AECOM

BRISTOL TIDAL FLOOD RISK MANAGEMENT STRATEGY –

Hydraulic Modelling Review Report

May 2017

Prepared for Bristol City Council

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GLOSSARY AND ABBREVIATIONS

CAFRA	Bristol Central Area Flood Risk Assessment (Bristol City Council, 2010-2012). CAFRA consisted of four Workstreams undertaken by Hyder and supported by others, described in more detail in this report. In the context of this report, CAFRA is typically used to refer to the 1D-2D (ISIS-TUFLOW) hydraulic model of Bristol that was developed as part of the CAFRA package of works. The CAFRA model is the accepted strategic baseline model for the city centre area and can be used to assess fluvial and tidal risk (and combinations of both).
FCERM	Flood and Coastal Erosion Risk Management. In the context of this report, FCERM relates to the DEFRA guidance for scheme appraisal.
FEH	Flood Estimation Handbook. The UK industry standard methodology used in hydrological analyses for the estimation of design event peak flows and hydrograph shapes.
GiA	Grant in Aid. This is a funding mechanism within the DEFRA guidance for FCERM scheme appraisal.
ISIS	1D Hydraulic modelling software (CH2MHill), now sold as Flood Modeller Pro. ISIS has been used for the 1D (in-channel) component of the CAFRA model.
QMED	The Median Annual Flow of a river, i.e. the flow which is statistically likely to be exceeded, on average, once every two years. An important component of the FEH methods.
TUFLOW	2D Hydraulic modelling software (BMT-WBM). TUFLOW has been used for the 2D (floodplain) component of the CAFRA model and also to represent the storage available in the Floating Harbour. TUFLOW models use a fixed (square) grid of cells but it is possible, as in the case of CAFRA, to have a multi domain model with a number of connected or unconnected 2D domains of differing grid sizes and dimensions.
UKCIP09	UK Climate Impact Predictions, 2009 Used to define the projected sea level rise allowances for climate change in the CAFRA model and TFRMS. UKCIP09 includes sea level rise allowances for a range of different emission scenarios. The TFRMS will be focussed on the Medium 95%ile emissions scenario, as per the DEFRA guidance for FCERM scheme appraisal.

1. INTRODUCTION

1.1 Context

A tidal risk management strategy for Bristol is vitally important for the city, not just because of the threat to lives and property but also because of the risk of long-term reputational damage on the city's attractiveness and economic performance.

This project will deliver a Tidal Flood Risk Management Strategy (the 'Strategy'). This will recommend an adaptive programme; identify when FRM interventions are needed and how they will be funded.

The Strategy, once adopted by BCC's Cabinet following a Key Decision, will provide evidence to support the partial refresh of Bristol's Local Plan. The Strategy may conclude that no strategic intervention is justified for some time if, for instance, another possible form of intervention(s) can achieve the objectives.

Hydraulic modelling and simulation of extreme water levels is a key aspect of Strategy development and is required to understand the risks faced, demonstrate the mechanisms of flooding, support the delivery of the economic case (calculating do nothing damages and benefit assessments) and also for testing and confirming management options.

1.1.1 *Project Objectives*

The project objectives are:

a) To develop an agreed understanding of flood risk from now until 2115. The impact of this risk on existing development and infrastructure, and future proposals needs to be quantified. This should be proportionate and build on the best available information (the CAFRA and River Avon Strategic Flood Defences First Phase Feasibility Study) to improve the evidence base and confidence in predictions, reflecting opportunistic synergies realised from infrastructure proposals such as Metrobus.

b) Intervention options should be confirmed, to form components of an adaptive strategic approach to maintain an acceptable level of flood risk from now until 2115 (subject to review on the basis of the preferred intervention(s) timing and type). The delivery cost and risk of these options needs to be determined, proportionate to the likelihood of progression, and when the options would be needed. Efficiencies from opportunistic synergies with other infrastructure proposals should be identified.

c) The justification for investment needs to be evaluated. We recognise the different drivers and priorities of BCC and the Environment Agency. However both organisations commit to actively work together and exploit mutually-beneficial synergies. The Environment Agency will evaluate against objectives to manage flood risk to people and property. BCC will also evaluate the impact on broader, strategic regeneration objectives. The consequence of inaction should be clarified.

1.1.2 *Project Boundaries*

- The project focus is the area of Bristol at risk of flooding from the River Avon – including the city centre (between Cumberland Basin and Netham), Shirehampton and Avonmouth. Consideration of downstream and upstream impacts to be given including Pill and Portbury.
- Flood risk is dominated by tidal events (approx. downstream of Avon Bridge) and this will be the focus of options and economic appraisal; however consideration for residual pluvial and fluvial flood risk is to be given and options addressing tidal flood risk must be demonstrated not to detrimentally increase flood risk from other sources.

1.1.2.1 *Epochs*

The Strategy is to appraise options and outline a preferred strategic approach to managing tidal flood risk over the next 100 years (2015 – 2115). To facilitate this, the 100 year appraisal period has been split into three time epochs:

- 2015 to 2030 (short term);
- 2030 to 2065 (medium term); and
- 2065 to 2115 (long term)

By developing management options in accordance with these time epochs it will allow for an adaptive approach to management that not only keeps pace with climate change and potential sea level rise, but also has sufficient flexibility to address uncertainty thereby ensuring the most appropriate strategic choices are taken now and in the future.

1.2 Purpose of this report

This report presents the findings of a model review undertaken by AECOM as part of the first stage of the hydraulic modelling activities of the Bristol TFRMS. This review has assessed the suitability of the existing model provided to support the development of the Strategy.

The review has evaluated the existing Bristol CAFRA (Work Stream 3) ISIS-TUFLOW model, focussing on its suitability for use in the Bristol TFRMS. This review has focussed on identifying the uncertainties within the CAFRA model and recommendations for any further actions have been made in order to complete the baseline modelling tasks for the TFRMS.

A full technical or QA review of the CAFRA model has not been undertaken because that has previously been undertaken on behalf of BCC and the model has been accepted as the approved strategic baseline for the assessment of flood risk in Bristol.

In particular this review sets out to answer the following technical questions as part of the review of the CAFRA model:

- Does the model run and on which software versions?
- How many ISIS nodes are there in the model? (Implications of model licences)
- How long does it take to run?
- How many tidal cycles does the current setup include?
- How has the surge been applied?
- What are the boundaries on the model (tidal and fluvial)? How have the boundaries been applied?
- How has the barrier been modelled?
- How are existing defences represented in the model?
- What water levels / scenarios have been run? What joint probability combinations have been run?
- Have any breach scenarios been tested?
- Has ‘good modelling practice’ been adopted throughout the model?
- Are there any areas which need increased resolution / extension / updates?
- How stable is the model?

1.3 The Bristol CAFRA Model

The initial Bristol City Council Central Area Flood Risk Assessment was undertaken by Hyder Consulting Ltd between 2010 and 2012. The original CAFRA study followed a workstream approach with a number of packages of work within each workstream. Each workstream (WS) has been reported separately, often with a number of additional technical notes and appendices to support the main report. The four CAFRA workstreams were:

- Workstream 1 – Collection & Review of existing hydraulic models, studies and survey data
- Workstream 2 – Hydrological statistical analysis of key sub-catchments to derive peak flows. These were used with predicted upper end tidal levels to inform the hydraulic model boundary conditions. The study considered the joint probability of high river flows coinciding with tidal surges and assessed climate change impacts for 2060 and 2110 epochs.
- Workstream 3 – documents the 1d-2d hydrodynamic model build. Combined predictions of flood water peak depth and extent for present day and with climate change allowances. Predicted flood risk assessed as the maximum of a composite range of tidal and fluvial events with the same probability of occurrence.
- Workstream 4 – reviewed fluvially-dominated flood risk, scoped fluvial flood risk management interventions and assessed the NSWI intake operational procedure. Included a parallel Harbour Study focussed on the tidally dominated central Bristol with separate modelling, building on the work of the Floating Harbour asset management strategy. Also included a pre-feasibility study of nominal River Avon tidal barrier options.

The four key objectives for the WS 3 CAFRA modelling were:

- "*Develop a detailed understanding of flood risk on all tidally influenced watercourses within Bristol City boundary;*
- *Assess and quantify the probability and impact of the coincidence of tidal-fluvial flood events, including determination of flood hazard and vulnerability;*
- *Determine the Standard of Protection (SOP) offered by existing flood defence assets and systems within the study area, now and in the future; and*
- *Utilising the latest guidance and data, assess the potential impact of climate change on fluvial and tidal flood risk within the study area*."

The WS3 model developed by Hyder was reviewed on behalf of BCC by JBA and is the accepted strategic baseline for flood risk assessment in Bristol. Following the original 2010-2012 CAFRA modelling, Hyder have undertaken two significant updates to the CAFRA WS3 modelling:

- 2014 assessment of the St Philips Marsh Flood Defences and lower return period events; and
- 2015 update work for climate change scenarios on tidally dominated events and assessment of Cumberland Road defence.

1.3.1 *Central Area Flood Risk Assessment (CAFRA) - St Philips Marsh Flood Defences. Hyder, December 2013*

The primary purpose of the 2013 modelling was to test the performance of two flood defence options for the St Philips Marsh area – a wall along the right bank of the River Avon with defence crest at either 9.1m AOD or 9.6m AOD. The option model was run for the 1 in 200 year tidally dominated event (tidal 1 in 200 year and fluvial 1 in 2 year) for three epochs: present day (2010), climate change 2060 and climate change 2110.

The 2013 updated modelling was also used to identify the return period (probability) of the event that triggers the First Property to Flood (FPTF) in the CAFRA study area and was run for extra events not considered in the original 2010-12 modelling to provide flood predictions for low return period flood events

The results of this modelling showed that flooding of properties in the St Philips Marsh area was predicted to occur in the 1 in 20 year intermediate (1 in 2 tidal and 1 in 2 fluvial) and tidally dominated (1 in 200 year tidal and 1 in 2 fluvial) scenarios. In these events flooding is also predicted around the area of Cumberland Basin. No flooding of properties in the St Philips Marsh is predicted to occur in the 1 in 20 year fluvially dominated (MHWS tidal and 1 in 100 fluvial) scenarios. However flooding of properties in the Mina Road and Ashton Gate area is predicted to occur in this scenario (even in a 1 in 2 year fluvial event).

An outcome of the 2013 modelling work was the identification that the following three events would provide an appropriate spread of low order events for informing BCC cost-benefit analysis:

- 1 in 2 year
- 1 in 5 year
- 1 in 10 year

For each of these events, a fluvial and a tidally dominated scenario were run but no intermediate events.

The 2013 reporting notes that as part of that modelling, the model was updated to run on newer versions of ISIS and TUFLOW than had previously been used.

1.3.2 *Central Area Flood Risk Assessment (CAFRA) – additional model climate change runs. Hyder, June 2015*

Further modelling was undertaken by Hyder in 2014-15. This modelling update had to key objectives:

- Update of climate change tidal levels for four epochs: 2015, 2030, 2065 and 2115 and for six joint probability tidal/fluvial events: 1 in 20, 75, 100, 200 and 1,000 years. See Section 2.2.3 for more information on climate change allowances.

- Assess the performance of a proposed flood defence wall between Cumberland Road and the River Avon which will be constructed as part of the Metrobus infrastructure project.

BCC has provided AECOM with a significant volume of CAFRA data including all the hydraulic modelling files from the original WS3 modelling and the 2015 update. This review has covered the suite of original CAFRA technical reports and summarises some key points arising within them that are significant to the hydraulic modelling for Bristol TFRMS. Where extracts of or results from the CAFRA hydraulic model are presented in this review, this is generally based on the 2015 update modelling files, unless noted otherwise.

