Central Area Flood Risk Assessment – Summary Report

November 2013

Hyder

Consulting

Key Findings and Summary of the Bristol Central Area Flood Risk Assessment (CAFRA)

Executive Summary

The central area of Bristol has a long and intimate history with the tidal River Avon, with much of Bristol's rich heritage and culture owing much to the river, its main tributaries and the Floating Harbour. However, as with any city sited near a major waterway, assessing and managing flood risk has always been an important consideration to ensure safe and prosperous development.

In recent years, strategic scale studies such as the Environment Agency's Catchment Flood Management Plan (CFMP) for the Bristol Avon[1] have summarised the predominant flood risk from the River Avon as being from tidal sources. The Bristol Strategic Flood Risk Assessment (SFRA)[2] also verified this conclusion. However, the CFMP also highlighted that little was known about the 'joint probability' of tidal and fluvial events coinciding and whether a moderate fluvial flood event combined with a moderate tidal flood event could produce more severe flooding than a large tidal flood event alone.

Bristol City Council proposed the Central Area Flood Risk Assessment (CAFRA) study through the Environment Agency administered Flood Defence Grant in Aid (FDGiA) process. The study had the following primary objectives:

1. Provide a more comprehensive strategic hydraulic modelling assessment of the flood risks posed from the River Avon and its tributaries, now and into the future, in central Bristol than had previously been completed;
2. Assess and reach a conclusion to the joint probability question posed by the CFMP;
3. Undertake an assessment of the key flood assets in the River Avon, its tributaries and the Floating Harbour;
4. Augment other recent studies such as the SFRA, Preliminary Flood Risk Assessment (PFRA) and Surface Water Management Plan (SWMP);
5. Enhance its partnership working with other Risk Management Authorities such as the Environment Agency and Wessex Water.

In addition to the above objectives, the CAFRA study also had nine specific objectives, identified by the Scoping Report, prepared by JBA Consultants in 2010. These are summarised in Table E- 1. The CAFRA study primarily included a large-scale, single model of the entire central area of Bristol. The model domain included the following rivers: Avon, Frome, Brislington Brook, Malago, Pigeonhouse Stream, Colliter's Brook, Longmoor Brook and the River Trym. The model was developed using previous hydraulic models such as that used in the SFRA, but enhanced to produce a comprehensive yet strategic assessment of flood risk.

A range of studies has been undertaken as part of the CAFRA project to address the various complex aspects of flooding in Bristol; the full list of studies is located in Table A- 1 of Appendix A The aim of this document is to provide strategic overview of all the studies and provide an overall summary of the

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[1] http://www.environment-agency.gov.uk/research/planning/114342.aspx

[2] http://www.bristol.gov.uk/page/planning-and-building-regulations/strategic-flood-risk-assessment-sfra

conclusions of the work, together with a clear action plan of how the findings will be taken forward to improve the future management of flood risk in Bristol.

Throughout this Strategic Overview Document, references/signposts to relevant sections of each of these studies are provided, where necessary in the document; the references will be included in the following form e.g. *CAFRA Study, Appendix D, Page 72*. References to other studies outside of CAFRA (such as the Surface Water Management Plan) are also provided where pertinent.

The CAFRA approach involved four main workstreams, as follows:

Workstream 1 – Data collection

Workstream 2 – Hydrological assessment and setting boundary conditions

Workstream 3 – Production of the baseline model

Workstream 4 – Flood risk asset review and strategic assessments of potential flood mitigation measures

Key Findings

The completion of the CAFRA Workstream 3 and hydrological analysis (including the joint probability assessment) concluded that the most significant predicted flooding would result from a tidally-dominant event. CAFRA has therefore dispelled the theory that a combination of a moderate fluvial flood event combined with a moderate tidal event would generate the most significant flooding.

The modelling results from CAFRA provided confirmation that in the present day, the standard of protection for much of the City centre has a standard of protection of around 0.5% AEP, with the major exception of the St Phillips Marsh area. However, the threat posed by climate change and sea level rise is such that for the 50-year and 100-year epochs, the flood risk in the centre is likely to be very significant. For example, a 5% AEP event is likely to cause flooding of areas of St Phillips Marsh and adjacent to the Cumberland Basin and Avon Crescent.

In the present day, the modelling also concluded that the principal flooding mechanism is for tidal waters from the Avon to flow overland into the Floating Harbour via three main flow path ‘low spots’; a) Cumberland Road/Avon Crescent, b) Bathurst Dam/Commercial Street and c) St Phillips Marsh. Workstream 3 predicts the flow paths are likely to become wider and propagate more water as sea levels rise into the future so that in 50 years approximately 850 residential properties would be at risk and in 100yrs approximately 1,400 properties would be at risk.

Workstream 4 concluded that the current arrangement of fluvial interceptors (e.g. the Malago Interceptors and Northern Stormwater Interceptor) provide significant flood risk benefits in the present day scenario. However, with the predicted impacts of climate change, these assets become increasingly flood-stressed, mainly due to the impacts of tidelocking.

The nine objectives of the Scoping Report were met by the CAFRA study. These are summarised in Table E- 1 below, along with how the CAFRA study has answered the objective.

Table E- 1 CAFRA Scoping Report Objectives and how the CAFRA study has met them

Objective	How CAFRA has met the Objective	Workstream and Document Reference
Develop a detailed understanding of flood risk on all tidally-influenced watercourses within the city boundary	Developed a detailed, strategic level, single hydraulic model with tidal and fluvial boundaries. Undertook a full joint probability assessment of the interaction with tidal and fluvial flooding. Created GIS layers showing flood depths, hazard and velocity.	Workstream 1, 2 and 3 (primarily the baseline Workstream 3 model build) and associated GIS layers. Conclusions summarised in Section 2.2 of Workstream 4 report, page 10
Assess and quantify the probability and impact of the coincidence of tidal-fluvial flood events, including determination of flood hazard and vulnerability	Undertook a full joint probability assessment of the interaction with tidal and fluvial flooding. Proved that the more dominant flood mechanism is from tidally-dominant events. Created GIS layers to identify the areas at highest flood hazard. Performed high-level assessments of potential flood mitigation measures to promote schemes and strategies to reduce the risk of flooding to more vulnerable areas.	Workstream 1, 2 and 3 (primarily the baseline Workstream 3 model build) and associated GIS layers. Conclusions summarised in Section 2.2 of Workstream 4 report, page 10Joint Probability assessment included as a Technical Note within Annex C of the main report.

Objective	How CAFRA has met the Objective	Workstream and Document Reference
Determine Standard of Protection (SoP) and Areas Benefiting from Defences (ABD) offered by existing defence assets and systems within the study area, now and in the future	Collated data relating to formal flood defences. Performed model runs to identify the level of protection provided by the various defences now and inclusive of climate change (year 2060 and 2110). Undertook analysis of key flood risk assets	Workstream 1, 3 and 4. SoP calculations explained in Section 18 of the Workstream 3 report (page 122). ABD explained in Section 14 (specifically 14.2, page 107) of the Workstream 3 report
Utilising latest guidance and data, assess the impact of climate change on fluvial/tidal flood risk within the study area	Utilised latest climate change advice (Adapting to Climate Change: Advice for Flood and Coastal Erosion Risk Management Authorities, EA, 2011) to derive hydrological boundaries for the baseline model with an allowance for climate change. Utilised two climate change epochs, 50 and 100 years.	Climate change considerations embedded throughout the study. Specific methodology described in Section 12.4 (page 89) of the Workstream 3 report

Objective	**How CAFRA has met the Objective**	**Workstream and Document Reference**
Review, model and assess the current operational procedures of the existing flood risk and water management structures. Investigate the feasibility of optimising their future performance/management to reduce flood risk and maintenance requirements	Baseline model included an accurate representation of the key flood risk assets in the central area. Performed relatively detailed analysis of the key assets in the Floating Harbour, identifying those that have a flood risk function. Analysed the performance of fluvial flood structures such as the Northern Stormwater Interceptor (NSWI) and Malago Interceptor and asses their performance now and in the future. Undertook analysis of operating procedures for the NSWI as well as the Harbour assets.	Workstream 3 and 4. Conclusions provided in Workstream 4, Section 2.2 (from page 10). Sensitivity and operational testing of fluvial structures included in Workstream 3, Section 15.2, page 111 (blockages) and Workstream 4, Section 4 (from page 31). Harbour assets reviewed as park of Harbour Workstream 4, within Annex F
Identify and assess flood risk management options, guiding future investment and streamlining future flood risk management strategies	Workstream 4 concentrated on undertaking assessments of flood risk and assessing flood management options such as mitigation measures and operational procedures. Outline constraints such as cost and environmental issues were scoped for many of the measures, which can be promoted through future strategies. CAFRA realised that a strategic mitigation measure would be required to mitigate future tidal flooding, which, due to the potential scale and political scrutiny of such measures, should be explored via a separate feasibility study. The CAFRA study outputs will be used by BCC to inform their Local Flood Risk Management Strategy	Throughout Workstream 4, both as part of fluvial review (Sections 3 and 4) and tidal (Harbour) in Annex F

Objective	**How CAFRA has met the Objective**	**Workstream and Document Reference**
Provide an evidence base to support the SFRA, SWMP and the Local Response Plan	The CAFRA outputs will be utilised in the BCC Local Flood Risk Management Plan to augment the understanding of flood mechanisms derived from other studies. The Local Response Plan will be updated to include the CAFRA outputs.	Embedded within Local Flood Risk Management Strategy (ongoing)
Put in place a framework and systems within Bristol City Council for flood risk data collection, management and dissemination	The data collected by the CAFRA study will be utilised within the BCC Flood Risk Asset Register.	Workstream 1 and Annex A
Take a strategic and planned approach to flood studies and data collection	The strategic nature of the study along with the relatively large study area has ensured a strategic approach by considering both tidal and fluvial flooding and the assets that help to manage these. Much of Workstream 4 included establishing an asset management timeline, particularly for Harbour assets. These issues will be further explored within the Local Flood Risk Management Strategy.	Embedded within Local Flood Risk Management Strategy (ongoing)

Future Mitigation – Action Plan

To mitigate against the increasing threat of climate change to Bristol, Workstream 4 concluded with an action plan to recommend short, medium and long term actions to be addressed through partnership working between all Risk Management Authorities in Bristol. The action plan is as follows:

- **Short-term -** Relatively minor works in the short term (0-5 years) to raise 'low spots' between the Avon and the Floating Harbour;
- **Medium Term -** Maintenance and upgrade of Harbour Assets to maintain a standard of protection in the short to medium term (5 – 10 years);
- **Long Term -** Invest in a large-scale, strategic flood mitigation solution to mitigate against the climate change impacts in the long term (10+ years).

The adaptive approach outlined above has many complexities, mainly due to the nature of the flooding mechanisms in Bristol. It has become evident from the work undertaken by CAFRA that future work to support the development of mitigation options is likely to require additional analysis of the CAFRA model.

The recommendations arising from this CAFRA report are based on the Workstream 3 Baseline model run that used the combination of a tidal event of 0.5% AEP (1 in 200yr) and a fluvial event of 50% AEP (1 in 2yr). This combination of events has a combined probability of 0.5% AEP (1 in 200yr return period) as agreed using Defra approved values and will form the basis for all future work.

1 Introduction

1.1 Background

Bristol is a city at risk of flooding from a number of sources; the most significant are fluvial and tidal flooding. The risk of tidal flooding emanates from tidal waters propagating up the Avon from the Severn estuary. The risk of fluvial flooding results from the numerous watercourses which flow toward the River Avon through the city. A number of these watercourses have a history of flooding (most notably in 1968) and therefore many of the larger watercourses (Brislington Brook, Frome, Malago and Pigeonhouse Stream) have been intercepted and diverted by large engineering schemes. The Bristol urban area has also grown significantly in the last 50 years, increasing the amount of surface water captured and diverted directly to these watercourses. Therefore the evolution and interconnectedness of the system makes it difficult to isolate sources of flooding without firstly understanding the complexities of the system.

The Bristol Avon Catchment Flood Management Plan (CFMP) was prepared by the Environment Agency to better understand the scale and extent of flooding now and in the future, and set policies for managing flood risk within the catchment. As the CFMP was a significant strategic flood risk study within the Bristol area, the City Council endorsed the conclusions that arose from it. The CFMP also prioritises key issues and actions for the catchment to ensure that funds are allocated to projects aimed at addressing these key issues. A copy of the actions nominated within the CFMP is presented below (text extracted from *Bristol Avon CFMP – Revised Action Plan, Policy Unit E):*

1 Carry out a study to determine the combined fluvial / tidal flood risk to Bristol from the tide, the River Avon and the Bristol Frome in order to reduce uncertainty relating to the level of risk this poses. This information will then be used to inform and further develop our flood risk management strategy for Bristol.

2 Identify if there are other specific areas where tide-locking of tributaries (for example the Malago Stream flowing into the River Avon from the South) are causing flooding problems, and look at ways of mitigating this risk.

3 Carry out integrated urban drainage studies to identify current and future risks, and propose mitigation.

4 Investigate the benefits of improved flood forecasting and flood warning using improved meteorological technology.

The Central Area Flood Risk Assessment (CAFRA) study arose from the first action nominated under the CFMP. The CFMP also highlighted that little was known about the 'joint probability' of tidal and fluvial events coinciding and whether a moderate fluvial flood event combined with a moderate tidal flood event could produce more severe flooding than a large tidal or fluvial flood event alone. One of the primary aims of the CAFRA project was to answer this question.

2 The Study Area

In order to adequately assess the tidal and fluvial influence on the Bristol central area, it is necessary to consider all the watercourses and their catchments contributing to the River Avon within the Bristol area. The study area therefore corresponds to the total catchment area of these watercourses, in addition to the River Avon as far upstream as Hanham Weir to the east. It also includes the numerous watercourses which flow toward the River Avon through the city including:

- River Frome,
- Brislington Brook,
- River Malago,
- Colliter's Brook,
- Ashton Brook,
- Boiling Wells Stream,

- Pigeonhouse Stream,
- Longmoor Brook,
- Horfield Brook,
- River Trym

Figure 1 shows the location of these watercourses, their catchments and the extent of the study area.

2.1 Catchment Overview

A number of key features influence the hydrological response of the catchment of the River Avon and its tributaries and the flooding mechanisms that dominate, including:

- Catchment size (surface area)
- Urbanisation
- Climate
- Soils and geology
- Land use
- Flooding regime
- Topography

These features are summarised below and in Appendix B.

2.2 Historical Flooding

The Bristol area has a long history of flooding. The CFMP, Bristol City Council Preliminary Flood Risk Assessment (PFRA) and the BHS Chronology of British Hydrological Events website citing several flooding instances over the last 200 years. More recently, Bristol was affected by severe flooding in July 1968 with almost every stream and river experiencing flooding. Seven people lost their lives, bridges that had stood for centuries were washed away or severely damaged and countless houses, shops, factories and other properties were inundated during this event.

The flooding history of the catchment indicates that major fluvial flood events are caused by relatively long duration storms, with a tendency toward a winter flood seasonality, although one of the worst floods in recent history (July 1968) was associated with a summer rainstorm event. Periodic flooding is also associated with spring tides affecting relatively localised areas in the lower Avon catchment, Plate 1 to Plate 4 show recent examples of flooding.

