no flooding in Malago area, which is likely due to the updated phasing applied for the Malago. OBC also has flooding removed at Paintworks.
- 2130 fluvial 1:100yr: OBC generally results in slightly greater flooding but this is likely due to greater amount of sea level rise applied in OBC modelling compared to SOC FCERM modelling. Slightly less flooding at the Unicorn Business Park. OBC shows no flooding at Cabot Circus and Broadmead whereas the SOC shows significant area of flooding here; this appears to be largely due to the updated LIDAR data which alters flow paths at the eastern edge of Cabot Circus.
- 2130 tidal 1:200yr: Very similar, some areas slightly more flooding, other areas slightly less flooding.

9.3 River Avon water levels

Table 16 and Table 17 show a comparison of the peak River Avon water levels from the updated baseline model vs the Bristol SFRA defended model at several key locations for the 2030 1:100yr event and the 2030 tidal 1:200yr event. Note that peak tidal water levels at Avonmouth are 0.046m higher in the updated model due to the simulation including an additional 8 years' worth of sea level rise.

Table 16: Comparison of peak river water level results for fluvial 1:100yr event for 2030 (BAFS OBC) and 2022 (SFRA) based on fluvial central allowance and tidal higher central allowance.

		Peak river water level (m AOD)		
Location	**Model node**	**BAFS OBC**	**SFRA**	**Change (m)**
Crews Hall Road (u/s end)	Av5_1886	10.25	10.05	0.19
Brislington Brook outfall	Av5_0672	9.86	9.70	0.16
St Philips Causeway Bridge (u/s)	Av6_5521	9.33	9.20	0.13
Totterdown Bridge (u/s)	Av6_4513	9.08	8.97	0.11
Cattle Market Bridge (u/s)	Av6_3662	8.84	8.78	0.06
Bathurst Basin	Av6_2352U	8.62	8.56	0.06
Vauxhall Bridge (u/s)	Av6_1281	8.54	8.49	0.06
Ashton Avenue Bridge (u/s)	Av6_0566	8.50	8.45	0.05
Entrance Lock	Av6_0075d	8.46	8.41	0.04
Sea Mills	Av7_4087	8.37	8.33	0.04
Shirehampton, Station Road	Av7_0873	8.27	8.22	0.05

Table 17: Comparison of peak river water level results for tidal 1:200yr event for 2030 (BAFS OBC) and 2022 (SFRA) based on fluvial central allowance and tidal higher central allowance.

		Peak river water level (m AOD)		
Location	**Model node**	**BAFS OBC**	**SFRA**	**Change (m)**
Crews Hall Road (u/s end)	Av5_1886	9.58	9.51	0.07
Brislington Brook outfall	Av5_0672	9.51	9.45	0.06

		Peak river water level (m AOD)		
Location	Model node	BAFS OBC	SFRA	Change (m)
St Philips Causeway Bridge (u/s)	Av6_5521	9.44	9.38	0.05
Totterdown Bridge (u/s)	Av6_4513	9.41	9.36	0.05
Cattle Market Bridge (u/s)	Av6_3662	9.39	9.34	0.05
Bathurst Basin	Av6_2352U	9.35	9.31	0.04
Vauxhall Bridge (u/s)	Av6_1281	9.34	9.29	0.05
Ashton Avenue Bridge (u/s)	Av6_0566	9.33	9.28	0.05
Entrance Lock	Av6_0075d	9.32	9.28	0.05
Sea Mills	Av7_4087	9.28	9.23	0.05
Shirehampton, Station Road	Av7_0873	9.20	9.15	0.05

The comparison of peak river water levels shows:

- At all locations shown, the updated model results in higher peak water levels than the SFRA model.
- The increase in water level between Cattle Market Road and Shirehampton, which is tidally dominated is 0.04 to 0.06m, which can be largely explained by the 0.046m increase in tidal water level at Avonmouth.
- The increase in water level becomes greater as one moves further upstream and is greatest in fluvially dominated events. The greatest increase in the Bristol area is at the upstream end of Crews Hall Road where there is a 0.07m increase. The increases are largely attributed to the updated bank levels, inclusion of the new flood defences at the Paintworks, orifice flow mode option turned on at surcharged bridges, and updated / refined hydrology upstream of Bristol.