1.3.3 *Verification of CAFRA model against 2014 tides – Hyder, August 2015*

This technical note details tide levels predicted by the CAFRA model (WS 2/3) compared to the observed levels, providing commentary as to any discrepancies. It examines the observed flood propagation routes and details how this compares to the predicted routes of the model. This report also provides recommendations for future investigative work.

The report documents that although the model predicts event flood levels to within +/-100mm where there is good confidence in observed data, there is one exception where the predicted water level is 170mm greater than the observed levels (Bathurst Basin). It should be highlighted that the 2015 study did not use observed data to drive the model boundaries, which may prove to be more accurate for both fluvial and tidal representation, but instead used similar boundary files which were readily available from previous WS. This may explain differences reported within this study.

In addition to the above, differences were between observed and modelled are also recorded at Netham Weir. Capita AECOM are currently undertaking a modelling study between Bath and Netham Weir which may be able to improve model confidence of fluvial aspects with the upstream boundary of the CAFRA model. As the Capita AECOM study is being undertaken under the Environment Agency's WEM Framework, this will need to be discussed further as to availability of study output.

Figures provided within the comparison of modelled against observed flood extents clearly demonstrate that the model predicts larger flood extents than which are experienced during a specific event. This is reported to be due to defacto defences not represented as such within the CAFRA model configuration. Where defacto defences may not be the ultimate cause for differences in flood extents, there may be cause to investigate any differences between LiDAR DTM (tolerance of +/-150mm) and available topographic survey. Any particular areas of concern could assist in a target approach for further ground truthing survey checks as required going forward.

A primary recommendation of this report is that de-facto defences, such as buildings and walls which are not formally recognised as flood defences, may play a significant part in impacting on event flood extents. To ensure that the CAFRA model more accurately represents the actual risk of flooding in Bristol, data should be considered as to its usefulness and entered into the model where key structures and flow obstructions may impact on identifying the real areas at risk to increase confidence and accuracy of the project outputs.

1.4 Other Documents and Models Reviewed

In addition to the CAFRA study, model and subsequent updates, BCC (and others) have made available to AECOM a number of other documents and models of relevance to the Bristol TFRMS. One particular study of relevance to the hydraulic modelling components of the TFRMS is noted below.

1.4.1 *CAFRA Workstream 4 Hydrology and Hydraulic Modelling, Mott MacDonald & Edenvale Young (2012)*

Following the CAFRA WS3 modelling, Mott MacDonald and Edenvale Young undertook a number of other hydrology and hydraulic modelling work packages as part of WS4.There were a number of components to this work.

Mott MacDonald and Edenvale Young undertook some further hydrological analysis including an estimation of QMED and FEH Statistical Peak flows within the Tidal Avon using an approach that varied in some elements from the previous hydrology analysis undertaken by Hyder in CAFRA WS3.

This WS4 hydrological analysis included a review of the design event hydrograph shapes used in the CAFRA modelling. The WS2 / WS3 approach had used design event hydrograph shapes derived using the ReFH method from catchment descriptors, making limited use of observed flow data and no use of observed data from any significant flood events. This WS4 hydrological analysis considered an alternative approach of deriving standardised hydrograph shapes using observed (gauged) data from three significant events and demonstrated that the hydrographs derived by this approach tended to have three – four times more flow volume than the ReFH design event hydrographs previously used. This difference in fluvial inflow volume becomes particularly important when considering flood risk management options (such as a tidal barrier) that involve the storage of the fluvial hydrograph.

The WS4 assessments undertaken used a 1D only model (developed by Edenvale Young from the Environment Agency's 1D flood forecasting model of the River Avon) which runs in minutes, compared to the two – three day run time of the CAFRA WS3 model. This enabled Edenvale Young to undertake a huge number (thousands) of simulations to assess the relative importance of four boundary condition variables: fluvial event return periods on the Frome and Avon, tidal surge level return periods on the Avon and the tidal phase shift (coincidence of fluvial and tidal peaks). The results of this scenario modelling are described in detail in the WS4 reporting, with key findings of particular relevance to the TFRMS listed below:

- The rate of flow over the Bathurst Basin spill (one of the key links between the New Cut and Floating harbour) is primarily dependent on the tidal return period;
- The water level in the Floating Harbour is most dependent on the tidal return period. At low tidal return periods, there is more dependency on the Frome return period and the phase shift of the tide. The 50% phase shift (6.2h) produces the highest water levels in the Floating Harbour; and
- Flow over Netham Weir is primarily dependent on the Avon return period.

It is recommended that the findings summarised above are used to guide the boundary condition sensitivity testing referred to in the recommendations from this review, see section 4 .

One element of the WS4 hydraulic modelling work included modelling to test the potential benefits (in terms of flood level reduction) of a tidal barrier across the River Avon. This modelling considered two potential barrier locations, one just upstream of the M5 and a second, further east, just downstream of the Northern Storm Water Interceptor. Edenvale Young used their in-house CALIBRE optimisation tool to optimise the barrier operation and demonstrated that a barrier at the M5 could deliver significant benefits in relation to flooding in Bristol by reducing peak water levels in the Floating Harbour.

It is proposed that this initial barrier testing (reported in a 2012 Bristol Avon Flood Barrier Phase 2 and 3 Report) is further developed within the Bristol TFRMS modelling. However, it is not proposed to model the same number of iterations or apply an automated optimisation approach as has been undertaken previously by Edenvale Young. It is proposed that AECOM would test a proof of concept in consultation engineering design constraints identified by AECOM. Once an appropriate site is identified, it is anticipated that further modelling shall be required to refine the location, design, operational procedure and fluvial impounding.

2. CAFRA MODEL DETAILS

2.1 Overview of CAFRA model extents and resolution

There have been numerous hydraulic modelling studies of the Tidal Avon, the River Avon, the River Frome and tributary watercourses in and around Bristol, with models generally developed by the Environment Agency for the purpose of flood mapping. The CAFRA study, and model, was the first attempt at pulling all those previous studies together and consolidating into a single, strategic, model for the assessment of fluvial and tidal flood risk within Bristol. As noted in the CAFRA WS3 technical report, the objectives of the hydraulic model are:

- To allow the simulation of tidal (sea) and fluvial (river) flood risk on all watercourses within the City of Bristol that are impacted by the tide.
- To incorporate up-to-date survey, where necessary, and utilise existing models, where available, to represent the most detailed representation available of flood risk within Bristol.
- To assess the risks of flooding from multiple sources (i.e. tidal and fluvial flooding) and represent a suite of design events which consider the joint probability of these sources.
- Provide a tool with which BCC and other stakeholders can investigate flood risk and determine levels of protection provided by existing defences and river banks, and investigate potential benefits provided by proposed flood risk management solutions (as set out under 'Workstream 4' in the CAFRA Scoping Report).

The extents of the CAFRA model are described in detail in the CAFRA WS3 report and shown in Appendix A , reproduced from that CAFRA report. For the Bristol TFRMS it is the city centre and downstream area that are at greatest risk of tidal flooding which are of most relevance.

The original CAFRA WS3 model is a multi-domain ISIS-TUFLOW model with more than 2,500 ISIS nodes and eight TUFLOW 2D domains. The original model was developed and run using the ISIS Version 3.5 and TUFLOW Version 2011-09-AE-iSP-w64 software builds. The 2015 Climate Change update runs have been run using the latest versions of the ISIS and TUFLOW software which has resulted in some minor changes in water levels compared to previous versions, particularly in the fluvial reaches of the model (with no interaction with the floating harbour). Any modelling undertaken by AECOM for the Bristol TFRMS will use the most recent ISIS and TUFLOW software builds available at the time.

The CAFRA WS3 model has been built using a combination of previous models (some 1D and some 1D-2D) and new and previous channel and structure survey data. The LiDAR DTM used as the base topographic model for the 2D domains is based on a composite grid of 1m and 2m data. The CAFRA WS3 technical report described some verification that was undertaken of the LiDAR DTM and how topography fixes have been applied within the model to smooth out irregularities in the data. Given the scale of the model, a targeted approach for ground truthing of LiDAR DTM against measured topographic levels would assist in providing confidence of the ground level representation of the model.

The following sections of the CAFRA model review consider, in more detail, the boundary conditions applied to the model (including fluvial inflows, tidal surge levels, climate change allowances, relative timing of fluvial and tidal peaks and joint probability / dependency of events).

2.2 Boundary Conditions

2.2.1 *Fluvial Inflows (hydrological analysis)*

The CAFRA WS2 study focussed on boundary conditions, joint probability and hydrological analysis to inform the CAFRA WS3 model. Hydrological analyses were undertaken by Hyder to develop design event inflow hydrographs at the upstream extents of modelling on each contributing watercourse. For the Bristol TFRMS AECOM has not undertaken a detailed technical review of the CAFRA hydrological analysis as this review has previously been undertaken by JBA for BCC. The magnitude of the peak flow estimates for the range of events considered has not been reviewed.

The general approach in the hydrological analyses has been to use ReFH design event hydrographs shapes, scaled to fit FEH statistical peak flow estimates. After detailed consideration, it was decided by Hyder and agreed with BCC for WS2 and WS3, that on each contributing watercourse, a catchment specific critical storm duration would be used, i.e. there is no application of a single storm duration across the whole modelled area. This was considered an appropriate approach for areas where one fluvial mechanism (e.g. the River Avon) dominates and interacts with the tide and was overall considered by Hyder to represent a precautionary case. This approach does not reflect a 'real' event in terms of weather patterns, but neither would a single catchment wide critical storm duration.

Concerns were raised in the WS4 Hydrology analyses (described above) about the ReFH design event hydrograph shape used in the WS3 model and a recommendation was made to further investigate replacing the ReFH design event hydrograph shapes from the CAFRA WS3 model with the standardised hydrograph shapes derived in the WS4 analysis. A change in hydrograph volume and duration would also influence the approach taken to the relative timing of fluvial and tidal peaks as the standardised hydrograph duration covers more tidal cycles than the original ReFH design hydrograph used. See Section 4.4 for more information about the recommended sensitivity testing in relation to hydrograph shapes and phasing.

It is understood that Capita AECOM are currently developing a 1D/2D model of the River Avon between Churchill Bridge in Bath and Netham Weir in Bristol for the purpose of improving the understanding of flood risk to communities along the river corridor. This study is being undertaken on the Environment Agency's WEM Framework. Should programme alignment allow, it may be possible (pending EA permission) for AECOM modellers on both projects shall, where agreed by the Environment Agency, liaise about the scope of work for each project to consider if there are any synergies and any potential efficiencies to be gained, for example in using the results of fluvial analysis for this stretch of the Avon compared to the previous CAFRA work. In doing this, the impact of any potential change in the existing scope of the River Avon TFRMS would be considered and communicated to Bristol City Council. However, as the River TFRMS is primarily a tidal study, there is unlikely to be a significant impact on tidal risk in Bristol as a result of the Bath – Netham Weir modelling work, but there may be opportunities to increase confidence in fluvial aspects of the model at Netham Weir, as reported within the CAFRA 2014 Verification report (Hyder, 2014).

2.2.2 *Joint Probability*

WS2 of the original 2010-2012 CAFRA study was concerned with deriving boundary conditions for the hydraulic modelling in WS3. The derivation of boundary conditions in WS2 consisted of two elements, tidal/fluvial joint probability analysis and hydrological analysis of the fluvial catchment. This section of the review includes a brief summary of the joint probability analysis undertaken in this previous study.

The joint probability analysis undertaken in WS2 was based on the most recent guidance available at the time, the FD2308 Defra and Environment Agency reports (2005 – 2006) to determine the individual return periods for the tidal and fluvial extreme events which combine to give the required joint probability events. This guidance is still recommended for use in fluvial/tidal joint probability analysis and therefore the approach is still considered suitable for a strategic level study (i.e. the 2016 Bristol TFRMS).