Plate 1 Flooding in Ashton during 1968 (Source: Google Images)

Plate 2 Flooding in Eastville 1968 (Source: BCC)

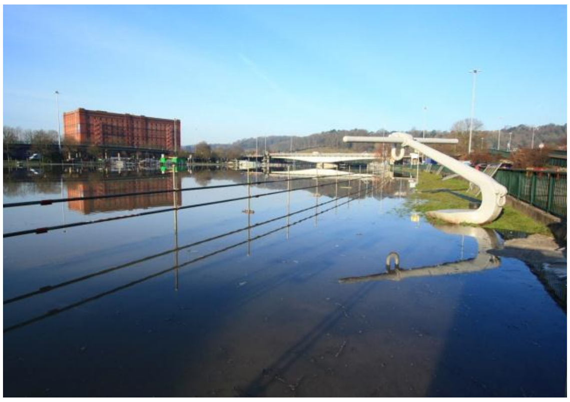


Plate 3 **Spring tide over the Cumberland Basin 2010 (Source: BCC)**

Plate 4 **Spring tide on the Portway 2010 (Source: BCC)**

2.3 Flood Alleviation

Due to the long history of flooding within the River Avon catchment, numerous engineering schemes have been implemented to divert and store floodwaters. Some of the major schemes include:

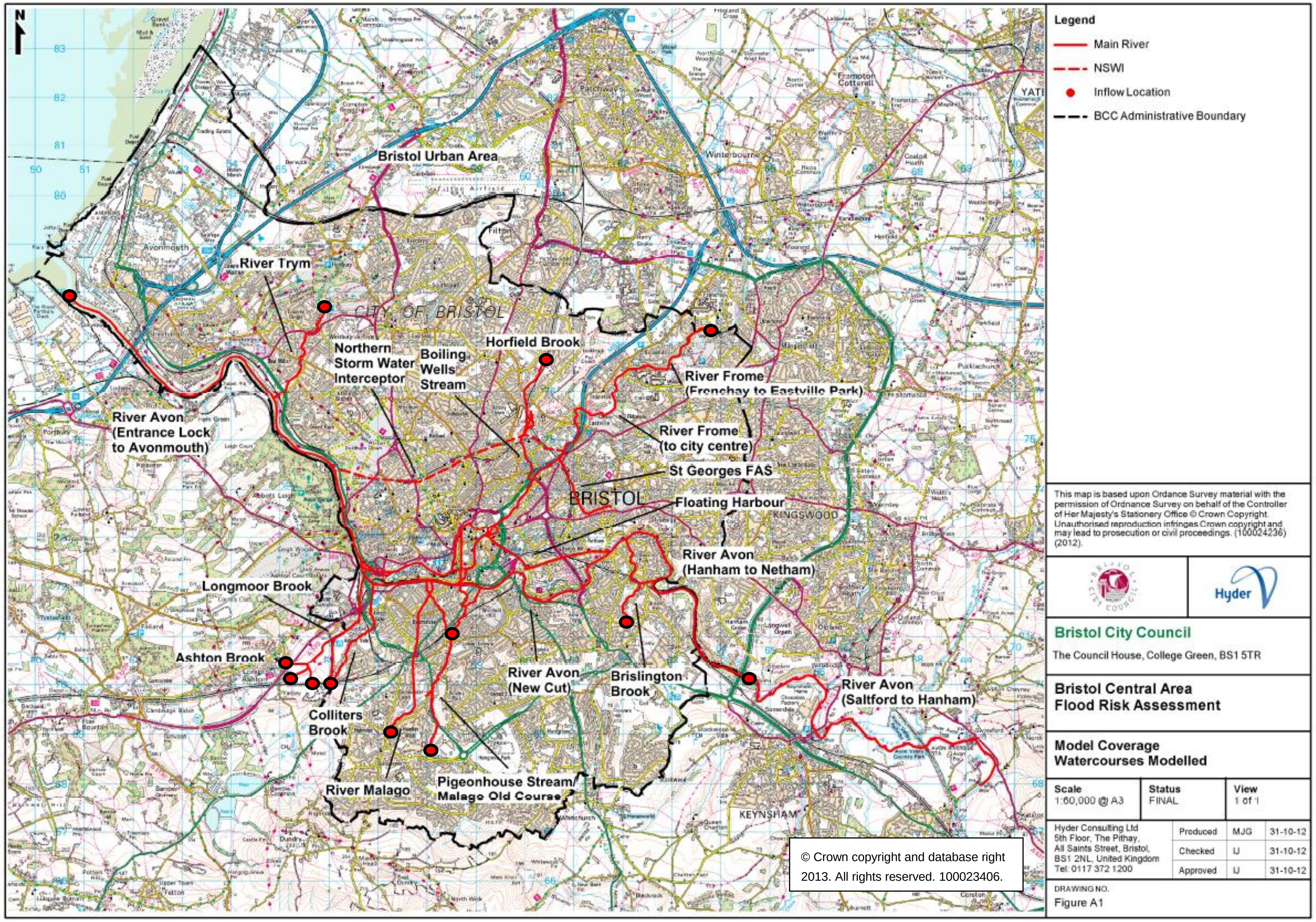
- Widening and deepening of rivers and removal of obstructions
- Building flood bypass tunnels, for example the Northern Stormwater Interceptor (NSWI) at Eastville, which diverts flood flows from the Bristol Frome and St George FAS away from the centre of Bristol to discharge directly to the tidal River Avon further downstream. There are also smaller diversion channels on the Ashton, Longmoor and Colliter's Brooks and the Brislington Brook.
- The Malago interceptor system takes storm water flowing from the upper areas of the catchment and channels the flow directly through culverts into the River Avon, reducing flows in the low lying areas.
- Reservoirs, such as the flood storage reservoir at Iron Acton to reduce flood risk downstream on the River Frome though Frampton Cotterell to Eastville. The Floating Harbour in the centre of the city also acts as a large storage area and has a vital role in protecting the city from combined tidal and fluvial flooding.

Thanks to the installation of these schemes, high flow events on the River Avon in 2000 and 2008, which would otherwise have caused widespread flooding, resulted in little damage.

2.4 Other Sources of Flooding

As stated above, the principal aim of the CAFRA study is to undertake an assessment of the fluvial and tidal flood risk posed to central Bristol. It is not aiming to undertake an assessment of the flood risks posed from groundwater, sewer or surface water flood risk. In this respect, it does not cover all the types of flooding that a typical Flood Risk Assessment for a proposed development or development strategy would. However, the aim of Bristol City Council and the other Risk Management Authorities within the Bristol area (Environment Agency, Wessex Water) is to use the outputs from CAFRA to augment other recent studies such as the SWMP, PFRA and SFRAs to increase our understanding of flood risk within Bristol and how different sources of flooding interact within the city.

Figure 1 Extract from Figure A1 in *CAFRA Study, Annex E, Appendix A* illustrating extent of watercourses included in the CAFRA model (model extents denoted by the red lines)



3 CAFRA Study Summary

3.1 Workstream Approach

Due to the size of the CAFRA, the project was split into Workstreams to package and deliver discrete elements of work (see Figure 2).

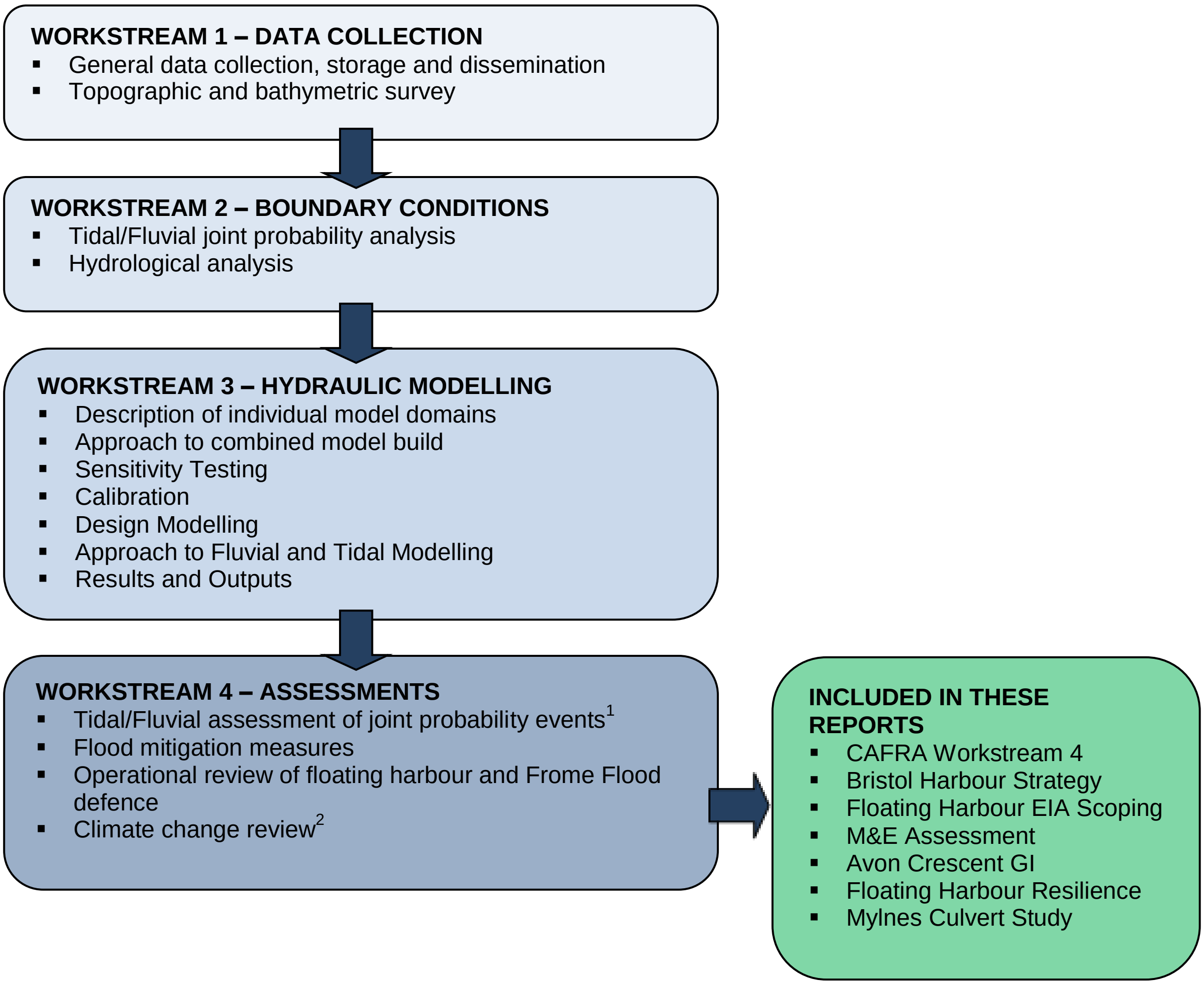


Figure 2 Bristol CAFRA Study Workstream-based Approach (modified at project completion)

1 included in Workstream 3 in agreement with BCC

2 Not included in final agreed scope for Workstream 4

Workstreams 1 to 3 encompassed the commencement of the CAFRA study and culminated in the production of a complex and detailed hydraulic model of the city centre area. Workstream 4 was split into several studies and outputs. Throughout the CAFRA study, a steering group of key consultees, including BCC, the Environment Agency, Wessex Water and JBA Consulting has been informed of project progress, provided input to project direction and agreed to proposed methodologies.

This section includes a high-level summary of the activities undertaken during each of these Workstreams.

3.2 Workstream 1 Data Collection

Workstream 1 involved a comprehensive data collection and analysis process. This included a review of all existing hydraulic models and as an outcome from the gap analysis, new topographic surveys were performed on a number of watercourses. Appendix C of this summary provides additional information regarding Workstream 1.

3.3 Workstream 2 Boundary Conditions Development

Workstream 2 focused on deriving boundary conditions for input to the CAFRA model as indicated in Figure 3.

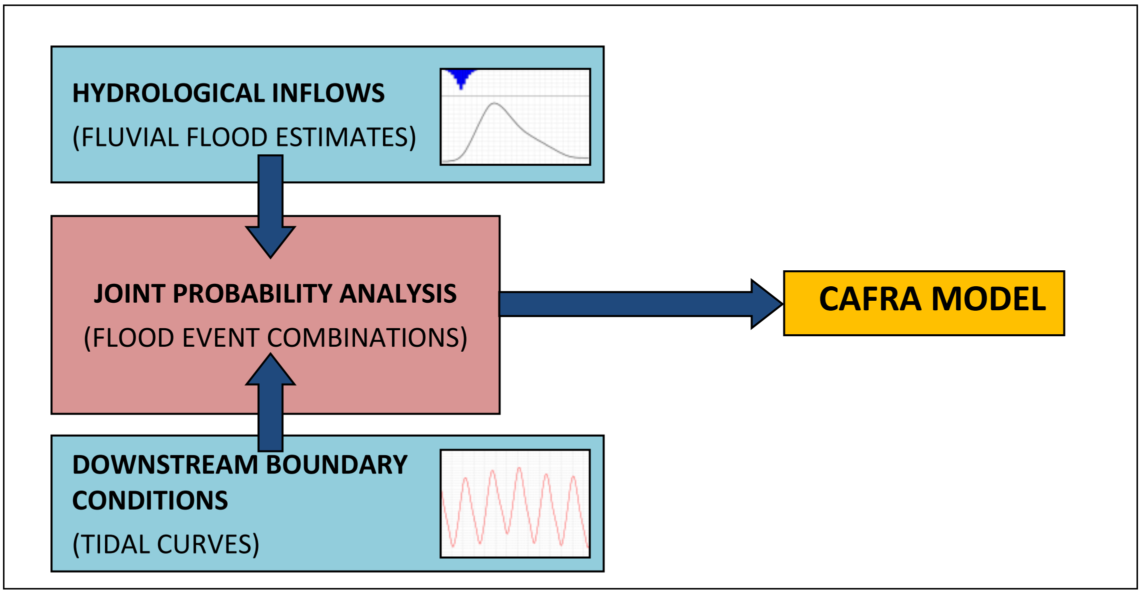


Figure 3 Workstream 2 inputs to the CAFRA model

To derive hydrological inflows, a comprehensive hydrological study was undertaken. This involved the application of Flood Estimation Handbook (FEH) techniques in line with Environment Agency guidelines, to carry out statistical analyses of each sub-catchment of the CAFRA model study area and derive peak flows and inflow hydrographs. The hydrological assessment is documented in *CAFRA Study, Annex E*. It was the subject of a comprehensive review and sign-off exercise involving hydrological input from JBA Consulting, and review and agreement by BCC and the Environment Agency.

Tidal downstream boundary conditions were derived based on application of the peak levels provided in the Coastal Flood Boundary Conditions suite of documents published by the Environment Agency in 2011. Extreme sea levels for Avonmouth were extracted from this document and updated to 2010, 2060 and 2110 to account for predicted sea level rise, based on the recent Environment Agency guidance on adapting to climate change (Coastal flood boundary conditions for UK mainland and islands SC060064, 2011, Environment Agency). These peaks were fitted to a design tidal curve (*CAFRA Study, Annex C and Annex E*).

Figure A2 in *CAFRA Study, Annex E, Appendix A* illustrates the locations within the study area where boundary conditions were required. Inflow locations for these boundary conditions are also indicated in Figure 1 above.

3.4 Workstream 3 Model Development

Workstream 3 represents the largest proportion of the CAFRA project, as it resulted in the development of a single comprehensive 1D-2D model of the entire study area, built to a high level of detail and subject to a robust review and checking process involving BCC and a third-party reviewer, JBA Consulting.

The Workstream 3 report is supplied in *CAFRA Study, Annex E* and it details the methods undertaken to synthesise existing modelling and survey with new and updated survey, new-build models and revised approaches to modelling and mapping within Bristol.

The model was developed using a packaged approach to divide the total area to be modelled into discrete sections based on the watercourses. This allowed the model to be built watercourse by watercourse without losing any of the finer detail, as may have been the case if the approach had been to build a combined model. This approach also allowed specific areas of interest to be targeted within each package. Each package was then integrated into the whole model to create the full CAFRA model.

