

Bristol City Council
Bristol FRM Strategy
Overview of flood modelling

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1 Introduction

1.1 Context

As with any city located close to rivers and the sea, Bristol has experienced many flood events in its past. While flooding can occur due to heavy rain, the city centre is at risk of widespread flooding from the River Avon. The location of the city centre means that it is at risk of flooding from the River Avon. Storms can increase river flows coming down the river (fluvial flooding). Storms can also force water to surge in the Severn Estuary, creating a tidal food up the river. Bristol has been lucky in recent years and has avoided severe flooding whilst many communities across the country have suffered widespread flood disruption, damage and danger to life. However, there have been over twenty ‘near-miss’ tidal flood events in the last decade. Increasing sea levels and storms, caused by climate change, mean the risk of flooding is increasing. The impact would be felt across the West of England due to Bristol’s regional importance for employment, transport, recreation, tourism and economic growth.

Bristol City Council is working with the Environment Agency and other partners to create a vital long-term strategy for managing the flood threat from the River Avon, supported by Arup. The strategy will outline action to be taken in phases to reduce the chance and impact of flooding from the River Avon, and how each phase will be funded. This is to be tested through consultation in advance of adoption by Bristol City Council and endorsement by the Environment Agency.

The preferred option of the Strategy comprises raised defences along the River Avon including new tidal stop gates for the Floating Harbour. The initial phase of construction is assumed for the 2020s and a subsequent phase of constructing additional defences and raising defences is assumed for the 2060s.

1.2 Scope

This report provides a concise overview of the flood modelling undertaken by Arup for the Bristol Flood Risk Management (FRM) Strategy, referred to here as ‘the Strategy’ to support the Strategic Outline Case (SOC) report. This work builds on a previous study undertaken by AECOM, which was informed by several previous studies, most notably the Bristol Central Area Flood Risk Assessment (CAFRA).

The main stages of the flood modelling work undertaken are:

1. Baseline model review, investigations and update;
2. Options development: consider raised flood defences and tidal barrier and subsequently review phasing of interventions and control of water levels in the Floating Harbour.
3. Support strategic growth and regeneration area project: assessed a) scale of precautionary raised defences to meet National Planning Policy Framework (NPPF) requirements for development, and b) residual flood risk to strategic growth and regeneration areas;

4. Assess detriment from the proposed scheme;
5. Develop detriment mitigation measures;
6. Determine required defence levels;
7. Flood damage modelling: to assess flood depths and hazard due to overtopping for use in the flood damage assessment;
8. Provide recommendations for future modelling.

1.3 Supporting reports

This overview report references the supporting modelling reports issued to Bristol City Council (BCC) and the Environment Agency (EA) during this study, which contain more detail. These supporting modelling reports and this overview report are listed in Table 1 against the relevant stage of the flood modelling work.

Table 1: Modelling reports and notes issued with key reports in bold.

Stage	Report / note	Date issued
Baseline review and update	Review of hydraulic modelling	02/04/2018
	Review of hydrology	02/04/2018
	Review of CAFRA WS3 calibration	28/08/2018
	Netham calibration investigation	21/09/2018
	Review of hydrograph shape for Avon and Frome	12/10/2018
	Testing of labyrinth weir unit at Netham Weir	22/10/2018
	Future climate JPA pairs (note this is based on superseded results and conclusions are no longer applicable)	26/10/2018
	Netham Weir sluices sensitivity tests	04/12/2018
	Review of updated baseline results	06/02/2019
Options development	Hydraulic modelling to support Bristol Temple Quarter project	10/12/2019
Support strategic growth and regeneration areas		
Assess detriment	Detriment assessment	11/11/2019
	Representation of lock gates in the model	25/11/2019
Develop detriment mitigation measures	Detriment mitigation option development (includes a summary of the detriment assessment)	24/06/2020
Determine required defence levels Flood damage simulations Recommendations for future modelling	Overview of flood modelling (this report)	29/09/2020

2 Overview of baseline model

The baseline model used in the Strategy was developed during the Bristol Central Area Flood Risk Assessment (CAFRA) studies before being adopted by AECOM for the initial development of the Strategy. The model is a linked 1d-2d model. The 1d component, which is based on Flood Modeller Pro, represents the watercourses and riverine structures plus some areas of floodplain upstream and downstream of Bristol. The 2d component, which is based on TUFLOW, represents floodplain areas within Bristol, the Floating Harbour and the Feeder Canal. The extents of the 1d and 2d components of the model are shown in Figure 1.

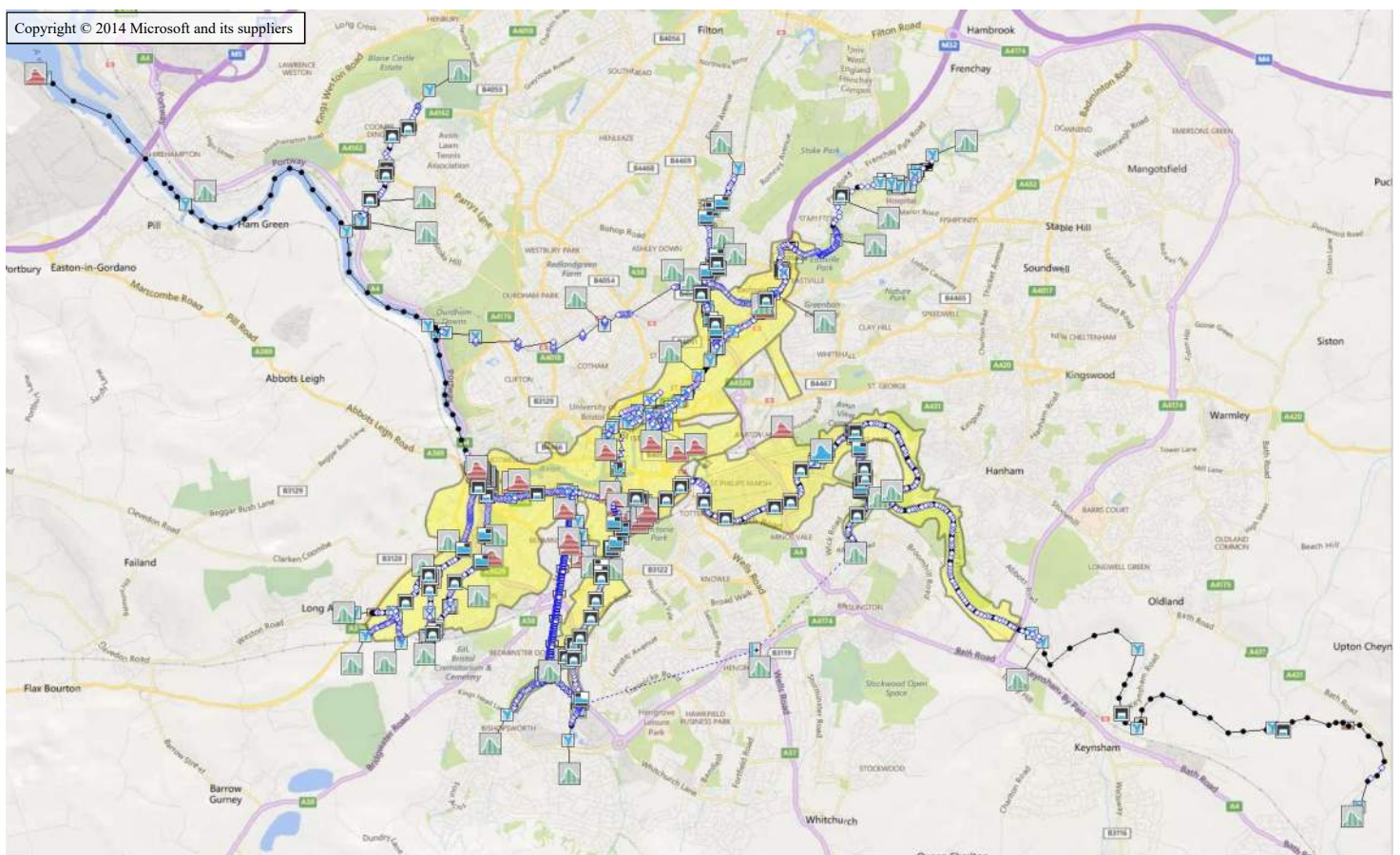


Figure 1: Extents of 1d model (node icons) and 2d model (yellow areas).

The 1d model covers the Avon from Saltford (upstream) to Avonmouth (downstream) and explicitly includes the key tributaries draining into the Bristol area, namely the Frome, Horfield Brook, Malago, Trym, Colliter's Brook, Longmoor Brook, Pigeonhouse Brook, and Brislington Brook.

The 1d model also includes the Northern Storm Water Interceptor (NSWI) and inlet sluices and weirs, which are represented as fully operational. The NSWI transfers a significant portion of fluvial flow from the River Frome to the River Avon near Clifton Down during fluvial flood events.

The 1d model also includes areas of floodplain upstream of the A4174 road and downstream of Entrance Lock. These are represented using a simple method of extended cross-sections and therefore flooding mechanisms are not accurately represented in these areas.

The in-channel parts of the 1d model are largely based on topographic survey of the channel and riverine structures collected between 2001 and 2011; most data used in the model is from 2005 onwards.

The 2d model has a 5m resolution and is largely based on LIDAR DTM data from 2010 and 2011. The 2d model is linked to the 1d model along the river banks and at the lock gates, which are also represented.

The model applies a water level vs time boundary condition at Avonmouth to represent tidal cycles including surge events. The model applies flow vs time boundary conditions at the upstream ends of the modelled watercourses and at locations along the modelled watercourses where flows enter. The phasing of the peak inflows and peak tide levels is configured so that these are synchronised at Bristol, which is conservative. Each model simulation represents a 70hr duration, which includes five full tidal cycles.

3 Baseline review and updates

3.1 Model review

The initial baseline and option modelling for the Strategy was undertaken by AECOM, which was informed by a number of previous studies, most notably the CAFRA studies.

To develop the Strategy further, additional hydraulic modelling was required to develop the preferred option and to support the economic analysis. Before any new modelling commenced, a brief review of the CAFRA and AECOM hydraulic modelling and associated hydrology was undertaken to identify any significant shortcomings, issues or risks associated with the modelling. It was agreed that a full technical or QA review of the model was not required because the CAFRA model had already been reviewed on behalf of BCC and accepted as the approved strategic baseline for the assessment of flood risk in Bristol.

The model review^{1,2} identified high, medium and low priority recommendations for additional work to reduce modelling uncertainties. It was agreed with BCC and the EA that the high priority recommendations listed in Table 2 were to be undertaken. It was subsequently agreed that sensitivity testing of the Netham Weir sluice operation should also be undertaken – this is included as the last row in the table below.

Table 2: Recommendations agreed to be undertaken.

	Recommendation	Description
A	Review and update of the hydrograph shape for the Avon and Frome.	Hydrograph shape and volume is important when considering flood storage options including any consideration of pre-lowering of the Floating Harbour water levels. CAFRA Workstream 3 inflows were used by AECOM but uncertainty over hydrograph shape adopted. The CAFRA Workstream 4 inflows are considered to be the result of only a partial removal of the tide effect and resulting volumes are considered likely to be overestimated. A more comprehensive approach, which includes the analysis of additional river and tidal gauge records is recommended to check / refine the hydrograph shape.
B	Review Appendix A of Arcadis report to confirm whether impact of dependency factor is provided.	The uncertainty in water level due to the uncertainty in dependency factor should be considered in the residual uncertainty analysis for setting design crest levels. No additional work anticipated assuming the 1d model water level results of the CAFRA Workstream 3 sensitivity test of high dependency factor can be provided.
C	Sensitivity testing to determine critical JPA pairs for 2115 epoch.	To test whether intermediate JPA events should be included for some return periods for future epochs.
D	Intermediate JPA pair for the present day 75yr and 100yr events.	It is recommended that an intermediate JPA pair is included for the present day 75yr and 100yr events as they result in slightly higher water levels near Netham Weir.

¹ Bristol FRM Strategy, File Note: Brief review of Bristol TFRMS hydraulic modelling, Arup, 02/04/2018.

² Bristol FRM Strategy, File Note: Brief review of Bristol TFRMS hydrology, Arup, 02/04/2018.

	Recommendation	Description
E	Re-run fluvial dominated events with appropriate tidal conditions.	Base tide has been used in AECOM's fluvial simulations. It is recommended that the appropriate nominal tidal event is selected from the Joint Probability scenarios and simulated in combination with the fluvial event. For the 20yr, a base tide is acceptable but for the 75yr and 100yr events, a 1yr tide should be applied and for the 200yr event a 2yr tide should be applied. If this is not undertaken, then water levels (and therefore defence levels) could be significantly under-estimated
F	Additional simulations to reduce inconsistencies / errors due to the "equivalency" approach used to reduce number of simulations.	The Additional Hydraulic Modelling Technical Note suggests inconsistencies / errors due to the "equivalency" approach used to reduce number of simulations. This is a potential cause of confusion and errors, particularly where the incorrect climate change allowance is applied to fluvial flows. It is recommended this risk is avoided by undertaking additional simulations as required. This recommendation was also given by AECOM.
G	Netham Weir - Sensitivity test using the labyrinth weir unit.	Netham Weir has been represented using a stage-discharge relationship; the derivation of which is unavailable. This approach does not explicitly represent the weir and may cause the impact of the tide on water levels and/or flows to be misrepresented here. It is recommended that the Labyrinth Weir unit is tested to see if this improves model performance at Netham. This work would initially undertake a sensitivity test for the 200yr fluvial event before any further work, such as re-running one or more calibration events. This recommendation was also given by AECOM.
H	Netham Weir - investigate calibration issues.	Fluvial calibration performance at Netham Weir appears inconsistent – reduces confidence in fluvial water levels here. Report suggests this is a hydrological issue, e.g. calibration flows, rather than a hydraulic issue. It is recommended that this is investigated and that either the model performance is improved and/or the uncertainty in water levels associated with this issue is estimated.
I	Incorporate modification to defence due to cycle path improvement.	A footbridge is under construction which has modified the EA flood defences at Totterdown/St Phillips north of Victor Street. The modified defence level should be incorporated into the hydraulic model.
J	Sensitivity testing of Netham Weir sluice operation.	During the calibration investigation (see H above), it was identified that the operation of the sluice gates on Netham Weir could influence water levels in the river and that this could, in part, explain the relatively inconsistent calibration performance at Netham Weir for fluvial events. All modelling from the CAFRA study and the Strategy omit these sluices, so they are effectively assumed to be closed. It was agreed that sensitivity testing should be carried out using the hydraulic model to assess the influence of the sluices on water levels in the river.

3.2 Model investigations and updates

The outcome of the agreed recommendations (Table 2) are summarised in Table 3. The impact on model results of updates to the model and associated hydrology are described in Section 3.3

Table 3: Outcome of recommendations.

	Recommendation	Outcome
A	Review and update of the hydrograph shape for the Avon and Frome.	The hydrograph shapes for the Avon and Frome were reviewed and updated based on analysis of historic flood events. The updated Avon hydrograph shape is not significantly different to the CAFRA Workstream 3 hydrograph shape used by AECOM. The updated Frome hydrograph shape is very similar to the CAFRA Workstream 4 hydrograph shape and has significantly greater volume compared to the CAFRA Workstream 3 hydrograph shape used by AECOM. More detail can be found in the 'Review of hydrograph shape for Avon and Frome' report ³ .
B	Review Appendix A of Arcadis report to confirm whether impact of dependency factor is provided.	Appendix was reviewed and was found to contain no information on impact of dependency factor on water levels. However, applying the high dependency factor would be roughly the equivalent to doubling the return period for the dominant flood type, e.g. going from a 100yr event to a 200yr event. The difference in river water levels between these return periods is 0.1 - 0.2m downstream of Netham Weir and 0.3 – 0.4m upstream of Netham Weir.
C	Sensitivity testing to determine critical JPA pairs for 2115 epoch.	Long-section plots of CAFRA model results identified that an intermediate JPA pair (combination of tidal and fluvial) were recommended for the 1:75yr event and the 1:100yr event for each epoch to capture maximum river water levels around Netham Weir. However, following the updates listed in this table, the model was re-run and results showed that intermediate JPA pairs were no longer required for the above return periods for any epochs. This is primarily due to the implementation of recommendation E below.
D	Intermediate JPA pair for the present day 75yr and 100yr events.	
E	Re-run fluvial dominated events with appropriate tidal conditions.	The boundary conditions were updated in the model for fluvial dominated events to apply a more appropriate tidal boundary based on the JPA combinations of fluvial and tidal derived in the CAFRA study. The 100yr fluvial was combined with a 1yr tide and the 200yr fluvial was combined with a 2yr tide. The 20yr and 75yr fluvial events were also combined with a 1yr tide because the JPA pairs for the 20yr include 20yr fluvial and 0.24yr tidal. Tidal water levels are only available for return periods down to 1yr; however, based on other studies where water levels have been derived for return periods down to 0.1yr, the 0.24yr water levels are predicted to be significantly closer to the 1yr water levels than the mean spring tide level, which is why the 1yr event has been selected. The fluvial 75yr has also been paired with the tidal 1yr event to approximate the exact JPA tidal events which is 0.9yr.
F	Additional simulations to reduce inconsistencies / errors due to the "equivalency" approach used to reduce number of simulations.	The updated model was run for each required return period (20yr, 75yr, 100yr, 200yr and 1000yr) for both tidally and fluvially dominated events. These simulations were run for each epoch year assessed using the appropriate climate change allowances so that equivalencies were not required.
G	Netham Weir - Sensitivity test using the labyrinth weir unit.	The labyrinth weir unit parameters were derived using topographic survey collected in April 2018. The labyrinth weir test model was run for the 2015 fluvial event. Two different modular limit formulation options in the labyrinth weir unit were tested. Results from both tests were compared against the original model which used a water level vs flow relationship to represent the weir. The results showed no significant impact on downstream water levels

³ Bristol FRM Strategy, Report: Review of design hydrograph shape for the Rivers Frome and Avon, Arup, 12/10/2018.