The joint probability analysis undertaken in WS2 is based on analysis of daily river flow in the Avon at Bathford and surge at the Avonmouth tide gauge and an assumption about the level of dependence between peak river flow and maximum surge. The joint probability analysis is based on a dependence (X) of 0.11 between the Bathford flow gauge and the Avonmouth tide gauge. The WS2 report took the view that this dependence value suggested that there is a possibility that they might occur on the same day.

Based on the dependence value, X=0.11, for each of the five joint probability scenarios assessed in CAFRA (and required for the Bristol TFRMS), five fluvial / tidal combinations were derived, see example in Table 1 for a 1 in 200 year joint probability scenario.

Table 1 – Example of fluvial / tidal event combinations making up the 1 in 200 year joint probability scenario

Combined return period (years)	Tidal event return period (years)	Fluvial event return period (years)
200	200	2
	100	5
	20	24
	5	97
	2	200

Although there are recognised limitations (e.g. simplicity) and associated uncertainties in the approach, given the strategic level of assessment required in the Bristol TFRMS, it is not proposed to make any refinements or modifications to the previous joint probability analysis undertaken by Hyder during workstream 2 of the CAFRA study as part of this project. It is recommended that in any more detailed work, such as appraisals for potential schemes, more detailed joint probability analysis is undertaken in the future.

In the original modelling, five different tidal/fluvial event combinations were tested for each joint probability scenario. Through this modelling it was established that the tidally dominated combination represented the highest risk for each joint probability scenario. Therefore, for the Bristol TFRMS it is proposed that for each joint probability event to be assessed (i.e. 1 in 5, 1 in 20y, 1 in 75y, 1 in 100y, 1 in 200y and 1 in 1,000y) one single tidally dominated event is used and one fluvial dominant event to consider the residual fluvial risk as a result of the proposed barrier as required.

2.2.3 *Climate Change and extreme water levels*

The original 2010-2012 CAFRA WS3 modelling adopted the “Upper End Estimates” for sea level rise, as defined in the Environment Agency’s guidance on Adapting to Climate Change: Advice for Flood and Coastal Erosion Risk Management Authorities (Environment Agency, 2011). The “Upper End Estimates” for sea level rise are based on the ‘high’ emissions climate change scenario. This scenario equates to sea level rise of +1.01m over the 100 year study period. This precautionary approach was adopted because of the potentially very high consequences of tidal flooding to Bristol and the close alignment with planning guidance (NPPF) which sets out development policy to adopt the Defra 2006 ‘high emissions’ scenarios of climate change.

The tidal boundaries used in the original CAFRA modelling related to a 2008 baseline from the Environment Agency National Coastal Boundary dataset. These were updated in WS3 to a 2010 baseline using the Upper End Estimates for sea level rise.

The Harbour Study uses the “95%ile medium emissions scenario” which is the recommended change factor for FCERM projects (Environment Agency: Adapting to Climate Change Guidance, 2011). The guidance also allows for an increase in surge (varies with return period) such that the allowance for sea level rise and storm surge is +0.74m for a 1 in 100 annual chance event and +0.82m for a 1 in 200 annual chance event.

The 2015 climate change update used the predicted Severn Estuary Strategy (Environment Agency, 2011) climate change allowance of 2.4mm/yr to derive sea level rise allowances from 2008-2015. The 2015 tide levels used in the climate change update study are in the top data block of Table 2.

Table 2 - Summary of extreme tide levels used in 2015 climate change update

EPOCH	JOINT PROBABILITY	FLUVIAL / TIDAL COMBINATION	Tide Level (m AOD)		
			Upper End SLR	Medium Emissions 95%ile SLR	High Emissions 95%ile SLR
2015	1 in 20y	FBASE T020	8.69	8.69	8.69
	1 in 75y	FBASE T075	8.94	8.94	8.94
	1 in 100y	FBASE T100	9.00	9.00	9.00
	1 in 200y	F002 T200	9.13	9.13	9.13
	1 in 1000y	F012 T1000	9.45	9.45	9.45
2030	1 in 20y	FBASE T020	8.78	8.77	Not considered
	1 in 75y	FBASE T075	9.03	9.02	Not considered
	1 in 100y	FBASE T100	9.09	9.08	Not considered
	1 in 200y	F002 T200	9.22	9.21	Not considered
	1 in 1000y	F012 T1000	9.54	9.53	Not considered
2065	1 in 20y	FBASE T020	9.11	9.01	9.08
	1 in 75y	FBASE T075	9.36	9.26	9.33
	1 in 100y	FBASE T100	9.42	9.32	9.39
	1 in 200y	F002 T200	9.55	9.45	9.52
	1 in 1000y	F012 T1000	9.87	9.77	9.84
2115	1 in 20y	FBASE T020	9.84	9.43	9.59
	1 in 75y	FBASE T075	10.09	9.68	9.84
	1 in 100y	FBASE T100	10.15	9.74	9.90
	1 in 200y	F002 T200	10.28	9.87	10.03
	1 in 1000y	F012 T1000	10.60	10.19	10.35

For the 2015 updated modelling study UKCP09 Medium Emissions 95%ile and UKCP09 High Emissions 95%ile (including allowances for vertical land movement) were investigated in order to support the assessment and management of flood risk in Bristol. Tide levels for the 2030, 2065 and 2115 epochs used in the climate change update study are in the lower data blocks of Table 2.

The Bristol TFRMS economic assessment (damages and benefits) will adopt the Medium Emissions 95%ile scenario as the change factor for future tide levels (as shown in the middle column of Table 2. This will ensure that the appraisal is consistent with other FCERMS projects and so the GiA eligibility can be assessed in accordance with FCERM-AG. Consideration and sensitivity testing of higher and lower climate change scenarios will also be made in accordance with national guidance released February 19th 2016 and in agreement with BCC.

To reduce the number of runs required, the proposed tidal levels for each scenario were examined and simulations were only generated for events which could not be assigned equivalent results (generally +/- 50mm) from other simulated design events or climate change scenarios. The 2015 climate change update includes an equivalency table summarising where it was possible to use previously run design events or climate change scenarios and where new events were run for the update. This is referred to as a 'substitution' or 'equivalency' approach and it is proposed to adopt the same equivalency approach as taken by Hyder in the 2015 climate change update within the Bristol TFRMS modelling work.

To take into account climate change impact on peak fluvial flows, a 10% fluvial flow increase has been adopted for the 2030 epoch, a 20% increase for the 2065 epoch and a 25% increase for the 2115 epoch.

As agreed by BCC on 14 March 2016 following extensive discussions on the definition of the Do Nothing and Do Minimum "baseline scenarios", the Bristol TFRMS baseline includes the new Cumberland Road wall defence (crest level at 9.2m AOD) in place. Table 3 shows the modelling scenarios that would be used, based on the Hyder equivalencies table from the 2015 climate change update. Version 132 of the CAFRA model includes the Cumberland Road defence.

Table 3 - Summary of model runs used to define the 'Do Minimum' baseline for the Bristol TFRMS

EPOCH	JOINT PROBABILITY	FLUVIAL / TIDAL COMBINATION	Tide Level (m AOD) Medium Emissions 95%ile SLR	Equivalencies - with Cumberland Road wall (9.2mOD modelled crest)
2015	1 in 20y	FBASE T020	8.69	CAFRA_132_20yr_Fbase_T020_2015
	1 in 75y	FBASE T075	8.94	CAFRA_132_75yr_Fbase_T075_2015
	1 in 100y	FBASE T100	9.00	CAFRA_132_100yr_Fbase_T100_2015
	1 in 200y	F002 T200	9.13	CAFRA_132_200yr_F002_T200_2015
	1 in 1000y	F012 T1000	9.45	CAFRA_132_1000yr_F012_T1000_2015_0.65a
2030	1 in 20y	FBASE T020	8.77	CAFRA_132_20yr_FBase_T020_2030Med
	1 in 75y	FBASE T075	9.02	Medium Emissions 95%ile SLR 2015 1 in 100 FBASE T100
	1 in 100y	FBASE T100	9.08	Medium Emissions 95%ile SLR 2015 1 in 200 F002 T200
	1 in 200y	F002 T200	9.21	CAFRA_132_200yr_F002_T200_2030Med
	1 in 1000y	F012 T1000	9.53	CAFRA_132_1000yr_F012_T1000_2030Med
2065	1 in 20y	FBASE T020	9.01	Medium Emissions 95%ile SLR 2015 1 in 100 FBASE T100
	1 in 75y	FBASE T075	9.26	CAFRA_132_75yr_FBase_T075_2065Med_0.65a
	1 in 100y	FBASE T100	9.32	CAFRA_132_100yr_FBase_T100_2065Med
	1 in 200y	F002 T200	9.45	Medium Emissions 95%ile SLR 2015 1 in 1000 F012 T1000
	1 in 1000y	F012 T1000	9.77	Medium Emissions 95%ile SLR 2115 1 in 100 FBASE T100
2115	1 in 20y	FBASE T020	9.43	CAFRA_132_20yr_FBase_T020_2115Med
	1 in 75y	FBASE T075	9.68	CAFRA_132_75yr_FBase_T075_2115Med_0.65a
	1 in 100y	FBASE T100	9.74	CAFRA_132_100yr_FBase_T100_2115Med
	1 in 200y	F002 T200	9.87	CAFRA_132_200yr_F002_T200_2115Med
	1 in 1000y	F012 T1000	10.19	CAFRA_132_1000yr_F012_T1000_2115Med

2.2.4 *Relative timing of fluvial and tidal peaks*

As noted above, for the WS3 CAFRA modelling, it was assumed that each fluvial sub-catchment has its own critical storm duration (used to define the ReFH hydrograph shape, but not peak) and that these inflows are phased to coincide with the peak flow on the receiving watercourse (Avon or Frome) which is in turn phased to coincide with the peak of the tidal surge; this is considered a conservative approach but was not subject to detailed sensitivity testing.

Modelling undertaken by MM/EVY as part of WS4 tested four possible relative timing scenarios including peak to peak coincidence and then three quarter tidal phase shifts (i.e. +3.1h, +6.2h, +9.3h) and demonstrated that, for a particular tidal surge level, the relative timing of fluvial and tidal peaks has a more significant impact on water levels in the Floating Harbour than the return period of fluvial events on the Avon and Frome.

Therefore, it is recommended that further sensitivity testing of the relative timing of fluvial and tidal peaks is considered in the Bristol TFRMS, and particularly following any change in the fluvial hydrograph shape used. A suitable and conservative timing scenario will be applied in the model to ensure adequate precaution is adopted in the simulation of flood risk from each given event. In considering the significance of using the gauged fluvial hydrograph data and its effect on the relative timing of fluvial and tidal peaks, the AECOM modelling team will expend some effort assessing the residual uncertainty of model predictions through proportionate sensitivity analysis. However, if the results of the sensitivity tests show a significant impact on the model baseline, it will be necessary to identify and communicate these to Bristol City Council, since this would be outside of agreed scope and it may require additional fee to cover the additional modelling time to rerun the baseline.

2.3 Representation of Floating Harbour

The Floating Harbour is connected to the River Avon through a number of structures, principally the entrance and exit locks at Netham and Cumberland Basin and Bathurst Basin and Totterdown Dam. There are other, overland connections between the Floating Harbour and the Avon over low points in the harbour banks within the city centre. Overtopping of these low points is one of the primary mechanisms for tidal flooding in the city centre.

The Floating Harbour was modelled in 2D in the CAFRA WS3 model (within the ‘Bristol’ domain) to resolve significant stability issues that were encountered when modelling in 1D. There are connections between the 1D model of the Avon and the 2D model of the harbour with 1D-2D SX connections at key structures and overland at the low spots mentioned above. The CAFRA WS3 model begins with an initial water level of 6.2m AOD in the Floating Harbour and provides storage volume above this level. Other structures (bridges) over the Floating Harbour are modelled with a 2D representation.

The representation of the Floating Harbour in the CAFRA WS3 model is described in more detail in the WS3 technical report. Some key features of the modelling approach for the harbour are summarised in the schematic sketch maps in Appendix B.