The finalised CAFRA model is a single ISIS-TUFLOW 1D-2D linked model that includes:

- Over 2,700 ISIS nodes covering a total watercourse length of 73km.
- Over 570,000 TUFLOW 5m grid cells covering a total floodplain area in excess of 14km^2.

Detailed descriptions of significant assets and structures along the watercourses have been included in the Workstream 3 report within *CAFRA Study, Annex E, Various Sections*.

Also included as part of the Workstream 3 report in *CAFRA Study, Annex E, Appendix G* are the review certificates illustrating how the model was ‘packaged’ for review by JBA Consulting and how comments were addressed iteratively with a final review confirming the model was satisfactorily constructed.

Blockage analysis, originally included in the scope for Workstream 4, whereby the CAFRA model was used to simulate the impact on fluvial flows of blockages at 11 locations across the various watercourses that drain the Bristol area, is also detailed in the Workstream 3 report and appendices.

Figures 4 and 5 provide example results from the CAFRA Workstream 3

The completed Workstream 3 model is the baseline model to be used for future works and scenario developing and testing related to tidal and fluvial flooding in the Central Area of Bristol.

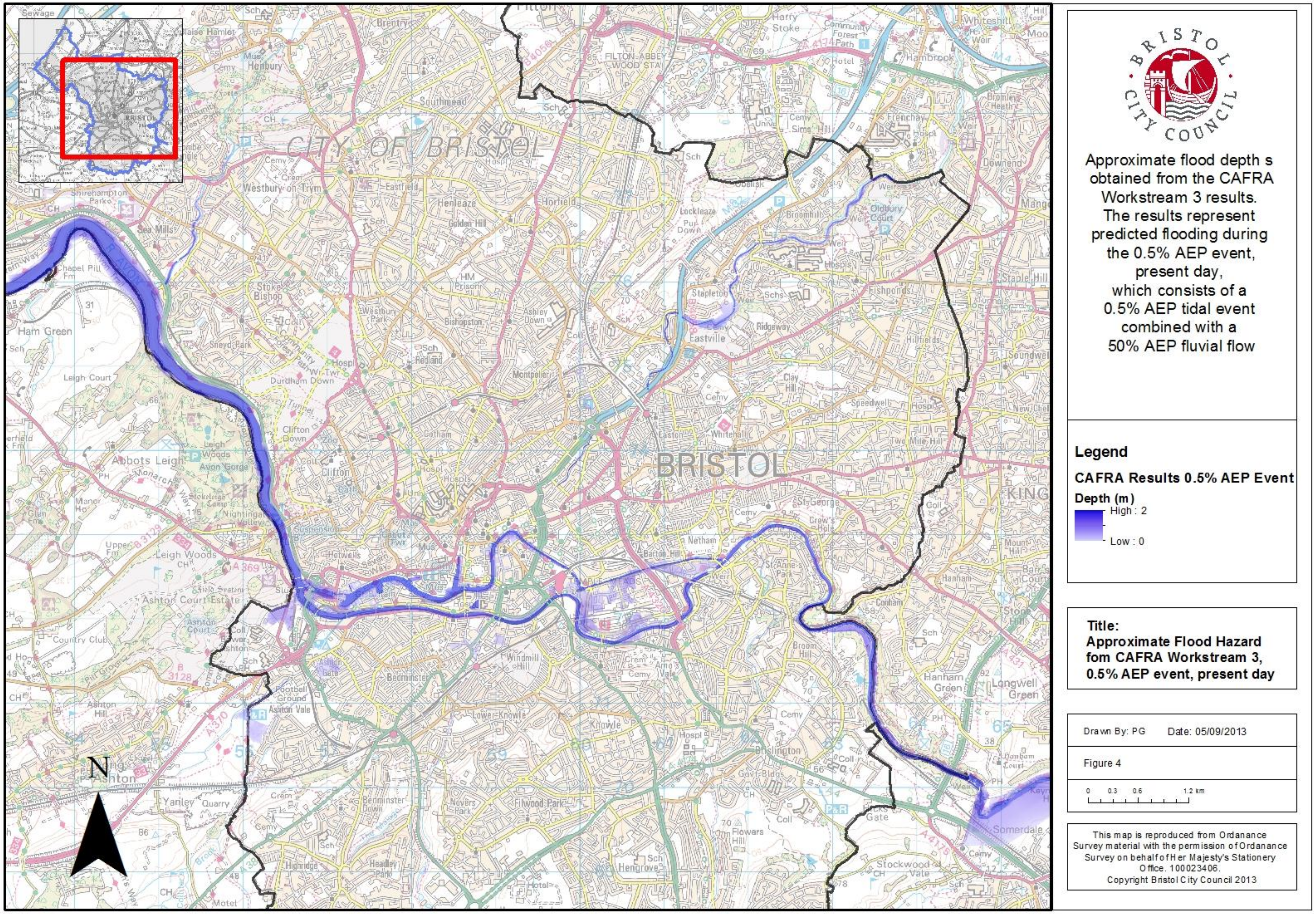


Figure 4 CAFRA Workstream 3 results from the 0.5% AEP tidally-dominant model run (0.5% AEP tide in combination with a 50%AEP fluvial flow), for the present day

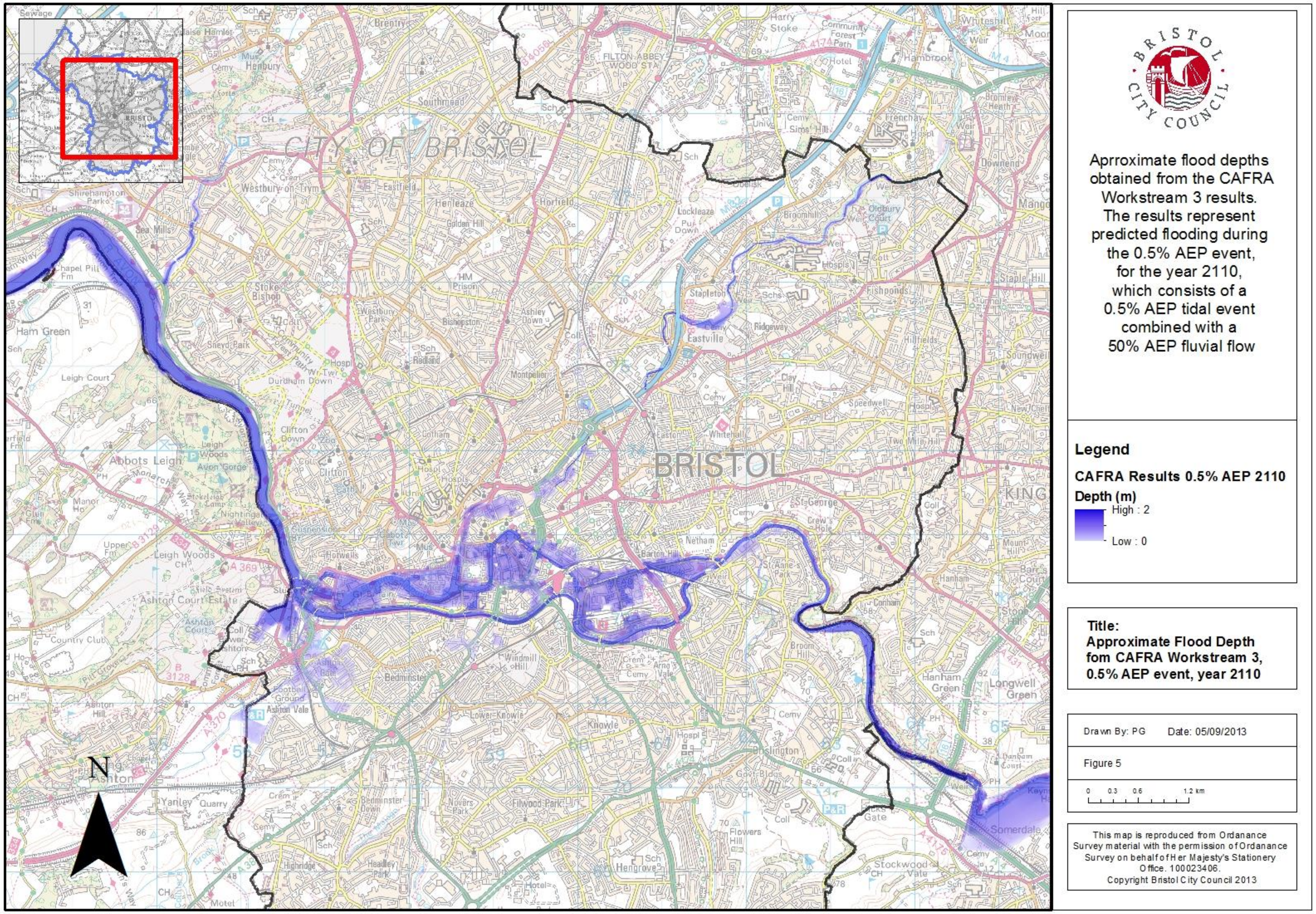


Figure 5 CAFRA Workstream 3 results from the 0.5% AEP tidally-dominant model run (0.5% AEP tide in combination with a 50%AEP fluvial flow), for the year 2110

3.5 Hazard Mapping

GIS layers of hazard have been produced for each event and have been provided as part of the GIS deliverables of the CAFRA Workstream 3 model. The areas hazard map for the 0.5% AEP event, year 2110, provided in Figure 6.

Accurate extents of the Hazard and the depths and velocities in these areas can be found in the GIS layers delivered as part of the Workstream 3 GIS deliverables.

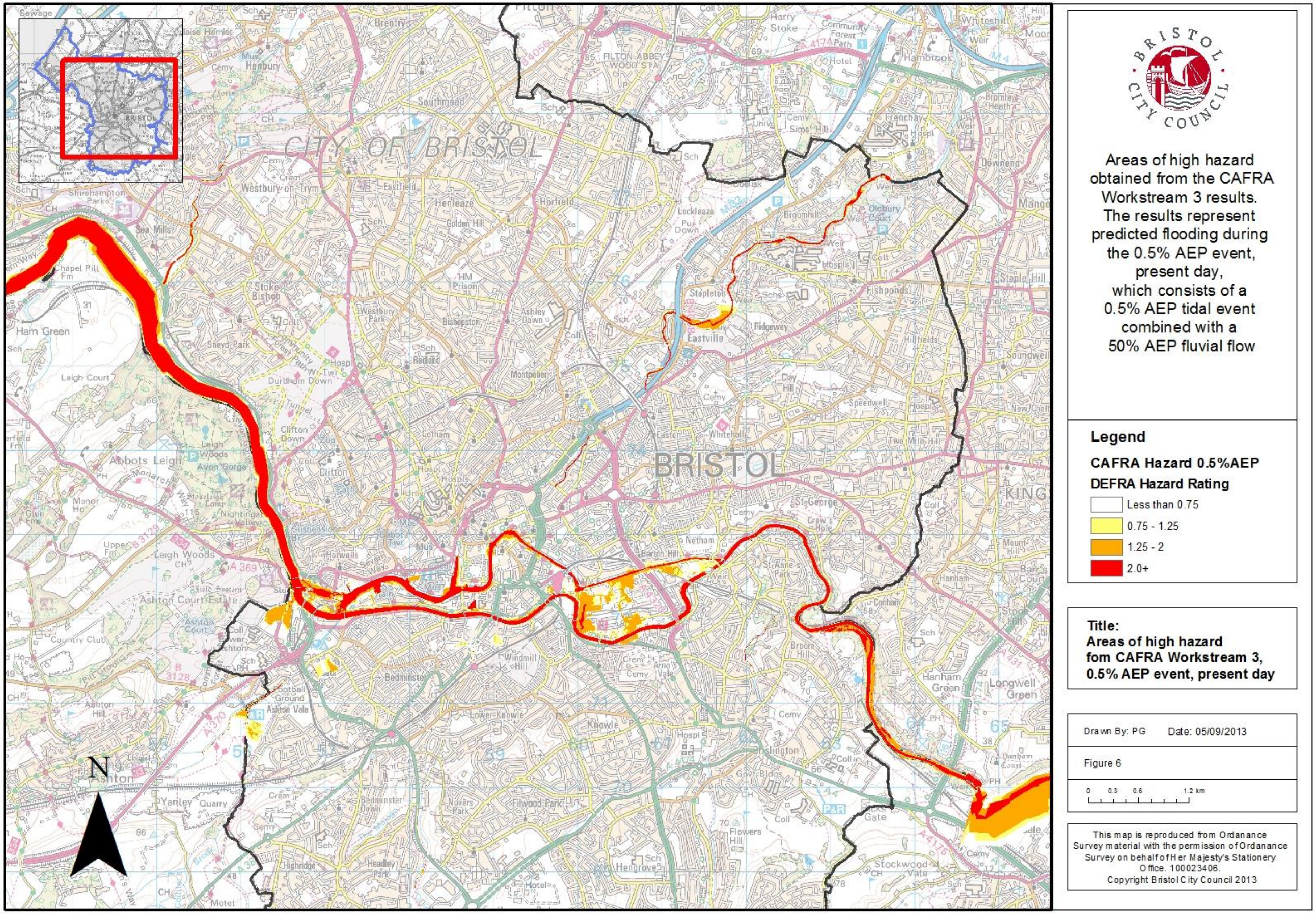


Figure 6 Areas of highest hazard for the 0.5% AEP, tidally dominant event (0.5% AEP tidal event combined with 50% AEP fluvial flow), for the present day

3.6 Workstream 4 Fluvial and Tidal Assessment

3.6.1 Overview

Workstream 3 answered many of the questions posed by the CFMP and the CAFRA Scoping Document, such as the joint probability issue and potential impact of climate change. Workstream 4 therefore had the objective of building on the knowledge gained from Workstream 3 and to apply this knowledge to undertaking further assessments. These assessments aimed to complete high level analyses of potential flood mitigation measures as well as operational arrangements for some of the critical flood risk infrastructure associated with the Floating Harbour and the River Frome.

During development of the CAFRA Workstream 3 baseline model, the scope of Workstream 4 was altered. BCC were, at the time of producing the CAFRA report, also undertaking the Bristol Floating Harbour Strategy, a piece of work being led by Mott Macdonald consultants. In order to streamline efforts and minimise duplication of work and align the CAFRA work with Floating Harbour Strategy, it was decided that the Floating Harbour Strategy would be extended to include the Workstream 4 assessments for the Floating Harbour. Therefore, the suite of documents produced by Mott Macdonald and referenced in the main CAFRA report reflects this change of scope. The objectives of the tidal Workstream 4 were therefore to build on the knowledge gained from Workstream 3 to undertake high-level assessments of potential flood mitigation options. In addition, its objectives included provision of an evidence base for future Harbour asset management plans, by indicating the Harbour management assets and equipment that serve a flood risk function.

The fluvial (non-Floating Harbour) aspects of Workstream 4 were retained by the original modelling team within Hyder Consulting.

3.6.2 Joint Probability Assessment

As mentioned in section 1.1, CAFRA was tasked with answering an important question regarding the joint probability of fluvial and tidal events. A key conclusion from CAFRA Workstream 3 was that the most extensive flooding in Bristol is predicted to be sourced from an event that is dominated by either an extreme tide or by an extreme flow. Therefore, a moderate tidal event combined with a moderate fluvial event may produce flooding, but such flooding would not be as severe as a 0.5% annual exceedance probability (AEP) (1 in 200 year return period) tidal event.