	Recommendation	Outcome
		but a more significant difference to upstream water levels (either a 0.1m reduction or a 0.2m increase depending on which modular limit formulation was used). It was agreed that item H below should include running fluvial calibration events to compare calibration performance for each modelled representation of the weir in order to select a preferred approach. More detail can be found in the 'Testing of labyrinth weir unit at Netham Weir' note ⁴ .
H	Netham Weir - investigate calibration issues.	<p>The calibration flows used in the CAFRA study were reviewed and updated using additional gauge data in an attempt to improve accuracy. The review identified sources of significant residual uncertainty in river flows. Model flows were also derived for two new calibration events (Feb 2009 and Dec 2013). More detail can be found in the 'Review of CAFRA WS3 calibration' note⁵.</p> <p>Calibration events were run using the original model and for the labyrinth weir model using the two different modular limit formulations.</p> <p>The calibration results suggest that overall, the best fit against the gauge readings is achieved using the original QH curve or the Labyrinth Weir using the ISIS modular limit formulation. Neither of these approaches gives consistently good calibration though, so there remains significant residual uncertainty in the model's performance upstream of Netham Weir. More detail can be found in the 'Netham calibration investigation' note⁶.</p> <p>It was agreed that the labyrinth weir unit with the ISIS modular limit formulation is adopted for the following reasons:</p> <ol style="list-style-type: none"> 1. Representation is based on measured levels and dimensions. 2. Facilitates understanding of model representation. 3. Facilitates possible future updates of the model, e.g. if Netham Weir is repaired / modified. 4. Appears to better represent tidal influence. 5. Gives similar overall calibration performance to the original stage-discharge relationship.
I	Incorporate modification to defence due to cycle path improvement.	This was incorporated into the updated model using a TUFLOW Zline based on the alignment and crest levels indicated on an annotated sketch drawing provided by BCC on 30/04/2018.
J	Sensitivity testing of Netham Weir sluice operation.	The model results showed the operation of the Netham Weir sluices has little impact on river water levels during flood events (0.04m reduction in water level upstream of the weir). It was agreed that the Netham Weir sluices should be represented as being closed for the assessment of flood risk in the River Avon and that the original model omission of the sluices, which effectively represents them as being closed, was acceptable. More detail can be found in the 'Netham Weir sluices sensitivity tests' note ⁷ .

⁴ Bristol FRM Strategy, File Note: Testing of labyrinth weir unit at Netham Weir, Arup, 22/10/2018.

⁵ Bristol FRM Strategy, File Note: Review of CAFRA WS3 calibration, Arup, 28/08/2018.

⁶ Bristol FRM Strategy, File Note: Netham calibration investigation – model results and recommendations, Arup, 21/09/2018.

⁷ Bristol FRM Strategy, File Note: Netham Weir sluices sensitivity tests, Arup, 04/12/2018.

Based on the above outcomes, the following updates were made to the baseline Do Minimum and Do Nothing strategy option hydraulic models:

- Update of the inflow hydrograph shapes for the Avon and Frome (item A in the above table).
- Applied more appropriate tidal conditions for fluvially dominated events (item E in the above table).
- Representation of Netham Weir changed from a QH relationship to a Labyrinth Weir unit using the ISIS modular limit formulation (items G and H in the above table).
- Incorporate modification to defence due to cycle path improvement (item I in the above table).
- Set up and run each required return period for both fluvially dominated events and tidally dominated events for each required epoch year (item F in the above table). This was undertaken for both the Do Minimum and Do Nothing strategy option hydraulic models.

3.3 Updated baseline model results

The results from the updated baseline modelling were reviewed and compared against the results from the AECOM and CAFRA baseline modelling to understand the impact of the model updates. This is described in the ‘Review of updated baseline results’ note⁸ which includes long-section plots of water levels along the Avon and flood extent comparisons. A summary of the main findings is given below.

In all cases, the baseline model assumes a) the NSWI and inlet sluices and weirs are fully operational; b) the Underfall Yard sluices are fully operational; and c) the Netham Lock, Entrance Lock and Junction Lock gates remain closed for the duration of the flood event.

River Avon water level long-sections:

These were produced for each modelled event. These show that for all return periods and epoch years, maximum water levels at each location are due to either a fluvially dominant event or a tidally dominant event, and not an intermediate combination of fluvial and tidal. Therefore, only two events require simulating for each return period epoch pair. The long-sections also showed that for 2015 climate, the transition from fluvial to tidal dominance occurs around Netham Weir for all return periods tested except for the 1000yr where the transition point is approximately 500m downstream of Netham Weir. For future climates, the transition point moves 1 to 2km downstream of Netham Weir. An example long-section plot is given for the Do Minimum option for 2065 (Figure 2).

⁸ Bristol FRM Strategy, File Note: Review of updated baseline results, Arup, 06/02/2019.

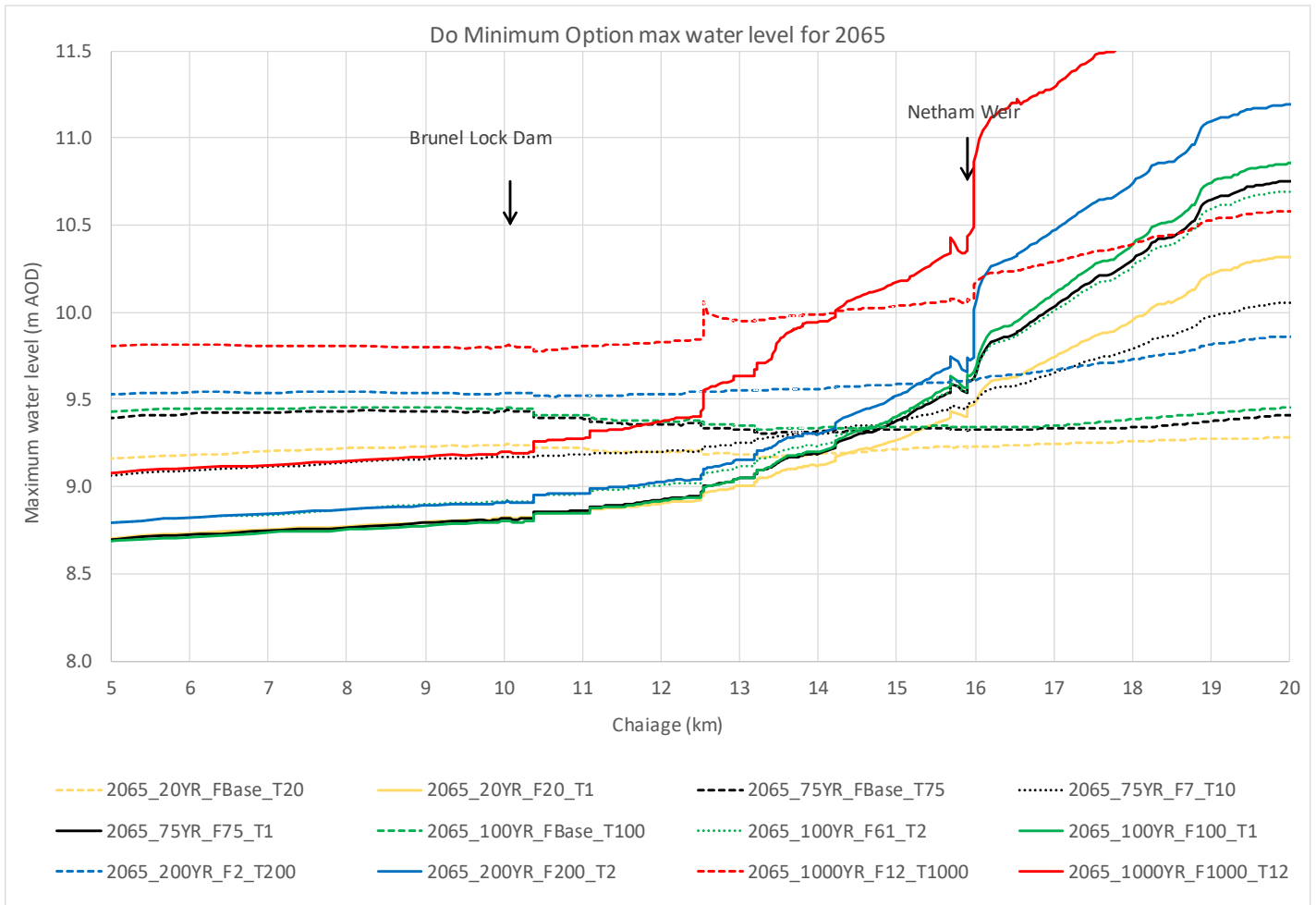


Figure 2: Do Minimum 2065 maximum water levels along the River Avon.

Flood depths:

For both Do Minimum and Do Nothing options and for both 2015 and 2115, the 200yr tidal event results in significantly greater flood depths than the 100yr fluvial event in most areas of the city, which demonstrates that tidal events dominate flood risk for Flood Zone 3 equivalent risk areas due to the significantly greater flood consequences.

Comparison against AECOM and CAFRA results:

As expected, the updated model results for the tidally dominated 200yr events are virtually the same as the AECOM results, albeit with a small increase in flooding around Canada Way.

The updated model results for fluvially dominated events show significantly more flooding compared to the equivalent CAFRA and AECOM results with the exception of the CAFRA 200yr results (see Figure 3 and Figure 4). An additional sensitivity test confirmed that this increase is because the updated modelling of the fluvially dominant events applies an appropriate tidal event based on the derived JPA pairs, whereas the AECOM and most of the CAFRA simulations

combined fluvial events with a mean spring tide. For 2015, the increase in flooding is most notable in St Philips Marsh whereas in 2115 a significant increase in flood extent occurs throughout the city from Hotwells to St Philips Marsh.

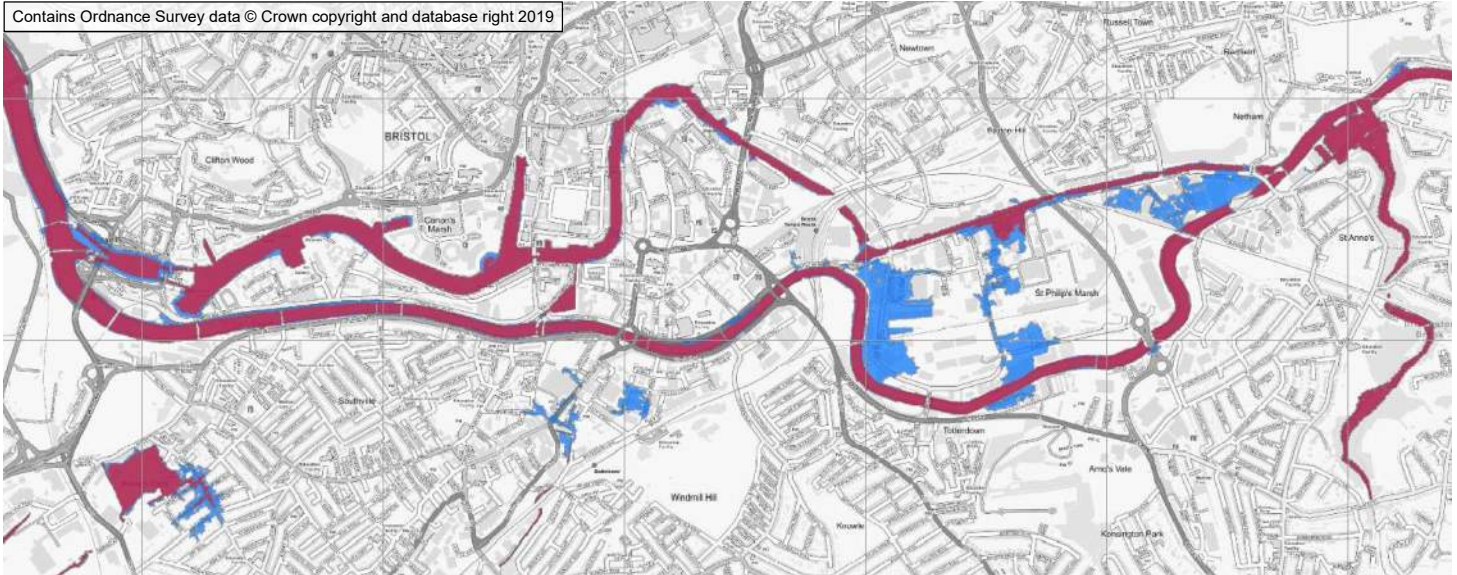


Figure 3: Do Minimum fluvially dominated 100yr event in 2015. Updated results (blue) vs AECOM results (purple).

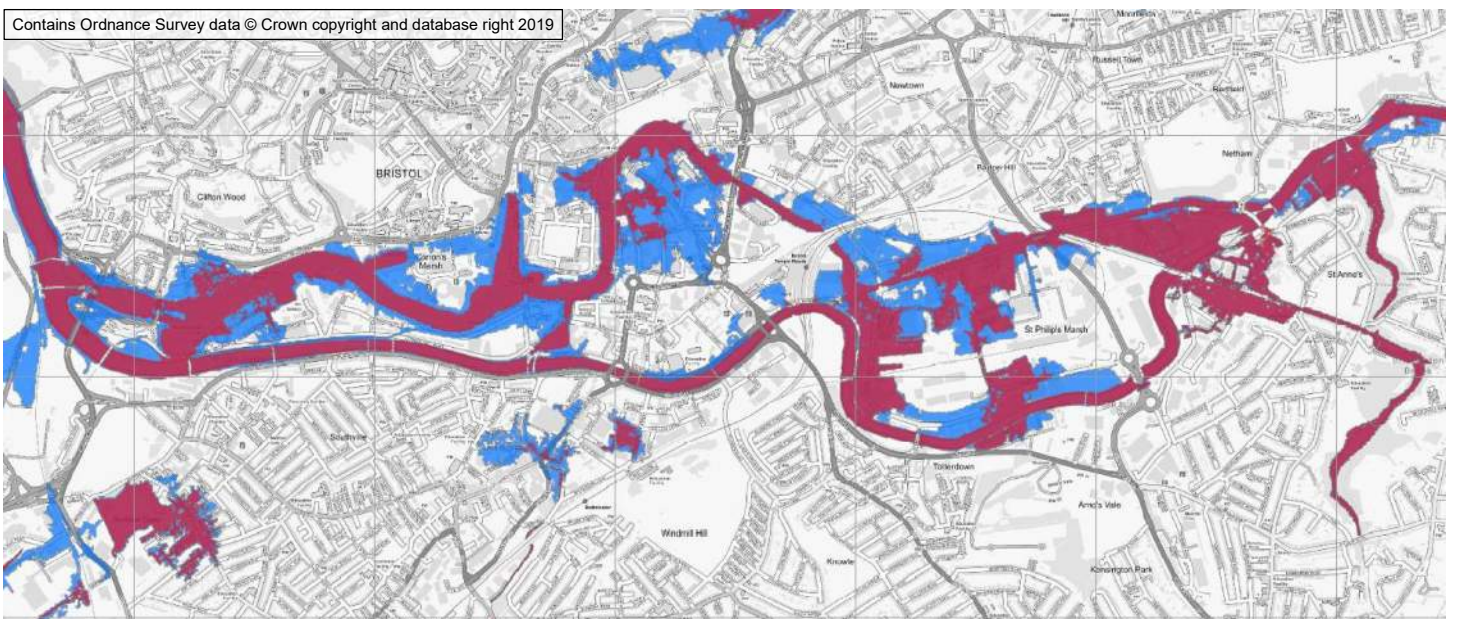


Figure 4: Do Minimum fluvially dominated 100yr event in 2115. Updated results (blue) vs CAFRA results (purple). Note CAFRA results actually correspond to 2110.

Flood progression:

At St Philips Marsh, the flow pathways and associated flood progression in the updated fluvially dominated 100yr event in 2015 was reviewed. These show overtopping occurs over a duration of less than 2hrs around the highest tide and

that most flooding is due to overtopping of the Avon with a smaller area of overtopping from the Feeder Canal. Some of the overtopping of the Avon flows northwards into the Feeder Canal. The equivalent AECOM results at St Philips Marsh show only a small area of overtopping from the Feeder Canal and no overtopping of the Avon.

4 Flow and tide conditions

4.1 Combinations of fluvial and tidal event

The following return periods were simulated for both fluvially dominated and tidally dominated events: 1:20yr, 1:75yr, 1:100yr, 1:200yr and 1:1000yr. These were chosen to provide enough detail to enable the subsequent economic analysis to be able to determine the optimum Standard of Protection (SoP) for the preferred Strategy option by applying the decision rule. The combinations of fluvial and tidal event simulated for each return period are given in Table 4. Where reference in this report is made to a 1:100yr fluvial event, this is modelled in combination with a 1:1yr tidal event and so on. The ‘base’ fluvial flow shown in the table below corresponds to the constant high winter baseflow values from the CAFRA and AECOM modelling. For the main inflow to the Avon, the baseflow is set to 65.7m³/s. This is approximately equal to the 5% exceedance flow based on the flow duration curve for the Avon at Bath ultrasonic gauge.

Table 4: Combinations of fluvial and tidal events.

Combined return period (years)	Tidal return period (years)	Fluvial return period (years)
20	20	Base
	1	20
75	75	Base
	1	75
100	100	Base
	1	100
200	200	2
	2	200
1000	1000	12
	12	1000

4.2 Present day conditions (2015)

Table 5 presents the flows and tide levels applied for the River Avon in the flood model for present day conditions based on the year 2015. The peak tide levels are applied at the downstream end of the model at Avonmouth and the peak flows for the Avon are applied at the upstream end of the model at Saltford.

Future conditions have also been assessed; these are described in the following section.

Table 5: Present day flows and tide levels for the River Avon.

Return period	Peak tide level at Avonmouth (m AOD)	Peak flow at Avon at Saltford (cumecs)
1:20yr	8.70	271
1:75yr	8.95	322
1:100yr	9.01	335
1:200yr	9.14	365
1:1000yr	9.46	446

4.3 Future conditions

The following epoch years were initially assessed, these being used in the AECOM modelling: 2015, 2030, 2065, 2115. It was later agreed that, given the first phase of the Strategy is anticipated to be constructed in the mid-2020s, the final epoch year assessed should be 2125 instead of 2115. To provide greater resolution to the flood damage calculation, an additional epoch year was assessed: 2045.