The addition of a small additional (sweetening) flow between the two lock gates at Netham was applied as an additional stability fix in the model for the Floating Harbour where instability was caused by standing water being trapped between the lock gates during low flows before and after the flood event.

2.4 Other defences

In addition to the flood defence infrastructure included in the CAFRA model as part of the representation of the Floating Harbour system and the various fluvial interceptors, there are two locations in the model area where formal raised flood defences exist, as denoted in the Environment Agency NFCDD data. These are at Albert Road (NGR 360020 172190) on the Avon in the Netham domain and at IKEA (NGR 360930 174950) on the Frome in the Frome domain. These raised defences were modelled using bespoke z-lines representing the surveyed tops of the defences, to raise the model representation above natural or normal bank levels.

The 2014 and 2015 updates of the CAFRA model incorporate new defences currently under construction at Cumberland Road and St Phillips Marsh which were not included in the original 2010-12 WS3 baseline model. It is intended to adopt the 2015 updated model including these new defences and other existing defences (e.g. Pill, Shirehampton and Chapel Pill) as the baseline for the Bristol TFRMS. As noted in EWC005 raised on 06/04/16, and accepted by BCC on 18/04/16, the 1D representation of the defences at Pill and Shirehampton requires additional work to implement a fix that will be undertaken through post-processing of model results using a GIS approach.

As noted in the Bristol TFRMS scope of works, there are a number of defacto defences within the area at risk of tidal flooding in Bristol City Centre which may exert local influences on flood mechanisms. Bristol

City Council is currently surveying these defacto defences with data to be provided in March 2016. When this data is available it will be reviewed and assessed to make a decision over the approach to incorporating these features into the CAFRA WS3 model and the potential requirement and scope for redefining the baseline flood risk for the Bristol TFRMS.

2.5 Model stability

The CAFRA WS3 technical report describes general and location / event specific instabilities encountered during the model development process and the methods that have been used to resolve these instabilities. The general conclusion of this review is that the stability fixes are within the range of what would be considered normal (or acceptable) for a strategic model of this complexity and therefore do not affect the suitability of the CAFRA WS3 model for use in the Bristol TFRMS. The instabilities and stability fixes applied are therefore not discussed in any more detail in this report.

It may be that updating the model to run in new ISIS and TUFLOW software builds (as will be undertaken when they become available during the Bristol TFRMS programme) reduces instabilities previously encountered by Hyder in the WS3 modelling and removes the need for some of the stability fixes previously applied. It is not proposed to address this as a discrete task, but it will be considered during the next modelling tasks of the TFRMS.

Given the complexity of the model and the difficulties encountered by Hyder during the WS3 modelling, it is possible that further modelling to be undertaken by AECOM as part of the TFRMS may reveal new instabilities or exacerbate existing instabilities in the model. Small instabilities that can be easily fixed by the AECOM modelling team will be addressed, as necessary, through the modelling process, to consider residual uncertainty of predictions using proportionate sensitivity analysis. However, there is a risk of more significant instabilities occurring, which may not be possible fix, within the current scope; we will identify and communicate these to Bristol City Council, because these fixes may require additional fee to cover the additional modelling time required to fix them. It is not possible to fully mitigate these risks in advance, but in order to get a better appreciation of the stability of the model during this review phase, AECOM have re-run some of the 2015 update scenarios and have also tested a method for incorporating a possible tidal barrier into the model. Following this testing, it is possible to have reasonable confidence that no significant instabilities will be encountered during the TFRMS process, but as noted above, this cannot be ruled out.

2.6 Model calibration

The CAFRA WS3 model has been calibrated against three tidal and three fluvial events on the River Avon, the results of which are reported in the WS3 technical report. No calibration was undertaken on the River Frome as the previous Frome model had already been successfully calibrated. The calibration of the River Avon model focussed on Netham Weir and the results showed that, particularly for the tidal events, the model was well calibrated at the weir and downstream but that upstream of the weir, the model was over-estimating levels compared to observed data, particularly at low tides. It was considered that this poorer model performance upstream of the weir may have been a consequence of the approach taken to representing the weir and this was investigated in more detail, see below.

Given the focus of model calibration work at Netham Weir, there is obviously a relative decrease in confidence in the model away from that location, either upstream or downstream. However, it is considered that the model calibration is sufficient in the main area of interest (i.e. the area of tidally dominated flood risk) and no further work is proposed to be undertaken in this aspect in the Bristol TFRMS.

2.6.1 *Netham Weir*

Netham Weir is a V-shaped (labyrinth) weir which broadly marks the tidal limit of the River Avon in Bristol. Modelling of labyrinth weirs, particularly in previous versions of ISIS, is inherently difficult because of the significant difference in effective weir length between non-drowned and drowned flow conditions.

The previous Bristol Avon 1D-2D model used a stage-discharge (QH) relationship to represent the effect of Netham Weir. The QH relationship in the previous model had been derived from earlier 3D modelling of the weir structure and was retained in the CAFRA WS3 model.

In light of the calibration issues at the weir noted above, the representation of the weir was considered further by Hyder as part of WS3 where alternative modelling approaches were considered, notably the use of an ISIS inline spill unit with varying spill coefficients tested. An attempt was made to verify the existing QH relationship using a 2D model of the channel but it was not possible to get a stable representation of the weir as levels rose (beyond drowning) on either a 2m or 4m grid. The only conclusion that could be made from the unstable results was that there was nothing significantly erroneous with the 1D QH relationship in the previous Bristol Avon model

Therefore CAFRA WS3 investigation concluded that the existing approach of representing the weir with a 1D QH relationship was appropriate. However the WS3 report did recommend that when newer versions of ISIS were released including a labyrinth weir unit, further investigation of modelling approaches at Netham should be made. This recommendation does not appear to have been taken up in any of the more recent CAFRA modelling updates. However, further work on the representation of this structure is not considered essential for the Bristol TFRMS as the WS3 CAFRA model has been shown to calibrate satisfactorily against observed data for tidal events in the main focus area for the strategy.

2.7 AECOM Model Runs

As noted above and as part of the baseline model review AECOM have undertaken a number of model runs to verify that the correct CAFRA model files have been provided to replicate previously undertaken model scenarios. The AECOM verification process has focussed on the tide level events and climate change epochs that are of greatest concern to the Bristol TFRMS and have used the 2015 Update to the CAFRA model which includes the new Cumberland Road defence; this is referred to as version 132 of the CAFRA model.

At the time of writing it had not been possible to re-run the low return period events (from the 2014 update modelling) and the 2030 climate change epoch runs (from the 2015 update modelling) because of some minor pieces of missing information. Communication from the Hyder modeller has filled in these gaps which should now allow AECOM to run these outstanding events.

Therefore at the time of writing AECOM have all the required files to re-run any of the 2015 CAFRA update model runs which may be required to define the baseline and which will form the basis of all further modelling undertaken by AECOM for the TFRMS.

3. EXISTING FLOOD RISK IN BRISTOL

3.1 Simulation Length and Timings of Flood Peaks

Figure 1 shows an example of in-channel modelled water levels from the ISIS component of the original WS3 CAFRA model. In-channel modelled water levels are shown at ISIS node AV7_7782 in the River Avon, between the Clifton Suspension Bridge and the Floating Harbour. The model is run for 70 hours, beginning with time = 0h on a low tide. The model is run for six high tides, with the peak surge level occurring on the fourth peak, 46 hours into the simulation.

The results shown in Figure 1 are for a 200 year return period surge level combined with a 2 year return period fluvial event on the Avon and Frome for present day (2010), 2060 and 2110. These results are an example from the original WS3 CAFRA model, not from the 2015 climate change update. TUFLOW (2D) mapped outputs are available from 30 hours into the simulation (they are not written for the early part of the simulation in order to manage output file size).

Figure 2 shows, at the same scale and for the same events as Figure 1, an example of modelled water levels from the ISIS model at Hanham, upstream of the Floating Harbour, showing the duration of the fluvial hydrograph on the River Avon below the tidal peaks.

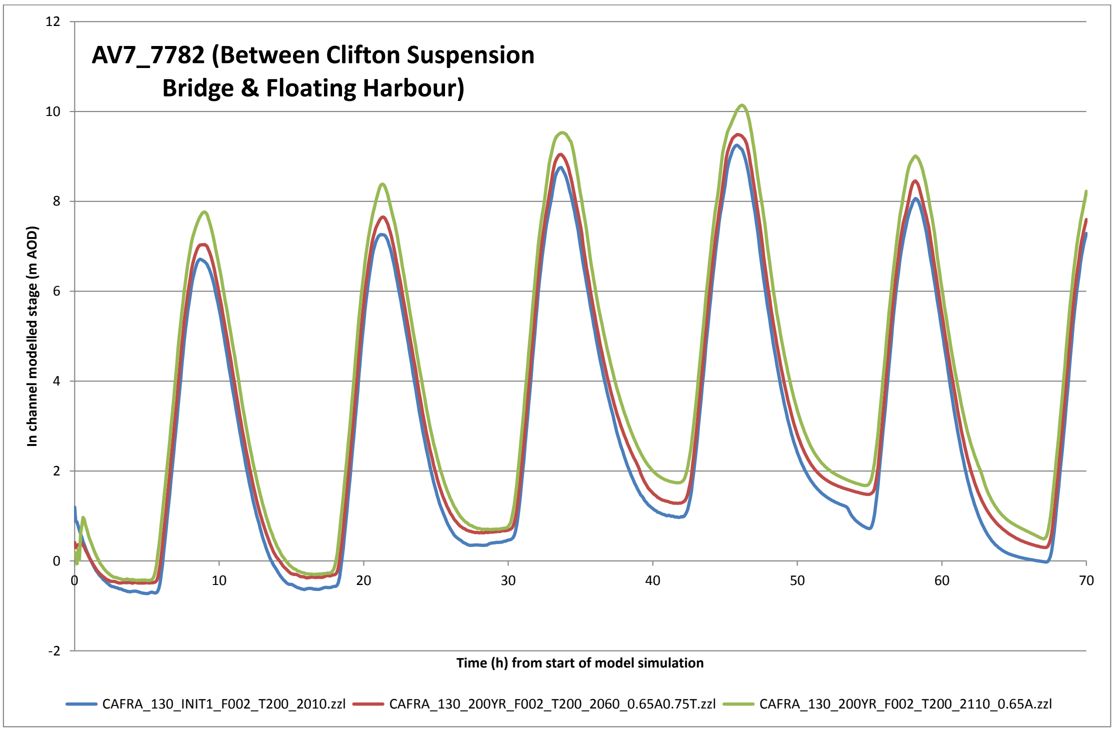


Figure 1 - Example of in-channel modelled water levels from ISIS model downstream of Floating Harbour

