Melbourne Water Corporation

Lower Yarra River Flood Mapping

September 2020

Table of contents

Table index

Figure index

Appendices

1. Introduction

1.1 Introduction

Melbourne Water (MW) is the regional drainage and floodplain management authority for the Port Phillip and Westernport Region. In addition to planning, this role involves maintaining and upgrading drainage to convey flood flow through a system made up of underground drains, open waterways and channels, and overland flow paths. Melbourne Water is working towards mapping and assessing catchments across its area of responsibility to identify areas of extreme flooding and reduce flood risk through both structural and non-structural mitigation.

1.2 Background and scope

Mapping of the lower reaches of the Yarra River upstream of Spencer Street has previously been completed with the 1D software package HEC-RAS as part of the "Yarra River Flood Mapping Hydrologic and Hydraulic Study (June 2016)" (SP Goh and Associates, 2016) – referred to herein as the *2016 Yarra River Study*. This was a large scale study that looked at the hydrology and hydraulics of entire Yarra River catchment between Upper Yarra Reservoir and Spencer Street. The 2016 Yarra River Study utilised RORB and HEC-RAS to estimate flood flows and levels for the area.

Given the relatively recent hydrological modelling of the Yarra River catchment and the Maribyrnong River (2016 and circa 2014 respectively), at Melbourne Water's request the current study has excluded updating the hydrology for the catchment (i.e. it was stipulated that inflows be adopted from exiting studies) – as a result the hydrology is based on Australian Rainfall and Runoff 1987 (ARR1987) approaches and data. The scope of the current Study was therefore to establish a detailed 2D hydraulic model using TUFLOW to provide flood levels and characteristics along the Yarra River and associated floodplain from MacRobertson Bridge downstream to near the West Gate Bridge.

The established hydraulic model was then used to run the modelling scenarios in Table 1 for the 48 hour and 72 hour duration storms events as specified by Melbourne Water. These scenarios differ from the standard scenarios defined in Melbourne Water's Guidelines and Technical Specifications for Flood Mapping Projects November 2016 (MWC 2016).

Table 1 Final scenarios modelled and mapped

Scenario	Impervious Fractions	Rainfall Intensities	Sea Level Rise	AEP				
				20%	10%	5%	2%	1%
Base Case	Existing	ARR1987	No	✓	✓	✓	✓	✓
Climate Change 1 (CC_B)	Existing	ARR1987	Yes	✓	×	×	×	×
Climate Change 2 (CC_C)	Existing	ARR1987 increased by 18.5%	Yes	✓	✓	✓	×	✓
Climate Change 3 (CC_D)	Existing	ARR1987 increased by 18.5%	No	✓	✓	✓	×	✓

1.3 Purpose of this report

The purpose of this report is to document the methodology, underlying assumptions used, and results of the modelling and flood mapping of the Lower Yarra River. The outputs of the project are intended to update Melbourne Water's flood mapping information, assisting with planning approvals and flood risk assessment and prioritisation.

1.4 Limitations

This report: has been prepared by GHD for Melbourne Water Corporation and *may only be used and relied on by Melbourne Water Corporation for the purpose agreed between GHD and the Melbourne Water Corporation as set out in Section 1.3 of this report.*

GHD otherwise disclaims responsibility to any person other than Melbourne Water Corporation arising in connection with this report. GHD also excludes implied warranties and conditions, to the extent legally permissible.

The services undertaken by GHD in connection with preparing this report were limited to those specifically detailed in the report and are subject to the scope and limitations set out in the report.

The opinions, conclusions and any recommendations in this report are based on conditions encountered and information reviewed at the date of preparation of the report. GHD has no responsibility or obligation to update this report to account for events or changes occurring subsequent to the date that the report was prepared.

The opinions, conclusions and any recommendations in this report are based on assumptions made by GHD described in this Report. GHD disclaims liability arising from any of the assumptions being incorrect.

GHD has prepared this report on the basis of information provided by Melbourne Water Corporation and others who provided information to GHD (including Government authorities)], which GHD has not independently verified or checked beyond the agreed scope of work. GHD does not accept liability in connection with such unverified information, including errors and omissions in the report which were caused by errors or omissions in that information.

1.5 Available information and limitations

The following information was utilised in undertaking this flood mapping study:

- General cadastral and planning information (e.g. properties boundaries, easements, roads, planning scheme zones and overlays).
- RORB model developed in previous Yarra River Flood Mapping Project (2016)
- RORB model developed in previous study for the Maribyrnong River (circa 2014)
- Aerial ortho-photos (circa 2017)
- General information obtained from Melbourne Water throughout the course of the project:
  - Survey drawings for a majority of the bridges along the Lower Yarra River.
  - Dredged profile information for past dredging schemes, including assumptions to be made where information was not available.
  - First return and processed LiDAR (circa 2008).
  - Tidal data for both existing and climate change scenarios, including related assumptions.
  - Model files from other local or upstream TUFLOW models, namely Southbank, Fisherman's bend and North East Link Project (NELP) "existing conditions" Yarra River model.

2. Catchment and drainage description

2.1 Catchment description

The Yarra River is the longest river under MW's control and this study looks at flooding along the final 15 km of the river before it discharges to Port Philip Bay. The approximate Lower Yarra River Study Area is shown in Figure 1 and covers an area of around 50 km² across six (6) municipalities – the cities of Yarra, Stonington, Melbourne, Port Phillip, Maribyrnong and Hobsons Bay. The contributing hydrologic area extends well beyond even the hydraulic model area shown, with a total contributing catchment area in excess of 4000 km².

Within the Study Area, there is a mix of land use including residential, commercial, industrial, open space and waterways/drainage easements, although the majority of the upper catchment is rural. Key public features of the Study Area include:

- Melbourne's Central Business District (CBD).
- South Bank
- Docklands development
- Sports precinct around Melbourne Cricket Ground (MCG), AAMI Park and Melbourne Park.
- Royal Botanic Gardens.
- Alexandra Gardens.
- Birrarung Marr

2.2 Melbourne Water drainage systems

The focus of this Study was "riverine flooding" along the Yarra River within the Study Area, so there are only three major MW assets that are included in the model, the Yarra River, Moonee Ponds Creek and the Maribyrnong River – these are briefly described in subsequent sections. The underground assets within the Study Area were not represented in the hydraulic model at the request of Melbourne Water. These assets typically respond to smaller local events and would be assessed as part of more localised investigations to inform the Planning Scheme Layers in these areas. Other MW assets exist within the hydraulic model boundary outside the Study Area, but given they are outside the area being mapped they are not documented here.

2.2.1 Yarra River

The Yarra River (MW Asset No. 4400) is a 'natural waterway' asset that passes through the centre of the Study Area. The asset is approximately 15 km long within the Study Area with the following general characteristics:

- Width of 40 m to 350 m
- Depth of 6.5 m to 12.5 m upstream of Spencer Street and up to 19 m downstream of Spencer Street.
- 17 major structures crossing the waterway.

The terrain of this model has been represented using a combination of surveyed cross-sections and bathymetry.

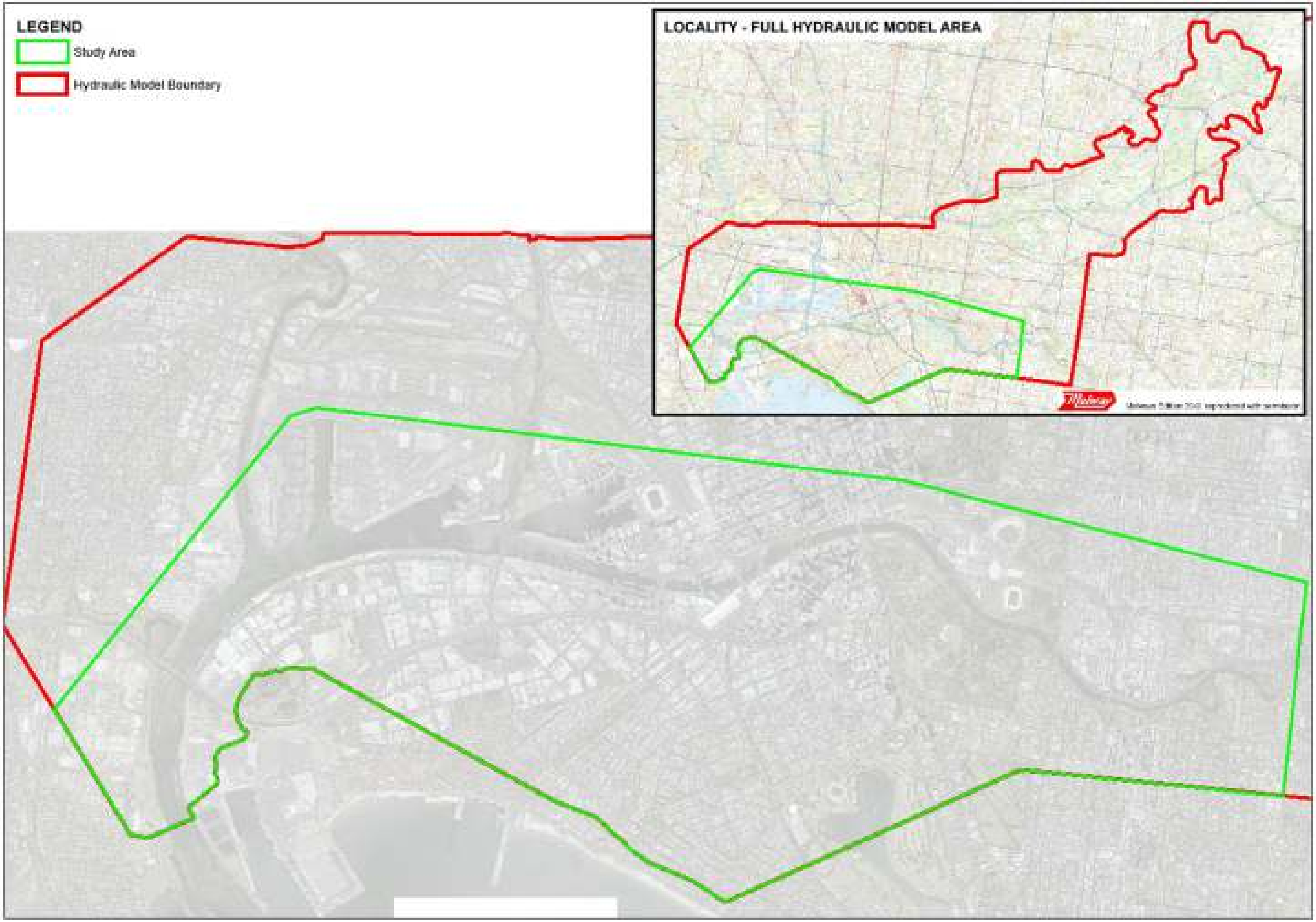


Figure 1 Study Area Location

2.2.2 Moonee Ponds Creek

Moonee Ponds Creek (MW Asset No. 4310) is a ‘drainage channel’ asset that joins the Yarra River immediately downstream of the Bolte Bridge. This asset has been included in the model from just downstream of Macaulay Road to the confluence with the Yarra River for the purpose of improving flow distribution and allowing the model to access storage within this waterway. In general, the terrain (bathymetry) is simply represented with a ‘gully’ line and shaping to better define the waterway.

2.2.3 Maribyrnong River

Maribyrnong River (MW Asset No. 4220) is a ‘natural waterway’ asset that joins the Yarra River approximately 1 km upstream of where the West Gate Bridge crosses. This asset has been included in the model from just downstream of Fisher Parade Road Bridge to the confluence with the Yarra River for the purpose of improving flow distribution and allowing the model to access storage within this waterway. In general, the terrain (bathymetry) is simply represented with a ‘gully’ line and shaping within the waterway area.

2.3 Known flood issues

No complete flood mapping of the Study Area has previously been completed, but modelling of the Yarra River upstream of Spencer Street (or Clarendon Street) bridge was completed as part of the 2016 Yarra River Study (SP Goh and Associates, 2016). This modelling utilised flows from RORB and the 1D hydraulic modelling package HEC-RAS to estimate flood levels. These results do not appear to have been used to update planning layers or designated levels.

Figure 2 shows the 100 year ARI extent and affected properties derived from previous flood mapping within parts of the Study Area. These results indicate 1247 properties are subject to flooding during a 100 year ARI event from ‘waterways’ within the Study Area.

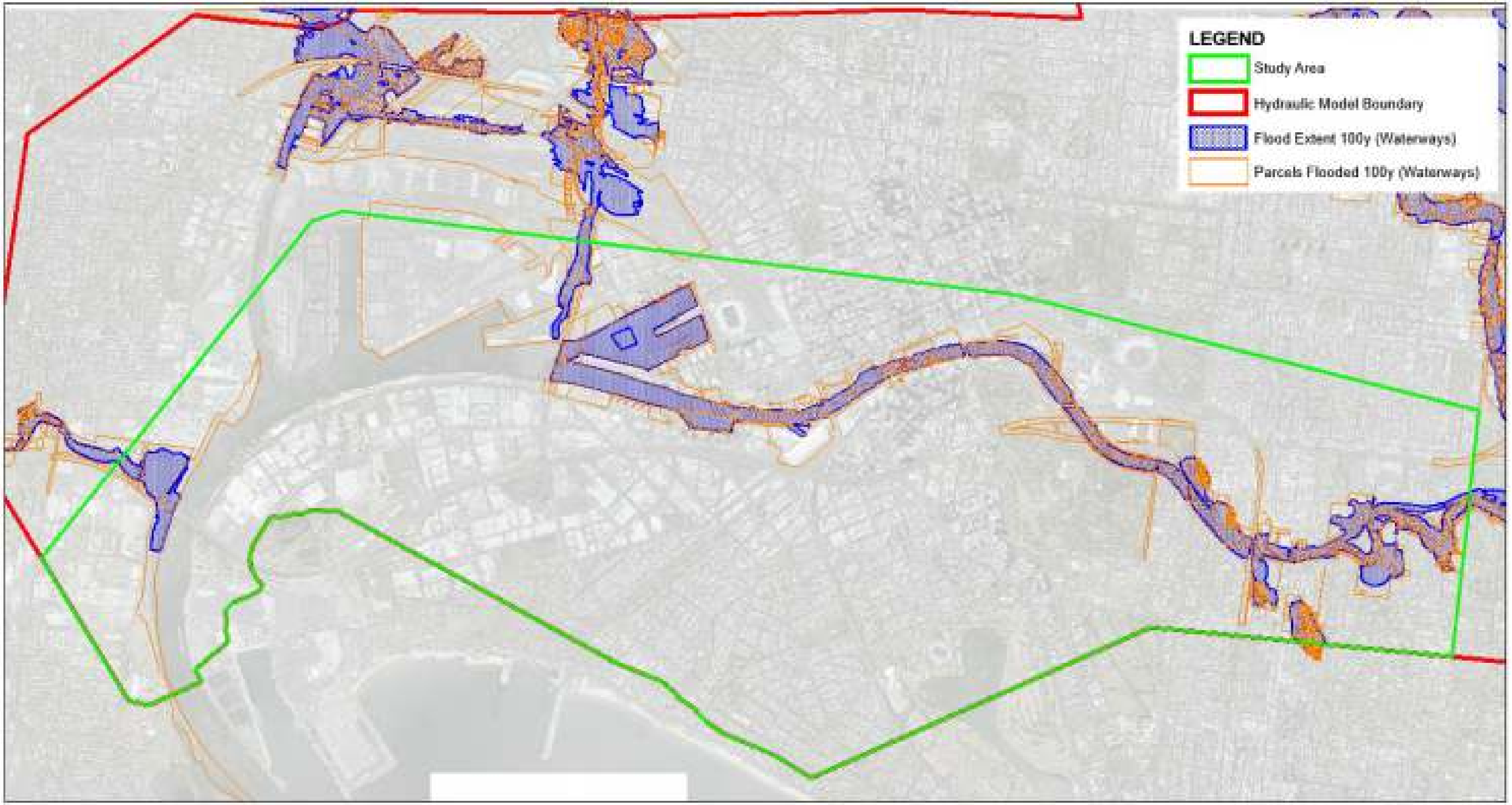


Figure 2 Previous 100 year ARI Flood Extents

3. Modelling approach

3.1 Overview

The general modelling approach utilised in this study is summarised in Figure 3, which includes the following general stages:

1. Preliminary Model – development of model used to determine appropriate grid size, assess representation of channel in 2D and understand run time.
2. Developed Model – initial scenario modelling of existing conditions and subsequent comparison of water level results to MW's designated levels (based on 1934 flood).
3. Quasi-Verification Model - revised scenario modelling based on incorporating terrain changes to quasi represent the channel profile for 1934 flood.
4. Initial Design Run Model – model used to prepare initial design run outputs that were subsequently discounted by MW over concerns in overbank flows around Southbank.
5. Southbank Refinement Model – additional detail added to model in Southbank overflow area to increase confidence in flood levels in area outside of the Yarra River, which was the focus of different local investigations for Southbank and Fisherman's Bend. This process primarily involved incorporating details from local hydraulic models (namely Southbank and Fisherman's Bend) and adding additional terrain detail across this overflow area. Model verification was also revisited.
6. Extended Yarra River Model – refined model above was extended to combine with the "existing" conditions North East Link Project of the Yarra River to increase confidence in the levels within the Study Area by reducing importance of upstream storage assumptions and allowing "verification" to historic levels along a larger length of the Yarra River in less tidally influenced sections of the Yarra River.
7. Revised Design Run Model – model used to compare impact of TUFLOW engine (Classic and HPC) and 'Sub-grid sampling' (SGS) functionality on the consistency of design event results with recorded historic levels.
8. Final Design Run Model – scenario runs used to generate deliverables.

Stage 1 to Stage 7 of this figure are discussed in more detail in Appendix A, whilst the setup for the model in Stage 8 is discussed and documented in this report.

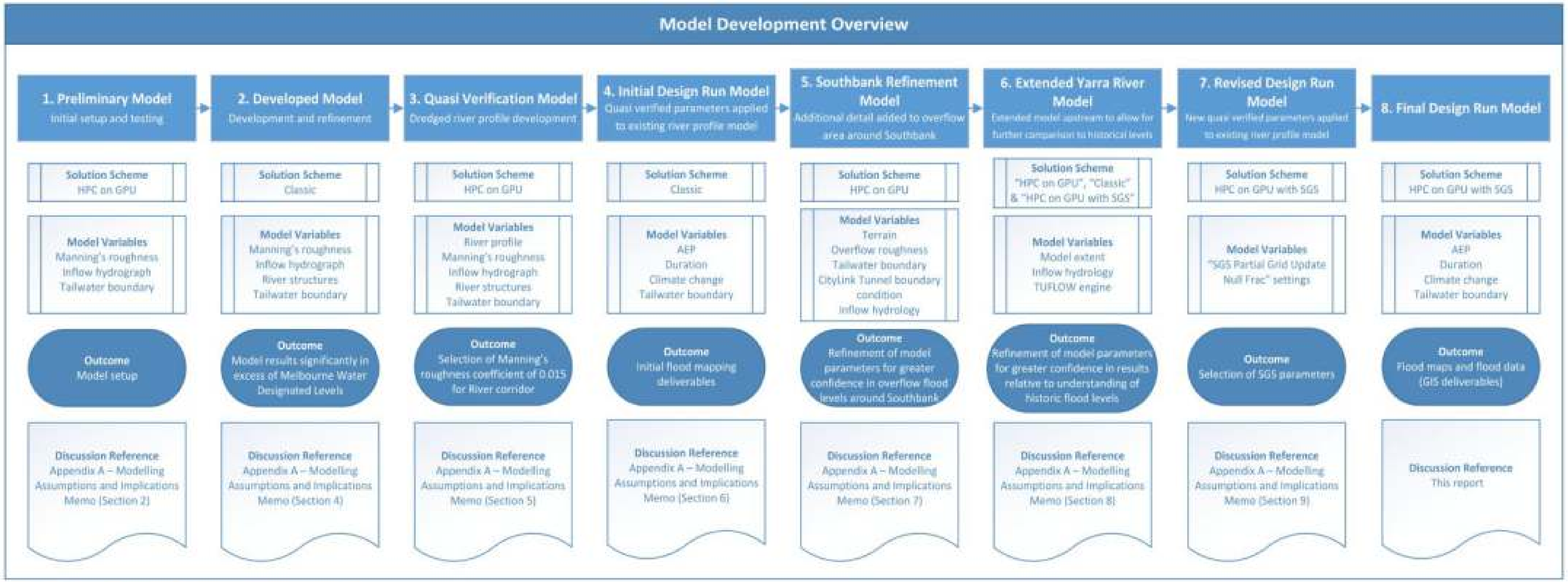


Figure 3 Overview of model development

3.2 Hydrology

The hydraulic model used for this Study required the following inflows along the three major waterways within the Study Area:

- Yarra River – a range of upstream inflows from tributaries or groups of subareas draining to Yarra River and individual subarea inflows along Yarra River corridor.
- Moonee Ponds Creek – one upstream inflow representing all flows entering the Yarra River from Moonee Ponds Creek.
- Maribyrnong River – one upstream inflow representing all flows entering the Yarra River from the Maribyrnong River.

All inflows from the first two waterways were adopted from the Yarra River RORB model established as part of the 2016 Yarra River Study (SP Goh and Associates, 2016) and the latter was adopted from a RORB model provided by Melbourne Water for the Maribyrnong River (dated circa 2014).

Due to the required scenarios and the location of required inflows, the two supplied RORB models were re-run with the agreed modelling parameters described in Table 2 to obtain the necessary inflows. Details of how these parameters were determined or selected are provided in Appendix A.

Table 2 RORB model inputs

Model	Yarra River	Maribyrnong River
RORB Version	6.45	6.45
Rainfall	Stormfiles with variable IFD (adjusted version of those adopted from 2016 Yarra River Study area due to application of ARFs)	ARR1987 IFD @ inbuilt "Keilor" location
ARF	Yarra catchment area (Assumed area = 3,870 km²)	Yarra catchment area (Assumed area = 3,870 km²)
Kc	180 (MW assumed value prior to 2016 Yarra River Study)	70
m	0.8	0.8
IL (mm)	Varies with interstation area: • YarRv@YarGlen-DummyGS = 30 • Catchment outlet = 15	20
Runoff Coefficient	Varies with ARI: • 100y = 0.60 • 50y = 0.55 • 20y = 0.50 • 10y = 0.45 • 5y = 0.40	Varies with ARI: • 100y = 0.6 • 50y = 0.55 • 20y = 0.45 • 10y = 0.35 • 5y = 0.25
Climate Change Scenario	Factored rainfall in stormfiles by 1.185 to represent 18.5% increase as per latest Tech Spec	Adjusted IFD parameters to increase rainfall intensity by 18.5%

3.3 Hydraulic modelling

3.3.1 Introduction

Hydraulic modelling for this Study Area was undertaken using TUFLOW, which is a hydrodynamic model used for simulating one-dimensional (1D) and two-dimensional (2D) flows (*BMTWBM 2016*). The model is based on the solution to the free-surface shallow water flow equations. The TUFLOW model for this Study consists of a 2D domain (TUFLOW) representing the catchment terrain and roughness together with a set of boundary conditions comprising the calculated RORB hydrograph inflows and the downstream water levels.

The modelling process and assumptions are outlined below:

- The general approach taken to setup the hydraulic model is shown in Figure 4 – with details of the steps shown summarised in the proceeding sections.
- The steps shown in this figure are described in detail in the following sections
- The hydraulic model area is shown in Figure 5.
- A summary of the adopted TUFLOW model parameters is provided in Table 3

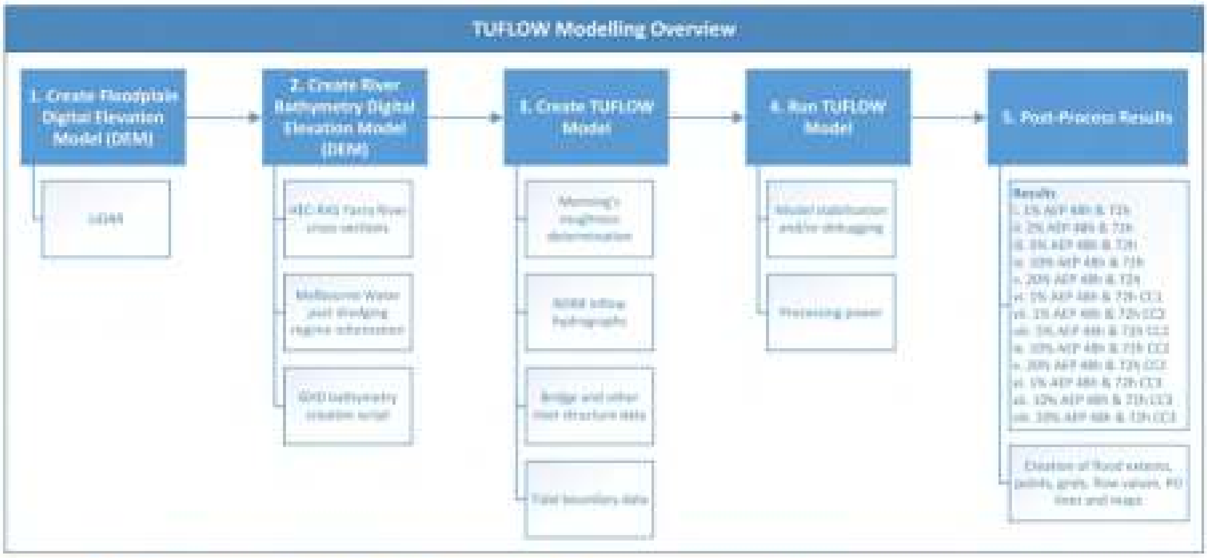


Figure 4 Overview of TUFLOW model setup process

Table 3 TUFLOW model inputs

Variable	Adopted Value/Source	Comment/Source
Model Purpose	Flood mapping outputs and deliverables	-
TUFLOW Version	2020-AB-ISP-w64	Latest available at time of final model runs (July 2020)
TUFLOW Engine	HPC on GPU with 'Sub-grid Sampling' (SGS) enabled	Modified default setting for SGS treatment of partially covered cells to be as follows – "SGS Partial Grid Update Null Frac == 0.6, 0.6" (see discussion in Appendix A).
Cell size (m)	10	Also has SGS enabled with a DEM sampling size of 2 m.
2D Timestep (sec)	2	Adaptive time stepping with maximum of the specified value in *.tcf
1D Timestep (sec)	0.5	Adaptive time stepping with maximum of the specified value in *.tcf
1D Network	Minimal.	Have included some 1d storage at upstream boundaries on Maribyrnong River and Moonee Ponds Creek to represent additional channel storage and to help avoid water sloshing off code boundary. Some minor structures were also adopted from NELP "existing conditions" model of Yarra River.
Inflows	Adopted from MW provided RORB models for the Yarra River catchment and Maribyrnong River catchments	2 upstream inflows on Maribyrnong River and Moonee Ponds Creek and a range of distributed SA inflows along the Yarra River.
Catchment Roughness	See spatial distribution on Figure 6	Default values for land use with manual overrides. Some areas adopted from provided local or upstream models. Manning's roughness along major waterways "quasi-verified".
Tail Water Level (TWL) or downstream (DS) Boundary	HT boundary (tidal curve) at Yarra River and HQ boundary (rating table based on slope) elsewhere.	See locations on Figure 5.

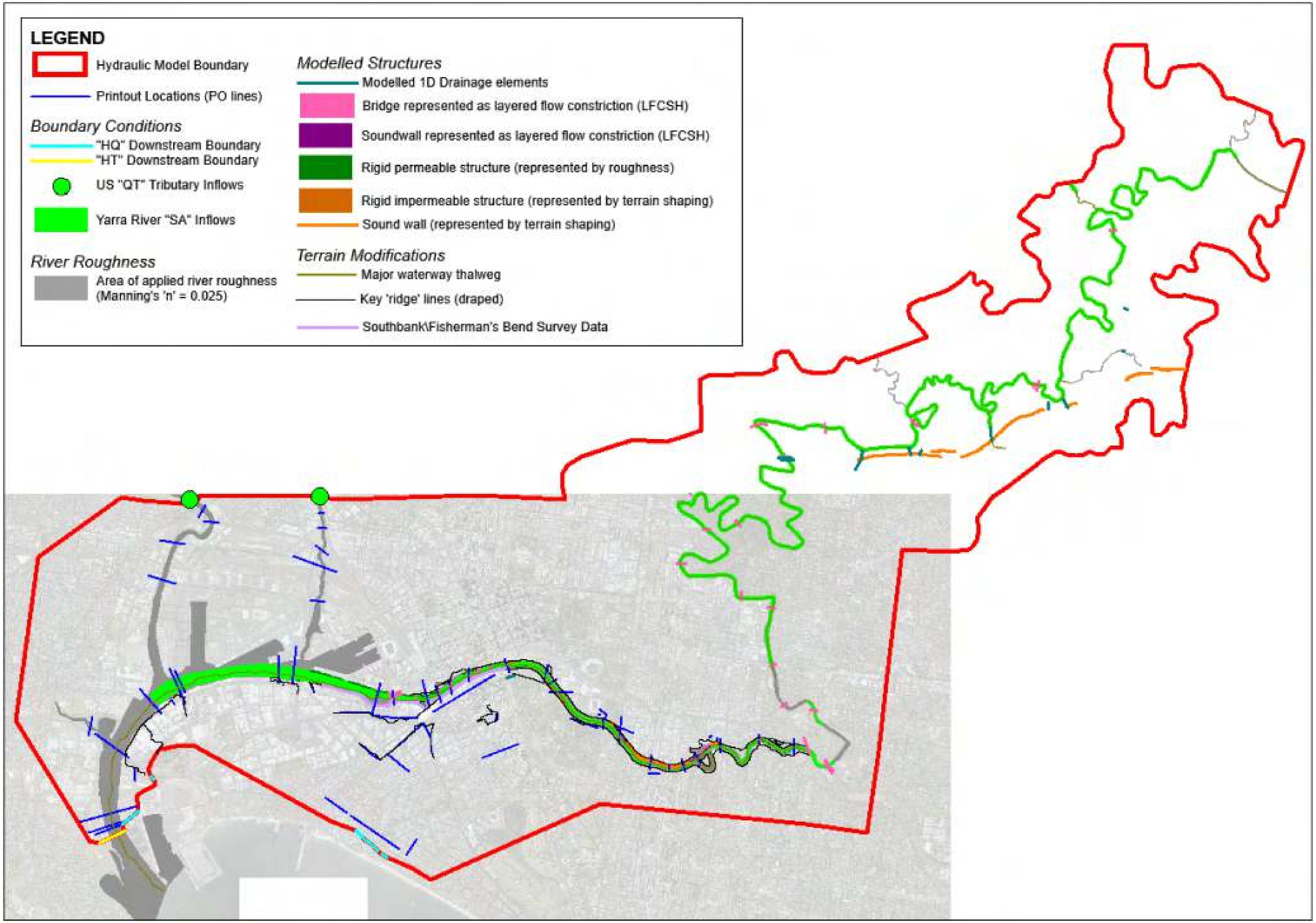


Figure 5 Hydraulic Model General Setup

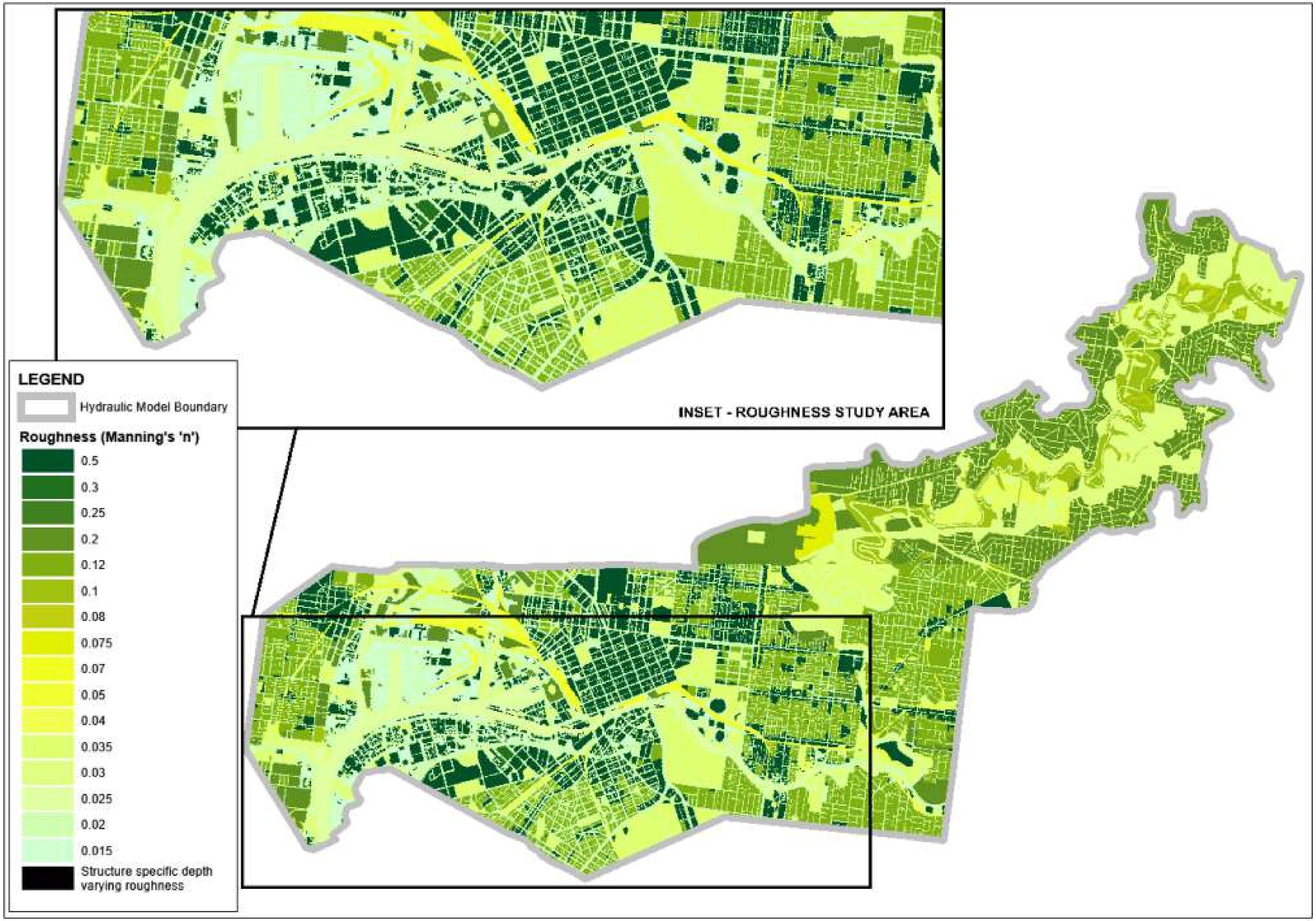


Figure 6 Hydraulic Model Roughness

3.3.2 2D domain

A Digital Terrain Model (DTM) was created to represent the ground features of the catchment both within the channel of the Yarra River (and its major tributaries) and across the floodplain within the Study Area. This DTM was supplemented by other DTMs supplied with the local or upstream models to cover the entire hydraulic model boundary as required. The final DTM created by TUFLOW upon reading in these separated DTMs was used as the basis of the ground surface in the hydraulic model, which when combined with the additional shaping and roughness parameters described in a later section defined the 2D Domain for the Study.

The accuracy of the terrain data was not checked by GHD as this is beyond the scope of this project. The following terrain data was supplied and used in the final DTM together with some breaklines created using engineering judgement to smooth the transition between data sources:

- LiDAR covering the Lower Yarra River project Study Area (circa 2008).
- Two DTMs provided with Southbank hydraulic model that were deemed to be more representative of this area:
  - "DEM_TIN_COASTAL.asc" – understood to be based on LiDAR data.
  - "dem_tin_clipped.asc".
- Three DTMs provided with NELP "existing conditions" model:
  - "clip_dtm10m_e_mga55.asc" – understood to be broader VicMap terrain data covering some of floodplain away from the Yarra River.
  - "dem_1m_mos.asc".
  - "dem_yarra_nela.asc" – understood to be terrain data provided by MW for NELP.
- HEC-RAS cross-section data for the portion of the Yarra River covered by the study area (sourced from the 2016 Yarra River Study) – these were interpolated using an in-house routine that followed the meandering flow path of the Yarra River (required as interpolated cross-sections in HEC-RAS couldn't represent 180 degree bends in river).
- Bathymetry data in the following areas:
  - Surveyed cross-section data for following areas
    - Yarra River upstream of Spencer Street (circa 2005 – adopted from Yarra River HEC-RAS model)
    - Maribyrnong River from upstream of around Footscray Road (circa 2004)
  - Surveyed cross-section and approx. thalweg point data in the following areas (circa 2014)
    - Yarra River roughly between the Bolte Bridge and just downstream of West Gate Bridge.
    - Maribyrnong River from the Yarra River to around Footscray Rd.
  - Detailed bathymetry point data for the following areas
    - Yarra River around Charles Grimes bridge (circa 2004) – extends from just downstream of Spencer Street to around Bolte Bridge
    - Maribyrnong River upstream of around Footscray Road (circa 2004).
  - Thalweg created along Moonee Ponds Creek based on linearly interpolating between inverts at key structures/junctions extracted from an existing HEC-RAS model.
  - Thalweg along Yarra River adopted from the NELP "existing conditions" model.

The final DTM was actually a combination of nine DTMs, six representing the floodplain and three the major waterways within the Study Area. The DTMs needed to be manipulated and/or merged together using terrain modification layers in TUFLOW in the following locations:

- Connection of a branch around Herron Island on the Yarra River
- Transitions between portions of bathymetric DTM created from HEC-RAS and that based on detailed bathymetric soundings
- Burnley Harbour.
- Victoria Harbour and nearby docks.

TUFLOW represented the terrain across the hydraulic model area with 10 m cells, with additional storage and conveyance detail obtained at a 2 m resolution using the 'sub grid sampling' (SGS) functionality in TUFLOW. This new feature essentially provides greater detail in the terrain without the full overhead of a smaller grid size (details of this feature are documented in 2020 TUFLOW Release Notes – BMT, 2020). and was adopted based on comparison of water levels along the Yarra River to historic levels with and without this feature enabled as discussed in Appendix A.

To improve the representation of key catchment characteristics a number of terrain modification layers were also read into the model, including:

- 'ridge' lines to reflect key flow control levels, such as channel banks, road embankments and flood/noise walls;
- 'gully' lines to provide connectivity along the channel thalweg to avoid unnecessary ponding, especially in areas upstream of the Study Area where the profile of the river below the water level at the time of when the terrain data was sourced was used to represent the channel; and
- 'shapes' to represent some permanent structures (see discussion on structures in Section 3.3.4).

3.3.3 Boundary conditions

This model required the following types of boundary conditions, which are summarised below:

- Upstream flows ('inflow boundaries')
- Upstream storages
- Downstream levels ('tailwater boundaries')
- Initial conditions

Inflow boundaries

Inflow hydrographs for the Yarra River, Moonee Ponds Creek and the Maribyrnong River were generated to represent the inflows to the Yarra River from its contributing catchments using RORB models supplied by MWC (see Section 3.2).

The hydrographs were applied as a combination of total hydrographs from groups of subareas upstream of modelled areas and individual subareas along the Yarra River. A summary of the hydrographs used in the modelling can be found in Appendix B.

Upstream Storages

Due to the fact that there is active storage upstream of the Study Area within the three major waterways, there was a need to represent this storage in some form. This was ultimately achieved by the following:

- Extending the hydraulic model upstream along the Yarra River to account for the storage explicitly within the river and on the adjacent floodplain, which is known to be engaged in the less frequent modelled events.
- Given the lack of bathymetry data readily available for the main tributaries within the Study Area, this upstream storage was represented as a 1D node with a "nodal area" based on the approximate surface area of active waterway within the tidally influenced zone.

Tailwater boundaries

A tailwater boundary was created to represent tidal influences on the lower Yarra River. This boundary was applied at the mouth of the Yarra River just before it enters the Port Phillip Bay. The agreed boundary conditions were derived from the following advice and data provided by Melbourne Water:

- Tidal sequences for 10y and 5y ARI events based on modelling by WaterTech. GHD's scope did not include any checking or review of these sequences.
- Advice on the how the peak tidal levels should be varied for other ARI events and climate change scenarios (i.e. sea level rise).
- Advice on extending modelled tidal curve to represent tide over complete modelled event (250 hours)
- Advice on the relative timing of the peak tidal level and the peak hydrograph flow through the Yarra River (refer to Appendix A, Attachment 2)

The modelled tidal data was simplified for reading into TUFLOW (required to avoid model instability issues due to noise in the provided tide curves) and was converted into a smoother curve using the cubic spline interpolation routine ("S" flag on "HT" boundaries) in TUFLOW.. The tidal curves were also shifted such that they achieved the peak tidal level as per Tech Spec requirements. A summary of the tidal curves adopted is shown in Table 4. The final tidal curves (i.e. the smoothed tidal curves as generated by TUFLOW) are shown in Appendix C.

Table 4 Tidal boundaries

ARI	Duration	Sea Level Rise?	Base Tidal Data	Tidal Peak Level (mAHD)	Tidal Peak Time (hours into simulation)
100y	48h & 72h	No	10y WaterTech data supplied by MWC	1.15	30
		Yes		2	
50y	48h & 72h	No		1.15	
20y	48h & 72h	No		1.15	
		Yes		2	
10y	48h & 72h	No		1.15	
		Yes		2	
5y	48h & 72h	No	5y WaterTech data supplied by MWC	1.05	
		Yes		1.9	

Initial water levels

The applied global initial water levels were based on the tidal levels at the beginning of the simulation (refer Appendix C) to avoid water rushing into the model. Each simulation was also run for 36 hours prior to the storm with a typical tide curve to enable the model to establish a dynamic tailwater level along the main waterways within the Study Area (i.e. provide initial conditions for each storm with a hydraulic grade based on tides).

3.3.4 Structures

Structures along the Yarra River have a significant impact on flood levels and therefore the resultant flooding in major storm events. As such, these structures were required to be modelled in some way to allow their impact to be represented appropriately.

Three types of structures were identified along the banks of or crossing the Yarra River – these were bridges, piers and floating structures. These structures and the ways in which they were modelled are discussed below.

Bridge Structures

Given that bridges are a hydraulically significant aspect of this investigation, their representation is important and as such, it was decided that they should be modelled in some detail. This involved modelling bridges in a number of different ways depending on the span direction of the bridge relative to the direction of flow of the river and the bridge characteristics. These approaches were as follows and where they were applied is summarised in Table 5.

- **Bridges perpendicular to the direction of flow** – These bridges were modelled with the use of layered flow constrictions. These objects allow the representation of up to three layers vertically, allowing the representation of bridge piers, deck and railings. These bridge layers all affect the flow of water through the bridge structure differently and so separate representation of these layers to represent this variation is important.

  This representation is made through the application of form loss coefficients and blockage percentages that vary for each layer. The detailed approach developed by GHD and adopted for this project is discussed in Appendix D and is specifically applicable to bridges that cross the Yarra River only.

- **Bridges parallel to the direction of flow** – While the abovementioned approach was adopted for bridges crossing the Yarra River, this same approach could not be used for bridges alongside the river due to TUFLOW applying form losses additively in the direction of flow, which would result in overstating of form losses. These bridges were instead represented using layered flow constrictions with only blockage applied to pier and deck layers to represent the obstruction to flow posed by such structures. The sound walls along CityLink were represented with a combination of thin z lines to completely block the lateral flow of water to a given varying elevation as appropriate or layered flow constrictions along the sides of river-side cells to allow water passage beneath the sound wall but not through at the appropriate elevations.

Table 5 Summary of bridges within hydraulic model

Model Area	Bridge No.	Bridge	Bridge direction relative to flow direction	Bridge representation
Initial Lower Yarra River model area	1	MacRobertsons Bridge	Perpendicular to direction of flow (crosses river)	Layered flow constrictions with form loss and blockage applied (refer Appendix D for details of approach)
	2	Church Street Bridge		
	3	Cremorne Bridge		
	4	Hoddle Street Bridge		
	5	Morell Bridge		
	6	Swan Street Bridge		
	7	Princes Bridge		
	8	Southbank Pedestrian Bridge		
	9	Sandridge Bridge		
	10	Queens Bridge		
	11	Kings Bridge		
	12	Clarendon Street Bridge		
	13	Seafarers Bridge		
	14	Wurundjeri Way		
	15	Webb Bridge		
	16	Citylink	Parallel to direction of flow (runs alongside river)	Layered flow constrictions with only blockage applied
	17	Jim Stynes Bridge		
	18	Bolte Bridge	Perpendicular to direction of flow (crosses river)	Within purely tidally influenced area. Not represented due to model stability issues and fact that impact will be negligible as in area of tidal influence.
	19	West Gate Bridge		
Gap between Lower Yarra River Study Area and NELP Yarra River model	20	Bridge Rd Bridge	Perpendicular to direction of flow (crosses river)	Layered flow constrictions with form loss and blockage applied (refer Appendix D for details of approach)
	21	Hawthorn Rail Bridge		
	22	Wallen Rd Bridge		
	23	Monash Fwy (inbound)		
	24	Monash Fwy (outbound)		
	25	Heyington Rail Bridge		

Model Area	Bridge No.	Bridge	Bridge direction relative to flow direction	Bridge representation
NELP Yarra River Model	26	Banskia St Bridge (including pipe track)	Perpendicular to direction of flow (crosses river)	Layered flow constrictions adopted from NELP model with form loss and blockage applied as provided (refer Appendix D for details of approach)
	27	Burke Rd Bridge		
	28	Chandler Highway		
	29	Eastern Freeway (outbound)		
	30	Eastern Freeway (inbound)		
	31	Main Yarra Trail SUP Bridge		Additional layered flow constrictions added to NELP model area with form loss and blockage applied (refer Appendix D for details of approach)
	32	Darebin Creek Trail Bridge		
	33	Fairfield Pipe Bridge		
	34	Kanes Bridge		
	35	Johnston St Bridge		
	36	Gipps St Main Yarra Trail		
	37	Main Yarra Trail - North of Burnley St		
	38	Barkers Rd Bridge		
	39	Dights Falls		Weir represented as terrain modification, but fishway not modelled due to minimal flow passing and the fact that this areas isn't currently being mapped.

Other Riverside Structures

Piers, jetties, walkways and other structures were identified along the Lower Yarra River within the Study Area. These structures and how they were modelled are described below.

- **Rigid and permeable structures** – These structures formed an obstruction to flow by introducing additional resistance to flow passing through the given structure. These structures included structures such as piers and jetties and were modelled using depth varying Manning's roughness coefficients to represent the increased resistance to flow caused by the given structure.
- **Rigid and impermeable structures** – These structures formed an obstruction to flow by a reduction in the cross-sectional area of the river. These structures included protruding walkways, ramps and similar types of structures, requiring to be modelled in instances where they were not represented by the underlying model terrain and being modelled using z shapes to build up the terrain as necessary.
- **Floating structures** – These structures were initially modelled using "flow constriction" layers in TUFLOW, but after much testing there was a bug identified in the software that required this type of layer not to be used. Alternative ways to represent these structures were investigated (i.e. altered roughness), but ultimately the change in roughness was found to be negligible and so were not explicitly modelled in this Study. This was also considered appropriate as it was agreed that the effect on the flow capacity of the Yarra River during major storm events was likely to be minimal.

Structures of this nature were not identified or modelled in the area upstream of the Study Area.

3.3.5 Manning's roughness

Bed resistance was allocated to each cell as a Manning's n value based on land use type and aerial photography within the Study Area. Outside the Study Area, roughness was adopted from the supplied models with the exception of the major waterways – which is explained further below.

Adopted Manning's n values for various land uses/surface types within the Study Area are tabulated in Table 6 and the spatial distribution of this roughness is shown in Figure 6. This figure also served as a visual check that the correct Manning's n values were being applied in the right locations.

The adopted roughness for major waterways was selected during the "verification" modelling phase of this Study, which is described in Appendix A. The value is within the range commonly used for major waterways and provided a model results acceptable to MW relative to historic levels given the combination of designated levels, design flows and other assumptions in the agreed modelling approach.

Table 6 Bed resistance values for 2D domain

Land Use	Manning's n
Roads (default)	0.020
Residential (outside of building footprints)	0.120
Open space - mostly grass	0.030
Open space - some bush	0.040
Open space - mostly dense bush	0.070
Creek or open space - mostly bush	0.050
Railway	0.050
Low density residential	0.100
Commercial	0.500
"Blocked out" buildings	0.500
Open space - some trees	0.035
Industrial	0.200
Concrete/carparks/bitumen	0.015
En-tout-cas tennis courts/compacted gravel driveway	0.030
Residential/mixed use full properties outside area of interest	0.200
Major waterways (active waterway area)*	0.025
Note: * indicates that this was an agreed value selected during the "verification" modelling phase of this Study, which is described in Appendix A	

3.3.6 Summary of TUFLOW model setup and commands

In addition to the general model setup described in the above sections and previous reports, the following parameters and commands have been adopted for all runs:

- 2D domain size – 24,000 m x 11,500 m.
- Varying end times to allow times of inundation to be adequately determined throughout the 2D domain for each run.
- Maximum Velocity Cutoff Depth == 0.05 (default is 0.1) – this allows maximum velocities to be recorded once depth is above 0.05 m.
- Cell Wet/Dry Depth == 0.0002 (default is 0.002).
- "Zero Z Point == WARNING" – this was required as we had terrain below 0 m AHD.
- "XF Files == OFF" – this turns off the use of "XF files"and requires TUFLOW to process raw input layers each time.
- Commands to activate "HPC on GPU" engine:
  - Solution Scheme == HPC
  - Hardware == GPU
- Commands to activate "SGS" functionality:
  - SGS == ON
  - SGS Sample Distance == 2
  - SGS Partial Grid Update Null Frac == 0.6, 0.6

3.3.7 Qualifications relating to flood mapping output

The hydraulic model and its results extend beyond the region being 'mapped' to achieve a number of objectives, including:

- To improve the distribution of model inflows;
- To reduce the significance of downstream boundary conditions;
- To allow for break away flow both within and upstream of the Study Area; and
- To enable comparison of the adopted modelling approaches with historic flood levels across a broader reach of the Yarra River with less tidal influence.

Therefore, the flood mapping output described in the following sections, and provided to Melbourne Water in accordance with the Guidelines and Technical Specifications for Flood Mapping Projects, November 2016 (*MWC 2006*), have been trimmed to a "Mapping Limit" polygon. This line designates the extent of meaningful results. Outside of the "Mapping Limit" the model results may be misleading for a number of reasons, including:

- Boundary conditions;
- Incomplete representation of drainage assets;
- A number of modelling approximations suitable for the current purposes within the mapping limit but not necessarily suitable for flood mapping requirements outside of the mapping limit.

All modelling results require appropriate interpretation. It should be noted that overland flows for the smaller, more frequent events, such as the 5 and 10 year ARI results, are produced using a hydraulic model established primarily for the purpose of modelling the 100 year ARI event. The implication of this is that, particularly for these smaller events, the modelling results will need to be appropriately interpreted with an understanding of their limitations.

Despite these limitations the results for the smaller, more frequent events are currently believed to be the best available with respect to identifying the effects of riverine flooding. Modelling of local catchments should always be considered particularly in regions adjacent and remote from the Yarra River.

The accuracy of the final results is in part a function of the resolution of the TUFLOW model (which uses a 10 m cell size with SGS at 2m). The higher resolution of results (provided on a 1 m grid) is provided as a partially interpreted data source for the convenience of Melbourne Water. This higher resolution grid of results does not infer a higher accuracy.

4. Mapping

4.1 Introduction

The raw results of the TUFLOW modelling were post-processed to produce the required GIS layers outlined in Melbourne Water's Guidelines and Technical Specifications for Flood Mapping Projects, November 2016 (*MWC 2016)* within the Study Area. Envelopes of maximum values were produced for each AEP and for each of the key output parameters (i.e. flood level, velocity, velocity-depth) using the "ASC to ASC" utility. The maximum flood level envelope from the above process was then further processed using TUFLOW's "remap" functionality in the latest "ASC to ASC" utility, which recalculates flood levels and depths based on a more detailed DEM (this feature is outlined in TUFLOW's latest release notes and/or the TUFLOW Wiki - https://wiki.tuflow com/index php?title=TUFLOW_Remapping). The adopted DEM for remapping was the "DEM_Z" file created by running an additional model based on the final "SGS" model on TUFLOW Classic with a 2 m cell size (which was the "SGS" sampling distance). The remaining maximum envelope results were 'filtered' by removing values where there was no depth result and used further to produce the various required output layers. Further details of the mapping output is described in the following sections.

4.2 1 m results grids

MapInfo layers were created containing points on a 1 m orthogonal grid for each of the events listed in Table 1. Each point contains the following information for the specific event:

- Maximum water level (m AHD – based on TUFLOW "h_Max.flt" results remapped to a finer DTM using TUFLOW's "ASC to ASC" utility)
- Maximum depth (m – based on TUFLOW "h_Max.flt" results remapped to a finer DTM using TUFLOW's "ASC to ASC" utility)
- Maximum velocity (m/s – based on TUFLOW "V_Max.flt" results)
- Maximum velocity-depth product (m^2/s – based on TUFLOW "Z0_Max.flt" results)
- Critical storm duration of maximum water level (minutes – based on TUFLOW "h_Max.flt"
- Minimum time to 350 mm depth (hours – based on TUFLOW "TExc_0.35m.flt" results)
- Minimum time to 500 mm depth (hours – based on TUFLOW "TExc_0.5m.flt" results)
- Maximum time of inundation above 350 mm depth (hours – based on TUFLOW "TDur_0.35m.flt" results)
- Maximum time of inundation above 500 mm depth (hours – based on TUFLOW "TDur_0.50m.flt" results)

The 'raw' 1 m points were trimmed back to the respective 'filtered and smoothed' flood extents, and then used in populating the "Parcels Flooded" and "Building Footprints" MapInfo layers (refer to Sections 4.6 and 4.7).

The 1 m point data will not exist where a small island has been removed from the flood extent. So that the data removed by the above processes is not 'lost', 'raw' and 'unfiltered' versions of the 1 m points have also been provided to Melbourne Water.

4.3 Flow values

The flow results at the locations of model 'printout' (PO) lines were collated and provided in MapInfo layers for each scenario. The flow values provided in each layer are:

- maximum total flows for each AEP
- maximum overland flows (1% AEP only – from the 2D domain)

The values are maximum from the modelled storms for the each AEP.

A set of "PO Flows" layers were also created to provide additional information not included in the "Flow Values" layers. These "PO Flows" layers were created for each of the events listed in Table 1 and contain the peak total flow and the critical storm in which the maximum "overland" flow occurs.

4.4 Flood extents

Flood extents were created for each of the events listed in Table 1 using a prescribed method provided by Melbourne Water, which is generally as follows:

- Create 'raw and unsmoothed' flood extent polygons based on calculated depth results.
- Remove 'puddles' or 'islands' that are less than 100 m^2 in area.
- Smooth the extents using an FME workspace provided by Melbourne Water, which utilises Densifier, McMaster Weighted Distance and NURBfit algorithms.

All flood extents were then trimmed back to a 'mapping limit', thus removing results in areas that were modelled purely for the purposes of establishing appropriate flow distribution and/or boundary conditions.

The remaining Base Case flood extents smaller than the 1% AEP extent were trimmed back to the 1% AEP extent, just to ensure that the "Planning Scheme Ready" process didn't result in the smaller extents being just outside the 1% AEP extent.

The flood extents created using this method are shown in Appendix E. This appendix also includes maps showing the water surface level and depth results within the Mapping limits of the Study.

There is an implication of removing islands from the flood extents in that this creates areas that look flooded but do not have any underlying flood data such as 1 m grid points or flood contours. No attempt has been made to 'create' data where islands have been removed. So that the data removed by the above processes is not 'lost', 'raw' and 'unfiltered' versions of the flood extents have also been provided to Melbourne Water.

4.5 Flood contours

MapInfo layers of flood contours were created for the 1% AEP events only (i.e. Base Case and Climate Change Scenarios). Flood contours were created at 0.5 m intervals from the 'raw and unfiltered' maximum water level envelopes and trimmed back to the respective 'filtered and smoothed' flood extents.

As per the discussion on the filtered grid data, flood contours will not exist where an island has been removed from the flood extent. So that the data removed by the above processes is not 'lost', 'raw' and 'unfiltered' versions of the flood contours have also been provided to Melbourne Water.

4.6 Parcels (properties) flooded

A MapInfo layer of parcels (properties) flooded was created from the Parcels layer provided by Melbourne Water that were touched by the Base Case 1% AEP flood extent.

The following flood information was assigned to each 'flooded' parcel polygon for the Base Case Scenario:

- Maximum 100, 50, 20, 10 and 5 year ARI flood levels
- Minimum 100 year ARI flood level
- Maximum 100 year ARI velocity
- Maximum 100, 50, 20, 10 and 5 year ARI depths
- Maximum 100, 50, 20, 10 and 5 year ARI velocity-depth product

All values attached were based on the 1 m results grids described in Section 4.2. Where a parcel was not affected by a smaller event, a data value of "-9999" was assigned. The assigned flood levels were checked to ensure that levels were in the right order. This processing identified a small number of parcels at the flood fringe that had values in the incorrect order due to TUFLOW's remapping function and these were manually adjusted.

It is noted that due to the flood extent smoothing process, some parcels that are selected by the Base Case 100 year ARI flood extent may not actually have an attributed 1 m grid point on them and hence have not been assigned 100 year ARI flood data. Where such parcels exist they have been left in the 'parcels flooded' layer.

A similar layer was created for the Climate Change Scenario, based on parcels touched by the Climate Change 1% AEP flood extent.

The total number of parcels flooded in each event for the Base Case and Climate Change Scenarios are summarised in Table 7.

Table 7 Total number of parcels flooded

Event	Total Number of Parcels Flooded in Base Case Scenario	Total Number of Parcels Flooded in Climate Change 1 Scenario	Total Number of Parcels Flooded in Climate Change 2 Scenario	Total Number of Parcels Flooded in Climate Change 3 Scenario
1% AEP	24,677	31,282	34,694	28,152
2% AEP	455	-	-	-
5% AEP	249	-	26,439	-
10% AEP	239	-	7,358	244
20% AEP	235	-	5,688	237

4.7 Building footprints flooded

A MapInfo layer of building footprints flooded was created from the layer of building footprints provided by Melbourne Water that were located within the parcels flooded in the Base Case Scenario. The maximum flood level was assigned to each 'flooded' building footprint polygon for the Base Case Scenario for the 100, 50, 20, 10 and 5 year ARIs.

All values attached were based on the 1 m results grids described in Section 4.2. Where a building footprint was located on an unflooded part of a parcel, or not affected by a smaller event, a data value of "-9999" was assigned. The assigned flood levels were checked to ensure that levels for each event were in the expected order. This checking did not identify the need for any adjustments.

A Flood Risk category was calculated for each building footprint polygon based the criteria provided by Melbourne Water and as shown in Table 8. Each building can only have one risk category assigned and the highest category satisfied governs.

Table 8 Flood Risk Categories

Flood Risk Category	Criteria
1	Building footprint is flooded in the 1% probability flood event but floor level is unknown
2	Floor level is flooded in the 1% probability flood event
3	Floor level is flooded in the 2% probability flood event
4	Floor level is flooded in the 5% probability flood event
0*	Floor level is above the 1% probability flood event
-999*	Building footprint is not flooded in the 1% probability flood event but is within a parcel flooded in the 1% probability flood event

Note: * categories added and defined by GHD.

The total number of building footprints and floors flooded are shown in Table 9 and Table 12 for the Base Case, Climate Change 1 (CC_B), Climate Change 2 (CC_C), and Climate Change 3 (CC_D) scenarios respectively.

Table 9 Total number of building footprints and floors flooded in the Base Case Scenario

Scenario Event	Number of Building Footprints Flooded	Number of Floors Flooded (where floor level is known)*	Number of Floors NOT Flooded (where floor level is known)*
1% AEP	484	62	30
2% AEP	45	0	92
5% AEP	7	0	92
10% AEP	5	0	92
20% AEP	4	0	92

Note: * indicates that 92 floor levels are known

Table 10 Total number of building footprints and floors flooded in the Climate Change 1 Scenario

Scenario Event	Number of Building Footprints Flooded	Number of Floors Flooded (where floor level is known)*	Number of Floors NOT Flooded (where floor level is known)*
1% AEP	758	68	17

Note: * indicates that 94 floor levels are known

Table 11 Total number of building footprints and floors flooded in the Climate Change 2 Scenario

Scenario Event	Number of Building Footprints Flooded	Number of Floors Flooded (where floor level is known)*	Number of Floors NOT Flooded (where floor level is known)*
1% AEP	1118	99	70
5% AEP	422	28	14
10% AEP	153	0	0
20% AEP	99	0	0

Note: * indicates that 182 floor levels are known

Table 12 Total number of building footprints and floors flooded in the Climate Change 3 Scenario

Scenario Event	Number of Building Footprints Flooded	Number of Floors Flooded (where floor level is known)*	Number of Floors NOT Flooded (where floor level is known)*
1% AEP	784	70	21
10% AEP	6	0	0
20% AEP	4	0	0
Note: * indicates that 97 floor levels are known			

4.8 GIS output

The MapInfo layers listed below were provided to Melbourne Water as a primary output of this flood mapping project. This report describes the methodology and steps taken to arrive at these layers. The primary layers listed in Table 13 conform to Melbourne Water's supplied metadata standards and naming conventions, as outlined in Melbourne Water's Guidelines and Technical Specifications for Flood Mapping Projects, November 2016 (*MWC 2016*). The projection of all layers is Map Grid of Australia Zone 55 (GDA94) with Bounds (0, 5500000) (1000000, 6500000). The additional "_RAW" layers, also listed in Table 13, while appropriately attributed do not comply with the Tech Spec format since they are raw layers.