The above is illustrated in Figure 7, which shows a long section on the Avon at the critical section of the model, between Netham Weir and Bristol Temple Meads. Here, the switch between fluvial and tidal dominance occurs for a 0.5% (1 in 200 year return period) event, but it can be seen that the ‘intermediate’ events never produce the highest flood levels for this joint probability. Figure 3 also illustrates some of the various combination of fluvial and tidal events that have a joint probability of 0.5% AEP. For example, a 20% AEP (1 in 5 year return period) fluvial flow occurring simultaneously with a 1% AEP (1 in 100 year return period) tidal event has a joint probability of 0.5% AEP (1 in 200 year return period)

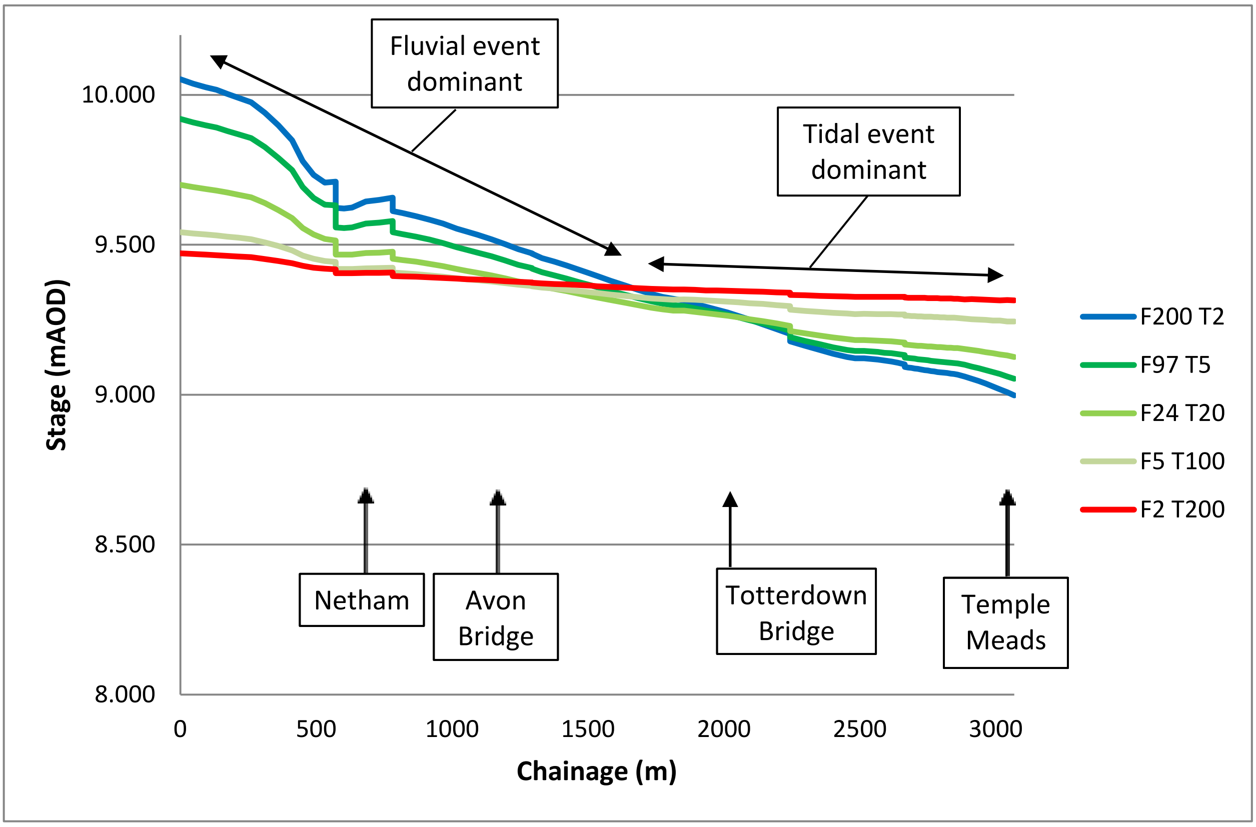


Figure 7 Long section showing a 0.5% AEP (1 in 200 year return period) peak water level on the Avon between the Brislington Brook outfall and Bristol Temple Meads Station. Key to legend – 'F' = fluvial flow return period, 'T' = tidal event return period

As a result of the above, the Workstream 4 assessments for the fluvial (non-Floating Harbour) areas of CAFRA concentrated on the Workstream 3 results that were produced by fluvial-dominated model runs.

Workstream 3 provided evidence that the flood mechanisms and hydrology in the Avon catchment is complex. In addition, due to the relatively large size of the CAFRA baseline (Workstream 3) model, it has a long run time. As a result of these factors, the Floating Harbour Workstream 4 analyses developed a more site-specific and rationalised version of the model to undertake many model runs and scenario tests in a short time period.

The model used for the Floating Harbour Workstream 4 was able to run multiple scenarios quickly. As a result, multiple model runs and interpretation of the outputs provided evidence to confirm that flooding in the Avon is dominated by the tide. The work also summarised that the phasing of the fluvial flow (i.e. the time at which the fluvial flow reaches its peak, relative to the tidal curve) is a more critical aspect than the rate of flow itself. As a result, the Harbour Workstream 4 analyses utilised a more conservative approach than the baseline Workstream 3 modelling to derive flood levels. The analyses utilised a 0.5% AEP tidal event in the Avon combined with a 10% AEP fluvial flow in the rivers Avon and Frome. According to the joint probability calculator used for Workstream 3, such a combination would result in an event with an AEP of less than 0.5% (typically, a 50% AEP fluvial flow would be used). However, such is the tidal dominance that using a 10%AEP fluvial flow rather than a 50% flow results in uplift in water level of 150mm. As a result, the levels used for Harbour Workstream 4 assessments are deemed to be conservative, inclusive of some freeboard, within modelling tolerances and effectively provide a series of sensitivity tests of the baseline Workstream 3 modelling.

All risks quantified by property numbers at risk in this and subsequent reports are based on the Workstream 3 baseline, defined at the start of this summary.

The CAFRA report indicated that due to the complexity of the flood risks facing Bristol, the most effective method of mitigating the flooding is likely to be an adaptive approach (as explained in section 6 of this summary) and would be a significant package of works, beyond the scope of the CAFRA study. In light of this and the methodology used for the Harbour Workstream 4 analysis outlined above, it is recommended that for future analysis or funding applications of flood mitigation methods, the CAFRA Workstream 3 baseline modelling is used. In addition, any future works will be primarily based on the tidally-dominant model, i.e. 0.5% AEP tidal event with a 50% AEP fluvial event, which gives an overall annual probability of 0.5%.

3.6.3 Standard of Protection

As part of the CAFRA study, it was a requirement to use the Workstream 3 modelling results to provide information on the standard of protection provided by existing banks and defences throughout the study area.

The term ‘standard of protection’ (SOP) has been defined as the largest flood event where the flood level does not exceed the bank/defence level minus a freeboard allowance. The term ‘annual exceedance probability’ (AEP) has been defined as the largest flood event where the flood level does not exceed the bank-defence level irrespective of a freeboard allowance (i.e. the point of direct overtopping).

SOP/AEP calculations have been undertaken by referencing the Environment Agency NFCDD (National Flood and Coastal Defence Database) GIS layer and assigning model results to each frontage.

The SOP/AEP analysis utilised the baseline Workstream 3 model and is included within the main report via a workbook. The workbook is included as part of the model and GIS deliverables alongside the *CAFRA Report* and a GIS layer has also been provided allowing SOP/AEP values to be thematically mapped and examined spatially.

Freeboard was assumed to be 300mm for raised defences and 600mm for natural banks, in line with Environment Agency recommendations. The SOP/AEP workbook allows for these values to be manually altered, with revised results instantly output.

It is important to note that this methodology only uses the level of the banks which have been surveyed at the cross section locations and does not allow for potential low points in the bank. Analysis of these low points would require an extensive search through bank survey (where available) or analysis of LiDAR data (which would most likely be too inaccurate). The SOP/AEP results should therefore be treated with caution, appropriate to the large-scale and strategic nature of the CAFRA model.

It should also be noted that, as the bank levels used are from the surveyed sections only, local ground levels can rise behind the surveyed bank tops. This means that, even though the SOP results show standards of protection below 1 in 20 at a large number of locations, quite often there is no property or infrastructure flooding. Figure 8 shows the main locations where overtopping is predicted to occur.

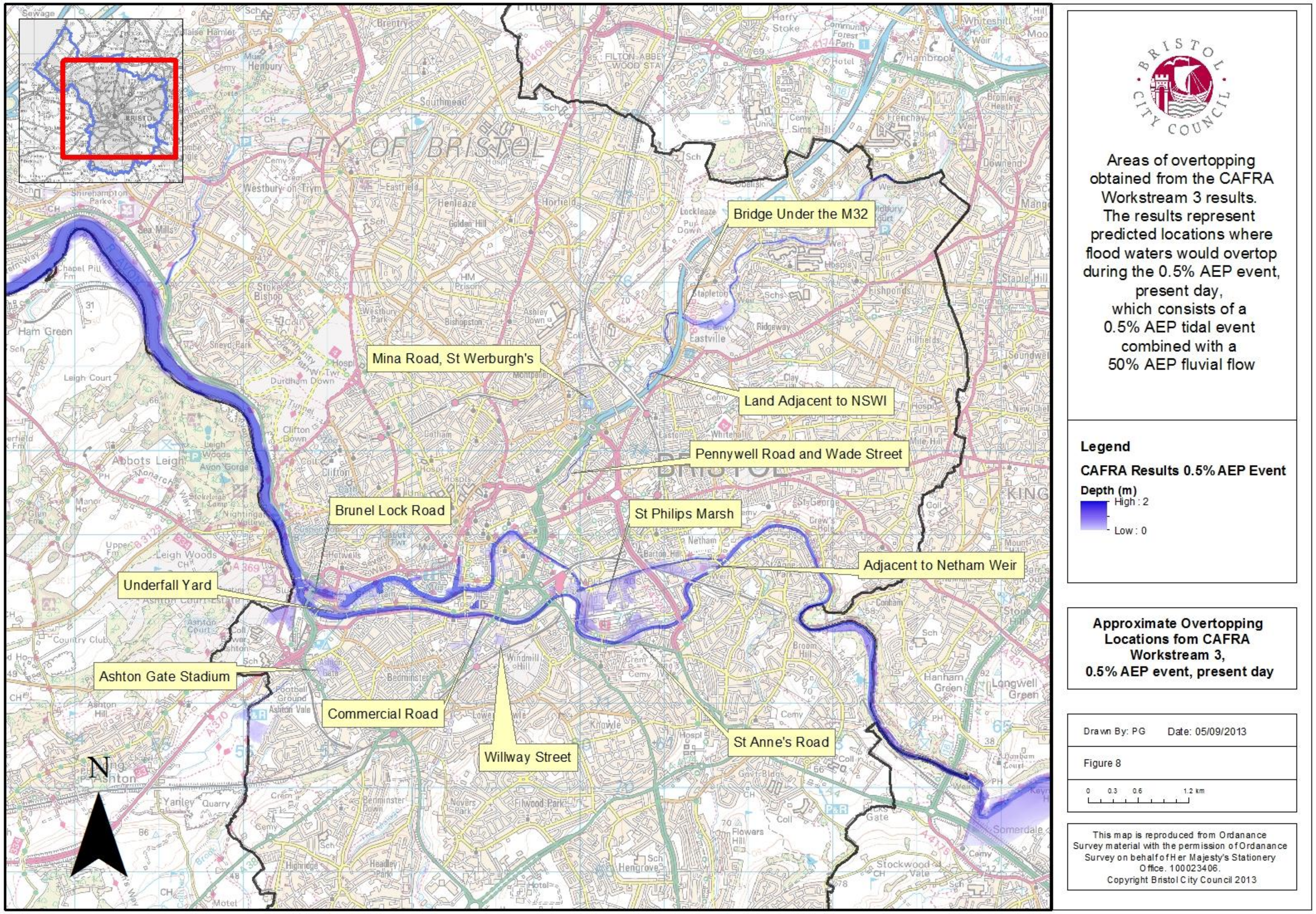


Figure 8 Areas of overtopping during the 0.5% AEP, tidally dominant event (0.5% AEP tidal event combined with 50% AEP fluvial flow), for the present day

3.7 Operational Procedures - Northern Storm Water Interceptor

A key output of the CAFRA study was a review of key flood risk assets within the central area of Bristol and assess whether a failure in the asset, or alteration in the operating rules, would significantly contribute to flooding in Bristol. One such asset is the Northern Storm Water Interceptor (NSWI). The (NSWI) plays a key role in fluvial flood risk management in Bristol by diverting flood flows from the River Frome out to the Avon at Black Rocks, before they can reach the centre of Bristol. The NSWI begins at the Eastville Intake, a large structure which actively controls the flow into the NSWI via four automated penstocks.

Four amendments to the NSWI operation were simulated (using the baseline Workstream 3 model) to investigate whether it was possible to optimise the NSWI operation by varying the existing control rules, including a simulation to assess the impact of the failure of the penstocks to open, whether caused by mechanical failure or power system failure.

Operational Review Run 1 – One of the secondary penstocks was amended to have the same rules as the primary penstocks, hence three gates operate as primary penstocks, increasing the initial flow into the NSWI.

Operational Review Run 2 – Both of the secondary penstocks were amended to have the same rules as the primary penstocks, hence all four gates operate as primary penstocks, increasing the initial flow into the NSWI by even more.

Operational Review Run 3 – One of the primary penstocks was amended to have the same rules as the secondary penstocks, hence three gates operate as secondary penstocks, reducing the initial flow into the NSWI, but allowing the full capacity to come on-stream once the trigger level is exceeded and the remaining primary gate is fully open.

Operational Review Run 4 – In this run, all penstocks fail to open, remaining shut. Flow entering the holding area is directed into the Frome via the overflow weir, but the letter box spills remain, as intended, a backup route into the NSWI.

These runs were simulated, as agreed with BCC, for the 5% AEP (1 in 20 year return period) and 1% AEP(1 in 100 year return period) present day scenarios and the 1% AEP 2060 scenarios. All runs were fluvial-dominated (e.g. a 5% AEP fluvial flow with a Mean High Water Spring tide).

The full results for the operational review of the NSWI can be found in the *CAFRA Study, Chapter 4.2 and Annex F.5;* below are the conclusions from the analysis.

It can be concluded, from Operational Review Runs 1-3, that the timing of opening of the primary and secondary penstocks is not what dictates peak water level at or around Eastville Intake. At the time of peak flooding for the extreme events considered, it is the capacity of the NSWI which is the biggest determinant on flooding upstream. Furthermore, Operational Review Run 4 has illustrated that the existing arrangement includes a suitable redundancy feature in the letterbox openings, which still serve to pass significant flow into the NSWI should the sluice gates fail. Under such a failure, however, elevated levels at the intake increase the flow passing downstream on the River Frome. In the present day this would result in slightly increase flooding downstream in the city centre for a 1% AEP flood event. Following predicted impacts of climate change over the next 50 years, however, such a failure event, coinciding with a 1% AEP flood, would result in a notable increase in flooding within the wider surroundings of the Floating Harbour. This suggests that continued operation of the NSWI and its upstream intake will become even more important over time, and in future there may be more benefit in undertaking further analysis to attempt to further optimise its operation.

It is also important to note that the impeding effect of the tide plays a key role in limiting flows through the NSWI (although the gradient and amount of flow during extreme fluvial events means that positive flow is always possible). Thus the NSWI system is always under greatest stress when flood events coincide with high tides, and it is during such scenarios that optimum performance of the intake arrangement is most necessary.