10. Sensitivity testing

10.1 Introduction

Sensitivity testing has been undertaken using the baseline model to understand the influence of the following key model parameters on baseline model results:

- Initial water level in the Floating Harbour
- Fluvial inflows
- Downstream boundary tidal water levels
- River channel roughness

Sensitivity testing has also been undertaken for the scheme "glass-wall" model as part of the residual uncertainty assessment to determine freeboard allowances - this is reported separately[22].

10.2 Floating Harbour initial water level sensitivity test

The normal operating range for the Floating Harbour water level is between 5.6 and 6.6m AOD. The initial water level used in the modelling to date is 6.2m AOD. To understand the impact of the initial water level in the Floating Harbour on model results, a sensitivity test has been run for the baseline model where the initial water level is set to 6.6m AOD, i.e., the top of the normal operating range. This has been modelled for the 2065 fluvial 1:100yr and 2065 tidal 1:200yr events. The 2065 epoch used as this sensitivity test was undertaken after the epoch year was updated to 2069; however, the results below still remain valid.

The model results show no impact on peak water levels, flood depths or flood extents. This is because the water levels in the Floating Harbour return to baseline (non-sensitivity test) levels long before the flood peak arrives, e.g. see the 2065 fluvial 1:100yr results in Figure 30. This is due to the operation of the Underfall Sluices discharging excess fluvial flows to maintain a level of 6.2m AOD in the harbour.

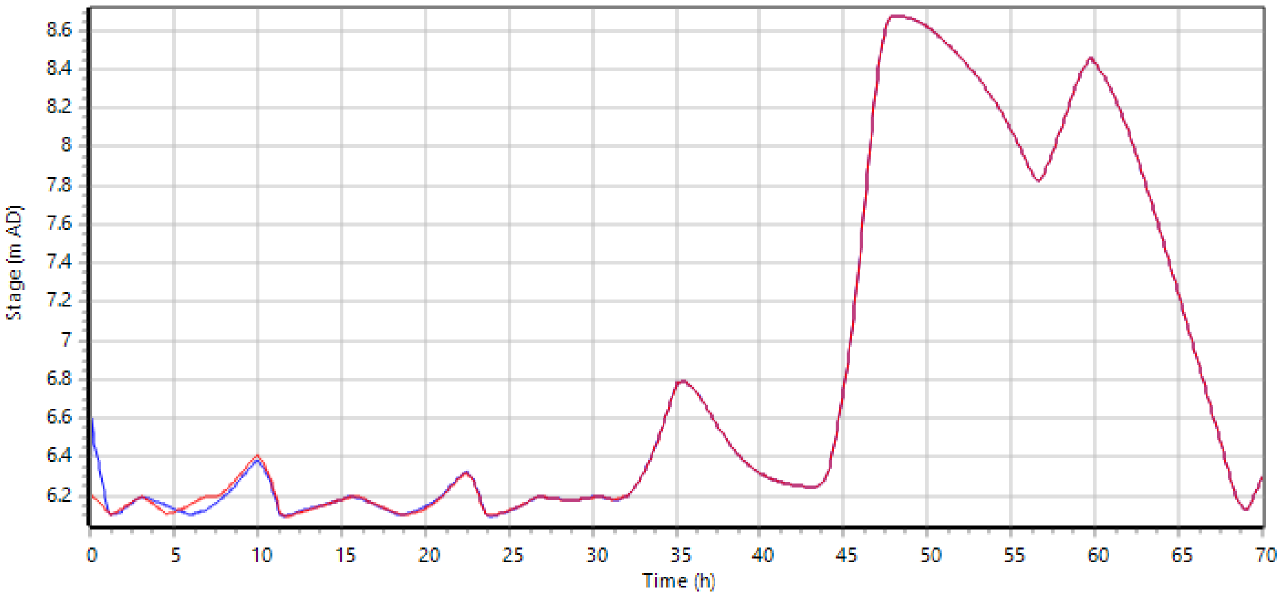

Figure 30: Impact of initial harbour water level on harbour water level.

10.3 Fluvial inflows

To understand the impact of changes in fluvial inflows, the following sensitivity tests has been undertaken on the baseline model for the 2030 fluvial 1:100yr event:

- Fluvial inflows decreased by 20% (F+20%).

- Fluvial inflows increased by 20% (F-20%).

The impact of this sensitivity test on peak River Avon water levels is shown in Figure 31. This shows river water levels are insensitive downstream of Netham Weir and sensitive upstream of Netham Weir as fluvial flows dominate over tidal conditions here.