Table 13 MapInfo Deliverables

Layer Name (*.TAB)	Description	Deliverable with "_RAW" suffix also provided? (Description)
4400_Points_100YR_1m	Base Case 100 year ARI 1 m results grid – trimmed to smoothed extent	YES (Points from max envelope of raw modelling results across entire model area)
4400_Points_50YR_1m	Base Case 50 year ARI 1 m results grid – trimmed to smoothed extent	YES (Points from max envelope of raw modelling results across entire model area)
4400_Points_20YR_1m	Base Case 20 year ARI 1 m results grid – trimmed to smoothed extent	YES (Points from max envelope of raw modelling results across entire model area)
4400_Points_10YR_1m	Base Case 10 year ARI 1 m results grid – trimmed to smoothed extent	YES (Points from max envelope of raw modelling results across entire model area)
4400_Points_5YR_1m	Base Case 5 year ARI 1 m results grid – trimmed to smoothed extent	YES (Points from max envelope of raw modelling results across entire model area)
4400_CC_B_Points_100YR_1m	Climate Change 1 100 year ARI 1 m results grid – trimmed to smoothed extent	YES (Points from max envelope of raw modelling results across entire model area)
4400_CC_C_Points_100YR_1m	Climate Change 2 100 year ARI 1 m results grid – trimmed to smoothed extent	YES (Points from max envelope of raw modelling results across entire model area)
4400_CC_C_Points_20YR_1m	Climate Change 2 20 year ARI 1 m results grid – trimmed to smoothed extent	YES (Points from max envelope of raw modelling results across entire model area)
4400_CC_C_Points_10YR_1m	Climate Change 2 10 year ARI 1 m results grid – trimmed to smoothed extent	YES (Points from max envelope of raw modelling results across entire model area)

Layer Name (*.TAB)	Description	Deliverable with "_RAW" suffix also provided? (Description)
4400_CC_C_Points_5YR_1m	Climate Change 2 5 year ARI 1 m results grid – trimmed to smoothed extent	YES (Points from max envelope of raw modelling results across entire model area)
4400_CC_D_Points_100YR_1m	Climate Change 3 100 year ARI 1 m results grid – trimmed to smoothed extent	YES (Points from max envelope of raw modelling results across entire model area)
4400_CC_D_Points_10YR_1m	Climate Change 3 10 year ARI 1 m results grid – trimmed to smoothed extent	YES (Points from max envelope of raw modelling results across entire model area)
4400_CC_D_Points_5YR_1m	Climate Change 3 5 year ARI 1 m results grid – trimmed to smoothed extent	YES (Points from max envelope of raw modelling results across entire model area)
4400_Flow_Values	Flow results from Base Case TUFLOW models	NO
4400_Flow_Values_CC1	Flow results from Climate Change 1 TUFLOW models	NO
4400_Flow_Values_CC2	Flow results from Climate Change 2 TUFLOW models	NO
4400_Flow_Values_CC3	Flow results from Climate Change 3 TUFLOW models	NO
4400_PO_Flows_100y	100 year ARI flow results from Base Case TUFLOW models	NO
4400_PO_Flows_50y	50 year ARI flow results from Base Case TUFLOW models	NO
4400_PO_Flows_20y	20 year ARI flow results from Base Case TUFLOW models	NO
4400_PO_Flows_10y	10 year ARI flow results from Base Case TUFLOW models	NO
4400_PO_Flows_5y	5 year ARI flow results from Base Case TUFLOW models	NO
4400_CC_B_PO_Flows_100y	100 year ARI flow results from Climate Change 1 TUFLOW models	NO
4400_CC_C_PO_Flows_100y	100 year ARI flow results from Climate Change 2 TUFLOW models	NO
4400_CC_C_PO_Flows_20y	20 year ARI flow results from Climate Change 2 TUFLOW models	NO
4400_CC_C_PO_Flows_10y	10 year ARI flow results from Climate Change 2 TUFLOW models	NO
4400_CC_C_PO_Flows_5y	5 year ARI flow results from Climate Change 2 TUFLOW models	NO
4400_CC_D_PO_Flows_100y	100 year ARI flow results from Climate Change 3 TUFLOW models	NO
4400_CC_D_PO_Flows_10y	10 year ARI flow results from Climate Change 3 TUFLOW models	NO
4400_CC_D_PO_Flows_5y	5 year ARI flow results from Climate Change 3 TUFLOW models	NO

Layer Name (*.TAB)	Description	Deliverable with "_RAW" suffix also provided? (Description)
4400 Flood Extent 100y Waterways	Base Case 100 year ARI flood extents –smoothed and trimmed to mapping limit (Planning Scheme ready)	YES (Raw extent from max envelope of modelling results - unaltered)
4400_Flood_Extent_50y_ Waterways	Base Case 50 year ARI flood extents – smoothed and trimmed to mapping limit	YES (Raw extent from max envelope of modelling results - unaltered)
4400_Flood_Extent_20y_ Waterways	Base Case 20 year ARI flood extents – smoothed and trimmed to mapping limit	YES (Raw extent from max envelope of modelling results - unaltered)
4400 Flood Extent 10y Waterways	Base Case 10 year ARI flood extents – smoothed and trimmed to mapping limit	YES (Raw extent from max envelope of modelling results - unaltered)
4400 Flood Extent 5y Waterways	Base Case 5 year ARI flood extents – smoothed and trimmed to mapping limit	YES (Raw extent from max envelope of modelling results - unaltered)
4400 CC B Flood Extent 100y Waterways	Climate Change 1 Scenario 100 year ARI flood extents – smoothed and trimmed to mapping limit	YES (Raw extent from max envelope of modelling results - unaltered)
4400 CC C Flood Extent 100y Waterways	Climate Change 2 Scenario 100 year ARI flood extents – smoothed and trimmed to mapping limit	YES (Raw extent from max envelope of modelling results - unaltered)
4400 CC C Flood Extent 20y Waterways	Climate Change 2 Scenario 20 year ARI flood extents – smoothed and trimmed to mapping limit	YES (Raw extent from max envelope of modelling results - unaltered)
4400_CC_C_Flood_Extent_10y_ Waterways	Climate Change 2 Scenario 10 year ARI flood extents – smoothed and trimmed to mapping limit	YES (Raw extent from max envelope of modelling results - unaltered)
4400_CC_C_Flood_Extent_5y_ Waterways	Climate Change 2 Scenario 5 year ARI flood extents – trimmed to smoothed extent	YES (Raw extent from max envelope of modelling results - unaltered)
4400 CC D Flood Extent 100y _Waterways	Climate Change 3 Scenario 100 year ARI flood extents – trimmed to smoothed extent	YES (Raw extent from max envelope of modelling results - unaltered)
4400 CC D Flood Extent 10y Waterways	Climate Change 3 Scenario 10 year ARI flood extents – trimmed to smoothed extent	YES (Raw extent from max envelope of modelling results - unaltered)
4400 CC D Flood Extent 5y Waterways	Climate Change 3 Scenario 5 year ARI flood extents – trimmed to smoothed extent	YES (Raw extent from max envelope of modelling results - unaltered)
4400_Flood_Contour_100y_ Waterways	Base Case 100 year ARI flood contours (0.5 m interval) – trimmed to smoothed extent	YES (Contours from max envelope of raw modelling results)
4400 Flood Contour 50y Waterways	Base Case 50 year ARI flood contours (0.5 m interval) – trimmed to smoothed extent	YES (Contours from max envelope of raw modelling results)
4400 Flood Contour 20y Waterways	Base Case 20 year ARI flood contours (0.5 m interval) – trimmed to smoothed extent	YES (Contours from max envelope of raw modelling results)
4400 Flood Contour 10y Waterways	Base Case 10 year ARI flood contours (0.5 m interval) – trimmed to smoothed extent	YES (Contours from max envelope of raw modelling results)

Layer Name (*.TAB)	Description	Deliverable with "_RAW" suffix also provided? (Description)
4400 Flood Contour 5y Waterways	Base Case 5 year ARI flood contours (0.5 m interval) – trimmed to smoothed extent	YES (Contours from max envelope of raw modelling results)
4400 CC B Flood Contour 100y_Waterways	Climate Change 1 Scenario 100 year ARI flood contours (0.5 m interval) – trimmed to smoothed extent	YES (Contours from max envelope of raw modelling results)
4400_CC_C_Flood_Contour_ 100y_Waterways	Climate Change 2 Scenario 100 year ARI flood contours (0.5 m interval) – trimmed to smoothed extent	YES (Contours from max envelope of raw modelling results)
4400_CC_C_Flood_Contour_20y_ Waterways	Climate Change 2 Scenario 20 year ARI flood contours (0.5 m interval) – trimmed to smoothed extent	YES (Contours from max envelope of raw modelling results)
4400_CC_C_Flood_Contour_10y_ Waterways	Climate Change 2 Scenario 10 year ARI flood contours (0.5 m interval) – trimmed to smoothed extent	YES (Contours from max envelope of raw modelling results)
4400 CC C Flood Contour 5y Waterways	Climate Change 2 Scenario 5 year ARI flood contours (0.5 m interval) – trimmed to smoothed extent	YES (Contours from max envelope of raw modelling results)
4400 CC D Flood Contour 100y_Waterways	Climate Change 3 Scenario 100 year ARI flood contours (0.5 m interval) – trimmed to smoothed extent	YES (Contours from max envelope of raw modelling results)
4400 CC D Flood Contour 10y Waterways	Climate Change 3 Scenario 10 year ARI flood contours (0.5 m interval) – trimmed to smoothed extent	YES (Contours from max envelope of raw modelling results)
4400 CC D Flood Contour 5y Waterways	Climate Change 3 Scenario 5 year ARI flood contours (0.5 m interval) – trimmed to smoothed extent	YES (Contours from max envelope of raw modelling results)
4400_Flood_Studies	Study Area	NO
4400_Mapping_Limit	Mapping Limit indicating extent of 'meaningful' results	NO
4400_SRR_LOW	Base Case Low safety risk polygons in roads – trimmed to smoothed extent	NO
4400_SRR_MED	Base Case Medium safety risk polygons in roads – trimmed to smoothed extent	NO
4400_SRR_HIGH	Base Case High safety risk polygons in roads – trimmed to smoothed extent	NO
4400_CC_B_SRR_LOW	Climate Change 1 Low safety risk polygons in roads – trimmed to smoothed extent	NO
4400_CC_B_SRR_MED	Climate Change 1 Medium safety risk polygons in roads – trimmed to smoothed extent	NO
4400_CC_B_SRR_HIGH	Climate Change 1 High safety risk polygons in roads – trimmed to smoothed extent	NO
4400_CC_C_SRR_LOW	Climate Change 2 Low safety risk polygons in roads – trimmed to smoothed extent	NO
4400_CC_C_SRR_MED	Climate Change 2 Medium safety risk polygons in roads – trimmed to smoothed extent	NO

Layer Name (*.TAB)	Description	Deliverable with "_RAW" suffix also provided? (Description)
4400_CC_C_SRR_HIGH	Climate Change 2 High safety risk polygons in roads – trimmed to smoothed extent	NO
4400_CC_D_SRR_LOW	Climate Change 3 Low safety risk polygons in roads – trimmed to smoothed extent	NO
4400_CC_D_SRR_MED	Climate Change 3 Medium safety risk polygons in roads – trimmed to smoothed extent	NO
4400_CC_D_SRR_HIGH	Climate Change 3 High safety risk polygons in roads – trimmed to smoothed extent	NO
4400_Parcels_Flooded_ Waterways	Property parcels flooded in the Base Case 100 year ARI (fully filtered version) with Base Case flood results attached	NO
4400 CC B Parcels Flooded Waterways	Property parcels flooded in the Climate Change 1 100 year ARI event (fully filtered version) with Climate Change 1 flood results attached	NO
4400_CC_C_Parcels_Flooded_ Waterways	Property parcels flooded in the Climate Change 2 100 year ARI event (fully filtered version) with Climate Change 2 flood results attached	NO
4400 CC D Parcels Flooded Waterways	Property parcels flooded in the Climate Change 3 100 year ARI event (fully filtered version) with Climate Change 3 flood results attached	NO
4400_Building_Footprints_ Waterways	Building footprints within the Base Case Parcels Flooded with Base Case flood results attached	NO
4400_CC_B_Building_Footprints_ Waterways	Building footprints within the Climate Change 1 Parcels Flooded with Climate Change 1 flood results attached	NO
4400_CC_C_Building_Footprints_ Waterways	Building footprints within the Climate Change 2 Parcels Flooded with Climate Change 2 flood results attached	NO
4400_CC_D_Building_Footprints_ Waterways	Building footprints within the Climate Change 3 Parcels Flooded with Climate Change 3 flood results attached	NO

5. Recommendations

It is recommended that:

- Melbourne Water consider the outcomes of this investigation to inform future planning decisions. This consideration should comprehend the strengths of the current investigation, which include a significantly improved understanding of flood flows as well as the potential for newer approaches such as ARR2019, additional gauge data and more comprehensive investigations that revise some of the hydrologic approaches to provide revised information in the future.
- Future investigations of the Yarra River consider the merit of updating the base data and/or assumptions used in this Study including:
  – Utilising ARR2019 hydrology approaches
  – Adopt latest LiDAR information and consider updating bathymetry data where assumptions were required (and/or to improve detailed coverage to reduce need for assumptions and interpolation)
  – Obtain data on structures crossing and along waterway, particularly where water is currently shown to break out of the river.
  – Undertake some verification of predicted flood levels against available gauge information where appropriate.
  – Consider generating flood estimates for historic event and comparing them with historic flood level records.

6. References

BMT (2020). TUFLOW Classic & HPC 2020-01 Release Notes. BMT, May 2020.

MWC (2019). Flood Mapping Projects – Guidelines and Technical Specifications. Melbourne Water Corporation, Victoria, September 2019.

MWC (2016). Flood Mapping Projects – Guidelines and Technical Specifications. Melbourne Water Corporation, Victoria, November 2016.

Bradley (1978). Hydraulics of Bridge Waterways. HDS 1, FHWA, Bridge Division, March 1978.

BMTWBM (2018). TUFLOW Classic/HPC User Manual – Build 2018-03-AD. BMTWBM, November 2018

BMT (2020). TUFLOW Classic & HPC 2020-01 Release Notes. BMT, May 2020

SP Goh & Associates (2016). Yarra River Flood Mapping - Hydrologic and Hydraulic Study (Final Report), June 2016.

Appendices

Appendix A – Modelling Assumptions and Implications Memo

Memorandum

30 July 2020

To	Melbourne Water Corporation		
Copy to			
From	Peter Woodman	Tel	
Subject	Modelling Assumptions & Implications	Job no.	3135474

1 Introduction

This document aims to outline the general model setup and testing that we have completed for the Lower Yarra River Flood Mapping project since Progress Meeting 1. The focus of this document is to explore the implications of key assumptions on results relative to the currently accepted flood level (referred to herein as the 'Designated Levels'). These assumptions include the following key model inputs:

- Downstream tailwater level (TWL);
- Flows for the Yarra River; and
- Surface roughness within Yarra River (as well as other key waterways)

This document also includes an initial test run with all bridge structures crossing the Yarra River represented upstream of Spencer Street.

2 Test Model Setup

The adopted model setup for the completed test runs discussed below is presented in Figure 1. Other key model assumptions were as follows:

- TUFLOW Engine/Solver = HPC – with GPU enabled (various TUFLOW versions – typically latest available at the time of modelling),
- 2D only model with 10 m cell size,
- Terrain based on combination of LiDAR, HEC-RAS cross-sections and river bathymetry data provided by MWC,
- Three (3) upstream inflows (Yarra River, Moonee Ponds Creek & Maribyrnong River) – "SA" inflow polygons to allow for distribution of flow based on depth,
- A single downstream boundary with a fixed or tidal relationship based on levels in Port Phillip Bay.
- No structures (except for one test run).

To test the implication of representing the river with 10 m cells, cross-sections from TUFLOW and HEC-RAS were compared at the four (4) locations presented in Figure 2. The actual comparisons of cross-sections are shown in Figure 3 - Figure 6, which indicate the TUFLOW representation is fairly comparable to HEC-RAS.

GHD Pty Ltd ABN 39 008 488 373
Level 9 180 Lonsdale Street Melbourne Victoria 3000 Australia
T +61 3 8687 8000 **F** +61 3 8732 7046 **E** melmail@ghd.com **W** www.ghd.com

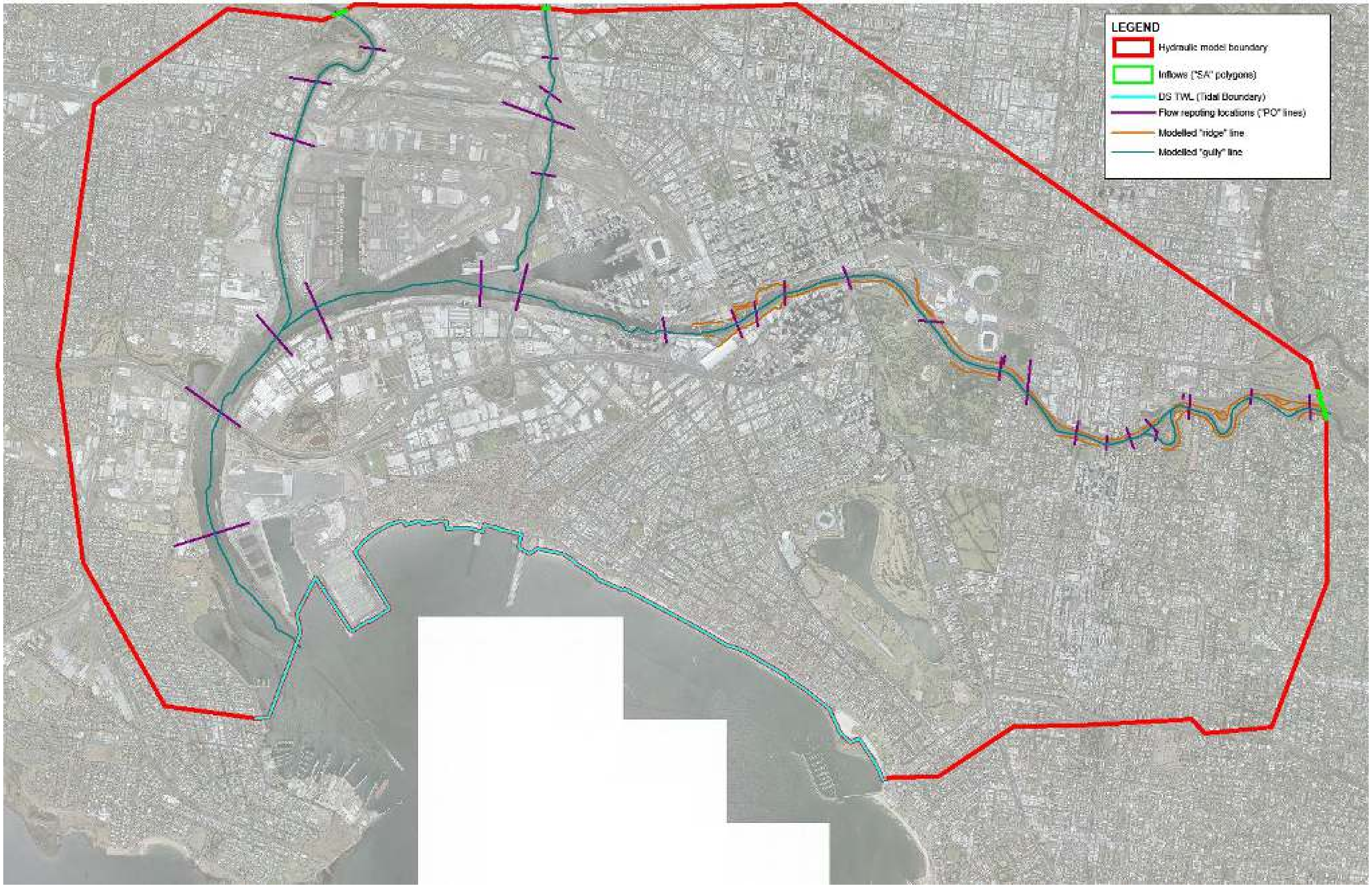


Figure 1 TUFLOW Model Setup for Testing

Figure 2 Location of cross-section comparisons

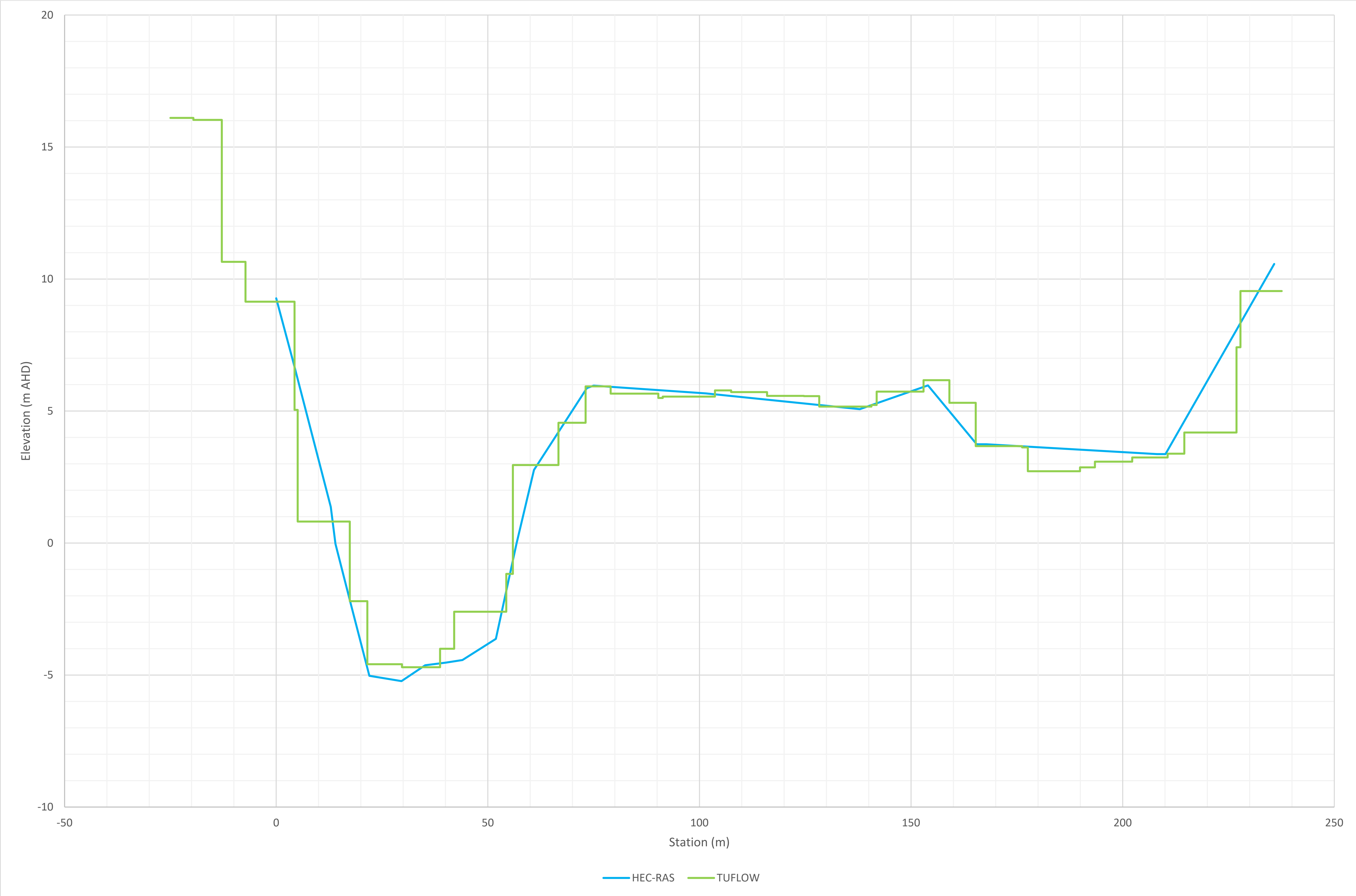


Figure 3 Cross-section comparison at between City Link and MacRobertson Bridge (HEC-RAS Ch 15052, Herr US-Pound DS)

Figure 4 Cross-section comparison at between Herring Island and Church Street Bridge (HEC-RAS Ch 12877, Spencer-Herr DS)

Figure 5 Cross-section immediately downstream of Morell Bridge (HEC-RAS Ch 11221, Spencer-Herr DS)

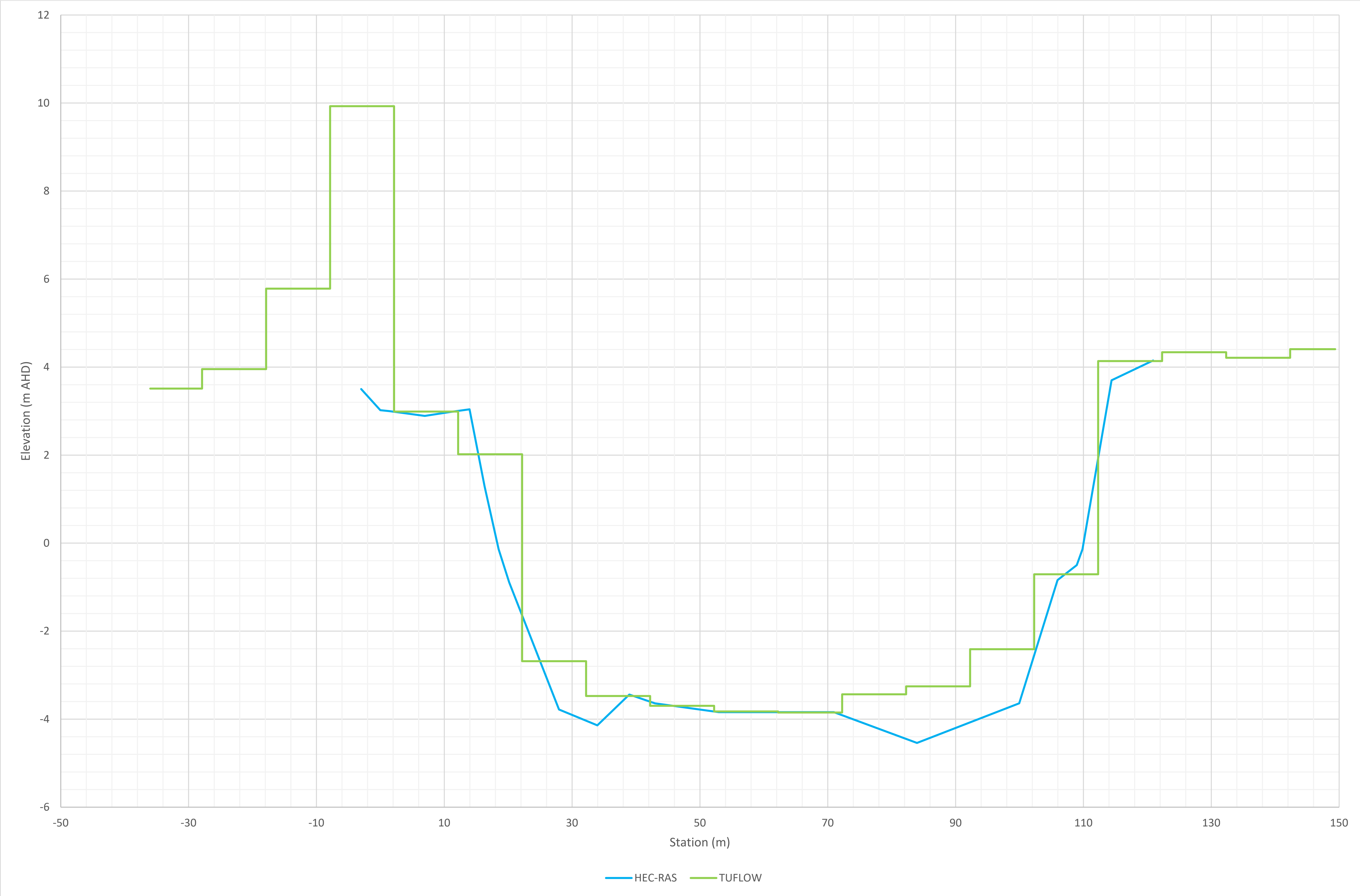


Figure 6 **Cross-section between Princes Bridge and Southbank Pedestrian Bridge (HEC-RAS Ch 9249, Spencer-Herr DS)**

3 HEC-RAS Modelling

The flows and bathymetry for this project were initially adopted from HEC-RAS modelling undertaken by Melbourne Water. GHD have compared the results of the MW HECRAS model with various tailwater levels (TWLs) to the current 'Designated Levels' within the study area. This is presented in Figure 7, which shows the following:

- Current HEC-RAS modelling provided to MWC (assumed TWL of 1.3 m AHD) doesn't match 'Designated Levels' very well within the study area, with HEC-RAS giving higher results for the entire area except for the top end of the model from just upstream of MacRobertson Bridge;
- Increasing the TWL to 1.6 m AHD (one of the currently requested scenarios) enlarges the differences to the 'Designated levels'; and
- Lowering the TWL to 0.6 m AHD or 0 m AHD reduces the difference to the 'Designated Levels' downstream of Swan Street Bridge and actually causes a slight increase upstream of Swan St Bridge.

Testing of other parameters, such as flow or roughness, within MW's HEC-RAS model was not undertaken.

4 Initial "Existing" TUFLOW Modelling

4.1 Modelling Overview

To test the TUFLOW model setup and determine the implications of the base assumptions regarding flows, TWLs and roughness, numerous TUFLOW model runs have been completed for the 100y ARI 72h storm to compare to both the Designated Levels and those from the previous HEC-RAS modelling (which stops just downstream of Spencer St). The completed model runs and their associated assumptions, summarised in Figure 8, present the modelling results of all these runs on a single plot. This plot includes four distinct colour bands that highlight runs with different TWLs as described below:

- Red – Tidal curve with a peak level of 1.4 m AHD
- Orange – Fixed level of 1.6 m AHD
- Green – Fixed level of 0.6 m AHD
- Blue – Fixed level of 0.0 m AHD

From this plot the following is evident:

- The Designated Levels are significantly lower than the vast majority of TUFLOW model runs,
- The HEC-RAS water surface levels generally lie somewhere in the middle of the TUFLOW model runs,
- Between chainages of 500 m and 7500 m the TWL has a significant effect on water surface levels within the Yarra River,
- Between chainages of 7500 m and 8000 m the TWL begins to have a less significant effect on water surface levels within the Yarra River,
- Above chainages of 8000 m factors other than the TWL (i.e. peak flows and Manning's coefficients applied along the Yarra River) have more significant effects on water surface levels within the Yarra River.

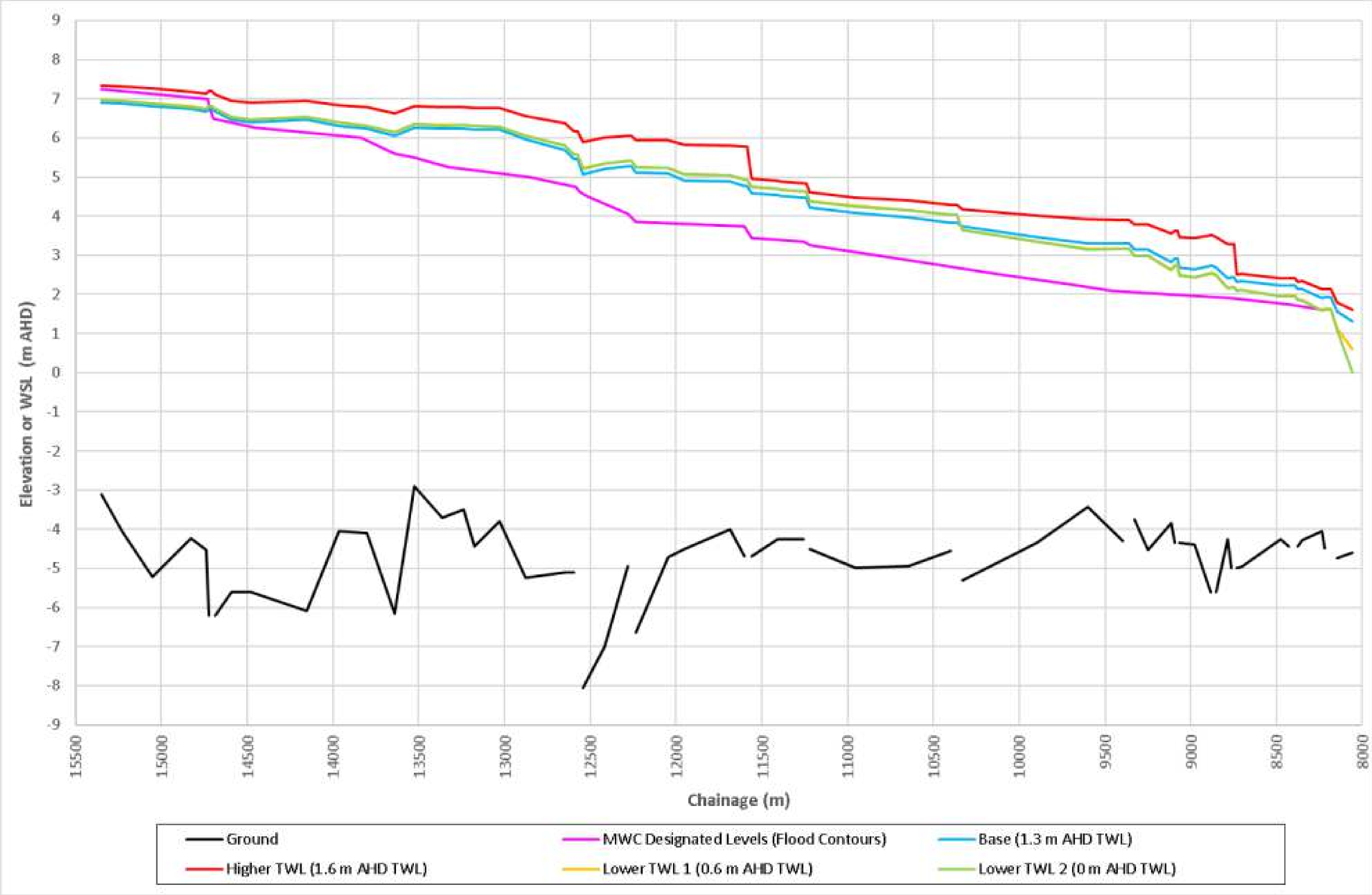


Figure 7 HEC-RAS WSL Result Comparison to MWC Designated Levels

Table 1 TUFLOW Model Scenarios

Model Scenario	Yarra River Flow (and Adopted Kc) (m^3/s)	River Roughness (Manning's 'n')	TWL* (m AHD)	Comment
MWC Designated Levels	-	-	-	Comparison levels adopted from MWC's "Flood_Contour_100yr_Waterways" layer
HEC-RAS	1480	0.025	1.3*	Comparison levels adopted from MWC's provided HEC-RAS model for Yarra River called "Yarra River high flow model (Oct 10)"
S1	1475 (145)	0.05	1.6	Initial 'Base Case' Scenario
S2	1475 (145)	0.05	Tidal (1.4 m AHD peak)	Test impact of fixed versus tidal boundary condition
S3	1475 (145)	0.05	0.6	Test impact of lower fixed DS TWL
S4	1475 (145)	0.05	0	Test impact of lower fixed DS TWL
S5	1475 (145)	0.025	1.6	Test impact of lower channel roughness
S6	1475 (145)	0.015	1.6	Test impact of lower channel roughness
S7	1475 (145)	0.025	Tidal (1.4 m AHD peak)	Test combined impact of lower channel roughness and tidal boundary condition
S8	1475 (145)	0.015	Tidal (1.4 m AHD peak)	Test combined impact of lower channel roughness and tidal boundary condition
S9	1475 (145)	0.025	0.6	Test combined impact of lower channel roughness and lower fixed DS TWL
S10	1475 (145)	0.015	0.6	Test combined impact of lower channel roughness and lower fixed DS TWL
S11	1475 (145)	0.025	0	Test combined impact of lower channel roughness and lower fixed DS TWL
S12	1475 (145)	0.015	0	Test combined impact of lower channel roughness and lower fixed DS TWL
S13	1314 (180)	0.05	1.6	Test impact of impact of lower Yarra River flows
S14	1314 (180)	0.025	1.6	Test combined impact of lower Yarra River flows and lower channel roughness
S15	1314 (180)	0.015	1.6	Test combined impact of lower Yarra River flows and lower channel roughness
S16	1314 (180)	0.025	0.6	Test combined impact of lower Yarra River flows, lower channel roughness and lower fixed DS TWL
S17	1314 (180)	0.015	0.6	Test combined impact of lower Yarra River flows, lower channel roughness and lower fixed DS TWL
S18	1314 (180)	0.025	0	Test combined impact of lower Yarra River flows, lower channel roughness and lower fixed DS TWL
S19	1314 (180)	0.015	0	Test combined impact of lower Yarra River flows, lower channel roughness and lower fixed DS TWL

Note:
* indicates that a fixed tailwater level was set at level specified, unless marked as "Tidal" in which case a simplified tide curve shifted to have a peak level at the level specified.

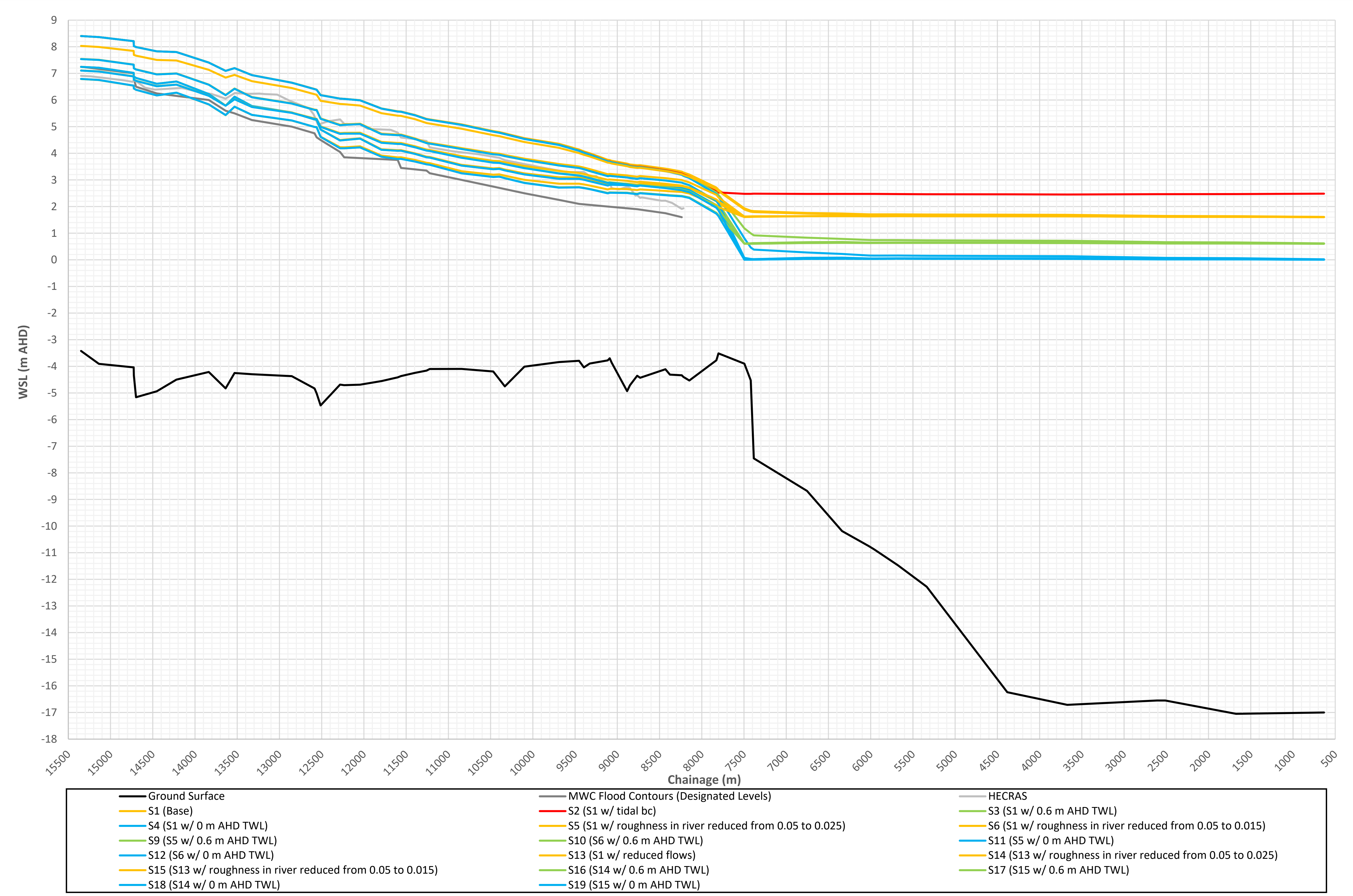


Figure 8 TUFLOW WSL Result Comparison to MWC Designated Levels and Current HEC-RAS results (Long Section 1)

To better assess the impact of other variables, plots showing the change in flow and roughness for each of the four different TWL conditions are presented in Figure 9 - Figure 12. In these plots the darker/lighter lines indicate higher/lower Manning's values (0.05, 0.025 and 0.015) while the triangle markers indicate runs with lower flows applied (peak of 1314 m^3/s as opposed to 1475 m^3/s). From these plots it can be seen that:

- Higher Manning's values produce higher water surface levels within the river,
- Lower flows produce lower water surface levels within the river,
- Results upwards of a chainage of 10,500 m cover similar ranges of WSLs,
- At a chainage of 10,500 m water surface level ranges are as follows compared to a Designated Level of 2.8 m AHD:
  - Long Section 2a – 4.8 m AHD,
  - Long Section 2b – 3.2 to 4.85 m AHD,
  - Long Section 2c – 3.1 to 4.8 m AHD,
  - Long Section 2d – 3.1 to 4.8 m AHD.
- At a chainage of 14,000 m water surface level ranges are as follows compared to a Designated Level of 6.05 m AHD:
  - Long Section 2a – 7.6 m AHD,
  - Long Section 2b – 6.0 to 7.6 m AHD,
  - Long Section 2c – 6.0 to 7.6 m AHD,
  - Long Section 2d –6.0 to 7.6 m AHD.

Following these base assumption tests, a test model was also run with bridge structure across the Yarra River modelled within the Study Area from Spencer St upstream to gain an appreciation of the likely increase in flood levels from including these. The modelling was for the 100y ARI 72h event with base assumptions from storms based on scenario 'S19' in Table 1 and is presented in Figure 13. From this plot it can be seen that increases in WSL due to structures range between 1 m and 1.7 m in the areas where bridge structures are modelled. Given that some bridges are still to be included in the model and that this model run did not include other riverside structures, this is likely to slightly increase further.

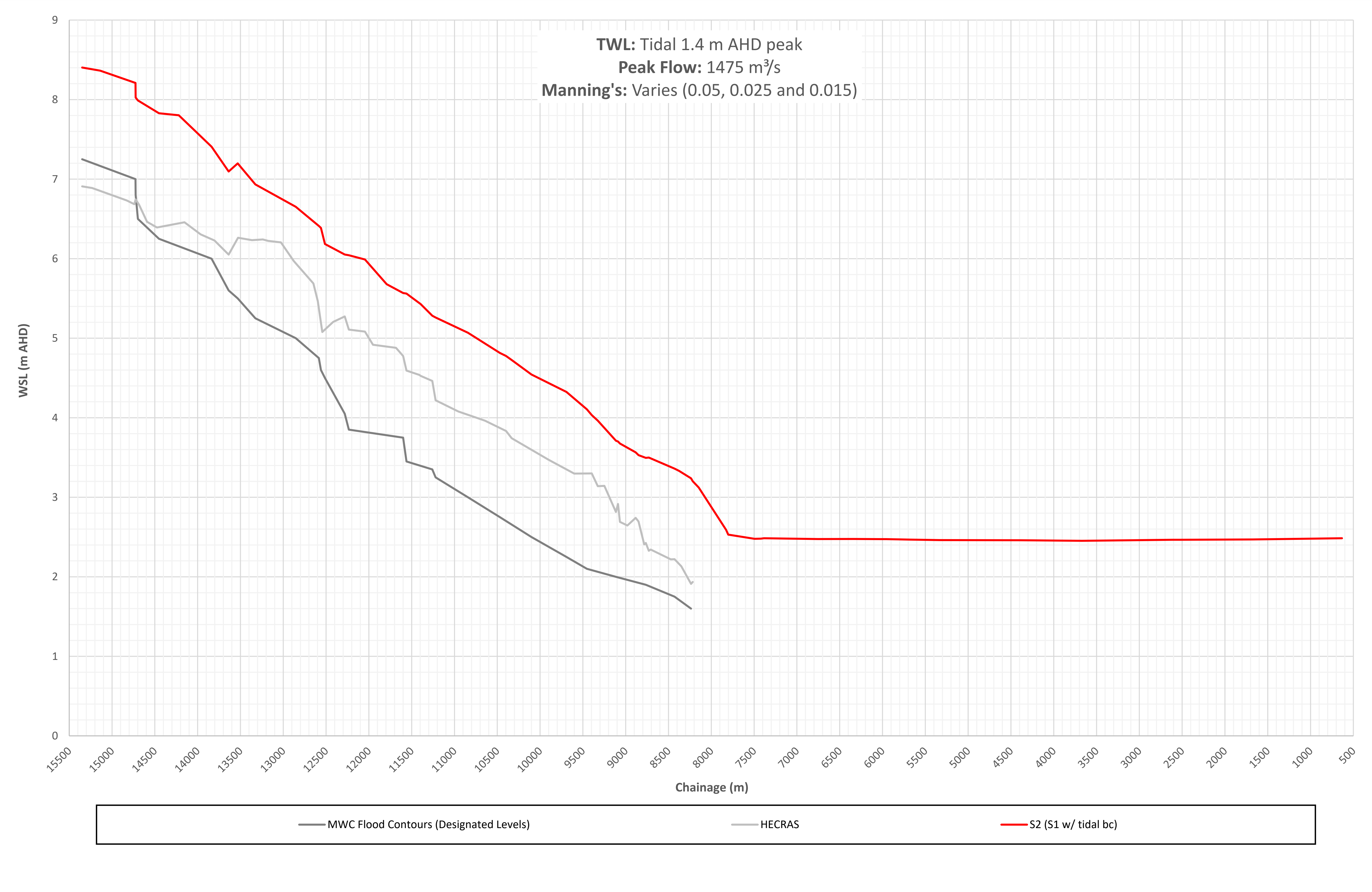


Figure 9 Tidal TWL TUFLOW WSL Result Comparison to MWC Designated Levels (Long Section 2a)

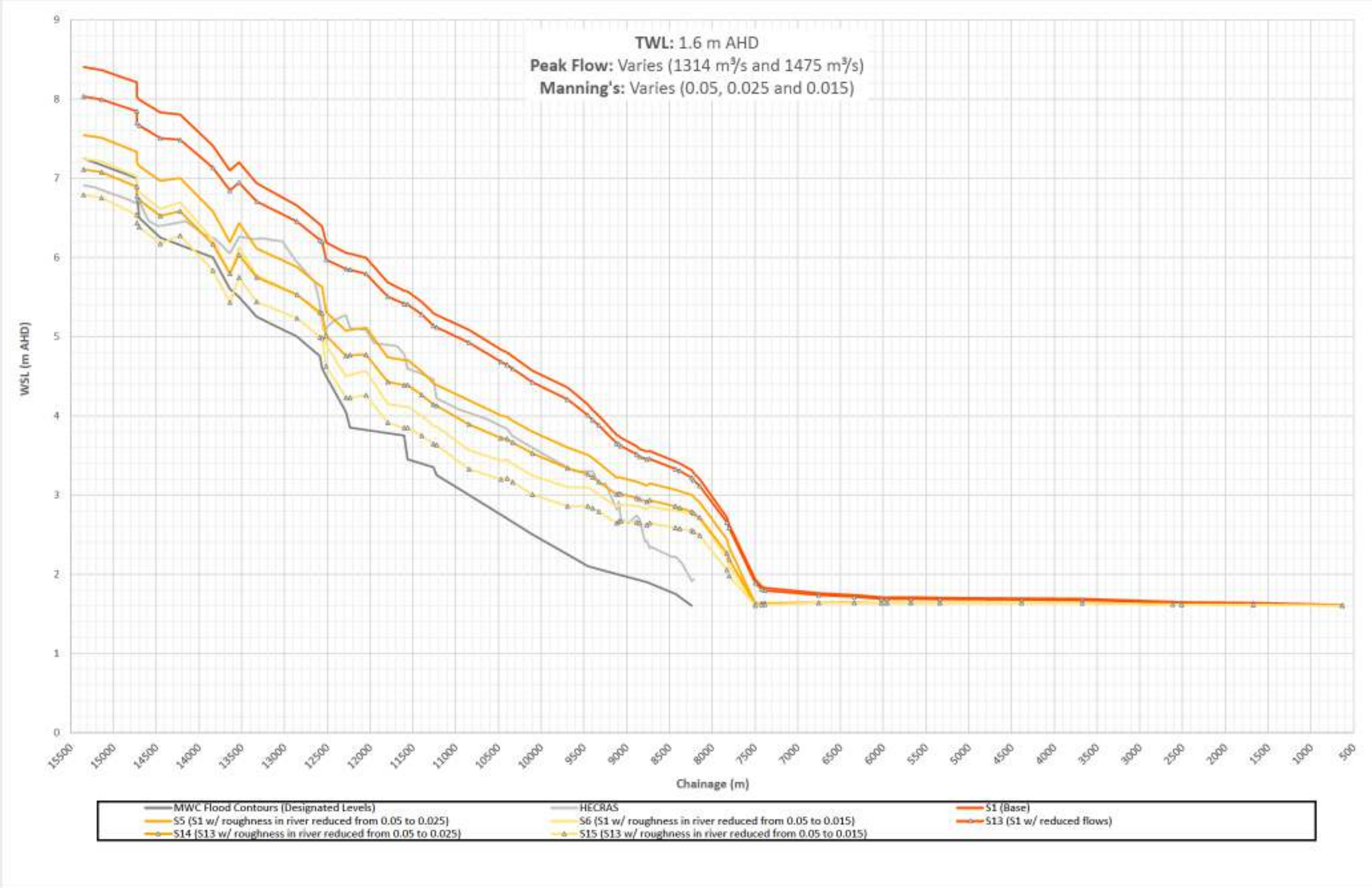


Figure 10 1.6 m AHD Fixed TWL TUFLOW WSL Result Comparison to MWC Designated Levels (Long Section 2b)

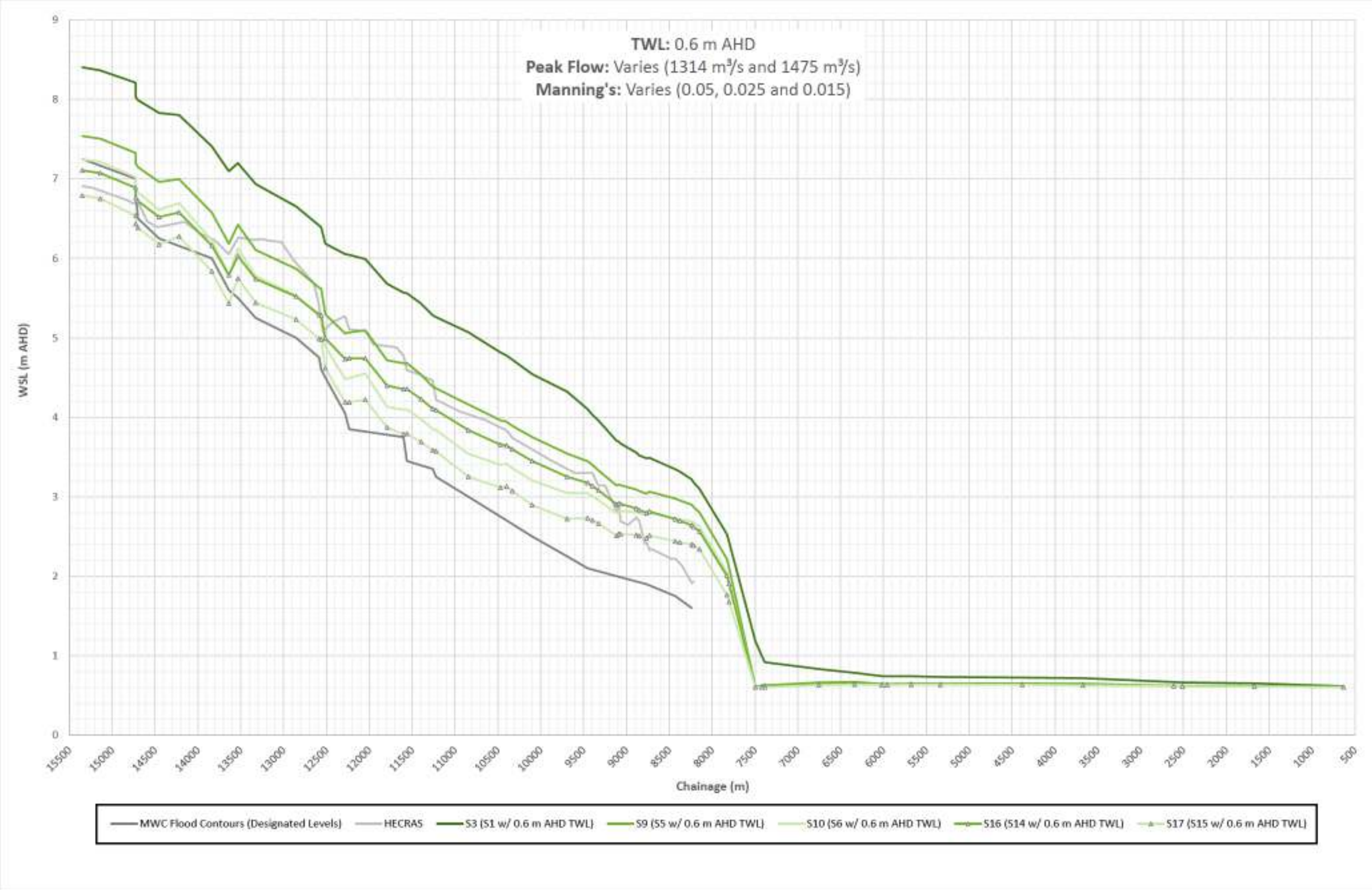


Figure 11 0.6 m AHD Fixed TWL TUFLOW WSL Result Comparison to MWC Designated Levels (Long Section 2c)

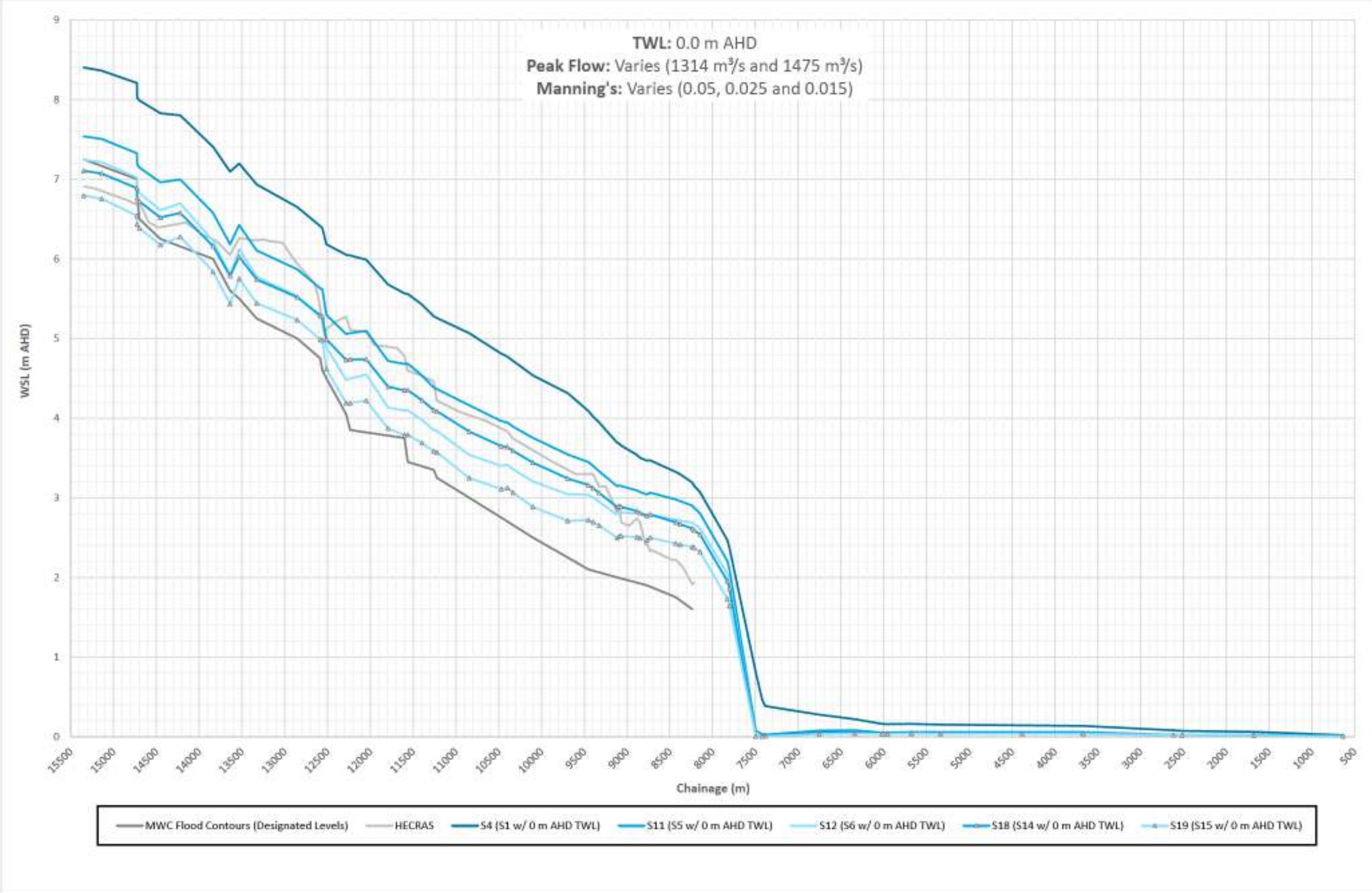


Figure 12 0.0 m AHD Fixed TWL TUFLOW WSL Result Comparison to MWC Designated Levels (Long Section 2c)

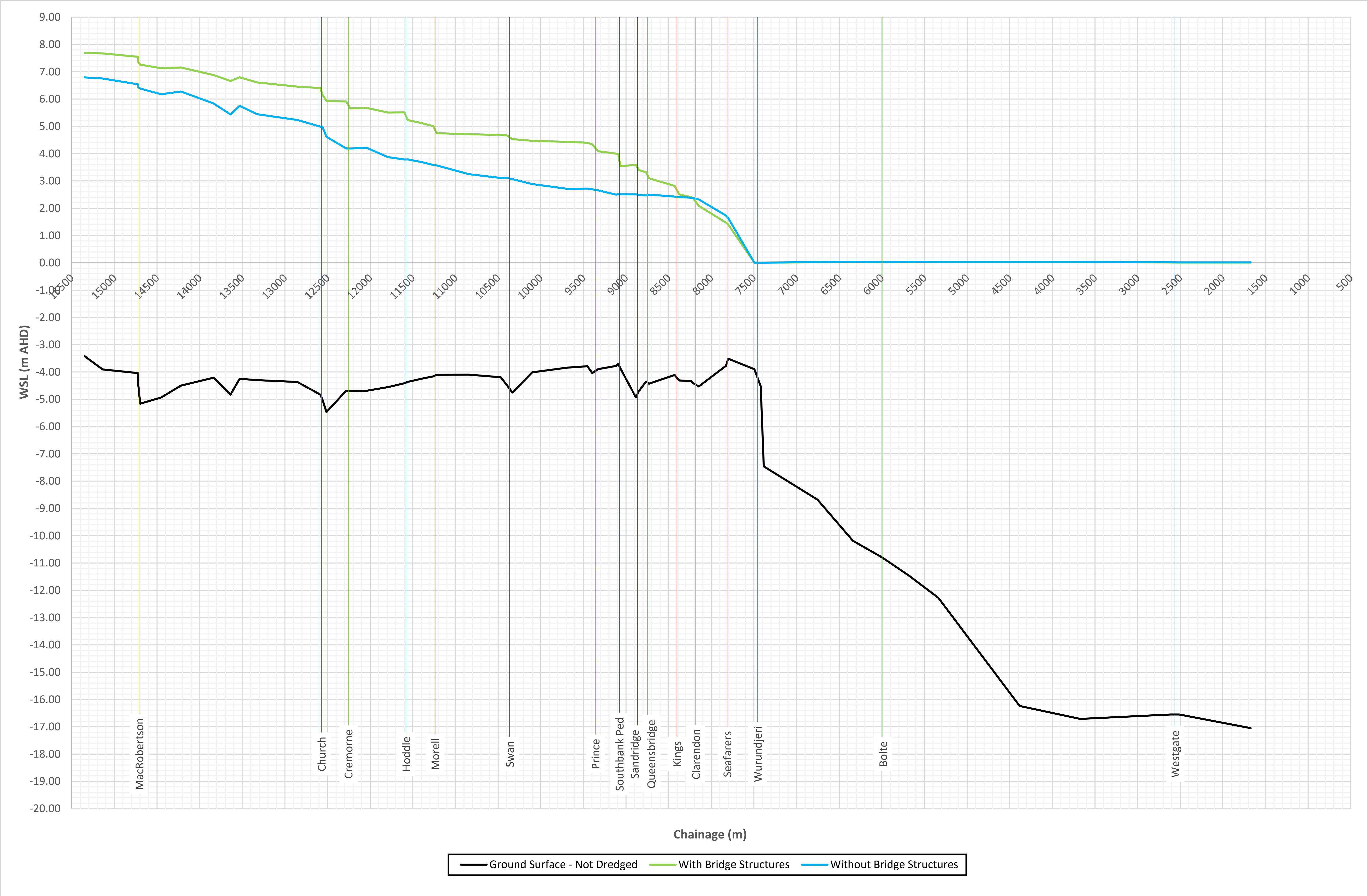


Figure 13 **TUFLOW WSL Result Comparison – Impact of Structures (Long Section 3)**

4.2 Results Discussion

Some of the differences in results above might be explained by one or a combination of the following factors:

1. Designated Levels are based on observations from the 1934 flood that is generally considered greater than a 100y ARI event (perhaps it was not greater than the 100 year at this location)
2. Designated Levels may be from an event which occurred when MWC was still dredging the Yarra River to a design profile that provides additional flow area (see Attachment 1 for a fax from MWC on a previous job in 1995).
3. The TWL for the event that generated the Designated Levels was much lower than the proposed design levels in the current scope (i.e. fixed TWL of 1.6 m AHD and 1.2 m AHD for the 100y and 5y ARI design events respectively). This raises the question of joint probability of bay levels and floods and perhaps also relates back to point 1.