Two different sets of climate change allowances were used in the modelling:

1. NPPF⁹: This has been used to determine the scale of raised defences that would be required for new development to meet NPPF requirements if other mitigation such as ground raising was not undertaken. It has also been used for the assessment of residual flood risk, to assess detriment from the proposed Strategy option and to determine the scale of detriment mitigation raised defences. The Environment Agency have advised that the higher central band for fluvial flows is used for new residential developments.
2. FCERM¹⁰: Guidance for Flood & Coastal Erosion Risk Management Authorities (FCERM) has been used to determine the crest level of all other raised defences. For fluvial flows, the Central allowance is used. For relative sea level rise, the UKCP09 medium emission 95% projection data is used. FCERM defence levels are those levels set by climate change allowances for risk management authorities (as opposed to those levels set by climate change allowances for planning, NPPF levels).

Following completion of all hydraulic modelling for the SOC, the EA published new FCERM climate change guidance¹¹. The allowances derived from the new guidance were compared to those from the previous FCERM guidance used in the modelling. The fluvial flow allowances are unchanged, but the sea level rise allowances are greater:

⁹ Flood risk assessments: climate change allowances, Environment Agency, February 2019.

¹⁰ Adapting to Climate Change: Advice for Flood and Coastal Erosion Risk Management Authorities, Environment Agency, April 2016.

¹¹ Flood and coastal risk projects, schemes and strategies: climate change allowances, Environment Agency, July 2020.

- 2065: New allowance is 0.375m (allowance used to date = 0.32m) therefore a 0.055m increase. Note the new FCERM allowance is very close to the NPPF allowance (0.390m)
- 2125: New allowance is 1.106m (allowance used to date = 0.92m) therefore a 0.186m increase. Note the new FCERM allowance is close to the NPPF allowance (1.235m).

Considering all modelling had been completed for the SOC before the new climate change guidance was published, BCC and the EA agreed that re-modelling using allowances from the new guidance was not required. However, given the new FCERM sea level rise allowances are now much closer to the NPPF allowances than they were previously, the difference between NPPF and FCERM raised defence crest levels and associated costs becomes less significant than has been assessed to date. Note that FCERM fluvial flow allowances, which also influence raised defence crest levels, have not been updated. It is recommended that the latest climate change guidance is used in any modelling required for future stages of work and that the relative difference between FCERM and NPPF raised defence levels are considered during options development and selection.

For reference, the climate change allowances used in the modelling are presented in Table 6 for the epoch years used in the modelling. The FCERM allowances presented are based on the April 2016 guidance¹⁰ used in the modelling as opposed to the July 2020 guidance¹¹.

This report refers to FCERM defence levels to indicate that defences are based on the climate change allowances to be used by risk management authorities as opposed to NPPF climate change allowances to be used for planning. In this report, FCERM defence levels do not necessarily corresponding to the optimum standard of protection as this has yet to be determined at the time of writing.

Table 6: Climate change allowances.

	FCERM allowances (April 2016 guidance ¹⁰)		NPPF FRA allowances (Feb 2019 guidance ⁹)		
	Fluvial flow increase (%)	Relative sea level rise since 2015 (m)	Fluvial flow increase for higher central allowance (%)	Fluvial flow increase for upper end allowance (%)	Relative sea level rise since 2015 (m)
2030	10	0.085	15	25	0.075
2045	20	0.178	25	40	0.195
2065	20	0.320	25	40	0.390
2115	25	0.743	35	70	1.055
2125 *	25	0.921	35	70	1.235

* Allowances for 2125 were extrapolated and agreed with EA.

5 Option development

This chapter gives an overview of the options tested and which were taken forward or dropped. More information, including model results, can be found in the ‘Hydraulic modelling to support Bristol Temple Quarter project’ report¹² for Sections 5.1 to 5.5.

5.1 Key assumptions

At the start of the options testing stage it was necessary to agree a set of pragmatic option assumptions to apply in the options testing and development stage and in the detriment assessment and mitigation modelling stage to expedite the modelling work; these are listed below.

- a) The Strategy will focus on managing flood risk from the River Avon, including the Entrance Lock and Netham Lock gates.
- b) The Strategy will include raised flood defences on the River Avon, raised lock gates at Entrance Lock and Netham Lock. Other measures were tested in combination with these.
- c) The Standard of Protection (SoP) assumed is 1:100yr for fluvial events and 1:200yr for tidal events. These return periods have been selected as they are the basis for Flood Zone 3 and represent the minimum design standard that would be required for new development to meet NPPF requirements if other mitigation such as ground raising was not undertaken. The optimum SoP will be subsequently determined using the Environment Agency’s standard FCERM economic appraisal and decision rule guidance which may demonstrate that funding for a lower or a higher standard of protection could be justified.
- d) The standard of protection must be sustained with future climate change.
- e) An initial set of raised defences are to be completed by 2030s to protect against river levels up to the 2060s. The defences would be raised in the 2060s, if required, to account for the projected increase in river water levels between the 2060s and 2125 (note 2115 was initially used).
- f) The last flood management intervention will be constructed in the 2060s (modelled as 2065) and will sustain the standard of protection up to 2125 (initially 2115 was used) but not beyond this date. No further interventions will be constructed after the 2060s.
- g) Raised defences that protect strategic growth and regeneration areas (Bristol Temple Quarter and Western Harbour) are assumed to be constructed to NPPF defence levels whereas all other defences are assumed to be constructed to FCERM defence levels. Note that for the flood damage simulations (see Section 10), FCERM defence levels are used throughout.

¹² Bristol FRM Strategy, Report: Hydraulic modelling to support Bristol Temple Quarter project, Arup, 10/12/2019.

- h) The modelled raised defences include a nominal 300mm freeboard. Note that for the flood damage simulations (see Chapter 10), freeboard is not included in the modelling for any of the proposed raised defences.

5.2 Defence alignment

The strategic defence alignment developed in the initial phase of the Strategy by AECOM was tested to determine whether it was sufficient to prevent outflanking. This was undertaken using a ‘glass-wall’ version of the model with the proposed raised defences set artificially high to prevent overtopping. The results showed that some outflanking occurred at Ashton, Hotwells and upstream of Netham Weir. The raised flood defences were therefore extended in the model to prevent outflanking.

It was agreed with BCC that a raised defence should be assumed along Feeder Road to prevent overtopping of the Canal causing flooding to the Bristol Temple Quarter (BTQ) site for the design event. This was tested in the model and found to work as intended.

The strategic defence alignment taken forward to options testing is shown in Figure 5. This figure also highlights the locations of the ‘masterplan defences’, i.e. the proposed raised defences that would be required to protect the strategic growth and regeneration areas if other mitigation measures such as land raising were not implemented. Note the ‘defences’ shown around the Floating Harbour and Cumberland Basin are not included in the proposed strategy option but are included in the modelling. This is to provide an indicative worst case for displacement of floodwaters and resultant detriment due to potential future ground raising within the Western Harbour strategic growth and regeneration area to meet NPPF requirements. This modelling approach has been used to determine the maximum required detriment mitigation (Chapter 8) in order to maximise flexibility at this concept stage.

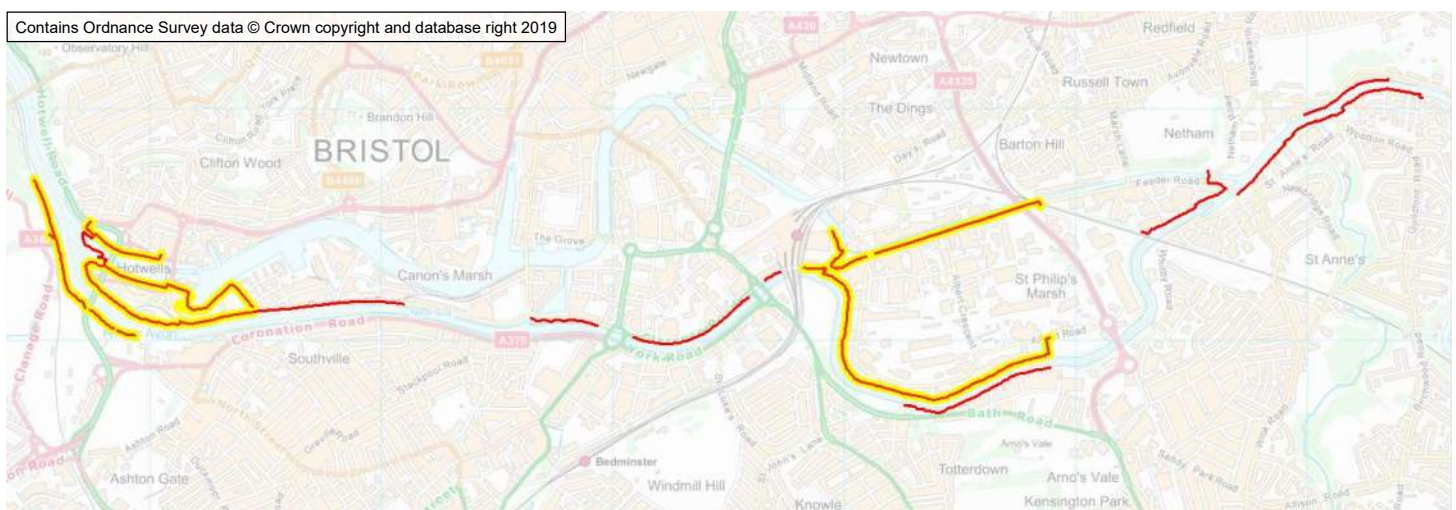


Figure 5: Raised defences included in the model (red) with masterplan defences highlighted yellow. Note defences around Cumberland Basin and the Floating Harbour are not proposed as part of the Strategy.

5.3 Fluvial options testing

The following options were tested for the 1:100yr fluvial event with ‘glass-wall’ defences along the proposed defence alignment, i.e. defences set artificially high to prevent overtopping.

- Option 1a: Raised defences only.
- Option 1b: Raised defences with modifications at Netham Weir where the weir crest is effectively lowered to bed level.
- Option 1c: Raised defences with Floating Harbour water level pre-lowered by 0.5m.

The model results showed:

- Lowering Netham Weir would reduce Avon water levels upstream of the weir by up to about 0.06m; the largest reduction is immediately upstream of the weir. However, there is little or no reduction in water levels downstream; there would be up to 0.04m increase in water level for 2065 and up to 0.02m increase in water level for 2115. Would have no impact on Feeder Canal water level.
- Pre-lowering the harbour water levels has no significant impact on maximum water levels in the Avon. Would reduce the Feeder Canal water level by 0.32m in 2030 and by 0.06m in 2065 but has no impact in 2115.

Following review and discussion of the results presented within this chapter, BCC confirmed that Option 1a: ‘Raised defences only’ should be taken as the preferred fluvial option and that Option 1c: ‘Raised defences and pre-lowering harbour’ should also be taken forward as an ‘alternative fluvial option’.

5.4 Tidal barrier testing

A tidal barrier was considered at Nibley, which was identified as the least-cost potentially feasible tidal barrier in the AECOM study. The barrier geometry was taken from the AECOM concept design presented in Figure 21 of the Preferred Option Report (Final v4 Apr-17) which is based on three radial gates: two 20m wide and one 10m wide. Logical rules were set up in the model by Arup to closely match the manual tidal barrier operation described in the AECOM reporting.

The following options were tested for the 1:100yr fluvial event and the 1:200yr tidal event with ‘glass-wall’ defences along the proposed defence alignment:

- Option 2a: Raised defences + No Barrier. This is the same as option 1a: ‘Raised defences only’ from Section 5.3.
- Option 2b: Raised defences + Barrier constructed in 2030.
- Option 2c: Raised defences + Barrier constructed in 2030 or 2065. Note the construction in 2065 option is effectively the same as option 2b for 2065 and 2115 epochs and therefore Option 2c is represented using Option

2a for present day climate and 2030 and using Option 2b for 2065 and 2115.

- Option 2d: Raised defences with Floating Harbour water level pre-lowered by 0.5m + Barrier constructed in 2030.

The model results showed:

- A tidal barrier could provide a significant reduction in maximum Avon water levels downstream of Netham for tidal events: up to 0.85m for 2030 and up to 1.2m for 2115.
- A tidal barrier would provide only marginal reductions in water level downstream of Brunel Lock Dam for a fluvial event in 2115. For fluvial events in 2030 and 2065, the tidal barrier increases water levels due to high fluvial flows quickly building up behind the barrier.
- Tidal events cause higher water levels than fluvial events in the River Avon downstream of Netham. Taking into account both fluvial and tidal events, results show that a tidal barrier could reduce defence levels by up to 0.8m for 2030 and 2065 and by up to 1.0m for 2115.
- A tidal barrier could reduce water levels by about 0.5m at St Philips Marsh.
- For the tidal barrier option, pre-lowering the harbour water level has no significant impact (less than 0.01m) on maximum water levels in the Avon. Based on this, it was agreed that the option to pre-lower the harbour water level should not be taken forward in the Strategy modelling.

The model results demonstrated that the construction of a tidal barrier in a future phase could reduce future defence height requirements. However, even with a tidal barrier, raised defences would still be required in the city. The initial work on the Strategy undertaken by AECOM identified that the Present Value costs for a tidal barrier alone would be almost five times the cost of raised defences required assuming no tidal barrier. BCC confirmed there remained uncertainty regarding whether a tidal barrier could be included within the Strategy as a potential ‘add-on’ / decision pathway. As such, it was agreed that the BTQ project team should consider the possibility of a tidal barrier when assessing residual flood risk to their strategic growth and regeneration area. However, for the Strategy, it was agreed that that the barrier should not be taken forward in the modelling and that the preferred option is Option 1a: ‘Raised defences only’.

5.5 Phasing of interventions

Model results from the fluvial options testing, tidal barrier options testing and the ‘glass-wall’ simulations undertaken using NPPF climate change allowances for the BTQ project (see Section 6.1) were reviewed to understand the influence of phasing of interventions. The outcomes of this work are summarised below. More detail can be found in Chapter 5 of the ‘Hydraulic modelling to support Bristol Temple Quarter project’ report¹².

The initial work on the Strategy undertaken by AECOM proposed three phases of construction:

- 2020s: Construct most defences.
- 2030s – 2060s: Construct additional defences.
- 2060s: Raise defences.

Review of the updated modelling by Arup identified that the vast majority of defences would need to be constructed in the first intervention (Figure 6).

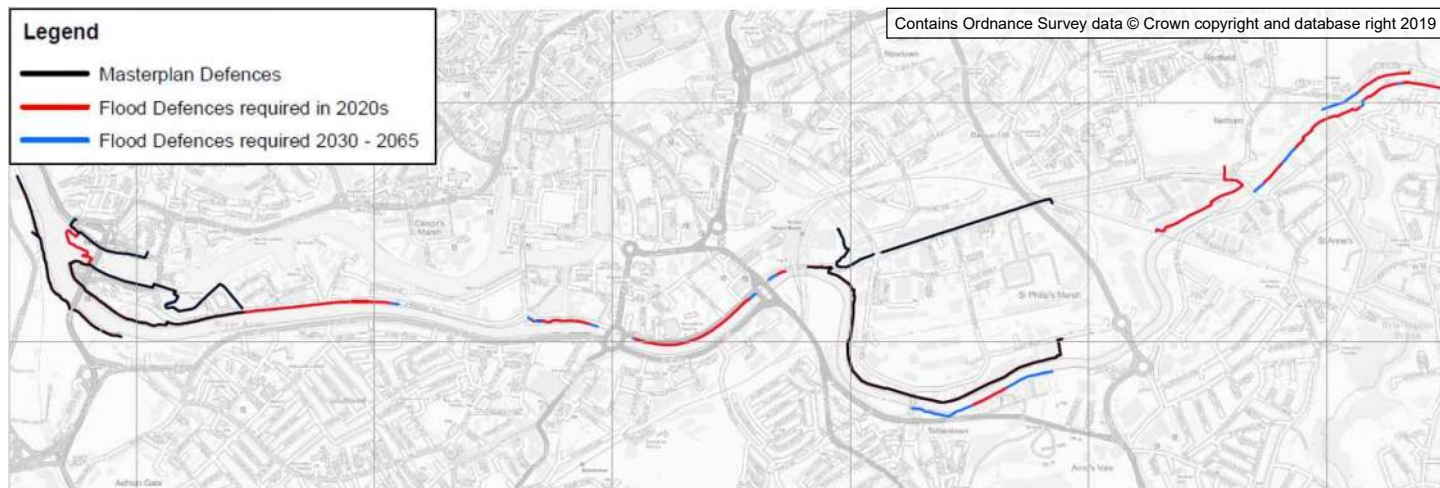


Figure 6: Defences required assuming AECOM phasing based on analysis of Arup results. Note ‘Masterplan defences’ required in 2020s. Note defences around Cumberland Basin and the Floating Harbour are not proposed as part of the Strategy.

The Avon raised defence levels required for the non-masterplan defences, which will be constructed and then raised in a later phase, are shown in Figure 7. The figure shows results for 2065 and 2115 for both, with and without a tidal barrier. Note that 2065 defence levels would be the same for both options as the barrier would not be built before then. Following the options testing stage, it was agreed that the barrier should not be taken forward in the modelling for the Strategy and that the preferred option is Option 1a: ‘Raised defences only’.

Figure 7 also includes the equivalent defence level that would be required for 2030 for comparison and to help understand the impact on defence level of having an earlier raising phase instead of or in addition to the 2065 raising phase. Given the first phase construction is not anticipated until the 2020s, raising of these defences would likely not occur until at least 2045. The plot shows that there is a relatively modest increase in water levels of about 0.3m between 2030 and 2065 and an even smaller increase can be expected between 2045 and 2065. This suggests that there would be little benefit in including an additional raising phase before the 2060s if the 2060s raising stage is retained. It was therefore agreed that subsequent modelling should assume only two phases of construction:

- 2020s: Construct defences.
- 2060s: Raise defences.