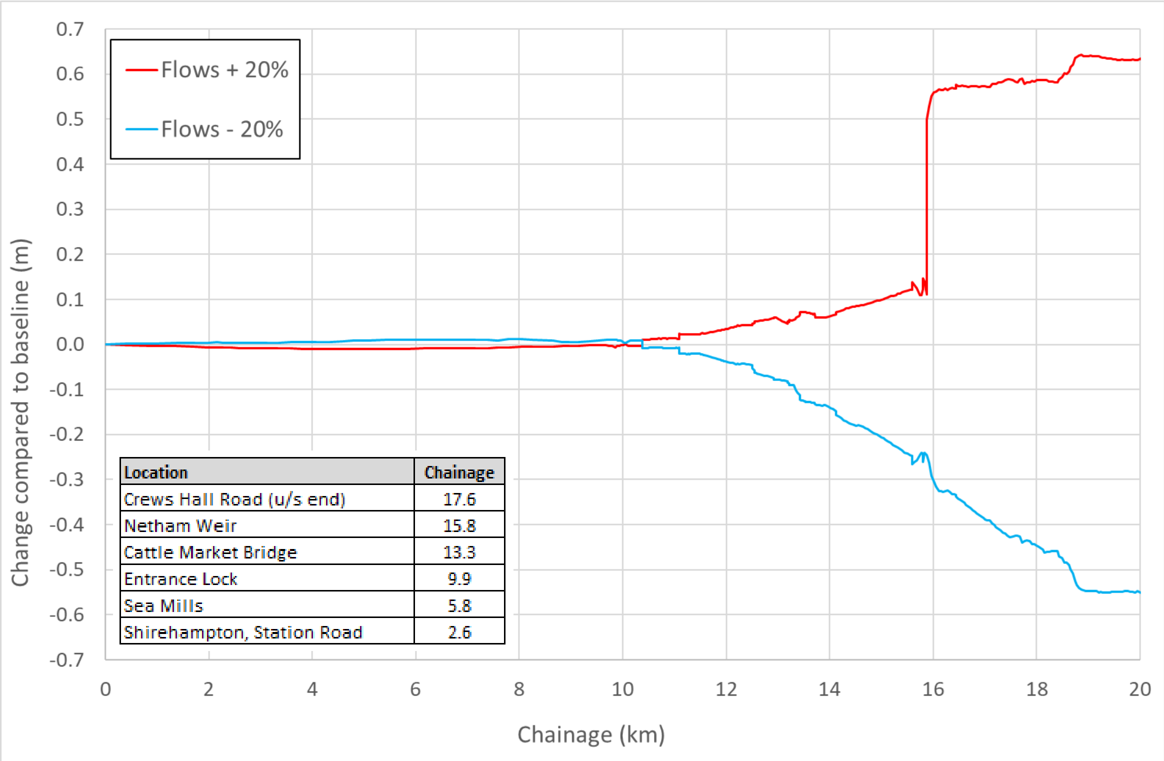

Figure 31: Impact of fluvial flows on peak River Avon water levels for 2030 fluvial 1:100yr event.

The impact of this sensitivity test on flood extent is shown in Appendix I.5. This shows the 2030 fluvial 1:100yr flood extent in Bristol is very sensitive to increases in flow, particularly around the Floating Harbour, Feeder Canal and River Frome. This is due to water levels being close to the threshold of flooding in these locations in the baseline. For the same reason, the flood extent in Bristol is generally relatively insensitive to decrease in fluvial flows; the areas exhibiting greatest sensitivity are St Anne's at the downstream end of Brislington Brook and the area to the south of Feeder Canal east of the rail crossing.

10.4 Downstream boundary tidal water levels

To understand the impact of changes in tidal water level, the following sensitivity tests has been undertaken on the baseline model for the 2030 tidal 1:200yr event:

- All tidal downstream boundary tidal water levels decreased by 0.25m (T-0.25m).
- All tidal downstream boundary tidal water levels increased by 0.25m (T+0.25m).

The impact of this sensitivity test on peak River Avon water levels is shown in Figure 32. This shows the sensitivity gradually diminishes in an upstream direction from the downstream boundary; within Bristol the sensitivity is in the order of 0.1 to 0.2m.