The loss or removal of the tidal flap itself, although allowing tidal water to propagate into the NSWI during low flow conditions, was found to do little to impact on the operation of the NSWI during a 1% AEP fluvial flood event. This is because the gradient of the NSWI and the amount of fluvial flow passing through the system were sufficient to ensure that positive flow still occurred out of the NSWI

3.8 Operational Procedures - Floating Harbour

As with the NSWI asset assessment, a key output of the CAFRA study was a review of flood risk assets within the Floating Harbour. Such analysis was primarily undertaken as part of the Harbour aspects of Workstream 4, as explained in section 3.6 of this summary report. It is envisaged that the outputs from such a review would identify the key assets that contribute to flood risk management in the Harbour. The conclusions could also be used by BCC and its partner Risk Management Authorities to augment on-going plans and procedures to better manage flood risks in and around the Harbour.

The Floating Harbour maintains a constant water level during normal operation. This level is approximately 6.1mAOD. The water level is controlled by an inflow through the Feeder Canal via Netham Locks and an outflow via Underfall Sluices. In advance of potential tidelocking scenarios, the Harbour is typically drawn down by up to approximately 300mm prior to the spring tide. This allows the Harbour to maintain sufficient storage to allow an inflow from the River Frome (as the Mylne's Culvert would be tidelocked). During exceptional circumstances, the Harbour can be drawn down up to 500mm, however this requires significant liaison with boat owners in the Harbour to slacken their moorings. Hence this process needs to be initiated days in advance of the drawdown.

One of the primary aims of the Workstream 4 assessments was to produce a high-level review and structural analysis of the principal control structures in the Floating Harbour. Coupled with this was an appreciation of the interaction the structures have with flood risk management. The results of both exercises can be used by the Council to improve the asset management regime in the Harbour and ensure continued and, where necessary, improved standard of protection provided by the assets is investigated. In addition, the CAFRA Workstream 4 assessments investigated various potential alterations to the existing Harbour operations, which are summarised in Table 1 below.

Table 1 Floating Harbour Operations Assessment

Operation Alteration	Potential Benefits	Potential Constraints	Investigated Further
Increasing Drawdown	Additional storage of floodwater from the Avon	Very difficult to administer. Potential structural instability issues with Harbour walls	No
Altering Underfall Sluices/Netham Lock opening	Allows additional water out of the Harbour, thus returning to normal level quicker	No additional improvement over existing arrangement	No
Investigate operational integrity of structures, systems and assets during flood events	Identifies the structures or systems (or physical access to them) that are at risk during a flood event	None – investigative work	Yes – via CAFRA Bristol Harbour Strategy, M&E Assessment and Operational Resilience work

As shown in Table 1, the CAFRA work summarised that the current operational regime of the Floating Harbour is relatively sound in terms of controlling flood risks as the existing assets are able to release sufficient water from the Harbour during the low tide sequence. Therefore, the assessments of Workstream 4 concentrated on the operational integrity of above-ground assets as well as investigating the potential effect following a failure in key control assets (e.g. Underfall Sluices).

As mentioned in section 3.6.2, progressing with any future works or studies in relation to the Floating Harbour assets will take account of the Workstream 4 assessments, but future model testing would utilise the baseline Workstream 3 hydraulic modelling.

Two specific studies were also completed as part of the Harbour Strategy that was incorporated into CAFRA Workstream 4, these studies are considered in the following sections.

3.8.1 Floating Harbour Mechanical and Electric (M&E) Assessment and Operational Resilience Study

The requirement for the *Mechanical and Electrical (M&E) Assessment and Operational Resilience* study was identified through the Bristol Harbour Strategy in order to undertake additional, more intrusive examinations of critical Harbour infrastructure.

The M&E Assessment was completed by Kenneth Grubb Associates and concentrated on the mechanical, electrical and hydraulic equipment at Underfall Yard and Brunel Dam Sluices. These assets are part of the automatic water level control of the Harbour. In particular, the assessment established the resilience of the existing equipment, when subjected to flooding. The assessment came to the following conclusions:

- The majority of the electrical systems are in good working order and raised above the present day flood level;
- The Underfall Sluices are in good overall condition but have evidence of corrosion, aging drive systems and have a poor sealing, resulting in leakages through the sluices even when fully closed.

The Operational Resilience Study was undertaken to assess the vulnerability of the existing Harbour control assets during flood conditions. The CAFRA results indicate that the Harbour would reach a water level of approximately 8mAOD. Although this water level would not cause significant flooding in Bristol, the Resilience study was tasked with estimating the impact such a level would have on the control assets. The study reached the following conclusions:

- The assets in Underfall Yard are vulnerable to flooding due to their low lying nature and could lead to significant debris in floodwater (cars, boats, equipment);
- Some manual operation of assets and alternative discharge methods is possible (e.g. Nova Dam) but accessing these is very difficult and hazardous during flood events;
- The impacts are likely to significantly increase with climate change;
- The walls at the back of Underfall Yard (facing Avon Crescent) have the potential to withstand up to 1.5m of water and thus form a defacto defence that would require further analysis as part of a future mitigation option development;
- Some relocation of electrical and mechanical equipment would aid in increasing flood resilience of Harbour control assets;
- The City Docks team could benefit from additional water level and meteorological data to improve responses during flood conditions and assist in Harbour wide emergency planning.

3.8.2 Mylne's Culvert Study

The Mylne's Culvert takes the flow of the River Frome through a culvert that flows beneath the Floating Harbour(via an inverted iron siphon in the vicinity of Prince Street Bridge), and discharges at a low topographic level into the River Avon, with tidal ingress prevented by a tide flap at the end of the culvert. The Mylne's Culvert has for many years presented an unknown risk to the Harbour for the following reasons:

- The actual condition of the culvert, inverted siphon and tide flap is largely unknown due to health and safety difficulties in inspecting these assets;
- The flood risk posed by the culvert (directly or via a failure in the flap or blockage/breakage of the culvert) is largely unknown;
- The culvert is believed to play a key role in maintaining the water quality of the Harbour;
- It is believed that the Harbour could result in significant and rapid drawdown in water level should the culvert fracture or tide flap fail.

It was agreed by the stakeholders that the study should form part of CAFRA due to the unknown aspects highlighted above. Therefore, an early appraisal of the culvert was undertaken as part of the Harbour Strategy aspect of Workstream 4. This work concluded that many unknowns still existing such that a specific study was required.

The study made the following conclusions:

- The condition is still largely unknown, couldn't be ascertained through desk studies and would require significant investigations and surveys, including man-entry surveys;
- CAFRA modelling indicated that the culvert does not pose a significant flood risk either directly through tidelocking or through a failure/fracture due to its relatively limited capacity;
- The culvert is likely to play a key role in maintaining a generally good water quality;
- If the structure were to fracture or tide flap fail, the Harbour would not experience rapid drawdown due to the limited capacity of the culvert.

As a result of the above conclusions (in particular those related to flood risk), it was agreed by the stakeholders that the management and mitigation of the Mylne's Culvert should be progressed as a separate item, outside of the CAFRA project.

4 Consideration of Options - Fluvial

Following completion of Workstream 3 and as part of Workstream 4, a high-level review was undertaken of fluvial flood risk to identify those areas where fluvial flooding was predicted to occur frequently, had the potential to impact on large numbers of properties or where potential schemes were likely to warrant further investigation. The following section summarises the work completed as part of the fluvial options assessments. As explained in previous sections, the interpretation of Workstream 3 results indicated the fluvial flooding in Bristol is somewhat less complex than tidal flooding Therefore, fewer model runs and scenario tests were required. As a result, the baseline Workstream 3 model was utilised for the fluvial aspects of Workstream 4.

The results of the high-level review were sub-divided by fluvial system, with the following key areas identified where clusters of properties (or infrastructure such as railway lines) were predicted by the CAFRA model to be affected by a specific fluvial flood source or pathway:

- River Avon:

A number of minor instances of fluvial flooding, for rare events only.

- Brislington Brook:

  Railway line flooding next to St Anne's Terrace.

  Flooding at the Chapel Way / St Anne's Road junction.

- River Malago / Pigeonhouse Stream:

  Flooding in the Bedminster area.

- Colliter's Brook:

  Flooding in and around Ashton Gate football stadium

- River Frome:

  Flooding downstream of the M32 in and around Stapleton Road

  Flooding on the opposite bank to IKEA, on Napier Road

  Flooding at Pennywell Road

  Flooding in the city centre around Wade Street

- Boiling Wells Stream:

  Flooding along Mina Road

This high-level review was presented to the CAFRA Steering Group and a prioritisation of fluvial flood risk areas identified, which resulted in the identification of a single area where a high-level appraisal of potential options would be carried out as part of the CAFRA study.

The results of the high level review are summarised in Appendix E, extracted from the CAFRA report.

For the majority of areas detailed in Figure 8, the high-level fluvial review has found that the frequency of fluvial flooding is often low (i.e. less than 1 in 20 annual chance). This limits the likelihood that annual average damages would be sufficiently high to justify intervention to alleviate the flooding predicted. Further assessment of intermediate (e.g. 1 in 5, 1 in 10, 1 in 50) flood events not in the CAFRA study scope may improve the detail of this assumed annual average damage curve, but since many of the flooded areas do not show properties impacted until 1 in 100 or 1 in 200 flood levels are reached, it is not necessarily a certainty that further analysis would increase estimated property damages.

Since the Mina Road area was shown to suffer predicted flooding from a 1 in 20 event, potentially affecting a total of 51 ground floor dwellings (rising to 81 for 1 in 100 and 120 for 1 in 200 events) it was considered that further analysis, including a high-level review of possible options, would potentially be of value. BCC therefore requested that review of the Mina Road area be included in the revised scope for CAFRA Workstream 4.

5 Consideration of Tidal Options – the Bristol Harbour Strategy

5.1.1 Background

The Workstream 3 results provided evidence that the predominant flood risk posed to central Bristol is from tidal sources, which is predicted to significantly increase in the future as the projected impacts of climate change influence tidal levels within the Avon catchment. Hence this summary provides greater detail on the Workstream 4 development of tidal options than the fluvial options.

As mentioned previously, given the interaction with the CAFRA work, the Harbour Strategy was included within the Workstream 4 assessments. The separate Workstream 4 report is provided as an Annex to the final CAFRA report for completeness. This section gives a summary of the findings of this report.

The principal finding of the study is that the primary risk to Bristol City Centre is from tidal inundation rather than fluvial flooding from the Rivers Avon and Frome. This is true in terms of the extents of flooding, the numbers of properties affected, the severity of the flooding in terms of depth and velocity, and the degree to which this flooding is expected to increase with climate change.

There are a number of primary flood mechanisms that were identified to affect properties adjacent to the Floating Harbour:

- Overtopping from the River Avon (New Cut) into the Floating Harbour via low points at Junction Lock, Avon Crescent/Underfall Yard and Bathurst Basin.
- Overtopping into low-lying St Philips area via Totterdown Dam and Victor Street
- Overtopping into low-lying areas around Netham.
- The report states that over 250 properties would be expected to be flooded by a present day 2% AEP (1 in 50 year return period) tidal flood event, with that number rising to over 500 for a 0.5% AEP (consisting of a 0.5% AEP tidal event combined with a 50% AEP fluvial flow) tidally-dominant event.

The report details a comprehensive series of model runs that was undertaken to establish the relative strength of the relationships between combinations of fluvial and tidal annual probabilities and water levels in the Floating Harbour. A series of Influence Diagrams were produced, which can be seen in the copy of the report supplied in Annex F of the final CAFRA report. Key findings were:

- There is a strong relationship between the AEP of a tidal or surge flood event and the water levels in the Floating Harbour. This is explained by the large volumes of water which flood up the Avon towards Bristol with the incoming tide and the connectivity of the Floating Harbour, via a series of low points in its frontages, to the tidal Avon.
- There is a far weaker relationship between the AEP of fluvial flooding on the River Avon and the levels in the Floating Harbour. This is explained by the fact that a large proportion of Avon flow passes down the New Cut away from the Floating Harbour and that the Floating Harbour has large amounts of storage to receive incoming fluvial flows associated with its surface area.
- The same was true of the River Frome, largely because of the smaller incoming flows on the Frome, and the presence of the NSWI (passing a significant proportion straight out to the Avon) as well as the relatively large amount of storage available in the Floating Harbour.
- The relative coincidence of the tidal and fluvial peaks was shown to exert around a 300mm variance on peak water levels for a given set of probability flood events, hence

the report states this is of more importance than the actual probability of the fluvial flood event under consideration. Thus tidal flooding takes up storage in the Floating Harbour and prevents the fluvial flows bypassing the harbour effectively via the New Cut and NSWI.

The Asset Condition Survey identified that the various MEICA and civil engineering assets which make up the Floating Harbour water management system pose a significant risk (see section 3 for more information on the MEICA assets), should they fail, in terms of increasing risk to the city. Failure of assets at Underfall Yard during a 0.5% AEP tidal event, for example, was found to affect approximately over 500 properties from Underfall Yard through the city centre and into the St Philips area.

The future management of flood risk, and adaption to climate change, within Bristol, relies on continued access and provision of power supplies to the Floating Harbour systems and the maintenance of sufficiently capable staff to operate and understand these assets during times of flooding.

5.1.2 Potential Mitigation

The CAFRA study considered a range of potential intervention options to reduce the risk of flooding to the Floating Harbour area. These options include a series of flood defences to address deficiencies (defined by various 'low spots') in the standard of protection around the Floating Harbour, including Avon Crescent, Totterdown Dam and Victor Street. Hydraulic modelling analyses were undertaken, demonstrating the ability of these options to reduce the extents of flooding in extreme events. Economic assessment was undertaken to determine benefits and illustrate a strong business case for undertaking such works funded by the public purse. By reducing significantly a Do Nothing present-value damage estimate of £30 million, all options considered had benefit cost ratios robustly greater than 10, with the highest as much as 47. Thus the CAFRA Workstream 4 tidal elements provide strong evidence to progress Project Appraisal activity for these options.

The modelling undertaken by Mott MacDonald/Edenvale Young reinforced the widely-held understanding that Bristol remains extremely vulnerable to climate change, largely because of predicted rises in sea level. The key impacts of climate change were identified as:

- Between the present day and 2110, a seven-fold increase in the total number of properties flooded for a 0.5% AEP tidal event coinciding with a 10% AEP fluvial event on the Rivers Avon and Frome. Resulting in 3,500 ground floor properties flooded, and numerous other dwellings and businesses disrupted.
- Significant increases in the extent of flooding, particularly in the first 25 and 50 year periods assessed. The study predicted that by 2110 over 400 hectares (ha) of the city centre would be directly inundated or isolated by a 0.5% AEP tidal event coinciding with a 10% AEP fluvial event.
- Increased depth and frequency of flooding of key waterside cultural historical and social assets including the SS Great Britain and a number of large public venues.
- Increasing risk of flooding over time to the commercial centre of the city, including Broadmead, Canon's Marsh, Redcliffe, St Phillips and the Local Enterprise Zone.
- Increasing risk of flooding to key emergency services centres such as the Central Fire Station.
- Increasing disruption to key road and rail routes within and through the city centre, with tidal inundation effectively preventing all movement between the north and the south of the city with the exception of St Phillips Causeway.

Given the above findings, the report concludes that climate change is a key determinant of future planning decisions and strategies in the city relating to flood risk. An adaptive approach, comprised of many elements, is recommended, with the following suggested inclusions:

- Improvement of flood management systems including the development of a Bristol Flooding Operation Manual. This should incorporate the Environment Agency Flood Forecasting and Warning systems with the management of water levels in the Floating Harbour and the use of the NSWI, reflecting a holistic systems-based approach to managing flood risk across the city.
- Improvements in the operational integrity of the Floating Harbour structures such as Underfall Yard Sluices, Junction Lock and the Nova Dam Sluices.
- The construction of flood defences to remove 'low points' along the Floating Harbour at Junction Lock, Avon Crescent, Bathurst Basin and between Totterdown Dam and Victor Street.
- Further development of large-scale intervention options such as a storm surge barrier on the Avon.