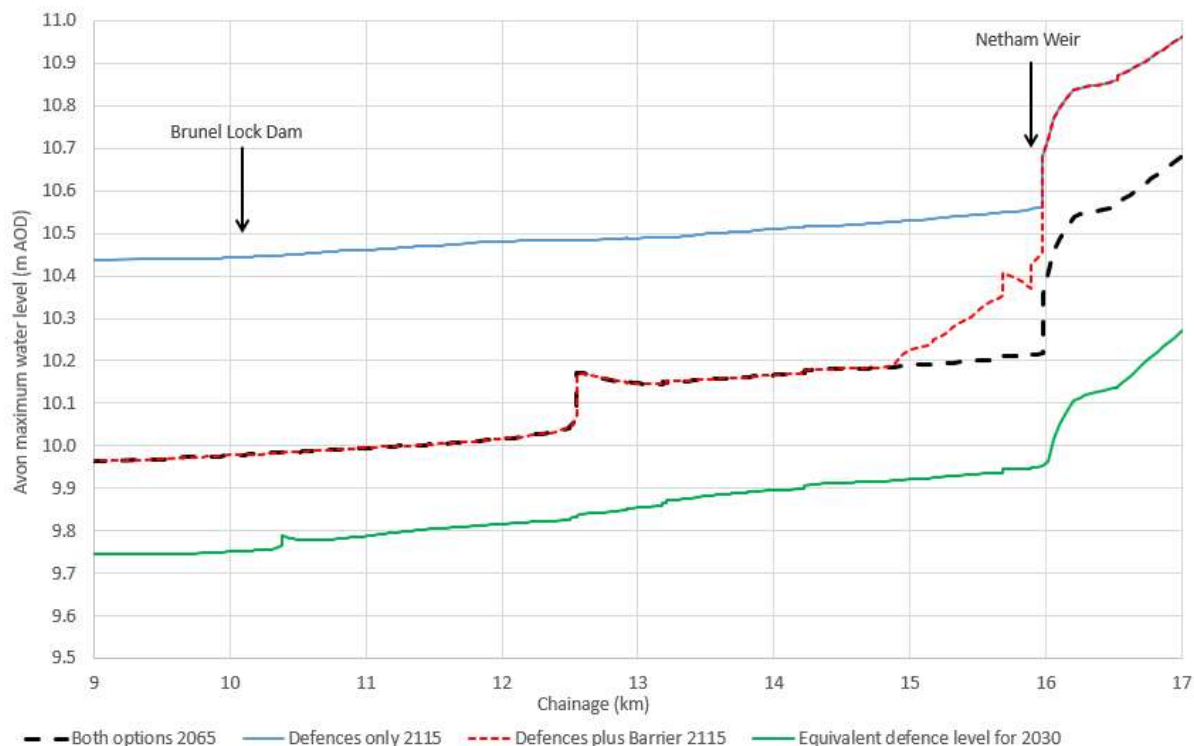


Figure 7: Defence level including 300mm freeboard for 2065 and 2115 based on FCERM climate change allowances for non-masterplan defences (with equivalent defence level for 2030 for comparison).

5.6 Control of Floating Harbour water levels

In parallel with the detriment assessment stage (Chapter 7), a review of the operation of lock gates and sluices to control the Floating Harbour water levels was undertaken¹³.

The baseline modelling assumes the Underfall Sluices are fully operational and that the Netham Lock, Entrance Lock and Junction Lock gates remain closed for the duration of flood events. For fluvially dominated events (which are combined with smaller tidal events), the permanently closed lock gates impound fluvial flows in the Floating Harbour originating from the River Frome.

The review and the associated model tests that were carried out identified a preferred approach for managing water levels in the Floating Harbour during fluvial events. The modelling is based on a controllable sluice-like structure, which demonstrated the principle would achieve the required level of control and outflow. The configuration and design of the infrastructure required to control water levels should be developed in subsequent studies as the Strategy option is developed.

¹³ Bristol FRM Strategy, File Note: Representation of the lock gates in the hydraulic model, Arup, 25/11/2019.

The proposed gate / sluice operation that was incorporated into the preferred option model was agreed with BCC and the EA. This enables the lock gates / sluices to open to release fluvial flows from the Floating Harbour when tidal conditions allow. The agreed operation is as follows:

- Lock gates / sluice gates at Entrance Lock and Junction Lock: These start to open 30 minutes after the trigger conditions are met, i.e. it is assumed that there will need to be a 30-minute lead time to mobilise. The sluices / gates take approximately 15 minutes to fully open. The trigger conditions that must both be met for the gates to open are a) water level in the Floating Harbour exceeds 7.0m AOD and b) water level in Floating Harbour exceeds the River Avon water level at Entrance Lock. The gates are set to close when the water level in the Floating Harbour drops to 6.2m AOD.
- Netham Lock gate: does not require opening during fluvial events as upstream river water levels are higher than the water level in the Floating Harbour for all events modelled.

6 Support to strategic growth and regeneration area studies

In parallel with the Strategy, BCC is developing high level proposals for the Bristol Temple Quarter (BTQ) strategic growth and regeneration area. Hydraulic modelling was undertaken to support the BTQ project and the Western Harbour strategic growth and regeneration area by assessing:

- a) scale of precautionary raised defences to meet NPPF requirements for development: this was used to assist in the design of the BTQ layout.
- b) residual flood risk: this was used to assist in the design of the BTQ layout and alignment of emergency access and egress routes.

This chapter gives an overview of the above. More information, including model results, can be found in the ‘Hydraulic modelling to support Bristol Temple Quarter project’ report¹².

6.1 Scale of precautionary raised defences

The scale of precautionary raised defences for the strategic growth and regeneration areas was determined based on the following assumptions:

- The (SoP) assumed is 1:100yr for fluvial events and 1:200yr for tidal events. These return periods have been selected as they are the basis for Flood Zone 3 and represent the minimum design standard that would be required for new development to meet NPPF requirements if other mitigation such as ground raising was not undertaken. The optimum SoP will be subsequently determined using the Environment Agency’s standard FCERM economic appraisal and decision rule guidance which may demonstrate that funding for a lower or a higher standard of protection could be justified.
- NPPF climate change allowances for FRAs (as opposed to FCERM allowances).
- Other mitigation such as ground raising is not undertaken.
- 300mm freeboard allowance.
- Defences to be constructed in the 2020s to their full height, i.e. they would not need to be raised in the 2060s.

Defence levels based on the above assumptions were derived using hydraulic modelling with ‘glass-wall’ defences along the proposed defence alignment. The model was run with NPPF climate change allowances applied to fluvial flows and tidal water levels. Defence levels were derived for two options:

- Option 1: Raised defences only.
- Option 3: Raised defences + tidal barrier constructed in the 2060s.

The results from the ‘glass-wall’ model simulations confirmed that the extent of the proposed raised defences was sufficient to prevent outflanking into the strategic growth and regeneration areas.

The results determined the required defence levels for the strategic growth and regeneration areas (based on the above assumptions). The results also showed NPPF defence levels for 2115 are about 0.3m higher than the FCERM defence levels; the difference for the 2065 defence levels is less than 0.15m.

Since the modelling work to support the BTQ project was undertaken, further modelling was undertaken to derive raised defence crest levels. This is described in Chapter 9, which also includes a table of minimum defence levels required for key locations.

6.2 Residual flood risk

To demonstrate to the satisfaction of the local planning authority that a development will be safe for its lifetime taking account of the vulnerability of its users, a flood risk assessment may need to show that appropriate evacuation and flood response procedures are in place to manage the residual risk associated with an extreme flood event. Examples of residual risks that are relevant to Bristol:

- the failure of flood management infrastructure such as a breach of a raised flood defence, blockage of a surface water conveyance system, overtopping of an upstream storage area, or failure of a pumped drainage system;
- a severe flood event that exceeds a flood management design standard, such as a flood that overtops a raised flood defence, or an intense rainfall event which the drainage system cannot cope with.

Areas behind flood defences are at particular risk from rapid onset of fast-flowing and deep water flooding, with little or no warning if defences are overtopped or breached.

The residual flood risk was assessed for the BTQ strategic growth and regeneration area to assist the BTQ project team in developing the site layout, including alignment of access and egress routes.

Flood modelling was undertaken to determine the worst-case residual flood risk to the BTQ site from overtopping. It was agreed with BCC that modelling of breaches and lock gate failures would not be undertaken as this information could be obtained from the AECOM reporting and mapping.

Residual risk was assessed using a hydraulic model with defence levels set to those derived in Section 6.1 but without freeboard added. Two options were assessed:

- Option 1: Raised defences only.
- Option 3: Raised defences + tidal barrier constructed in the 2060s.

For Options 3, the EA noted that they would only be able to rely on the barrier with allowance for one gate failing open/closed. As agreed with the EA, the tidal barrier gate is assumed to fail open for tidal events and assumed to fail closed for fluvial events. Two failure scenarios are presented for fluvial and for tidal:

- Pessimistic: All three tidal barrier gates failed.
- Optimistic: Two out of the three tidal barrier gates failed. It is assumed that the two larger gates would fail.

It was agreed that modelling should be undertaken for the ‘pessimistic’ scenario and that the ‘optimistic’ scenario only requires assessment for the 2065 climate.

As specified by the EA, residual risk was assessed for:

- fluvial events up to and including the 1 in 100 chance flood event using the upper end climate change allowance or the 1 in 1000 event not including climate change (current day), whichever is higher;
- tidal events up to the 1 in 1000 event not allowing for climate change.

The model results from the residual risk scenarios are presented in Appendix D of the BTQ modelling report¹². The residual maps demonstrate that fluvial residual risk is far greater than tidal residual risk.

Observations for residual risk in 2065:

- Tidal: no flooding at BTQ for either option even with all gates failed open.
- Fluvial: flood depths > 1.2m for about half of BTQ area for Option 1 and most of BTQ area for Option 3. Flood depths are extreme for Option 3 for the pessimistic failure scenario (3/3 gates failed closed); flood depths approximately 2m higher than for Option 1. This is because fluvial flows cannot discharge until the water level upstream of the tidal barrier exceeds the top of the tidal barrier gates (10.9m AOD). For Option 3, the optimistic scenario (2/3 gates failed closed) would result in significantly lower flood depths compare to the pessimistic scenario with flood depths only about 0.5m higher than for Option 1.

Observations for residual risk in 2115:

- Tidal: flood depths > 1.2m for a relatively small proportion of BTQ area for Option 1; Option 3 results in a greater extent of flooding over 1.2m deep compared to Option 1.
- Fluvial: Similar pattern of flooding as in 2065 but greater in extent and depth.
- The main fluvial flooding mechanism to BTQ is from the River Avon overtopping Netham Lock into Feeder Canal, which then overtops the proposed Feeder Road defence.

7 Detriment assessment

For the scheme proposals to be consented, it must be demonstrated that any increase in flood risk to properties caused by the proposals (detriment) can be managed. A detriment assessment of the preferred option was undertaken, which identified areas where detriment affects properties, including areas upstream and downstream of Bristol, if no mitigation action is taken. This is summarised below. More details can be found in the ‘Detriment mitigation option development’ report¹⁴ and the ‘Detriment assessment note’¹⁵.

7.1 Criteria for detriment assessment and mitigation

Detriment is defined as the increase in water levels and flood depths caused by the proposals, compared against the baseline Do Minimum option, which represents the existing situation.

The following criteria were agreed with BCC and the EA:

- a) A figure of 25mm should be used as the threshold for classifying any increase of flood water level due to the proposed raised defences as this is considered indicative of the tolerance of the hydraulic model results.
- b) Detriment must be mitigated for return periods up to the design standard, e.g. if the proposed scheme has a 1:100yr SoP then detriment must be mitigated for flood event magnitudes up to and including the 1:100yr event. Detriment mitigation is not required for flood event magnitudes that exceed the SoP.
- c) Detriment should be assessed for a range of return periods for fluvially dominated and tidally dominated events.
- d) Detriment should be assessed and mitigated for present day and future climate up to 2125 based on NPPF climate change allowances.
- e) Detriment to properties (buildings only) and key transport infrastructure (active rail lines and the resilient road network) requires mitigation to achieve the above criteria.

7.2 Option assumptions

The modelling assumptions used for the raised defences option for the assessment of detriment (without detriment mitigation) are the same as the key assumptions used for options testing (given in Section 5.1) with the addition of:

- 1) The alignment of raised defences used in the detriment assessment modelling is shown in Figure 5. Note the defences shown around the Floating Harbour and Cumberland Basin are not included in the proposed strategy option but are included in the detriment assessment and detriment

¹⁴ Bristol FRM Strategy, Report: Detriment mitigation option development, Arup, 24/06/2020.

¹⁵ Bristol FRM Strategy, File Note: Detriment assessment, Arup, 11/11/2019.

mitigation modelling to provide an indicative worst case for displacement of floodwaters and resultant detriment.

- 2) The SoP assumed in the detriment mitigation option modelling is 1:100yr for fluvial and 1:200yr for tidal events. The scale/timing of detriment mitigation works will depend on the SoP selected for the city centre and this SoP has not yet been determined at the time of writing.
- 3) Control of Floating Harbour water levels to discharge fluvial flows as per the assumptions given in Section 5.5.

7.3 Areas of detriment identified

The results of the detriment assessment are presented as a series of detriment maps that are included as an appendix to the detriment mitigation option development report¹⁴.

The detriment assessment showed the areas of detriment listed below and shown in Figure 8.

- A. Most of the harbourside, city and St Philips Marsh in 1:1000yr fluvial events. The preferred option has been amended since the issue of the November 2019 detriment assessment note¹⁵ to include gate / sluice operation to discharge flows from the Floating Harbour during fluvial events (see Section 5.5). **As a result, there is no longer detriment in these areas.**
- B. Off left bank of the Avon, adjacent to the Malago in 2125 1:200yr tidal event. There is no detriment here in 2065, so the measures to mitigate this would not need to be constructed until at least 2065.
- C. Off left bank of the Avon, just upstream of St Philips Causeway in 2125 1:200yr tidal event. There is no detriment here in 2065, so the measures to mitigate this would not need to be constructed until at least 2065.
- D. At the downstream end of Brislington Brook and associated floodplain for all events except 2125 1:1000yr tidal event. Detriment in this area is associated with the proposed defences from the date of construction, therefore, measures to mitigate this detriment would require constructing mitigation measures at the same time as the raised defences (2020s).
- E. Downstream of Bristol city centre, at Sea Mills, Shirehampton and Pill. The detriment assessment results for 2030 fluvial 1:100yr and tidal 1:200yr events show that detriment occurs in 2030 at Sea Mills and the eastern part of Shirehampton but not at Pill. The detriment assessment results for 2065 fluvial 1:100yr and tidal 1:200yr events show that detriment occurs in 2065 at Sea Mills, Shirehampton and the eastern part of Pill, near Watch House Road and Underbanks. Therefore, detriment mitigation measures for Sea Mills, Shirehampton and the eastern edge of Pill would require constructing at the same time as the raised defences (2020s). The detriment mitigation measures for the rest of Pill would not need to be constructed until at least 2065. Worst case detriment appears to

be for the 2125 Tidal 1:100yr event. From the mapping and LiDAR, rough estimates of numbers of properties affected are given below:

- a. Sea Mills: about 10 properties affected by up to 0.15m.
 - b. Shirehampton: about 50 properties affected by up to 0.08m.
 - c. Pill: about 100 properties affected by up to 0.08m.
 - d. The impact at Shirehampton and Pill is generally less than 0.03m for other events.
- F. Upstream of Netham, detriment occurs as far as Swineford. Note that Figure 8 only includes the main area of detriment as far upstream as the A4174 road as the model is 1d upstream of here and results are not accurate. However, the 1d model results suggest there are about 10 to 20 properties affected between Kingswood and Keynsham which are affected by between 0.1 and 0.25m for the tidal 1:200yr and fluvial 1:100yr events. The area around Keynsham is affected by up to about 0.1m which would likely affect in the order of 50 properties. Detriment in this area is predicted to occur immediately after construction of raised defences and therefore measures to mitigate this detriment would require constructing at the same time as the raised defences (2020s).

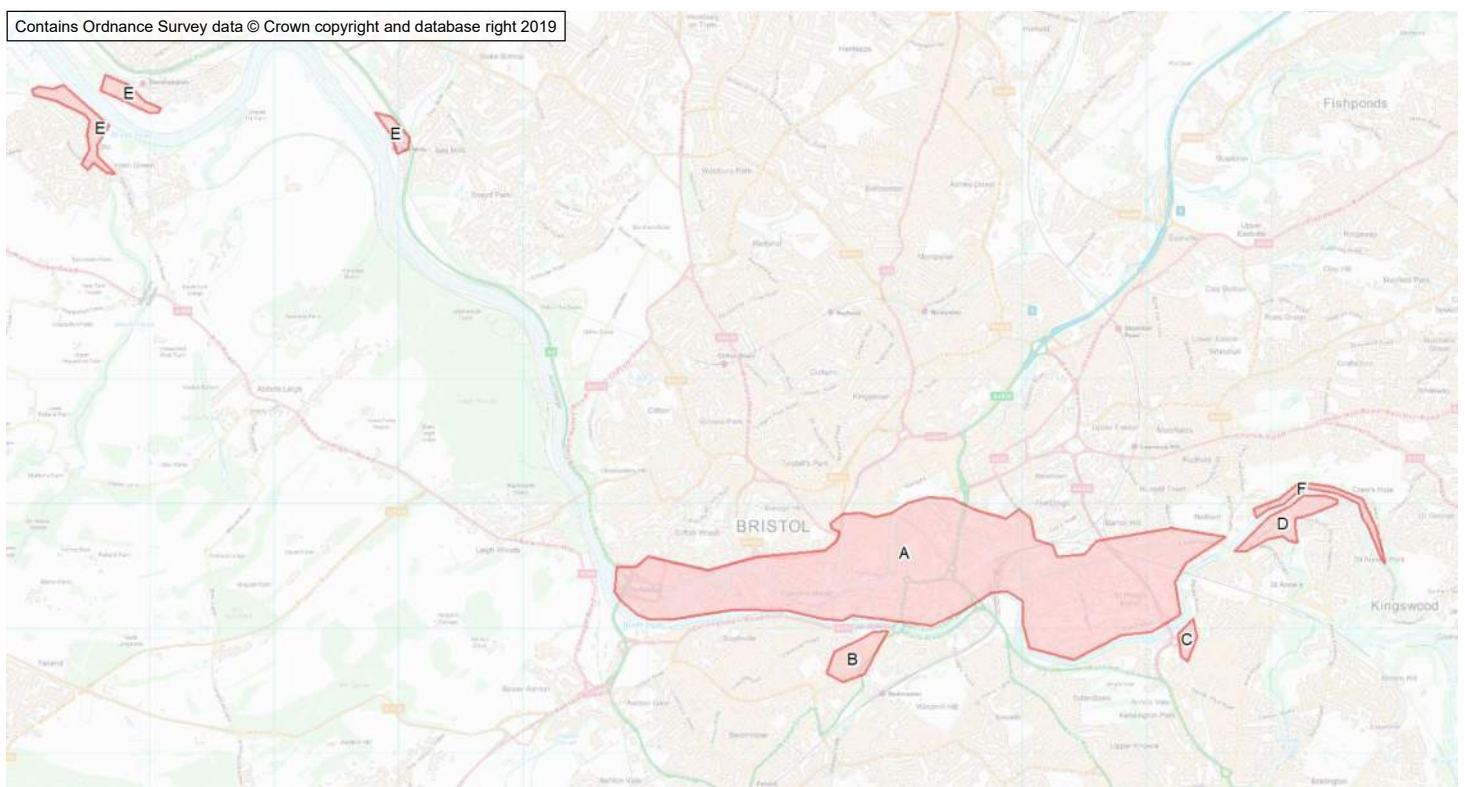


Figure 8: Main areas of detriment downstream of the A4174 road.