4.3 Recommendation/Conclusion

As the preliminary results are so different to the current MWC Designated Levels it seemed appropriate that the potential implications of this be considered and that the project scope and assumptions be confirmed before the project proceeded. Following discussion with MWC it was decided that additional investigation should be undertaken to help understand the difference. To do this a quasi-verification of the model was proposed.

MWC Designated Levels represent the best currently available flood information along the Lower Yarra and as such a quasi-verification of the model to this data was deemed appropriate. As MWC Designated Levels were derived from the 1934 event and a dredging regime was maintained at the time, it was decided a dredged profile along the Yarra should be added to the model to represent the additional flow capacity dredging would have provided during the event. Comparing these results to the MWC Designated Levels would then highlight the impact of the dredged profile and facilitate an assessment of whether other factors could be responsible for any remaining difference.

5 Revised "Existing" and "Dredged" TUFLOW Modelling

5.1 Modelling Overview

Following the "initial" modelling discussed in Section 4, Melbourne Water commissioned a further investigation to:

- Better understand the difference between the "design storm" model results and their Designated Levels; and
- Assist in "verifying" some of the modelling assumptions.

MW Designated Levels were derived from the 1934 flood at which time the river is believed to have been actively dredged. Previous modelling represented existing river conditions that did not include dredging and so further investigation has involved the following:

- Applying a dredged river profile representing a likely 1934 dredging regime (available data did not cover full extent of likely works) – see discussion below under "*Dredged Profile*";
- Revising application of downstream tidal conditions to reflect latest information and improving the interpolation of bathymetry data along the thalweg – see discussion under "*Further Model Enhancement*"; and
- Comparing model results to the Designated Levels using a long-section profile along the river.

Dredged Profile

Based on available information (see Attachment 1) a defined dredged profile for the Yarra River was known between Hoddle Street Bridge and Spencer Street Bridge with the properties shown in Table 2 and Figure 14. This generated the simplified long-section profile shown in Figure 15, which shows that without further manipulation there would be barriers to conveyance upstream and downstream of the known dredged profiles. Given that the purpose of the dredging was to provide increased conveyance and the fact that the modelling was only to "verify" model assumptions, it was agreed with Melbourne Water that additional areas should be dredged to remove upstream and downstream humps in the channel invert. The revised extent of dredging is also shown in Figure 15.

Table 2 Dredged Profile Details

	Dimensions (m)	
Location	**Depth (D)**	**Width (W)**
Spencer Street Bridge to Princes Bridge	6.2	70
Princes Bridge to Swan Street Bridge	5.8	68
Swan Street Bridge to Hoddle Bridge	5.3	66

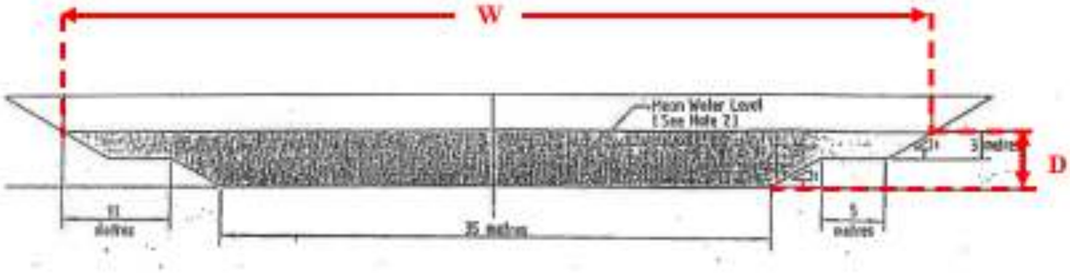


Figure 14 Provided dredged profile cross-section shape (extracted from Attachment 1)

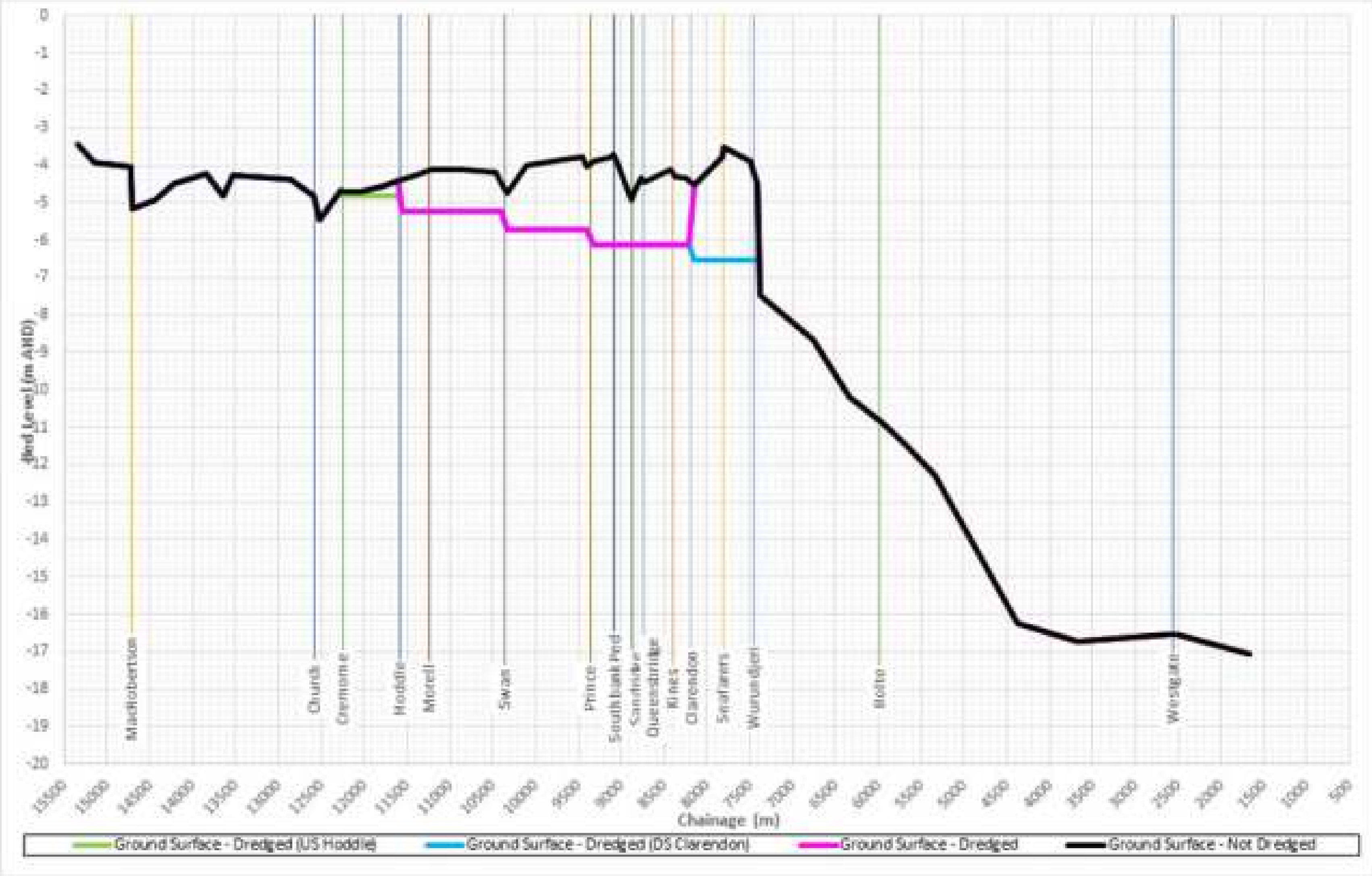


Figure 15 Simplified Long-Section Profile showing implications of dredged profile

Further Model Enhancement

As part of this second round of "exploratory" modelling, the following model enhancements were made:

1. The tidal curve shown in Figure 16 was adopted based on the following data provided by MWC:
    a. Tidal curves produces by Water Technology on another project
    b. Peak water levels to which to adjust peak tides for design event modelling based on the project brief and the MW Tech Spec
    c. Advice on the timing of the tidal curve relative to the peak of the hydrograph from 1934 event (refer to attached email dated 18/04/2019), which was adopted for the design events given the aim to provide confidence in the model results relative to the current Designated Levels.
2. Revised interpolation of bathymetry data based on HEC-RAS cross-sections to improve the representation of the thalweg, including its undulations. This change did alter the cross-sectional area of some of the river, but was confined to the low flow area that was already full due to the assumed initial water conditions and baseflow.

These enhancements require re-running of the "existing" conditions scenario so that the impact of the dredging could be clearly understood – see discussion in Section 5.2 on modelling scenarios.

Figure 16 Adopted tidal boundary

5.2 Model Scenarios

Following finalisation of tidal curves and river bathymetry inputs, the 24 model scenarios shown in Table 3 (i.e. all combinations of variables represented) were run in TUFLOW (HPC GPU) for the 1 in 100 year AEP 72 hour storm event. A definition of the variables for each scenario is also provided in Table 4 below. These results were then compared against the MW Designated Levels with the subset of these results marked in Table 3 presented in Figures A-D (see results in Section 5.3).

Table 3 Full suite of scenarios run in TUFLOW and Summary of Plotted Results

River profile	Structures	Flow	Manning's			Number of Scenarios
			0.015	0.020	0.025	
Dredged	Modelled	High	A1/C1			3
		Low		B1/D1		3
	Not modelled	High			A2	3
		Low			B2	3
Existing[1]	Modelled	High	C2			3
		Low		D2		3
	Not modelled	High				3
		Low				3
					Total Number of Modelled Scenarios	**24**

Note:
[1] indicates these models were rerun based on model refinements relating to:
- application of bathymetry data along the Yarra River corridor
- representation of tidal boundary based on latest information from MWC

Table 4 Scenario Definitions

Scenario		Definition
River profile	Dredged	Yarra River profile representing a likely 1934 dredging regime, using dredged profiles documented in “Attachment 1” and some agreed assumptions to provide a constant downhill grade along the Yarra River
	Existing	Yarra River profile representing current conditions, using the latest bathymetry and survey data available
Structures	Modelled	Structures modelled including: - Bridges crossing the Yarra River from MacRobertson Bridge to the Westgate Bridge - Piers along the river edge - CityLink bridge following the river edge (including sound walls)
	Not Modelled	No structures modelled
Flow	High	Yarra River flows obtained from the supplied Yarra River RORB model with a peak flow of 1475 m^3/s (k_c of 145). MWC current recommended flow.
	Low	Yarra River flows obtained from an adjusted version of the supplied Yarra River RORB model with a peak flow of 1314 m^3/s (k_c of 180). Sensitivity flow for comparison to MWC Designated Levels.
Manning’s	0.015	Estimated lower bounds of Manning’s n roughness for main channel areas of Yarra River (this lower bound is based on physical properties of channel from aerial)
	0.020	Intermediate estimate of Yarra River Manning’s n roughness for main channel areas of Yarra River
	0.025	Estimated upper bounds of Manning’s n roughness for main channel areas of Yarra River (this upper bound is based on physical properties of channel from aerial)

5.3 Results

This section presents the results for the subset of scenarios identified in Table 3 using the following four figures:

- Figures A & B (Figure 17 & Figure 18) show the selection of best-fit Manning’s values for a dredged river profile
- Figures C & D (Figure 19 & Figure 20) show the application of these best-fit Manning’s values to the existing river profile.

A brief discussion of each of these figures is presented below. A summary of the WSL results presented on each of the long sections is also provided in tabular format in Table 5.

Figure A

Figure A (Figure 17) presents model results along the Yarra River for the dredged river profile with high flows. The purpose of this figure is to identify the Manning’s value that produces results closest to the MW Designated Levels for the given combination of scenarios.

Where structures were not modelled a Manning's value of 0.025 provided the best fit, while if structures were modelled a Manning's value of 0.015 provided the best fit.

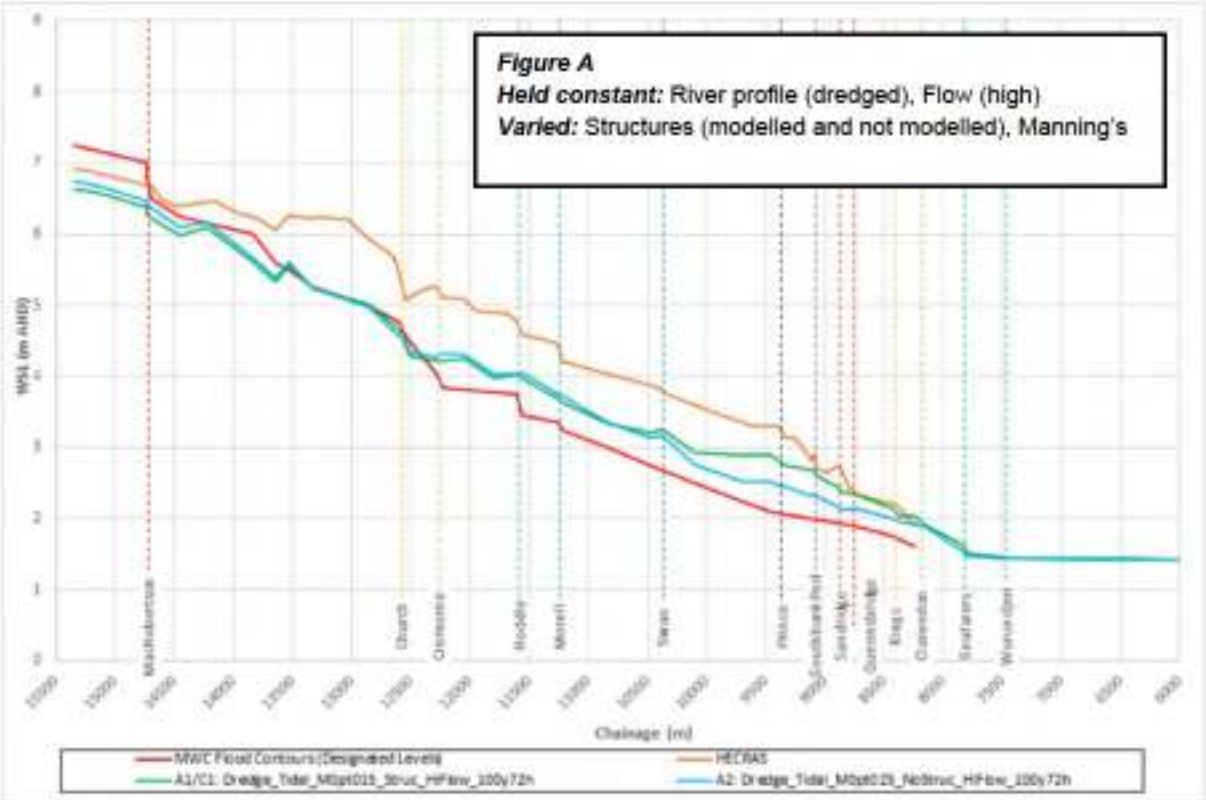


Figure 17 Dredged river profile with high flows (Figure A)

Figure B

Figure B (Figure 18) presents model results along the Yarra River for the dredged river profile with low flows. The purpose of this figure is to identify the Manning's value that produces results closest to the MW Designated Levels for the given combination of scenarios.

Where structures were not modelled a Manning's value of 0.025 provided the best fit, while if structures were modelled a Manning's value of 0.020 provided the best fit.

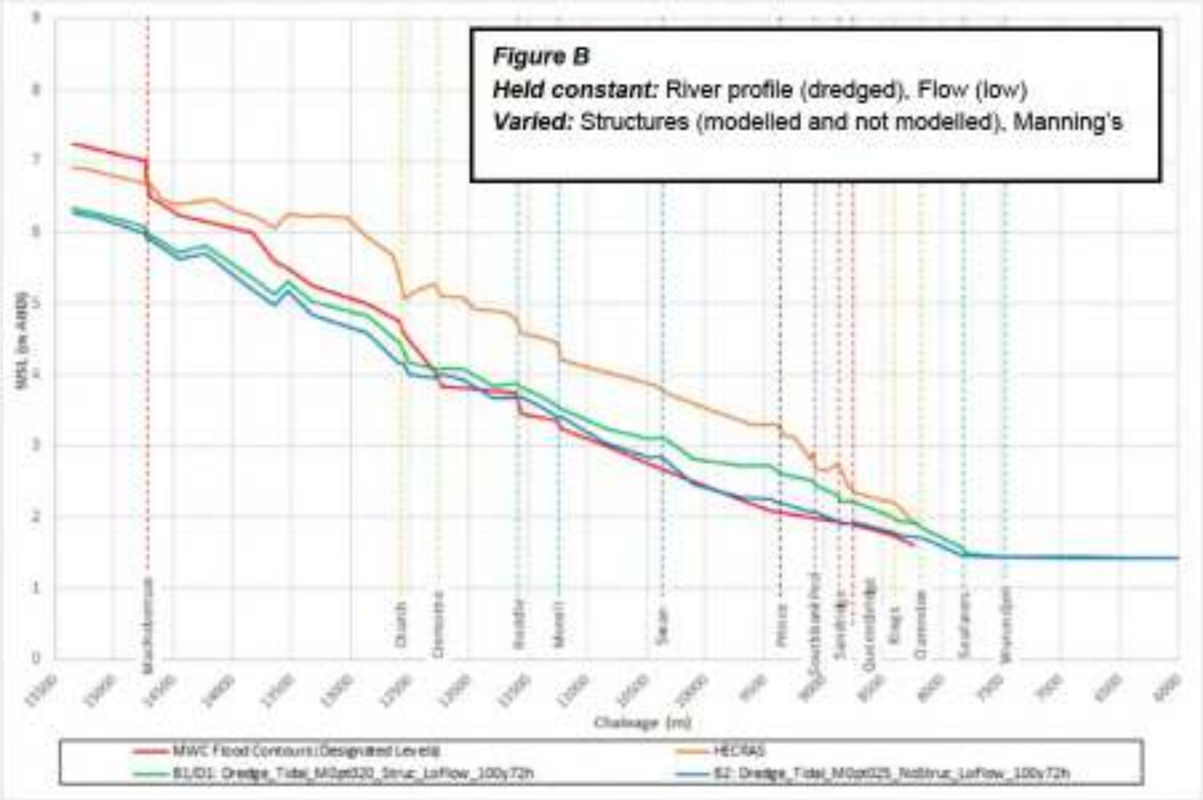


Figure 18 Dredged river profile with low flows (Figure B)

Figure C

Figure C (Figure 19) presents model results along the Yarra River for the same scenarios as in Figure A but with the existing river profile applied rather than the dredged river profile. The purpose of this figure is to observe model results when applying the best-fit Manning's value from Figure A to the existing river profile and to compare model results to the MW Designated Levels.

Model runs utilising the existing river profile can be seen to produce significantly higher levels than those of the dredged profile equivalent shown in Figure A.

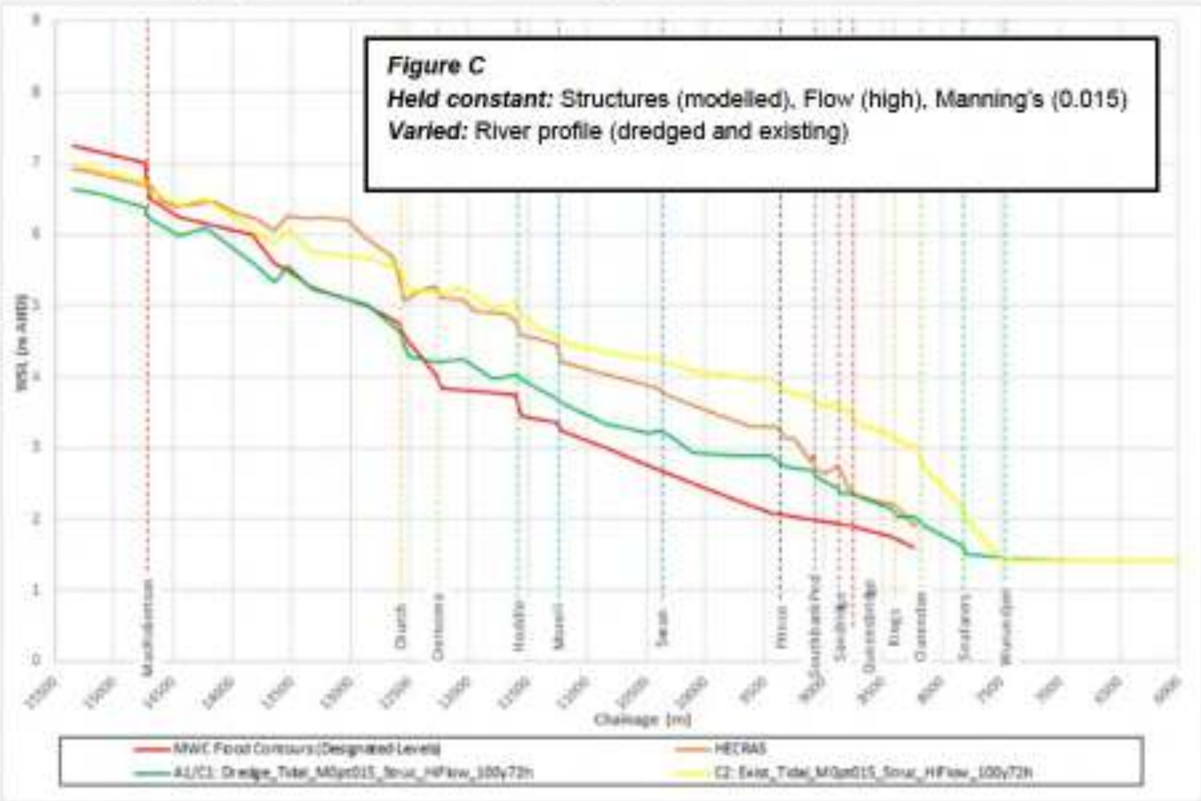


Figure 19 Existing vs dredged river profile with high flows, structures modelled and Manning's of 0.015 (Figure C)

Figure D

Figure D (Figure 20) presents model results along the Yarra River for the same scenarios as in Figure B but with the existing river profile applied rather than the dredged river profile. The purpose of this figure is to observe model results when applying the best-fit Manning's value from Figure B to the existing river profile and to compare model results to the MW Designated Levels.

Model runs utilising the existing river profile can be seen to produce significantly higher levels than those of the dredged profile equivalent shown in Figure B.

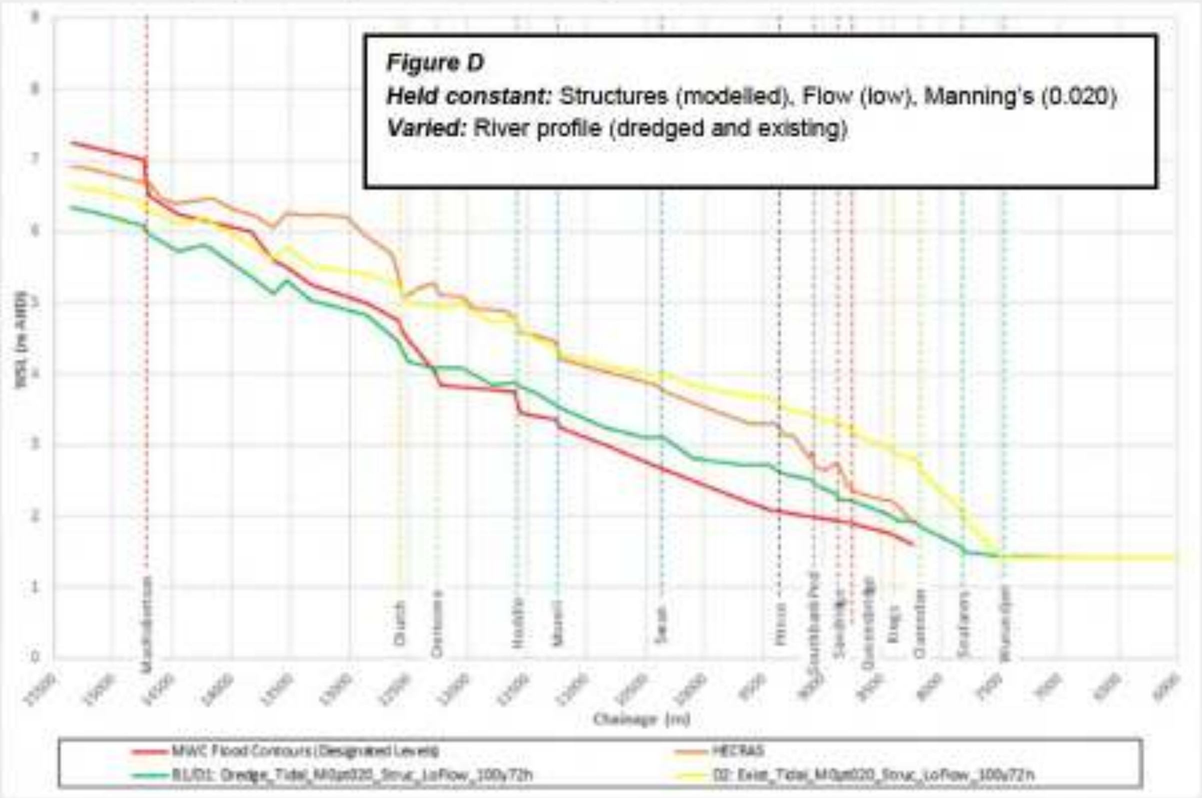


Figure 20 Existing vs dredged river profile with low flows, structures modelled and Manning's of 0.015 (Figure D)

Table 5 Summary of WSL results along Yarra River

		Event:	100 year 72 hour					
		River Profile:	Dredged	Dredged	Dredged	Dredged	Existing	Existing
		Flow:	High	High	Low	Low	High	Low
		Structures:	Yes	No	Yes	No	Yes	Yes
		Manning's:	0.015	0.025	0.02	0.025	0.015	0.02
			PLOT ID FOR FIGURES A – D (Figure 17 - Figure 20) and Table 3					
Description	**Chainage**	**MWC 100y WSL Contour (m AHD)**	**A1/C1**	**A2**	**B1/D1**	**B2**	**C2**	**D2**
	15349	7.25	6.64	6.75	6.34	6.28	6.97	6.63
	15138	-	6.57	6.68	6.26	6.20	6.91	6.57
	14726	7	6.37	6.46	6.08	5.99	6.74	6.41
US MacRobertson	14724	6.8	6.28	6.39	6.01	5.93	6.66	6.34
DS MacRobertson	14698	6.5	6.23	6.37	5.97	5.91	6.61	6.30
	14452	6.25	5.98	6.09	5.72	5.63	6.41	6.10
	14220	-	6.09	6.18	5.81	5.70	6.50	6.18
	13837	6	5.61	5.67	5.36	5.20	6.08	5.81
	13638	5.6	5.34	5.38	5.13	4.97	5.88	5.62
	13532	5.5	5.56	5.61	5.32	5.18	6.07	5.77
	13326	5.25	5.23	5.23	5.03	4.84	5.77	5.51
	12854	5	5.02	4.98	4.82	4.59	5.66	5.41
US Church	12584	4.75	4.64	4.54	4.46	4.17	5.52	5.25
DS Church	12560	4.6	4.49	4.55	4.34	4.18	5.41	5.16
	12513	4.5	4.29	4.34	4.17	4.01	5.23	5.00
US Cremorne	12282	4.05	4.21	4.28	4.08	3.95	5.20	4.96
DS Cremorne	12234	3.85	4.22	4.33	4.08	4.00	5.18	4.94
	12046	-	4.24	4.31	4.09	3.94	5.24	4.97
	11792	-	3.98	4.03	3.85	3.67	4.97	4.71
US Hoddle	11600	3.75	4.03	4.02	3.87	3.67	5.03	4.76
DS Hoddle	11561	3.45	3.97	4.04	3.82	3.69	4.87	4.63
	11395	-	3.83	3.90	3.71	3.57	4.68	4.47
US Morell	11259	3.35	3.69	3.74	3.57	3.42	4.57	4.36
DS Morell	11221	3.25	3.64	3.73	3.53	3.41	4.49	4.30
	10843	3	3.33	3.36	3.25	3.05	4.34	4.12
	10469	2.75	3.21	3.14	3.11	2.83	4.25	4.00
US Swan	10397	-	3.24	3.16	3.12	2.85	4.25	4.00
DS Swan	10332	-	3.21	3.11	3.09	2.80	4.22	3.98
	10100	2.5	2.93	2.75	2.83	2.46	4.09	3.85
	9692	2.25	2.89	2.52	2.73	2.27	4.00	3.72
	9453	2.1	2.89	2.52	2.72	2.25	3.95	3.66
US Prince	9396	-	2.82	2.47	2.66	2.21	3.91	3.63
DS Prince	9326	-	2.75	2.45	2.60	2.19	3.80	3.53
	9114	2	2.68	2.31	2.52	2.08	3.71	3.44
US Southbank Ped	9090	-	2.68	2.31	2.52	2.08	3.73	3.46
DS Southbank Ped	9067	-	2.59	2.31	2.44	2.08	3.61	3.37
US Sandridge	8884	-	2.46	2.16	2.31	1.95	3.59	3.33
DS Sandridge	8850	-	2.36	2.13	2.23	1.92	3.57	3.30
US Queensbridge	8765	1.9	2.34	2.12	2.21	1.91	3.51	3.24
DS Queensbridge	8730	-	2.33	2.14	2.20	1.92	3.36	3.14
US Kings	8430	1.75	2.15	2.00	2.03	1.79	3.20	2.97
DS Kings	8377	-	2.04	1.96	1.94	1.76	3.09	2.88
	8237	1.6	2.05	1.92	1.93	1.73	3.03	2.82
US Clarendon	8217	-	2.01	1.90	1.90	1.71	3.02	2.82
DS Clarendon	8147	-	1.91	1.89	1.83	1.71	2.72	2.59
US Seafarers	7827	-	1.63	1.54	1.58	1.47	2.17	2.08
DS Seafarers	7802	-	1.52	1.48	1.49	1.46	2.03	1.95
US Wurundjeri	7495	-	1.45	1.44	1.45	1.44	1.44	1.44
DS Wurundjeri	7420	-	1.45	1.44	1.44	1.44	1.44	1.44
	7384	-	1.43	1.44	1.43	1.44	1.43	1.43
	6754	-	1.43	1.44	1.43	1.43	1.43	1.43
	6339	-	1.43	1.43	1.43	1.43	1.43	1.43
US Bolte Bridge	6019	-	1.43	1.43	1.43	1.43	1.43	1.43
DS Bolte Bridge	5957	-	1.43	1.43	1.43	1.43	1.43	1.43
Confluence with Moone Ponds Creek	5677	-	1.43	1.43	1.43	1.43	1.43	1.43
	5337	-	1.43	1.43	1.43	1.43	1.42	1.42
	4383	-	1.42	1.43	1.42	1.42	1.42	1.42
Confluence with Maribyrnong River	3673	-	1.42	1.42	1.42	1.42	1.42	1.42
US Westgate Bridge	2613	-	1.41	1.41	1.41	1.41	1.41	1.41
DS Westgate Bridge	2512	-	1.41	1.41	1.41	1.41	1.41	1.41
US Westgate Bridge	1674	-	1.41	1.41	1.41	1.41	1.41	1.41
DS Westgate Bridge	633	-	1.40	1.40	1.40	1.40	1.40	1.40

5.4 Discussion

For the modelled event (100 year ARI, 72 hour storm), looking at the dredged model results with structures and high flows applied (Figure A) a Manning's of 0.015 seems to produce results closest to the MWC Designated Levels. This scenario resulted in the following general model differences to MW Designated Levels:

- Minimal variance around Cremorne Rail Bridge.
- Lower levels upstream of Cremorne Rail Bridge, with a maximum difference of over half a metre just upstream of Cremorne Rail Bridge.
- Higher levels downstream of Cremorne Rail Bridge, with a maximum difference of nearly 1 metre at Princes Bridge.

Utilising the "best fit" Manning's 'n' value from the dredged scenario and applying to the existing scenario with structures modelled and high flows applied (Figure C) resulted in the following general model differences to MW Designated Levels:

- Minimal variance at the upstream end of the model (around MacRobertson Bridge).
- Increasing differences downstream of MacRobertson Bridge (modelled WSLs greater than Designated Levels), exceeding 1 metre at Cremorne Bridge and reaching a maximum of almost 2 metres at Princes Bridge.
- Water levels downstream of Wurundjeri Way (beyond the extent of MWC Designated Levels) are dominated by tidal conditions.

Given that both the existing and dredged "verification" results are so different to the current MWC Designated Levels it seems appropriate that the potential implications of this are considered and that the project scope and assumptions are confirmed before the project proceeds. Reasons for this variance may include the following:

1. Designated Levels are based on observations from the 1934 flood that is generally considered greater than a 100 year ARI event (perhaps it was not greater than the 100 year ARI at this location).
2. Design event hydrology does not simulate real event hydrology.
3. The hydrologic model from which the 100 year ARI hydrographs were extracted may have represented an ARI in excess of the 100 year ARI due to rainfall likely not applying areal reduction factors (ARFs) and thus point storms are being applied throughout the catchment
4. The adopted design hydrology may have been significantly adjusted to improve the fit of the HECRAS hydraulic model across a much larger extent of the Yarra River.
5. While the river profile was altered to represent 'dredged' 1934 conditions, the surrounding terrain and structures have not been modified from those that represent 'existing' conditions to those that would represent conditions during the 1934 event
6. The LiDAR used to define the ground surface around the Yarra River (not including the river bathymetry) may not be completely accurate and reliable.

5.5 Recommendation/Conclusion

In discussions with Melbourne Water, GHD raised concerns that there were potential limitations in the hydrology and/or terrain that may be influencing the “verification” modelling results. Of particular concern were the following items:

- The lack of Areal Reduction Factors (ARFs), which would increase volume and peak flows.
- The adoption of RORB routing parameters to generate design hydrographs for use in TUFLOW (a 2D hydraulic model) based on ‘calibration’ of a HEC-RAS model (1D hydraulic model) – when we could adopt parameters based on ‘calibration’ of hydrologic flows using RORB.
- A comparison of current LiDAR circa 2018 to that used for this Study circa 2009 shows some noticeable differences in levels that may influence results (particularly where overtopping levels are affected).

However, MWC advised that they were comfortable with the current assumptions in the hydrology/hydraulics used for the “verification” modelling (refer to attached email train dated 6/9/2019) and that GHD should proceed with the required “design runs” with the main channel roughness that achieves results closest to the current MW designated levels.

6 Initial Design Run Assumptions and Developments

6.1 Model Setup and Assumption

Based on outcomes of modelling discussed in Section 5, GHD commenced design run modelling with the general agreed setup shown in Figure 21 and the following parameters/assumptions:

- Adopt provided MWC hydrologic models with assumptions as per Table 10
- Adopt final model setup as per Section 6, with a Manning’s ‘n’ roughness of 0.015 for the major waterway areas.

Table 6 Hydrologic Assumptions

Model Parameter	**Yarra River**	**Maribyrnong River**
RORB Version	6.15	6.15
Rainfall	Stormfiles with variable IFD (adopted from 2016 Yarra River Study)	ARR1987 IFD @ inbuilt “Keilor” location
ARF	None (adopted from 2016 Yarra River Study)	None (for consistency with 2016 Yarra River Study)
Kc	145 (adopted from 2016 Yarra River Study)	70
m	0.8	0.8
IL (mm)	Varies with interstation area: • YarRv@YarGlen-DummyGS = 30 • Catchment outlet = 15	20
Runoff Coefficient	Varies with ARI: • 100y = 0.60 • 50y = 0.55 • 20y = 0.50 • 10y = 0.45 • 5y = 0.40	Varies with ARI: • 100y = 0.6 • 50y = 0.55 • 20y = 0.45 • 10y = 0.35 • 5y = 0.25
Climate Change	Factored rainfall in stormfiles by 1.16 to represent 16% increase as per latest Tech Spec	Adjusted IFD parameters to increase rainfall intensity by 16%

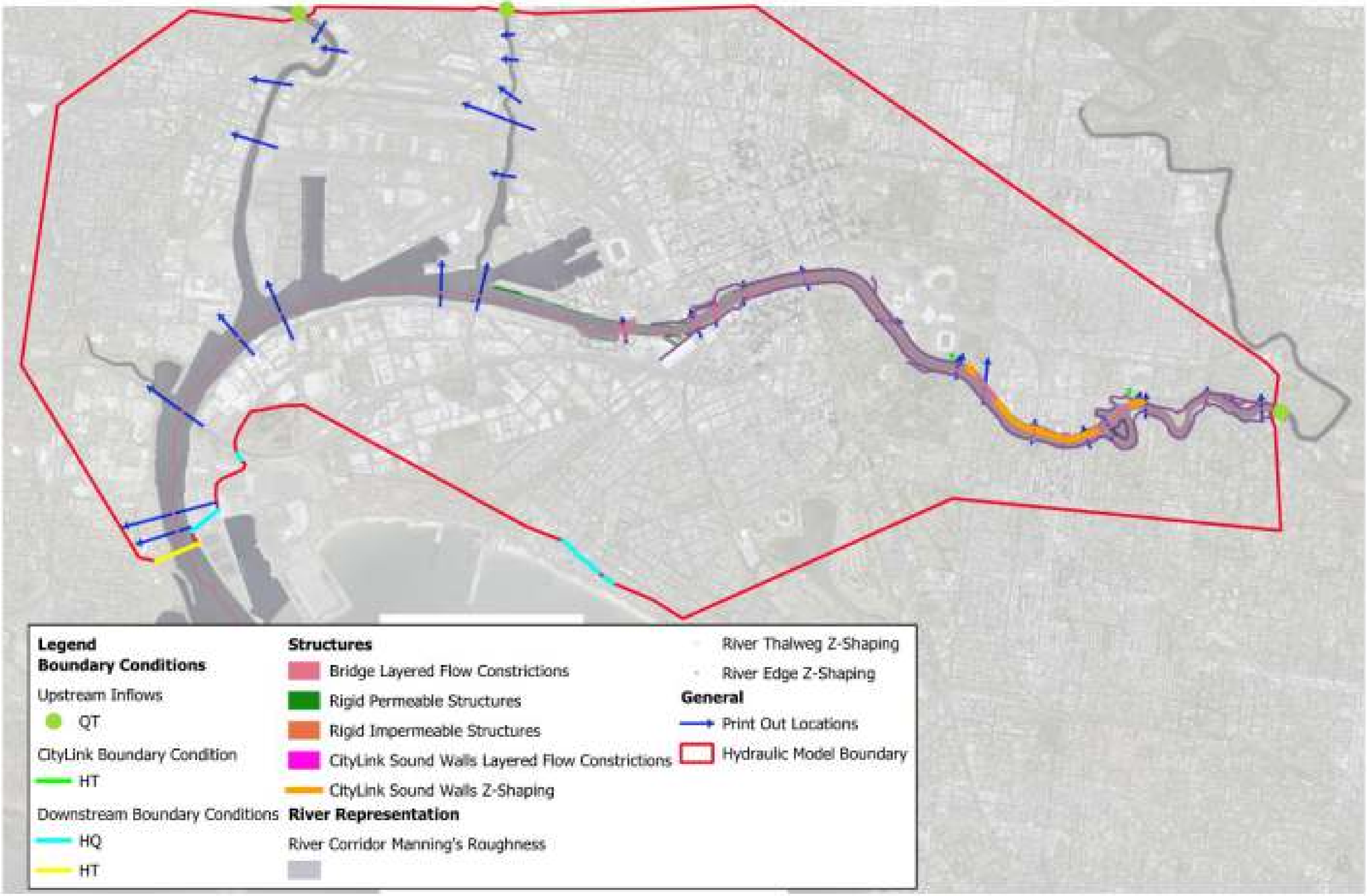


Figure 21 **Final TUFLOW Model Setup (after "verification" and initial "design run" modelling)**

6.2 Additional model changes required

During the process of undertaking the “design runs”, GHD discovered a number of issues with the coding in the TUFLOW software that required changes or simplifications to the modelling approach to achieve a stable model result. The following changes were required after much testing and discussion with TUFLOW Support:

- Remove “SMS Triangles” output format as this was not compatible with traditional flow constrictions;
- Adjust model setup to allow for modelling of tidally influenced areas upstream of Study Area (see revised model setup in **Figure 21**):
  - Add “HX” lines and 1d_nodes to upstream end of three tributaries with inflows to represent storage upstream of the Study Area and reduce potential sloshing off code boundary
  - Alter downstream code boundary to avoid undulating terrain and converted non-Yarra River boundary conditions to “HQ” – i.e. only tidal boundary is on Yarra River
  - Run model for a period (choose 36 h) prior to event starting to set up initial conditions based on a typical tidal cycle (i.e. enables the model to establish an appropriate initial water surface profile along the Yarra River)
- Removed traditional “flow constriction” and “cell width reduction” layers from models as these layers couldn’t handle the range of depths present in the model and were generating corrupt or erroneous results.

6.3 MW review of “Design Run” results

Following delivery of the “design run” results, MW reviewed the results in more detail and became concerned with the level of overtopping around Southbank (which were outside the current assigned mapping limit) and the difference in the modelled levels with both the current designated and historic 1934 flood levels. This review was undertaken by a new project manager at MW who observing that the modelled levels were considerably higher than expected recommended undertaking some model refinements to gain greater confidence in levels outside the tidally influenced confines of the lower Yarra River,. There was also concern over the current directive to model a 100 year ARI with a 100 year bay level given the joint probabilities of these events.

7 Southbank Overflow Refinement Modelling

7.1 Modelling Overview

After discussion regarding the initial design runs, it was decided that additional effort should be made to refine the models representation of the overflow area along Southbank. This refinement focussed on adopting details from the following existing local models, which were adjusted as required for the different grid size and alignment:

- Fisherman’s Bend;
- Southbank.

The key changes to the model used for the ‘design runs’ were as follows:

1. The use of a different terrain model in the Southbank model area;
2. The introduction of additional terrain modifications from local models, in particular the:
    - The surveyed level along the southern Yarra River bank (stretching from St Kilda Road to just east of the Bolte Bridge);
    - The level defining the spill elevation into the Southbank City Link tunnel portal.
3. The review and refinement of the catchment roughness (materials layer).

4. The adoption of an alternate boundary condition arrangement with the 100 year ARI flood event being matched with a 10 year tidal bay level to match assumptions of local modelling and simplistically considers the joint probability concerns.

Considering that we are trying to understand impact of flooding emanating from the Yarra River spilling, it was agreed that the local drainage should not be added as this is likely to be heavily influenced by the presence of non-return mechanisms and/or pump stations that may restrict or alter the magnitude and timing of back flow.

After some initial runs, the concerns with the current hydrology outlined in Section 5.5 were revisited and some models with alternate hydrology were run as discussed further below.

7.2 Model Scenarios

Based on all the previous discussions and validation modelling the scenarios defined in Table 7 were ultimately run for this model configuration using “HPC on GPU” engine in TUFLOW to facilitate a more efficient comparison of scenarios. A comparison of the modelled inflows and the change in downstream boundary conditions for these models are also presented in Figure 22 and Figure 23 respectively. These scenarios were run in three phases as highlighted in Table 7, with the scope of the next phase being defined based on discussion of results of the previous phase

7.3 Results and Discussion

The results of the three phases of modelling undertaken at this stage are presented in detail as Attachments 4 – 6, but can be summarised as follows:

- Phase 1
  - Results showed that model refinements did reduce the flood extent in the Southbank area, but there was still some substantial differences in results between the local models and significant inflow to the City Link tunnel portal in this area which was of concern as this was not previously thought to occur (see Figure 24). Refer to Attachment 4 for all presented results.
  - After discussing the results in detail, it was jointly agreed that the concerns over the hydrology should be revisited with some new model runs and that the output of these runs should also be compared to 1934 historic level points.
- Phase 2
  - Results showed that the alternate hydrology brought the modelled flood levels along the Yarra River more in line with historic levels (see Figure 25) and reduced, but didn’t eliminate inflows to City Link tunnel portal in Southbank. Refer to Attachment 5 for all presented results.
  - After discussing the results in detail, it was jointly agreed that the river roughness should be re-considerred against historic levels using the alternate hydrology that uses the Kc parameter from MW work prior to “2010 - SP Goh & Associates Study” and applies Areal Reduction Factors (ARFs). This would reduce concern that current river roughness was at the extreme smooth end of values that could be justified based on literature.
- Phase 3
  - Results showed that a number of roughness could provide results that are fairly consistent with MW’s understanding of the relative magnitude of the 1934 flood (see Figure 26). There was however discussion over a change in the fit at around Chainage 12,500 and why this might be occurring (such as limitations of the current upstream simplification of inflow application and the representation of available storage upstream.

Table 7 Overflow Refinement Model - Modelled Scenario Definitions

Phase	Runs	Hydrology	Yarra River Inflow (m^3/s)	Yarra River Inflow Volume (m^3)	Downstream Tailwater Level (TWL)	River Roughness (Manning's 'n')
1	1	Base 1% AEP (Kc=145 w/o ARFs)[1] [Solid blue line on Figure 22]	1475	517,000,000	1% AEP Tide	0.015
1	2	Base 1% AEP (Kc=145 w/o ARFs)[1] [Solid blue line on Figure 22]	1475	517,000,000	10% AEP Tide	0.015
2	3	Base 1% (Kc=237 w/o ARFs)[2] [Solid orange line on Figure 22]	1115	517,000,000	10% AEP Tide	0.015
2	4	Base 1% AEP (Kc=180 w/ ARFs)[3] [Solid green line on Figure 22]	1091	432,000,000	10% AEP Tide	0.015
2	5	CC 18.5% 1% AEP (Kc=145 w/o ARFs) [1] [Dashed blue line on Figure 22]	1792	621,000,000	10% AEP SLR Tide	0.015
2	6	CC 18.5% 1% AEP (Kc=237 w/o ARFs) [2] [Dashed green line on Figure 22]	1352	621,000,000	10% AEP SLR Tide	0.015
2	7	CC 18.5% 1% AEP (Kc=180 w ARFs) [3] [Dashed green line on Figure 22]	1293	509,000,000	10% AEP SLR Tide	0.015
3	8	Base 1% AEP (Kc=180 w/ ARFs) [3]	1091	432,000,000	10% AEP Tide	0.020
3	9	Base 1% AEP (Kc=180 w/ ARFs) [3]	1091	432,000,000	10% AEP Tide	0.025
3	10	Base 1% AEP (Kc=180 w/ ARFs) [3]	1091	432,000,000	10% AEP Tide	0.030
3	11	CC 18.5% 1% AEP (Kc=180 w ARFs) [3]	1293	246,000,000	10% AEP SLR Tide	0.020
3	12	CC 18.5% 1% AEP (Kc=180 w ARFs) [3]	1293	246,000,000	10% AEP SLR Tide	0.025
3	13	CC 18.5% 1% AEP (Kc=180 w ARFs) [3]	1293	246,000,000	10% AEP SLR Tide	0.030
3	14	CC 18.5% 10% AEP (Kc=145 w/o ARFs)[1]	831	291,000,000	10% AEP SLR Tide	0.015
3	15	CC 18.5% 10% AEP (Kc=180 w ARFs) [3]	616	246,000,000	10% AEP SLR Tide	0.020
3	16	CC 18.5% 10% AEP (Kc=180 w ARFs) [3]	616	246,000,000	10% AEP SLR Tide	0.030

Note:
[1] indicates that the Kc parameter is based on calibration to flood levels using HEC-RAS from "2010 - SP Goh & Associates Study", which didn't use ARFs.
[2] indicates that the Kc parameter is based on calibration to gauge flows from "2010 - SP Goh & Associates Study" , which didn't use ARFs
[3] indicates that the Kc parameter is based on MW work prior to "2010 - SP Goh & Associates Study", but with the application of ARFs

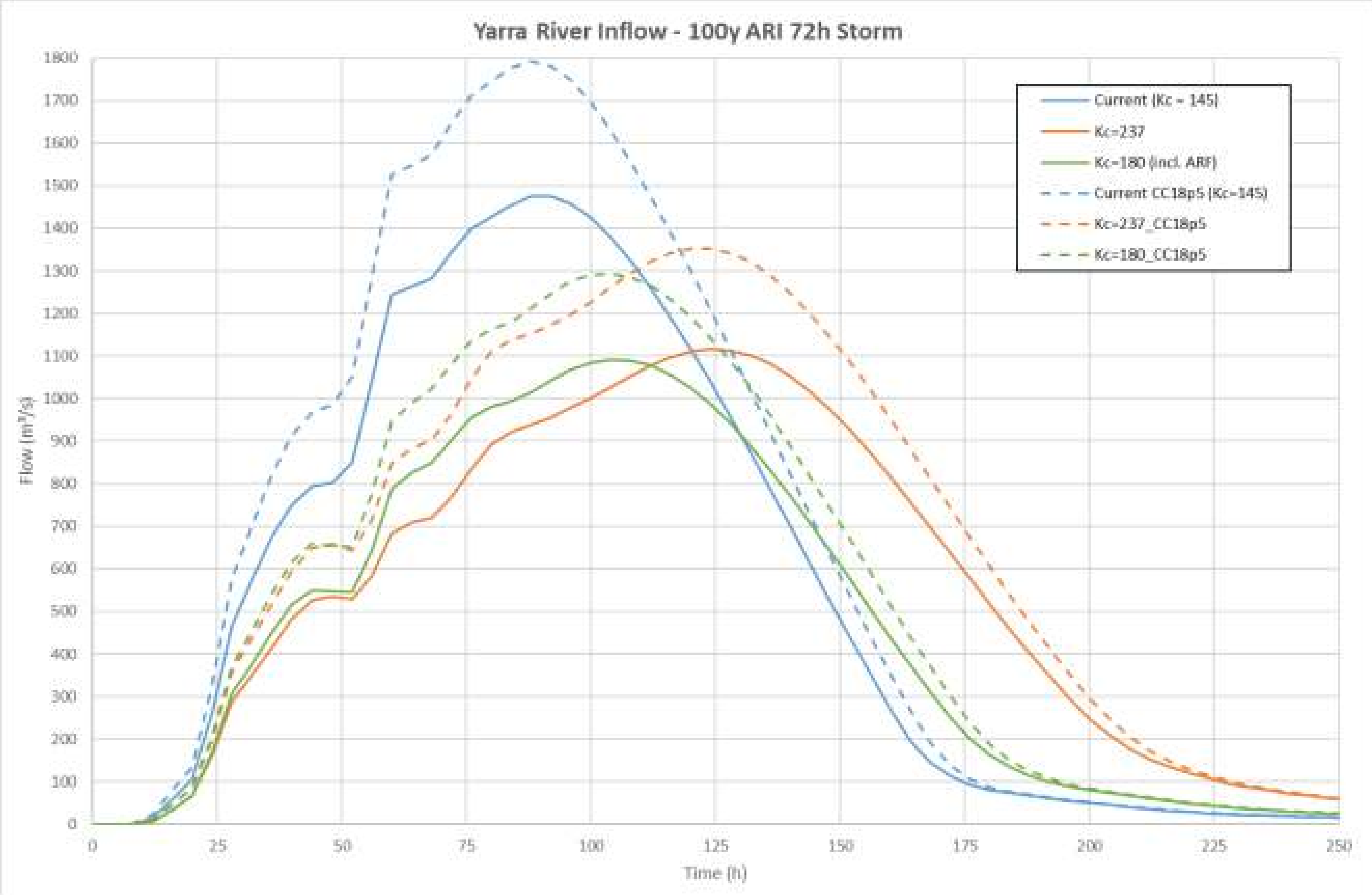


Figure 22 Comparison of modelled Yarra River inflows

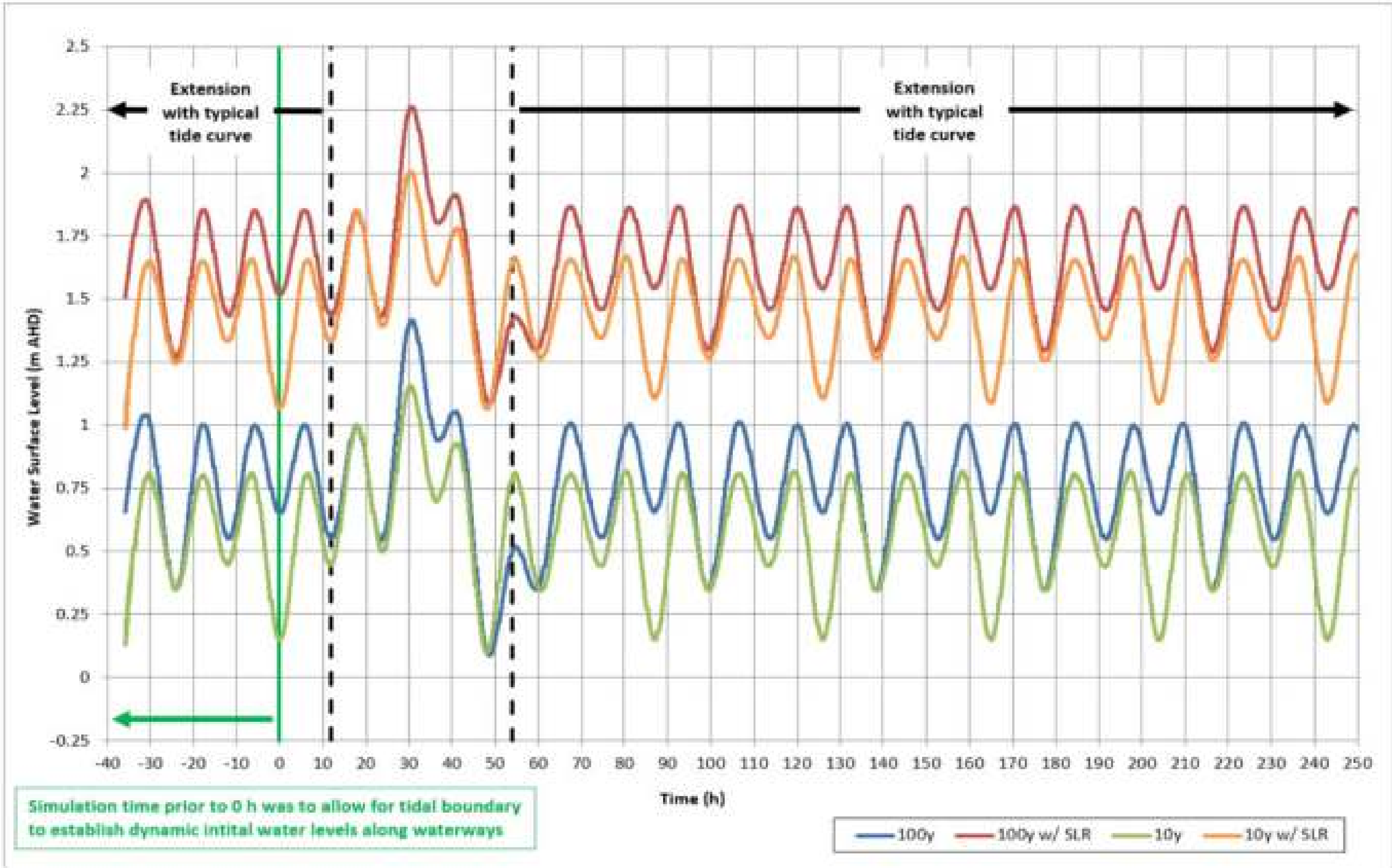


Figure 23 Comparison of modelled downstream boundary condition or TWL

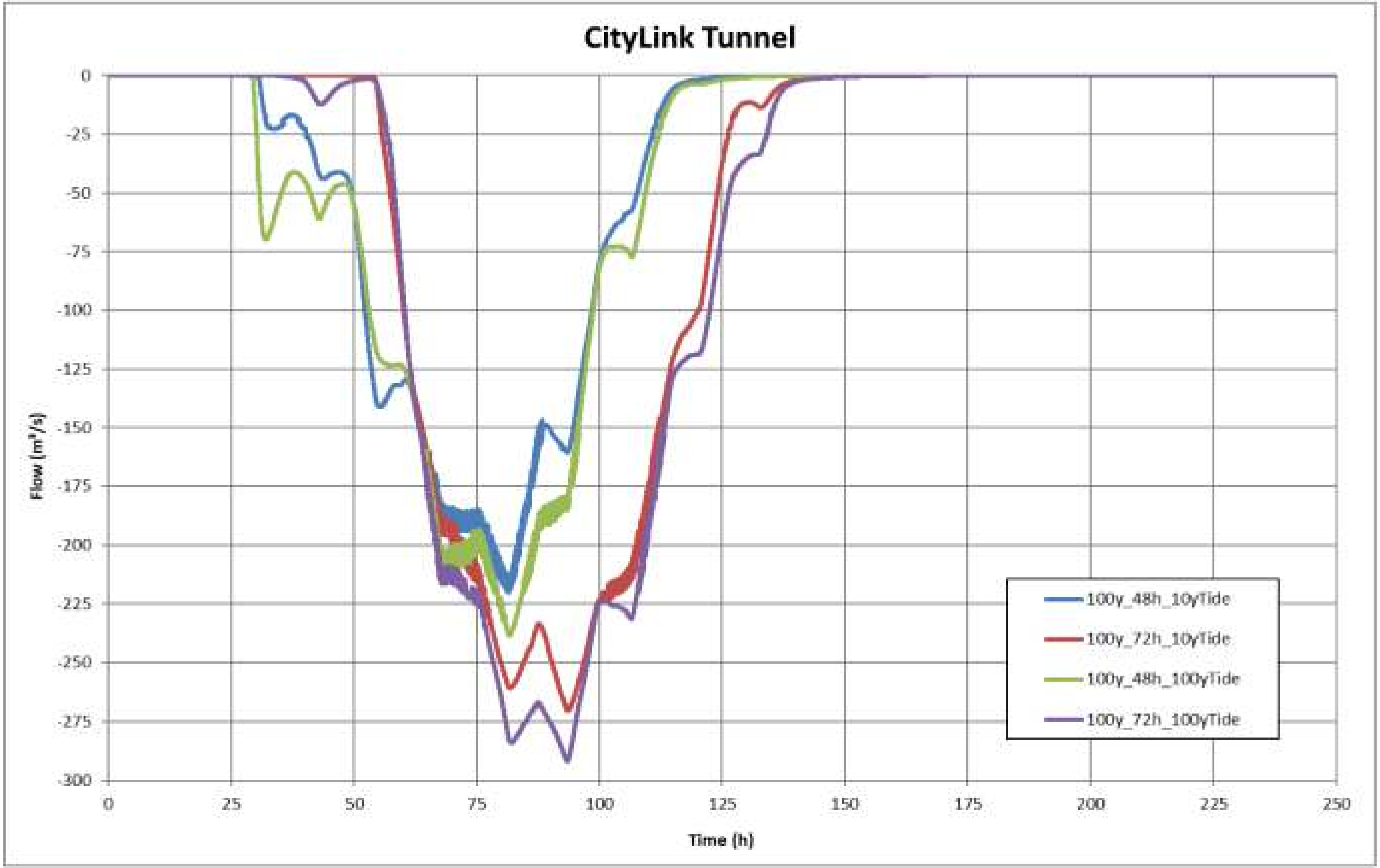


Figure 24 Phase 1 Model Refinement – City Link Tunnels Southbank Portal flows

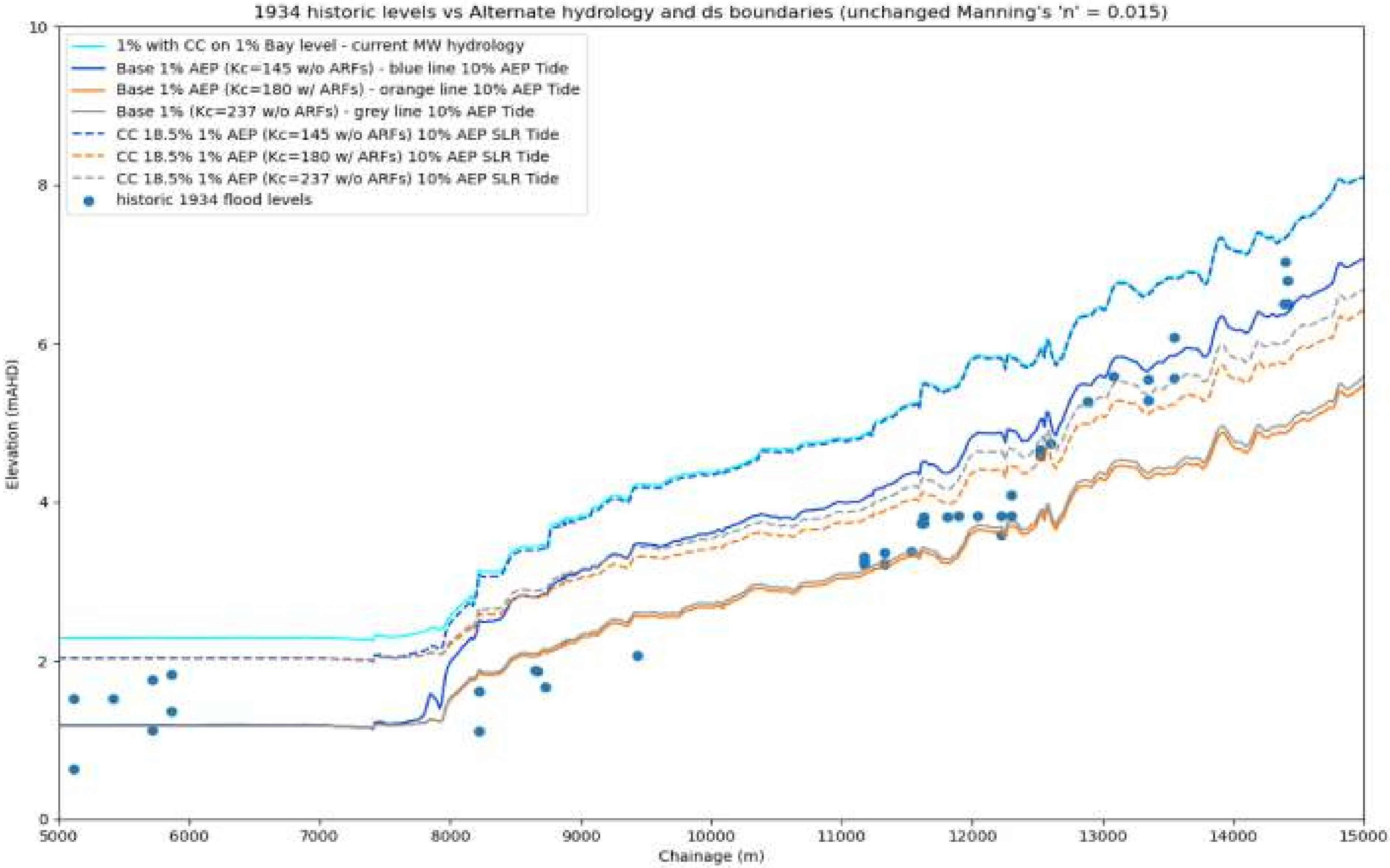


Figure 25 Phase 2 Model Refinement – Yarra River Long-Section comparison to historic levels

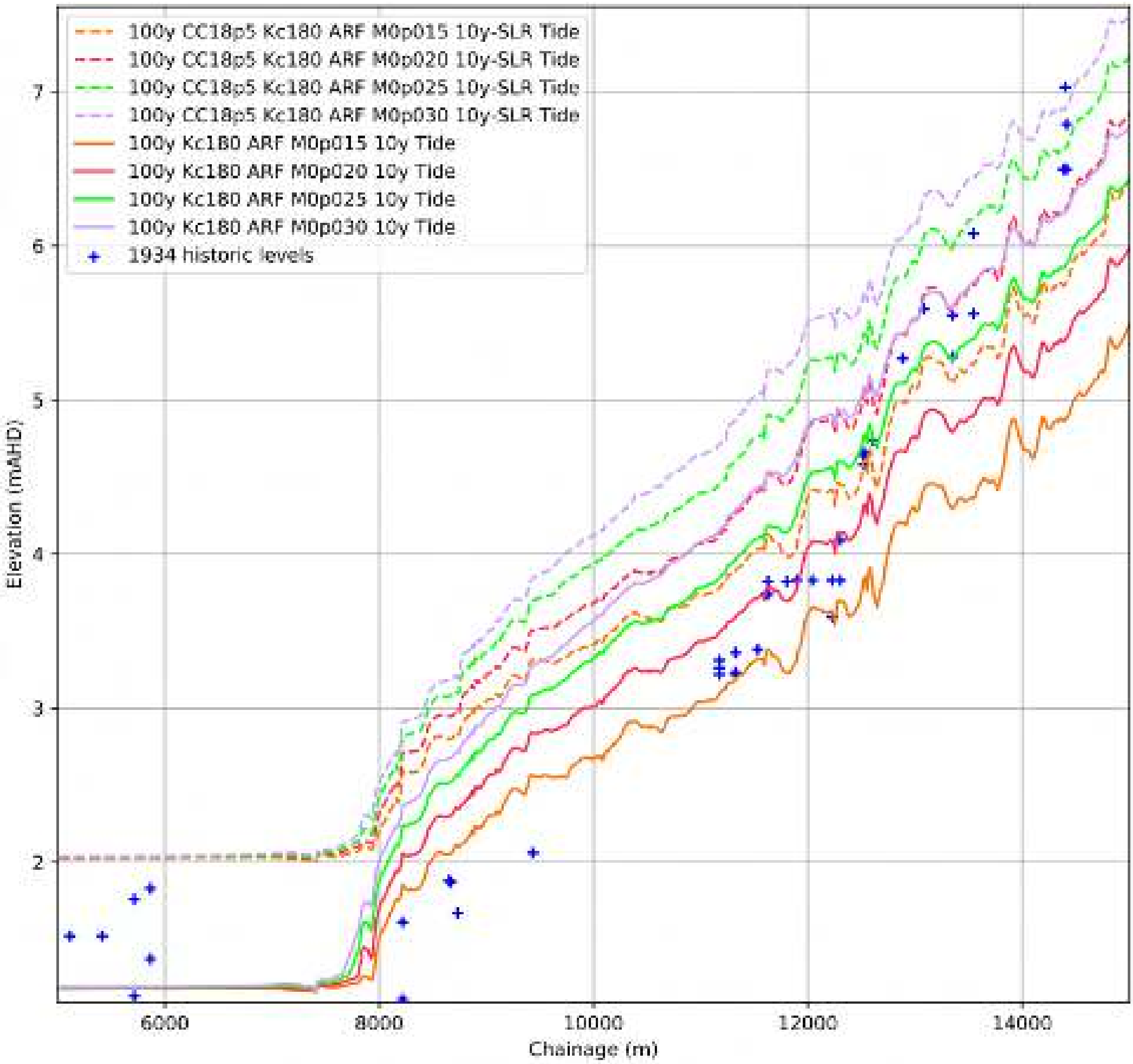


Figure 26 **Phase 3 Model Refinement – Yarra River Long-Section comparison to historic levels**

7.4 Recommendation/Conclusion

Based on the results of this phase of model refinements, it was jointly agreed that the model should be extended upstream along the Yarra River using data from an existing TUFLOW model developed for the North East Link Project (NELP) and then filling in the gap between the models. This extension of the model will remove or at the very least reduce the magnitude of potential boundary condition effects on results and facilitate a greater understanding of the impact of assumptions like the assumed roughness of the waterway over a greater distance of the Yarra River and the associated "Validation against 1934 flood levels.