The Floating Harbour Strategy was undertaken to augment the main CAFRA study's understanding of the flood risk vulnerability of the Floating Harbour. It undertook this by completing condition assessments of the principal Harbour assets and establishing a risk-based analysis and strategy for future improvements or maintenance of the assets. The study provided a risk-based analysis of the Harbour assets that will enable the regulatory authorities to formulate a management regime for them. The study also made the following recommendations:

- Of all the assets, those in and around Underfall Yard perform a vital function in flood risk management but require additional, more intrusive, surveying (including the mechanical and electrical systems);
- The Mylne's Culvert is a potential liability and has been subject to separate consideration. Initial scoping has shown that the culvert does not present a significant flood risk to the City Given this finding it has also been established that the cost of a full structural survey and subsequent refurbishment cannot currently be justified. BCC, Wessex Water and The Environment Agency have therefore agreed to maintain a watching brief on this structure but have no current plans for further investigations or improvements.

5.1.3 Development of the Mitigation Options

It became evident through the completion of the CAFRA study that the potential options to mitigate tidal flood risk in the centre of Bristol is complex. Central Bristol is a regionally and nationally important political and economic area (for example, it houses the Temple Quarter Local Enterprise Zone). It is also subject to ambitious and dynamic regeneration initiatives, which at present are constrained by flood risk. In addition, whilst the options to mitigate flood risks in the short to medium term may be relatively simple to deliver, the future scenario is much less so. Therefore, the development of suitable mitigation options is likely to be a lengthy process subject to significant political and public scrutiny.

As a result of the above, whilst the CAFRA project proposed a number of potential mitigation options, the project stakeholders agreed that development of these options should be subject to a separate commission, albeit based on the CAFRA study.

In order to assist with the future options development, an early screening assessment was undertaken as part of Workstream 4, which is summarised in Table 2.

Table 2 Strategic Mitigation Scoped

Potential Measure	Mitigation Method	Scoped In/Out of Future Works	Reason
Tidal Surge Barrier	Prevent tidal surges migrating upstream	In	Feasible solution. Potential benefits to tidelocking
Flood Walls	Prevent tides spilling into the Harbour and hinterland	In	Feasible solution
Complete drawdown of the Floating Harbour	Provide storage of floodwater once spilt from the Avon	Out	Unfeasible solution. Complete drawdown might destabilise Harbour walls. No protection to hinterland. Storage provided by Harbour not likely to be sufficient
Pumping of floodwater	Removes floodwater from affected areas	Out	Unfeasible solution. Unlikely to provide sufficient pump rate to remove significant volumes of floodwater. Unsustainable solution

6 The Way Forward

6.1 Strategic Assessment of Flood Risk in Bristol

Following the reports summarised in this document and discussions on the 22nd February 2013 between BCC, the EA and the consultants who wrote the reports, a strategy has been developed for going forward. This strategy has been divided into short, medium and long term aims.

6.1.1 Short-term aims

Several short term aims have been agreed; these tend to relate to the policy governing flood risk in Bristol and continued investigation. The aims are listed below:

- Improvement/rationalisation of the policies and procedures relating to and governing the Floating Harbour.
- Continued assessment of liabilities such as low-points on the harbour frontage
- Use of the CAFRA models and outputs to be agreed between the Environment Agency and Bristol City Council. This will inform on-going and future assessment of developments

6.1.2 Medium-term aims

Medium term aims relate to the progression of the study of the watercourses as techniques and statistical estimates improve, as well as ensuring that the outputs from this study are utilised to inform and minimise risk.

- Monitor climate change science and revise CAFRA modelling as necessary to re-appraise flood risk outlook and ensure knowledge of the catchment remains robust and as complete as possible.
- Maintenance and upgrade of key flood risk asset, either Harbour (tidal) or fluvial assets;
- Work with developers to ensure that developments take advantage of the outputs of this study and minimise risk to new development, whilst safe-guarding the on-going economic growth of Bristol.

6.1.3 Long-term aims

The long term aim is to assess the potential for future funding of larger-scale options such as an Avon Barrier or strategic flood wall raising to address the future threat posed by climate change to the Floating Harbour and city centre.

6.2 Implications for Key Development areas

Bristol, as a Core City, is a regionally and nationally important economic and regeneration area. Much of the vibrancy and growth within Bristol is situated within the central area, as exemplified by the Temple Quarter Enterprise Zone. Over the last 10 years or so, there has been an increasing scrutiny on flood risk posed to proposed development sites and regeneration areas. Recent flood risk studies such as the SFRA, PFRA and SWMP have indicated the flood risks posed to central Bristol, which the CAFRA Workstream 3 results have largely verified. The results indicate that the flood risks posed many regeneration areas, including the Temple Quarter Enterprise Zone, are potentially manageable in the short term. However, the shadow of climate change has in recent years presented a significant constraint to regeneration initiatives in Bristol. CAFRA has confirmed that the significance of the predicted climate change flood scenario is sufficient enough that all stakeholders need to work together to develop the most appropriate mitigation strategy. Agreeing a strategic mitigation approach can build confidence amongst stakeholders that ongoing regeneration requirements can be met whilst minimising the hazards posed to people and places now and in the future.

The CAFRA work has indicated that given their position as Lead Local Flood Authority, Harbour Authority, Highways Authority, Planning Authority as well as being a key Enterprise Zone partner, Bristol City Council is well placed to take a lead on the development of a flood mitigation solution. However, no scheme could be progressed without close partnership with fellow Risk Management Authorities (Environment Agency, Wessex Water).

Appendix A

Studies Overview

List of Contributing Studies

Table A- 1 CAFRA - List of Contributing Studies

Study Name	Study Focus	Produced By	Date Completed	Document Reference/Link
CAFRA	Combined fluvial and tidal risk to all tidally influenced watercourses	Hyder	December 2012	5028-UA002318-GDR-02-CAFRA_Final_Report_WS4_F.pdf
Bristol Harbour Strategy	Risk based review and analysis of the Floating Harbour assets and operational regime	Mott Macdonald/ Edenvale Young	June 2010	120625 CAFRA Workstream 4 Main Report Rev E.pdf
Floating Harbour EIA Scoping	Desktop environmental assessment of the Harbour Workstream 4 and Harbour Strategy	Mott Macdonald/ Edenvale Young	February 2012	EIA Scoping Combined_120612.pdf
M&E Assessment	Condition assessment of mechanical, electrical and hydraulic equipment associated with Harbour control assets	Kenneth Grubb Associates	June 2012	C0732B_005_A Condition Assessment Report.pdf
Avon Crescent Ground Investigation	Scoping assessment for ground investigation requirements in support of potential flood walls/embankments	Mott Macdonald	March 2012	2012.03.27_BCC Underfall Yard GI_DHEMR_revA.pdf
Floating Harbour Resilience Report	Assessment of Floating Harbour key operational assets and their susceptibility to/operation during flood inundation	Mott Macdonald/ Edenvale Young	January 2013	Floating_Harbour_Resilience_Report_final.pdf
Mylne's Culvert Study	Review of Mylne's Culvert operation and integrity. Outline optioneering for potential improvements	Mott Macdonald/ Edenvale Young	April 2013	Bristol Central Area Flood Risk Assessment_Mylne's Culvert Study

Appendix B

Catchment Overview

Table B-1 Catchment Characteristics

Urbanisation

Many of the catchments within Bristol are heavily urbanised. Therefore, within the CAFRA study area the degree of urbanisation has a significant influence on the hydrological response, with some of the smaller tributaries responding to intense, short duration storm events. Historic flood alleviation schemes are another significant influence and are discussed further in section 2.3.

Flooding regime

Tide levels, peak fluvial flows and flood volumes all affect the flooding regime and, due to the large size of the catchment, some flood events will be caused by a runoff response generated in only certain parts of the catchment.

Climate

The climate of the region is typical of the cool temperate maritime type experienced in western Britain with mild, wet winters. Mean annual rainfall for the Avon catchment ranges from 792 mm in the Frome sub-catchment to 912 mm in the Ashton Brook sub-catchment, giving an Avon catchment average of approximately 845 mm.

	Avon	Upper Frome	River Frome to Floating Harbour	Ashton Brook	River Trym	Malago and Brislington Brook	Markham Brook
Catchment Description	The catchment of the River Avon drains parts of Gloucestershire, Wiltshire and Somerset and flows through the major cities of Bristol and Bath to the Severn Estuary at Avonmouth. The direction and flow path of the river is dictated by the catchment's topography and results in the river following a crescent shape, initially flowing south from its source in the Cotswolds near Chipping Sodbury before bending west through Bath and Bristol.	The Upper Frome drains a catchment area of approximately 150km^2, to Frenchay Gauging Station and receives an average annual rainfall of 792mm. Tubb's Bottom detention reservoir is located within the catchment, upstream of Frampton Cotterell, and is used to control flooding on the River Frome.	The Lower River Frome drains a total catchment area of approximately 176km^2, this includes the Upper River Frome catchment. The total catchment receives an average annual rainfall of 793mm. The lower reaches include Horfield Brook, Boiling Wells stream and Cranbrook; several reaches of the river channels are culverted. Across the Lower River Frome catchment the Northern Stormwater Interceptor (NSWI) at Eastville, diverts flood flows from the Bristol Frome and St George Flood Alleviation Scheme (FAS) away from the centre of Bristol to discharge directly to the River Avon.	Ashton Brook includes Longmoor Brook and Colliter's Brook, adjacent catchments to the south of Bristol City Centre. The watercourses are culverted in their lower reaches and discharge through outlets fitted with flapped valves into the tidal River Avon. Longmoor Brook to the west drains a total area of approximately 10 km2 and receives an average annual rainfall of approximately 867 mm. The Colliter's Brook catchment, immediately to the east, covers approximately 7 km^2 and receives an average annual rainfall of approximately 912 mm.	The River Trym has its headwaters in the suburbs of Southmead and Filton to the northwest of Bristol City Centre and flows in a generally south westerly direction to its confluence with the tidal River Avon at Sea Mills. The river drains a total catchment area of 21km^2 which receives an average annual rainfall of 806 mm.	The Malago catchment drains a total area of approximately 15.5 km^2 with Brislington Brook, located immediately to the east, draining approximately 11.2 km^2. The average annual rainfall for Malago and Brislington Brook catchments is 870mm and 840mm respectively. The upper reaches of these catchments include a complex flood management scheme which utilises large interceptors and tunnels to take water from both catchments directly to the River Avon.	Markham Brook drains a total catchment area of 4.4 km^2 to its confluence with the River Avon. The watercourse is culverted, through the urban area of Pill, before discharging through a tidal flap into the River Avon. The catchment is bisected by the A369 road and receives an average annual rainfall of 882 mm.
Soils and Geology	The main geological features of the catchment are the limestone Mendip Hills, the oolitic limestone Cotswolds and the chalk downs in the east, all of which are major aquifers affecting the hydrology of the catchment. Impermeable clays lie between the west-sloping strata of the limestone and the chalk, while sandstone and mudstone are exposed in the west of the catchment.	The catchment is underlain by complex geology. The eastern and central catchment is dominated by sandstones of the coal measures and Mercia mudstone. The western catchment is less permeable with Mercia mudstone and Liassic clays. Superficial deposits comprise meltwater gravel and terraces, mainly in the west.	The catchment has complex geology, with eastern and central parts dominated by sandstones of the coal measures and Mercia mudstone. The western catchment is less permeable with Mercia mudstone and Liassic clays. Superficial deposits comprise meltwater gravel and terraces, mainly in the west.	Longmoor Brook is underlain by relatively permeable soils and the soils in Colliter's Brook catchment have a lower permeability than the western catchment of Ashton Brook.	The River Trym has cut through soft overlying rocks into much harder limestone. The catchment descriptors identify that this is not a permeable catchment.	Both the Malago and Brislington catchment descriptors display a low level of permeability. The Dundry Hills have a complex limestone geology and the lower catchments flow through a complex geology of marls and carboniferous Coal Measures that are mostly acidic sandstone.	In the upper and middle reaches of the catchment, geology of sandstone and carboniferous limestone is overlain by well drained soils. The catchment is classified as permeable. In the lower catchment soils have lower permeability and may be prone to seasonal waterlogging. The permeability of the catchment will result in relatively high infiltration and a damped runoff response to rainfall.
Land Use	Predominantly rural comprising arable agriculture, woodland and grassland. Approx 10%of the total catchment is urbanised. As well as Bristol and Bath, its main urban areas include Chippenham, Frome, Trowbridge, Devizes, Melksham, Malmesbury, Calne, Keynsham, Westbury, Midsomer Norton and Radstock, Yate and Chipping Sodbury, Bradford-on-Avon and Corsham.	The lower part of the catchment is crossed by the M4 motorway. South of the motorway contains large amounts of urban development. The land use in the catchment north of the motorway, with the notable exception of Yate and Chipping Sodbury, is generally made up of arable agriculture, woodland and grassland. The lower reaches' soil permeability and urban extent will result in a quick runoff response.	Heavily urbanised which will result in a quick catchment response.	In the upper reaches the catchments share more rural land uses, as confirmed by the FEH catchment descriptors. Notably, the lower reaches of Colliter's Brook are moderately urbanised.	Very heavily urbanised and several reaches of the river are culverted.	Both catchments are heavily urbanised and culverted for much of its lower reaches.	Slightly urbanised - the urban area of Pill is located north of the A369 to the confluence with the River Avon, the area south of the A369 is predominantly rural,
Topography	The watershed of the Avon is delineated by the Mendip Hills to the south, the Cotswold Hills to the north, the Marlborough Downs and Salisbury Plain to the east and the Severn Estuary to the west. Along some reaches the River Avon has a broad floodplain, whereas in other areas the Avon and its tributaries are constrained by engineered channels or steeper valley sides.	The catchment rises at an altitude of approximately 190 m AOD and has an average altitude of 105 m AOD.	The catchment rises at an altitude of approximately 190 m AOD and has an average altitude of 100 m AOD.	Colliter's Brook rises in the Dundry Hills and has an average altitude of 115 m AOD. Longmoor Brook rises at an altitude of approximately 75 m AOD and has an average altitude of 45 m AOD. The Barrow Gurney Reservoir does not drain into the Colliter's Brook catchment, therefore the surface area of the reservoir (0.2 km^2) was excluded from the catchment.	The catchment rises at an altitude of approximately 90 m AOD and has an average altitude of 48 m AOD.	The Malago and Brislington Brook rise in the Dundry Hills and flow to their confluence with the River Avon. The Malago has an average altitude of 115 m AOD and the Brislington has an average altitude of 95 m AOD.	The catchment rises at an altitude of approximately 150 m AOD and has an average altitude of 80 AOD.

Appendix C

Workstream 1 – Data Collection

In such a vast urban area as Bristol, crossed by numerous rivers and streams, a thorough data collection and review process is vital. Data was collected through BCC, logged and reviewed. A data register, listing all data sources made available for the CAFRA study, is provided in *CAFRA Study, Annex A*. A number of existing studies, including existing flood models, were used to inform the CAFRA study, including:

- ISIS models of the Ashton Brook and Colliter's Brook built as part of an Environment Agency Section 105 study by Symonds Group in 2002
- An ISIS-TUFLOW model of the River Avon, originally built as part of the Avon Flood Forecasting Project and updated to 1D-2D as part of the Environment Agency Corston to Avonmouth Flood Zone Compliance study undertaken by Halcrow in 2007.
- An ISIS-TUFLOW model of the River Frome originally built in ISIS as part of the Frome Flood Risk Management Strategy by Atkins in 2005 and updated to ISIS-TUFLOW by Halcrow as part of the Bristol Frome Model Improvements study for the Environment Agency in 2010.
- An ISIS-TUFLOW model of the River Malago (and Pigeonhouse Stream) and the Brislington Brook, developed as part of the Malago and Brislington Brook Flood Risk Mapping Study by Halcrow for the Environment Agency in 2010.
- A HEC-RAS model of the River Trym, built by Symonds Group in 2002 as part of the River Trym, Henbury Trym and Hazel Brook Section 105 Study.