7.4 Detriment to resilient road network:

The detriment assessment for the preferred option (without detriment mitigation) identified the following sections of the BCC resilient road network to be at detriment:

- Sections of Hotwell Road / Portway between Cumberland Basin and Sea Mills: BCC confirmed that the detriment criteria given in Section 7.1 can be relaxed here and that no mitigation is required. This is because the Portway is undefended and assumed to be non-operational during extreme events. BCC are separately promoting measure to reduce overtopping of the Portway during more frequent events.
- Netham Road Bridge (Figure 9): BCC confirmed that the detriment criteria given in Section 7.1 can be relaxed here and that no mitigation is required as this is a river crossing and mitigation is not feasible without prohibitively costly/impactful replacement of bridge.
- St Anne’s Road (Figure 9): It was agreed that the detriment to this section of resilient road network should be mitigated.

Detriment assessment showed there is no detriment to any A-Roads within Bath and North East Somerset Council’s area.

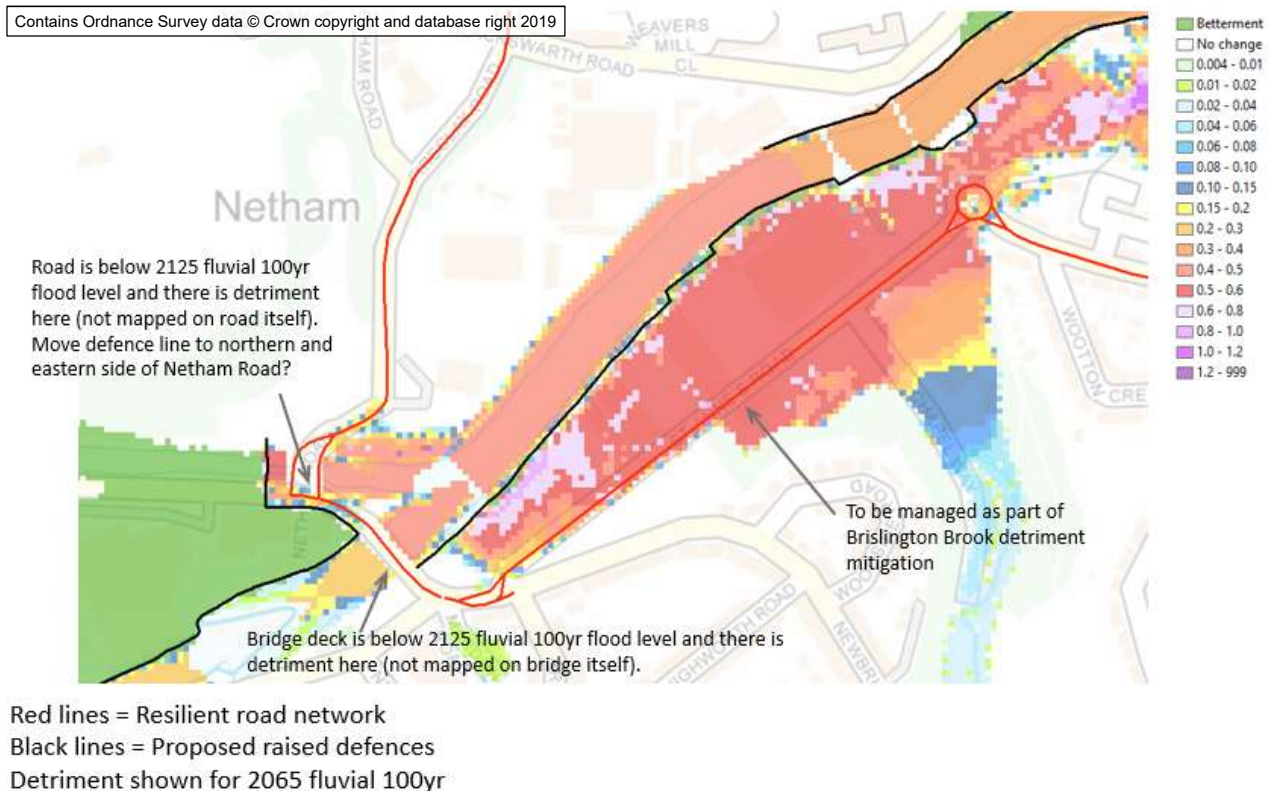


Figure 9: Detriment to Bristol City Council resilient road network at Netham Road Bridge and St Anne’s Road.

8 Detriment mitigation options development

Possible detriment mitigation measures have been identified, developed and tested using the hydraulic model. The outcome of this work has been a list of recommended detriment mitigation measures and timing, and recommendations for future study to reduce uncertainties associated with these. This is summarised below. More details can be found in the ‘Detriment mitigation option development’ report¹⁴.

8.1 Approach

The effectiveness of potential mitigation measures was tested using the hydraulic model. This was undertaken by incorporating one or more detriment mitigation measures into the raised defences option model. The raised defences option model assumptions used for detriment assessment and detriment mitigation tests are given in Chapter 7.

The detriment mitigation work has mainly focused on the central area of Bristol, but also considers areas downstream (Shirehampton, Sea Mills and Pill) and upstream as far as the A4174 main road¹⁶. Individual interventions and combinations of measures were investigated and tested using the model.

The criteria for detriment mitigation (see Section 7.1) was applied to determine whether detriment mitigation measures achieved the required level of mitigation and to develop and prioritise detriment mitigation options.

8.2 Recommended detriment mitigation measures

The selection of the measures to be adopted in the SOC was discussed with BCC in a meeting on 19/02/2020 and this reflects the recommendations summarised below in Table 7 and Figure 10, Figure 11 and Figure 12. Note 2020s signifies construction is required at the same time as the first phase of construction of the scheme raised defences.

Table 7: Recommended detriment mitigation measures and timing. Note height and level of detriment mitigation raised defences will depend on the SoP selected for the scheme.

No.	Measure	Anticipated required construction date
1	100m Avon left bank raised defence near Malago.	2065
2	100m Avon left bank raised defence u/s of St Philips Causeway.	2065
6d	Netham left bank raised defence to NPPF levels and realign around Brislington Brook. Note: slightly lower levels would be required if the Chapel Way defence is constructed higher than 13.4m AOD.	2020s and then raised in 2065

¹⁶ Detriment and mitigation measures were also ascertained upstream of the A4174, however, the work is only preliminary, as the hydraulic model in this area is 1D only.

11	Chapel Way raised defence to reduce Brislington Brook overland flow. Crest level required is approx. 13.4m AOD.	2020s
14	Raised defence on right bank of Avon at Crew's Hole.	Downstream half: 2020s and then raised in 2065. Upstream half: possibly 2065 (threshold survey required to confirm).
17	Upstream detriment mitigation (raised defences). These are shown in Figure 12.	2020s and then raised in 2065
13	Downstream detriment mitigation (raised defences) at Shirehampton, Sea Mills and eastern end of Pill (Watch House Road and possibly Underbanks Road). These are shown in Figure 11.	2020s and then raised in 2065
13	Downstream detriment mitigation (raised defences) at most parts of Pill. These are shown in Figure 11.	2065
18	Extended and raised Avon right bank at Netham.	2020s and then raised in 2065
20	Enlargement of Brislington Boat Screen culvert inlet (increasing effective width from 1.22 to 1.98m).	2020s likely
21	Flood storage on Malago at 'Marksbury Open Space'. Details to be developed in future studies but for now assume 10.5m AOD invert level for storage area over the area shown with bank level lowered to 10.85m AOD.	2065
22	120m Malago left bank raising upstream of Parson Street. Details to be developed in future studies but for now assume 0.75m raising is required.	2065

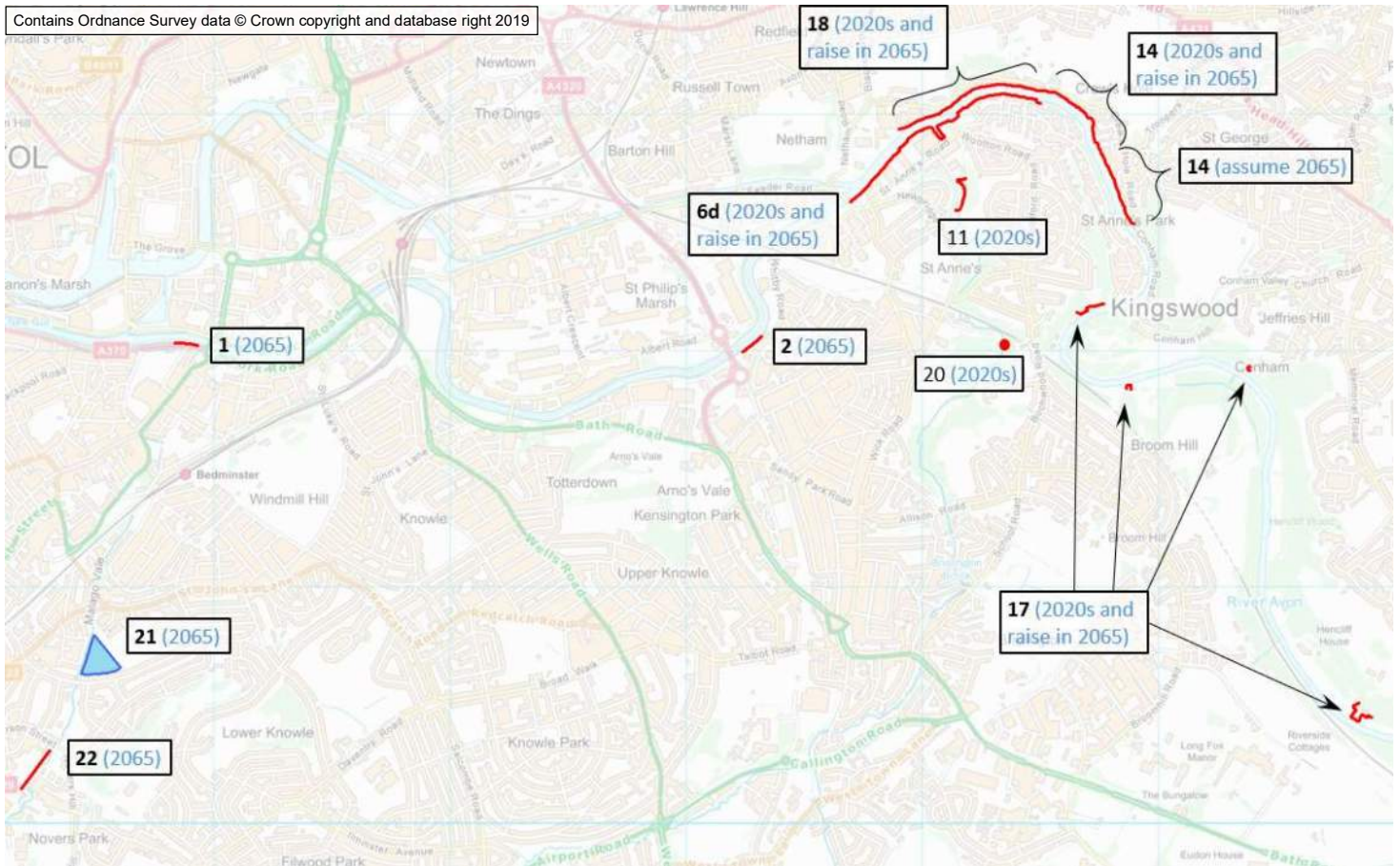


Figure 10: Detriment mitigation measures in Bristol and assumed construction phasing. Refer to Table 7 for more information. Note scheme defences that are not required for detriment mitigation are not shown.

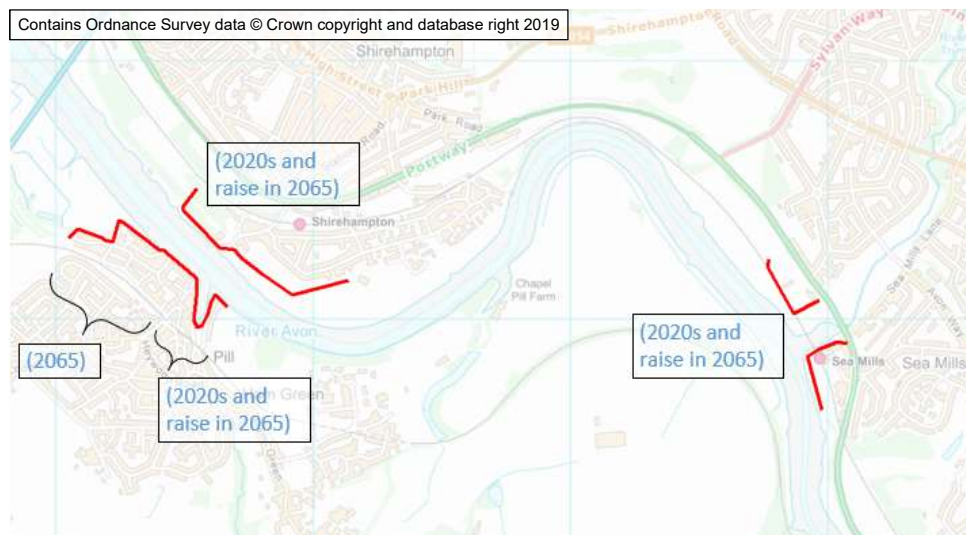


Figure 11: Detriment mitigation measures downstream of Bristol and assumed construction phasing. These correspond to detriment mitigation measure 13 in Table 7.

8.3 Mitigation of upstream detriment

Detriment extends upstream as far as Swineford. Possible detriment mitigation measures have been identified upstream of the A4174 main road as far as Swineford (Figure 12). However, these fall outside of the 2d model domain and therefore the effectiveness and flood risk impact of these measures cannot be accurately tested within the current Bristol FRM Strategy hydraulic model. It was therefore agreed that the modelling of these measures should be excluded from the current scope of the SOC but that the development and testing of these measures should be undertaken in future stages of the project, potentially at OBC stage.

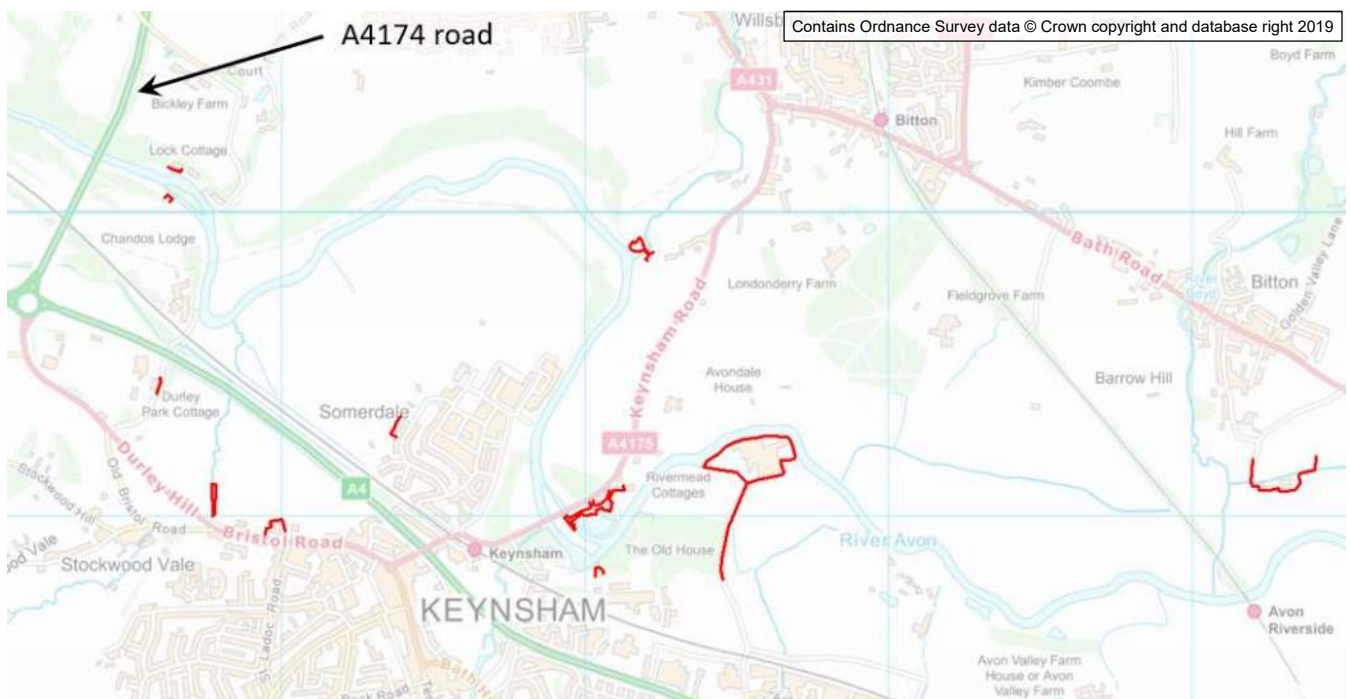


Figure 12: Possible detriment mitigation measures upstream of the A4174 road required in 2020s. These correspond to detriment mitigation measure 17 in Table 7

8.4 Consideration of surface water

The hydraulic model used for the Strategy represents flooding from the main rivers but excludes:

- ordinary watercourses (non-main river);
- surface water flooding arising directly from rainfall before the water gets into watercourses;
- the below ground surface urban drainage network or the flooding that may arise from this.

Given these limitations, there is uncertainty if and how the proposed scheme and/or the increases in River Avon water levels as a result of the proposed scheme, would affect surface water flood risk associated with urban drainage systems and ordinary watercourses that discharge into the Avon.