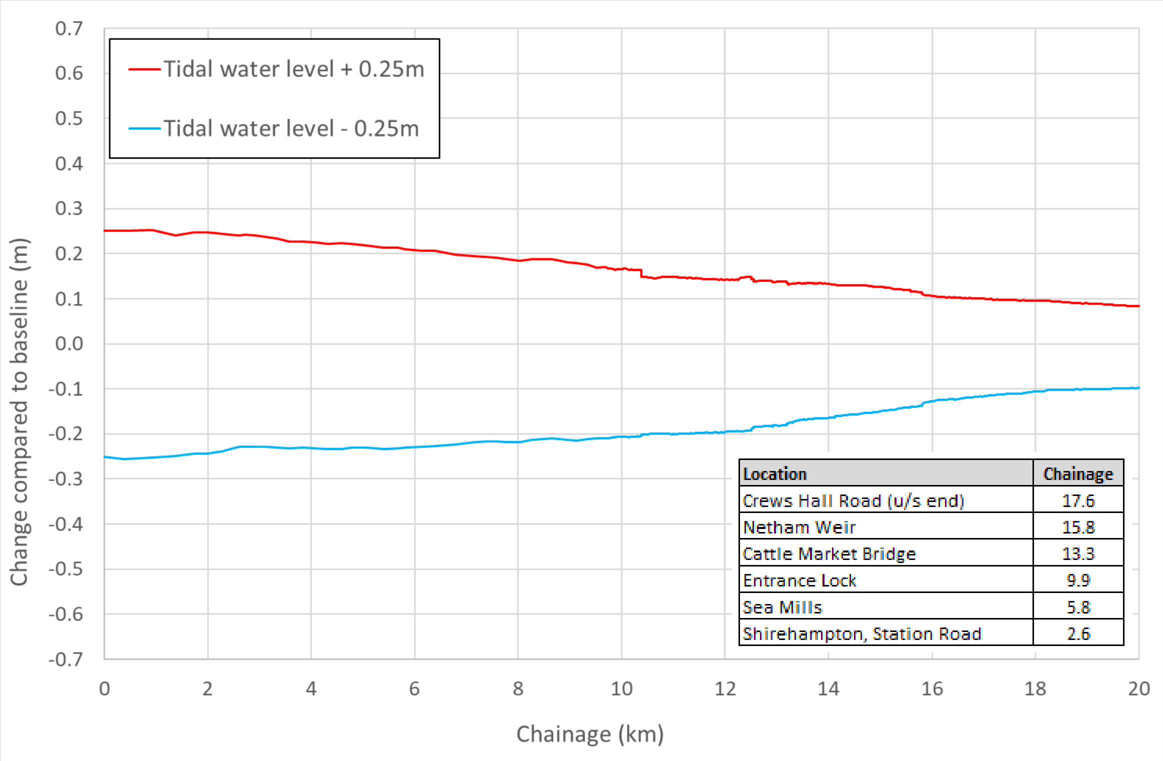

Figure 32: Impact of tidal water levels on peak River Avon water levels for 2030 tidal 1:200yr event.

The impact of this sensitivity test on flood extent is shown in Appendix I.5. This shows the 2030 tidal 1:200yr flood extent in Bristol is sensitive to increases in tidal water level around the Floating Harbour and Feeder Canal but is generally insensitive in other areas. The sensitivity around the Floating Harbour and Feeder Canal is due to water levels being close to the threshold of flooding in these locations in the baseline. For the same reason, the flood extent in Bristol is generally insensitive to decrease in tidal water levels.

10.5 River channel roughness

To understand the impact of changes in river channel roughness, the following sensitivity tests has been undertaken on the baseline model for the 2030 fluvial 1:100yr event:

- River Avon and Brislington Brook channel roughness Manning's *n* value decreased by 20% (R-20%).
- River Avon and Brislington Brook channel roughness Manning's *n* value increased by 20% (R-20%).

Note river channel roughness is only modified for the River Avon and Brislington Brook in this sensitivity testing because (a) the River Avon is the focus of the current study and (b) the proposed scheme also includes a flood defence on the Brislington Brook to manage scheme impacts.

The impact of this sensitivity test on peak River Avon water levels is shown in Figure 33. This shows river water levels are insensitive downstream of Netham Weir and sensitive upstream of Netham Weir as fluvial flows dominate over tidal conditions here.