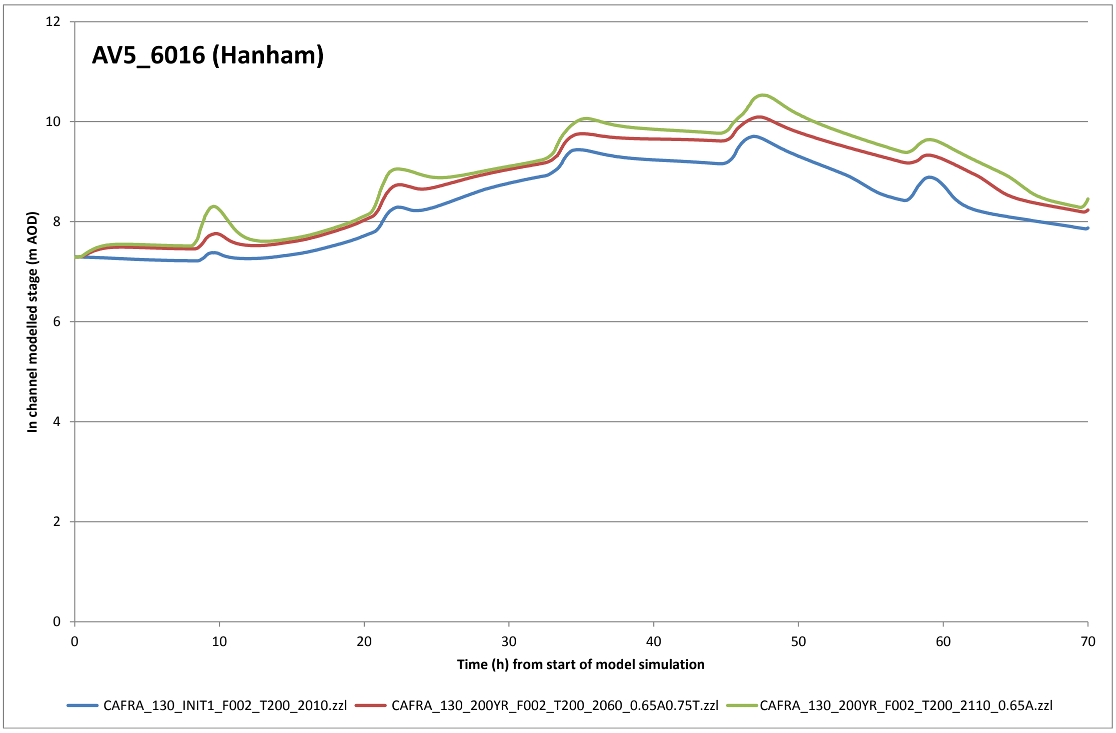


Figure 2 - Example of in-channel modelled water levels from ISIS model upstream of Floating Harbour at Hanham

3.2 Modelled Water Levels in the Floating Harbour

The model starts with an initial water level in the 2D representation of the Floating Harbour at 6.2m AOD and subsequently the water level in the Floating Harbour is controlled by flow overtopping low points between the Avon and the harbour, e.g. Cumberland Road and by flow overtopping the closed lock gates on the highest surge tides. In the 2010 model run, at the west end of the Floating Harbour, tidal flows from the Avon first overtop and enter the harbour over Cumberland Road on the high tide before the highest surge.

Table 4 shows the maximum modelled water levels at two locations in the Floating Harbour, extracted from the ISIS model results from the original WS3 CAFRA model. The model results shown are for a 200 year return period surge level combined with a 2 year return period fluvial event on the Avon and Frome for present day (2010), 2060 and 2110.

Table 4 - Modelled Water Levels in the Floating Harbour

Tidal surge event	Fluvial event	Epoch	Underfall Sluices	Netham Lock
			ISIS node: UFS1aS / UFS2aS	FH5990
200 year	2 year	2010	8.59 m AOD	9.35 m AOD
		2060	9.38 m AOD	9.56 m AOD
		2110	10.11 m AOD	10.30 m AOD

Once the tidal surge ingresses into the Floating Harbour, the available storage volume fills and water levels overtop the harbour walls causing flooding in the city centre as described in Section 3.3.

The CAFRA WS3 and WS4 modelling demonstrated a strong relationship between the annual probability of the tidal surge event on the Avon and modelled water levels in the Floating Harbour due to the large surge volume incoming up the Avon and the connections between the Floating Harbour and the tidal Avon, across a series of low points.

3.3 Flood Mechanisms in Bristol City Centre

The CAFRA WS3 modelling demonstrated that the primary flood risk to Bristol City Centre is from tidal inundation and this is the main source of flood risk under consideration in the Bristol TFRMS. The three main flooding mechanisms in the city highlighted by the CAFRA modelling are:

- Overtopping from the Tidal Avon into the Floating Harbour over low points at Junction Lock, Avon Crescent / Underfall Yard and Bathurst Basin;
- Overtopping onto St Phillips via Totterdown Dam and Victor Street; and
- Overtopping into low lying land at Netham.

The present day (2010) Standard of Protection (SoP) assessment undertaken as part of CAFRA indicated that the majority of frontages in Bristol have less than a 1 in 20 year standard (including best practice allowances for uncertainty), the smallest event included in the original CAFRA modelling. It is noted that the Bristol TFRMS will consider events of a lower magnitude / higher frequency in the damages assessment. Some assessment of lower magnitude events was included in the 2014 CAFRA updates. When actual overtopping levels are considered without allowances for uncertainty, some frontages may not even overtop in a 1,000 year event. Plan figures representing the modelled onset of flooding at frontages shall be considered as to their usefulness during the next stage of the River Avon TFRMS.

3.3.1 *Impact of Climate Change*

The original CAFRA WS3 modelling demonstrated that there would be a seven-fold increase in the number of properties flooded for a 1 in 200 year tidal event (combined with a 1 in 10 year fluvial event on the Avon) between the present day and 2110.

4. RECOMMENDATIONS FOR USE OF THE CAFRA MODEL IN THE BRISTOL TFRMS AND RESIDUAL UNCERTAINTIES

4.1 Baseline scenario – Do Nothing

4.1.1 *Definition*

Do Nothing – It is important to understand what would happen if no further work was undertaken to address flood risk in Bristol (i.e. the 'walk away' option). Doing nothing is not considered a viable long term approach in Bristol but has been included as it provides a hypothetical baseline against which all other measures and strategic options can be compared.

Under this approach, all maintenance, repair and renewal work of existing flood defences, together with assets whose function influences flood risk (e.g. lock gates) would cease immediately. There would be no investment in asset maintenance from the present day onwards. If this option were adopted, existing flood defences would deteriorate, and any damage would not be repaired. It is assumed that all water level management assets (e.g. lock gates, sluices and lock systems) would fail and remain in an open position throughout the duration of the appraisal period. This would result in the defence system being in a poor condition immediately and this would further deteriorate over time.

As sea levels rise and the defence condition deteriorates, flood risk would increase significantly from both failure of the defences and through inundation over areas of low-lying topography. Eventually many of the existing residential and commercial assets within Bristol would be written off. Economic prosperity, opportunities for growth and community viability in Bristol would significantly decrease, and therefore this approach would be politically unacceptable.

This approach would result in the escalation of uncertainty and this, with the loss of investor confidence, and lack of policy or infrastructure solution would result in the whole city and environs being prejudiced, and investment blocked or withdrawn.

For a detailed breakdown of the assumed time periods in which specific defences are likely to fail under the Do Nothing scenario please refer to the Baseline scenarios technical note (Appendix C). This note also defines the assumptions and modelling representation of a Do Minimum scenario.

4.2 Defences

It is recommended that the new defences currently under construction at Cumberland Road, and being considered in the St Phillips Marsh area, are included in the 'Do Minimum' baseline modelling for the Bristol TFRMS. These defences have been modelled in the 2014 and 2015 CAFRA updates. The representation of these defences in the model updates will be reviewed against 'as built' or final design drawings (whichever are available) to determine whether the previous model representation is sufficient or if a refined representation is needed in light of the final design.

When the defacto defence survey information becomes available in March 2016, a decision will be made, in partnership with BCC, about whether / how to incorporate these defences into a refined baseline model.

4.3 Climate Change – Sea Level Rise Allowances

It is recommended that the **UKCP09 Medium Emissions 95%ile sea level rise allowances** are adopted for use in underpinning the economic appraisal for the Bristol TFRMS. These allowances for sea level rise allowances have been modelled in the 2015 CAFRA update work and it is recommended that tidal surge boundary conditions used in that CAFRA 2015 update work are adopted for the TFRMS modelling. Upper and lower end estimates of sea level rise will also be simulated and considered in the sensitivity testing of options as required.

4.4 Fluvial Event Hydrographs

The WS4 hydrological analysis undertaken by Mott MacDonald / Edenvale Young has demonstrated that the ReFH design event hydrographs used by Hyder in the WS2/WS3 modelling underestimate the volume of flow in fluvial events, compared to what has been observed in gauged data from historic events. This appears to be due to the fact the CAFRA WS2/WS3 hydrographs are based on FEH catchment descriptors and do not make used of gauged flood data. The WS4 technical work demonstrated that the ReFH design event hydrographs may be under-estimating the actual flow volume by a factor of three to four.

The conclusion of this review for the Bristol TFRMS is that this is a **potentially significant** issue for the study because the operation and success of a barrier is dependent on the volume of fluvial inflow that might have to be stored behind the barrier when closed.

Therefore it is recommended that some **sensitivity testing** is undertaken using the 2015 updated CAFRA model to assess the impact on flood levels in the city centre if the ReFH design event hydrographs used by Hyder in the WS3 modelling are replaced with the Mott MacDonald / Edenvale Young standardised hydrograph shapes derived in the WS4 modelling.

The results of a few sensitivity tests can then be used to determine whether all baseline and climate change scenarios need to be re-run with the WS4 standardised hydrograph inflows; any potential need for additional fee as a consequence of the results of sensitivity testing would be communicated to Bristol City Council.

4.5 Relative Timing of Fluvial and Tidal Peaks

The WS2 hydrological assessment adopted individual critical storm durations for each contributing fluvial catchment, rather than applying a single catchment wide storm duration across the whole model area. These event durations were used to define the ReFH design event hydrograph shapes that were fitted to the FEH statistical peak flow estimates. See section 2.2.1 above for comments on these hydrograph shapes.

In the CAFRA WS3 modelling, the inflow hydrographs from these contributing watercourses were phased so that the peak coincided with peak flows in the receiving watercourse (the Avon or Frome) and, in turn, so that the peak flows on the Frome and Avon coincided with the peak of the tidal surge in the Floating Harbour. Given the number of design event simulations and sensitivity test runs already undertaken within WS3, there was very limited sensitivity testing of this assumption.

The hydraulic modelling undertaken by Mott MacDonald / Edenvale Young in WS4 using their 1D model tested a large number of potential boundary combinations including various phasing shifts on the fluvial and tidal peaks demonstrated that in some parts of the model, including the Floating Harbour, there is a **strong dependency** between the modelled flood level and the phasing shift.

Therefore, the conclusion of this review is that some further (but limited) **sensitivity testing** should be considered using the updated CAFRA WS3 modelling to assess the impact of the relative timings of fluvial and tidal peaks on modelled flood levels in the City area. The results of these targeted sensitivity tests can then be used to determine whether all baseline and climate change scenarios need to be re-run with a revised assumption on peak timing coincidence to redefine the baseline.

It is recommended that this sensitivity testing is undertaken after the fluvial event hydrograph sensitivity testing recommended above, in Section 0. This is because the effect of the relative timing of fluvial and tidal peaks will depend on the duration of the fluvial event hydrographs so it would be beneficial to have determined the appropriate inflow hydrograph shapes before assessing the influence of coincidence or phasing of peaks. Any potential need for additional fee as a consequence of the results of sensitivity testing of the relative timing of fluvial and tidal peaks would be communicated to Bristol City Council.

4.6 Joint Probability

Eden Vale Young (EVY) expressed concerns that the joint probability approach used by Hyder in the CAFRA WS3 model to determine appropriate fluvial/tidal combinations for each joint probability scenario is too simplistic, given the complexity and interdependence of flood mechanisms in Bristol.

The conclusion of this review for the Bristol TFRMS is that whilst the joint probability method could be developed with more sophisticated analysis, this is **not necessary** for the TFRMS which is focussed on tidal flooding and on the development of a strategy to reduce tidal flood risk in the city centre. The assignment of a joint probability to any particular fluvial and tidal event combination is not essential for the TFRMS and the assessment methodology proposed for it.

However, it will be necessary to select an appropriate fluvial event (or events) to combine with the range of tidal surge levels to be tested in the assessment. This becomes more significant in the testing of barrier options where the volume of fluvial input to be stored within the system, behind the barrier is a critical factor in the success of the barrier at mitigating flood risk. The AECOM modelling team will give some consideration to barrier storage volume as part of investigating the residual uncertainty of model predictions through proportionate sensitivity analysis. However, if barrier storage test runs lead to model instability, these will be identified and communicated to Bristol City Council, since significant instabilities would be outside of agreed scope. As described in Section 2.3, these may not be possible to fix and could require additional fee to cover the additional modelling time required to resolve them.