Given the fluvial response of the Avon is much slower than that of surface water flooding, the flood peaks for the two sources of flooding are likely to be significantly desynchronised with the fluvial peak occurring significant later than the surface water flood peak.

It is possible that there will not be any detriment >25mm on ordinary watercourses and drains that have flapped outfalls, e.g. the detriment maps show no detriment for Colliters Brook, which is included in the hydraulic model. This is because the increase in River Avon water levels does not cause a material increase in the duration that the outfall is locked closed by River Avon water levels.

The EA national ‘Risk of Flooding from Surface Water’ (RoFfSW) mapping dataset provides information on surface water flood depths for the 1 in 30yr, 1 in 100yr and 1 in 1000yr present day rainfall events. The data is derived from national scale surface water modelling supplemented with data from more detailed local models where available. For Bristol, the data has been supplemented with outputs from the Bristol Surface Water Management Plan (SWMP) integrated modelling from 2011, which includes representation of the subsurface drainage and overland flow. Example RoFfSW mapping for the 1 in 100yr surface water flood event is shown against the Do Minimum 2030 1 in 100yr fluvially dominated event at Netham (Figure 13). This shows there is significantly more fluvial flooding than surface water flooding here. Assuming a scheme SoP of at least 1 in 100yrs, the scheme would significantly reduce the maximum combined extent of surface water and fluvial flooding. However, for some events in future epochs, this will be more marginal.

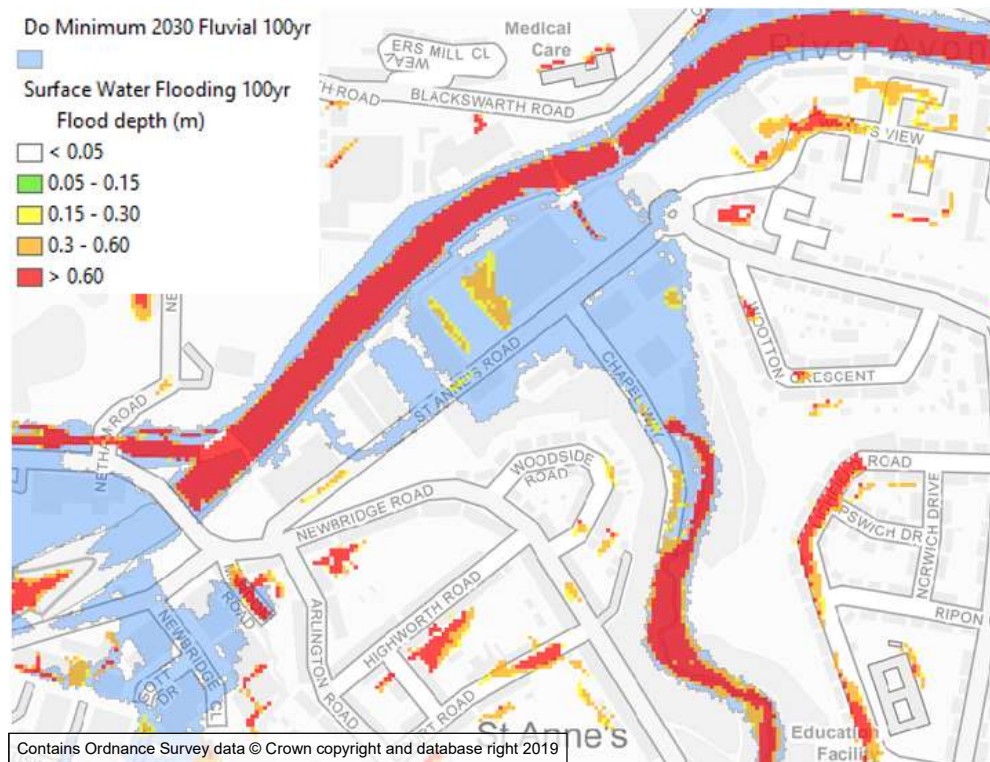


Figure 13: EA National Surface Water flood map depths for 1 in 100yr event vs Do Minimum 2030 1 in 100yr fluvial outline.

It is recommended that future stages consider the potential impact of the scheme and the scheme detriment on surface water flood risk taking into account the relative timing of fluvial, tidal and surface water flood peaks. Future work should consider using existing surface water modelling outputs and assess the need for undertaking new surface water modelling, possibly integrated with the river model. Existing model outputs include the RoFfSW and more recent modelling undertaken by JBA for the updated SWMP¹⁷ which has not yet been incorporated into the EA national surface water mapping dataset. Synergies should be sought through ongoing partnership projects such as with Wessex Water at Ashton.

Note that surface water (pluvial) flood risk is considered within the economic analysis based on the EA national surface water flood mapping dataset. The economic analysis is reported separately – please refer to the SOC report and relevant appendices for more information.

8.5 Recommendations

It is recommended that future stages of the project undertake further studies to reduce uncertainty in the following areas:

- Brislington Brook culvert: It is recommended that future studies review drainage plans to determine whether there are any connections to the culvert and the feasibility of diverting these.
- Crew's Hole Road: The existing LiDAR data suggests that flooding to many of these properties is marginal, particularly for 2065. It is therefore recommended that threshold survey is undertaken in future studies to reduce uncertainty in required defence alignment here and the associated costs. Refining the alignment of the defence, e.g. set-back where ground levels are higher, subject to constraints, should be considered in later stages of the Strategy to reduce visual impact and costs.
- New housing estate adjacent to the Malago at Malago Drive: There is significant uncertainty in the predicted detriment here due to the new housing estate and therefore the mitigation options should be treated as indicative only and further refinement is not recommended until the new housing estate has been incorporated into the flood model. Updating the model to incorporate the new housing estate is recommended for future stages of the project to reduce uncertainty of detriment and associated mitigation measures. It is assumed that 'Marksbury Open Space' can be used for flood storage; this should be reviewed in future studies.
- Surface water: There is uncertainty if and how the proposed scheme and/or the increases in River Avon water levels as a result of the proposed scheme, would affect surface water flood risk associated with urban drainage systems and ordinary watercourses that discharge into the Avon. It is recommended that future stages consider the potential impact of the scheme and the scheme detriment on surface water flood risk taking into account the relative timing of fluvial, tidal and surface water flood peaks. Use of existing surface water modelling and mapping datasets should be

¹⁷ Bristol SWMP Model - Review and Update - Phase 2, JBA Consulting, September 2018.

considered and the need for new surface water modelling should be assessed.

- Undertake more detailed modelling to assess detriment and develop detriment mitigation options upstream of the A4174 road, which is only modelled in 1d in the current Strategy modelling. This could potentially use the Environment Agency's 1d-2d model of the River Avon from Bath to Bristol developed by Capita AECOM.

9 Derivation of defence level

Crest levels for proposed raised defences are required for developing the outline design and for costing the proposed interventions. Crest levels have been derived for:

- the first intervention to be constructed in the 2020s, which will be raised defences high enough to sustain the design standard until the 2060s (taken as 2065 in the modelling);
- the second intervention to be constructed in the 2060s (taken to be 2065 in the modelling), which raise defences high enough to sustain the design standard until 2125;
- the 75yr SoP, 100yr SoP and 200yr SoP to enable application of the decision rule in the economic assessment;
- FCERM requirements and NPPF requirements.

Crest levels were derived using a ‘glass-wall’ version of the model with the proposed raised defences set artificially high to prevent overtopping.

9.1 Raised defences option assumptions

The following modelling assumptions have been used for the modelling used to derive defence levels:

- Proposed raised defences (see Figure 5) are included except for the precautionary raised defences around the Floating Harbour and Cumberland Basin. Note the proposed raised Entrance Lock gate is included.
- The recommended detriment mitigation measures (Table 7) are included.
- Proposed lock / sluice gate operation for controlling the Floating Harbour water levels (see Section 5.6).

The proposed raised defences and detriment mitigation measures in Bristol assumed in the flood damage modelling in Bristol are shown in Figure 14.

The presence of the proposed detriment mitigation raised defences downstream of Bristol at Pill, Shirehampton and Sea Mills (see Figure 11) were represented in the model by removing the floodplain areas from the adjacent cross-sections.

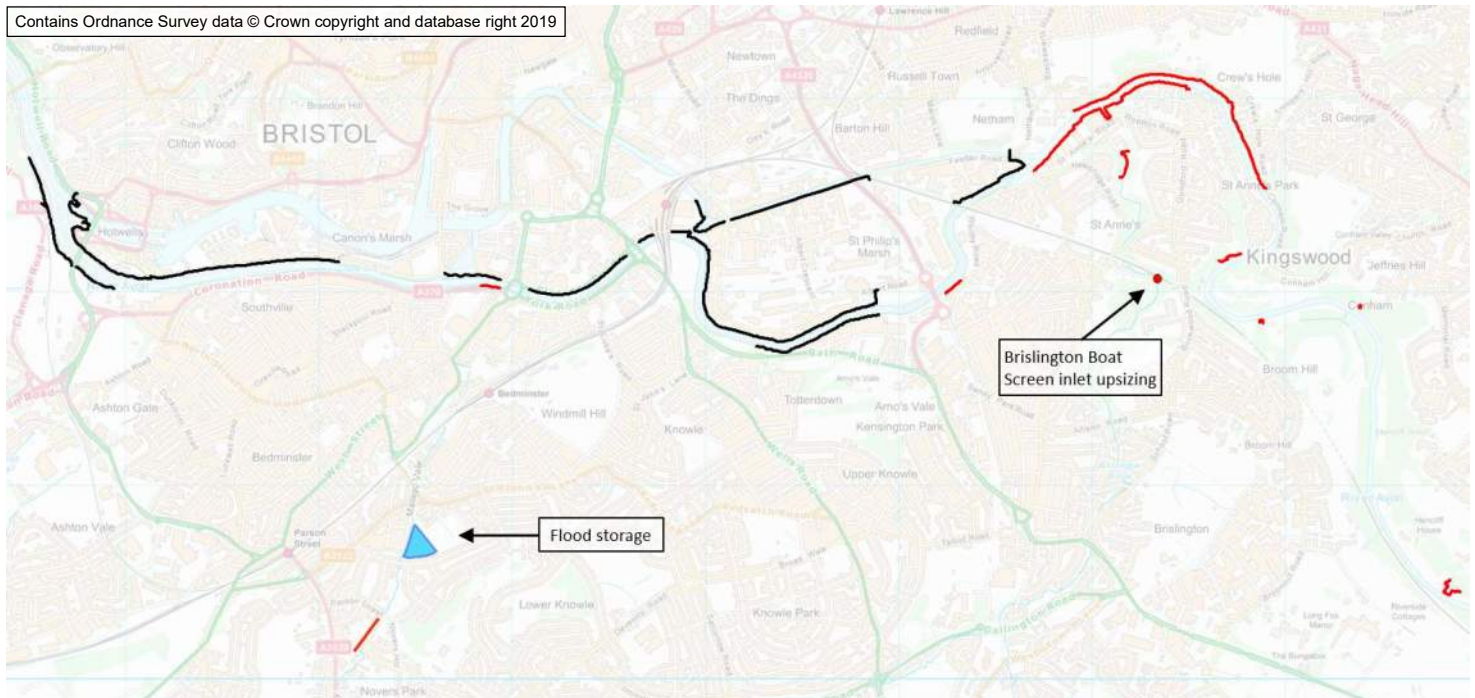


Figure 14: Raised defences (black) and detriment mitigation measures (red and blue) assumed in the flood damage modelling.

9.2 Flood events simulated

The 24 model simulations undertaken to derive defence levels are listed in Table 8. Water level results for the River Avon and the Feeder Canal were extracted to determine the design crest levels. A freeboard of 300mm has been used for setting the design crest levels in the Strategy for all defences except those that function as detriment mitigation measures (which are to be based on NPPF allowances). The 300mm freeboard value should be refined as the design is developed and as uncertainties in the modelling are reduced.

Table 8: Model simulations undertaken to derive defence levels.

Return period	Type of flood event	FCERM allowances		NPPF allowances	
		2065	2125	2065	2125
75yr	Fluvially dominated	✓	✓	✓	✓
	Tidally dominated	✓	✓	✓	✓
100yr	Fluvially dominated	✓	✓	✓	✓
	Tidally dominated	✓	✓	✓	✓
200yr	Fluvially dominated	✓	✓	✓	✓
	Tidally dominated	✓	✓	✓	✓

The initial results for the NPPF 2125 200yr fluvially dominated event showed detriment mitigation raised defence on the left bank of the Avon at Netham outflanked at the upstream end at Pilgrims Wharf causing some detriment here. The detriment mitigation raised defence would therefore need to be extended by approximately 110m upstream adjacent to Pilgrims Wharf for the 200yr SoP to

prevent this detriment. The model was updated to include this extension to the raised defence (Figure 15).

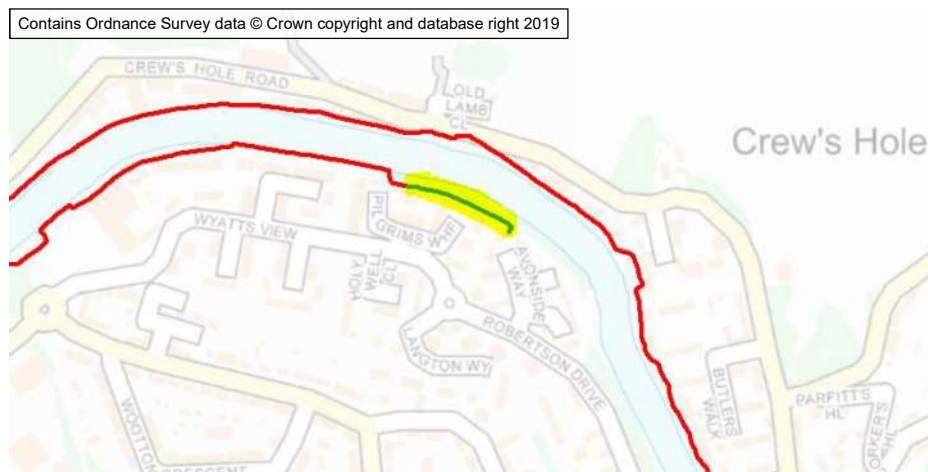


Figure 15: Extension to detriment mitigation raised defence at Netham required for the 200yr SoP (highlighted yellow).

9.3 Defence levels

The minimum required defence levels, including 300mm freeboard, are given in Table 9 for a selection of locations. These are given for:

- FCERM allowances for each SoP assessed; and
- NPPF allowances based on the fluvial 1:100yr and tidal 1:200yr events which represent the minimum design standard that would be required for new development to meet NPPF requirements if other mitigation such as ground raising was not undertaken.

Table 9: Minimum defence levels, including 300mm freeboard for defences excluding those that function as detriment mitigation measures.

Location	FCERM 75yr SoP		FCERM 100yr SoP		FCERM 200yr SoP		NPPF F100 & T200 SoP	
	2065	2125	2065	2125	2065	2125	2065	2125
New Brislington Bridge	10.30	10.74	10.38	10.84	10.67	11.11	10.52	11.17
Railway Bridge	10.03	10.50	10.09	10.58	10.33	10.76	10.28	11.00
St Philips Causeway	9.86	10.36	9.90	10.43	10.23	10.72	10.26	11.00
Totterdown Road Bridge	9.77	10.25	9.81	10.30	10.21	10.70	10.24	11.00
Cattel Market Railway Br	9.77	10.28	9.81	10.33	10.19	10.67	10.22	10.97
Bedminster Road Bridge	9.81	10.33	9.85	10.38	10.23	10.68	10.30	10.97
Vauxhall Footbridge	9.83	10.38	9.88	10.44	10.06	10.63	10.03	10.93
Ashton Avenue Foot Br	9.83	10.39	9.88	10.44	10.04	10.61	10.02	10.92
Entrance Lock	9.85	10.41	9.90	10.46	10.03	10.61	10.02	10.92
Feeder Road	8.34	8.54	8.43	8.62	8.72	9.02	8.61	8.86

The minimum required defence levels for the detriment mitigation defences are based on NPPF allowances without 300mm freeboard; these are given in Table 10 for each SoP assessed for a selection of locations adjacent to detriment mitigation defences. These levels are considered precautionary but indicative. Although detriment mitigation only needs to ensure no worsening of flood risk rather than preventing all flooding, the crest level of detriment mitigation defences would need to be set very close to the NPPF level to prevent detriment. This is because there is generally little flood storage on the landward side of the defence relative to the associated overtopping volume of the flood peak, therefore overtopping would cause the flood level to quickly rise to the river level. Modelling to optimise defence levels could be undertaken at a later stage but this is not anticipated to enable a significant reduction in defence levels.

It is important to note that in order to be able to claim the benefits (flood damages avoided) associated with the detriment mitigation defences, the crest level for the detriment mitigation defences should be set to the higher of the following two values:

- FCERM level including 300mm freeboard (from Table 9)
- NPPF level without freeboard (from Table 10)

Table 10: Minimum defence levels for detriment mitigation measures, based on NPPF allowances without freeboard.

Location	NPPF 75yr SoP		NPPF 100yr SoP		NPPF 200yr SoP	
	2065	2125	2065	2125	2065	2125
Riverside Cottages	11.16	11.60	11.28	11.77	11.62	12.22
Pump House Lane	10.73	11.25	10.85	11.38	11.17	11.72
Crew's Hole Rd (u/s)	10.58	11.13	10.69	11.25	11.02	11.59
New Brislington Bridge	10.13	10.78	10.22	10.87	10.52	11.20
St Philips Causeway	9.66	10.39	9.72	10.44	9.96	10.71
Sea Mills	9.53	10.34	9.59	10.40	9.67	10.54
Pill & Shirehampton	9.42	10.25	9.48	10.31	9.58	10.44

10 Flood damage modelling

Model simulations were undertaken to determine flood depths and flood hazard associated with overtopping. The results have been used to determine flood damages in the economic analysis for the SOC (reported separately) to calculate the benefits of each option. The option benefits and option costs are used to aid selection of a preferred option.