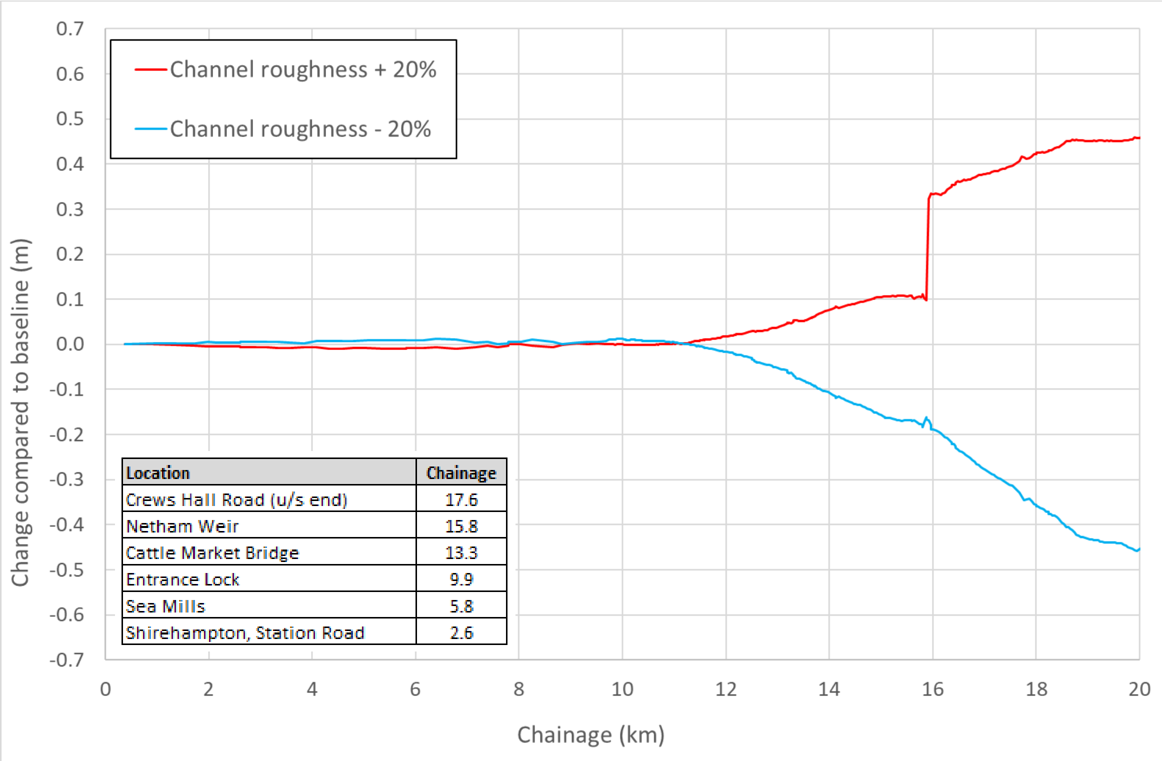

Figure 33: Impact of channel roughness on peak River Avon water levels for 2030 fluvial 1:100yr event.

The impact of this sensitivity test on flood extent is shown in Appendix I.5. This shows the 2030 fluvial 1:100yr flood extent in Bristol is moderately sensitive to increases in channel roughness, largely in areas such as around the Floating Harbour and Feeder Canal where baseline water levels are close to the threshold of flooding. Increasing channel roughness causes an increase in water level of 0.32m in the Avon immediately upstream of Netham Weir, which significantly increases overtopping of flood water into Feeder Canal at Netham Lock, which increases water level in the Floating Harbour by 0.35m. The flood extent in Bristol is insensitive to decrease in channel roughness.

11. Summary

11.1 Summary of work completed

The Bristol baseline hydraulic model has been updated for use in the BAFS OBC study to support the scheme design, consenting and economic assessment. The scope for the updates were developed in consultation with BCC and the EA during an inception stage and were informed by reviews of the relevant existing flood modelling.