4.7 Use of Edenvale Young 1D Model

The Edenvale Young 1D model has now been made available and its potential use has been reviewed by AECOM. A detailed modelling review or testing exercise has not currently been undertaken on the model.

This 1D model runs significantly faster than the existing CAFRA WS3 model but it does not provide the spatial flood depth information required for the economic appraisal within the TFRMS.

However, the merit of reviewing and drawing upon the significant range of runs previously completed is recognised and this may assist in option appraisal. There could be merit in utilising and running this 1D model at a subsequent stage in the project (e.g. shortlist option testing) if it is deemed to be a more efficient tool to test options.

Therefore it is proposed that the updated CAFRA (2015) model is used as the main modelling tool to support Strategy development and provide data for the economic appraisal. This approach may be reviewed at a later stage in the project if any of the sensitivity tests and other model changes recommended above cause stability problems in the CAFRA WS3 model. It is envisaged that AECOM shall review our approach to revisiting the EVY model during the option testing and shortlisting to preferred option phase.

4.8 Summary

This final section of the document collates the outcomes of this review of the CAFRA model in relation to the original questions set out in Section 1.2 of this report (see Table 5). More detail on some of these points is covered earlier in this report.

Table 5 - Review Summary

Does the model run and on which software versions?	AECOM has successfully re-run the model for a number of scenarios from the 2015 update modelling (including the Cumberland Road wall). At the time of writing it has not been possible to re-run all simulations from that update, but the missing information has now been provided to run the final simulations. AECOM has run the model on the latest versions of ISIS (3.7) and TUFLOW (2013-12-AE) It is noted that a significant update to the TUFLOW computational engine is expected in early 2016 and it recommended that the TFRMS modelling moves to this newer version once available.
How many ISIS nodes are there in the model? (Implications of model licences)	There are more than 2,500 ISIS nodes in the CAFRA model and it therefore requires an unlimited nodes ISIS licence to simulate.
How long does it take to run?	The model runs from 0 to 70h (five high tides). Model simulations have been taking between 30 – 50 hours on AECOM modelling PCs. The variability in run times is a function of the number of wet cells in the model runs, i.e. the model takes longer to run the highest events.
How many tidal cycles does the current setup include? How has the surge been applied?	The 70 hour model simulation includes five high tides with the surge applied across the 3rd, 4th and 5th high tide (highest on the 4th). Early investigations suggest it may be possible to shorten the model run times for tidal events by removing the first (and possibly second) high tide from the run times. This will be fully tested by AECOM during the TFRMS development to ensure that any change in run length does not affect model results.
What are the boundaries on the model (tidal and fluvial)? How have the boundaries been applied?	A tidal boundary is applied at the downstream extent of the ISIS part of the CAFRA model. There are a number of fluvial boundaries applied at the upstream extents of each watercourse modelled. The boundaries have been applied such that the peak fluvial flow on each contributing watercourse coincides with the peak flow on the receiving watercourse (Avon or Frome) which in turn coincides with the peak surge on the Avon. As noted in the report, during the WS4 investigations, Edenvale Young raised some concerns in relation to the fluvial hydrograph shape on the River Avon and it is recommended that sensitivity testing is undertaken within the TFRMS.
How has the barrier been modelled?	The barrier was not modelled in the CAFRA ISIS-TUFLOW model. It has been modelled in a 1D only model by Edenvale Young as part of an initial feasibility study. The EVY model WS4 model has not been reviewed in detail by AECOM at the time of writing given WS3 model being used as the primary modelling tool. As part of this baseline review AECOM has tested a method for representing a potential tidal barrier in the CAFRA ISIS-TUFLOW model which has demonstrated that it is possible to

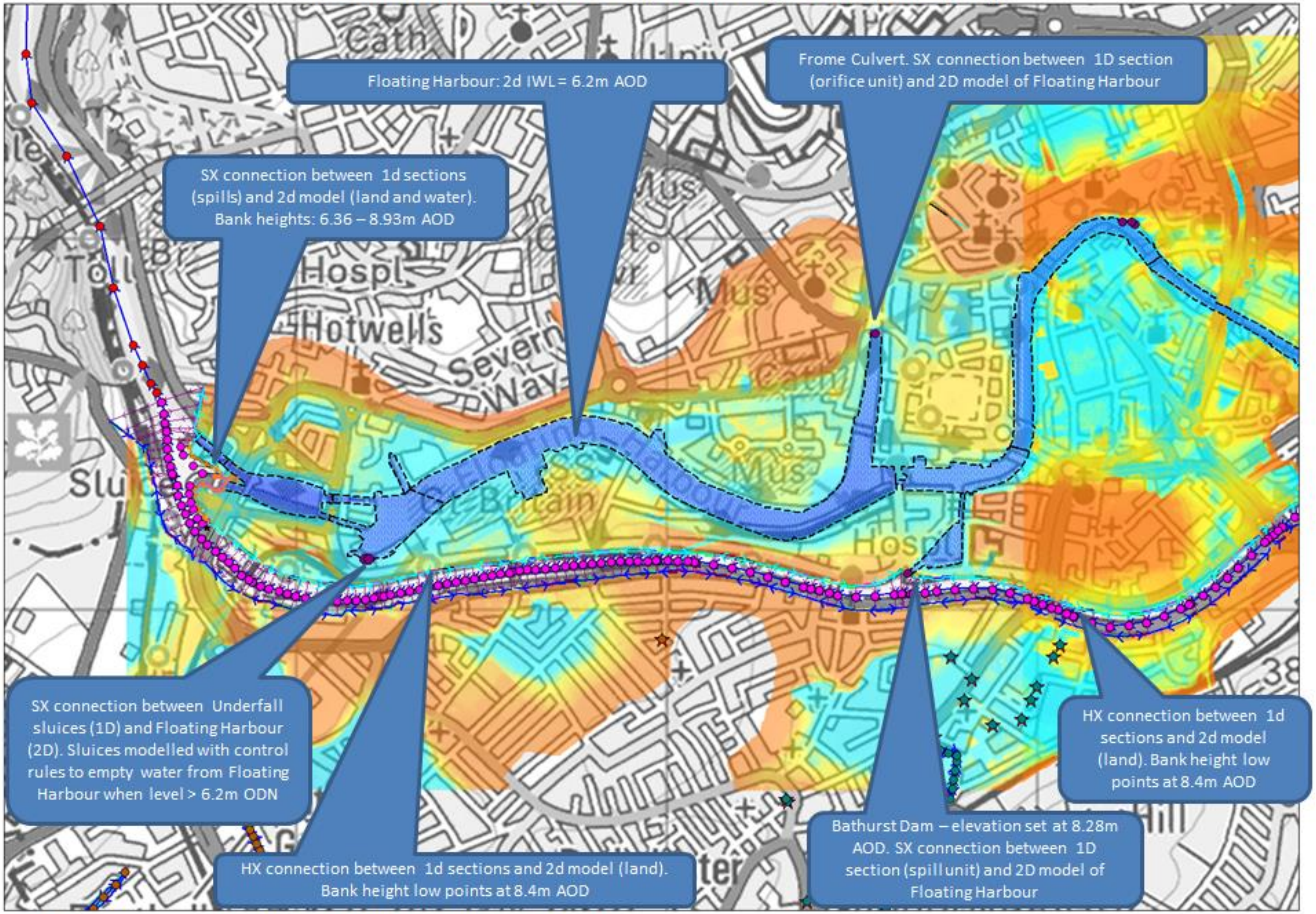
	use the CAFRA ISIS-TUFLOW model to test barrier options. However the WS4 model may be adopted by AECOM to test options where there is merit in doing so.
How are existing defences represented in the model?	Existing and new defences are included in the model through topographical modifications on the 2D domains (using TUFLOW 'Z lines' to enforce defence crest elevations). Some undefended scenarios were run in CAFRA for the purpose of Environment Agency Flood Zone mapping.
What water levels / scenarios have been run? What joint probability combinations have been run?	**Error! Reference source not found.** and **Error! Reference source not found.** in this report list some of the scenarios that were run in the 2015 CAFRA update modelling which would be used in the TFRMS. The highest event run in the CAFRA model is a 1000 year return period tidal surge projected to the 2115 climate change epoch. The CAFRA joint probability analysis involved running five different fluvial and tidal combinations for each required joint probability event. This demonstrated that the tidally dominated events created the highest risk in Bristol city Centre and it is these tidally dominated events that will be the focus of the TFRMS modelling. The TFRMS will also need to proportionately consider some fluvially dominated events when testing strategy options including a tidal barrier which would need to store fluvial events. The TFRMS economic assessment will need results of low return period events (e.g. 2 year) up to extreme events (e.g. 1,000 year)
Have any breach scenarios been tested?	No, there do not appear to have been any breach tests in the CAFRA model.
Has 'good modelling practice' been adopted throughout the model?	Yes. The extreme complexity of this model has necessitated some generalised and some location / event specific stability fixes in the CAFRA model. Those fixes are considered by AECOM to be reasonable for a model of this nature (but would not be in a simpler model).
Are there any areas which need increased resolution / extension / updates?	No, from this review, it seems that the resolution and extents of the CAFRA model are suitable for using this model in the TFRMS.
How stable is the model?	The model is sufficiently stable to run the 2015 CAFRA simulations. However, it is recognised that Hyder encountered several stability issues during the development of the CAFRA model. Some residual instabilities remain (particularly obvious in the early parts of the model simulations) which does present a risk for the further use of the model in this study.

APPENDIX A OVERVIEW OF CAFRA MODEL EXTENTS TAKEN FROM HYDER WS4 REPORT

When creating the final PDF insert Figure A1 (A3 landscape page) from \\br-man-002\SW South Projects\Flood Risk Assessment\PROJECTS\60478613 - R Avon TFRMS\0400 Info in\2015-10-15 ITT Add Info\App 2 Supp Info\2012 CAFRA\ANNEX E WORKSTREAM 3 RPT\App A Figures

APPENDIX B SCHEMATIC OF CAFRA MODEL SETUP IN THE FLOATING HARBOUR

Schematic of CAFRA Model Setup of Floating Harbour (West part)