Flood damage simulations were undertaken for the following options, which is described in greater detail in the options appraisal report:

- Do Minimum: This represents the current situation and assumes current maintenance regime will continue into the future. This uses the baseline model described in Chapter 3.
- Do Nothing: This is a hypothetical baseline against which all other options should be compared. This option represents a ‘walk away’ scenario where all maintenance and operation of flood risk assets would cease immediately. The same assumptions are used as those agreed in earlier stages of the Strategy have been used for this option.
- Proposed raised defences 75yr SoP
- Proposed raised defences 100yr SoP
- Proposed raised defences 200yr SoP

10.1 Raised defences option assumptions

For the raised defences options, the same assumptions were used as those used to derive defence levels (see Section 9.1). The defence levels derived from the glass-wall modelling (see Chapter 9) were incorporated into the raised defences flood damage models as follows:

- For all raised defences except those that function as detriment mitigation measures (Table 7), defence levels are based on FCERM allowances throughout. This is so that the economic analysis and selection of the economically preferred option (reported separately) complies with the Treasury Green Book rules that are required when seeking Defra grant-in-aid funding. BCC can use scheme costs derived for FCERM and NPPF and for different SoPs to decide whether they wish to implement a Local Choice for a design standard that is different to the economically preferred option. Note: as NPPF defence levels have not been used in the flood damage modelling, the economic benefits of setting defences to NPPF levels as opposed to FCERM levels cannot be explicitly determined.
- For raised defences that function as detriment mitigation measures (Table 7), defence levels were set to the NPPF levels (see explanation in Section 9.3). Following the modelling work, it was identified that using NPPF levels resulted in an over-estimation of benefits claimed from the

detriment mitigation defences resulting in a very small over-estimation of the scheme-wide benefits – this is discussed in Section 10.4.

- All defence levels exclude freeboard, as required by FCERM Appraisal Guidance. The freeboard allowance is excluded from flood damage assessment because it is used in the design to manage uncertainty in modelled water levels as opposed to intentionally providing a higher design standard.

For the raised defences options, a total of 6 models were set up as follows:

Table 11: Models set up for the raised defences option for flood damage assessment.

SoP	Phase 1 model: following construction of 1 st (used for 2025 – 2065)	Phase 2 model: Following construction of 2 nd phase (used for 2065 – 2125)
75yr	✓	✓
100yr	✓	✓
200yr	✓	✓

10.2 Flood events simulated

For each option, a range of flood event magnitudes were simulated for several points in time during the 100yr appraisal period. This was required to provide sufficient detail in the flood damage assessment. A full list of simulated flood events is given in Table 12. It was agreed that 2030, which was already simulated for Do Minimum and Do Nothing options, could be used as the first point in time given its proximity to the assumed construction date of 2025 for the first phase of works.

As required by FCERM Appraisal Guidance, climate change allowances are based on FCERM guidance¹⁰ as opposed to NPPF guidance⁹.

For the raised defences options, flood events for 2065 were simulated for both the phase 1 and phase 2 models. This is to enable the flood damage assessment to accurately represent the step change in flood damages due to the phase 2 works.

Table 12: Model simulations undertaken for the flood damage assessment.

Return period	Type of flood event	2030	2045	2065	2125
20yr	Fluvially dominated	✓	✓	✓	✓
	Tidally dominated	✓	✓	✓	✓
75yr	Fluvially dominated	✓	✓	✓	✓
	Tidally dominated	✓	✓	✓	✓
100yr	Fluvially dominated	✓	✓	✓	✓
	Tidally dominated	✓	✓	✓	✓
200yr	Fluvially dominated	✓	✓	✓	✓
	Tidally dominated	✓	✓	✓	✓
1000yr	Fluvially dominated	✓	✓	✓	✓

Return period	Type of flood event	2030	2045	2065	2125
	Tidally dominated	✓	✓	✓	✓

The total number of simulations carried out for each option is given in Table 13.

Table 13: Number of simulations carried out for each option.

Option	Number of simulations
Do Minimum	40
Do Nothing	40
Raised defences 75yr SoP	50
Raised defences 100yr SoP	50
Raised defences 200yr SoP	50
All options (total)	230

10.3 Model results

Maximum water level and maximum flood hazard results were extracted from the 2d model for each simulation for use in the flood damage assessment (reported separately). Model results were checked to ensure results were as expected based on option, epoch year, return period, and standard of protection modelled for the raised defences options.

The Do Minimum and Raised defences option results are compared in Figure 16 to Figure 19 for the fluvial 1:100yr and tidal 1:200yr events in 2065 and 2125. These return periods correspond to those that are used to define Flood Zone 3; though the climate change allowances are different (see Section 10.2). For the Raised defences option, the 2065 results shown are for before the second phase is constructed in 2065. Note that for the 1:100yr fluvial event, the 75yr SoP and 100yr SoP options give the same model results.

The results show significant areas of Bristol that would benefit from the proposed scheme even if a 75yr SoP was selected. The 75yr and 100yr SoP results are similar. For the 1:200yr tidal event for both 2065 and 2125 but particularly for the latter, there is significant residual flooding in the 75yr and 100yr SoP options, i.e. noticeably more flooding than the 200yr SoP option.

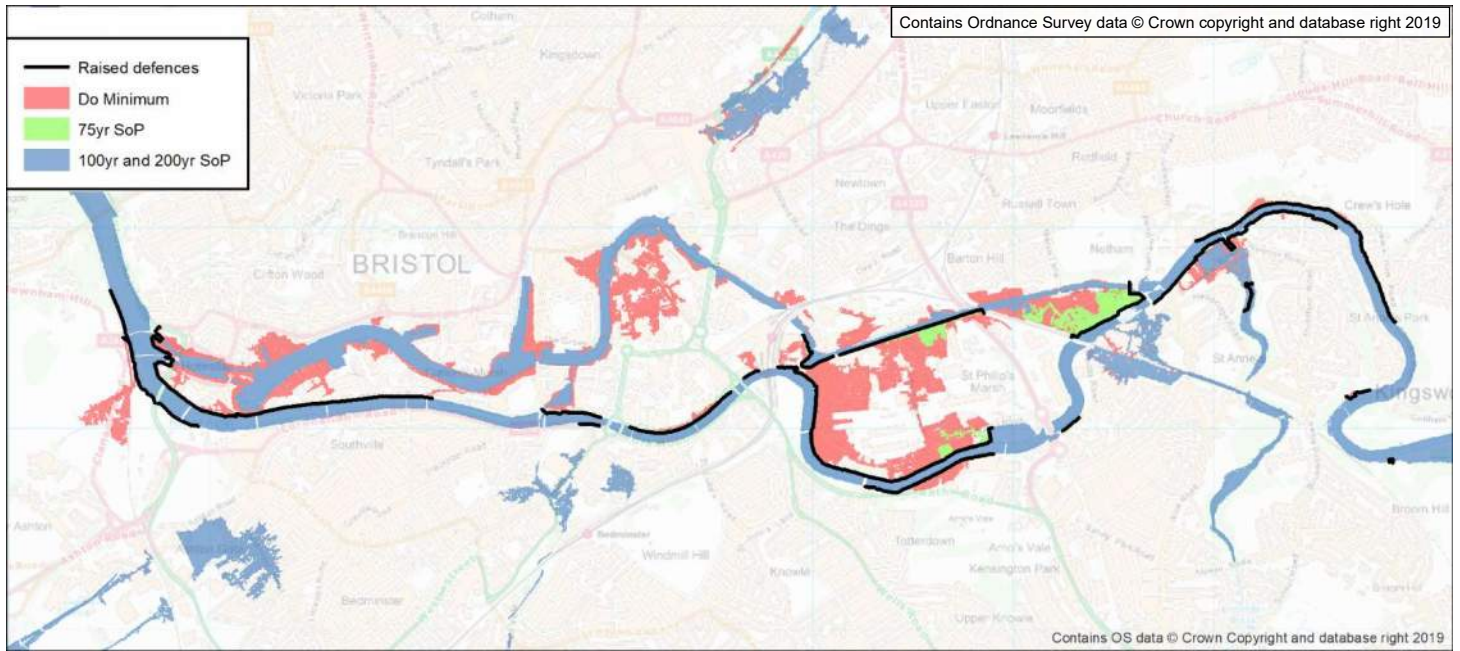


Figure 16: Flood extents of raised defences options vs Do Minimum for 2065 fluvial 100yr event.

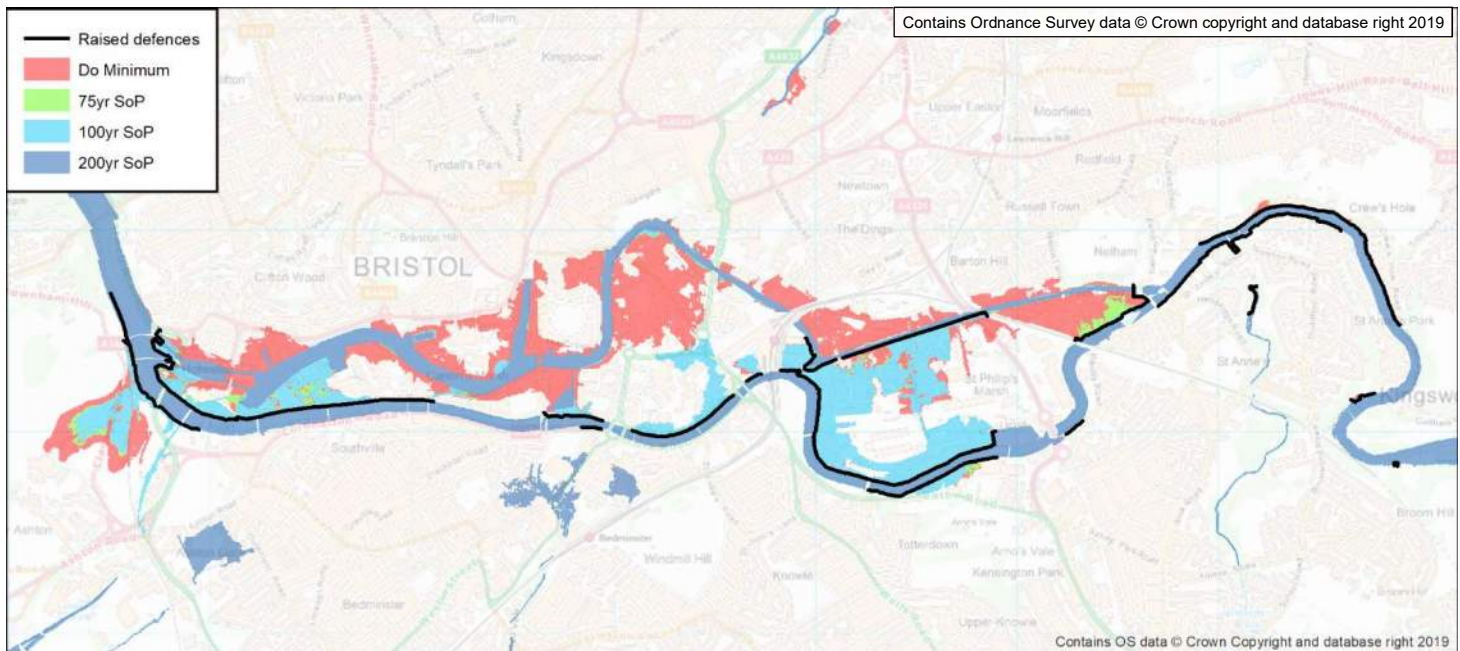


Figure 17: Flood extents of raised defences options vs Do Minimum for 2065 tidal 200yr event.

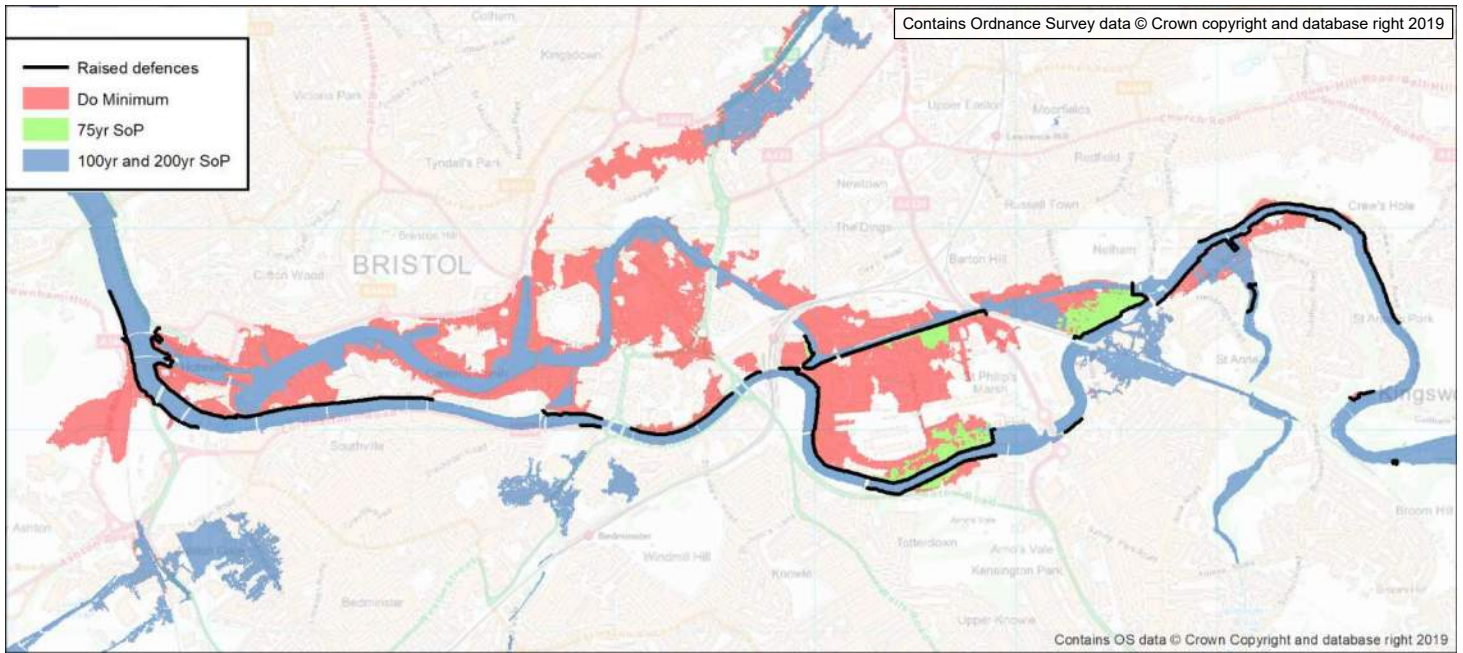


Figure 18: Flood extents of raised defences options vs Do Minimum for 2125 fluvial 100yr event.

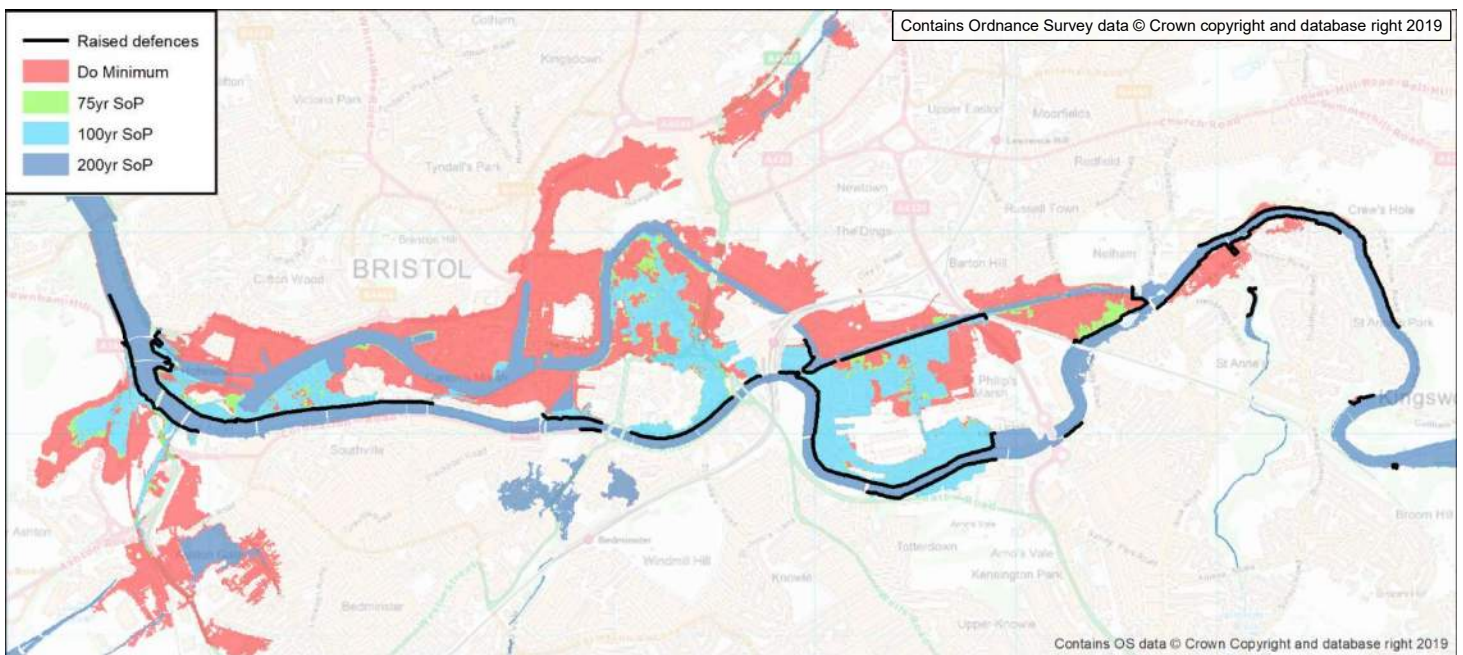


Figure 19: Flood extents of raised defences options vs Do Minimum for 2125 tidal 200yr event.

10.4 Benefits modelled behind detriment mitigation defences

Following the modelling work, it was identified that using NPPF levels for the detriment mitigation defences resulted in an over-estimation of benefits claimed from the detriment mitigation defences resulting in a very small over-estimation of the scheme-wide benefits. This issue and the impact on results is described below and is also flagged up in the economics report which assesses the impact of the issue to have negligible impact on the scheme-wide benefits. Given the negligible impact on the scheme-wide benefits, further modelling was not considered necessary.