For this work to take place MW would need to get approval from NELP team to utilise the 'existing conditions' model and provide GHD with details of the missing structures between the upstream limit of the Lower Yarra River model and the downstream limit of the NELP model.

8 Extension of model further up Yarra River

8.1 Modelling Overview

Based on outcomes of the Southbank Overflow model refinements, the model was extended to include the Yarra River all the way to the upstream limit of the NELP "existing conditions" model near the confluence with Plenty River. Following agreement from NELP, this process involved the following key changes:

- Extended code boundary and adding terrain sources from both models adopting grid orientation from Lower Yarra River model;
- Merge materials layers from models and create one river materials layer that allows for consistent modification of river roughness;
- Adjusting terrain modifications and any 1d elements from 'existing" conditions NELP model to suit new grid orientation;
- Modifying inflow application so that tributary inflows and subarea inflows for the Yarra River are applied incrementally with the agreed revised parameters (i.e. Kc of 180- with ARFs); and
- Adding terrain, initial conditions and structure details for the following features within the "existing conditions" NELP model or between it and Lower Yarra River models:
  - Yarra River thalweg.
  - Dights Falls (including upstream initial water level pond).
  - A preliminary representation of additional bridges and structures across the river, including:
    - Monash Freeway.
    - Chandler Highway.
    - Eastern Freeway.
    - Bridge Road.
    - Hawthorn Rail Bridge.
    - Wallen Road.
    - Heyington Rail Bridge.
    - Banksia Street
    - Main Yarra Trail (x3) and Darebin Creek Trail shared user path (SUP) bridges.
    - Fairfield Pipe Bridge.
    - Kanes Bridge
    - Johnston Street.
    - Barkers Road.

The setup of the extended model is also summarised in Figure 27, which highlights the new extent of the model and the key features/inputs of this new model.

After some initial runs, the extended model setup was tested with TUFLOW Classic and then with TUFLOW's new 'Sub-Grid Sampling' (SGS) functionality due to the apparent differences with the previous "HPC on GPU" results, as well as the historical 1934 flood levels and current MW designated levels.

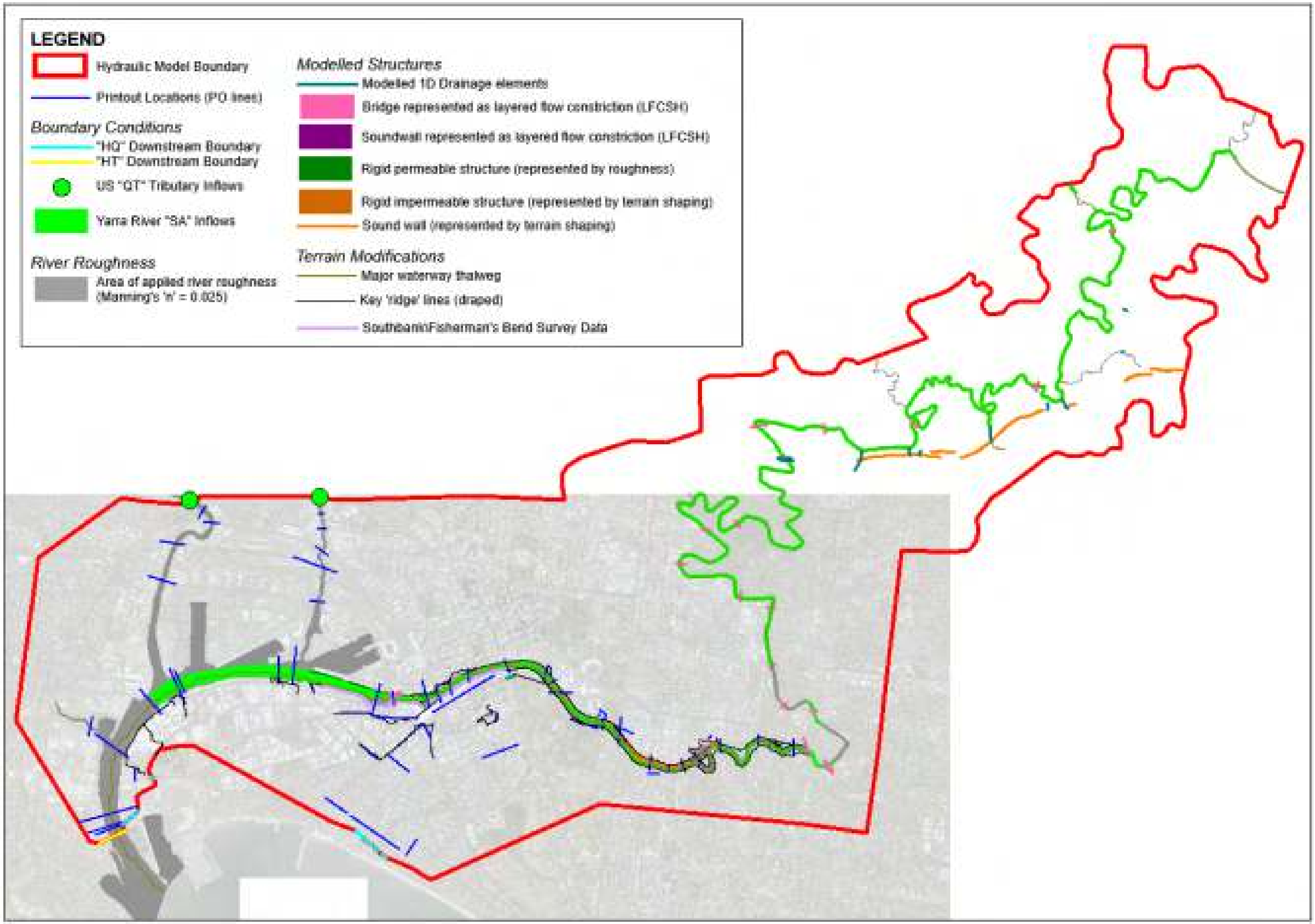


Figure 27 Extended TUFLOW Model Setup

8.2 Model Scenarios

Based on all the previous discussions and validation modelling the scenarios defined in Table 8 were ultimately run for this model configuration. A comparison of the modelled inflows and the change in downstream boundary conditions for these models are also presented in Figure 22 and Figure 23 respectively in Section 7.2. These scenarios were run in several phases as summarised in Table 8, with the scope of subsequent phases being defined based on discussion of results of the previous phase(s)

Table 8 Extended Model - Modelled Scenario Definitions

Phase	Run	*Hydrology* [1]	Yarra River Inflow (m^3/s)	Yarra River Inflow Volume (m^3)	Downstream Tailwater Level (TWL)	River Roughness (Manning's 'n')	TUFLOW Engine
1	1	*Base 1% AEP*	1091	432,000,000	10% AEP Tide	0.020	HPC (DP)
1	2	*Base 1% AEP*	1091	432,000,000	10% AEP Tide	0.025	HPC (DP)
1	3	*CC 1% AEP (18.5% increased intensity)*	1293	246,000,000	10% AEP SLR Tide	0.020	HPC (DP)
1	4	*CC 1% AEP (18.5% increased intensity)*	1293	246,000,000	10% AEP SLR Tide	0.025	HPC (DP)
2	5	*Base 1% AEP*	1091	432,000,000	10% AEP Tide	0.025	Classic
2	6	*Base 1% AEP*	1091	432,000,000	10% AEP Tide	0.025	HPC (SP)
2	7	*Base 1% AEP*	1091	432,000,000	10% AEP Tide	0.025	SGS (Default - SGS Partial Grid Update Null Frac == 0.1, 0.9)
3	8	*Base 1% AEP*	1091	432,000,000	10% AEP Tide	0.025	SGS (SGS Partial Grid Update Null Frac == 0.6, 0.6)
3	9	*Base 1% AEP*	1091	432,000,000	10% AEP Tide	0.025	SGS (SGS Partial Grid Update Null Frac == 0.1, 0.1)

Note:
[1] indicates that the Kc parameter is based on MW work prior to "2010 - SP Goh & Associates Study", but with the application of ARFs

8.3 Results and Discussion

The results of the three phases of modelling are summarised as follows:

- Phase 1
  - Results showed that model extension generally brought flood levels down relative to the smaller model, which allows for more characteristic roughness values to be utilised to see reasonable correlation with the historic levels along the full length of the model. The results also showed that the hydrology based on Kc of 180 with ARFs were generally more realistic in the TUFLOW model than the parameters adopted by MW from their recent work on the Yarra River using HECRAS as documented in Section 5. The full results are presented in Attachment 5, with the key output summarised by the long-section plot presented in Figure 28.
  - After discussing the results in detail, it was jointly agreed that the model adopting a river roughness of 0.025 should be used for a test of TUFLOW Classic engine and that the output of these runs should also be compared to those from the “HPC on GPU” run.
- Phase 2
  - Afflux results for a test model of the 1% AEP run with TUFLOW’s “Classic” engine compared to the “HPC on GPU” run are presented in Figure 29. This plot shows that the TUFLOW “Classic” results are substantially different to the “HPC on GPU” results, which raises questions over the validity of this engine for production (or design) runs given the now poor fit with historic levels.
  - After discussing the results in detail, it was jointly agreed that the model should be re-run with the new ‘Sub-grid Sampling’ (SGS) functionality – which has been shown for deeper flows relative to grid size, through benchmarking and calibration on Brisbane River, to provide greater correlation with TUFLOW Classic results than HPC alone, and more importantly, greater correlation with real world examples (flume tests and flood events). It was agreed that the “SGS” test model should adopt default settings and a sampling size of 2 m (or 1/5 of the cell size).
- Phase 3
  - The results of the “SGS” modelling is presented in Figure 30, which shows that the results with SGS enabled provide a better fit than the TUFLOW “Classic” engine results compared to the historic levels. The “SGS” levels were lower than the “HPC on GPU” runs that were used to test the hydrology, model extent and roughness – but through discussions with MW were deemed the most appropriate because it is anecdotally believed that the 1934 historic levels are higher than the 1% AEP in this area.

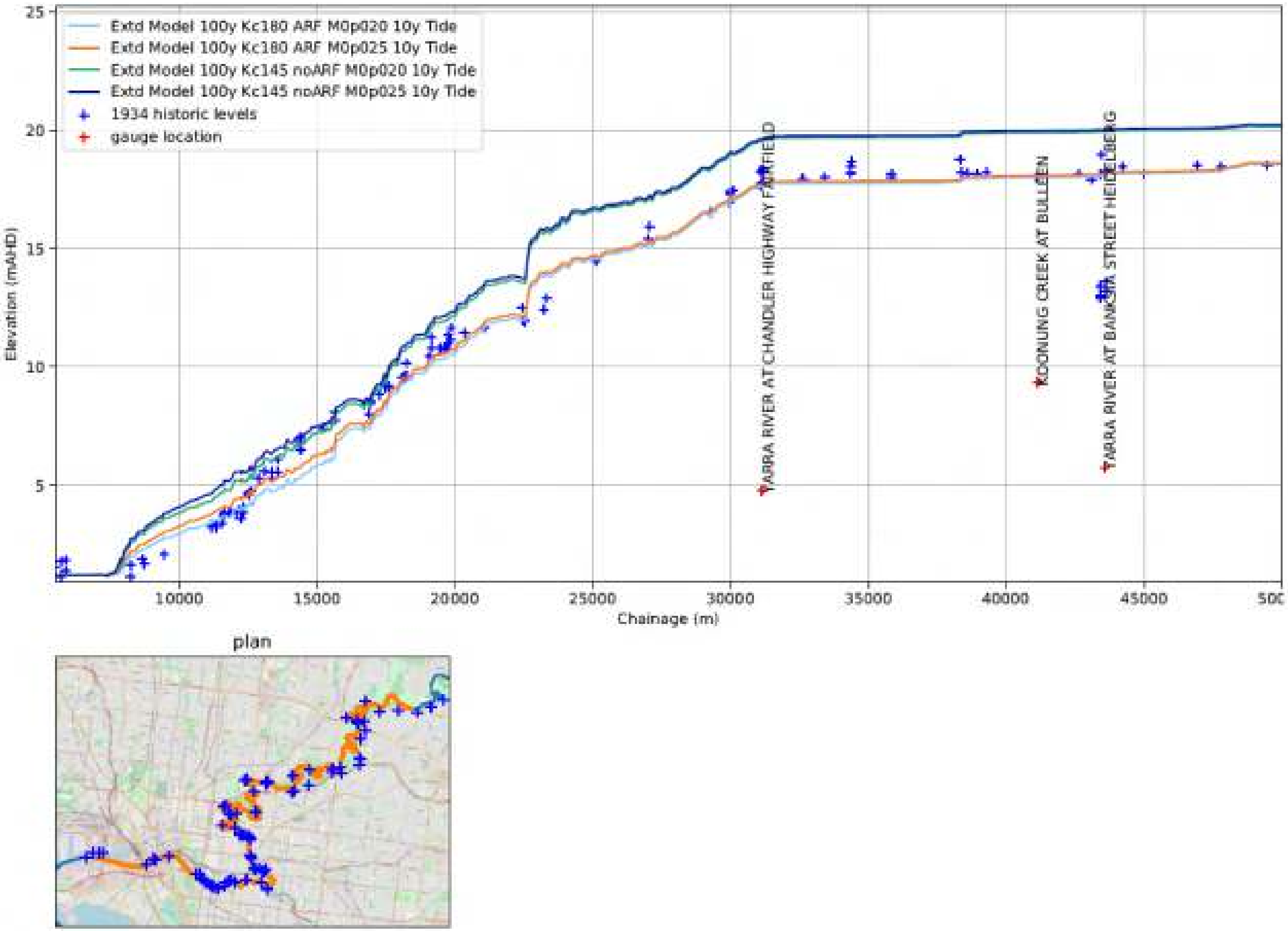


Figure 28 Phase 1 Model Extension – Yarra River Long-Section comparison of water level from various hydrologic assumptions to historic levels

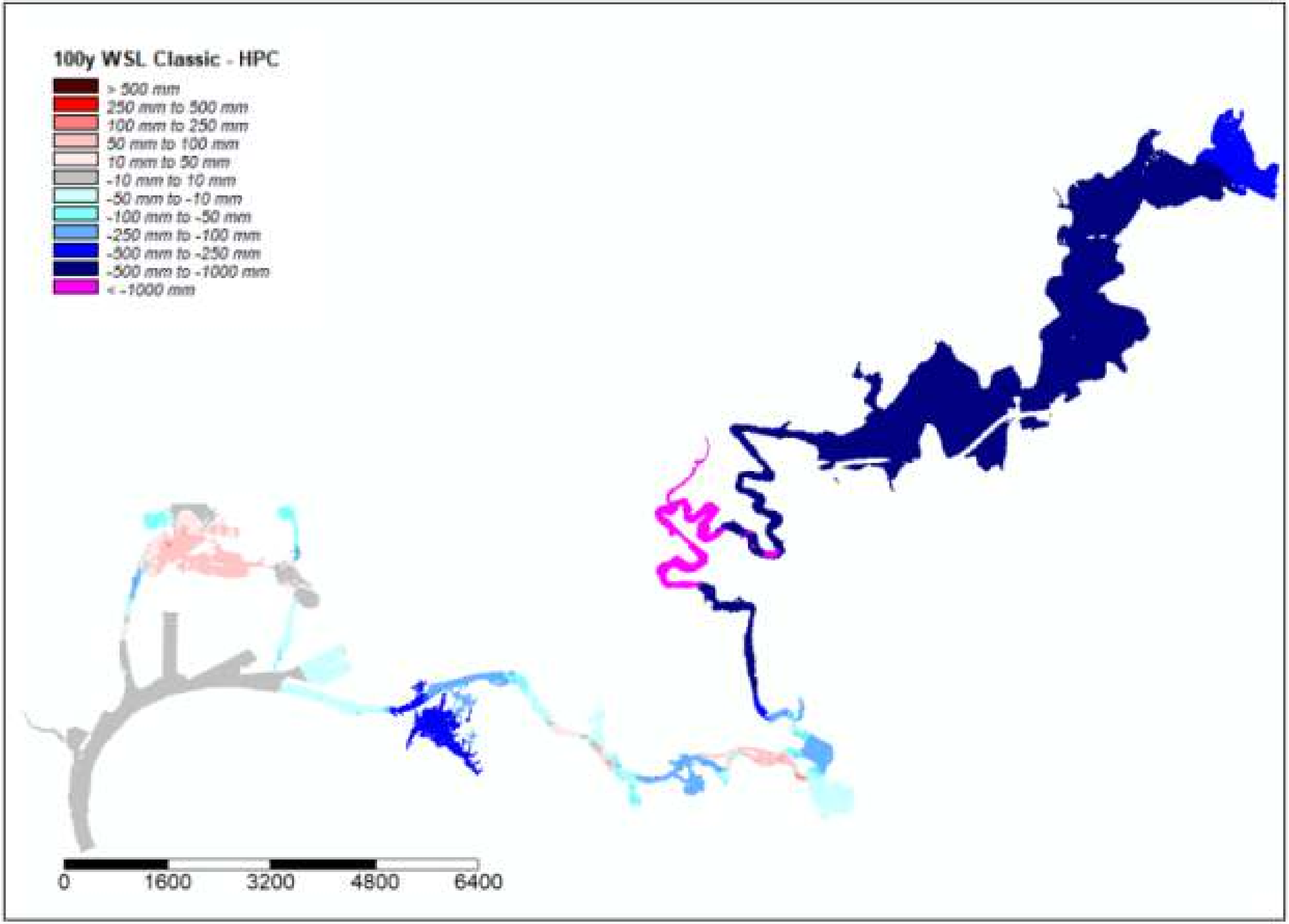


Figure 29 Phase 2 Model Extension – Afflux between TUFLOW Classic and TUFLOW "HPC on GPU"

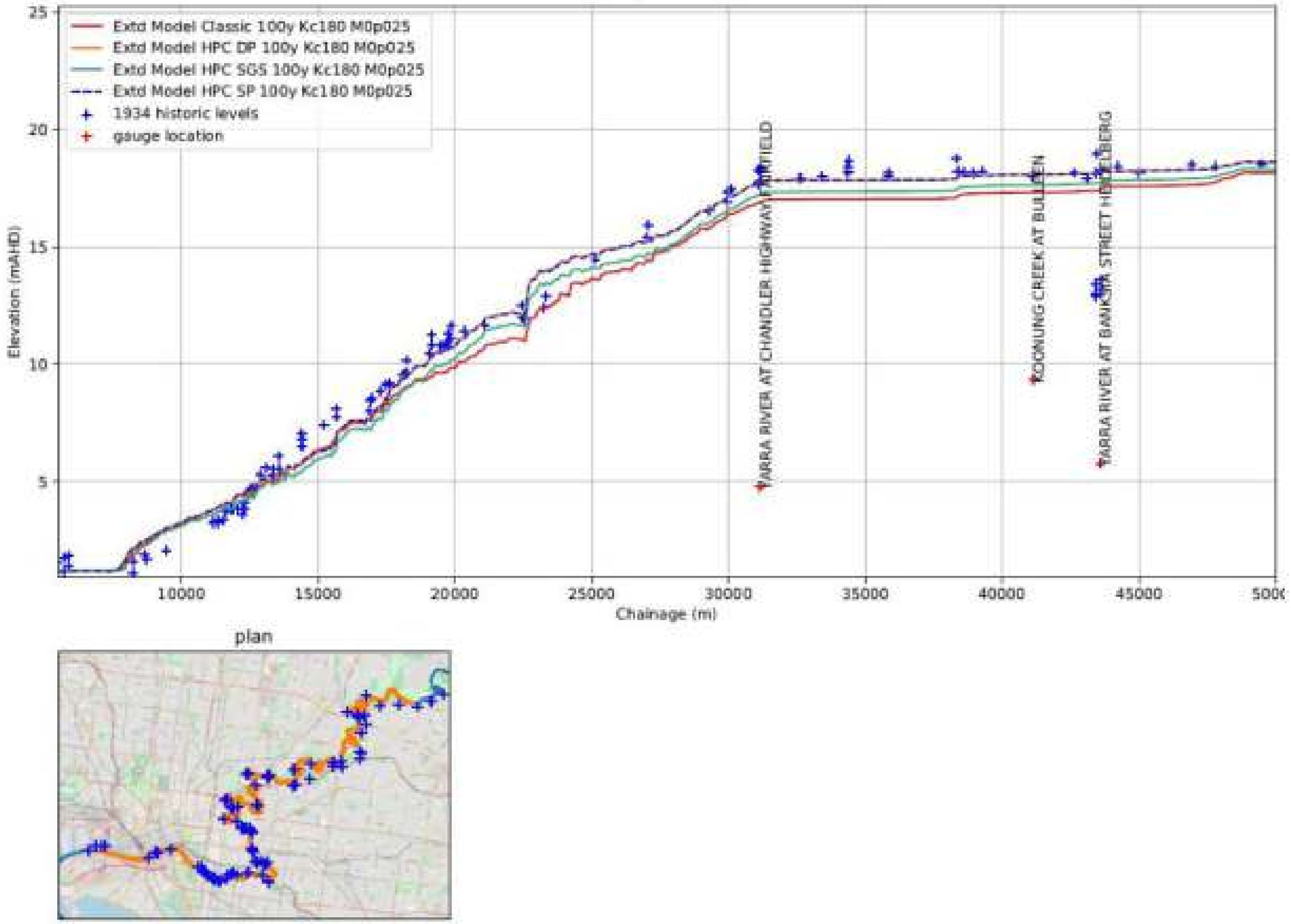


Figure 30 Phase 3 Model Extension – Yarra River Long-Section comparison of modelled flood levels with various TUFLOW engines to historic levels

8.4 Recommendation/Conclusion

Based on the results of this phase of model refinements, it was jointly agreed that following model assumptions should be used for the "design runs" for flood mapping purposes:

- Extended TUFLOW model.
- TUFLOW "HPC on GPU" engine with the SGS functionality enabled (default settings with sampling size of 2 m).
- Hydrology based on MW's previously adopted Kc value of 180 and the application of ARFs (assuming area upstream of mapping limit).
- Adopting a Manning's 'n' value of 0.025 for major waterways.
- Revised "design run" model scenarios as per Table 9, which includes altered downstream boundary conditions.

Table 9 Revised "Design Run" Definitions

Run ID	Scenario	Hydrology	TWL
1	Base Case (A)	1% AEP	10% AEP Tide
2	Base Case (A)	2% AEP	10% AEP Tide
3	Base Case (A)	5% AEP	10% AEP Tide
4	Base Case (A)	10% AEP	10% AEP Tide
5	Base Case (A)	20% AEP	20% AEP Tide
6	Climate Change 1 (CC_B)	1% AEP	10% AEP SLR Tide
7	Climate Change 2 (CC_C)	1% AEP Climate Change (18.5% increase intensity)	10% AEP SLR Tide
8	Climate Change 2 (CC_C)	5% AEP Climate Change (18.5% increase intensity)	10% AEP SLR Tide
9	Climate Change 2 (CC_C)	10% AEP Climate Change (18.5% increase intensity)	10% AEP SLR Tide
10	Climate Change 2 (CC_C)	20% AEP Climate Change (18.5% increase intensity)	20% AEP SLR Tide
11	Climate Change 3 (CC_D)	1% AEP Climate Change (18.5% increase intensity)	10% AEP Tide
12	Climate Change 3 (CC_D)	10% AEP Climate Change (18.5% increase intensity)	10% AEP Tide
13	Climate Change 3 (CC_D)	20% AEP Climate Change (18.5% increase intensity)	20% AEP Tide

9 Final Design Run Developments

Based on outcomes of modelling discussed in Section 8, GHD commenced design run modelling with the agreed setup and upon processing results found that the default 'SGS' settings resulted in the '2DM' having some holes in it that prevented results being recorded at a number of locations across the model. With agreement from MW, the model files were sent to TUFLOW Support who agreed there was an issue and recommended that we adjust the default settings of how the 'SGS' functionality treats partially covered cells using the "SGS Partial Grid Update Null Frac" command in the *.tgc file. This command is explained in 2020 TUFLOW Release Notes, but in essence tells TUFLOW what to do with cells only partially covered by the terrain model (or DEM) being processed, with the two numbers representing a lower and upper bound for the null fraction (i.e. the fraction of cell not covered by the DEM currently being processed). The 'SGS' function does the following based on these numbers (extracted from 2020 TUFLOW Release Notes – BMT, 2020):

- *"If the null fraction is below the lower limit, TUFLOW applies the values from the new DEM";*
- *"If the null fraction is between the lower and upper limits, update the null value from current ZC ZU ZV and ZH values. "the cell are interpolated from current Zpts (ZU, ZV, ZH & ZC)";* and
- *"If the null fraction is higher than the upper limit, do not update the Zpt."*

As part of their investigation into the issue TUFLOW Support indicated that the default values of "0.1,0.9" for the "SGS Partial Grid Update Null Frac" command should be altered to either of the following depending on what terrain source we wanted to take priority:

- "0.6,0.6" – this would give preference to elevations from earlier read in terrain sources; or
- "0.1,0.1" – this would give preference to elevations from the terrain source currently being processed.

The following is a summary of our approach and initial thoughts on the most appropriate approach to adjusting the default settings for the "SGS Partial Grid Update Null Frac" command as described above:

- Our initial thoughts were to adopt the "0.6, 0.6" on the basis that it favoured the last read in terrain, which reflects the inherent confidence in that terrain selected during the model build. This showed the afflux in Figure 31 and Figure 32 for the terrain and WSL respectively.
- Given the afflux from above models and the fact that this is a new and untried functionality - we then tested the other approach (values of "0.1, 0.1") to understand the implications on the results. This showed the afflux in Figure 33 and Figure 34 for the terrain and WSL respectively.
- Upon reviewing the results and some reflection we then favoured the "0.1, 0.1" approach because the differences stem from changes in terrain at the interfaces of the terrain sources and the biggest area of change is that between the LiDAR and bathymetry. The interface between the LiDAR and bathymetry is typically high on the river bank, which is generally well covered by LiDAR and actually likely to be more representative when you consider the bathymetry terrain was largely formed from cross section data that has outer banks represented by a sparse set of points relative to LiDAR data points in this area.
- It was also noted that both changes to default settings increase the water level within the Yarra River and hence improve correlation with our understanding of the 1% AEP levels compared to the historic 1934 flood levels, but the "0.1,0.1" set seemed to provide the best fit.

After discussing the results with MW, it was decided that the design runs should adopt the "0.1,0.1" setting for the "SGS Partial Grid Update Null Frac" command.

Unfortunately, some of the other design runs not used in the sensitivity testing phase described above went unstable with this parameter set at various points within the model run – sometimes in the initial tidal wetting phase and others part way into the modelled storm event. Given that this wasn't occurring in all runs and a quick review of TUFLOW's interpretation of the terrain didn't identify any major concerns, it was agreed with Melbourne Water that the "0.6,0.6" setting for the "SGS Partial Grid Update Null Frac" command could be used instead. This was tested with the problematic design runs and these runs ran through to completion with no problematic errors to report – and was hence adopted for the final design runs.

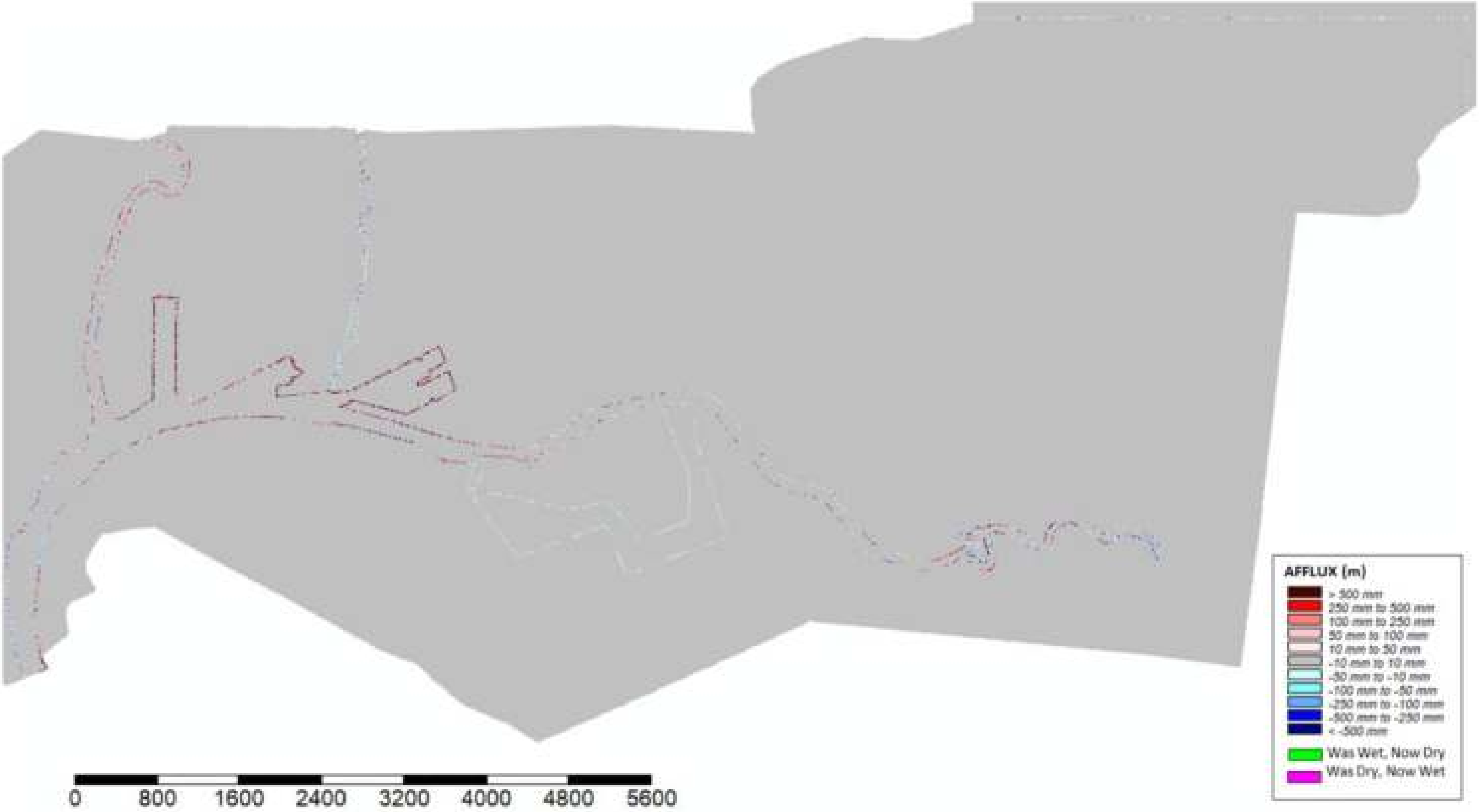


Figure 31 Terrain Difference: 'SGS w/ last read in terrain preferenced on partially covered cells (SGS Partial Grid Update Null Frac = 0.6,0.6)' minus 'SGS w/ default settings on partially covered cells (SGS Partial Grid Update Null Frac = 0.1,0.9)'

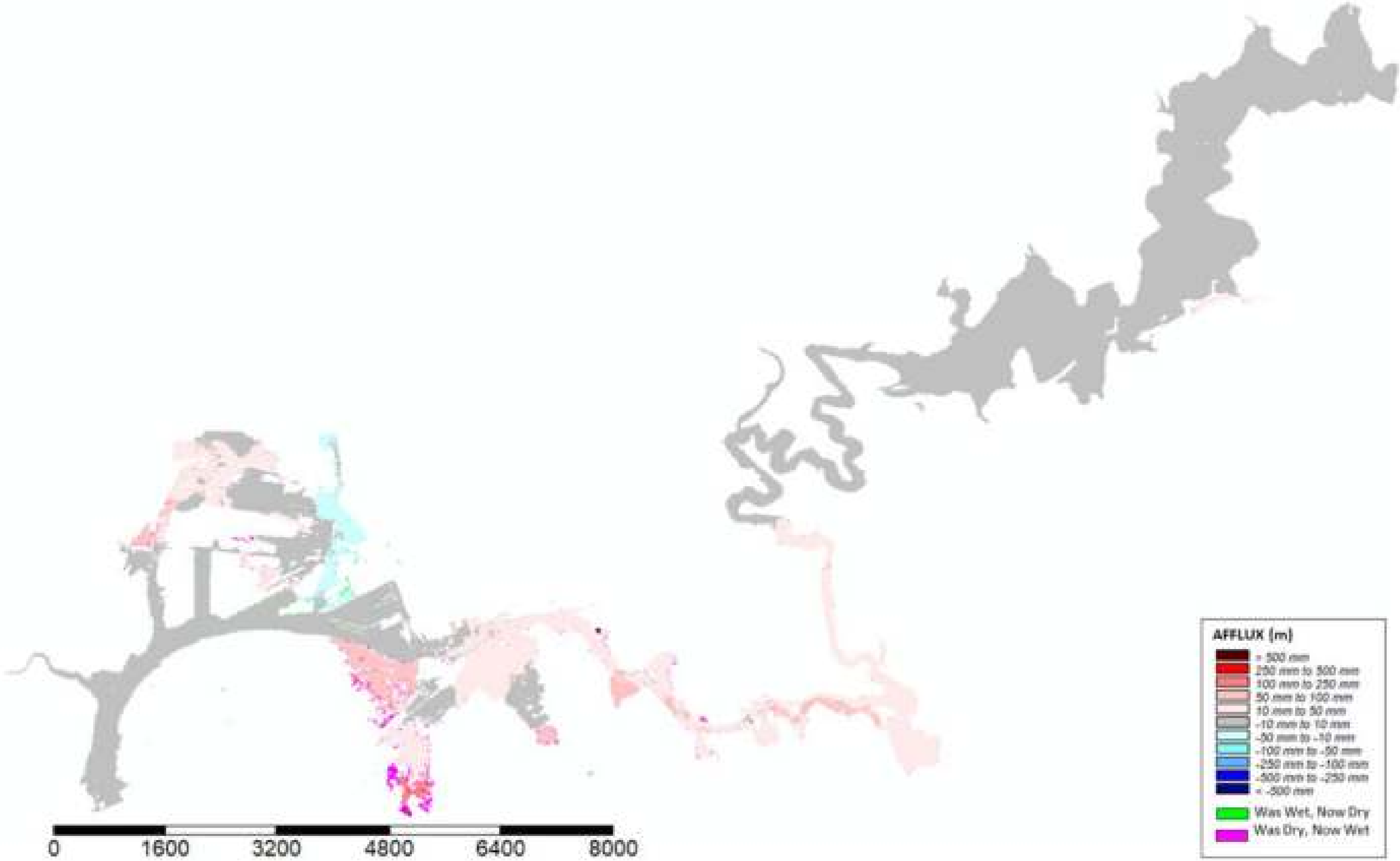


Figure 32 **WSL Afflux: 'SGS w/ last read in terrain preferenced on partially covered cells' minus 'SGS w/ default settings on partially covered cells'**

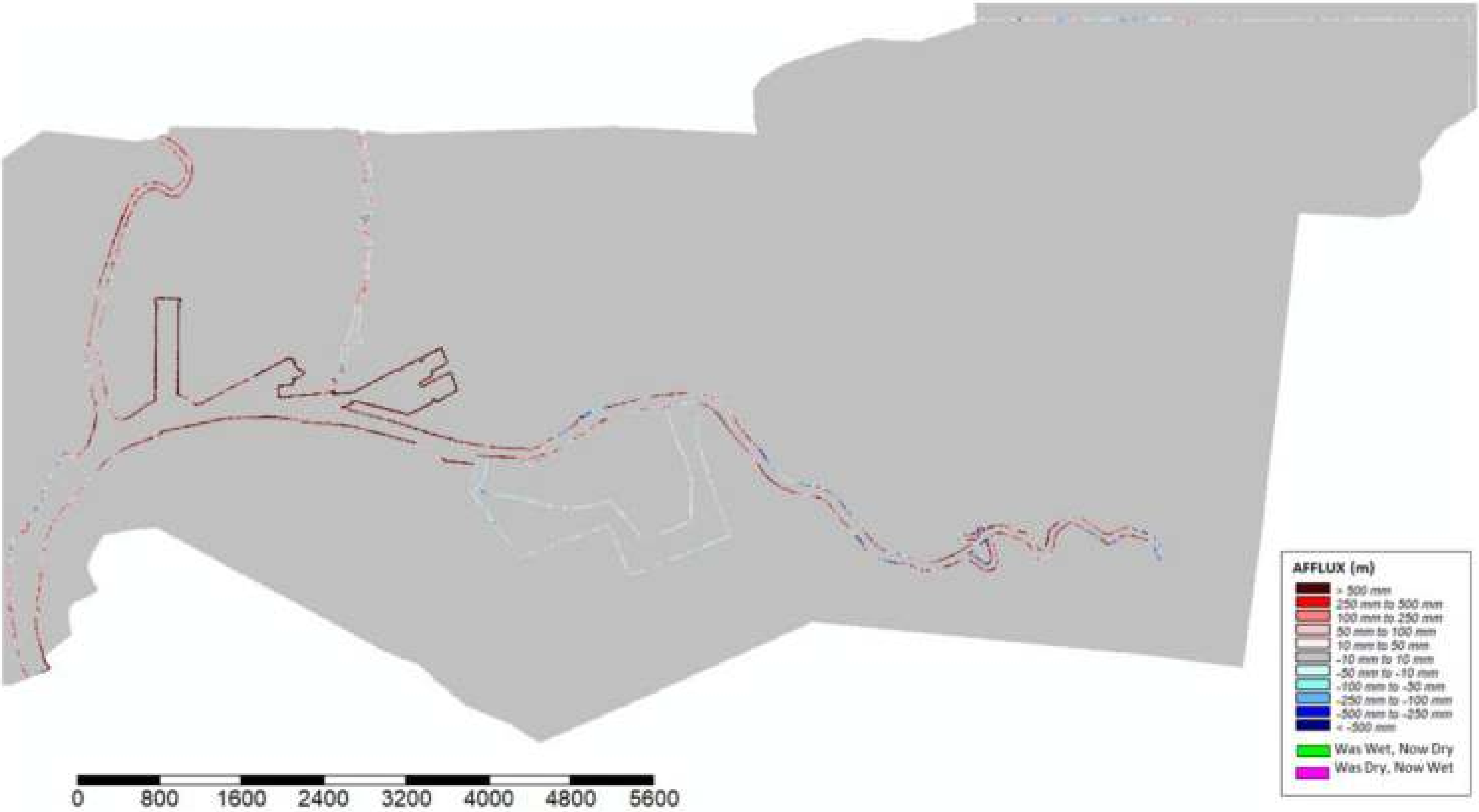


Figure 33 Terrain Difference: 'SGS w/ earlier read in terrain preferenced on partially covered cells (SGS Partial Grid Update Null Frac = 0.1,0.1)' minus 'SGS w/ default settings on partially covered cells (SGS Partial Grid Update Null Frac = 0.1,0.9)'

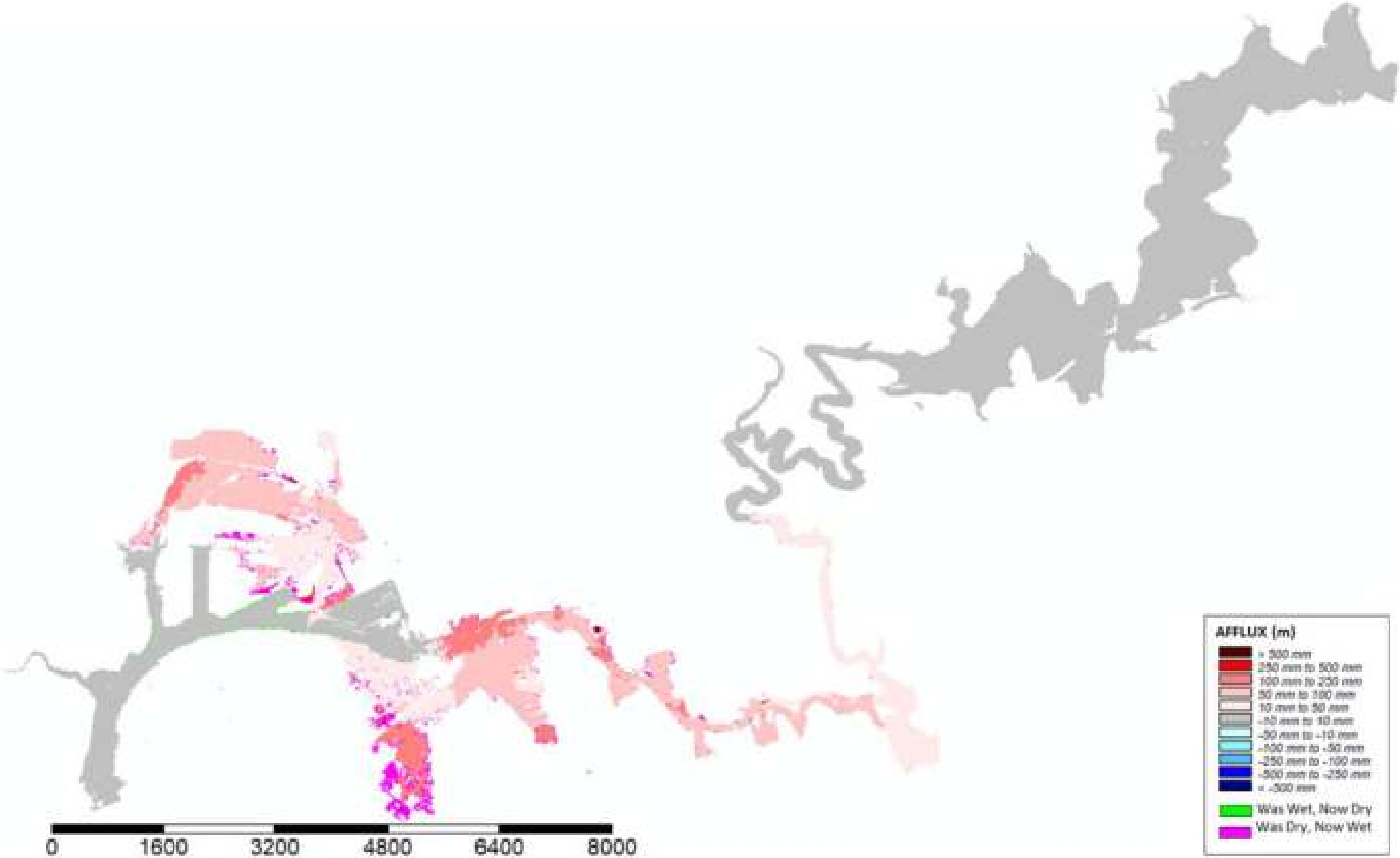


Figure 34 WSL Afflux: 'SGS w/ earlier read in terrain preferenced on partially covered cell' minus 'SGS w/ default settings on partially covered cells'

10 Conclusion

Based on the outcomes of this modelling, it was agreed that the following parameters should be used for the final "design run" models:

- Adopt provided MWC hydrologic models with assumptions as per Table 10
- Adopt final model setup as per Figure 27 in Section 8, with a Manning's 'n' roughness of 0.025 for the major waterway areas.
- Adopted TUFLOW "HPC on GPU" engine with sub-grid sampling (SGS) functionality enabled with the following settings as confirmed in Section 9:
  - "SGS Sample Distance == 2" – a command that sets the sub-grid sampling to a size of 2 m.
  - "SGS Partial Grid Update Null Frac == 0.6, 0.6" – a command that stipulates how terrain is to be treated for partially covered cells. These parameters are reduced from defaults of "0.1, 0.9" to remove holes from DEM and give preference to terrain from the later terrain sources as indicated by TUFLOW Support. This was required as prioritising earlier data sources (our original preferred approach) resulted in some model runs becoming unstable.

Table 10 Hydrologic Assumptions

Model	Yarra River	Maribyrnong River
RORB Version	6.45	6.45
Rainfall	Stormfiles with variable IFD (adjusted version of those adopted from 2016 Yarra River Study area due to application of ARFs)	ARR1987 IFD @ inbuilt "Keilor" location
ARF	Yarra catchment area (Assumed area = 3,870 km²)	Yarra catchment area (Assumed area = 3,870 km²)
Kc	180 (MW assumed value prior to 2016 Yarra River Study)	70
m	0.8	0.8
IL (mm)	Varies with interstation area: • YarRv@YarGlen-DummyGS = 30 • Catchment outlet = 15	20
Runoff Coefficient	Varies with ARI: • 100y = 0.60 • 50y = 0.55 • 20y = 0.50 • 10y = 0.45 • 5y = 0.40	Varies with ARI: • 100y = 0.6 • 50y = 0.55 • 20y = 0.45 • 10y = 0.35 • 5y = 0.25
Climate Change	Factored rainfall in stormfiles by 1.185 to represent 18.5% increase as per latest Tech Spec	Adjusted IFD parameters to increase rainfall intensity by 18.5%

Regards

Peter Woodman
Senior Environmental Engineer
61 3 8687 8351

References

BMT (2020). TUFLOW Classic & HPC 2020-01 Release Notes. BMT, May 2020.

Attachments:

- *Attachment 1* Fax from MWC regarding Yarra River dredging profile from City Link crossing work in 1996.
- *Attachment 2* Advice from MWC regarding timing of tide relative to timing of Yarra River flows
- *Attachment 3* Email train regarding initial design run assumptions (final email dated 6/9/2019).
- *Attachment 4* Phase 1 Southbank Overflow Refinement Results Memo
- *Attachment 5* Phase 2 Southbank Overflow Refinement Results Memo
- *Attachment 6* Phase 3 Southbank Overflow Refinement Results Memo
- *Attachment 7* Phase 1 Model Extension Results Memo

Attachment 1

Fax from MWC regarding Yarra River dredging profile from City Link crossing work in 1996.

ACER/CMP JV - MCL Project			
Date 17/10/95		Recorded	
File		Doc IS-1233	
M ... CO	Action	Initial	Date
RW	AI	RW	17/10
AM	A.		
A – Action I – Information		Entered	

copy to M.M TQS

FAX DATE: October 17, 1995 **TIME:** 11:25 AM

TO: Tony Schependonk, Angus Mitchell, Acer/CMP Joint Venture — **PHONE:** 9272 6666 **FAX:** 9272 0300

FROM: Michael Brown, Waterways & Drainage — **PHONE:** 9615 4014 **FAX:** 9615 4003

RE: Yarra Crossing, Cut and Cover Tunnel

With regard to your request for details of Melbourne Water's requirements for Yarra River cross sections in the reach of the tunnel crossings, I advise as follows:

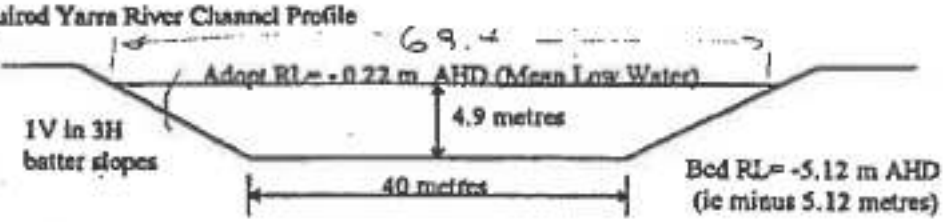
- the requirements provided in Melbourne Parks and Waterways letter of 6 January 1995 are supported as the dredging profile provides a depth and waterway profile that will ensure the river can pass a 1 in 100 year flood event below the adopted 1% AEP Flood Levels in this area. It also provides a channel form that meets operational requirements and provides for better riverbank stability.

- Flood levels for this reach of the river are based on the actual flood event resulting from the storm of November/December 1934. At the time of this flood, the subject reach of river had been modified to the channel form known as the "botanical gardens cut" as recommended by the "Yarra Floods Board" in 1892. The realignment, widening and deepening of the river was carried out in the late 1890's. When the MMBW became responsible for Metropolitan drainage in 1924, it undertook further improvement works to improve the flood carrying capacity of the Yarra River. MMBW survey and design cross section dated 1929/30 indicate the design channel and siltation that had occured at that time. The design cross sections represent Melbourne Water's minimum requirements for hydraulic performance and consists of a trapezoidal shape with a depth of 16 feet (4.9 metres) below the low water mark. covered

- The Flood levels for the 1934 flood between Morell Bridge (downstream side) and Swan Street Bridge (upstream side) are 3.26 and 2.75 metres AHD respectively.

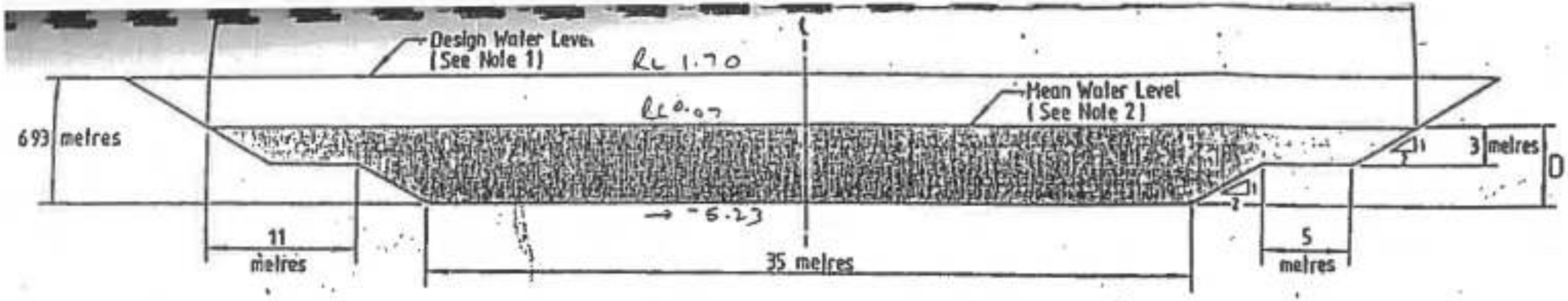
- Hydraulic modelling for the tidal reaches of the Maribyrnong River, by Consultants associated with Monash University, has indicated that scouring of the bed occur during high flows. River bed survey, at that time, confirmed these findings. A Value Management Study of "Dredging in the Yarra and Maribyrnong Rivers" in 1989 supported the view that scouring during flood events creates adequate flow capacity, and consequently the dredging operation was suspended, in the short term, pending hard data concerning sediment deposition and scour rates. Dredging currently occurs for navigational purposes and the aesthetic amenity of the river. Monitoring of the river silt levels is being undertaken by Melbourne Parks and Waterways. Maintaining the design cross section will ensure the capability of the river channel passing a 1% flood event with no increase in the designated flood levels.

- Required Yarra River Channel Profile



I advise that the channel profile shown above is Melbourne Water's minimum requirement. The river will silt up from time to time but during a major flood, the river will scour this silt away down to at least our minimum profile.

M Brown
17/10/95



REACH OF RIVER	DIMENSIONS (Metres)	
	D	W
Spencer St. Bridge to Princes Bridge	6·2	70
Princes Bridge to Swan St. Bridge	5·8	68
Swan St. Bridge to Hoddle Bridge	5·3	66 ✓

DWL. (20yr)

1.70

NOTE:

1. The Design Water Level is the level reached by a flow of 710 cumecs (This flow is based on the 1923 flood and is estimated to have a 1 in 20 year frequency of recurrence.)

2. The Mean Water Level is R.L. 0·07 metres A.H.D. (This level is derived from records of M.M.B.W. tidal gauges at Hanna St. M.D. outlet and at Burnley Depot.)

APPENDIX 3

TRACED	PLANS	MELBOURNE AND METROPOLITAN BOARD OF WORKS	SCALE NOT TO SCALE
CHECKED		ENGINEERING BRANCH — DRAINAGE DIVISION	DRAWING NO.
GROUP LEADER	F.B. / L.B. / FILE NO.	YARRA RIVER (LOWER)	4400/YRD
SECTION ENGINEER	DESIGNED / DRAWN	PROFILE FOR DREDGING	1

Attachment 2

Advice from MWC regarding timing of tide relative to timing of Yarra River flows

Peter Woodman

From: [redacted]
Sent: Thursday, 18 April 2019 4:22 PM
To: Nathan Lindner
Cc: [redacted]
Subject: RE: Lower Yarra Tidal Curves

Hi Nathan

With regards to your email. If the approach suggested gives the right outcome then happy for you to adopt it.

For the extended time series of tide data, the extended time series used in the Skye Karingal flood mapping project can be adopted for this project.

Regards

[redacted]

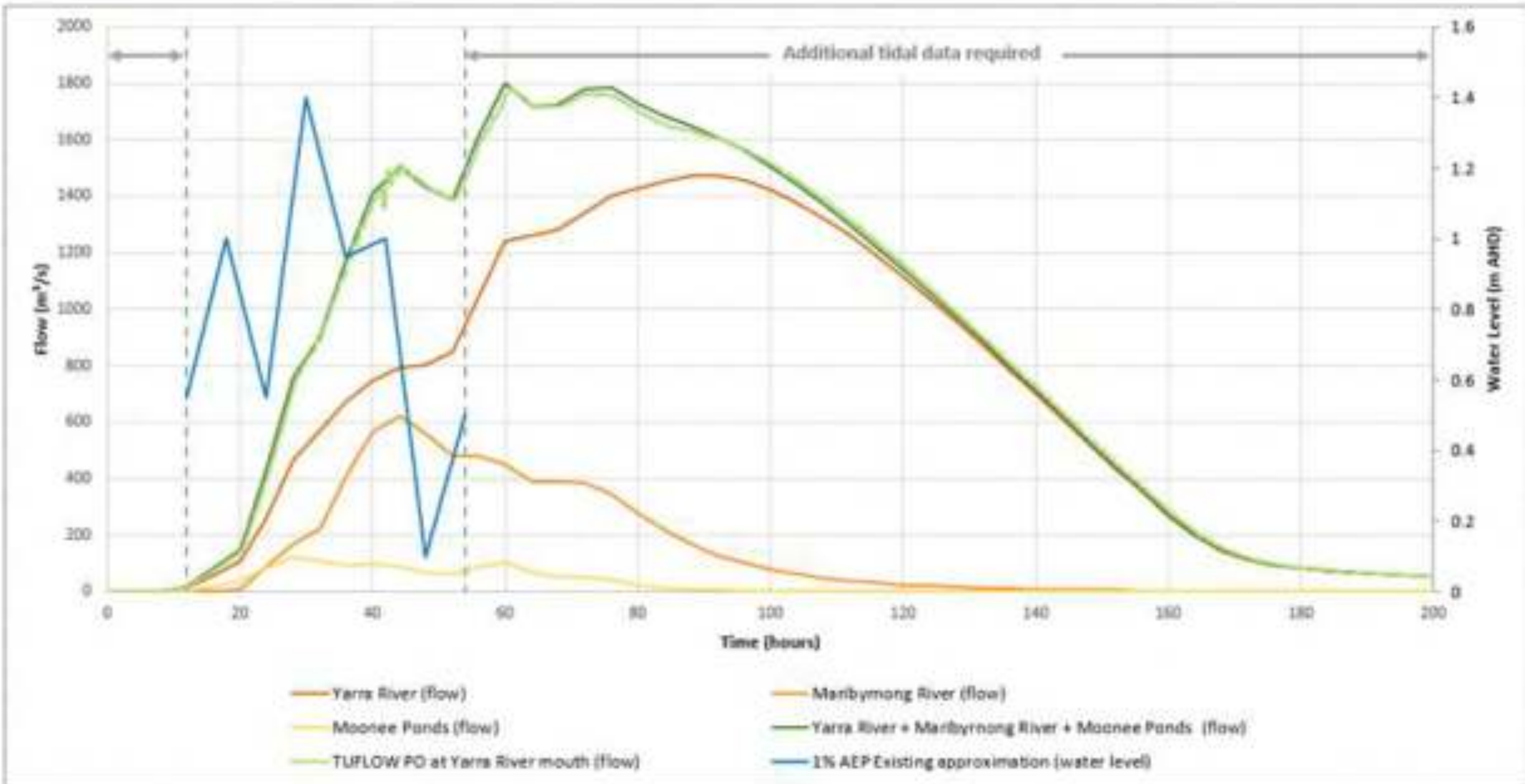
[redacted]
Asset Practitioner - Mapping and Modelling Engineer, Flood Information, Asset Management Services, Service Delivery Group | **Melbourne Water**
T: [redacted] | e[redacted]
990 Latrobe St, Docklands 3008 | PO Box 4342 Melbourne VIC 3001 | melbournewater.com.au

Enhancing Life and Liveability.