The baseline model updates include:

1. Update of fluvial inflows based on review of latest gauge data, including adjusting the phasing of the Malago and Brislington Brook and tributaries upstream of Bristol. The 1:1yr fluvial flows were also derived for use with tidal dominated events. A non-stationarity assessment was undertaken in consultation with the EA.
2. Incorporate the current design tide levels.
3. Incorporate the current climate change allowances based on current guidance. The fluvial flow climate change allowances from the FRA climate change guidance are consistent with those from the FCERM climate change guidance. For sea level rise, the updated modelling uses the allowances from the FRA climate change guidance as were found to be marginally higher than those from the FCERM guidance. For 2030 and 2069 epochs, the maximum difference between the two sets of guidance was only 10mm and for the 2130 epoch the difference was 24mm for the higher central allowance and 92mm for the upper allowance.
4. Update floodplain elevations using the latest LIDAR data.
5. Reduce uncertainties in key areas of the model. This included reviewing the model against topographic survey and drawings and reviewing the structure control rules. As part of the project, topographic survey was commissioned, collected and incorporated into the model – this covered river bank levels, wall levels, culverts and property threshold in areas that were sensitive to scheme impacts.
6. Improved representation of Floating Harbour control.
7. Extended the model to Bath by incorporating the North Keynsham model (developed from the EA Bath to Bristol model) and converting the model to 1d-2d from Bath to Bristol and at Sea Mills, Pill and Shirehampton.
8. Numerous small refinements, including updates to structures to improve representation of hydraulics, adding a missing bridge to the model, adding interpolate cross-sections, refinement of panel markers.
9. Improve file management to facilitate model updates, reduce duplication and reduce the risk of errors / inconsistencies.
10. Implementing HPC solver to enable TUFLOW component to run on GPU card. This greatly reduced model run times for the extended model from circa 5 days to 6hrs.
11. Updates to improve stability.

A third party review of the updated baseline model was undertaken and subsequent updates were made to the model to address review comments. The updated model was then validated against the March 2020 tidal event – the model results showed good agreement with the river gauge data and locations of observed flooding. Sensitivity testing has also been undertaken to understand the influence of key model parameters on model results. To help understand the impact on model results of the numerous updates, comparisons against the SFRA model results and the BAFS SOC model results are also presented.

11.2 Limitations and recommendations

The Bristol hydraulic model has been updated for the purposes of the BAFS OBC study. Before the updated model is used in any other studies, it is recommended that a review of the model, modelling assumptions and boundary conditions is undertaken. In particular, the following should be assessed:

- Whether any changes to ground levels or river channels / structures have occurred since the current study.
- Whether any new / updated information such as topographic survey is available that could be incorporated into the model.
- Whether new hydrometric data is available to refine the hydrology.

Specific assumptions and limitations related to the BAFS OBC modelling:

- The model runtime and stability are generally good. However, during simulation of the full suite of return periods and epochs it was identified that the model would occasionally fail in the 1d component with error E1100 ("*stopped in putcff*") at different nodes / times. This was overcome by increasing or decreasing the maximum number of iterations (usually by 1).
- The Malago system is complex, steep and the hydrology has a very short time to peak. Moving part of the Malago system from FMP to ESTRY was undertaken to prevent the model failing on the Malago system during modest flow conditions. However, the updated model is not able to model a 1:1000yr fluvial event on the Malago system without becoming unstable. As the focus of the current study is the River Avon, the fluvial 1:1000yr event has been simulated using a 1:200yr fluvial event on the Malago and a 1:1000yr fluvial event on all other watercourses. This is considered acceptable as it is very unlikely a 1:1000yr event would occur on both watercourses at the same time. However, for any future studies that use the model to specifically assess flood risk on the Malago, updates will be required to stabilise the model if the 1:1000yr fluvial event needs to be assessed. It is also recommended that consideration is given to the tidal conditions and phasing of Malago flows vs high peak tidal level.
- Based on the review of the Frome culvert undertaken in this study, the overall representation of this culvert is considered acceptable for the current BAFS study. However, it is recommended that updating the culvert representation to better match available topographic survey is considered for future studies where the focus is flood risk from the River Frome.

Appendix A

Draft modelling methodology report

Appendix B

Agreed baseline model updates scope

Appendix C

Hydrology reporting

Appendix D

Operating rules review

Appendix E

Topographic survey

E.1 Survey scope

E.2 New survey (2022) deliverables

E.3 Other data used for checks

E.4 Pill topographic survey

Appendix F

Baseline model updates review

Appendix G

Agreed simulation list

Appendix H

File naming convention

Appendix I

Flood extent figures

I.1 Validation event flood results

I.2 JPA sensitivity tests

I.3 Flood outlines comparison against Bristol SFRA model

I.4 Flood outlines comparison against Bristol SOC model

I.5 Baseline sensitivity tests