In order to claim benefits behind the detriment mitigation defences, they are required to be constructed to the higher of the two values, as described in Section 9.3:

- NPPF level without freeboard
- FCERM with freeboard (we've assumed 300mm freeboard to date)

However, the benefits that can be claimed are those corresponding to the overtopping assuming they are set to FCERM level without freeboard, i.e. same approach as the standard (non-detriment mitigation) defences. The modelled NPPF level is higher than the FCERM level. The difference is 0.13 to 0.16m for 2065 and 0.33 to 0.39m for 2125. This means that, for the purposes of calculating benefits, there is less overtopping than there should be (or no overtopping) for the detriment mitigation defences during the fluvial exceedance events. However, in the 1000yr fluvial event, the detriment mitigation defences are drowned out, so the defences have no impact for this event. Therefore, only the following exceedance events result in over-estimation of benefits:

- 75yr SoP option: 100yr fluvial and 200yr fluvial events
- 100yr SoP option: 200yr fluvial events

Figure 20 shows the areas where benefits are over-estimated in the 75yr SoP and 100yr SoP options. These areas are derived from the Do Minimum 2125 fluvial 200yr flood outline. The largest of the areas affected is also flooded from Brislington Brook so there is still flooding in this area for most exceedance events but not as much as if the Avon defence was set to FCERM levels.



Figure 20: Areas (yellow) where benefits are over-estimated for the 75yr SoP and 100yr SoP option.

An example of where overtopping is under-predicted is given for the 100yr SoP option for the 2125 fluvial 200yr event (Figure 21). However, the same comparison for 2065 before the second phase of raising is carried out, shows that overtopping of the detriment mitigation defences occurs resulting in slightly greater flood depths compared to the Do Minimum option resulting in disbenefits (Figure 22).

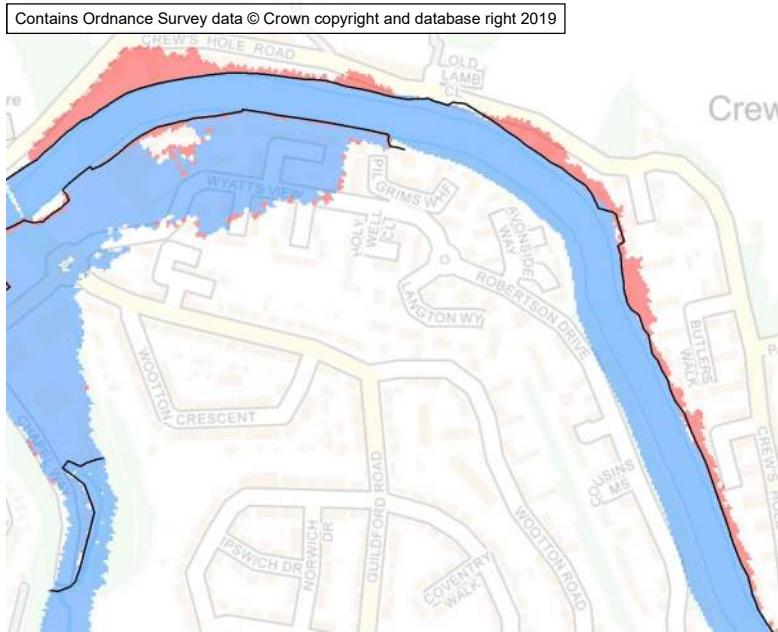


Figure 21: Do Minimum (red) vs 100yr SoP option (blue) for 2125 fluvial 200yr event. Blue is on top of red. This shows areas where overtopping does not occur at detriment mitigation defences.

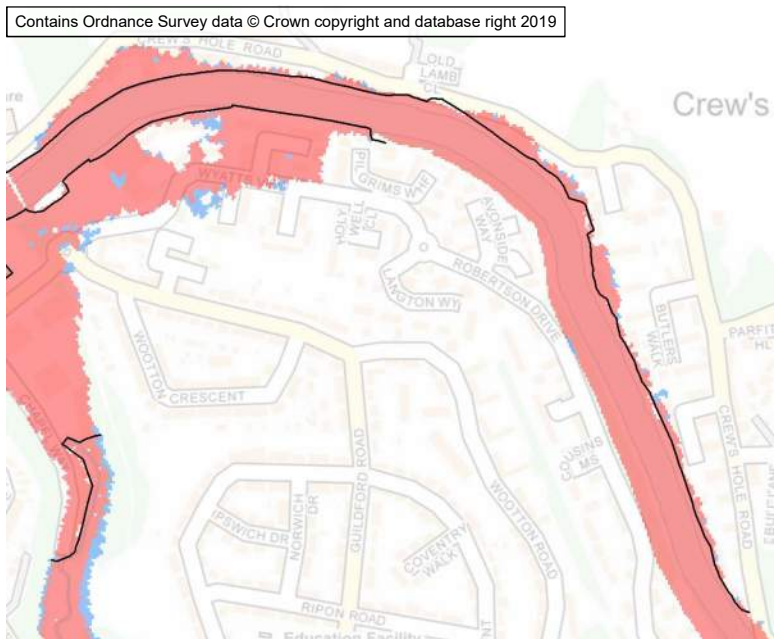


Figure 22: Do Minimum (red) vs 100yr SoP option (blue) for 2065 fluvial 200yr event before the second phase of raising is carried out. Red is on top of blue. This shows the 100yr SoP option results in disbenefits behind detriment mitigation defences in this scenario.

It is recommended that any future modelling undertaken to derive damages and benefits for economic analysis should set the detriment mitigation defences to FCERM level without freeboard. For assessing detriment, the proposed design crest levels should be used.

10.5 Pill, Shirehampton and Sea Mills

As previously explained, the flood model is 1d only downstream of Bristol with floodplain areas represented using extended cross-sections. As such, flooding mechanisms at Pill, Shirehampton and Sea Mills, where properties are at risk, is not accurately represented. To include these areas within the flood damage assessment, water levels have been calculated for flood risk areas that share the same section of frontage or defence and can be considered as being ‘hydraulically connected’ based on review of ground levels. The flood risk areas are shown in Figure 23.

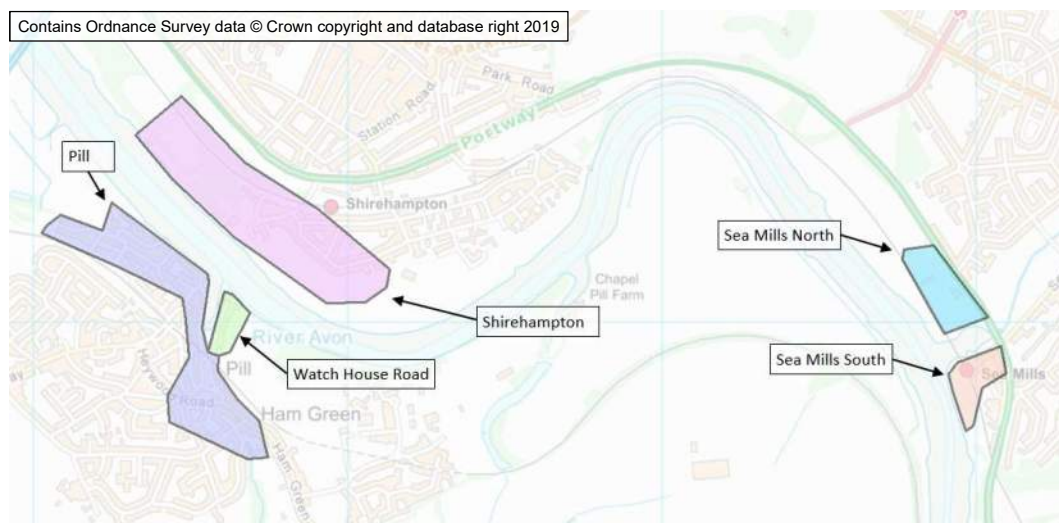


Figure 23: Flood risk areas downstream of Bristol.

Water levels have been calculated using the following simple method, which is considered acceptable for SOC stage given that the flooding mechanism in these locations is tidal so will be driven by water levels rather than fluvial volumes:

- If the maximum River Avon water level is below the spill level for a given flood risk area, then the water level for all properties in the flood risk area is set to zero.
- If the maximum River Avon water level is above the spill level for a given flood risk area, then the water level for all properties in the flood risk area is set to the adjacent River Avon water level.

The spill level is the crest level of the lowest section of bank or defence. For the Do Minimum option, the spill levels used are given in Table 14. The spill levels for Pill, Watch House Road and Shirehampton were taken from the defence levels identified by AECOM from survey information as shown in Figure 7 of the associated AECOM report¹⁸. The spill levels for Sea Mills north and south were estimated from LiDAR data. For the Raised defences options, the spill levels were set to the defence level required for the given SoP, which were derived from the glass-wall modelling (see Chapter 9).

¹⁸ River Avon TFRMS, Technical Note: Defacto Defences, Pill and Shirehampton updates, AECOM, 19/01/2017.

Table 14: Existing spill levels (used for the Do Minimum option) for each flood risk area.

Flood risk area	Existing spill level (m AOD)
Pill	9.31
Watch House Road	7.61
Shirehampton	8.85
Sea Mills north	8.70
Sea Mills south	8.00

11 Recommendations for future modelling

As the preferred option is developed and the scheme progresses from Strategic Outline Case to Outline Business Case and beyond, it is recommended that uncertainties in the hydraulic modelling are reduced, particularly where these directly impact the option design. The following recommendations should be considered for future modelling work undertaken to support the Strategy and the resultant schemes:

1. Reconsider recommendations made during the model review in April 2018¹ that have not been undertaken. Following discussion of the recommendations with BCC and the EA, it was agreed that the following should be flagged up as recommendations to be addressed in future stages of work:
 - a. Incorporate the latest available LIDAR data. At the time of writing, this is the LIDAR Composite DTM 2019 data that was published in 2020. This is derived from a combination of the EA's Time Stamped archive and National LIDAR Programme, which has been merged and re-sampled to give the best possible coverage. Where repeat surveys have been undertaken the newest, best resolution data is used. The 2019 LIDAR Composite contains surveys undertaken between 12th March 1998 and 1st September 2019. The index metadata files that accompany the Composite DTM 2019 data show that the LIDAR for the Bristol area was last flown in January 2019, which was undertaken as part of the National LIDAR Programme. It is recommended any new LIDAR is read into the TUFLOW model in native grid format rather than Zpoints.
 - b. Issues relating to accuracy of LIDAR data may cause misrepresentation of bank top levels where LIDAR has been used instead of topographic survey. Additional topographic survey would reduce the risk of inaccuracies. Where topographic survey is available, it does not always follow the proposed defence alignment; in these locations new topographic survey along the proposed defence alignment would enable defence heights and costs to be calculated more accurately.
 - c. It is recommended that the TUFLOW model 'snap tolerance' command is removed and any snapping issues are fixed.
 - d. Resolve TUFLOW model warning messages.
 - e. It is recommended that the roughness patches in the TUFLOW model are removed or reduced if and where model stability allows.
 - f. Ensure flow pathways between 2d domains is represented correctly. Consider merging domains into a single 2d domain.
2. The areas of Pill, Shirehampton and Sea Mills are at known flood risk. A tidal flood on 11th and 12th March 2020 caused flooding to the road, parked cars and a property along Sea Mills Lane, combined with many

properties deploying their own individual flood barriers/gates. This highlights that Sea Mills is an area which is particularly vulnerable to flooding during high tide events. Pill, Shirehampton and Sea Mills are covered by the Strategy model, but these areas are only represented in 1d which does not accurately represent flooding mechanisms. It is recommended that more detailed modelling is undertaken for these areas to better understand flood risk and to develop flood risk management options here. This could be achieved by developing a new model or by refining the Strategy model in these areas, e.g. by representing the floodplain in a TUFLOW 2d domain. Consideration should also be given to whether the Avonmouth Severnside model could be used or merged with the Strategy model.

3. Undertake more detailed modelling to assess detriment and develop detriment mitigation options upstream of the A4174 road, which is only modelled in 1d in the current Strategy modelling. This could potentially use the Environment Agency's 1d-2d model of the River Avon from Bath to Bristol developed by Capita AECOM.
4. There is significant uncertainty in the predicted detriment at the new housing estate adjacent to the Malago at Malago Drive. Updating the model to incorporate the new housing estate is recommended for future stages of the project to reduce uncertainty in detriment and associated mitigation measures for the Malago.
5. If any new works are undertaken that modify the geometry of the river, riverine structures, bank levels or floodplain ground levels, then these should be assessed and incorporated into the model if they are considered to have a material impact on model results, particularly if they could affect the option design.
6. Consider updating the tidal boundary conditions using the latest information, which at the time of writing is the 2018 update of the coastal flood boundary conditions¹⁹ that was issued in 2019.
7. Update climate change allowances to reflect any changes in allowances since the publication of the guidance used in this study^{9,10}. The new FCERM allowances published in July 2020, following completion of the hydraulic modelling for the SOC, are much closer to the NPPF allowances. The difference between NPPF and FCERM raised defence crest levels and associated costs becomes less significant than has been assessed to date. It is recommended the relative difference between FCERM and NPPF raised defence levels are considered during options development and selection.
8. A freeboard of 300mm has been used for option design in the Strategy. This freeboard value should be refined as the design is developed and as

¹⁹ Coastal flood boundary conditions for the UK: update 2018, Technical Summary Report, Environment Agency, May 2019.

uncertainties in the modelling are reduced, using current guidance.²⁰ This should consider the remaining residual uncertainties in the modelling.

9. Consider the potential impact of the scheme and the scheme detriment on surface water flood risk taking into account the relative timing of fluvial, tidal and surface water flood peaks. Future work should consider using existing surface water modelling outputs and assess the need for undertaking new surface water modelling, possibly integrated with the river model. Existing model outputs include the RoFfSW and more recent modelling undertaken by JBA for the updated SWMP²¹ which has not yet been incorporated into the EA national surface water mapping dataset. Synergies should be sought through ongoing partnership projects such as with Wessex Water at Ashton.
10. Any future modelling undertaken to derive damages and benefits for economic analysis should set the detriment mitigation defences to FCERM level without freeboard. For assessing detriment, the proposed design crest levels should be used.

²⁰ Accounting for residual uncertainty: updating the freeboard guide, Environment Agency, February 2017.

²¹ Bristol SWMP Model - Review and Update - Phase 2, JBA Consulting, September 2018.

12 Summary

Bristol City Council is working with the Environment Agency and other partners to create a vital long-term strategy for managing the flood threat from the River Avon, supported by Arup. The strategy will outline action to be taken in phases to reduce the chance and impact of flooding from the River Avon, and how each phase will be funded. This is to be tested through consultation in advance of adoption by Bristol City Council and endorsement by the Environment Agency.

The preferred option of the Strategy comprises raised defences along the River Avon including new tidal stop gates for the Floating Harbour. The initial phase of construction is assumed for the 2020s and a subsequent phase of constructing additional defences and raising defences is assumed for the 2060s.

Flood modelling has been undertaken by Arup for the Bristol FRM Strategy to support the SOC report. This has been undertaken in close consultation with BCC and the EA. The main stages and outcomes are summarised below.

1. **Baseline model review, investigations and update:** The updated baseline modelling showed greater flood risk from fluvial events, particularly in St Philips Marsh. This change was due to selecting a more appropriate tidal event to simulate in combination with each fluvial event. Some uncertainties in the model were reduced, including a) the representation of Netham Weir in the model, which was updated using survey data, b) impact of Netham Weir sluices investigated, c) reviewed and updated the Avon and Frome hydrographs shapes based on historic event data.
2. **Options development:** The alignment of proposed raised defences was tested and refined to prevent outflanking. Fluvial options and tidal barrier options were assessed and discounted from further consideration in the Strategy. The phasing of interventions and control of water levels in the Floating Harbour were also investigated. A control philosophy for the Floating Harbour water levels during fluvial events was tested and adopted within the preferred option.
3. **Support the BTQ strategic growth and regeneration area project:** Modelling was undertaken to determine the scale of precautionary raised defences to meet NPPF requirements for development for the BTQ and Western Harbour strategic growth and regeneration areas. Modelling was then undertaken to assess the residual flood risk to these areas due to overtopping of the defences. This was undertaken for both with and without a tidal barrier and considered both pessimistic and optimistic failure scenarios for the tidal barrier. The residual flood risk modelling results were used to produce a suite of residual flood depth maps provided to the BTQ project for developing the site layout, including alignment of access and egress routes.
4. **Assess detriment from the proposed scheme:** This assessed where the proposed scheme would cause flood depths to increase compared to the baseline 'as is' situation. This identified areas of detriment in Bristol, most notably off the left bank of the Avon upstream of Netham Weir and off the right bank of the Avon adjacent to Crew's Hole Road. The assessment also identified detriment extends as far downstream as Pill and as far upstream as

Swineford, including the light industrial estate near Keynsham. BCC's resilient road network would also be affected by detriment at Hotwell Road / Portway between Cumberland Basin and Sea Mills and Netham Road Bridge; BCC confirmed that this did not require mitigation. However, detriment to St Anne's Road does require mitigation. There is no detriment to any A-Roads within Bath and North East Somerset Council.

5. Develop detriment mitigation measures: Possible detriment mitigation measures have been identified, developed and tested using the hydraulic model. The outcome of this work has been a list of recommended detriment mitigation measures and timing, and recommendations for future study to reduce uncertainties associated with these.
6. Determine required defence levels: Modelling has been undertaken to derive minimum required crest levels for raised defences and detriment mitigation defences for the 75yr, 100yr and 200yr SoP options. Defence levels required for 2065 and for 2125 have been derived for both FCERM and NPPF standards. The crest levels have been used in developing the outline design and costing the proposed interventions.
7. Flood damage modelling: Modelling has been undertaken to determine flood depths and flood hazard associated with overtopping for a range of return periods and future years. This has been undertaken for the baseline Do Minimum and Do Nothing options and for the Raised defences option for the 75yr, 100yr and 200yr SoPs. A simplified approach has been used for Pill, Shirehampton and Sea Mills to account for the limitations of the hydraulic model here. The model results have been used to determine flood damages in the economic analysis for the SOC (reported separately) to calculate the benefits of each option. The option benefits and option costs are used to aid selection of a preferred option.
8. Provide recommendations for future modelling: A set of recommendations has been provided that should be considered in future modelling work undertaken to support the Strategy and the resultant schemes. These will enable uncertainties in the hydraulic modelling to be reduced, which is particularly important where these uncertainties directly impact the option design.