From: Nathan Lindner [mailto:Nathan.Lindner@ghd.com]
Sent: Thursday, 18 April 2019 1:13 PM
To: [redacted]
Cc: [redacted]
Subject: RE: Lower Yarra Tidal Curves

Hi [redacted],

From [redacted] email below it appears he is suggesting that we shift our tide curve (the one developed by Water Tech and simplified by us) so that the peak occurs 30 hours into the simulation, and either side of this tide curve adopt some 'typical' tidal curve. I've produced a figure below to show what this would look like compared to flow hydrographs.



Would you be happy for us to proceed with this approach? If so, could you please provide an extended time series of tide data for us to derive a 'typical' tide curve to be adopted either side of the peak tide curve?

As mentioned in the previous email, derivation of a typical tidal curve is outside the current scope based on previous discussion (see extract from Progress Meeting 1 minutes below). In the variation to complete the dredged profile modelling we allowed $784 to determine the peak tidal boundary and will likely spend this amount again to derive the typical tidal curve. Due to the small magnitude of the cost we won't request a variation for this at this stage but may include it in a future variation should one be required.

Minutes	Outcome/Action
Downstream boundary conditions and location	
• GHD reiterated that approach was to have single downstream boundary along bay with matching IWL. Boundary will be either fixed TWL or tide curve as supplied by MWC	MWC agreed with approach

If you would like to discuss please call either Pete Woodman or myself.

Regards

Nathan Lindner
Civil Engineer – Water Resources

GHD
T: +61 3 8687 8205 | V: 318205 | E: nathan.lindner@ghd.com
180 Lonsdale Street, Melbourne VIC Australia 3000 | http://www.ghd.com/
WATER | ENERGY & RESOURCES | ENVIRONMENT | PROPERTY & BUILDINGS | TRANSPORTATION

From: [redacted]
Sent: Monday, 25 March 2019 11:28 AM
To: [redacted]
Cc: Gavin Hay <Gavin.Hay@ghd.com>; Peter Woodman <Peter.Woodman@ghd.com>; Nathan Lindner <Nathan.Lindner@ghd.com>
Subject: RE: Lower Yarra Tidal Curves

[redacted]
For discussion.

What GHD have proposed in Figure 2 is also in line with the tide cycle from 2014 at Williamstown. (With timing about the same as in the word document above.)

Extending the tide cycles as was done for Skye Karingal in Figure 3 would be perfectly acceptable.

However, there could be some discussion on starting time for the rainfall event and tide cycle.

Reportedly from Adams Report "Tide Levels During the November 1934 Flood Event and High Tide Frequency Analysis for Williamstown" (1987), peak tide level occurred at 9pm on 30th November.

If we look at the 1934 hydrograph at Johnson Street for the Yarra, 30% flow would have been about 33 hours into the rainfall event.

Without getting too precise about travel times, given the difficulty anyway of the probability of events lining up, it might be prudent to add some tide cycles to the start of what GHD propose, more in line with their figures 1a and 1b below.

The rise time for the combined GHD hydrographs is quicker than the 1934 hydrograph, and 30% flow occurs after about 26 hours. Maybe, say peak tide at about 30 hours after rainfall starts.

Have a think and we can all decide between us.

[redacted]

[redacted] Technical Lead, Catchment Strategies and Services, Waterways & Land Service Delivery Group| **Melbourne Water**
990 Latrobe Street, Docklands, VIC 3008 | PO Box 4342 Melbourne VIC 3001 | www.melbournewater.com.au

Enhancing life and liveability

From: Nathan Lindner [mailto:Nathan.Lindner@ghd.com]
Sent: Friday, 22 March 2019 5:36 PM
To: [redacted]
Cc: [redacted] Gavin Hay; Peter Woodman
Subject: Lower Yarra Tidal Curves

Hi [redacted]

In regards to the tidal curve to be applied at the downstream end of the Lower Yarra model, we have received Water Tech modelled tidal data for 1% and 10% AEPs for both existing and 'sea level rise' (SLR) conditions. Given we are running 1%, 5% and 20% AEP events, we need to manipulate this data to approximate 1%, 5% and 20% AEP tidal curves for the length of our model runs (approximately 250 hours). Our proposed approach is as follows:

1. Simplify this data for input into TUFLOW by creating triangular curves approximating the Water Tech modelled data (refer **Figure 1a** and **Figure 1b**)
2. Set the above simplified curve to start this tidal curve at the beginning of the TUFLOW simulation to avoid the peak tide level coinciding with the peak of the hydrograph and the associated joint probabilities of this occurring (refer **Figure 2**)
3. Shift the simplified tidal curve vertically (in elevation) by an amount to make the peak level equal to that specified in Table B2 in the Tech Spec (Nov 2016) for a given AEP and scenario (i.e. existing conditions or some climate change scenario) - the base tidal curve and relevant levels to shift peak levels to are shown in **Table 1**. Alternatively, should we adopt advice regarding tidal curves in Appendix R of current Tech Spec (Nov 2018) – this indicates that we should adopt curves as is and shift by different amounts?
4. Extend the adopted curve from step 3 with a 'typical' tidal relationship for times outside the bands of the Water Tech modelled data (the Water Tech modelled data covers ~40 hours only, while the TUFLOW model runs for up to 250 hours) (refer to **Figure 2** and example in **Figure 3**)

Currently the above data manipulations are out of scope but given the lack of a ready-to-go tidal curve to apply in TUFLOW, these manipulations are likely necessary. Would Melbourne Water like to internally develop tidal curves for use or shall GHD provide a fee estimate for this?

If Melbourne Water would like to us proceed with this approach, then with reference to the numbered items above:

1. Are Melbourne Water happy for us to proceed with the approximation of the Water Tech modelled tidal data shown in **Figure 1a** and **Figure 1b** (this assumes 6 hours between high and low tide)?
2. Are Melbourne Water happy with starting the approximated Water Tech curves at the start of the TUFLOW model run?
3. Are Melbourne Water happy with the previously agreed tidal vertical shifts (in elevation) in Table 1 or should we adopt new guidance in Tech Spec from Nov 2018?
4. Are Melbourne Water able to provide tidal data for an extended period so that a typical tidal curve can be developed and adopted?

If you would like to discuss please feel free to call either Peter, Gavin or myself.

Figure 1a. Approximation of 1% AEP Water Tech modelled tidal curves

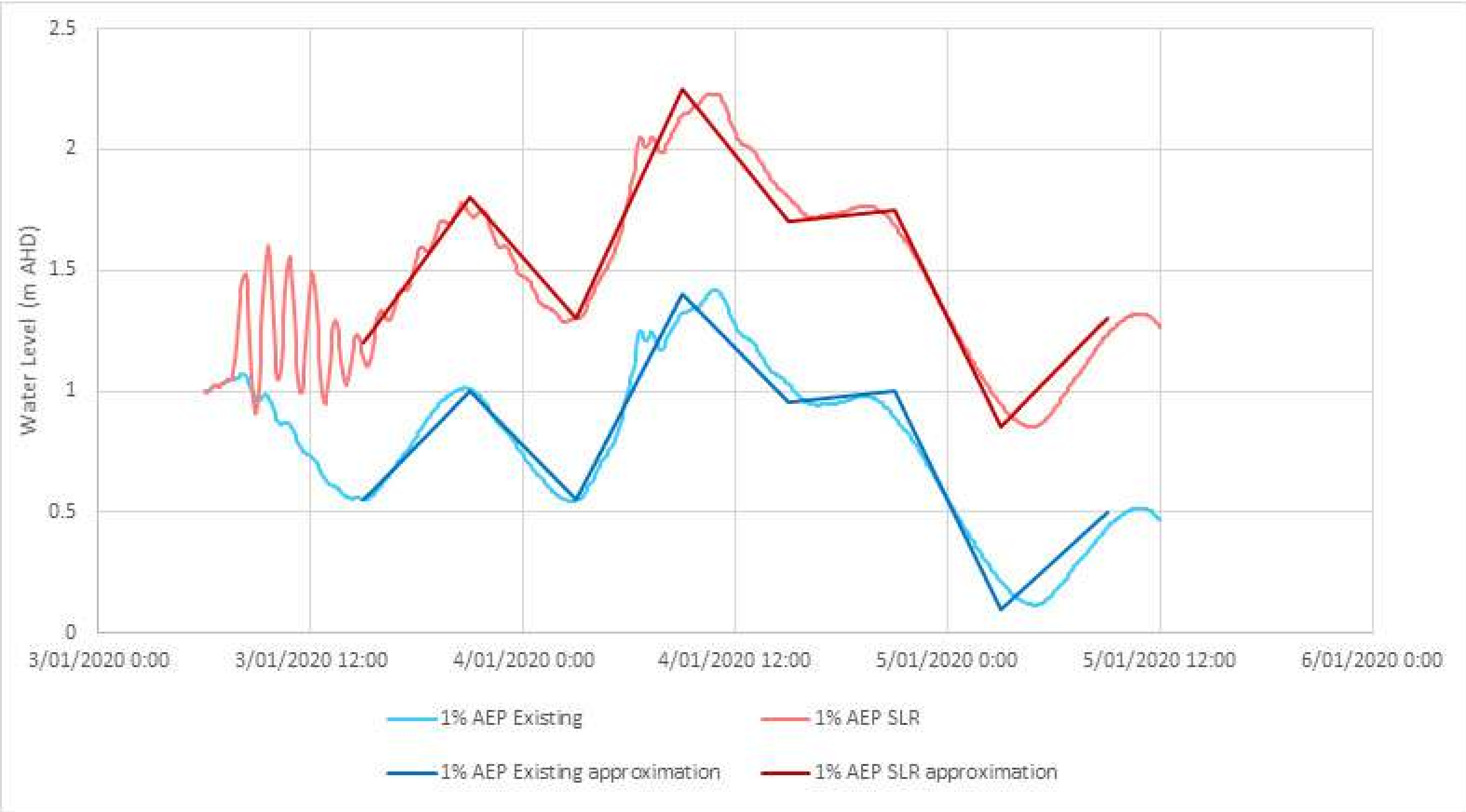


Figure 1b. Approximation of 10% AEP Water Tech modelled tidal curves

Figure 2. Tidal curve and hydrograph timing

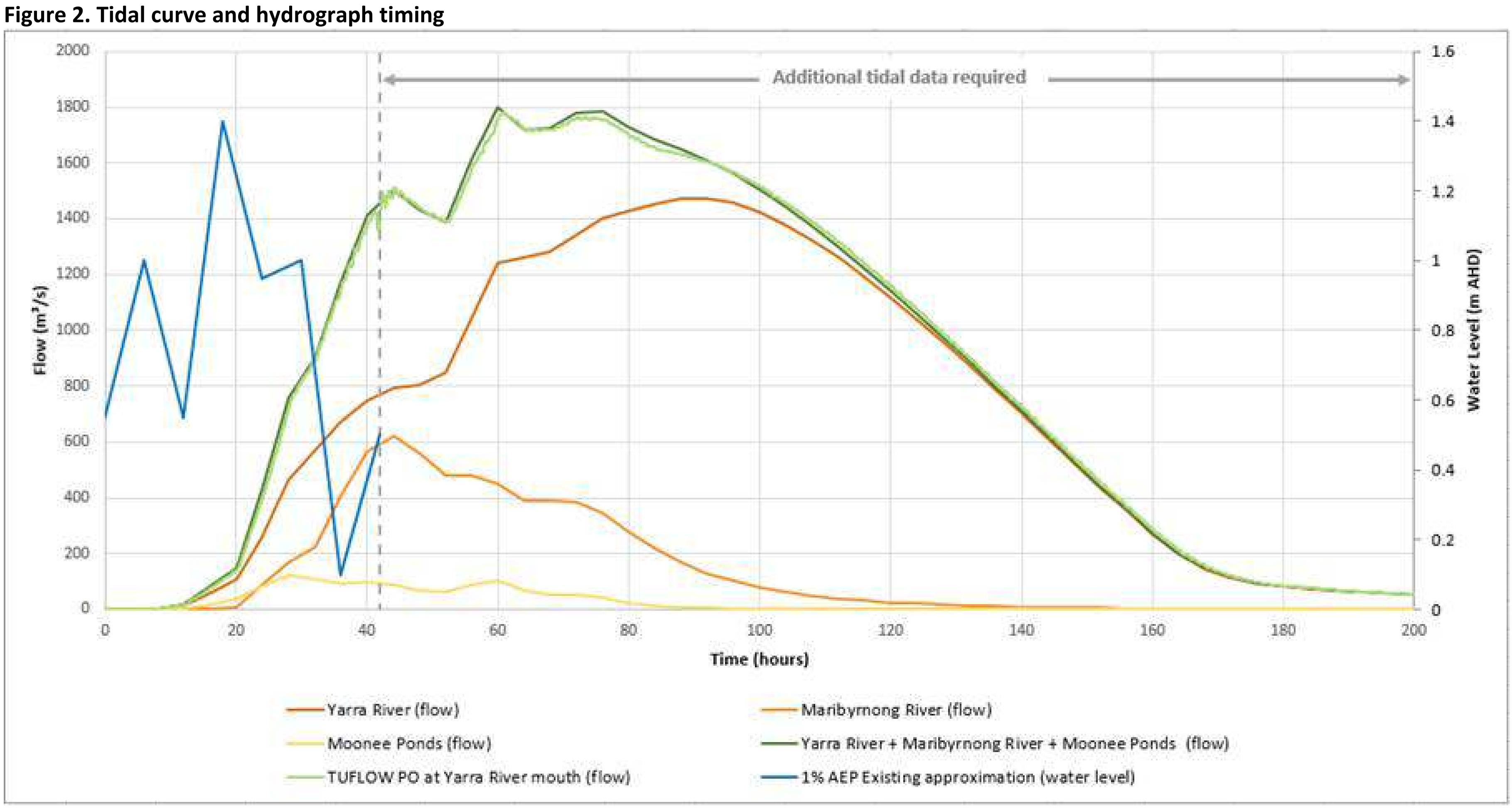
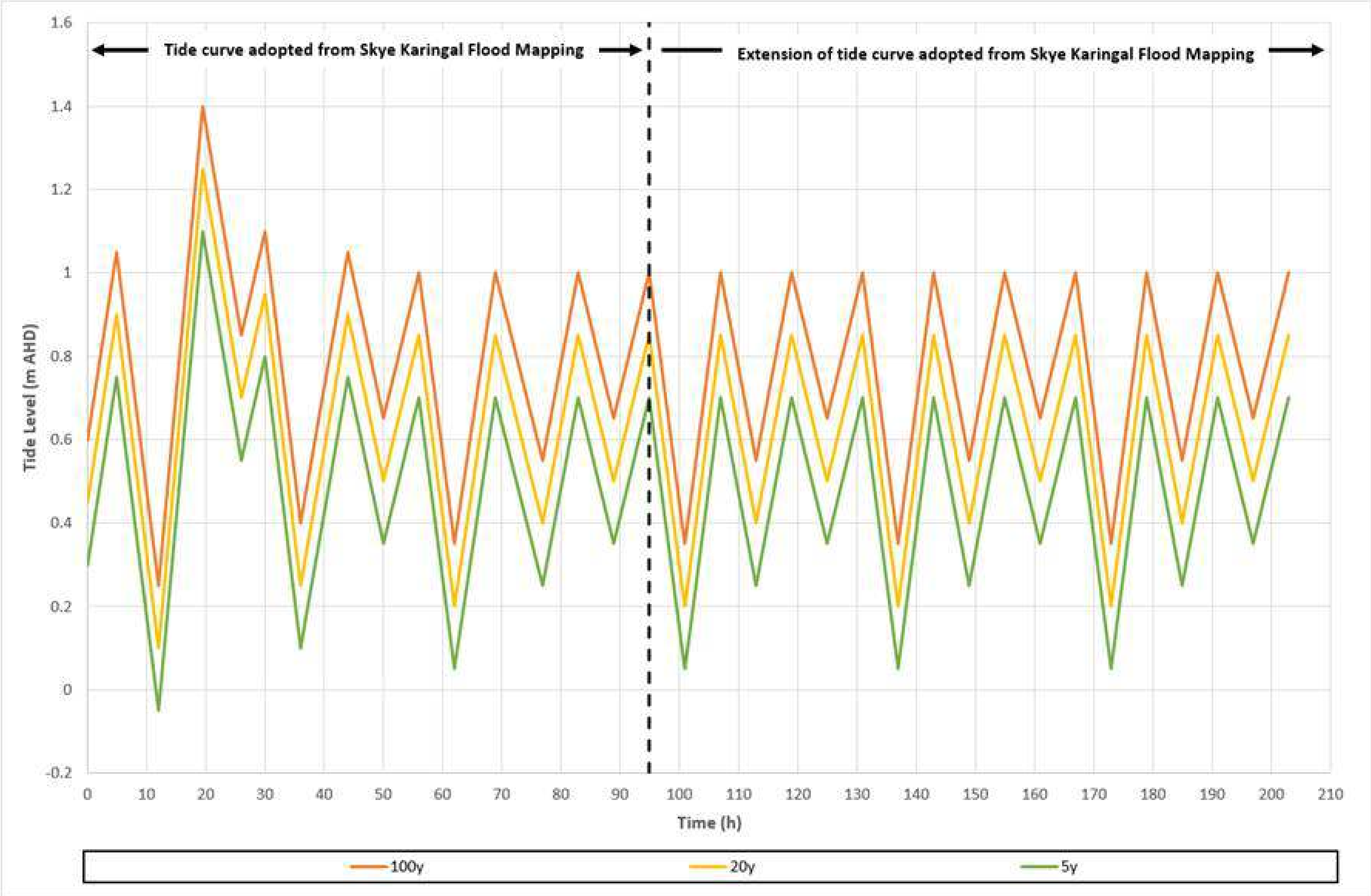


Table 1.

AEP	Base Tidal Curve (AEP)	Peak TWL (existing conditions)	Peak TWL (climate change – sea level rise)
1%	1%	1.6	2.4
5%	1%	1.25	2.05
20%	10%	1.1	1.9

Figure 3. Example of extended tide curve from Skye Karingal Flood Mapping project



Regards

Nathan Lindner
Civil Engineer – Water Resources

GHD
T: +61 3 8687 8205 | V: 318205 | E: nathan.lindner@ghd.com
180 Lonsdale Street, Melbourne VIC Australia 3000 | http://www.ghd.com/
WATER | ENERGY & RESOURCES | ENVIRONMENT | PROPERTY & BUILDINGS | TRANSPORTATION

CONFIDENTIALITY NOTICE: This email, including any attachments, is confidential and may be privileged. If you are not the intended recipient please notify the sender immediately, and please delete it; you should not copy it or use it for any purpose or disclose its contents to any other person. GHD and its affiliates reserve the right to monitor and modify all email communications through their networks.

If you have received this email in error, please notify the sender by return email, delete it from your system and destroy any copies.

This e-mail has been scanned for viruses

Attachment 3

Email train regarding initial design run assumptions (final email dated 6/9/2019)

From: Peter Woodman
To: [redacted]
Cc: [redacted]
Subject: [illegible]
Date: [illegible] September 2019 [illegible]
Attachments: [illegible]

[illegible]

Thanks for confirming the approach going forward – we will get cracking on setting off the final model runs in the agreed priority order.

[illegible]

[illegible]

If you would like to discuss, please feel free to give me a call [illegible]

Regards

Peter Woodman
Senior Environmental Engineer – Water Resources
[illegible]
GHD
[illegible]
Level 8, 180 Lonsdale Street Melbourne VIC 3000 Australia [illegible]
Water | Energy & Resources | Environment | Property & Buildings | Transportation

Please consider the environment before printing this email

From: [redacted]
To: Peter Woodman
Cc: [redacted] Gavin Hay; Nathan Lindner; Nathan Clements
Subject: [illegible]
Date: Friday, 6 September 2019 [illegible]
Attachments: [illegible]

Hi Peter

Thankyou for the information on the Lidar difference review.

Melbourne Water agrees with GHDs' proposal to commence the required design runs using the hydrology and Lidar provided for this project.

Melbourne Water urgently requires a timeline for this project by COB today, 6 September 2019.

##.

##.

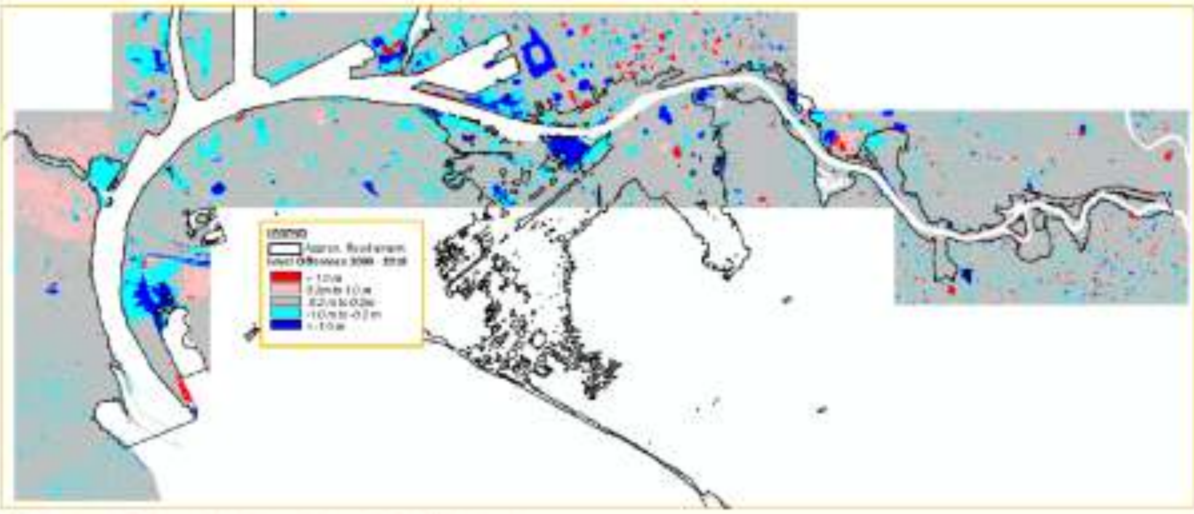
Regards
[redacted]
Asset Practitioner – Mapping and Modelling Engineer, Flood Information, Asset Management Services, Service Delivery Group | Melbourne Water
[redacted]
990 Latrobe St, Docklands 3008 | PO Box 4342 Melbourne VIC 3001 | melbournewater.com.au
Enhancing Life and Liveability.

From: Peter Woodman [mailto:Peter.Woodman@ghd.com]
Sent: Thursday, 5 September 2019 10:14 AM
To: [redacted]
Cc: [redacted] Gavin Hay; Nathan Lindner; Nathan Clements
Subject: [redacted] for Lower Yarra River Flood Mapping

[redacted]

Thank you for arranging for the provision of the LiDAR difference plot earlier in the week.

As requested, we have reviewed this information and have prepared the plot below that highlights the differences between the 2009 and 2018 LiDAR. On this plot the shades of red represent a decrease in elevation between 2009 and 2018 (of >0.2m), and shades of blue represent an increase in elevation between 2009 and 2018 (of >0.2m). The grey areas are is considered to have no change outside of the tolerance of the vertical LiDAR accuracy.
From this we note that there are a number of level differences (both increases and decreases), which may be significant to the final results, particularly where overtopping thresholds are affected.



Confidence in the results from this project could be improved by undertaking additional investigations such as:

- A thorough review (and as appropriate extension), of previous investigations to improve the hydrologic modelling for this part of the Yarra River
- An update of the terrain model to include the new LiDAR.

Our understanding from several conversations with Melbourne Water is that completion of this project is urgent, and that additional investigations as noted above are not compatible with the current project time frames – which we now understand are by the end of September. Consequently, these additional investigations and refinements will not be possible within the project timeline, but should be strongly considered at a later time, perhaps as part of a future update to ARR2019 methodologies. On this basis, unless advised otherwise, we intend to ignore the current limitations with respect to hydrology and survey as part of this current engagement, and proceed to commence the required design runs to complete this project as quickly as possible using the hydrologic parameters and original LiDAR (circa 2009) both provided by Melbourne Water. Please advise by the end of this week (COB 06/09/2019) if you disagree with the proposed approach. If we don't hear otherwise, we will commence with the model finalisation and will keep you updated as to expected delivery dates.

If you would like to discuss, please feel free to give Gavin (8687 8741) or myself a call.

Regards

Peter Woodman
Senior Environmental Engineer – Water Resources

GHD
Proudly employee owned
T: [illegible] | [illegible] | peter.woodman@ghd.com
Level 8, 180 Lonsdale Street, Melbourne, VIC 3000 Australia | http://www.ghd.com/
Connect

WATER | ENERGY & RESOURCES | ENVIRONMENT | PROPERTY & BUILDINGS | TRANSPORTATION

Please consider the environment before printing this email

GHD acknowledges the Traditional Owners of Country throughout Australia.
We pay respect to their continuing culture and Elders past, present and emerging.
Click here to learn about our Reconciliation Action Plan.

From: Peter Woodman
Sent: Wednesday, 28 August 2019 [illegible] PM
To: [redacted]
Cc: [redacted] Gavin Hay
<Gavin.Hay@ghd.com>; Nathan Lindner <Nathan.Lindner@ghd.com>
Subject: RE: DRAFT Modelling Assumptions and Implications Memo

[redacted]

[illegible]

[illegible]

[illegible]

Regards

Peter Woodman
Senior Environmental Engineer – Water Resources

On leave every second Monday

GHD
Proudly employee owned
[illegible]
Connect

[illegible]

[illegible]

GHD acknowledges the Traditional Owners of Country throughout Australia.
We pay respect to their continuing culture and Elders past, present and emerging.
Click here to learn about our Reconciliation Action Plan.

From: [redacted]
Sent: Thursday, 22 August 2019 [illegible] PM
To: Peter Woodman <Peter.Woodman@ghd.com>
Cc: [redacted] Gavin Hay
<Gavin.Hay@ghd.com>; Nathan Lindner <Nathan.Lindner@ghd.com>
Subject: RE: DRAFT Modelling Assumptions and Implications Memo

Hi Peter

With regards to your email dated the 19 August 2019 on the hydrology to be used for the Lower Yarra River project.

Melbourne Water has further discussed and has concluded that Scenario 2 in Table 1 below is to be used for the Lower Yarra River project. So kc = 140, m = 0.8 with flow of 1,425 cumecs is to be adopted.

The higher flow is from a model calibrated to recorded flood levels and the lower flow is a flood frequency analysis of gauged flow based on a rating curve. The gauge flow is quite accurate for more frequent flood event, the flow is within the waterway profile. For rare flood event, the flow is over the top of banks, the rating curve is not very accurate because the curve is extrapolated.

As previously advised on the 22 July 2019, Melbourne Water is satisfied with the process that was used to determine the design rainfall depths.

Regard
[redacted]
[illegible] | Melbourne Water
[redacted]
[illegible] | melbournewater.com.au
Enhancing Life and Liveability.

From: Peter Woodman [mailto:Peter.Woodman@ghd.com]
Sent: Monday, 19 August 2019 [illegible] PM
To: [redacted]
Cc: [redacted]; Gavin Hay; Nathan Lindner
Subject: RE: DRAFT Modelling Assumptions and Implications Memo

[redacted]

[illegible]

[illegible]

1. [illegible]
2. [illegible]

[illegible]

[illegible]

Table 1 – 1% AEP [illegible] Yarra River inflow at confluence with [illegible] Creek

Scenario	Kc	m	Initial Loss (mm)	Runoff Coefficient	Scenario Description	Flow (m³/s)
1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
2	[illegible]				[illegible]	[illegible]
3	[illegible]				[illegible]	[illegible]
Note: [illegible]						

[illegible]

[illegible]

[illegible]

Regards

Peter Woodman
Senior Environmental Engineer – Water Resources
On leave every second Monday

GHD
Proudly employee owned
[illegible]
Connect

[illegible]

[illegible]

GHD acknowledges the Traditional Owners of Country throughout Australia.
We pay respect to their continuing culture and Elders past, present and emerging.
Click here to learn about our Reconciliation Action Plan.

From: [redacted]
Sent: Friday, 16 August 2019 5:46 PM
To: Peter Woodman <[illegible]>
Cc: [redacted] [illegible]
<[illegible]>; Nathan Linder <[illegible]>
Subject: RE: DRAFT Modelling Assumptions and Implications Memo

Hi Peter

Thanks for your email.

Regards

[redacted]

[illegible] | **Melbourne Water**

[redacted]

[illegible] | [illegible]

Enhancing Life and Liveability

From: Peter Woodman [[illegible]]
Sent: Friday, 16 August 2019 4:46 PM
To: [redacted]
Cc: [redacted] Gavin Hay; Nathan Linder
Subject: RE: DRAFT Modelling Assumptions and Implications Memo

[redacted]

[illegible]

[illegible]

Regards

Peter Woodman
Senior Environmental Engineer – Water Resources
On leave every second Monday

GHD
Proudly employee owned
[illegible]
[illegible]
Connect

[illegible]

[illegible]

GHD acknowledges the Traditional Owners of Country throughout Australia.
We pay respect to their continuing culture and Elders past, present and emerging.
Click here to learn about our Reconciliation Action Plan.

From: [redacted]
Sent: Friday, 16 August 2019 12:39 PM
To: Peter Woodman <[illegible]>
Cc: [redacted] Gavin Hay
<[illegible]>; Nathan Linder <[illegible]>
Subject: RE: DRAFT Modelling Assumptions and Implications Memo

Hi Peter

Thanks for your email detailing the items to progress this project. Our comments have been included in your email below in red font.

Regards

[redacted]

[illegible] | **Melbourne Water**

[redacted]

[illegible] | [illegible]

Enhancing Life and Liveability

From: Peter Woodman [[illegible]]
Sent: Thursday, 15 August 2019 [illegible] PM
To: [redacted]
Cc: [redacted] Gavin Hay; Nathan Linder
Subject: RE: DRAFT Modelling Assumptions and Implications Memo

[redacted]

[illegible]

[illegible]

[illegible]

- [illegible]
    1. [illegible]
    2. [illegible]
    3. [illegible]

  [illegible]
- [illegible]
- Run "verification" models for new scenarios to identify roughness that correlates closest to designated levels. [illegible]
- Run design events in following priority order in TUFLOW Classic for [illegible] durations (with tide timing based on MWC advice):
    1. 1% AEP Base Case Scenario with 1% AEP Water Tech tidal curve Agree
    2. 10% AEP Base Case Scenario with 10% AEP with Water Tech tidal curve Agree
    3. 1% AEP Climate Change 2 Scenario with 1% AEP Water Tech Sea Level Rise tidal curve Agree
    4. 10% AEP Climate Change 2 Scenario with 10% AEP Water Tech Sea Level Rise tidal curve Agree
    5. 2% AEP Base Case Scenario with 1% AEP with Water Tech tidal curve adjusted to have a peak level as per Table 1 below Agree
    6. 5% AEP Base Case Scenario with 1% AEP with Water Tech tidal curve adjusted to have a peak level as per Table 1 below Agree
    7. 20% AEP Base Case Scenario with 10% AEP with Water Tech tidal curve adjusted to have a peak level as per Table 1 below Agree
    8. 0.2% AEP Base Case Scenario with 1% AEP Water Tech tidal curve Agree
    9. 1% AEP Climate Change 1 Scenario with 1% AEP Water Tech Sea Level Rise tidal curve adjusted to have a peak level as per Table 1 below [illegible]
    10. 1% AEP Climate Change 2 Scenario with 1% AEP Water Tech Sea Level Rise tidal curve Agree
    11. 10% AEP Climate Change 1 Scenario with 10% AEP Water Tech Sea Level Rise tidal curve Agree
    12. 1% AEP Climate Change 3 Scenario with 1% AEP Water Tech tidal curve [illegible]
    13. 5% AEP Climate Change 3 Scenario with 1% AEP Water Tech tidal curve adjusted to have a peak level as per Table 1 below [illegible]
    14. 10% AEP Climate Change 3 Scenario with 10% AEP Water Tech tidal curve adjusted to have a peak level as per Table 1 below [illegible]
    15. 10% AEP St Kilda Marina sensitivity scenario with St Kilda Marina tidal curve (have some data from [redacted] that would need to be extended and will need to agree on timing – see attached email) [illegible]
    16. 10% AEP Williamstown sensitivity scenario with Williamstown tidal curve (have some data from [redacted] that would need to be extended and will need to agree on timing – see attached email) [illegible]

Table 1 – [illegible]

AEP	Nov 2016 Tech Spec TWL (m AHD)		Water Tech Tide Curves TWL (m AHD)		Adopted TWL (m AHD)	
	Base Case	Sea Level Rise (Difference to Base Case)	Base Case (Difference to Tech Spec)	Sea Level Rise (Difference to Base Case) / (Difference to Tech Spec)	Base Case	Sea Level Rise
0.2%	–	–	–	–	1.6*	–
1%	1.4	2.4 (+0.8 m)	1.4 [illegible]	2.20 [illegible]	1.4	2.25
2%	1.35	–	–	–	1.35*	–
5%	1.25	2.05 (+0.8 m)	–	–	1.25*	–
10%	1.2	–	1.15 (-0.05 m)	2 [illegible]	1.15	2
20%	1.1	1.9 (+0.8 m)	–	–	1.05*	1.9*
Note: * [illegible]						

Based on the above approach, there are a number of items that have not currently been allowed for in the project scope – these include re-running hydrology with ARFs, producing hydrographs for Moonee Ponds Creek and Maribyrnong River and climate change variations of [illegible] doing verification runs and setting up tide curves for St Kilda and Williamstown. These additional tasks could be undertaken for a fee of **$[illegible] excl GST**. [illegible] the comments provided above by Melbourne Water.

If you can confirm that you are happy with our approach outlined above before lunch tomorrow, I should be able to provide a program for the [illegible] tomorrow. For the updated timeline, could you please assume the [illegible] work, the DTM is provided by the end of next week and at this stage only commitment on delivering priorities 1 [illegible]. We would like the timeline to show enough detail to determine the impact of the [illegible] work.

Happy to discuss further if you'd like.

Regards

Peter Woodman
Senior Environmental Engineer – Water Resources
On leave every second Monday

GHD
[illegible]
[illegible]
[illegible]
Connect
[illegible]

Please consider the environment before printing this email

GHD acknowledges the Traditional Owners of Country throughout Australia.
We pay respect to their continuing culture and Elders past, present and emerging.
Click here to learn about our Reconciliation Action Plan.

From: [redacted]
Sent: Thursday, 15 August 2019 10:26 AM
To: Peter Woodman <[illegible]>
Cc: [redacted] Gavin Ray <[illegible]>; Nathan Lindner <[illegible]>
Subject: RE: DRAFT Modelling Assumptions and Implications Memo

Hi Peter

From our meeting yesterday, Wednesday 14 August 2019, the priority of the modelling is listed in the table below.

Also, as agreed GHD will be providing today a timeline for the completion of the project.

Modelling Scenario		Event	Tailwater Level (m AHD)	Priority
A	Base Case	0.2% AEP	Appropriate level to be discussed and jointly agreed	3
		1% AEP	2.0	Not required
		1% AEP	1.4 (expanded sensitivity test)	1
		2% AEP	1.35	2
		5% AEP	1.25	2
		10% AEP	1.2 / MWC Tidal Curve*	1
		20% AEP	1.1	3
B	Climate Change 1 – Sea level rise	1% AEP	2.4	3
		10% AEP	MWC Tidal Curve*	3
C	Climate Change 2 – Sea level rise and increased rainfall intensity	1% AEP	2.4	1
		5% AEP	2.05	2
		10% AEP	MWC	1
		20% AEP	1.9	2
D	Climate change 3 – Increased rainfall intensity	1% AEP	1.4	3
		5% AEP	1.25	3
		20% AEP	1.1	4

Regards
[redacted]
Senior Practitioner – Planning and Modelling Engineer, Flood Information, Asset Management Services, Service Delivery Group | Melbourne Water
[redacted]
990 La Trobe St, Docklands, 3008 | PO Box 4342 Melbourne VIC 3001 | [illegible]
Enhancing Life and Liveability

From: Peter Woodman [[illegible]]
Sent: Wednesday, 14 August 2019 11:06 AM
To: [redacted]
Cc: [redacted] Gavin Ray; Nathan Lindner
Subject: DRAFT Modelling Assumptions and Implications Memo

[redacted]

Please find attached a "draft" version of the revised "Modelling Assumptions and Implications" memorandum, which summarises all the verification modelling undertaken to date. Since the previous issue we have updated the [illegible] revised conclusion from previous modelling (Section 4) and added the last section on the [illegible] modelling (Section 5).

We thought we'd send this through prior to the meeting as Section 5 summarises the current modelling, which we have presented in a series of previous emails and plan to discuss later today.

Regards

Peter Woodman
Senior Environmental Engineer – Water Resources
On leave every second Monday

GHD
[illegible]
[illegible]
[illegible]
Connect
[illegible]

Please consider the environment before printing this email

GHD acknowledges the Traditional Owners of Country throughout Australia.
We pay respect to their continuing culture and Elders past, present and emerging.
Click here to learn about our Reconciliation Action Plan.

Attachment 4

Phase 1 Southbank Overflow Refinement Results Memo

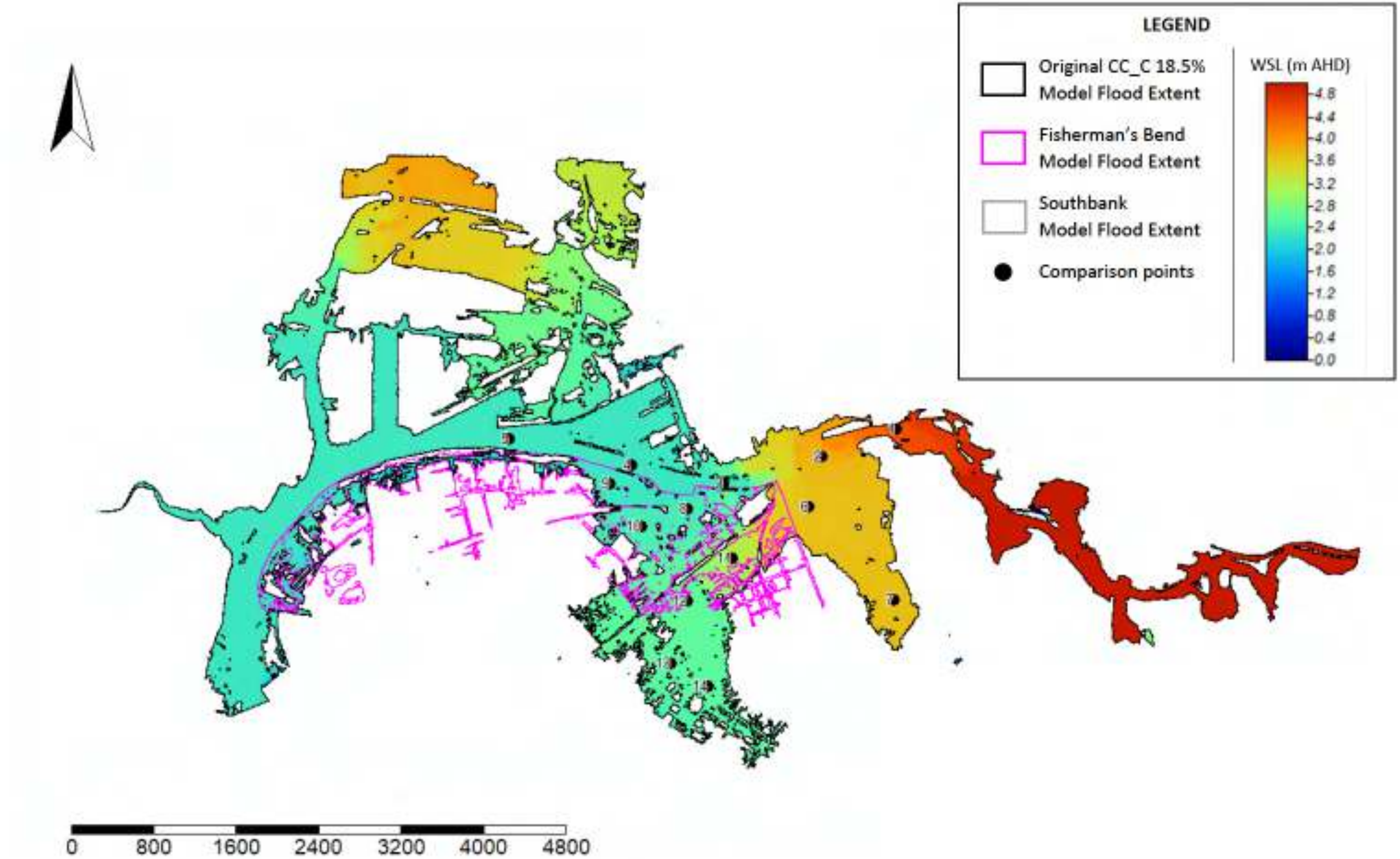


Figure 1 **Original Yarra River Model Peak 100y WSL (100y Tide)**

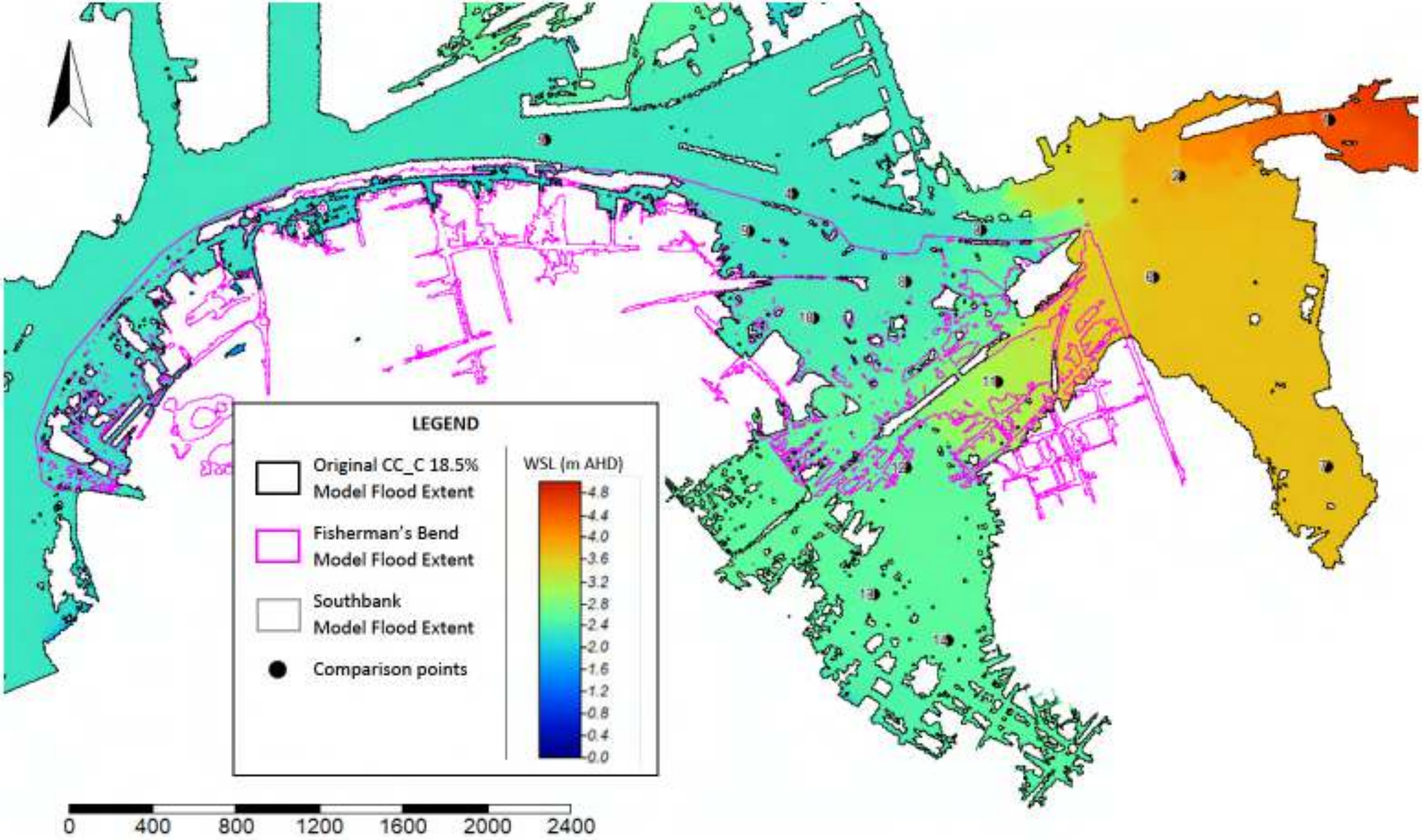


Figure 1B **Original Yarra River Model Peak 100y WSL (100y Tide) – Zoomed to overflow refinement area**

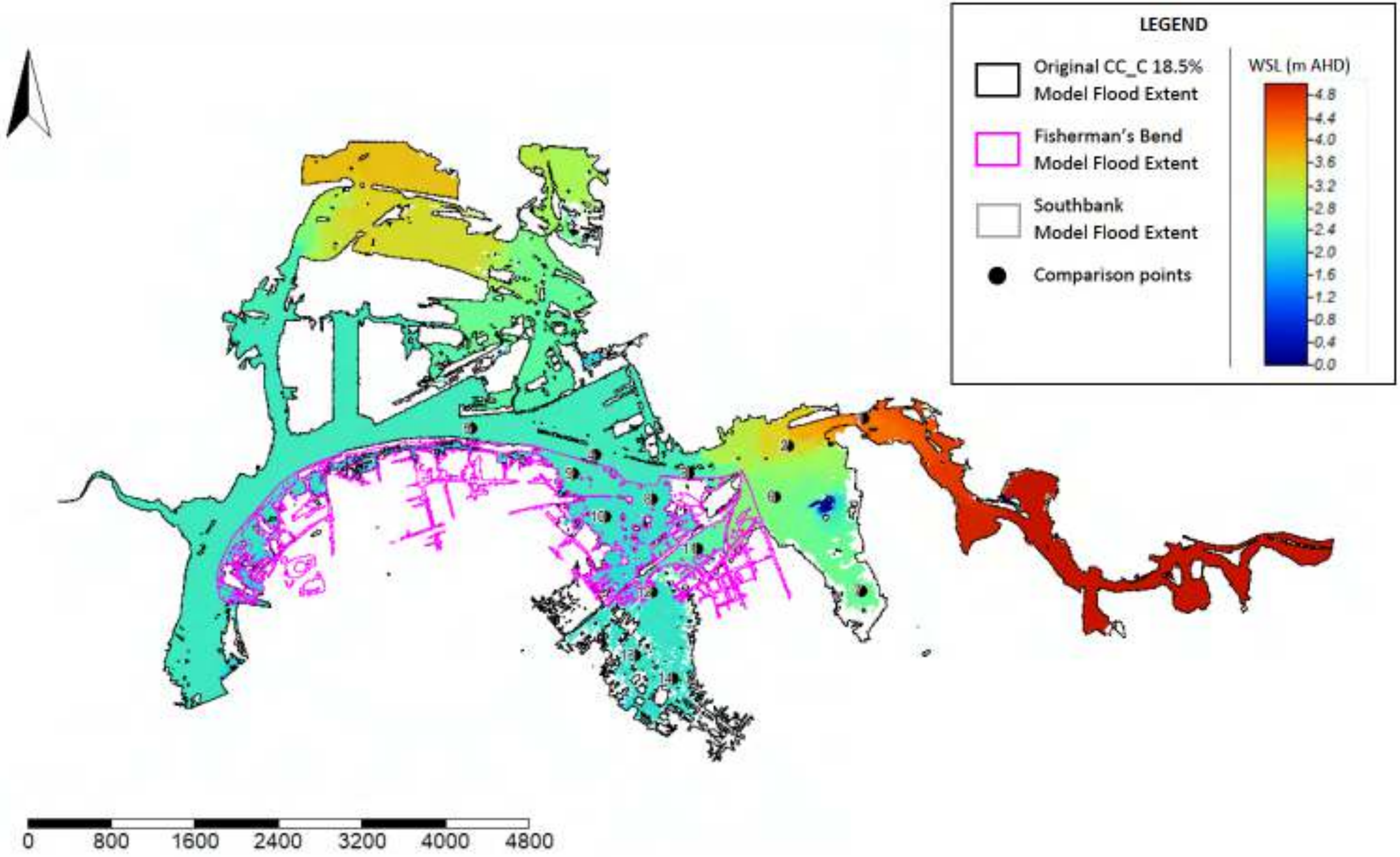


Figure 2 **Overflow Refinement Yarra River Model Peak 100y WSL (100y Tide)**

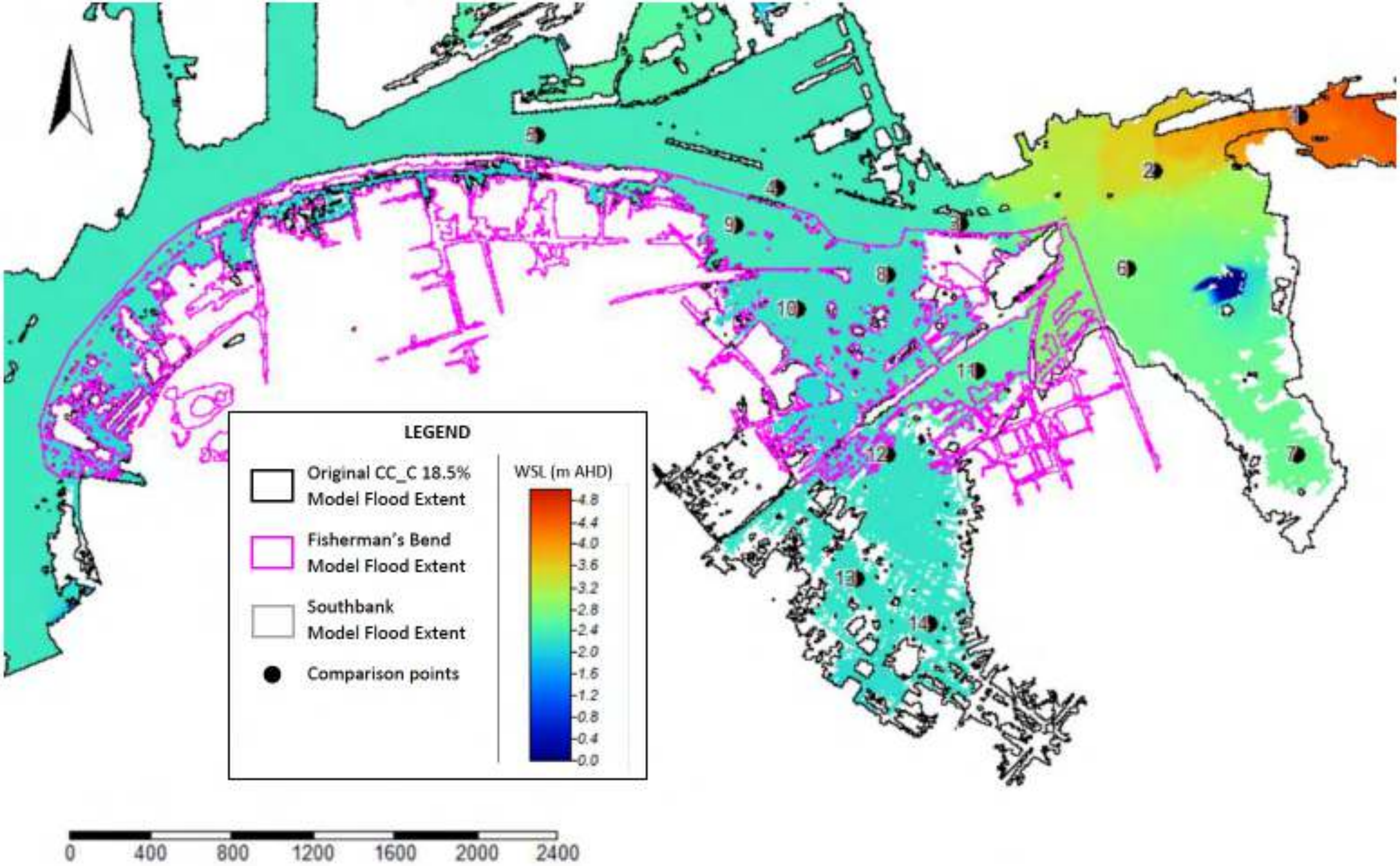


Figure 2B **Overflow Refinement Yarra River Model Peak 100y WSL (100y Tide) – Zoomed to overflow refinement area**

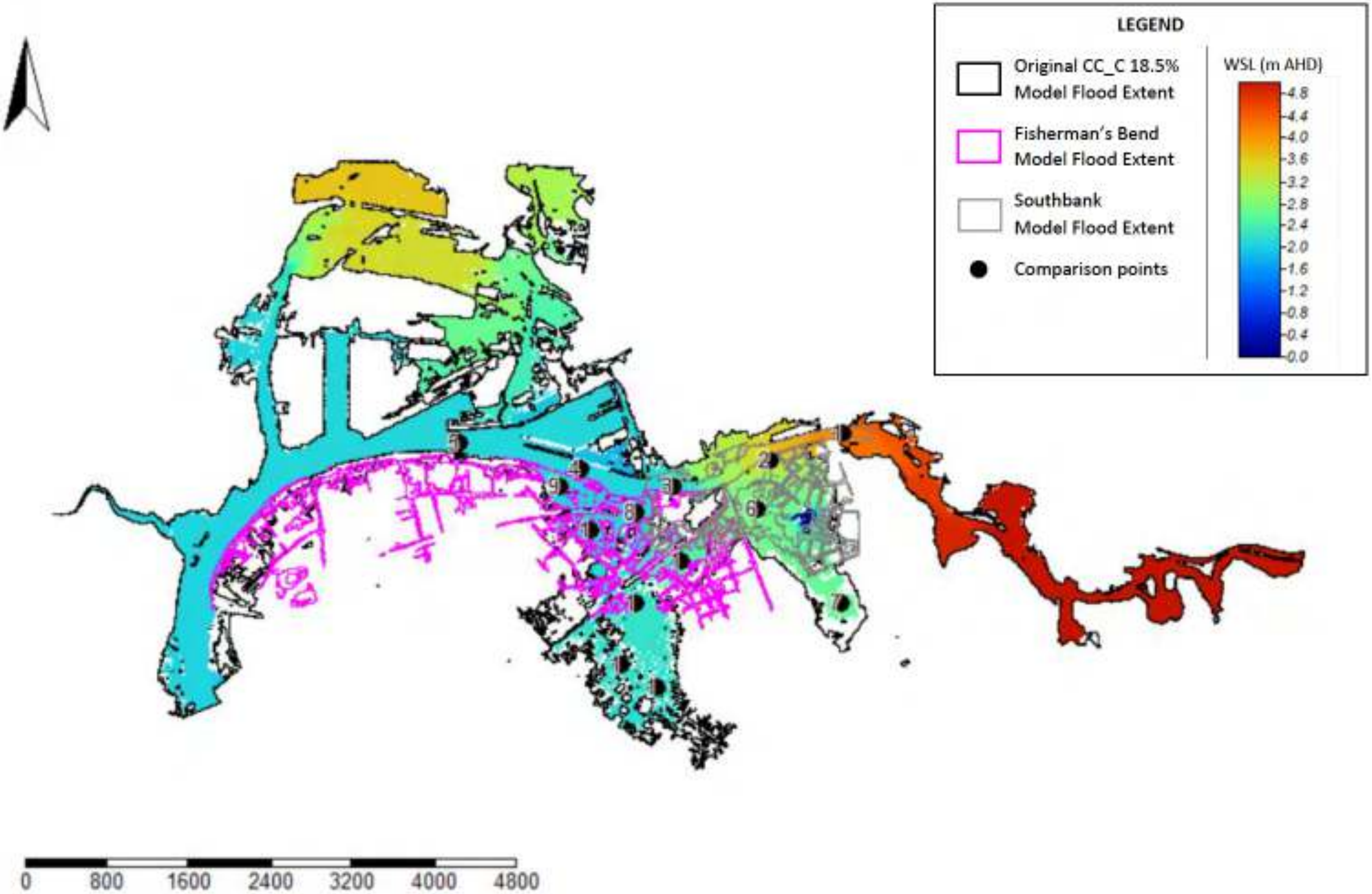


Figure 3 **Overflow Refinement Yarra River Model Peak 100y WSL (10y Tide)**

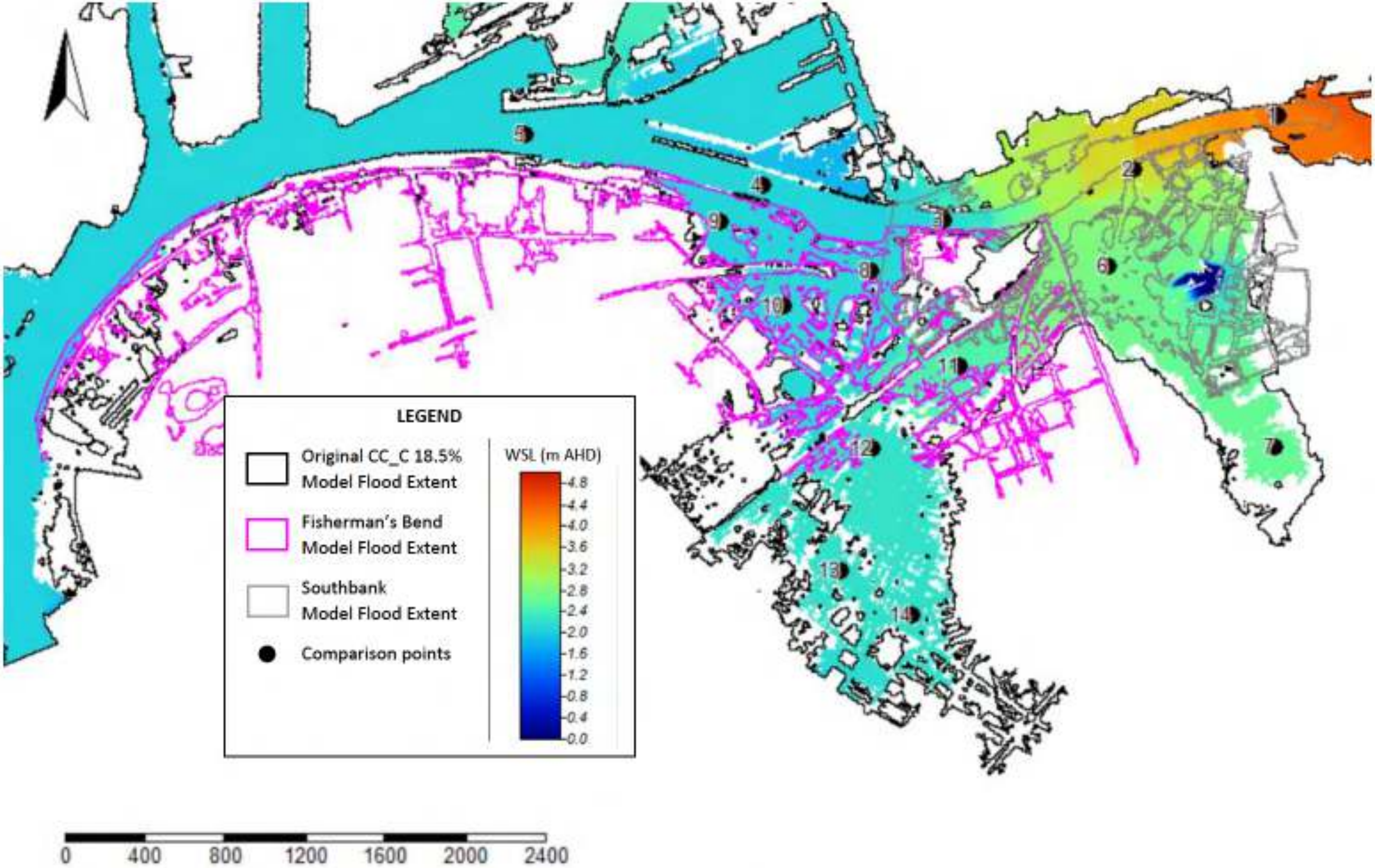


Figure 3B Overflow Refinement Yarra River Model Peak 100y WSL (10y Tide) – Zoomed to overflow refinement area

Table 1 **Comparison Point Locations**

ID	Description	Peak 100y ARI WSL w/ 100y Tide			Peak 100y ARI WSL w/ 10y Tide		
		Original Lower Yarra River Model	Overflow Refinement Lower Yarra River Model	Fishbend Model	Overflow Refinement Lower Yarra River Model	Southbank Model	Fishbend Model
1	Yarra River 1 (US)	4.48	4.22	-	4.19	2.14	-
2	Yarra River 2	3.84	3.31	-	3.25	1.74	-
3	Yarra River 3	2.29	2.34	-	2.09	2.14	-
4	Yarra River 4	2.27	2.29	-	2.04	-	-
5	Yarra River 5 (DS)	2.29	2.29	-	2.04	-	-
6	South Bank Pond	3.67	2.72	-	2.69	1.28	-
7	Sth Park St	3.68	2.61	-	2.58	-	-
8	Fwy\Montague St	2.36	2.20	2.25	2.08	-	1.82
9	Lorimer St \ Boundary St	2.27	2.28	2.25	2.03	-	1.82
10	Approx. Boundary St \ Gittus St	2.37	2.20	2.25	2.08	-	1.82
11	Approx. Buckhurst St \ George St	3.10	2.44	2.13	2.41	-	1.89
12	Approx. Heath St \ Raglan St	2.58	2.21	-	2.19	-	-
13	Edwards Park	2.53	2.20	-	2.18	-	-
14	Approx. St Vincent St \ Iffla St	2.53	2.20	-	2.18	-	-