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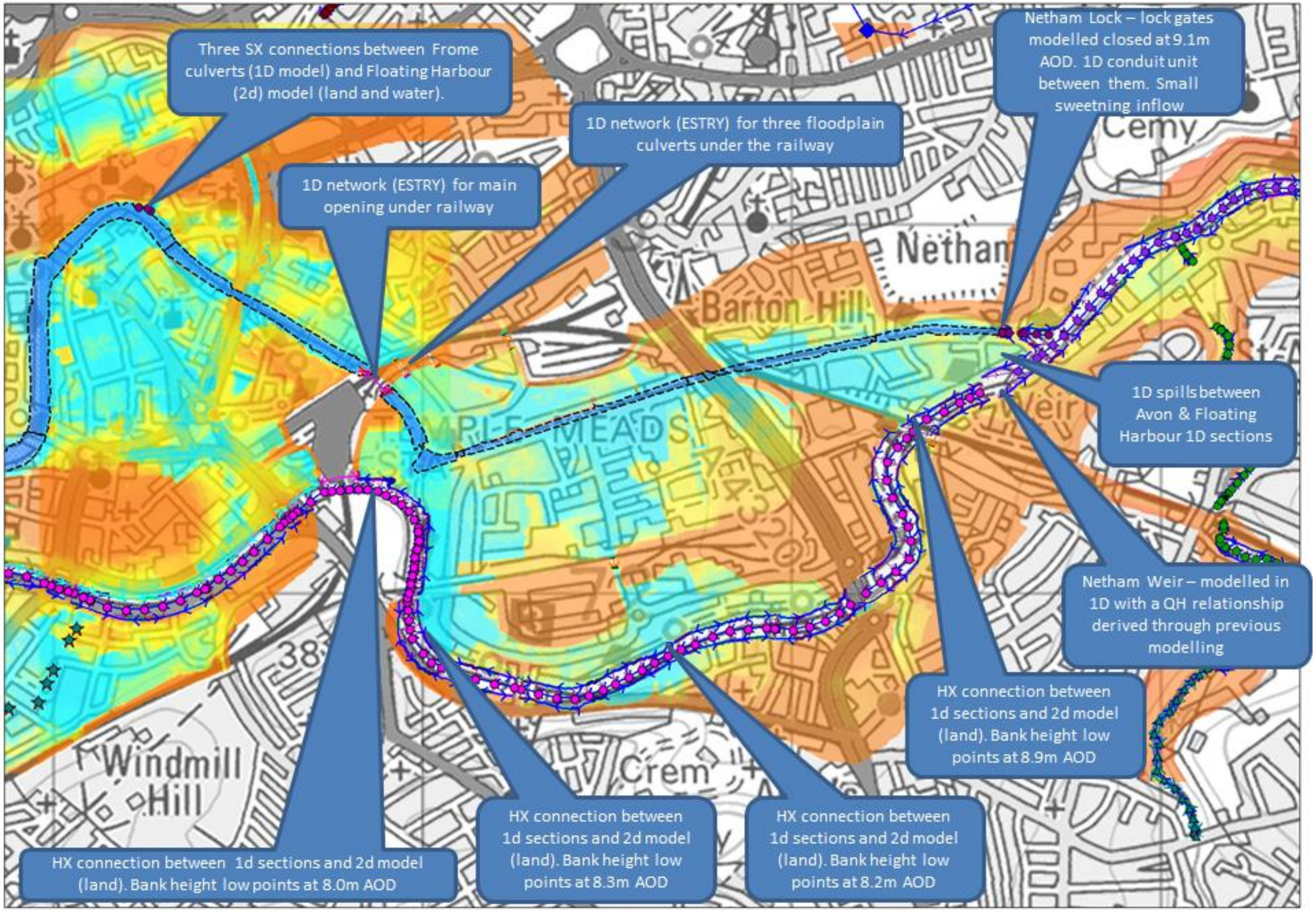
Schematic of CAFRA Model Setup of Floating Harbour (East part)



Appendix C - River Avon TFRMS – Baseline Scenarios Note

Overview

This note sets out the definition of baseline scenarios for the Strategy and sets out the approach to representation for the simulation of associated flood risk to support the damage assessment as part of the baseline economic appraisal.

The following two baseline scenarios will be adopted in the Strategy (see full definitions and descriptions below):

- Do Nothing
- Do minimum

In accordance with FCERM-AG principles these will provide scenarios against which 'do something' or improve options can be compared. The outputs of the damage assessments for these scenarios undertaken as part of the economic appraisal will provide the justification for implementing the Strategy preferred options, and will describe the problem being faced.

Definitions of Baseline Scenarios

Do Nothing
It is important to understand what would happen if no further work was undertaken to address flood risks in Bristol (i.e. the 'walk away' option). This is a hypothetical baseline against which all other options should be compared.

All maintenance, repair and renewal work of existing flood defences, together with assets whose function influences flood risk e.g. lock gate, throughout the study area would cease immediately. There would be no investment in asset maintenance from the present day onwards. If this option were adopted existing flood defences would deteriorate, and any damage would not be repaired. . It is assumed that all water level management assets (e.g. lock gates, sluices and lock systems) and would fail and remain in an open position throughout the duration of the appraisal period. This would result in the defence system being in poor condition immediately and this would further deteriorate over time.

As sea levels rise and the defence deteriorates, flood risk would increase significantly from failure of defences and through inundation over the low-lying topography. Eventually many of the existing residential and commercial assets would be written off with abandonment of much of the centre of Bristol.

This approach would result in the escalation of uncertainty and this, with the loss of investor confidence, and lack of policy or infrastructure solution will result in the whole city and environs being prejudiced, and investment will be blocked or will be withdrawn. The community will face deteriorating property values and businesses will relocate. This will result in decline in its economic prospects and community viability which will be politically unacceptable.

Do Minimum
This option is effectively representing what happens if we maintain the 'status quo'. This involves a continuation of maintenance of existing Floating Harbour water level control structures and raised defences throughout the duration of the Strategy appraisal period (2015 – 2115).

It is assumed that under this scenario the functioning of the Floating Harbour water level control structures will be sustained until 2115, and maintenance will include improving the resilience of MEICA control systems and electrical systems to flooding. Like for like replacement of mechanical infrastructure e.g. lock gates is assumed but with no improvements in performance to account for sea level rise. The raised defences within the city and at Avonmouth (including Pill and Shirehampton) will be maintained to ensure their flood defence function continues; however, the defences will not be raised and consequently the standard of flood protection will fall over time, in response to sea level rise.

Timeline of asset failure under each baseline scenario and the assumptions

The tables below present the time epochs in which the existing flood defence assets within the Strategy area are assumed to fail. A table is provided for both the Do Nothing and Do Minimum scenarios and the asset failures will be incorporated into the baseline modelling runs.

In addition to the information presented in the tables, a number of general assumptions have been made in defining the scenario representation. These are discussed below:

For the Do Nothing scenario, following the initial failure of an asset, it is assumed that the asset will remain in a failed condition for the remainder of the Strategy appraisal period. For instance, if an asset is expected to fail in 2015 by breaching (i.e. in epoch 1), it is assumed that this asset will continue to be breached during epochs 2 and 3 of the Strategy appraisal period.

- For the Do Nothing scenario, it is assumed that the Floating Harbour water level controls such as the flood gates, sluices and lock systems (i.e. the ‘moving parts’) will initially fail in an ‘open position’ and will remain so for the duration of the appraisal period. This is because in the CAFRA WS4 modelling outputs demonstrate that the spatial extent and depth of flooding results under this scenario

- Given the minimal impact on tidal flood risk, the failure of specific culverts (e.g. Mynles culvert) will not be considered.

- No consideration has been made to the potential failure of the fluvial water interceptor sewers (such as the NSWI) which are in operation within the study area. These assets do not directly impact the tidal flood risk and their potential failure has therefore been excluded from this assessment.

- No consideration has been made to the potential failure of the Floating Harbour retaining walls, channel and dockside walls. There is a considerable risk under the Do Nothing scenario that water levels in the Floating Harbour will dramatically fall (i.e. drawdown) following failure of the water level control structures (i.e. the ‘moving parts’). It is likely that this drop in water level could lead to the collapse of retaining and dockside walls. However, this is not expected to increase the tidal flood risk (as land levels behind the walls are equivalent or higher) and has therefore not been considered in any more detail in this assessment.

- The defences along the River Frome, Brislington Brook and Longmore Brook, such as at IKEA, Abercombe Walk, Ashton Vale and Lyons Court Road will be kept in position (i.e. they will not be breached) in the Strategy baseline model runs as the flood risk in these areas is not considered to be tidally dominated.

Do Nothing

Time period	Asset Location and descriptions	Comments / Assumptions	Representation / failure commentary for modelling
2015 to 2065	Raised defences		
	- Avonbank Industrial Estate (immediately to the W of the M5); re-graded bank / embankment	- BCC FRAR condition: poor.	Outside of previous study area. Covered in Severnside Strategy area. Likely to fail in this epoch but failure not considered in this Strategy. Options for management of embankment will still be evaluated.
	- Totterdown (Mid to N side of site, Albert Road): masonry wall, brick wall, concrete wall	- Poor condition / failing. Local issues / gaps in defences. Failure by breaching in model runs.	Defences removed in undefended runs, Modelling to assume failure of these defences by breaching.
	- Pill and Shirehampton; raised flood gates	- Manually operated.	Modelling to assume that gates are left open during flood events.
	Floating Harbour water level control structures		
	- Netham Lock gates / sluice system	- New lock gate so condition: good. Sluice paddles and operating system condition: poor. Low resilience of operating system to flooding.	Modelling to assume failure in 'open' position across all epochs.
	- Totterdown Dam / lock system	- No available info. Construction form unknown having been infilled and covered. Assume condition: Fair.	Modelling to assume failure in 'open' position across all epochs.
	- Nova dam and sluices	- Condition: fair. Sluices and electricical system condition: very good and resilient to flooding. Standby generator may be vulnerable to flooding.	Modelling to assume failure in 'open' position across all epochs
	- Junction Lock gates and sluices	- New stop gates, upper gates and sluices condition: very good. Old backup gates condition: poor. Inundated during high springs.	Modelling to assume failure in 'open' position across all epochs.
	- Entrance Lock gates	- Fairly resilient to flooding.	Modelling to assume failure in 'open' position across all epochs.
	- Underfall Yard; culverts, sluices and gates	Condition concern. High vulnerability to flooding.	Modelling to assume failure in 'open' position across all epochs.
	- Brunel Dam sluices / gates	Condition concern. High vulnerability to flooding.	Modelling to assume failure in 'open' position across all epochs.

Time period	Asset Location and descriptions	Comments / Assumptions	Representation / failure commentary for modelling
	- BCC outfalls	- Assumed open.	CAFRA scenarios run with sluices open to assess impact on drainage.
2065 to 2115	Raised defences - Avonbank Industrial Estate (immediately to the W of the M4); wall + embankment	- BCC FRAR condition: fair.	- Outside of previous study area. Covered in Severnside Strategy area. Likely to fail in this epoch but failure not considered in this Strategy. Options for management of embankment will still be evaluated.
	- Marine Parade (Pill); masonry flood wall	- BCC FRAR condition: good.	Modelling to assume failure by breaching. Outside of previous study area.
	- Marine Parade (Pill): embankment	- BCC FRAR condition: fair.	Modelling to assume failure by breaching. Outside of previous study area.
	- Shirehampton Sailing Club; embankment	- BCC FRAR condition: good.	Modelling to assume failure by breaching. Outside of previous study area.
	- Shirehampton Sailing Club; flood wall	- BCC FRAR condition: good.	Modelling to assume failure by breaching. Outside of previous study area.
	- N side of Totterdown (previous construction site); wall	- BCC FRAR condition: fair	Modelling to assume failure by breaching.
	- Under footbridge at Bristol RSPCA Dog Home (within Totterdown defences); concrete flood wall	- BCC FRAR condition: fair. Failure by breaching.	Modelling to assume failure by breaching. Defence removed in previous undefended model runs.
	- Downstream of RSPCA Dog Home (within Totterdown defences): embankment	- New construction in 2003. BCC FRAR condition: good.	Modelling to assume failure by breaching. Defence removed in previous undefended model runs.
	- Downstream of RSPCA Dog Home (within Totterdown defecnes): wall	- BCC FRAR condition: fair.	Modelling to assume failure by breaching.
	- Cumberland Road; wall	- New structure, < 50 year design life without maintenance	Modelling to assume failure by breaching
	- New cut; retaining wall and drainage (900m)	- Risk to Cumberland Road wall. Small slope failure in 2014. Recommendations to replace drainage	Modelling to assume failure by breaching.