For a number of the streams in Bristol, new survey data was required in order to allow modelling to be undertaken to the required level of detail, or for the existing models to be appropriately updated or revised. This was acquired during the period November 2010 to March 2011 and the management and review of new survey data was a significant part of the Workstream 1 activity. This resulted in new survey of the following watercourses:

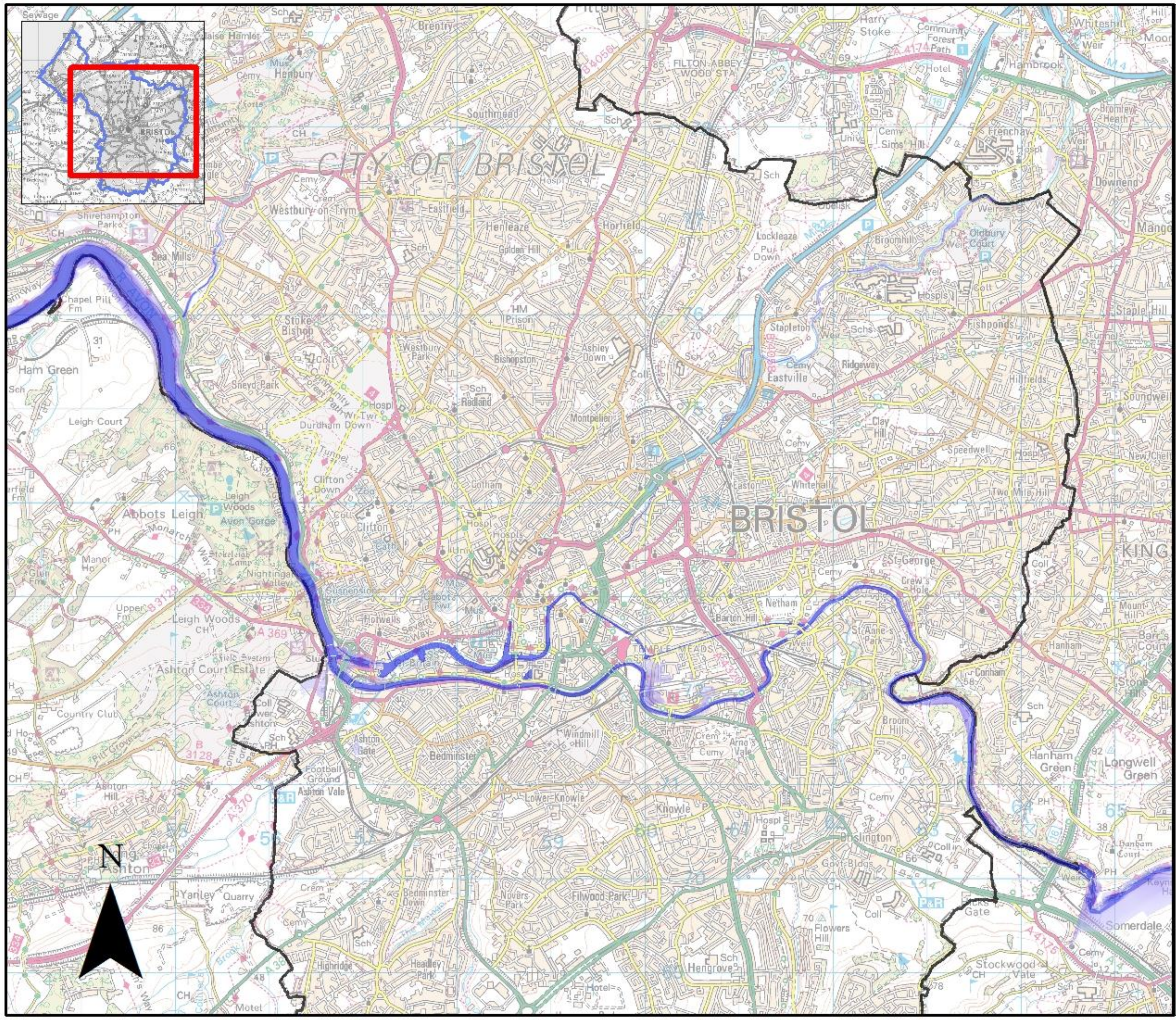
- The Horfield Brook
- The Boiling Wells Stream
- The Ashton, Longmoor and Colliter's Brooks
- The Brislington Brook
- The Cranbrook
- The River Malago
- The Pigeonhouse Stream

As part of Workstream 1, all existing and new survey data was reviewed, prepared for input to a hydraulic model (where required) and assessed for quality, with discussions held with BCC and additional survey requirements identified where existing data was found to be deficient. All new survey data collected is supplied, alongside this report, in *CAFRA Study, Annex B*

Appendix D

Additional CAFRA Workstream 3 Results Maps

Results during 5% AEP tidally dominant event (5% AEP tidal event in combination with a base fluvial flow), present day



Approximate flood depth obtained from the CAFRA Workstream 3 results. The results represent predicted flooding during the 5% AEP event, present day, which consists of a 5% AEP tidal event combined with a base fluvial flow

Legend

CAFRA Results 5% AEP Event

Depth (m)

High : 2

Low : 0

Title:
Flood Depths fom CAFRA Workstream 3, 5% AEP event, present day

Drawn By: PG Date: 05/09/2013

Figure 6

0 0.3 0.6 1.2 km

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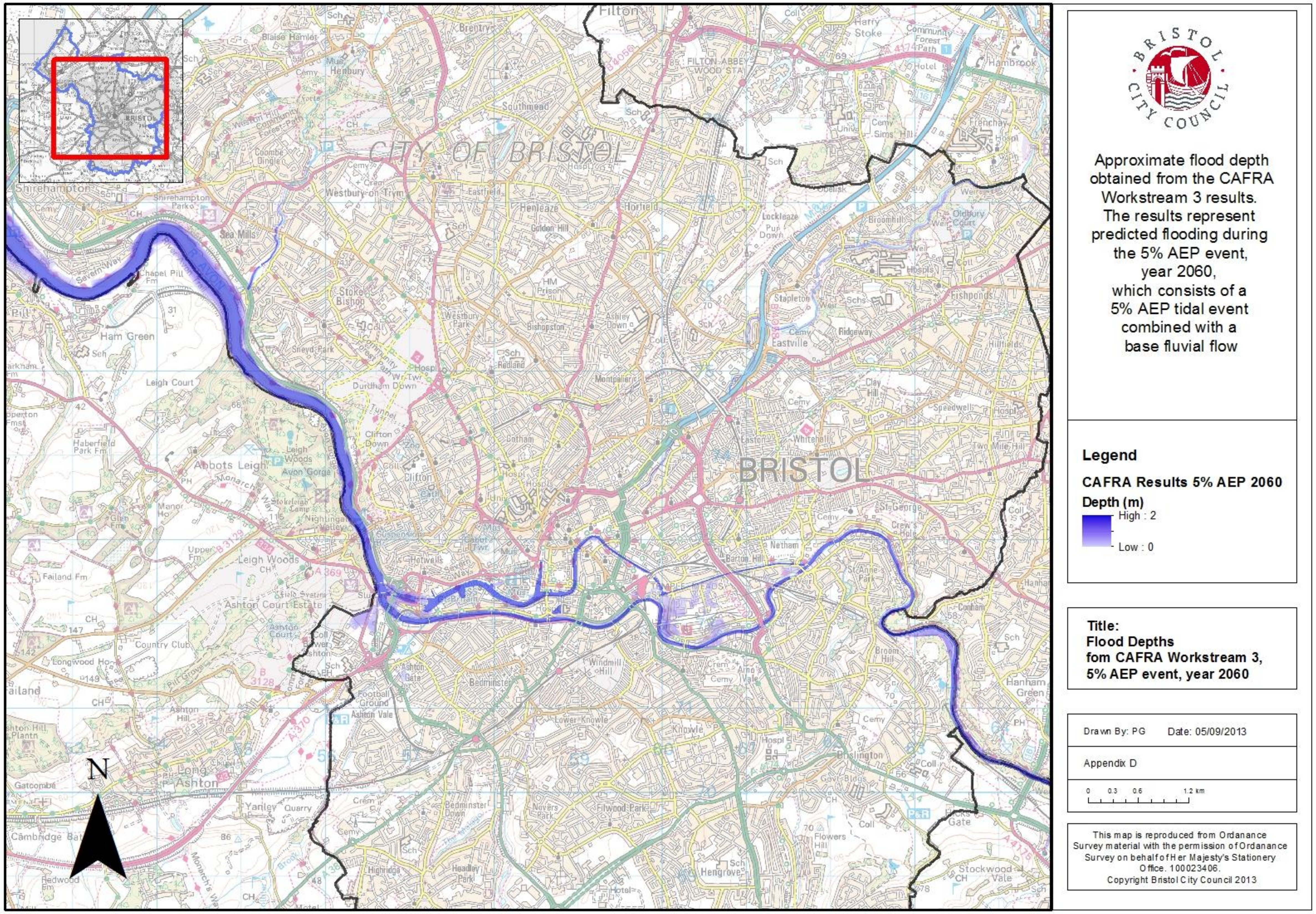
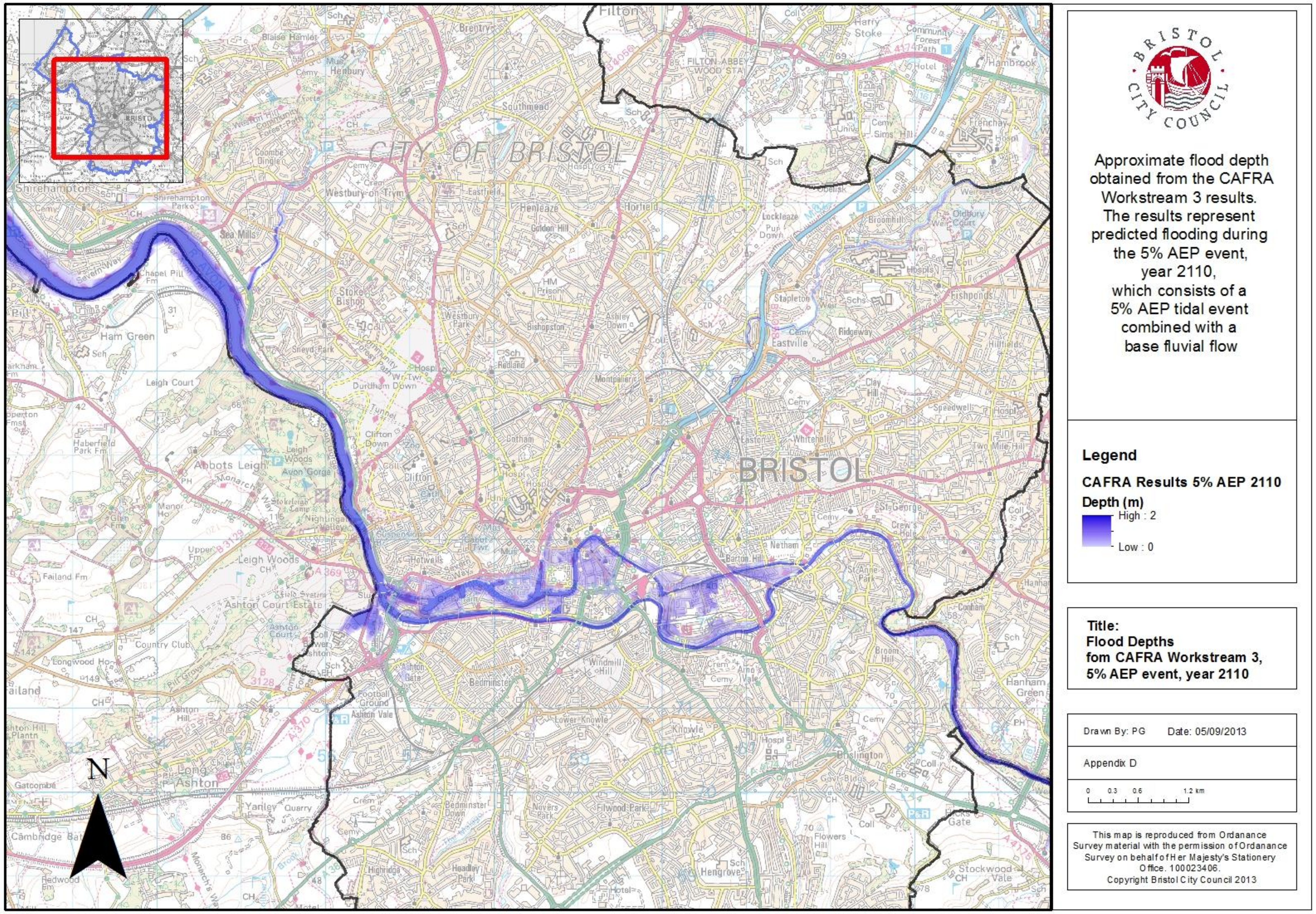
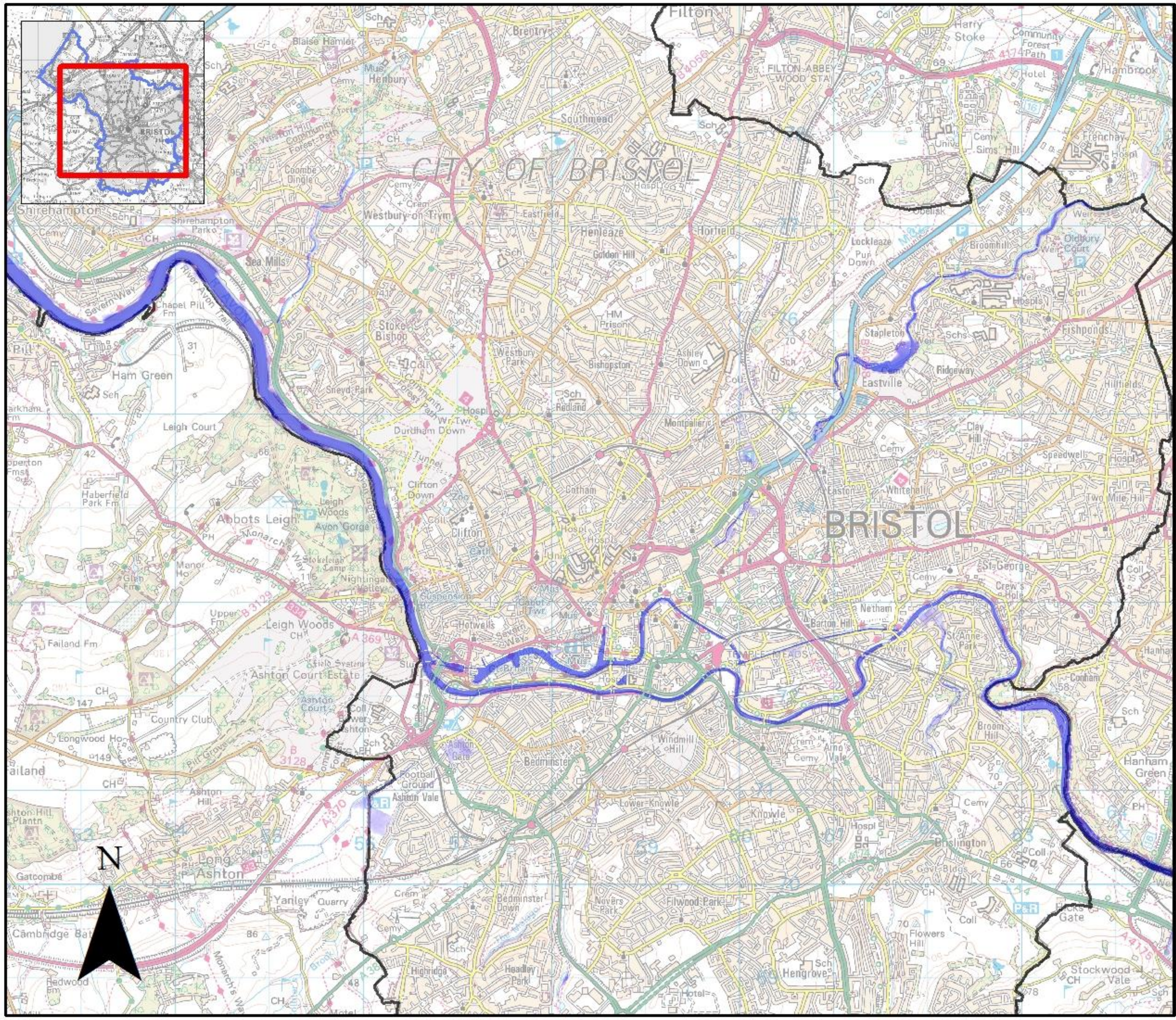
Results during 5% AEP tidally dominant event (5% AEP tidal event in combination with a base fluvial flow), year 2060