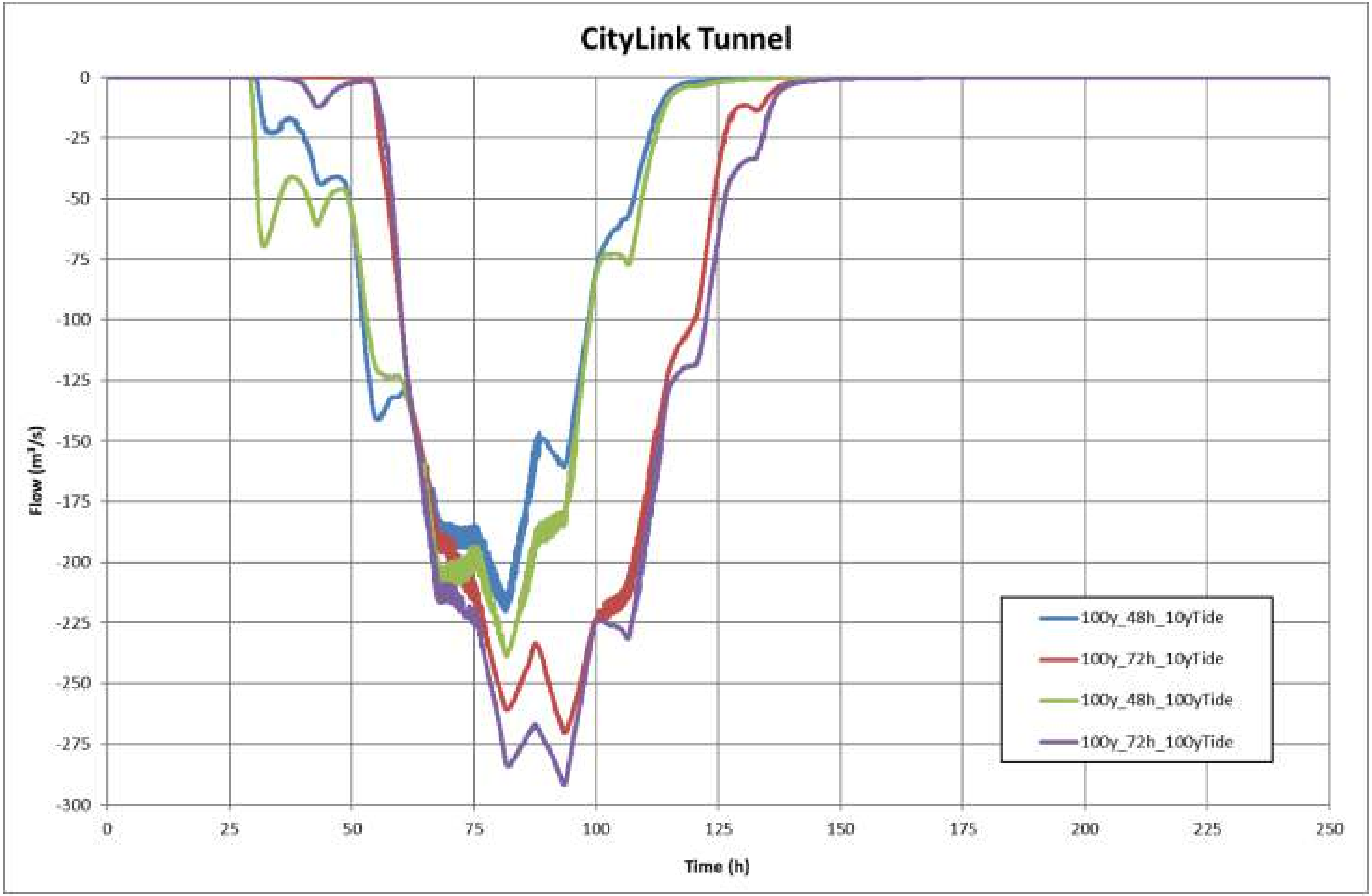


Figure 4 **Flow leaving model via City Link Tunnel portal near Southbank**

Attachment 5

Phase 2 Southbank Overflow Refinement
Results Memo

Table 1 Modelled Scenarios

Runs	Flows	DS TWL	Plot Legend
1	Base 1% AEP (Kc=145 w/o ARFs) - blue line	10% AEP Tide	Current (Kc145)
2	Base 1% AEP (Kc=180 w/ ARFs) - orange line	10% AEP Tide	Kc180
3	Base 1% (Kc=237 w/o ARFs) - grey line	10% AEP Tide	Kc237
4	CC 18.5% 1% AEP (Kc=145 w/o ARFs)	10% AEP SLR Tide	Current CC18p5 (Kc145)
5	CC 18.5% 1% AEP (Kc=180 w/ ARFs)	10% AEP SLR Tide	Kc180_CC18p5
6	CC 18.5% 1% AEP (Kc=237 w/o ARFs)	10% AEP SLR Tide	Kc237_CC18p5

Results Presented

- Figure 1 -> Compartison of Yarra River inflow
- Figure 2 - Figure 7 -> WSL Plots
- Figure 8 -> Long-section along Yarra River
- Table 2 & Figure 9 -> Model Comparison Points
- Table 3 & Figure 10 -> 1934 Historic Level Comparison Points
- Figure 11 & 12 and Table 4 -> City Link Tunnel flows and volumes
- Figure 13 -> River roughness sensitivity results (previous modelling)

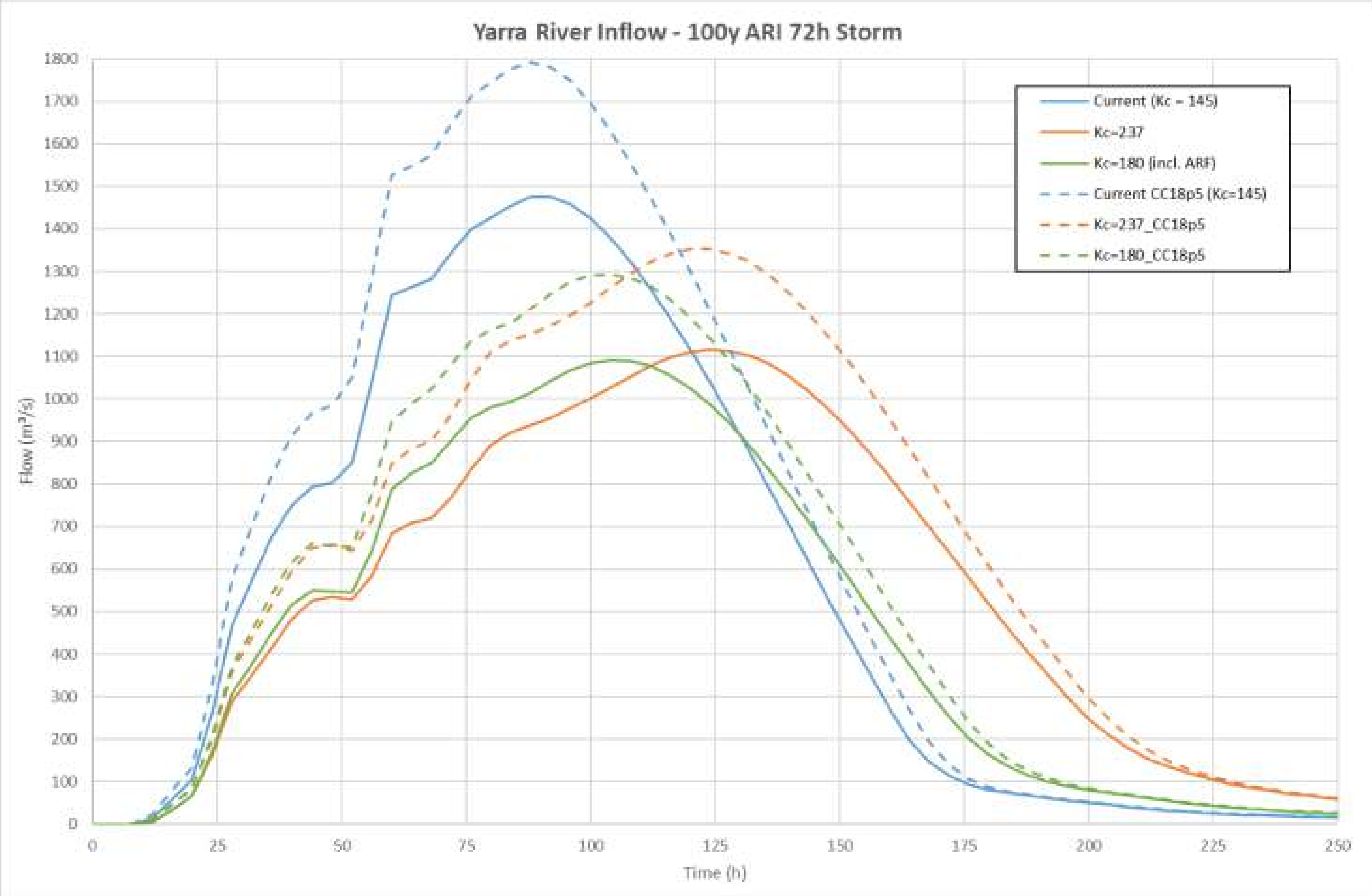


Figure 1 **Comparison of Yarra River Inflows**

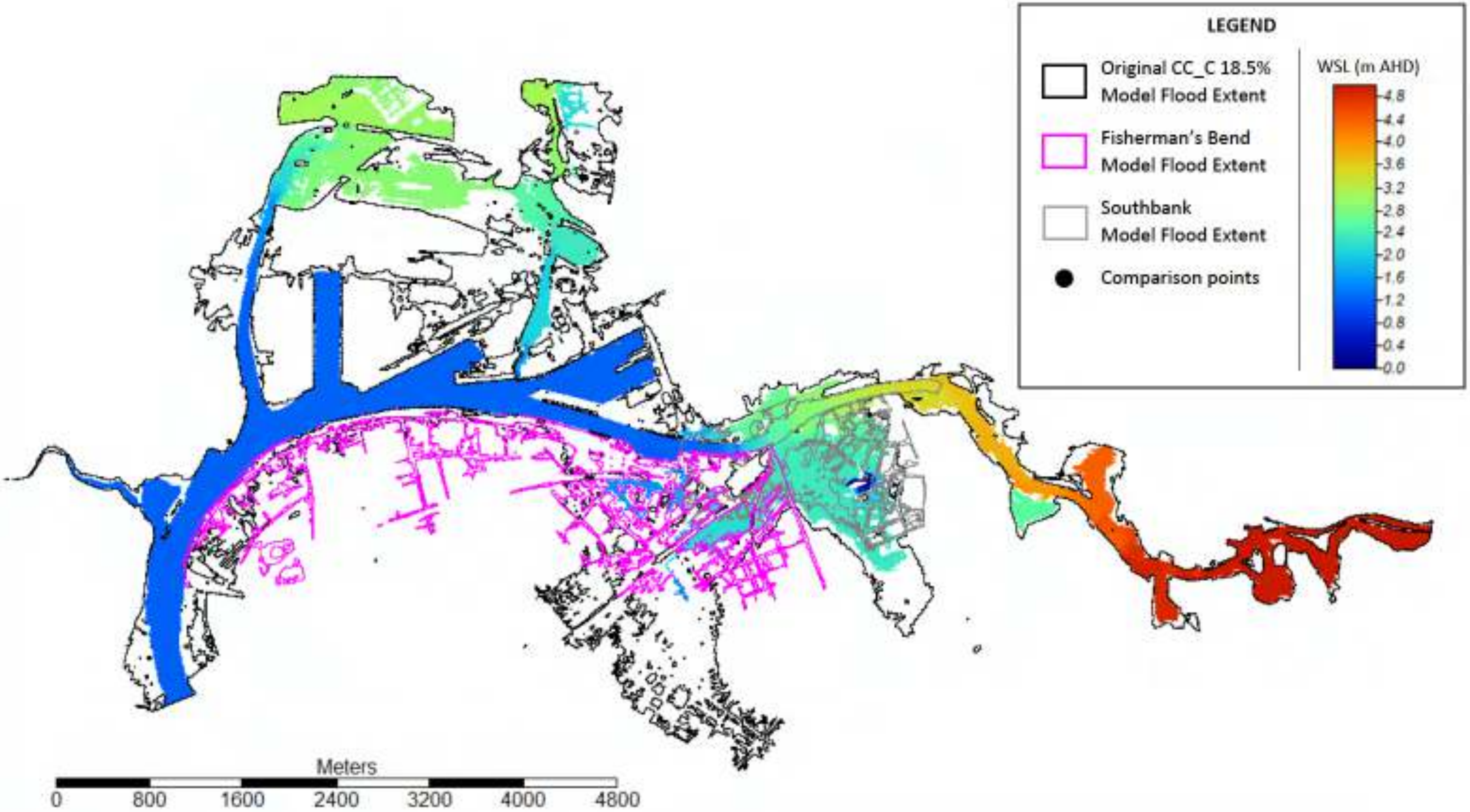


Figure 2 Current (Kc=145) Yarra River Model Peak 100y WSL (10y Tide)

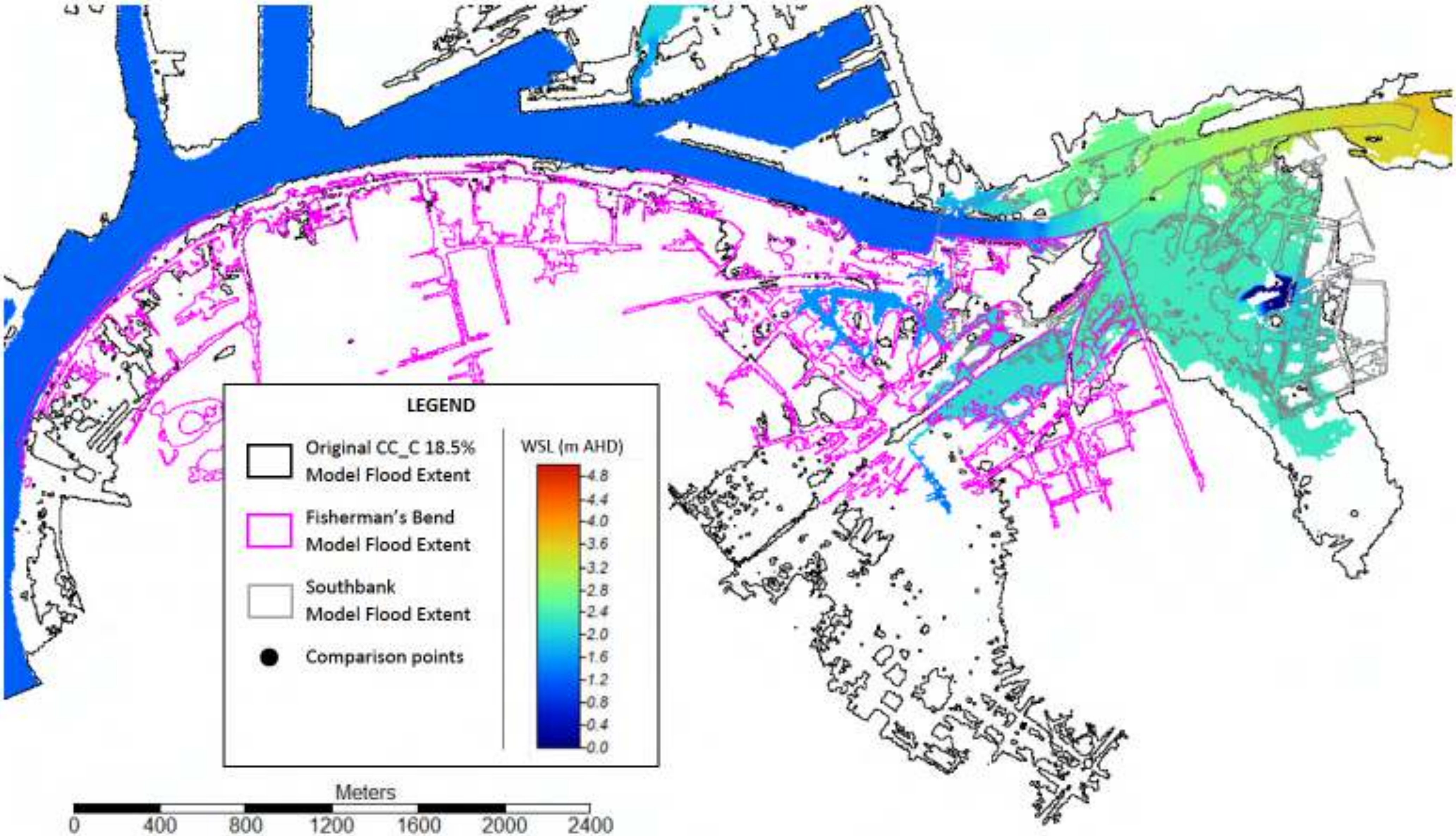


Figure 2B Current (Kc=145) Yarra River Model Peak 100y WSL (10y Tide) – Zoomed to overflow refinement area

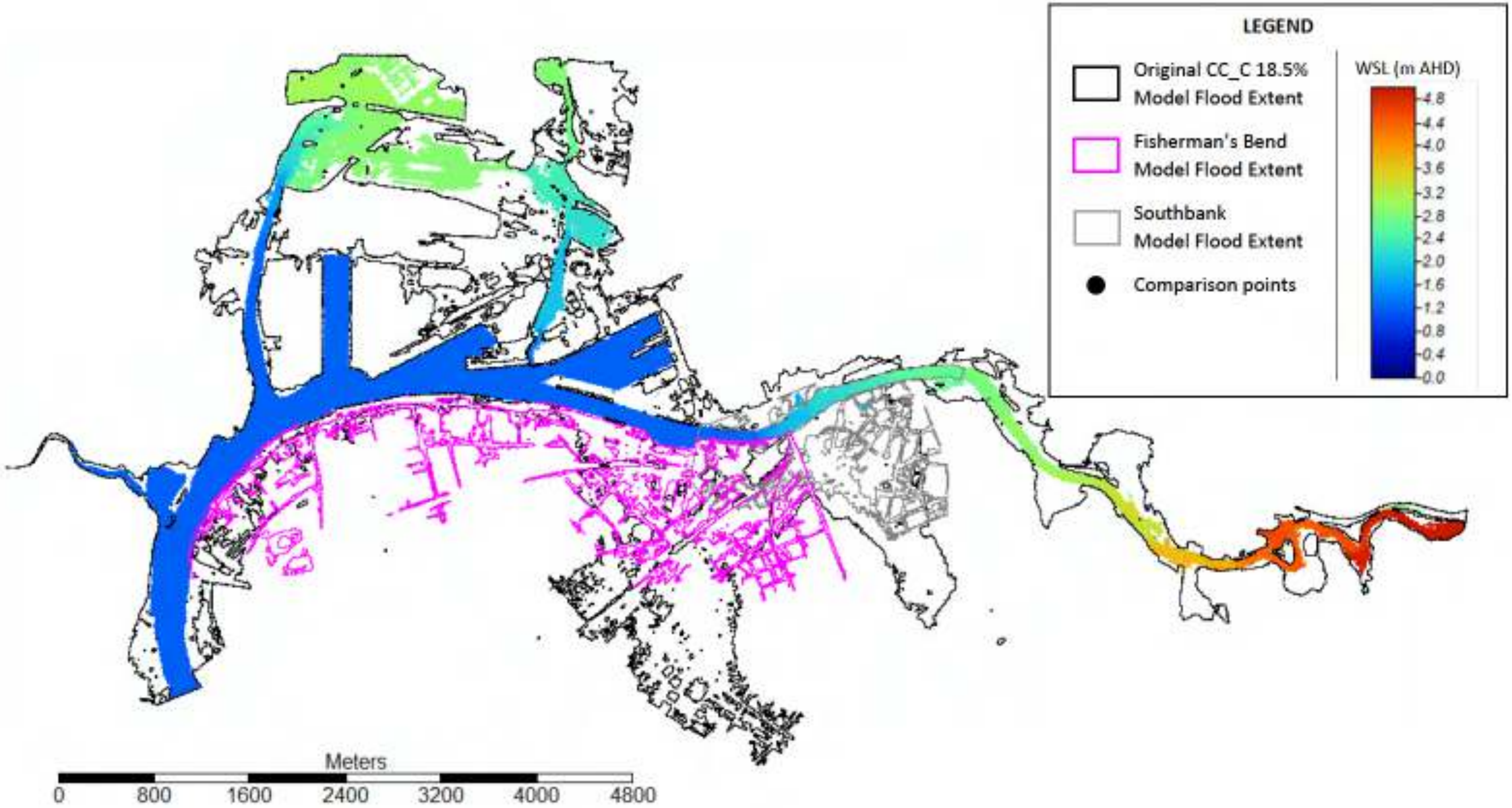


Figure 3 Kc=237 Yarra River Model Peak 100y WSL (10y Tide)

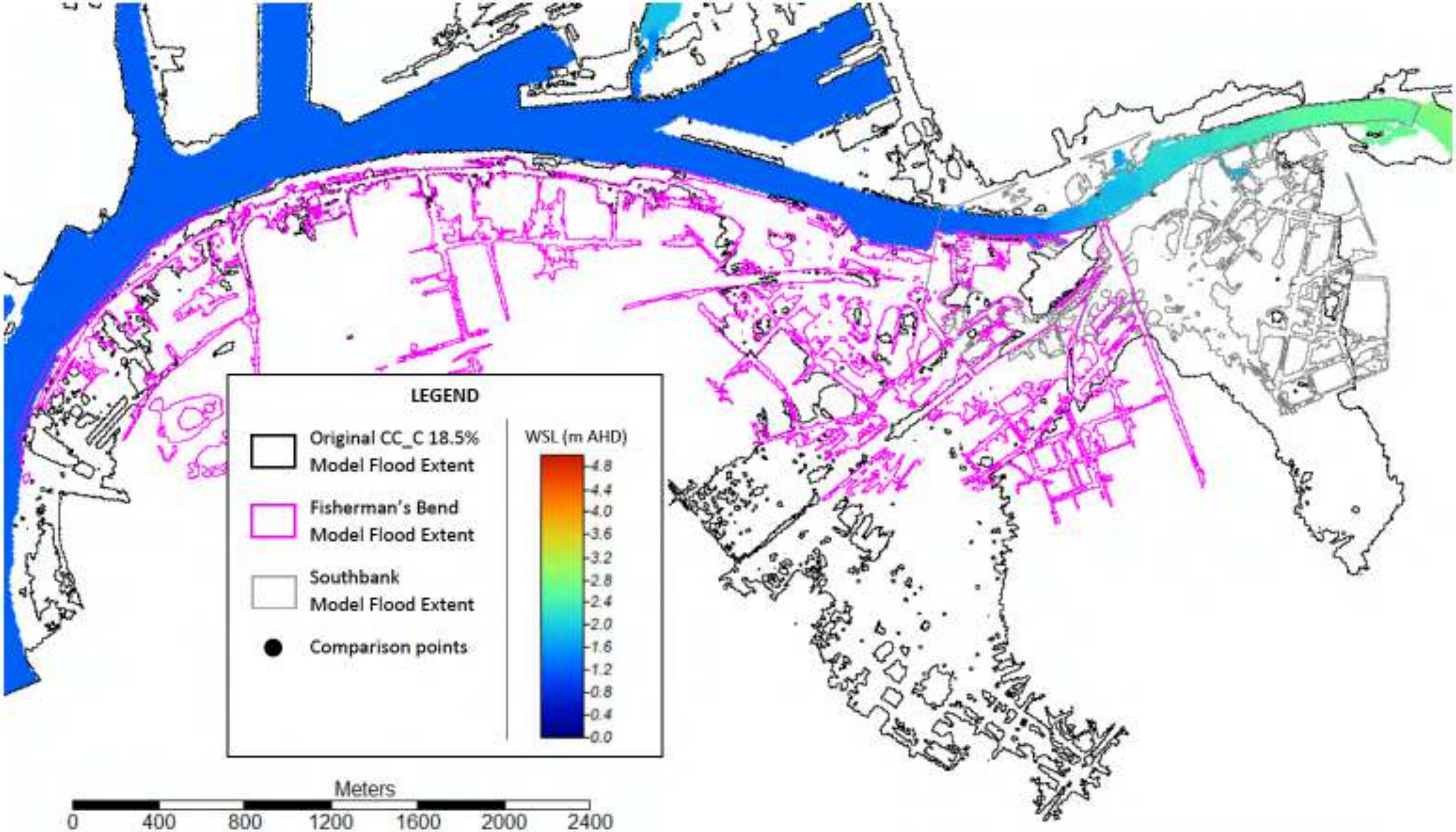


Figure 3B Kc=237 Yarra River Model Peak 100y WSL (10y Tide) – Zoomed to overflow refinement area

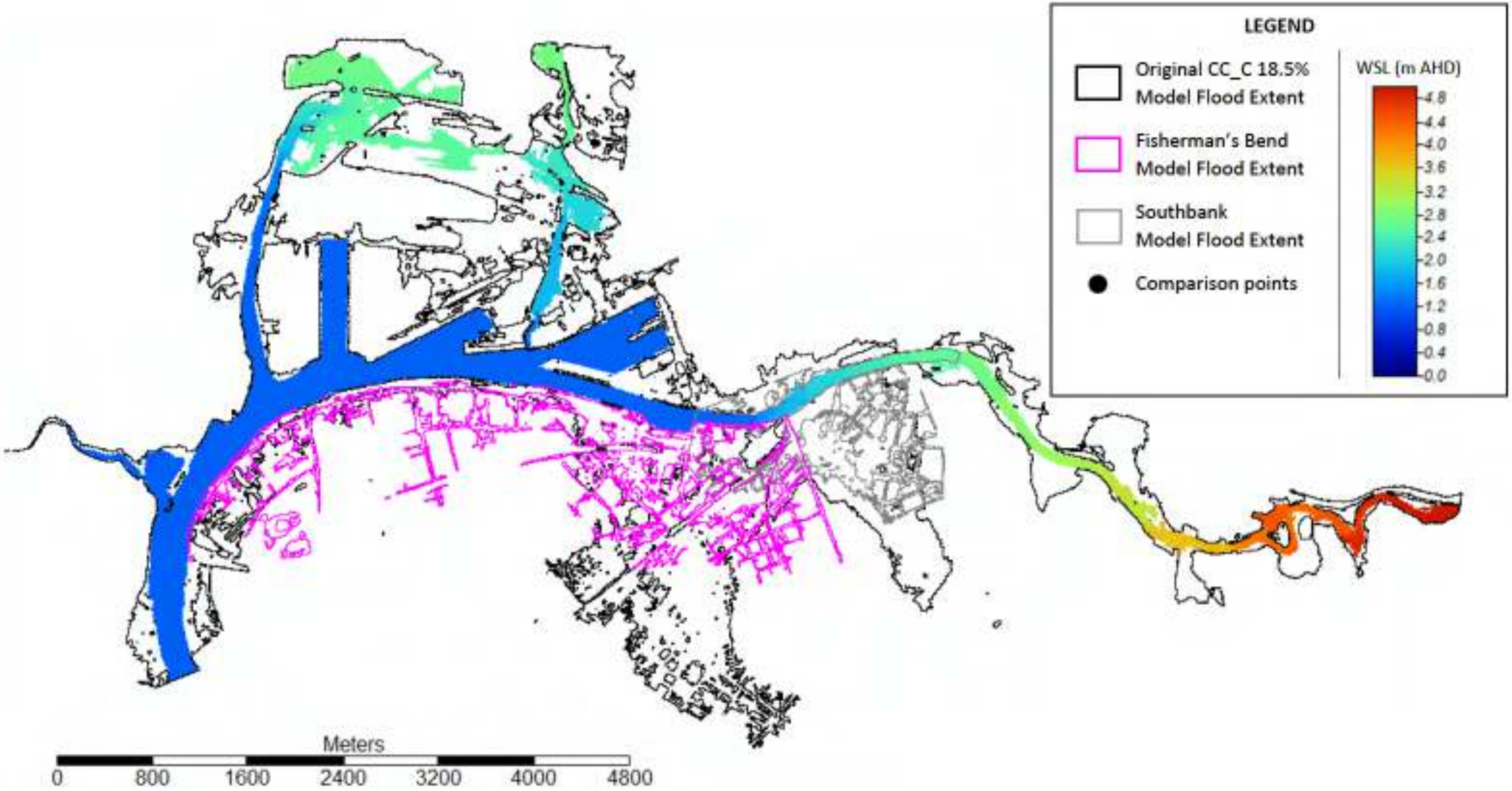


Figure 4 Kc=180 (incl. ARF) Yarra River Model Peak 100y WSL (10y Tide)

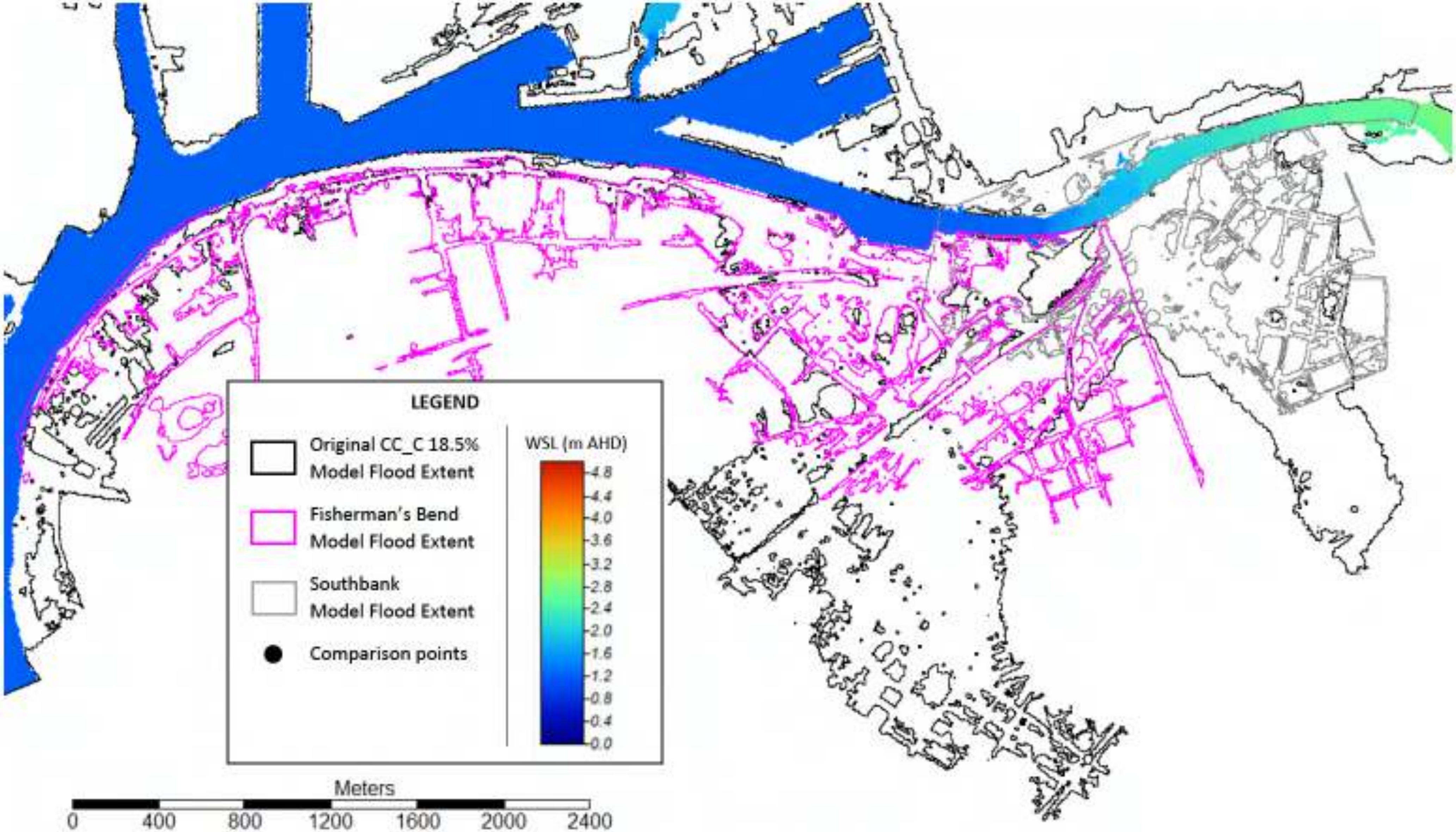


Figure 4B Kc=180 (incl. ARF) Yarra River Model Peak 100y WSL (10y Tide) – Zoomed to overflow refinement area

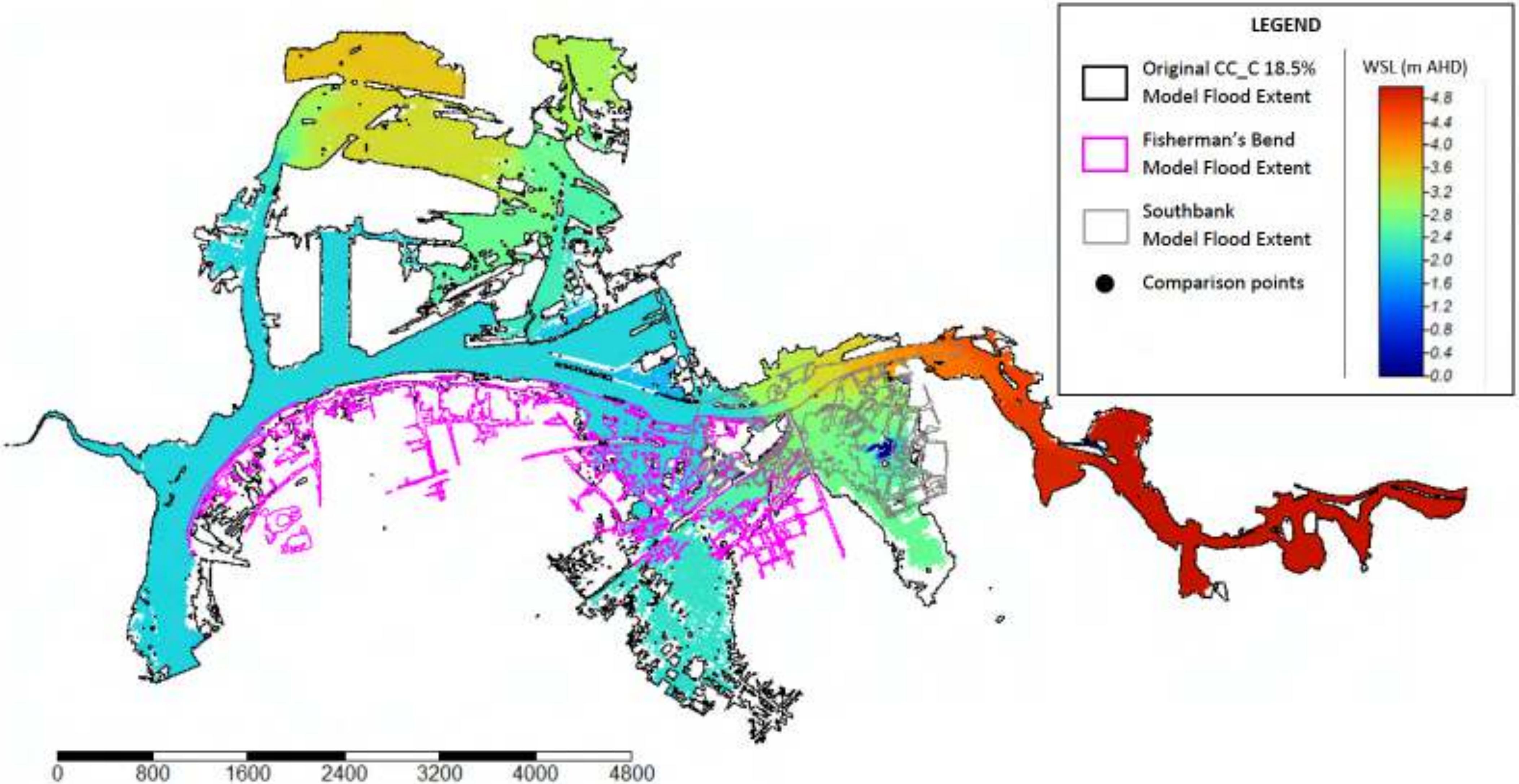


Figure 5 Current CC18p5 (Kc=145) Yarra River Model Peak 100y WSL (10y SLR Tide)

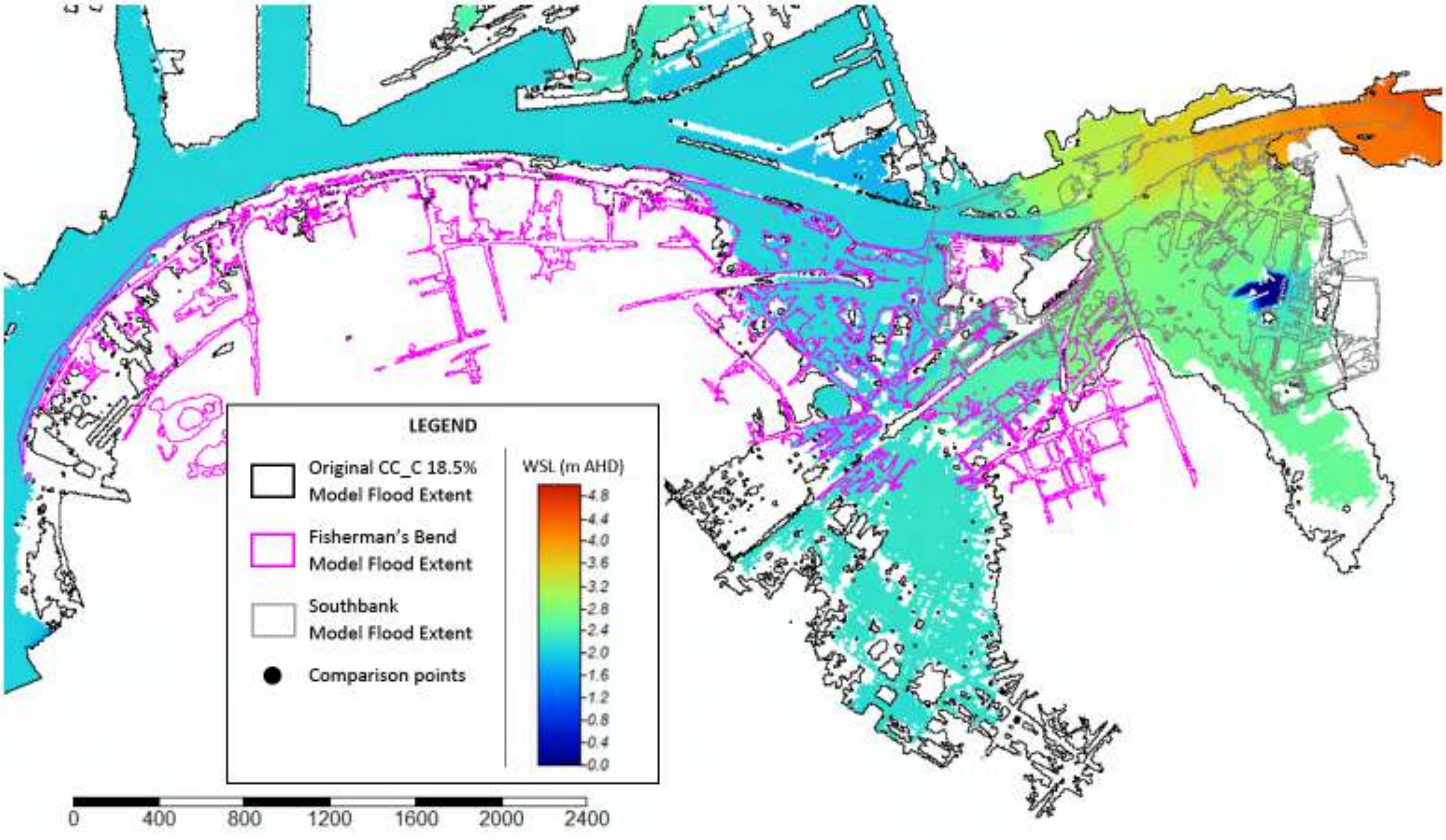


Figure 5B Current CC18p5 (Kc=145) Yarra River Model Peak 100y WSL (10y SLR Tide) – Zoomed to overflow refinement area

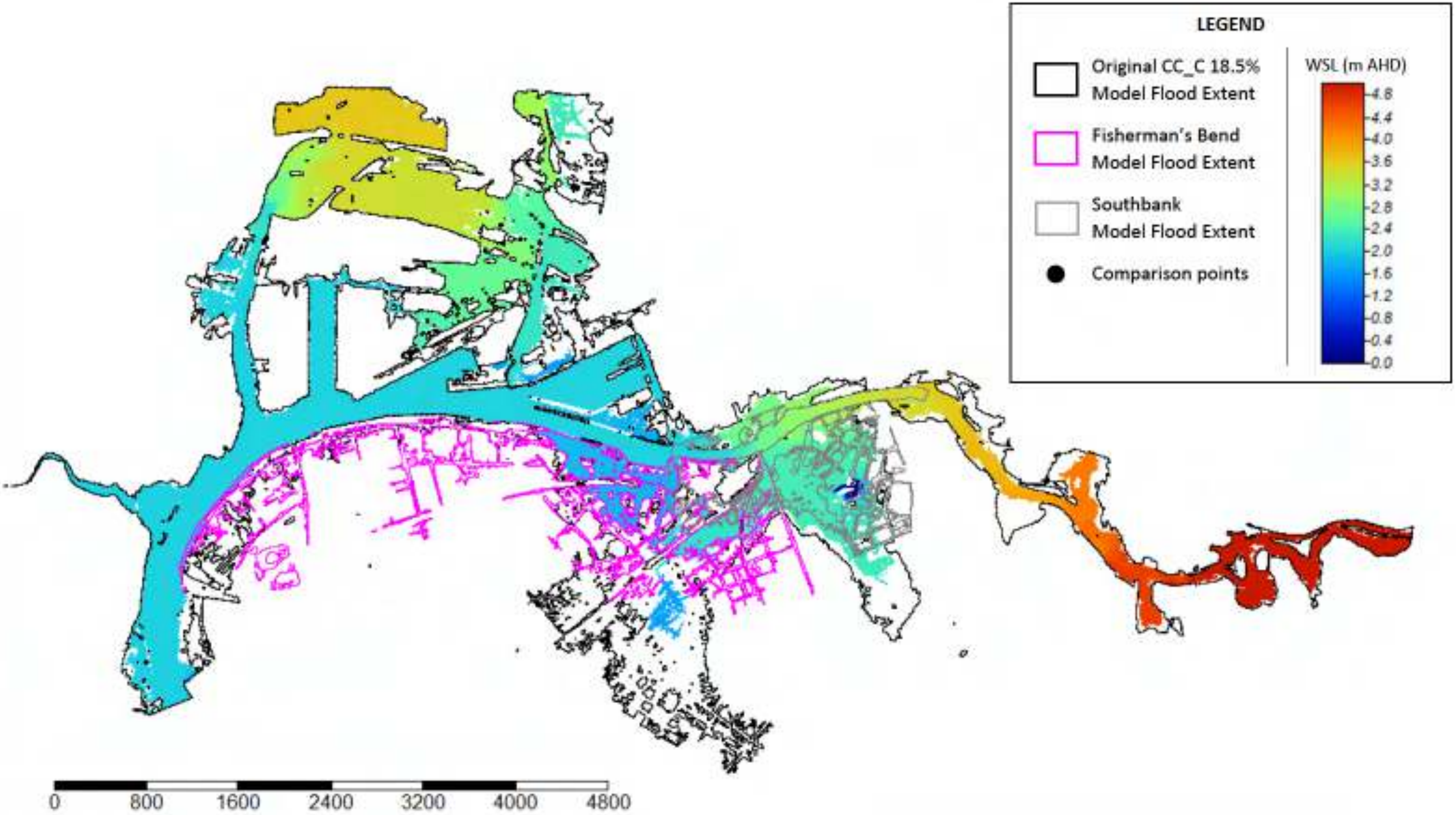


Figure 6 Kc=237 CC18p5 Yarra River Model Peak 100y WSL (10y SLR Tide)

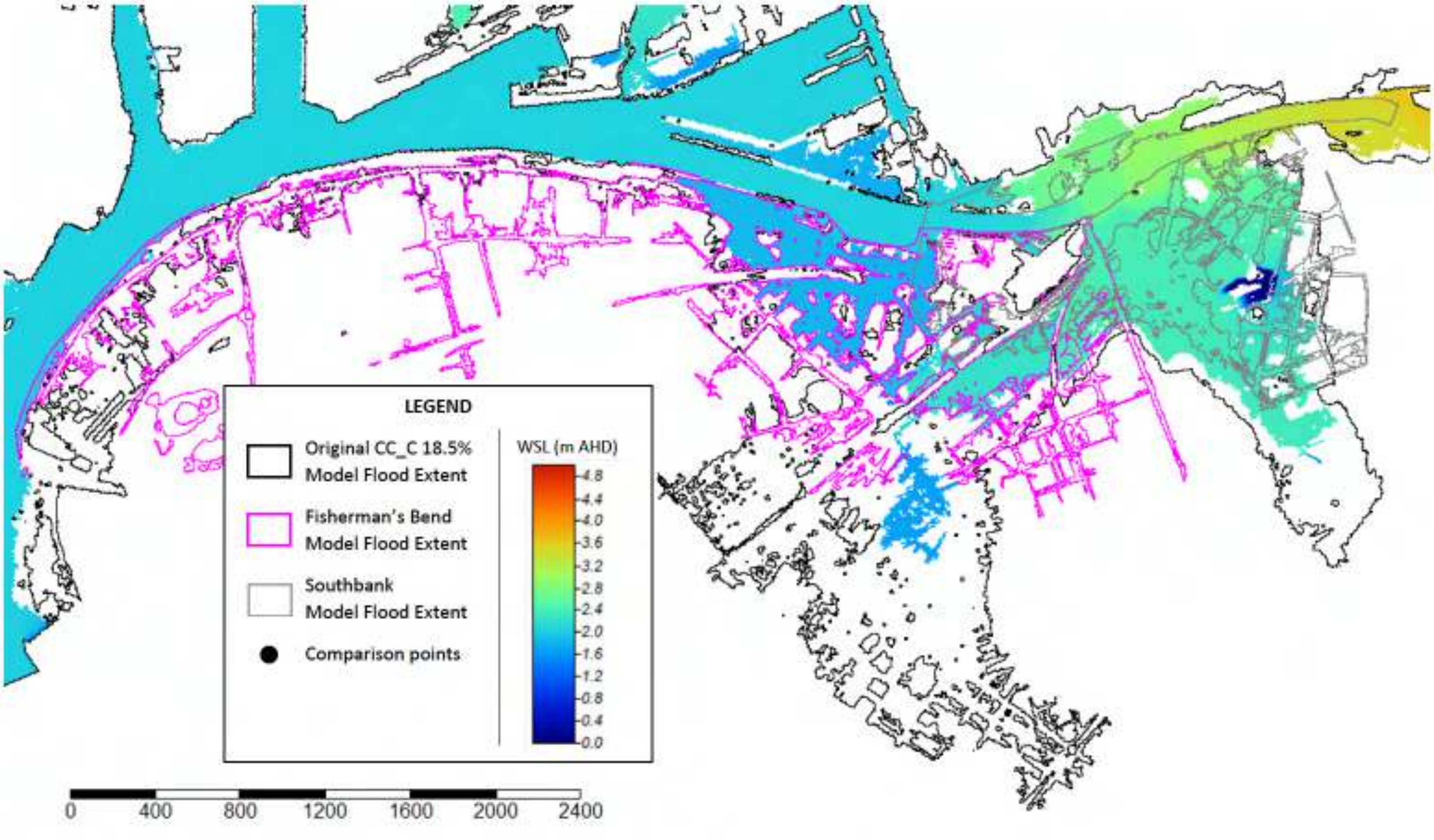


Figure 6B Kc=237 CC18p5 Yarra River Model Peak 100y WSL (10y SLR Tide) – Zoomed to overflow refinement area

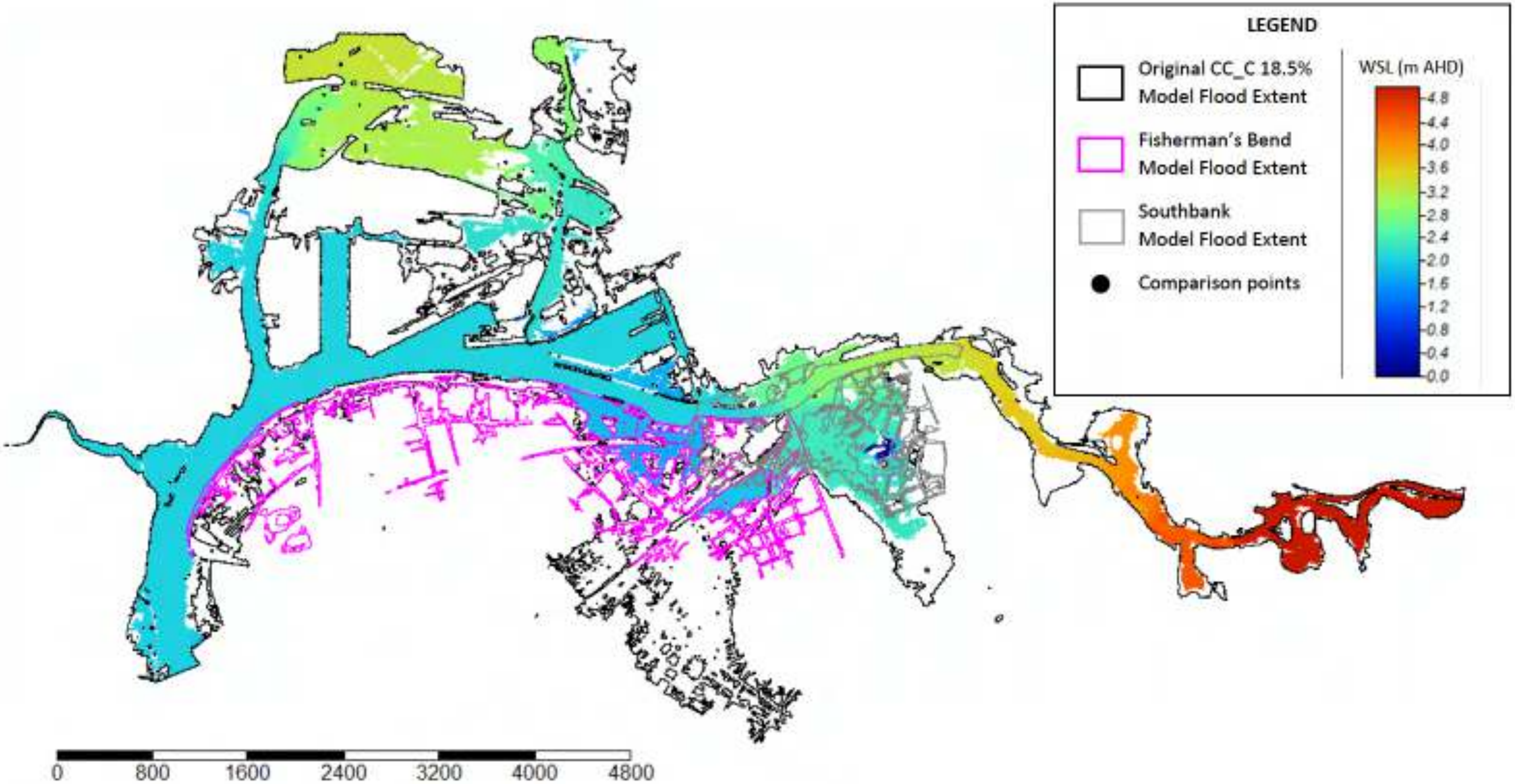


Figure 7 Kc=180 CC18p5 (incl. ARF) Yarra River Model Peak 100y WSL (10y SLR Tide)

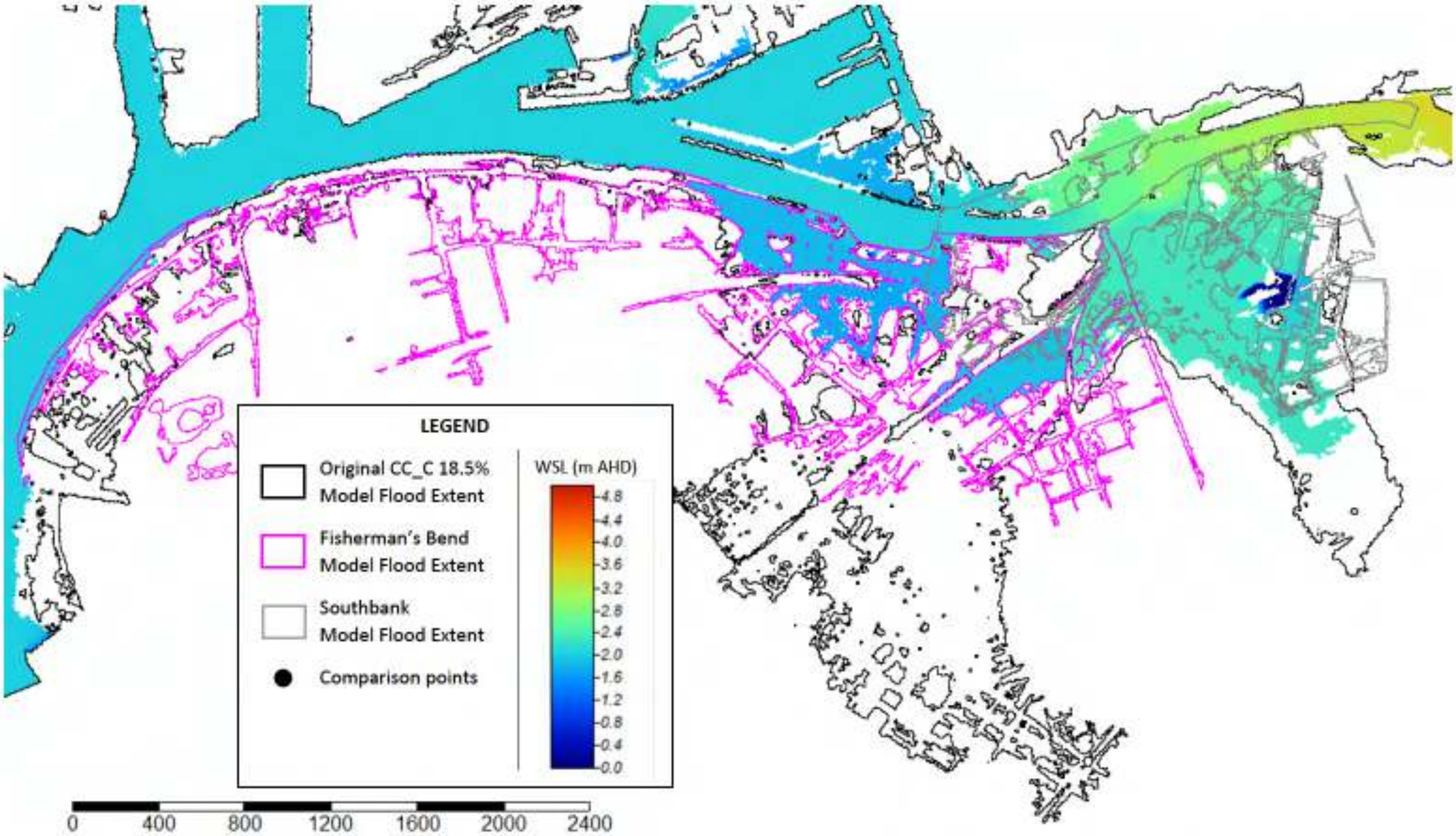


Figure 7B Kc=180 CC18p5 (incl. ARF) Yarra River Model Peak 100y WSL (10y SLR Tide) – Zoomed to overflow refinement area

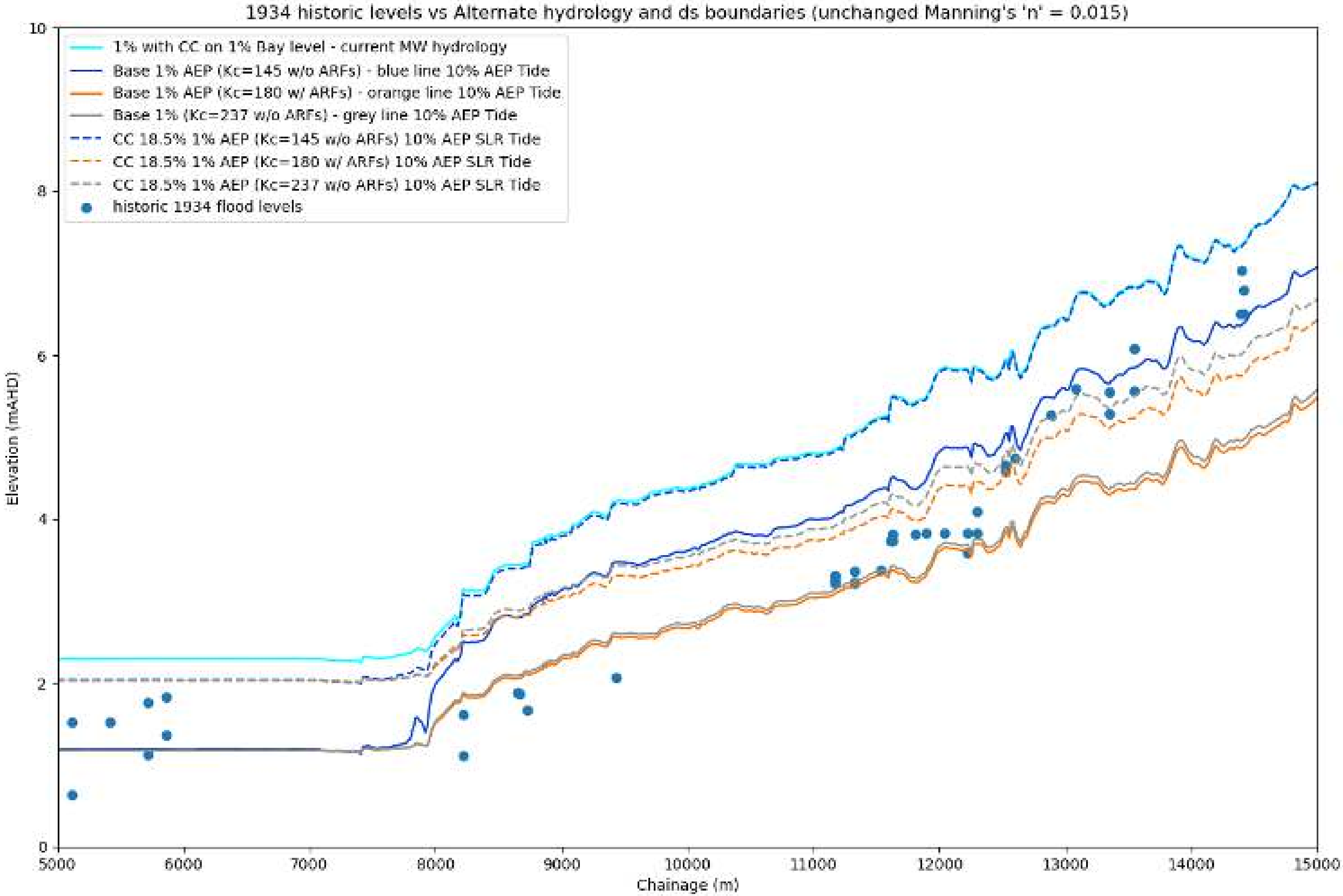


Figure 8 Comparison of WSL Long-Section along Yarra River

Table 2 Comparison Point Locations – Base 100y Flows with 10y Tide

ID	Description	1% AEP w/ 1% AEP SLR Tide	1% AEP w/ 10% AEP Tide			1% AEP w/ 10% AEP SLR Tide				
		Current (Kc=145)	Current (Kc=145)	Kc=237	Kc=180 (incl. ARF)	Current (Kc=145)	Kc=237	Kc=180 (incl. ARF)	Fishbend	Southbank
1	Yarra River 1 (US)	4.22	3.48	2.60	2.55	4.19	3.43	3.31	-	2.14
2	Yarra River 2	3.45	2.81	2.10	2.06	3.40	2.89	2.81	-	2.14
3	Yarra River 3	2.34	1.24	1.20	1.20	2.09	2.06	2.05	-	2.14
4	Yarra River 4	2.29	1.19	1.18	1.18	2.04	2.03	2.03	-	-
5	Yarra River 5 (DS)	2.29	1.19	1.18	1.18	2.04	2.03	2.03	-	-
6	South Bank Pond	2.72	2.31	-	-	2.69	2.36	2.30	-	1.28
7	Sth Park St	2.61	-	-	-	2.58	-	-	-	-
8	Fwy\Montague St	2.20	-	-	-	2.08	1.80	1.79	1.82	-
9	Lorimer St \ Boundary St	2.28	-	-	-	2.03	1.83	1.83	1.82	-
10	Approx. Boundary St \ Gittus St	2.20	1.53	-	-	2.08	1.80	1.70	1.82	-
11	Approx. Buckhurst St \ George St	2.44	2.13	-	-	2.41	2.21	1.91	1.89	-
12	Approx. Heath St \ Raglan St	2.21	-	-	-	2.19	-	-	-	-
13	Edwards Park	2.20	-	-	-	2.18	-	-	-	-
14	Approx. St Vincent St \ Iffla St	2.20	-	-	-	2.18	-	-	-	-

Figure 9 Location of Comparison Points

Table 3 Comparison Point Locations – Climate Change (18.5% increased intensity) 100y Flows with 10y SLR Tide