Time period	Asset Location and descriptions	Comments / Assumptions	Representation / failure commentary for modelling
	- Netham weir masonry sub-structure, concrete crest and rock apron	- Sub-structure and concrete crest currently in fair condition. Rock apron in poor condition. Consequence of rock apron failure likely to lead to undermining and failure of weir itself.	Assumed that the rock apron will fail in 2065, which will undermine and lead to failure of the weir itself. However in the Do Nothing model simulations the weir structure will not be breached as the flood risk arising from failure of the structure will be represented by the failure open of the Netham gates and sluices in epoch 3.
	Floating Harbour water level control structures	Assume removal / open failure of all mechanical control structures (as per epoch 1 and 2)	Removal or breaching of all control structures (open failure)

Do Minimum

Time period	Asset Description and Location	Comments / Assumptions	Representation / model commentary
2015 - 2115	All assets functioning as present day (Floating Harbour Water Level Control Structures, and Raised Defences)	Assumed that maintenance work would be carried out to ensure the continued operation and improved resilience of the Floating Harbour Water level control structures (i.e raising level of electrical control systems during maintenance). Raised defences to be maintained / reconstructed to the existing standard of flood protection to ensure that the flood defence function of the assets is sustained.	Yes –CAFRA WS3/4 include continued operation of MEICA systems and presence of raised defences. Majority of runs within equivalencies outputs. However, a few additional runs for low RP events.

Modelling Approach

Some scenarios and failures of defence assets are covered within existing modelling for a selection of return periods / epochs. For consistency and completeness it is proposed to run Do Nothing scenarios for required return periods at each time point to inform the economic appraisal. However, on further inspection if beneficial re-use of existing model outputs can be achieved, opportunities to do this will be sought to minimise new modelling runs.

If DTM or model updates are required (e.g. following an exercise of LiDAR validation and ground-truthing using topographic survey information) new modelling will be required for all time periods and scenarios as utilising previous model setup outputs will no longer be possible.

Figure 3 Estimated epoch of asset failure under Do Nothing scenario (Bristol City Centre, Floating Harbour)

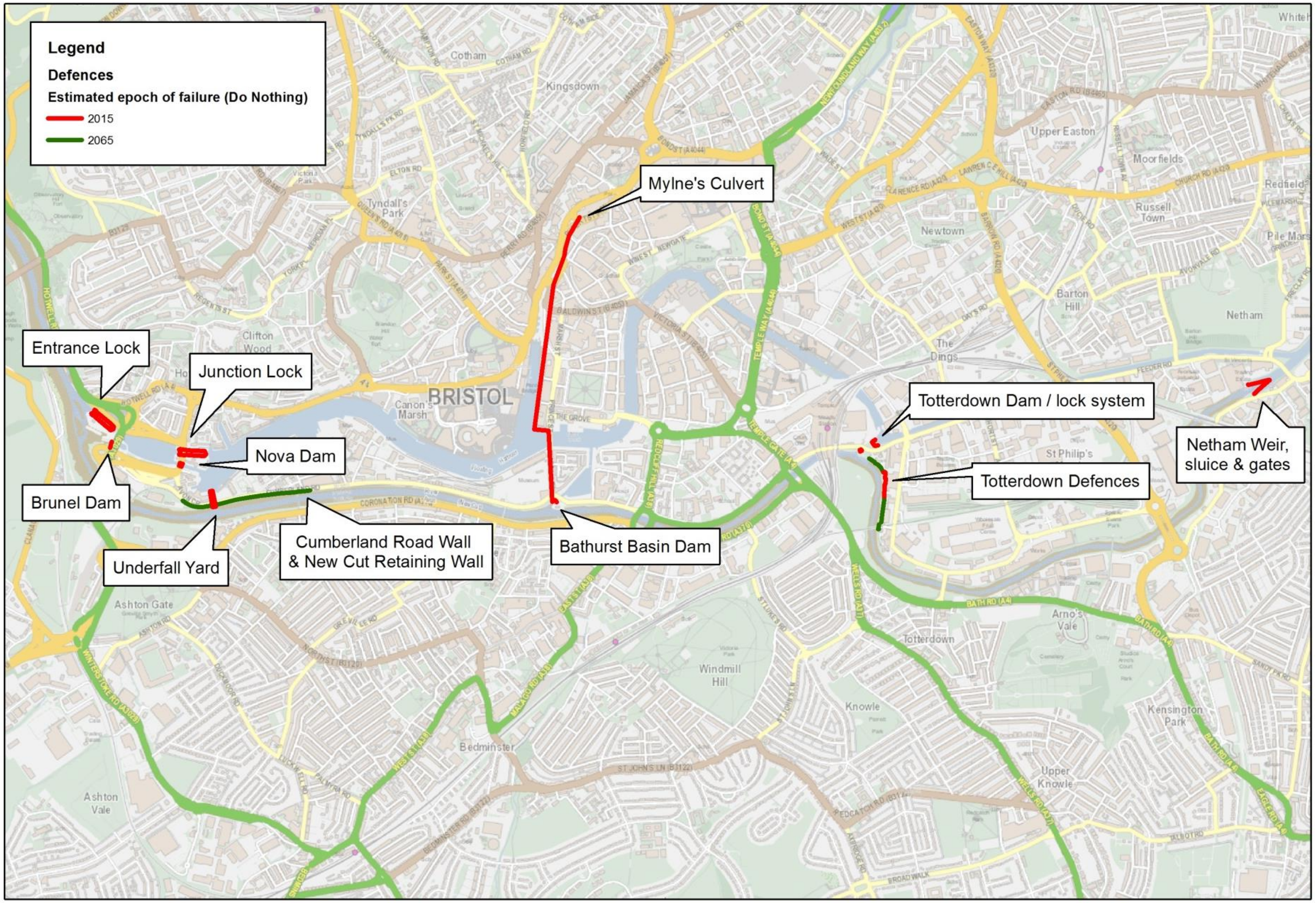
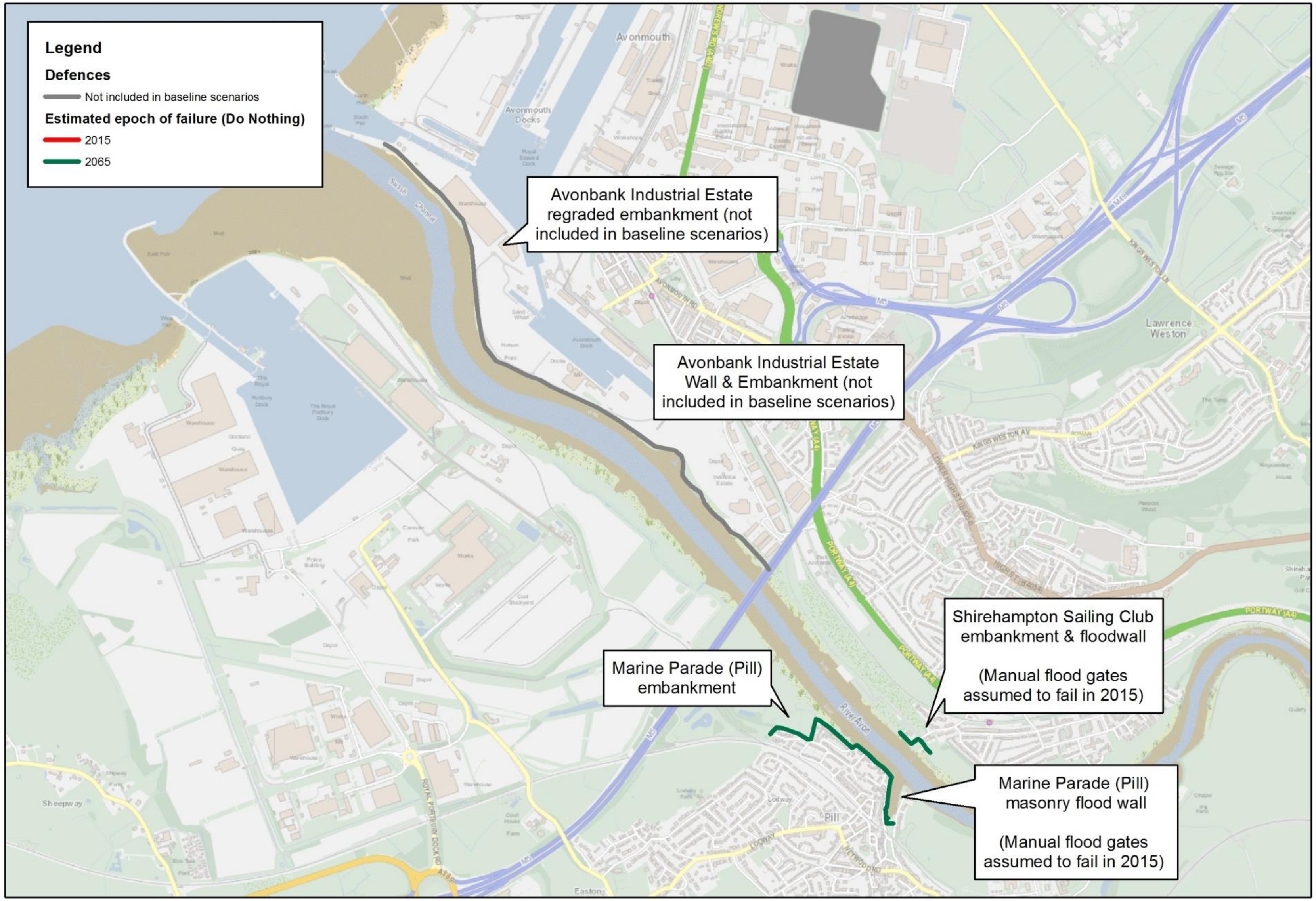


Figure 4 Estimated epoch of asset failure under Do Nothing scenario (Avonmouth, Pill and Shirehampton)



Next steps

On agreement of the scenario definitions and assumed asset failure timings, the resulting flood depths and extents resulting from a specified number of return period events will be generated at each time point. This will be achieved either through utilising existing model results (where possible), or through utilising, modifying and running the ISIS TUFLOW model to represent the landscape and defence status (eliminating those assets which have failed).

The UKCP09 Medium emissions scenario 95%tile will be utilised as the change factor for sea level rise as per EA 2011 guidance for FCERM projects.

For the economic appraisal flood data will be required the following range of return period events (for both baseline scenarios) will be needed at each of the four time points.

- 1:2 year (50% AEP)
- 1:20 year (5% AEP)
- 1:75 year (1.33 % AEP)
- 1:200 year (0.5% AEP)
- 1:1000 year (0.1% AEP)

Economic Appraisal

Once the flood data is generated and mapped, a point inspection using cleaned NRD 2011data will be undertaken to attribute flood depths to each asset for all of the above events. It is likely that saline short duration flooding will be used (flooding duration < 8 hours), or if modelling demonstrates longer duration flooding (>8 hours) this will be used.

The asset flood depths will be converted into theoretical damages for each event using the MCM 2015 methodologies. This process will follow normal good practice in terms of sense checking damages (particularly large commercial values) and visual verification of damages against the flood mapping will be undertaken. Upper floor properties will be removed from the assessment. Other damages, wider benefits and intangibles including Loss of life, health, tourism, environmental and heritage assets, highways and infrastructure, health and vehicle damage will be included in the economic assessment. If more detailed tourism benefits (qualifying for GiA) are available through commission of additional study assessing tourism value this will also be included within the assessment.

FCERM economic appraisal spreadsheets will be used as the vehicle for the appraisal and baseline do nothing and do minimum damages will be presented in Cash and PV terms over the whole life.

Shortlisted options, including ‘Do Minimum’ will be costed. Option benefits (through reducing flood risk will be simulated in the model and the residual damages and benefits calculated in a similar manner to the process described above.

A Cost Benefit assessment on the short listed options will then be undertaken and presented and the partnership funding calculator will be used to indicate potential GiA eligibility and potential funding shortfalls for each of the options.

Proportionate sensitivity testing against alternative sea level rise futures will be undertaken as required for testing adaptive capacity of shortlisted options. Lower and upper bound estimates will be used in this assessment.

A supporting high level GVA assessment will be undertaken, primarily focussing on providing an indication of the local economic impacts of ‘Do Nothing’ or ‘Do minimum’. This will consider aspects such as location dependence, adaptability and resilience of businesses in the enterprise zones and will provide a high level quantitative valuation of impacts. This will be useful for informing the wider business case and leveraging contributions, even if such impacts are not able to be counted in the national sense in applying for GiA for schemes.