Results during 5% AEP tidally dominant event (5% AEP tidal event in combination with a base fluvial flow), year 2110



Results during 1% AEP fluvial dominant event (1% AEP fluvial flow in combination with a Mean High Water Spring), present day



Approximate flood depth obtained from the CAFRA Workstream 3 results. The results represent predicted flooding during the 1% AEP event, present day, which consists of a 1% AEP fluvial flow combined with a mean high water spring tide

Legend

CAFRA Results 1% AEP Event

Depth (m)

High : 2

Low : 0

Title:
Flood Depths from CAFRA Workstream 3, 1% AEP fluvial event, present day

Drawn By: PG   Date: 05/09/2013

Appendix D

0 0.3 0.6 1.2 km

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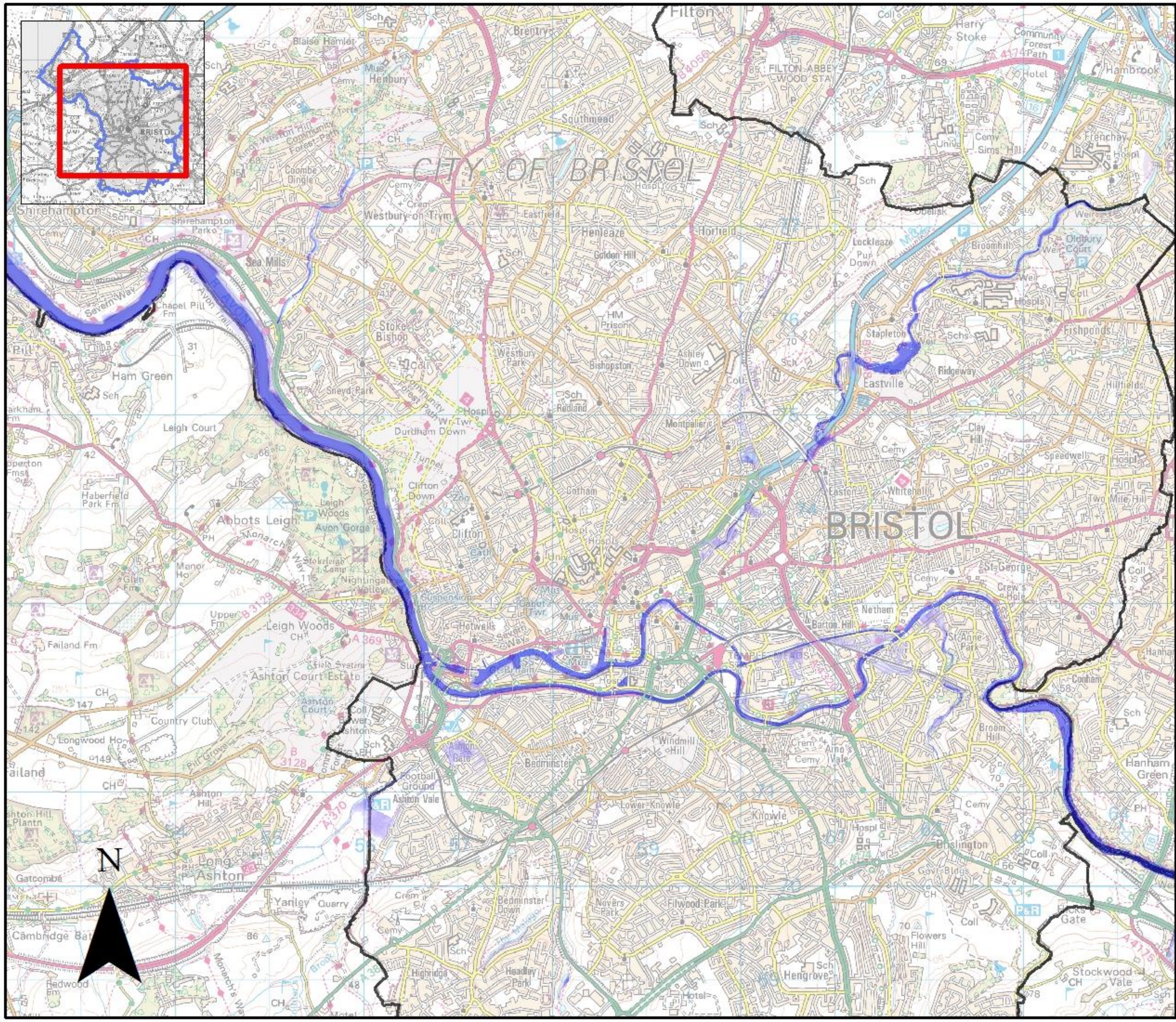
Results during 1% AEP fluvial dominant event (1% AEP fluvial flow in combination with a Mean High Water Spring), year 2060



Approximate flood depth obtained from the CAFRA Workstream 3 results. The results represent predicted flooding during the 1% AEP fluvial event, year 2060, which consists of a 1% AEP fluvial flow combined with a mean high water spring tide

Legend

CAFRA Results 1% AEP 2060

Depth (m)

High : 2

Low : 0

Title:
Flood Depths from CAFRA Workstream 3, 1% AEP fluvial event, year 2060

Drawn By: PG Date: 05/09/2013

Appendix D

0 0.3 0.6 1.2 km

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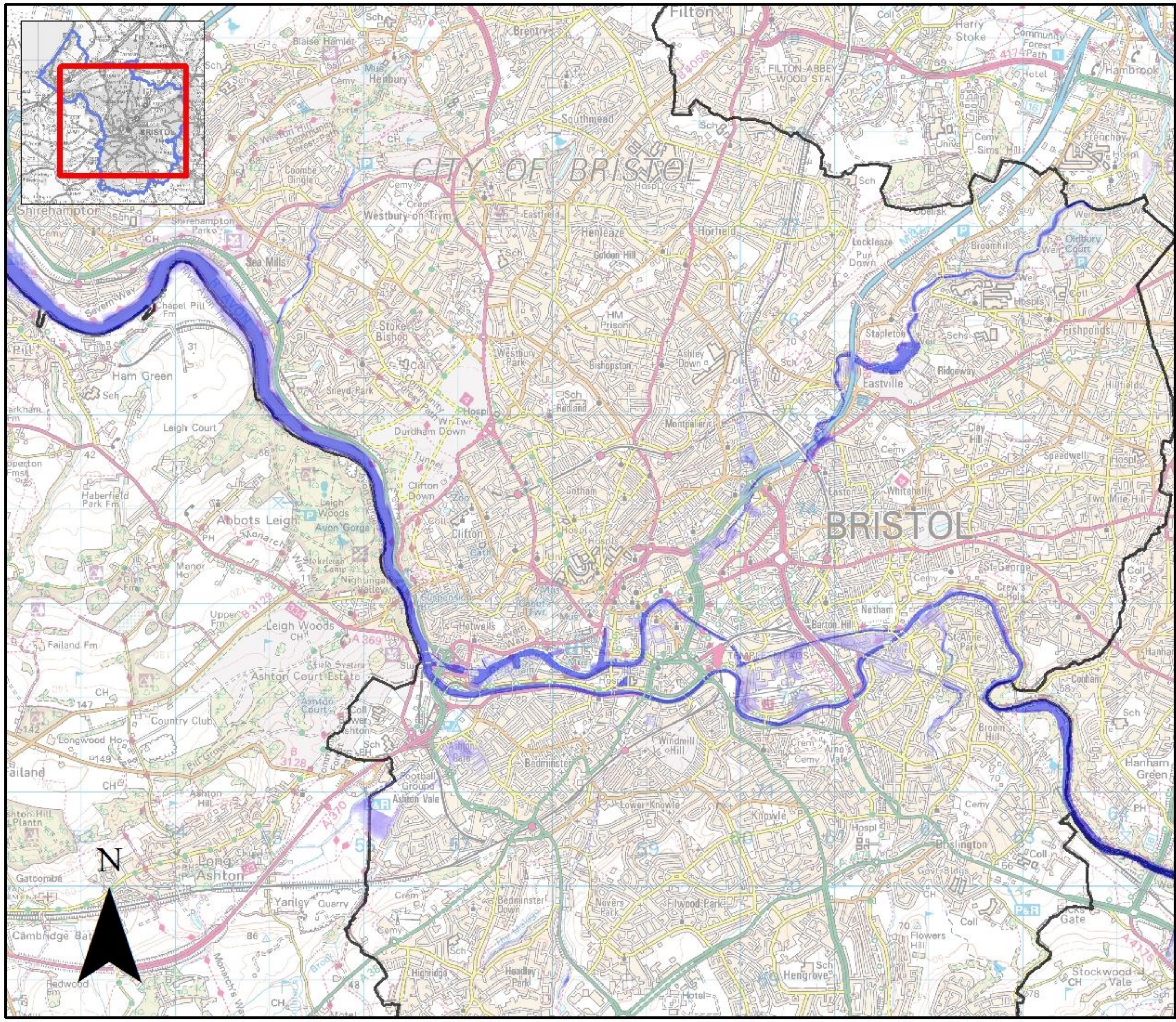
Results during 1% AEP fluvial dominant event (1% AEP fluvial flow in combination with a Mean High Water Spring), year 2110



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Approximate flood depth obtained from the CAFRA Workstream 3 results. The results represent predicted flooding during the 1% AEP fluvial event, year 2110, which consists of a 1% AEP fluvial flow combined with a mean high water spring tide

Legend

CAFRA Results 1 AEP 2110

Depth (m)

High : 2

Low : 0

Title:
Flood Depths from CAFRA Workstream 3, 1% AEP fluvial event, year 2110

Drawn By: PG Date: 05/09/2013

Appendix D

0 0.3 0.6 1.2 km

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Appendix E

Fluvial Options Summary Table

Summary of high-level fluvial flooding review

Watercourse	Area	Comments	Outcome
River Avon	Springwater Trading Estate	Potential for a handful of buildings to flood in a present day 1 in 200 event. Possibly impacted by a 1in 100 but would require further investigation of building levels	Not progressed for further assessment at this time
	Right Bank at Netham Weir	Avonside industrial estate affected by a 1 in 200 fluvial flood in the present day, rising to a 1 in 100 in 2110. Impacts of tidal flooding are far greater in this area, however.	Not progressed for further assessment at this time.
Brislington Brook	Railway line flooding at St Anne's Terrace	Flows can back up behind the railway line, potentially affecting the local community hall. In a present day 1 in 200 event, these flows can pass along the railway to the Eldonwall Trading Estate.	Not progressed for further assessment at this time but noted by the Environment Agency as a point for discussion with Network Rail.
	Chapel Way / St Anne's Road Junction	24 non-residential properties potentially affected by a 1 in 75 event. No residential damages expected. Some potential for transport disruption.	Not progressed for further assessment at this time.
River Malago / Pigeonhouse Stream	Bedminster area	Fluvial flooding cannot escape via flapped outfalls at high tide, but flows are in-bank up to and including a 1 in 100 event. A large number of properties could be affected by a more extreme, but low probability event.	Not progressed for further assessment at this time.
Colliter's Brook	Ashton Gate	A 1 in 20 event results in flooding around the stadium, with potentially 10 ground floor dwellings affected. The 1 in 75 extents are very similar, however, with only three additional properties shown to be within the extents. By a 1 in 100 event, the flooding extends into nearby roads, affecting two additional ground floor dwellings. An additional 111 are potentially impacted in a 1 in 200 flood. There are a large number of upper floor flats around the stadium area according to the NRD.	Not progressed for further assessment at this time. Potentially the subject of a follow-on study.
River Frome	Downstream of M32 on Stapleton Road	The Merchant Arms pub is shown as potentially flooded by a 1 in 20 but this is likely to only affect the gardens until a 1 in 100 flood level is reached. By a 1 in 75 event one property at the end of Cotterell Road is within the flood extent, but it is unlikely to be internally flooded. It is not until a 1 in 200 event that an additional 39 houses on Cotterell Road and Stapleton Road are potentially affected.	Not progressed for further assessment at this time.
	Opposite IKEA on Napier Road	A 1 in 20 event is mostly in-bank, with 22 ground floor dwellings and eight non-residential dwellings potentially affected by a 1 in 75 event. Very few additional properties are added in a 1 in 100 event, but 53 additional ground floor dwellings and 8 additional non-residential properties are within the 1 in 200 extents.	Not progressed for further assessment at this time.
	Pennywell Road	Potential for a 1 in 20 event to impact on the car dealership between the road and the River Frome, but the dealership has a raised threshold. By a 1 in 75 event, 40 terraced houses on Robinson Drive are within the flood extent. 1 additional property is added in a 1 in 100 event, with 21 additional residential properties and 2 non-residential properties in a 1 in 200 event.	Not progressed for further assessment at this time.
	City Centre around Wade Street	The 1 in 20 event is mostly in-bank with limited property flooding likely. A 1 in 75 event is predicted to flood the left bank around James Street, affecting nine non-residential NRD data points which would warrant further investigation to confirm they are commercial properties. A 1 in 100 event results in some flooding on the right bank near Elton Street, adding two more non-residential properties to the flood extents. A 1 in 200 event floods a larger area extending down towards the city centre, affecting 16 ground floor dwellings along River Street and 7 additional non-residential properties. The 1 in 500 and 1 in 1,000 extents cover a much larger area extending down to the Floating Harbour, illustrating that although frequency of flooding might be low, the consequences in this largely commercial area of the city centre are potentially very high.	Not progressed for further assessment at this time.
Boiling Wells Stream	Mina Road (N)	Out-of-bank flooding is predicted by the model for all events modelled in the CAFRA study, with a 1 in 20 event potentially affecting six ground floor dwellings. An additional three could be affected by a 1 in 75 event, with an additional eight affected by a 1 in 100. By the 1 in 200 event, the total number of ground-floor residential properties potentially affected could reach 24.	Taken forward, combined with Mina Road (S) for further assessment in the revised CAFRA Workstream 4.
	Mina Road (S)	Flows are shown to pass under the railway line from Mina Road to the north, passing along Mina Road and potentially flooding ground floor dwellings, in total: 1 in 20: 45; 1 in 75: 60; 1 in 100: 64; 1 in 200: 96.	Taken forward, combined with Mina Road (N) for further assessment in the revised CAFRA Workstream 4.