ID	1934 Flood Level	1% AEP w/ 1% AEP SLR Tide	1% AEP w/ 10% AEP Tide			1% AEP w/ 10% AEP SLR Tide		
		Current (Kc=145)	Current (Kc=145)	Kc=237	Kc=180 (incl. ARF)	Current (Kc=145)	Kc=237	Kc=180 (incl. ARF)
HL1	3.59	5.80	4.85	3.67	3.61	5.78	4.62	4.39
HL2	3.83	5.83	4.89	3.75	3.69	5.81	4.66	4.45
HL3	4.58	5.93	5.03	3.88	3.83	5.90	4.80	4.59
HL4	4.74	5.97	5.04	3.90	3.84	5.95	4.82	4.61
HL5	1.52	2.29	1.19	1.18	1.18	2.04	2.03	2.03
HL6	0.64	2.29	1.19	1.18	1.18	2.04	2.03	2.03
HL7	1.76	2.46	-	-	-	-	-	-
HL8	1.13	2.46	-	-	-	-	-	-
HL9	1.83	2.46	-	-	-	2.24	-	-
HL10	1.37	2.46	-	-	-	2.24	-	-
HL11	1.11	3.15	2.50	1.88	1.85	3.08	2.66	2.59
HL12	1.88	3.47	2.84	2.11	2.07	3.42	2.91	2.83
HL13	3.26	4.86	4.05	3.15	3.10	4.83	3.92	3.79
HL14	3.23	5.05	4.19	3.24	3.18	5.02	4.04	3.89
HL15	3.22	5.05	4.19	3.24	3.18	5.02	4.04	3.89
HL16	3.38	5.23	4.36	3.36	3.31	5.21	4.19	4.03
HL17	3.74	5.51	4.52	3.43	3.38	5.49	4.31	4.13
HL18	6.5	7.31	6.34	4.93	4.85	7.29	5.98	5.72
HL19	5.28	-	-	-	-	-	-	-
HL20	5.56	6.83	5.84	4.43	4.36	6.81	5.50	5.23
HL21	6.5	7.36	6.38	4.97	4.88	7.34	6.02	5.76
HL22	1.87	3.44	2.80	2.09	2.06	3.39	2.88	2.80
HL23	3.83	5.80	4.85	3.67	3.61	5.78	4.62	4.39
HL24	4.09	5.83	4.89	3.75	3.69	5.81	4.66	4.45
HL25	4.64	5.93	5.03	3.88	3.83	5.90	4.80	4.59
HL26	6.08	6.84	5.85	4.40	4.32	6.82	5.51	5.23
HL27	7.03	7.03	6.07	4.68	4.60	7.02	5.72	5.46
HL28	1.61	3.15	2.50	1.88	1.85	3.08	2.66	2.59
HL29	6.79	7.36	6.38	4.97	4.88	7.34	6.02	5.76
HL30	4.66	5.93	5.03	3.88	3.83	5.90	4.80	4.59
HL31	5.27	5.96	-	-	-	5.96	-	-
HL32	3.22	4.86	4.05	3.15	3.10	4.83	3.92	3.79
HL33	2.06	4.22	3.48	2.61	2.56	4.18	3.43	3.31
HL34	3.82	5.43	4.40	3.33	3.28	5.41	4.21	4.01
HL35	3.83	5.48	4.46	3.35	3.30	5.46	4.26	4.03
HL36	3.74	5.33	4.46	3.42	3.36	5.31	4.27	4.10
HL37	3.83	5.72	4.81	3.79	3.74	5.70	4.65	4.49
HL38	1.52	2.29	1.19	1.18	1.18	2.04	2.03	2.03
HL39	3.31	4.86	4.05	3.15	3.10	4.83	3.92	3.79
HL40	3.82	5.51	4.52	3.43	3.38	5.49	4.31	4.13
HL41	3.36	5.05	4.19	3.24	3.18	5.02	4.04	3.89
HL42	5.55	-	-	-	-	-	-	-
HL43	1.67	3.45	2.83	2.15	2.12	3.40	2.90	2.82
HL44	5.59	6.84	5.88	4.58	4.50	6.82	5.57	5.32

Figure 10 **Location of 1934 Historic Flood Levels**

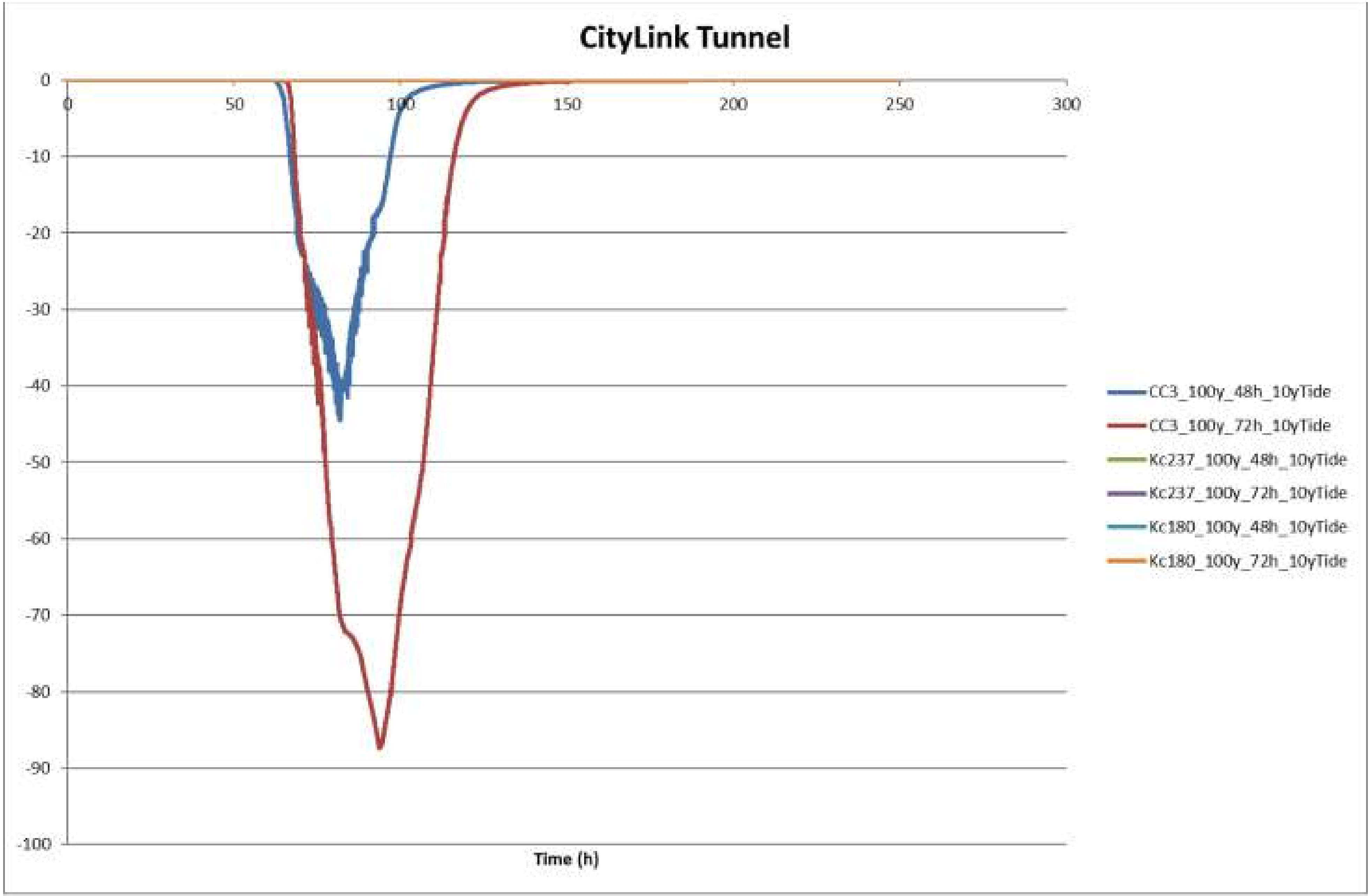


Figure 11 **Flow leaving model via City Link Tunnel portal near Southbank with Base Case hydrology**

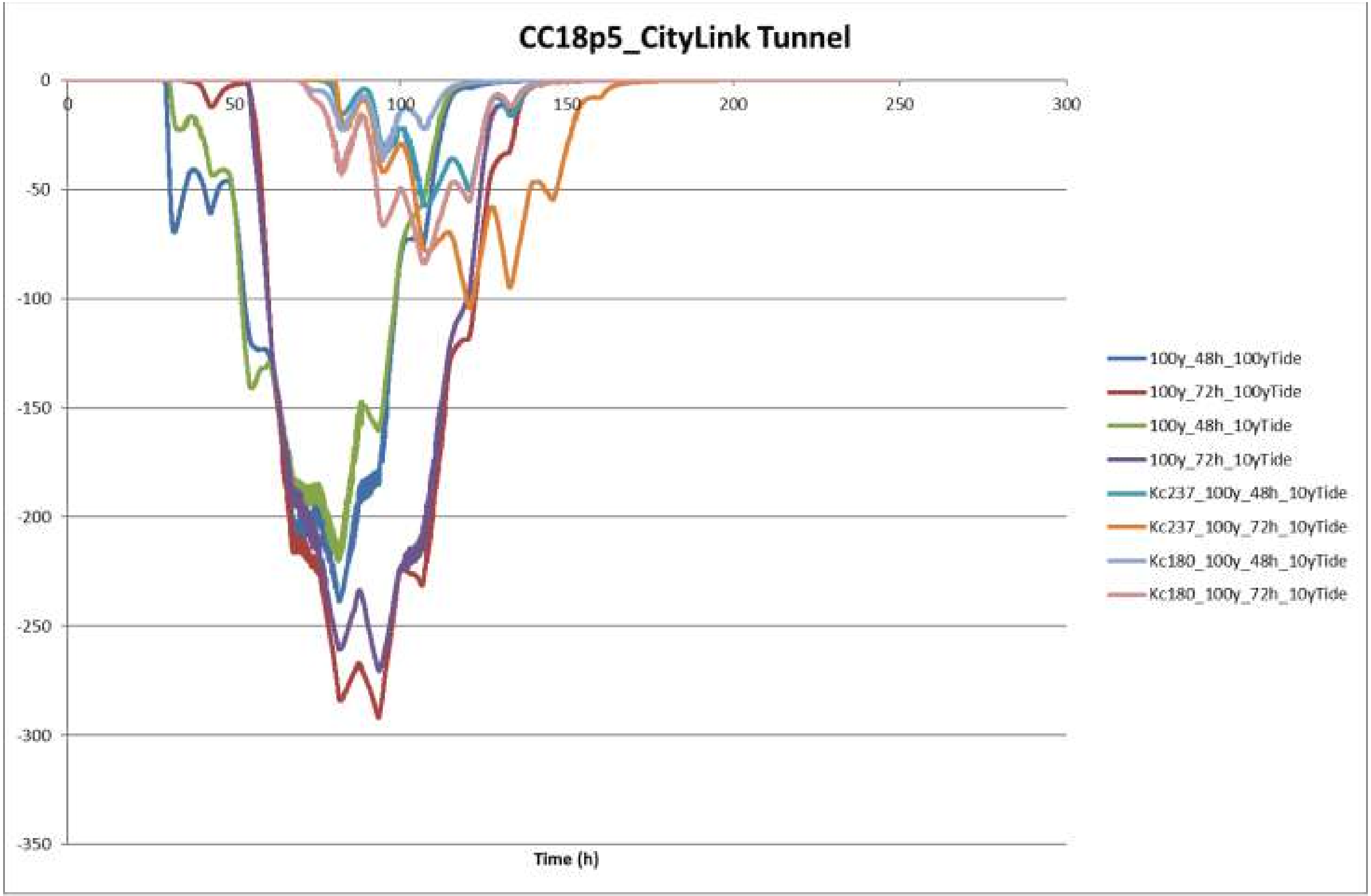


Figure 12 **Flow leaving model via City Link Tunnel portal near Southbank with Climate Change (18.5%) hydrology**

Table 4 Southbank City Link Tunnel Portal Flows & Volumes

Scenario	Peak Flow (m^3/s)	Peak Volume (m^3)
Current CC18p5 (Kc=145) - 1% AEP SLR Tide	-292.03	-51,296,280
Current CC18p5 (Kc=145) - 10% AEP SLR Tide	-270.58	-46,754,266
Kc=237 CC18p5 - 10% AEP SLR Tide	-104.48	-14,283,613
Kc=180 CC18p5 (incl. ARF) - 10% AEP SLR Tide	-83.89	-9,027,424
Current (Kc=145) - 10% SLR Tide	-87.37	-9,669,632
Kc=237 - 10% AEP Tide	0	0
Kc=180 (incl. ARF) - 10% AEP Tide	0	0

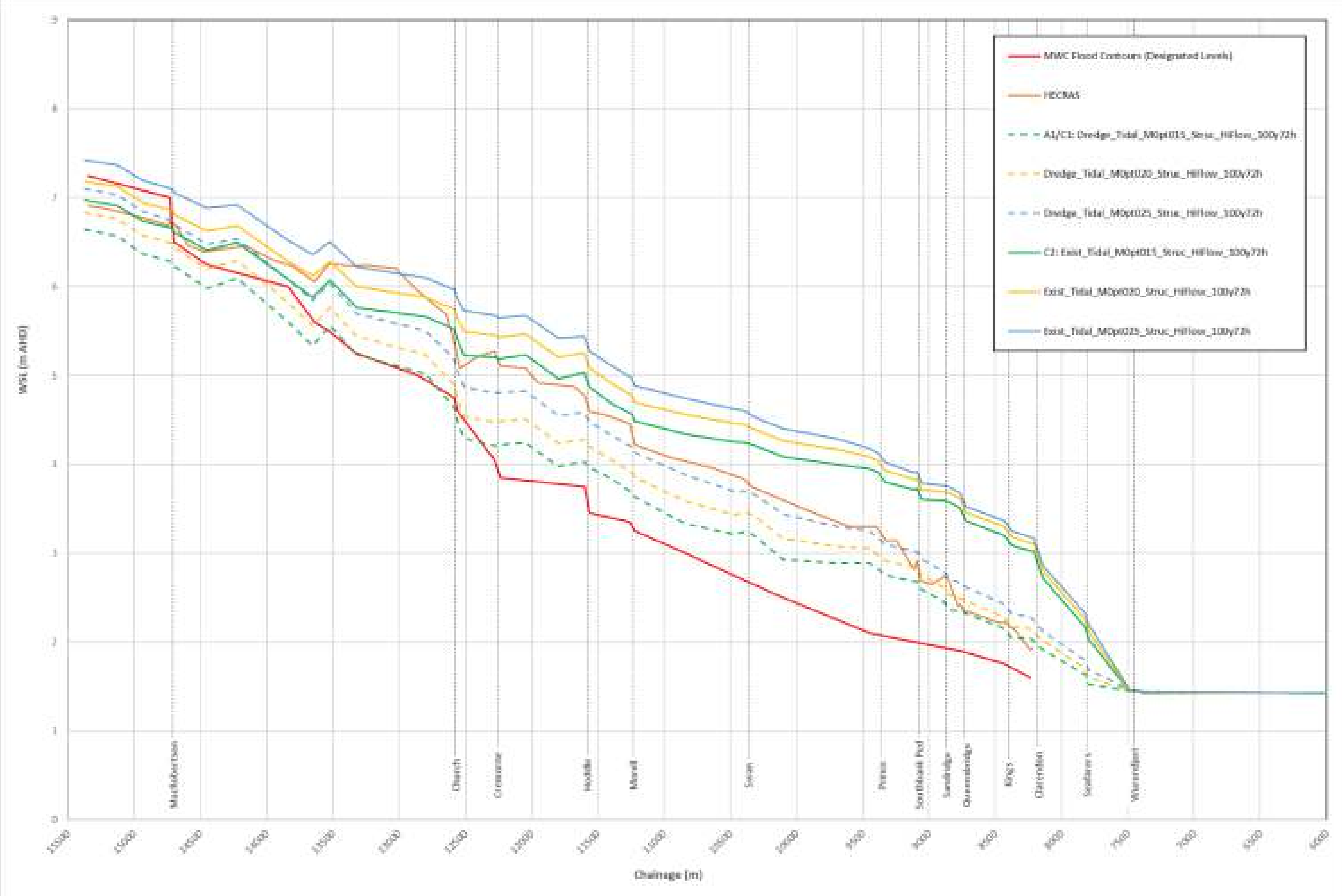


Figure 13 **Waterway Manning's 'n' roughness Sensitivity Modelling**
(results from modelling undertaken for "Modelling Assumption and Implications Memo")

Attachment 6

Phase 3 Southbank Overflow Refinement Results Memo

Stage 1A – Summary of Results Post-Overflow Refinements

Table of contents

Table index

Figure index

1. Project Diary

Table 1 summarises of the agreed model refinements carried out on the Lower Yarra River Flood Mapping TUFLOW model since the delivery of the 'Draft Deliverables' in February 2020.

Table 1 Progression of Model Refinement

Date	Time	Description\Outcome
23-04-2020	9:00 am	Skype meeting to discuss the Lower Yarra mapping limit
28-04-2020	5:29 pm	Emailed proposal $######
29-04-2020	8:30 am	Meeting to discuss scope for Lower Yarra
29-04-2020	12:58 pm	Revised proposal $######
29-04-2020	3:24 pm	MW accepted revised proposal
06-05-2020	10:19 pm	GHD provide Stage 1A results
07-05-2020	10:00 am	Discussion of stage 1A results
07-05-2020	3:30 pm	Meeting to discuss next steps
08-05-2020	10:07 am	Email to MW clarifying scope, fees and discussions with NELP
08-05-2020	2:50 pm	Emails back and forth, MW emailed NELP with formal request
08-05-2020	3:12 pm	MW confirm request for all 6 runs.
12-05-2020	2:57 pm	GHD provide results for the additional 6 runs
13-05-2020	8:30 am	Meeting to discuss results
13-05-2020	3:11 pm	GHD provided email to summarise revised scope
14-05-2020	3:21 pm	MW request information of the 10year tidal boundary time series
14-05-2020	3:45 pm	GHD referred MW to Appendix C of the report
15-05-2020	7:17 am	MW requested GHD to proceed in accordance with revised scope (13/5)
15-05-2020	3:58 pm	MW provide additional info on 1934 event
15-05-2020	4:10 pm	GHD advised that we had responded to NELP and expected that NELP would advise MW of their decision
18-05-2020	6:00 pm	NELP approve use of existing conditions TUFLOW and RORB models for MW

2. Preliminary Results for Discussion

2.1 Modelled Scenarios

Table 2 summarises the modelled scenarios completed since the initial overflow refinement modelling, which added terrain details from the Southbank and Fisherman's Bend TUFLOW models, a new boundary condition at the City Link portal in Southbank area, and a DS tidal boundary based on 10% AEP.

Table 2 Modelled Scenarios

Runs	Hydrology	Yarra River Inflow (m^3/s)	Yarra River Inflow Volume (m^3)	DS TWL	River Roughness (Manning's 'n')	Plot Legend
1	Base 1% AEP (Kc=145 w/o ARFs)[1] [Solid blue line on Figure 1]	1475	517,000,000	10% AEP Tide	0.015	100y Kc145 NoARF M0p015 (Current)
2	Base 1% (Kc=237 w/o ARFs)[2] [Solid orange line on Figure 1]	1115	517,000,000	10% AEP Tide	0.015	100y Kc237 NoARF M0p015
3	Base 1% AEP (Kc=180 w/ ARFs)[3] [Solid green line on Figure 1]	1091	432,000,000	10% AEP Tide	0.015	100y Kc180 ARF M0p015
4	CC 18.5% 1% AEP (Kc=145 w/o ARFs)[1] [Dashed blue line on Figure 1]	1792	621,000,000	10% AEP SLR Tide	0.015	100y CC18p5 Kc145 NoARF M0p015 (Current)
5	CC 18.5% 1% AEP (Kc=237 w/o ARFs)[2] [Dashed green line on Figure 1]	1352	621,000,000	10% AEP SLR Tide	0.015	100y CC18p5 Kc237 NoARF M0p015
6	CC 18.5% 1% AEP (Kc=180 w ARFs)[3] [Dashed green line on Figure 1]	1293	509,000,000	10% AEP SLR Tide	0.015	100y CC18p5 Kc180 ARF M0p015
7	Base 1% AEP (Kc=180 w/ ARFs)[3]	-	-	10% AEP Tide	0.020	100y Kc180 ARF M0p020
8	Base 1% AEP (Kc=180 w/ ARFs)[3]	-	-	10% AEP Tide	0.025	100y Kc180 ARF M0p025
9	Base 1% AEP (Kc=180 w/ ARFs)[3]	-	-	10% AEP Tide	0.030	100y Kc180 ARF M0p030
10	CC 18.5% 1% AEP (Kc=180 w ARFs)[3]	-	-	10% AEP SLR Tide	0.020	100y CC18p5 Kc180 ARF M0p020
11	CC 18.5% 1% AEP (Kc=180 w ARFs)[3]	-	-	10% AEP SLR Tide	0.025	100y CC18p5 Kc180 ARF M0p025
12	CC 18.5% 1% AEP (Kc=180 w ARFs)[3]	-	-	10% AEP SLR Tide	0.030	100y CC18p5 Kc180 ARF M0p030
13	CC 18.5% 10% AEP (Kc=145 w/o ARFs)[1]	831	291,000,000	10% AEP SLR Tide	0.015	10y Kc145 NoARF M0p015 (Current)
14	CC 18.5% 10% AEP (Kc=180 w ARFs)[3]	616	246,000,000	10% AEP SLR Tide	0.020	10y CC18p5 Kc180 ARF M0p020
15	CC 18.5% 10% AEP (Kc=180 w ARFs)[3]	616	246,000,000	10% AEP SLR Tide	0.030	10y CC18p5 Kc180 ARF M0p030

Note:

[1] indicates that the Kc parameter is based on calibration to flood levels using HEC-RAS from "2010 - SP Goh & Associates Study", which didn't use ARFs.

[2] indicates that the Kc parameter is based on calibration to gauge flows from "2010 - SP Goh & Associates Study" , which didn't use ARFs

[3] indicates that the Kc parameter is based on MW work prior to "2010 - SP Goh & Associates Study", but with the application of ARFs

2.2 Yarra River Boundary Conditions

Figure 1 and Figure 2 summarise the key boundary condition assumptions for the modelling presented in Section 2.1.

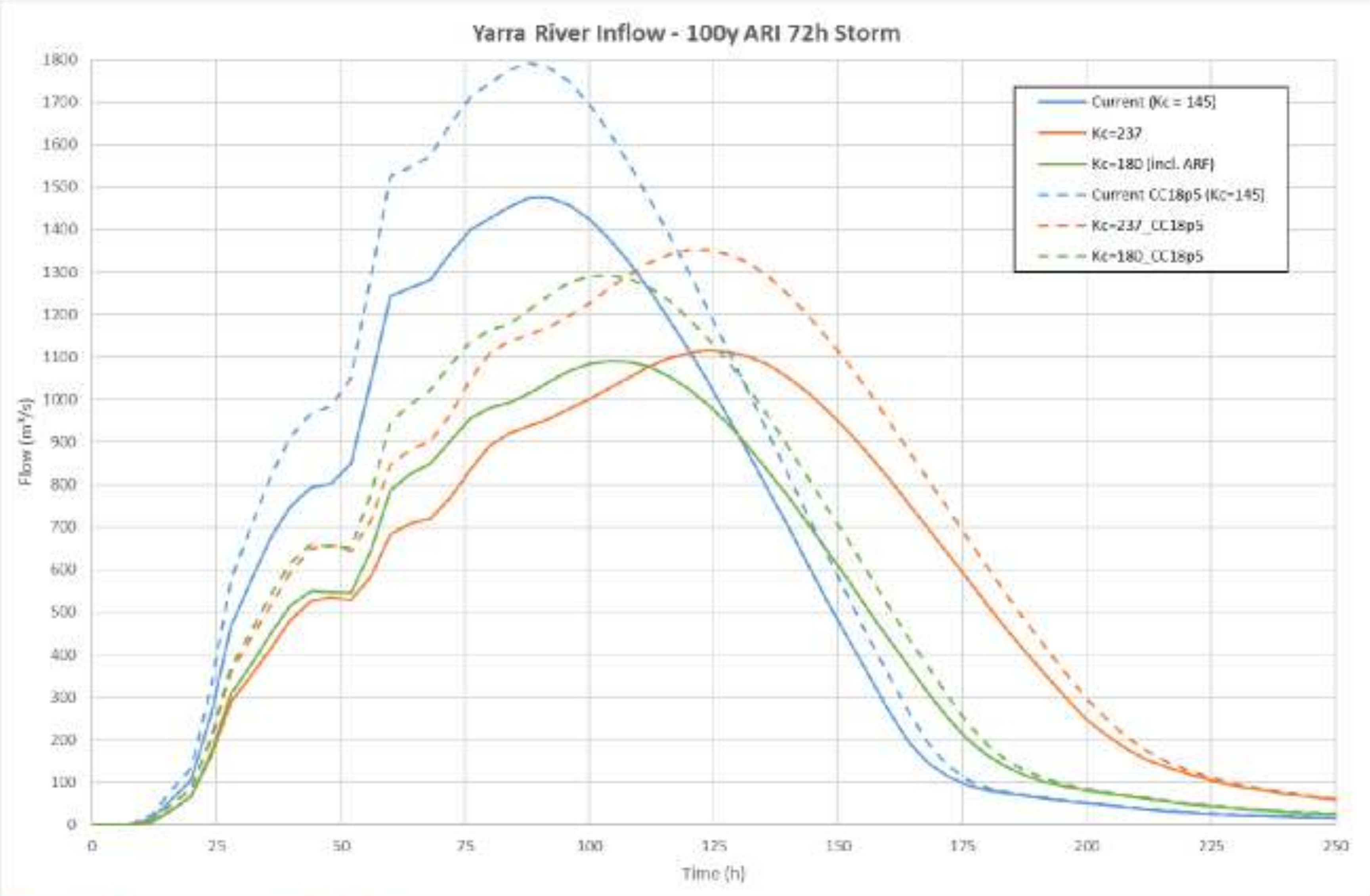


Figure 1 Comparison of Yarra Inflows

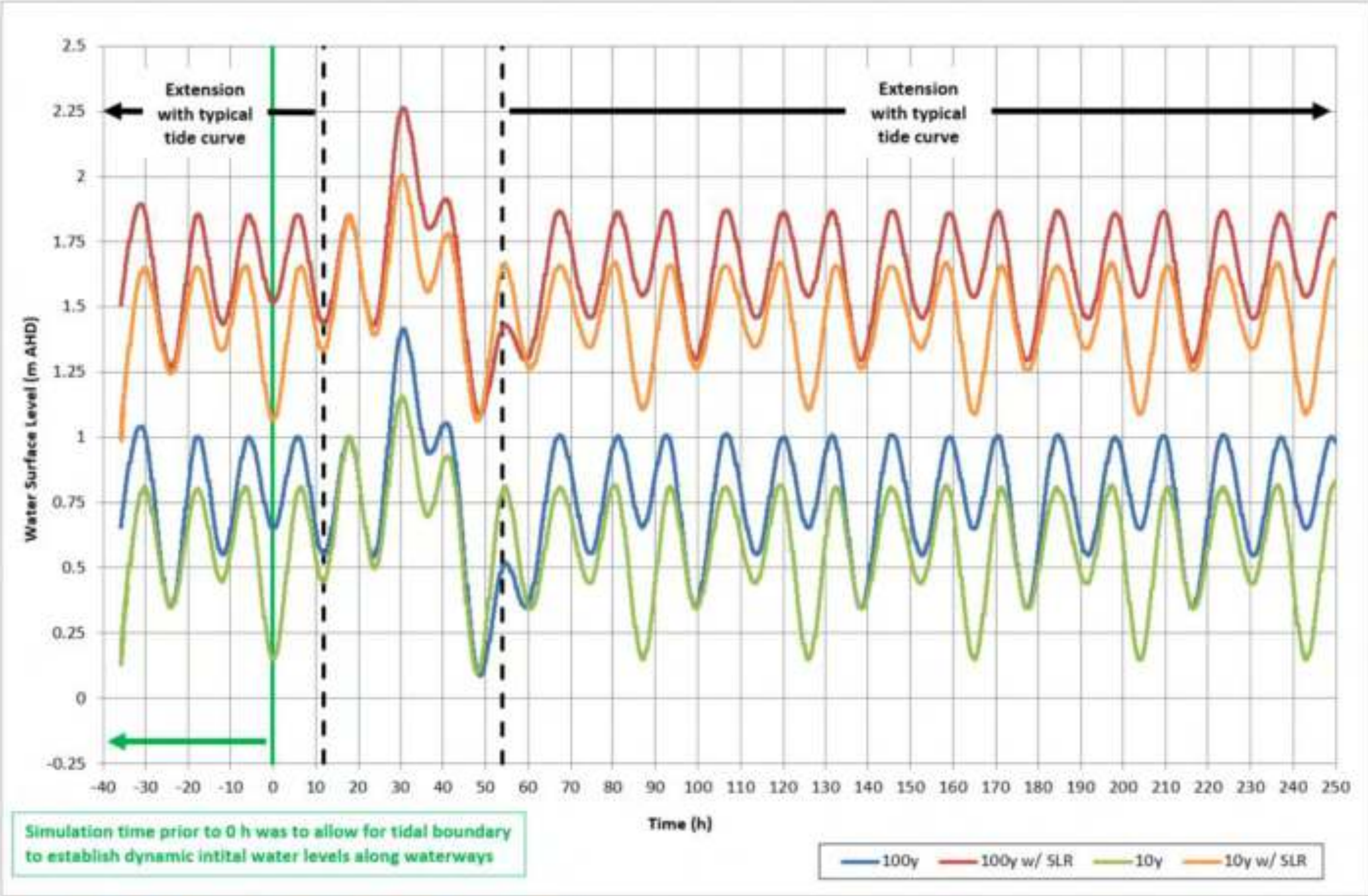


Figure 2 Adopted Yarra River DS Tidal Boundary Curves

2.3 Flood Extents

2.3.1 Run 1

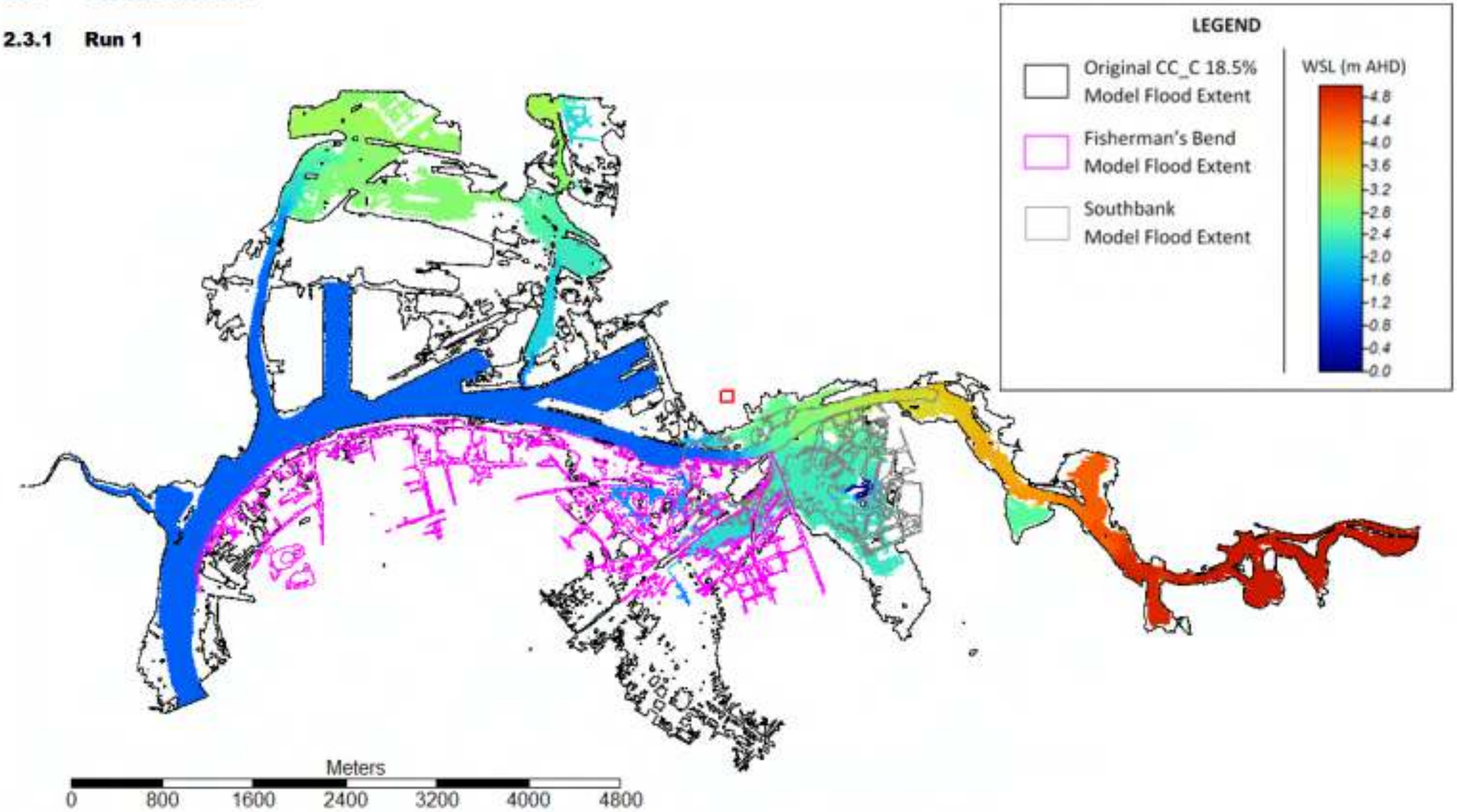


Figure 3 Peak 100y WSL Current (Kc=145 w/o ARFs, 10y Tide & River Manning's 'n' of 0.015)

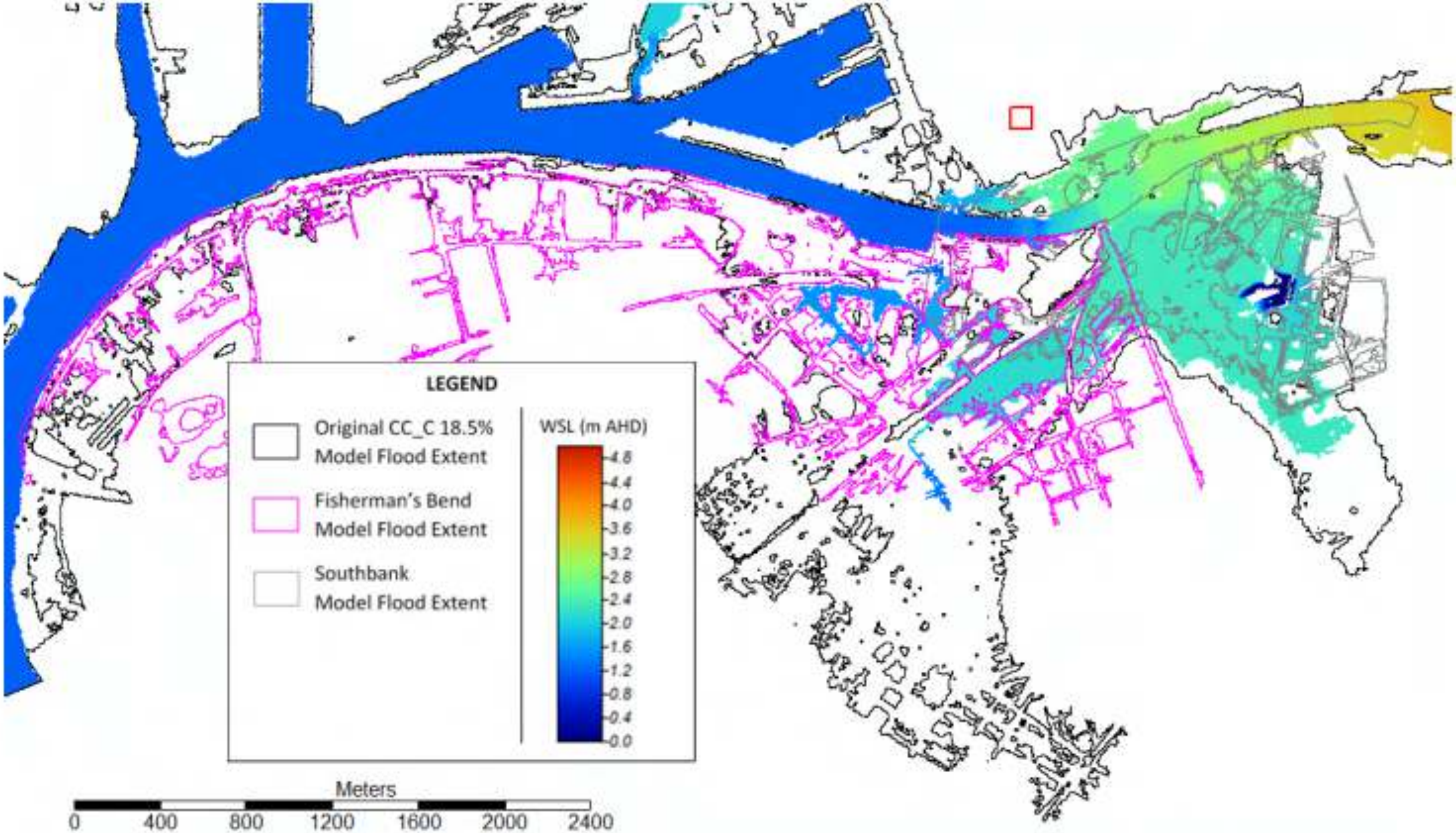


Figure 4 **Peak 100y WSL Current (Kc=145 w/o ARFs, 10y Tide & River Manning's 'n' of 0.015) – Zoomed to refinement area**

2.3.2 Run 2

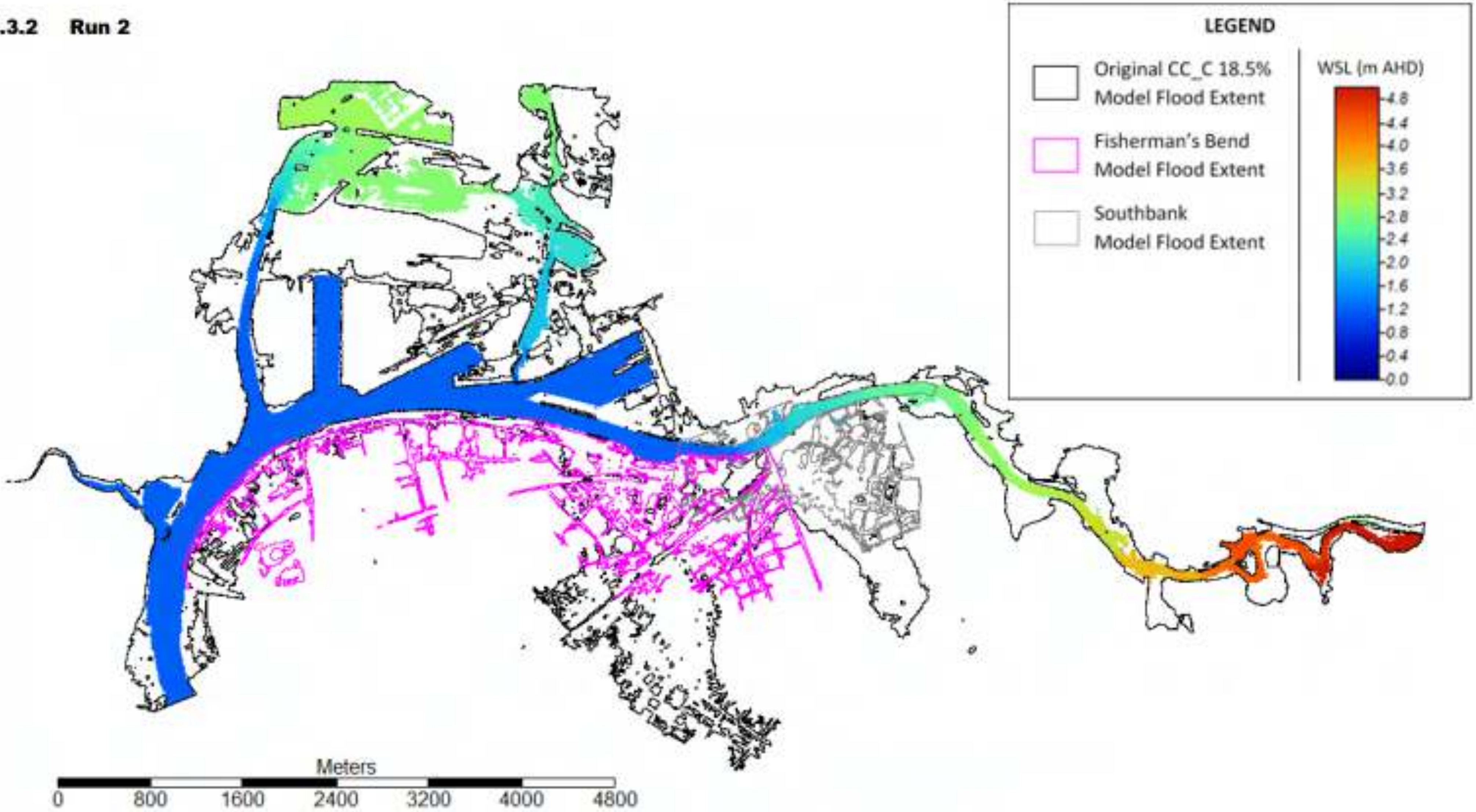


Figure 5 Peak 100y WSL Current (Kc=237 w/o ARFs, 10y Tide & River Manning's 'n' of 0.015)

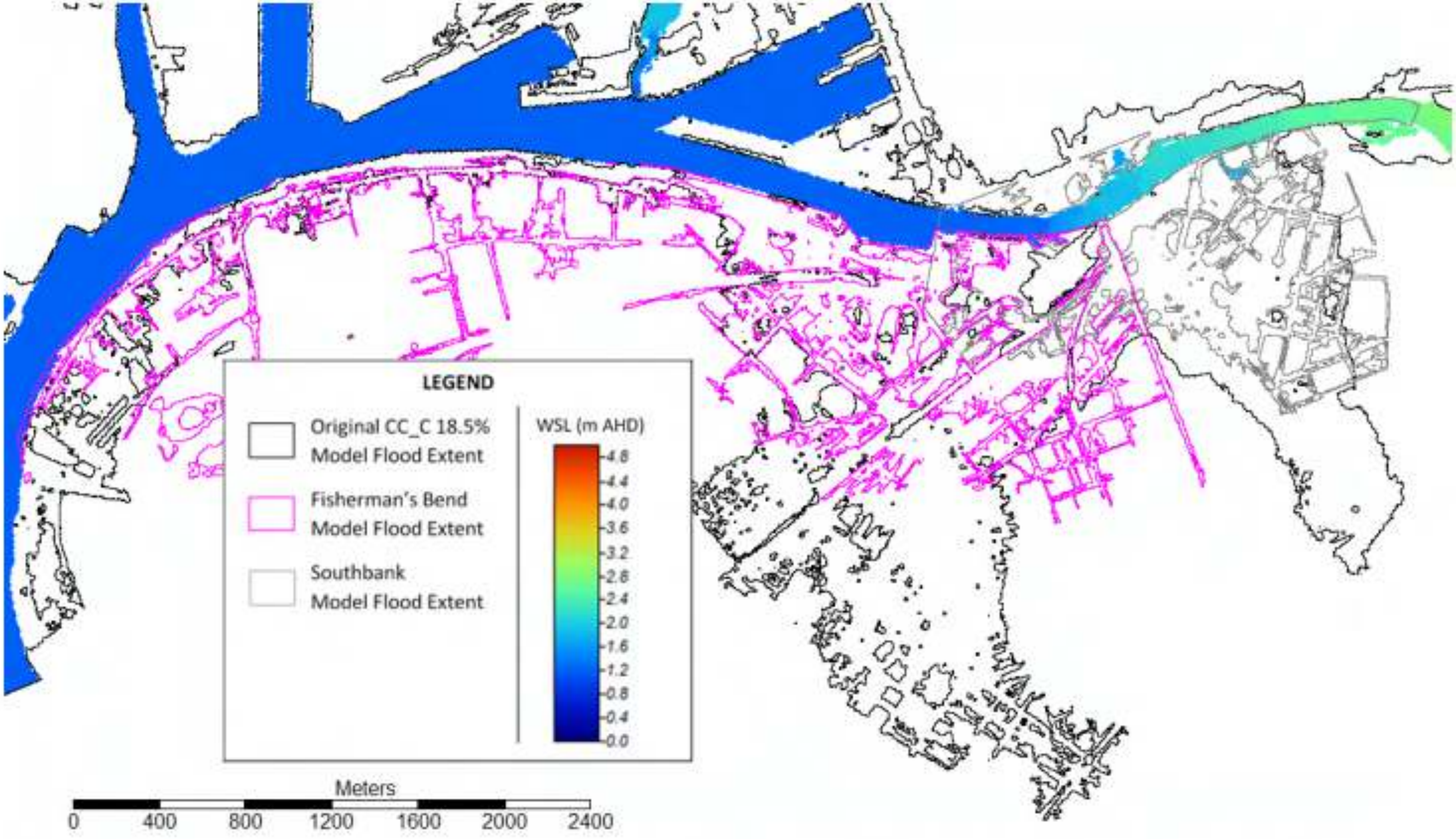


Figure 6 Peak 100y WSL Current (Kc=237 w/o ARFs, 10y Tide & River Manning's 'n' of 0.015) – Zoomed to refinement area

2.3.3 Run 3

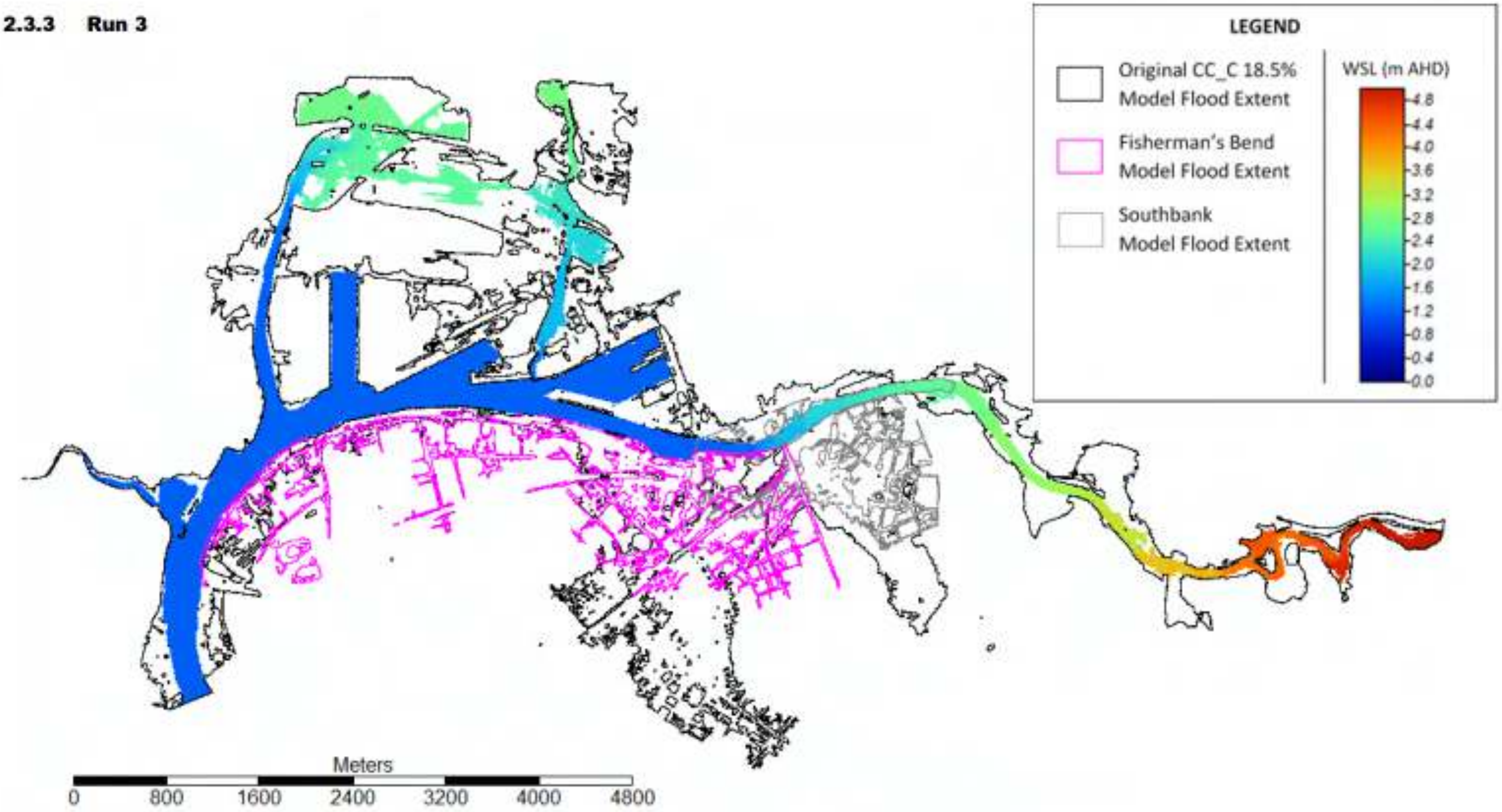


Figure 7 Peak 100y WSL Current (Kc=180 w/ ARFs, 10y Tide & River Manning's 'n' of 0.015)

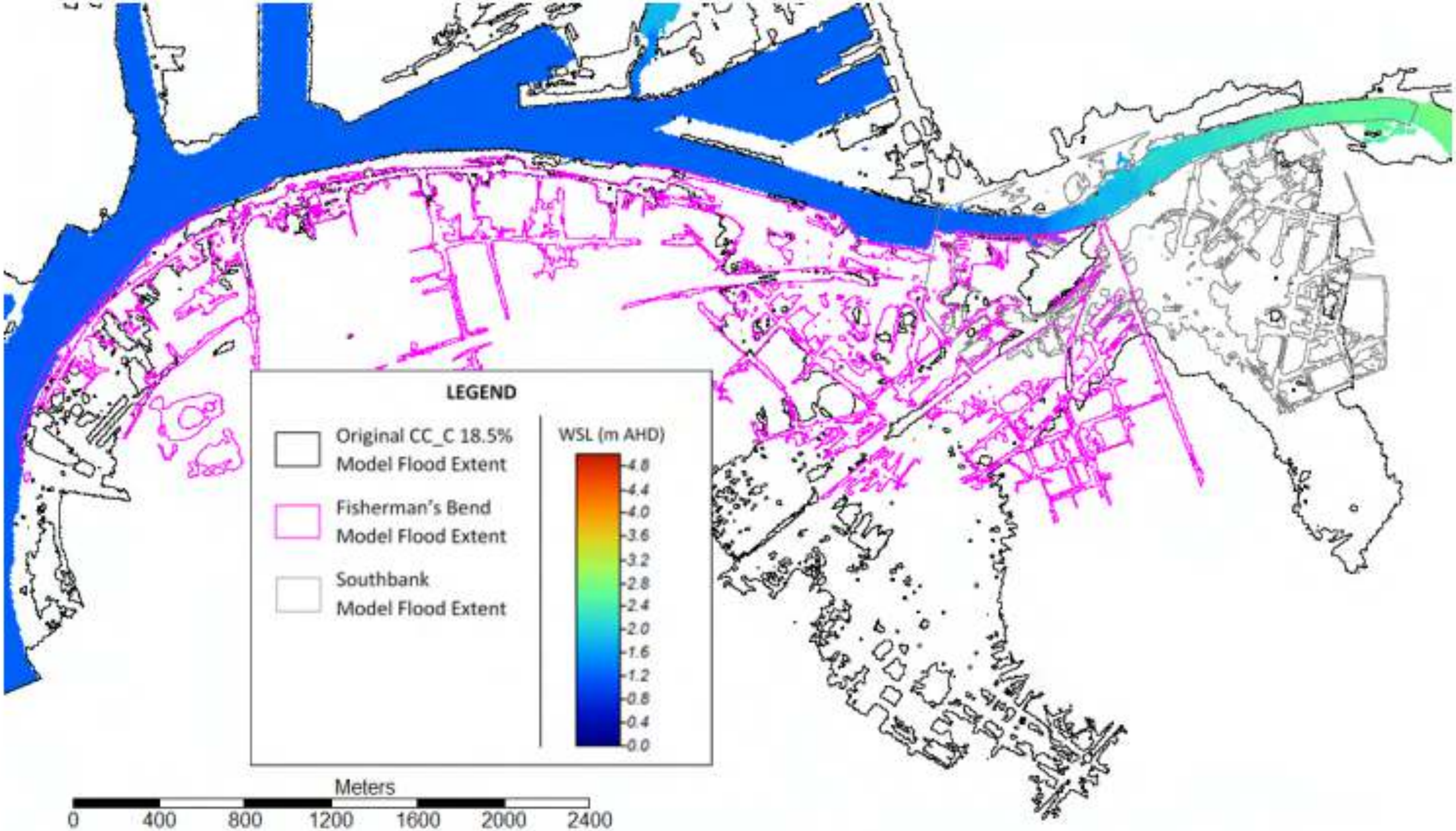


Figure 8 Peak 100y WSL Current (Kc=180 w/ ARFs, 10y Tide & River Manning's 'n' of 0.015) – Zoomed to refinement area

2.3.4 Run 4

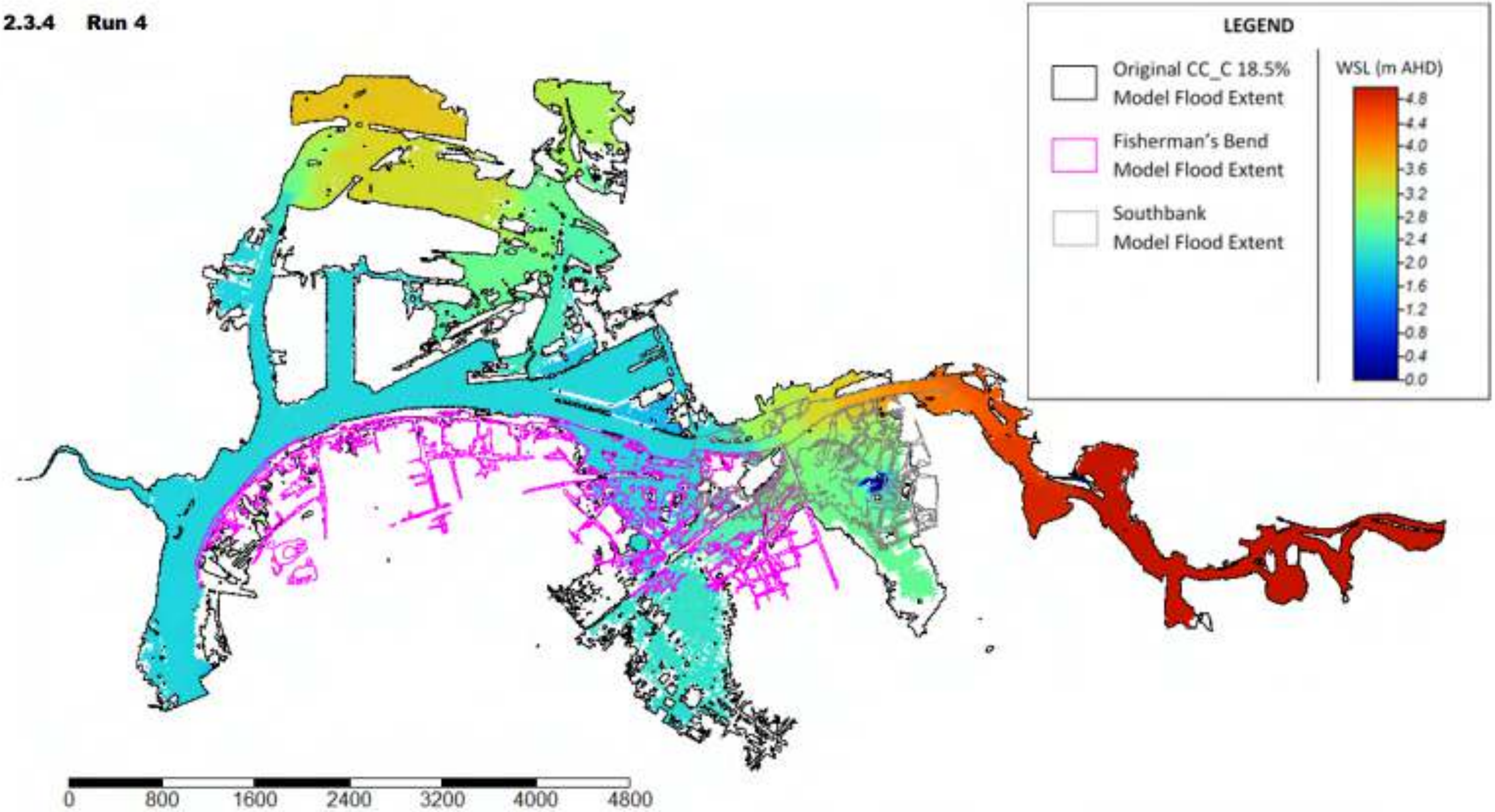


Figure 9 Peak 100y WSL Current CC18p5 (Kc=145 w/o ARFs, 10y Tide & River Manning's 'n' of 0.015)

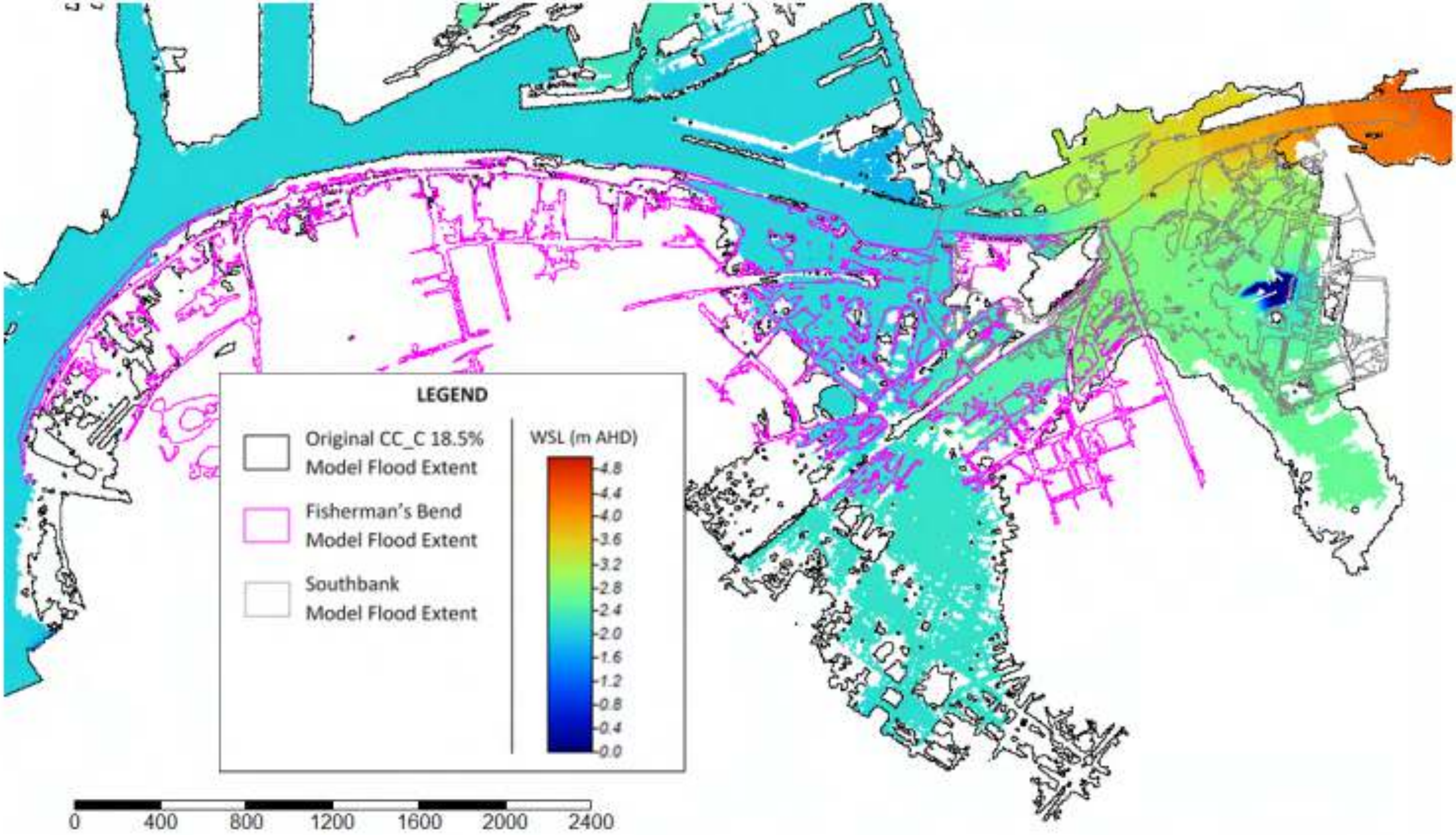


Figure 10 Peak 100y WSL Current CC18p5 (Kc=145 w/o ARFs, 10y Tide & River Manning's 'n' of 0.015) – Zoomed to refinement area

2.3.5 Run 5

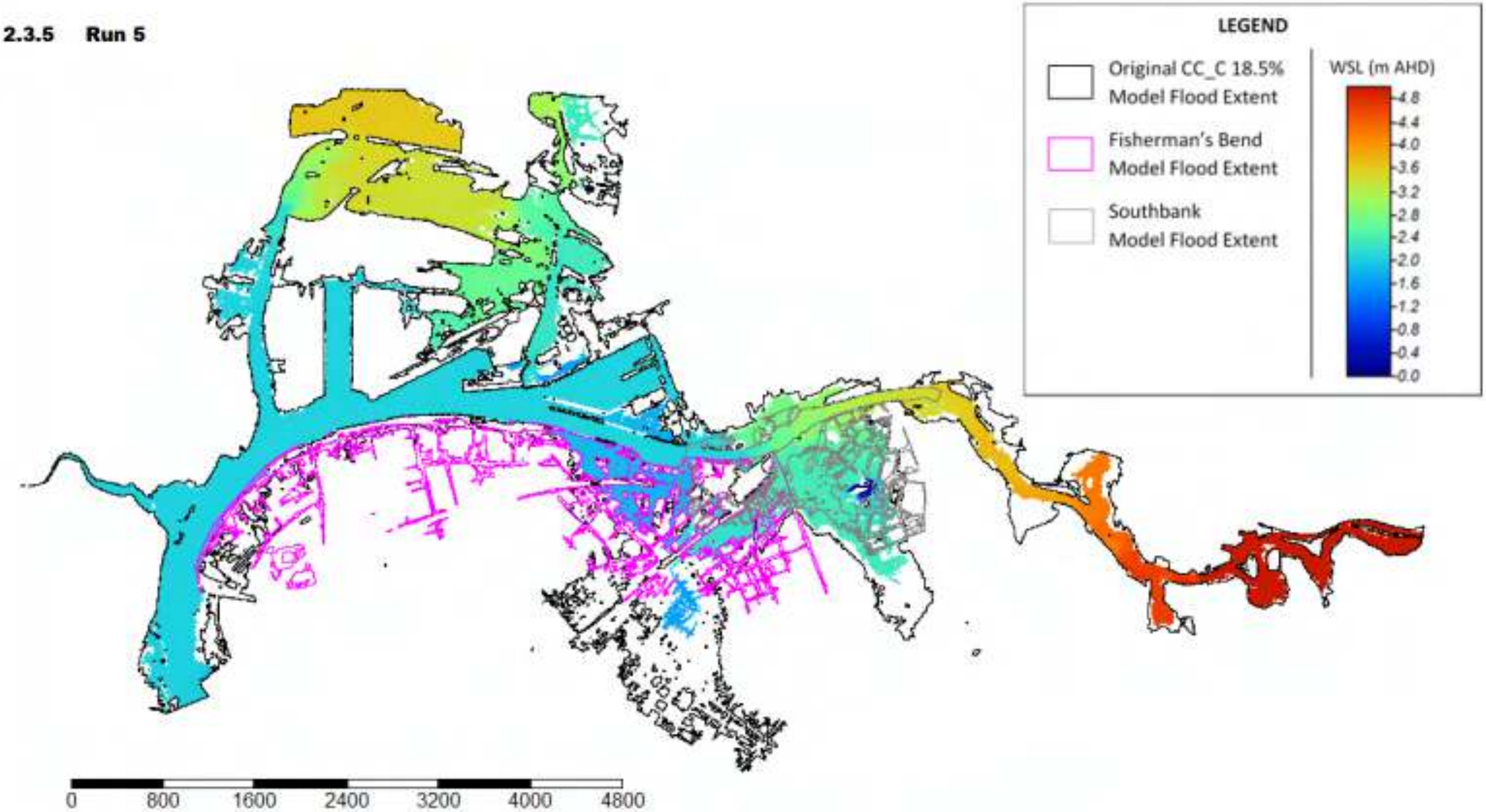


Figure 11 Peak 100y WSL Current CC18p5 (Kc=237 w/o ARFs, 10y Tide & River Manning's 'n' of 0.015)

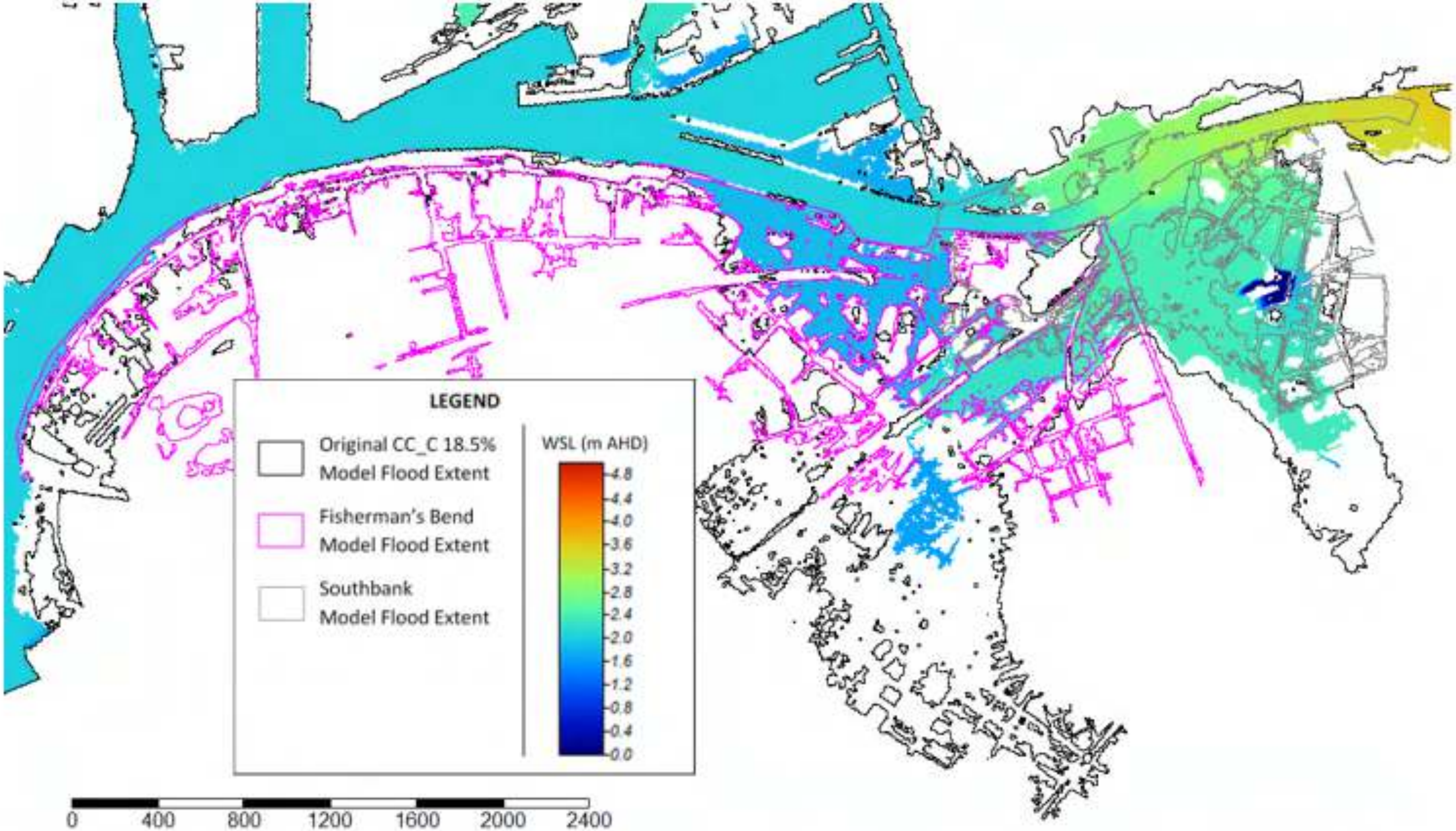


Figure 12 Peak 100y WSL Current CC18p5 (Kc=237 w/o ARFs, 10y Tide & River Manning's 'n' of 0.015) – Zoomed to refinement area

2.3.6 Run 6

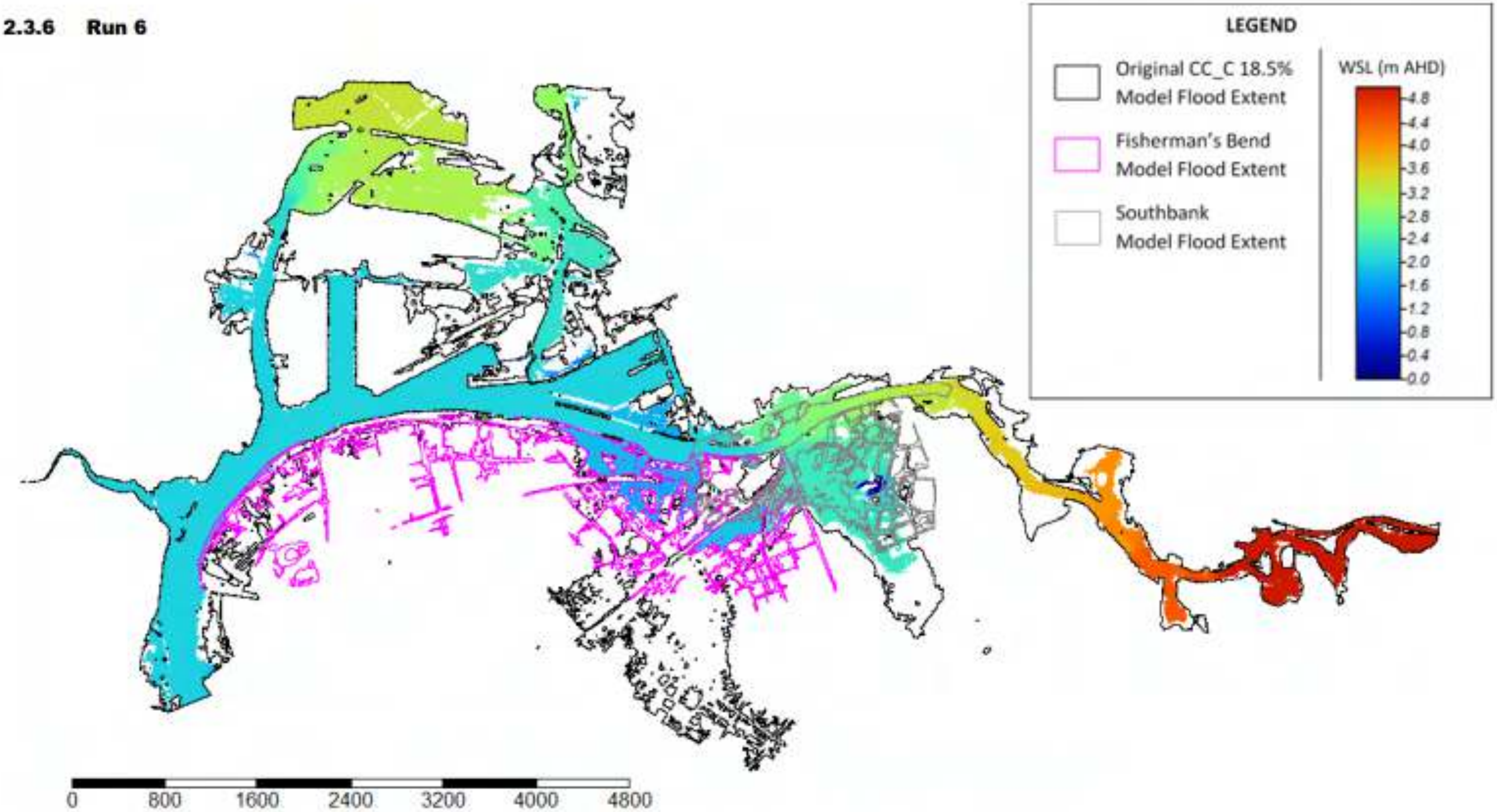


Figure 13 Peak 100y WSL Current CC18p5 (Kc=180 w/ ARFs, 10y Tide & River Manning's 'n' of 0.015)

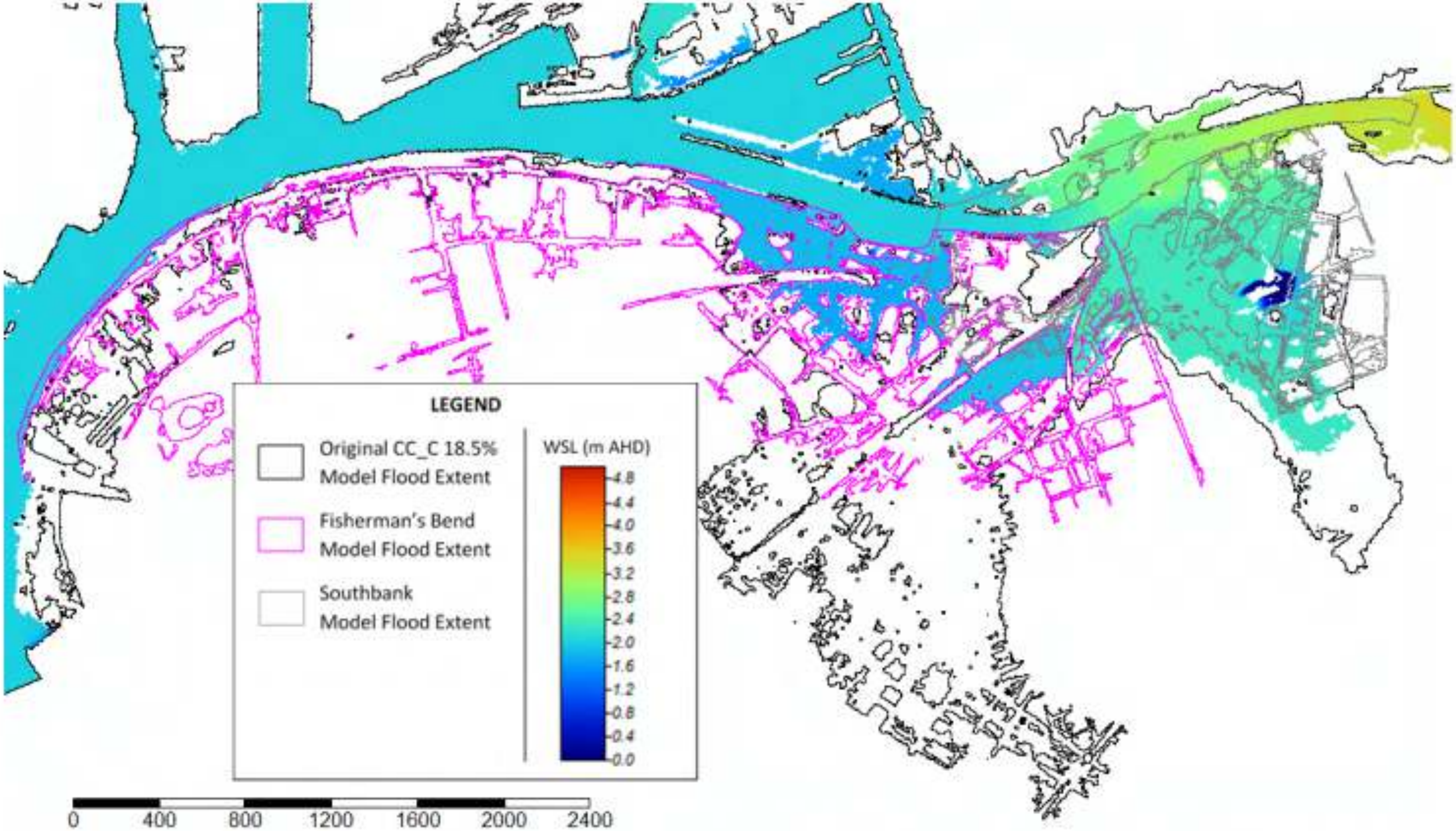


Figure 14 Peak 100y WSL Current CC18p5 (Kc=180 w/ ARFs, 10y Tide & River Manning's 'n' of 0.015) – Zoomed to refinement area

2.3.7 Run 7

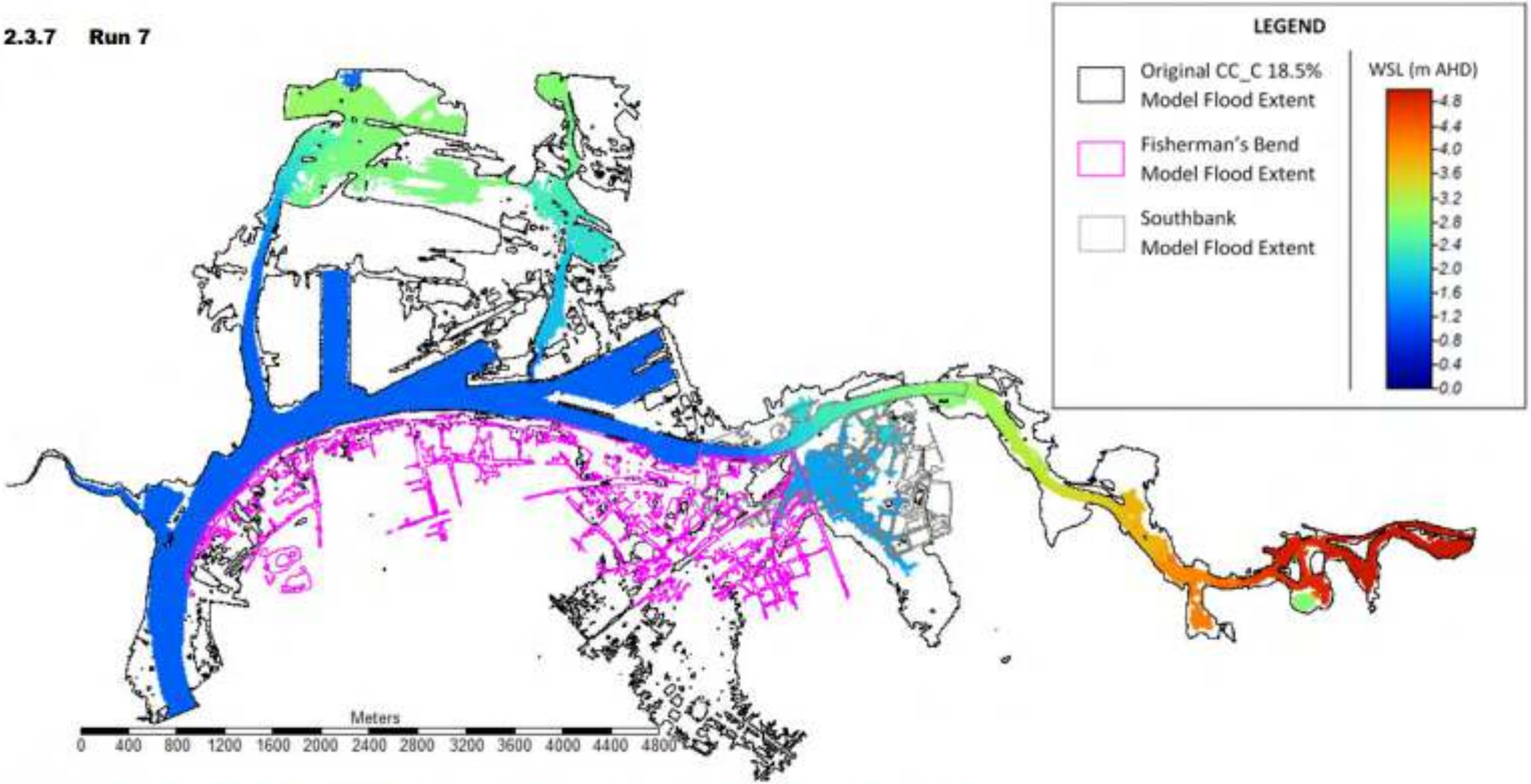


Figure 15 Peak 100y WSL Current (Kc=180 w/ ARFs, 10y Tide & River Manning's 'n' of 0.020)

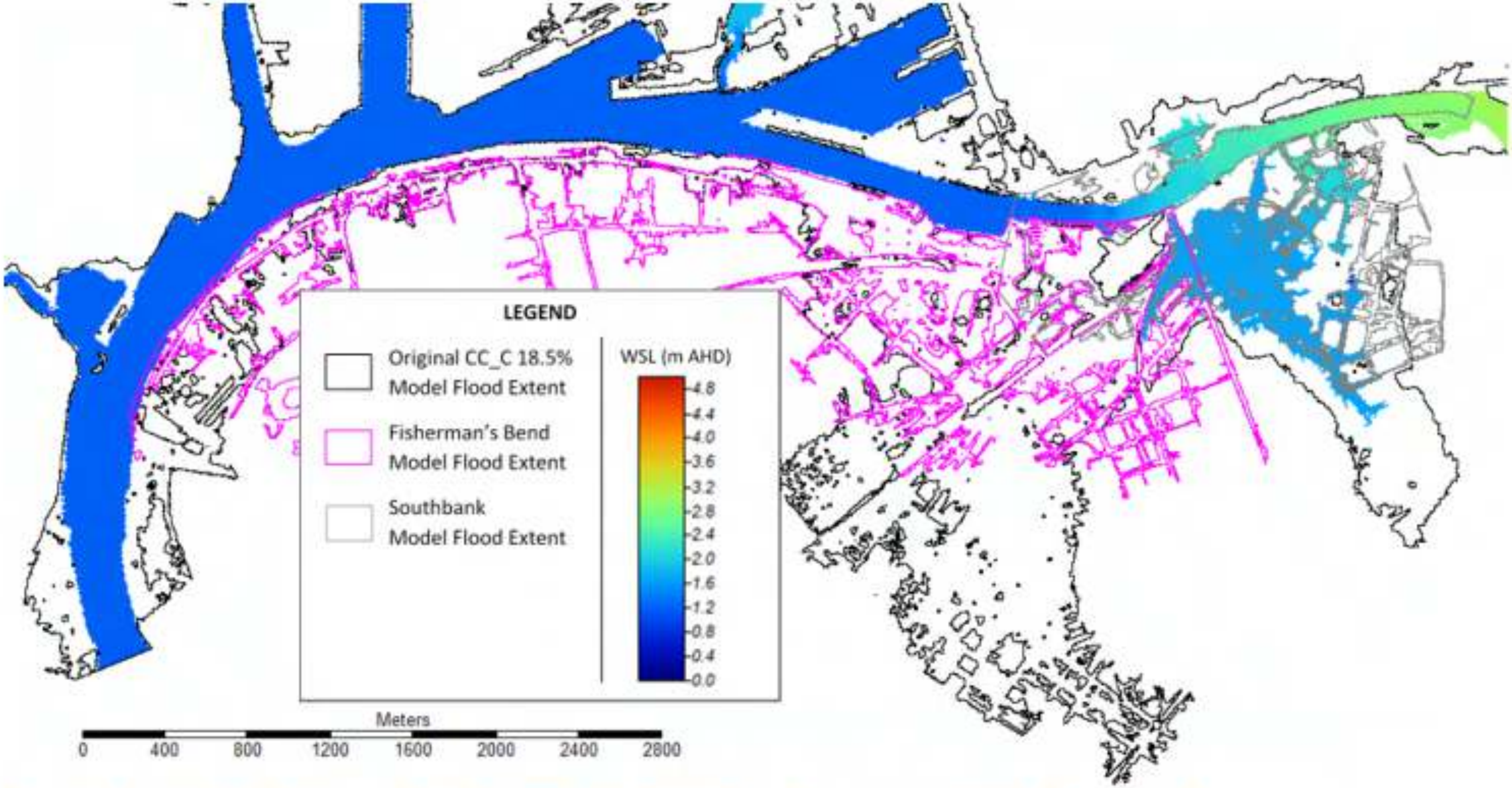


Figure 16 Peak 100y WSL Current (Kc=180 w/ ARFs, 10y Tide & River Manning's 'n' of 0.020– Zoomed to refinement area

2.3.8 Run 8

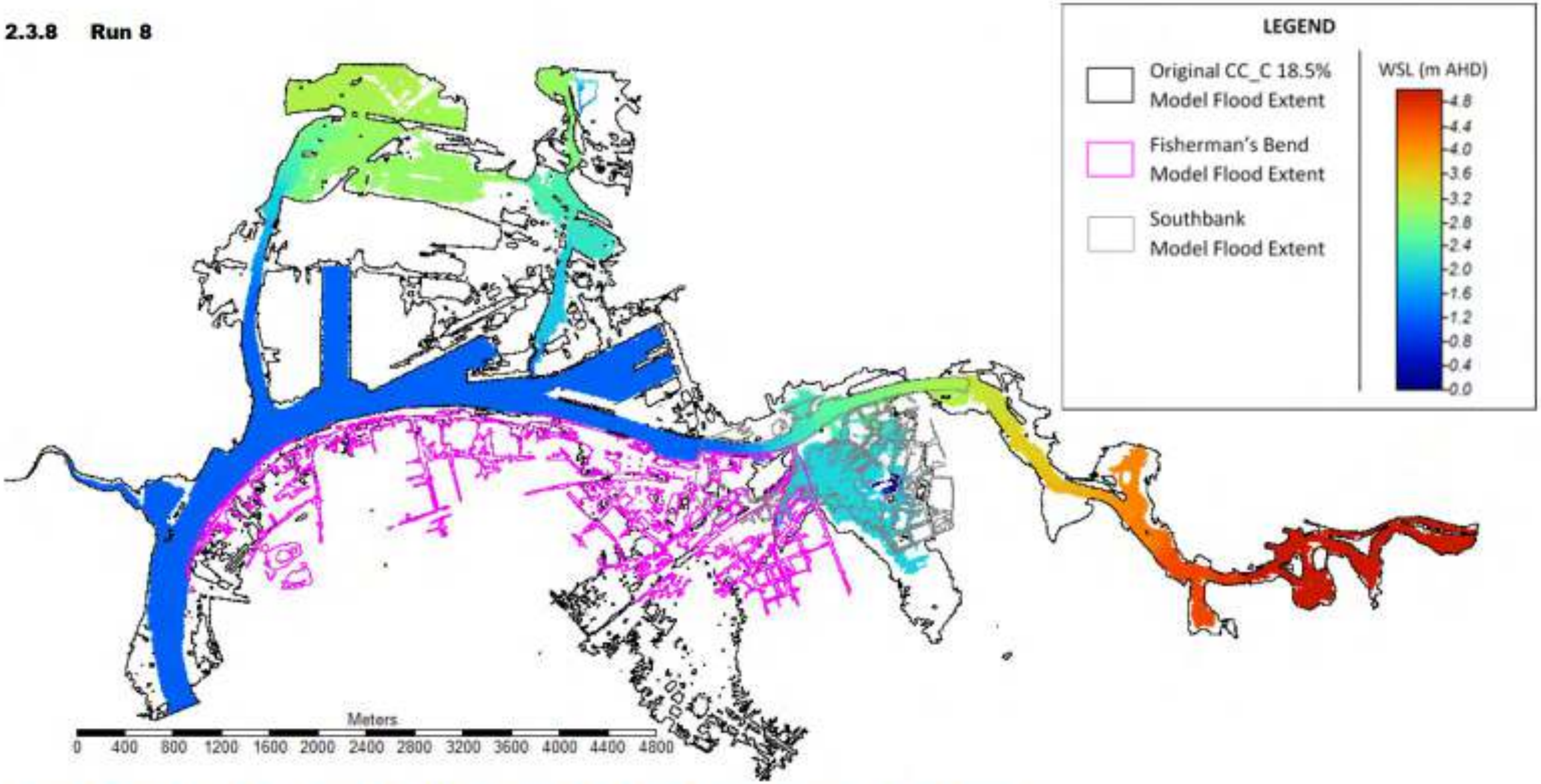


Figure 17 Peak 100y WSL Current (Kc=180 w/ ARFs, 10y Tide & River Manning's 'n' of 0.025)

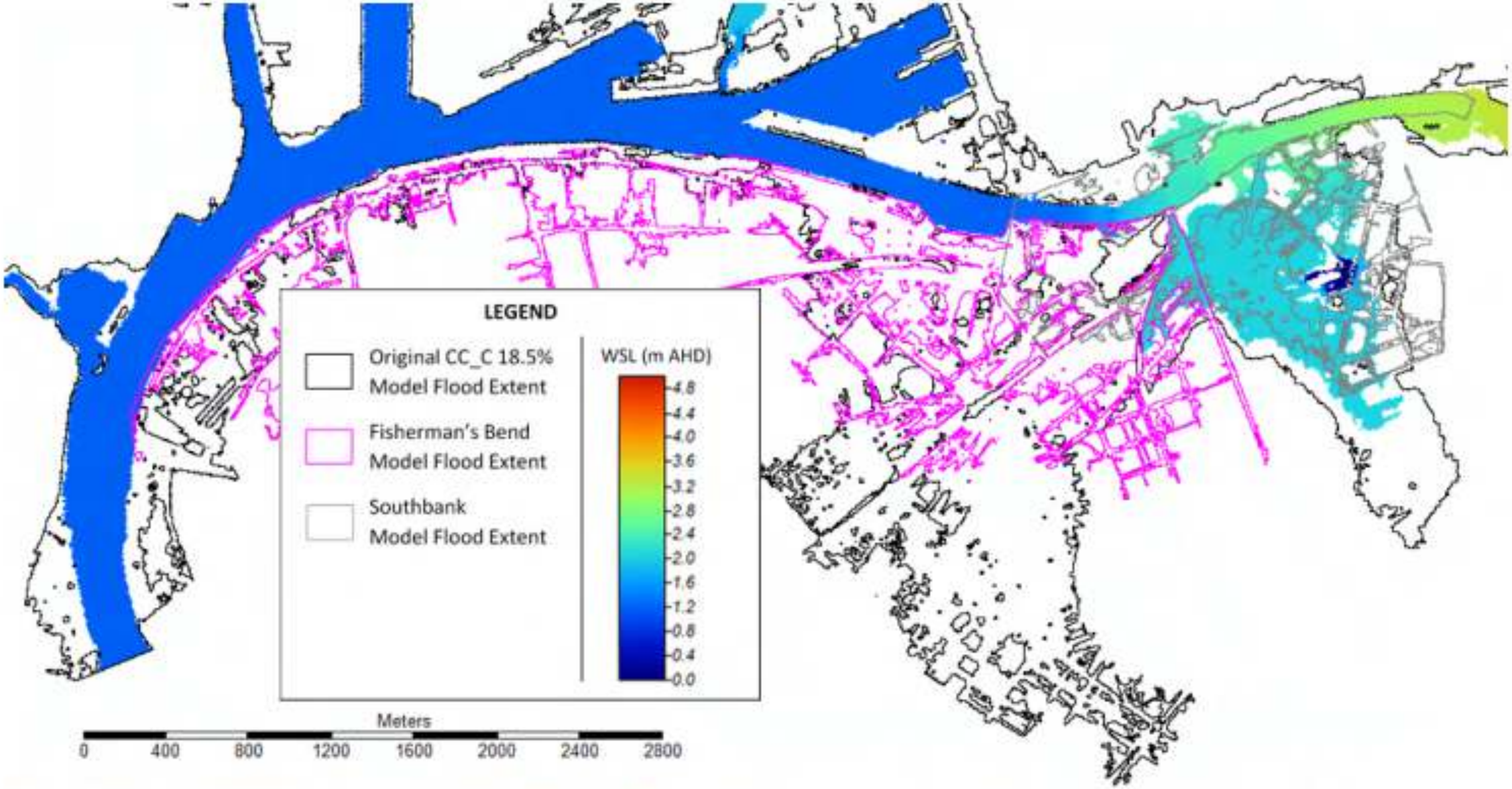


Figure 18 Peak 100y WSL Current (Kc=180 w/ ARFs, 10y Tide & River Manning's 'n' of 0.025) – Zoomed to refinement area

2.3.9 Run 9

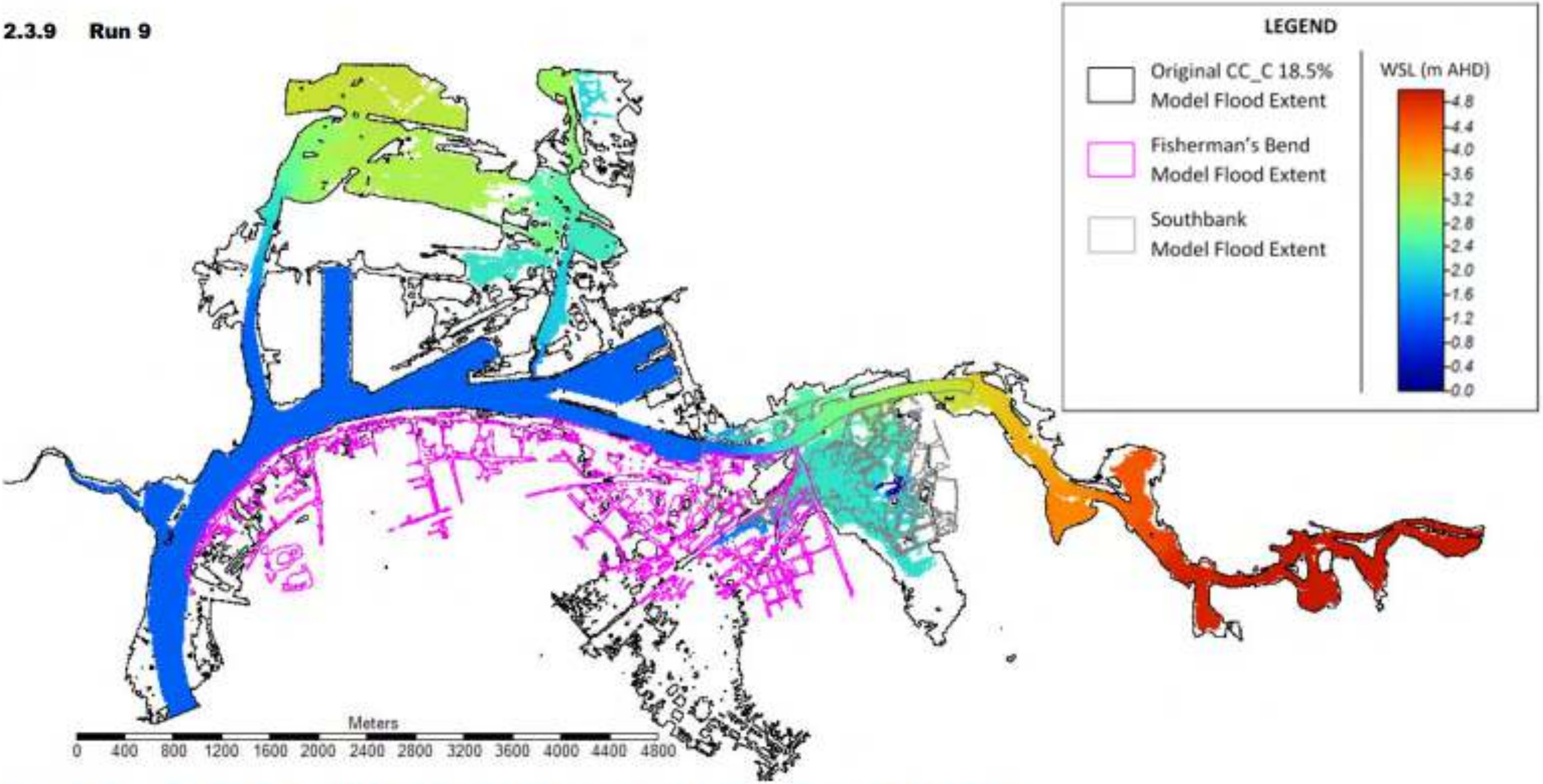


Figure 19 Peak 100y WSL Current (Kc=180 w/ ARFs, 10y Tide & River Manning's 'n' of 0.030)

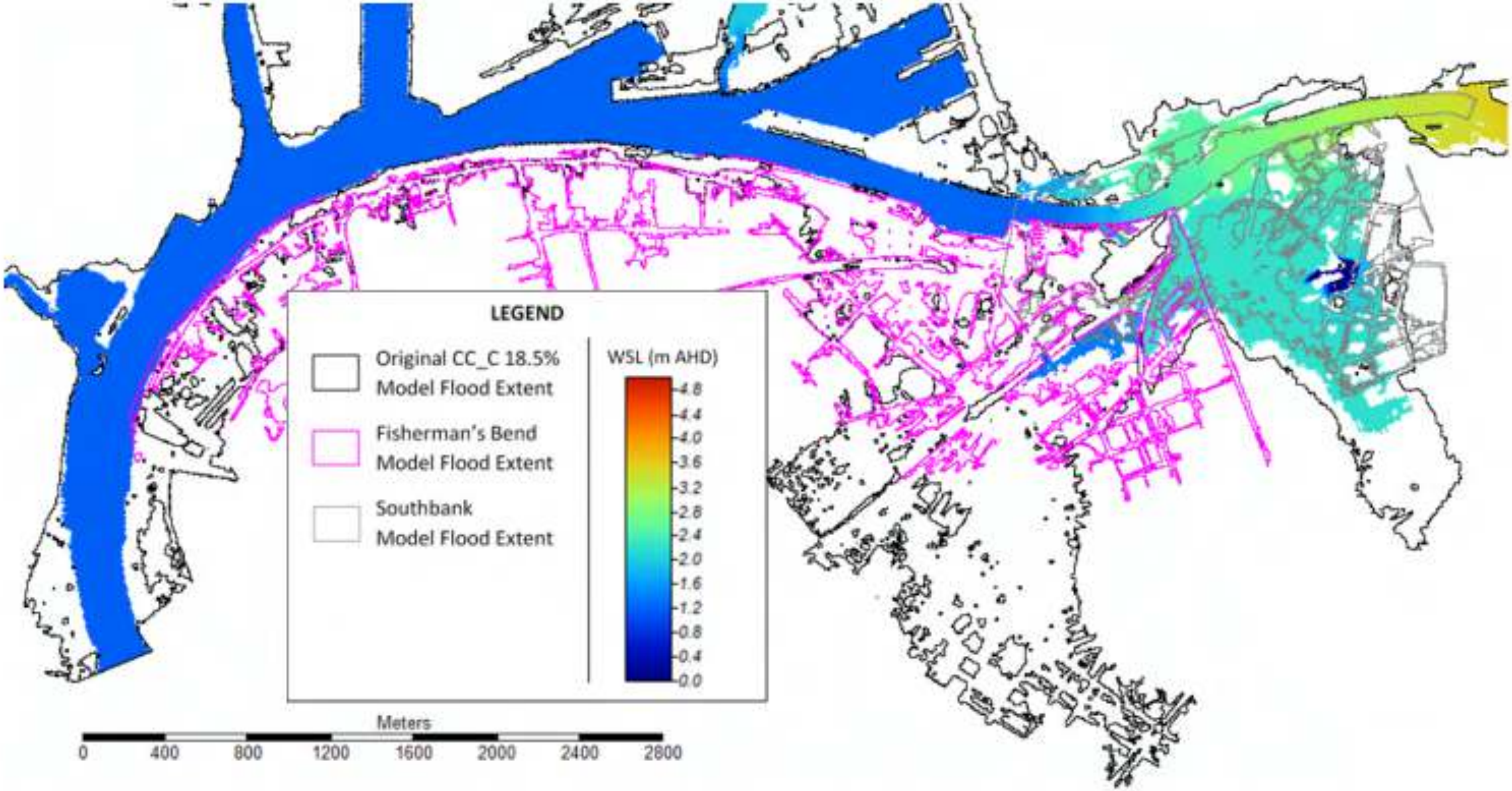


Figure 20 Peak 100y WSL Current (Kc=180 w/ ARFs, 10y Tide & River Manning's 'n' of 0.030) – Zoomed to refinement area

2.3.10 Run 10

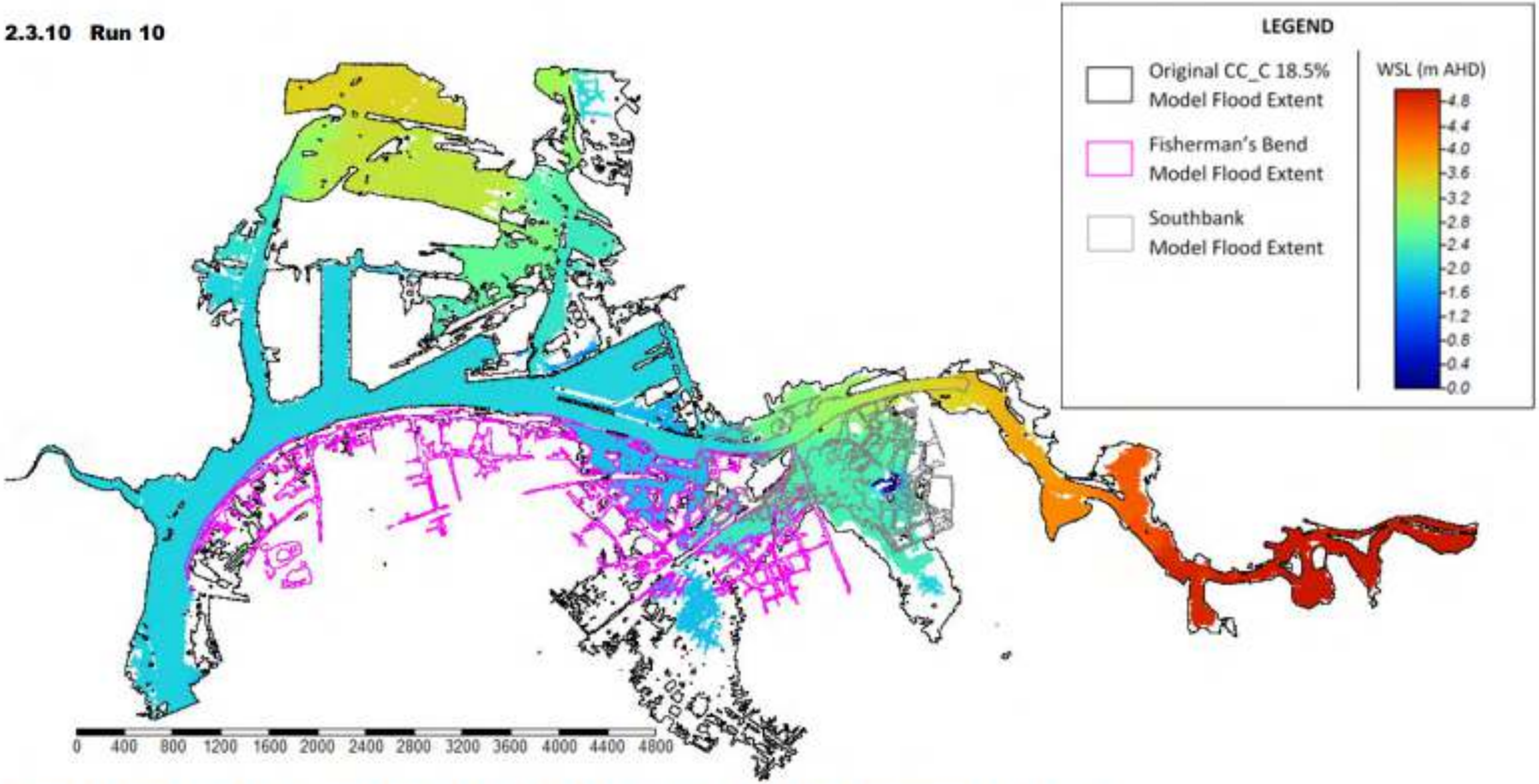


Figure 21 Peak 100y WSL Current CC18p5 (Kc=180 w/ ARFs, 10y Tide & River Manning's 'n' of 0.020)

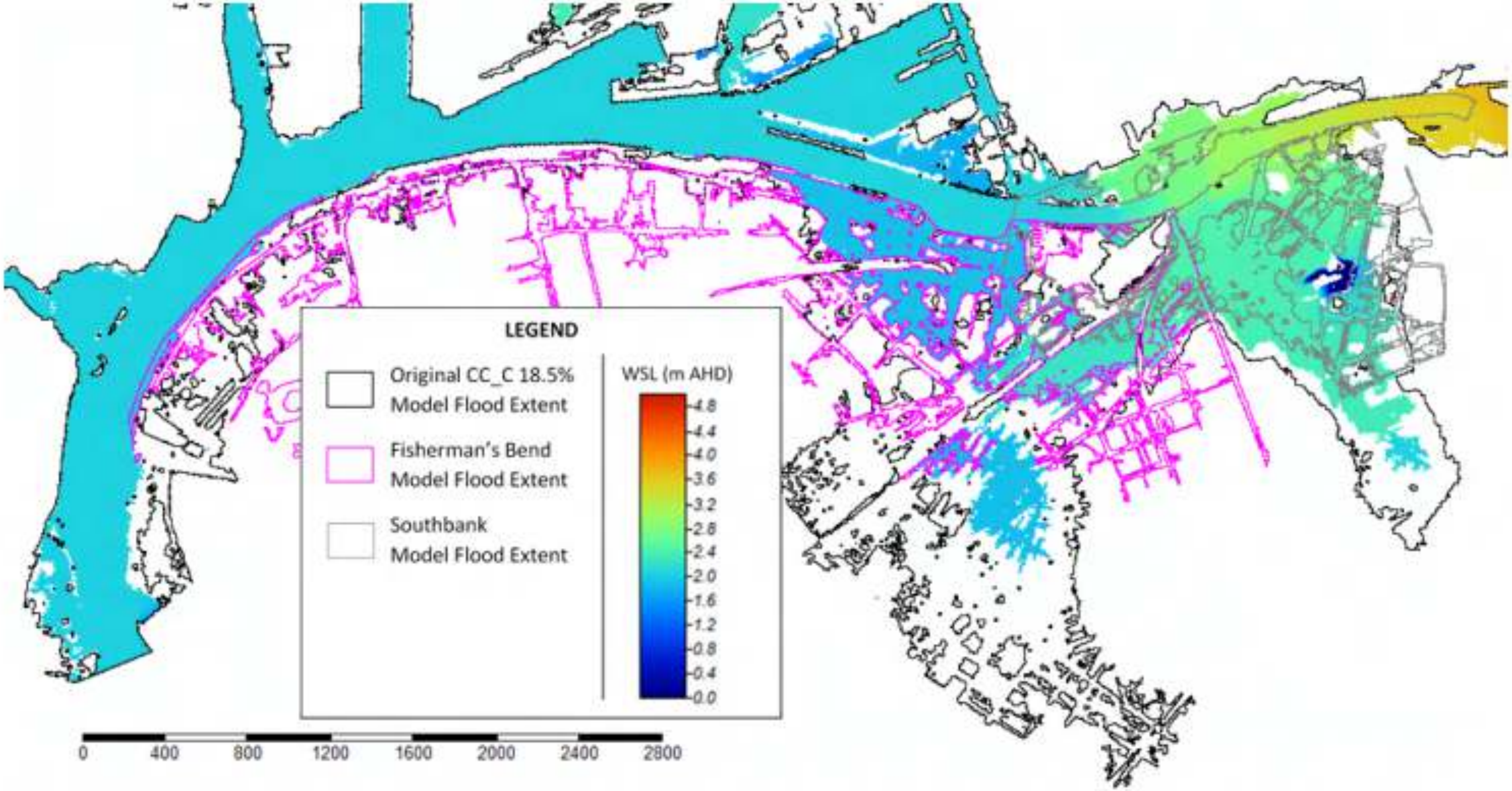


Figure 22 Peak 100y WSL Current CC18p5 (Kc=180 w/ ARFs, 10y Tide & River Manning's 'n' of 0.020) – Zoomed to refinement area

2.3.11 Run 11

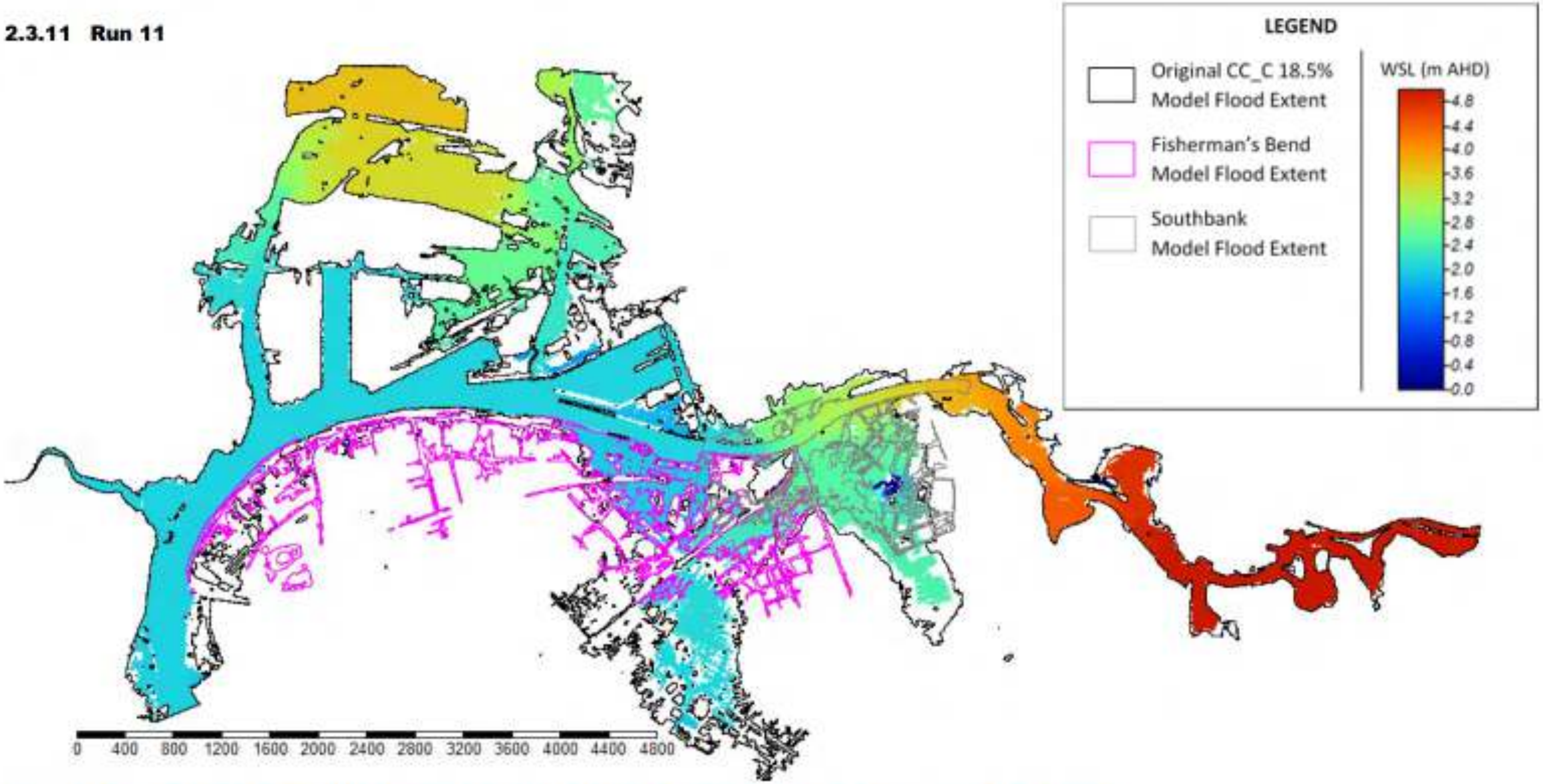


Figure 23 Peak 100y WSL Current CC18p5 (Kc=180 w/ ARFs, 10y Tide & River Manning's 'n' of 0.025)

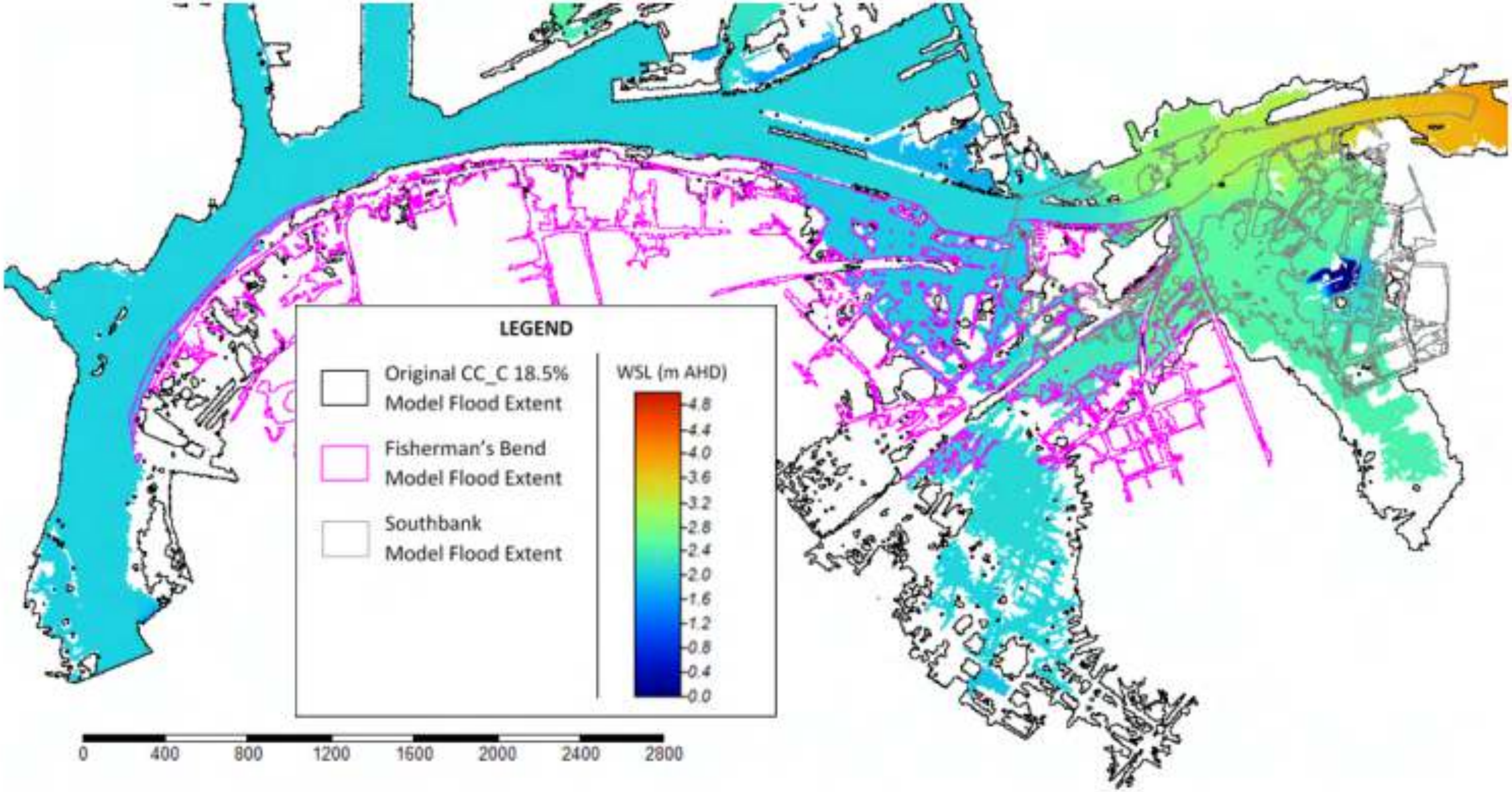


Figure 24 Peak 100y WSL Current CC18p5 (Kc=180 w/ ARFs, 10y Tide & River Manning's 'n' of 0.025) – Zoomed to refinement area

2.3.12 Run 12

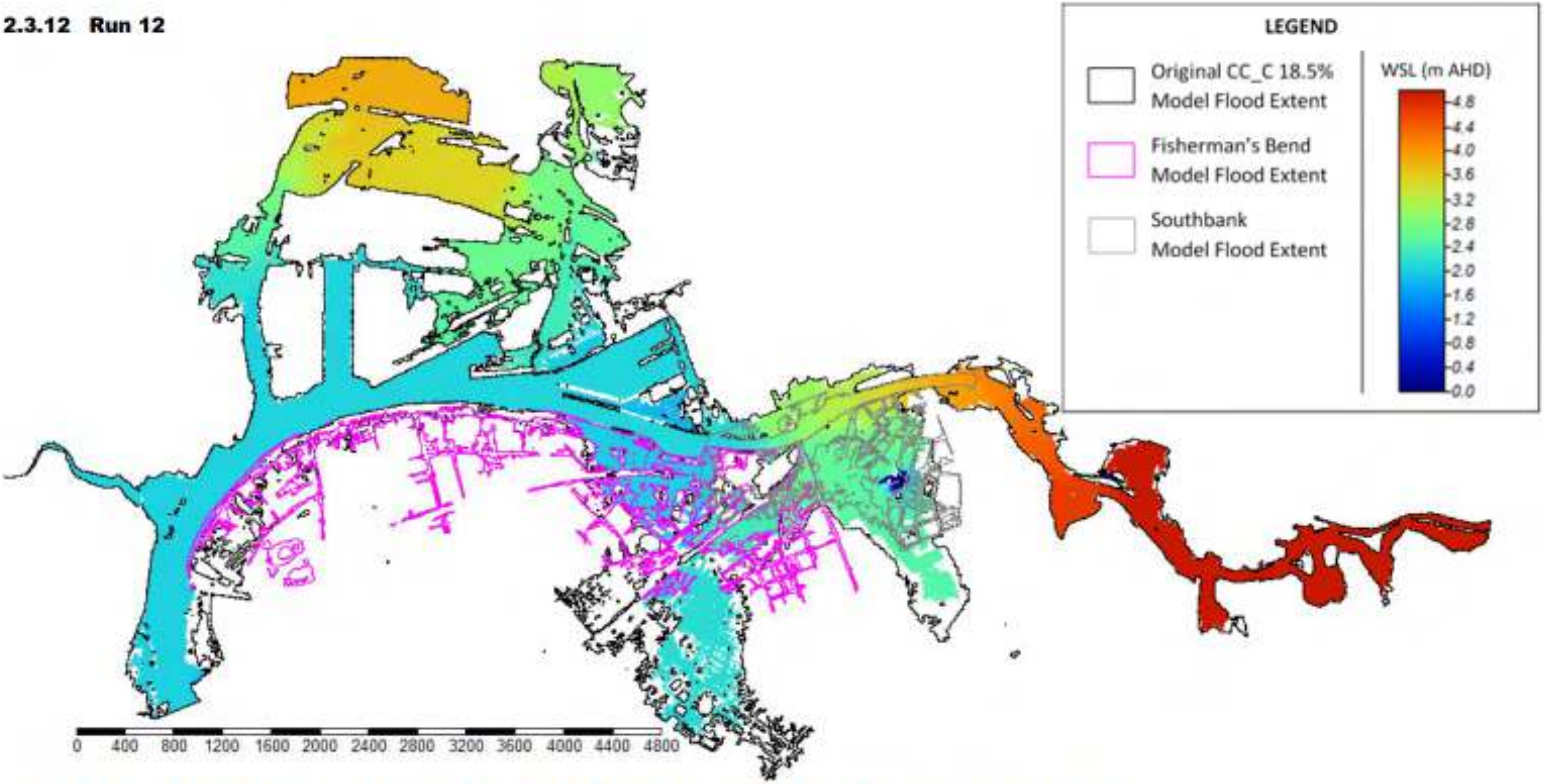


Figure 25 Peak 100y WSL Current CC18p5 (Kc=180 w/ ARFs, 10y Tide & River Manning's 'n' of 0.030)

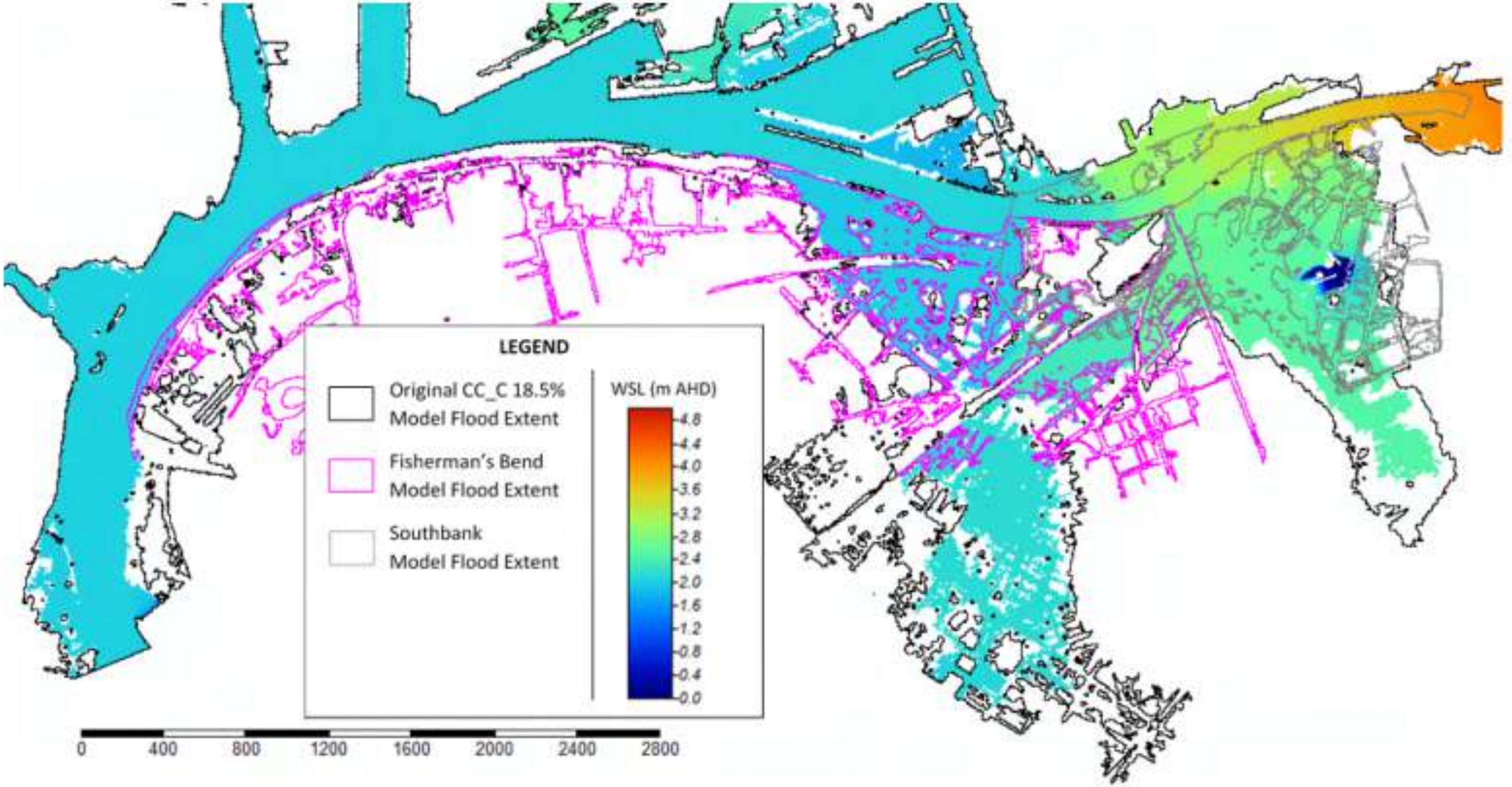


Figure 26 Peak 100y WSL Current CC18p5 (Kc=180 w/ ARFs, 10y Tide & River Manning's 'n' of 0.030) – Zoomed to refinement area

2.4 Long Sections

2.4.1 Runs 1 to 6 - Varying flow (kc and ARF) and d/s boundaries

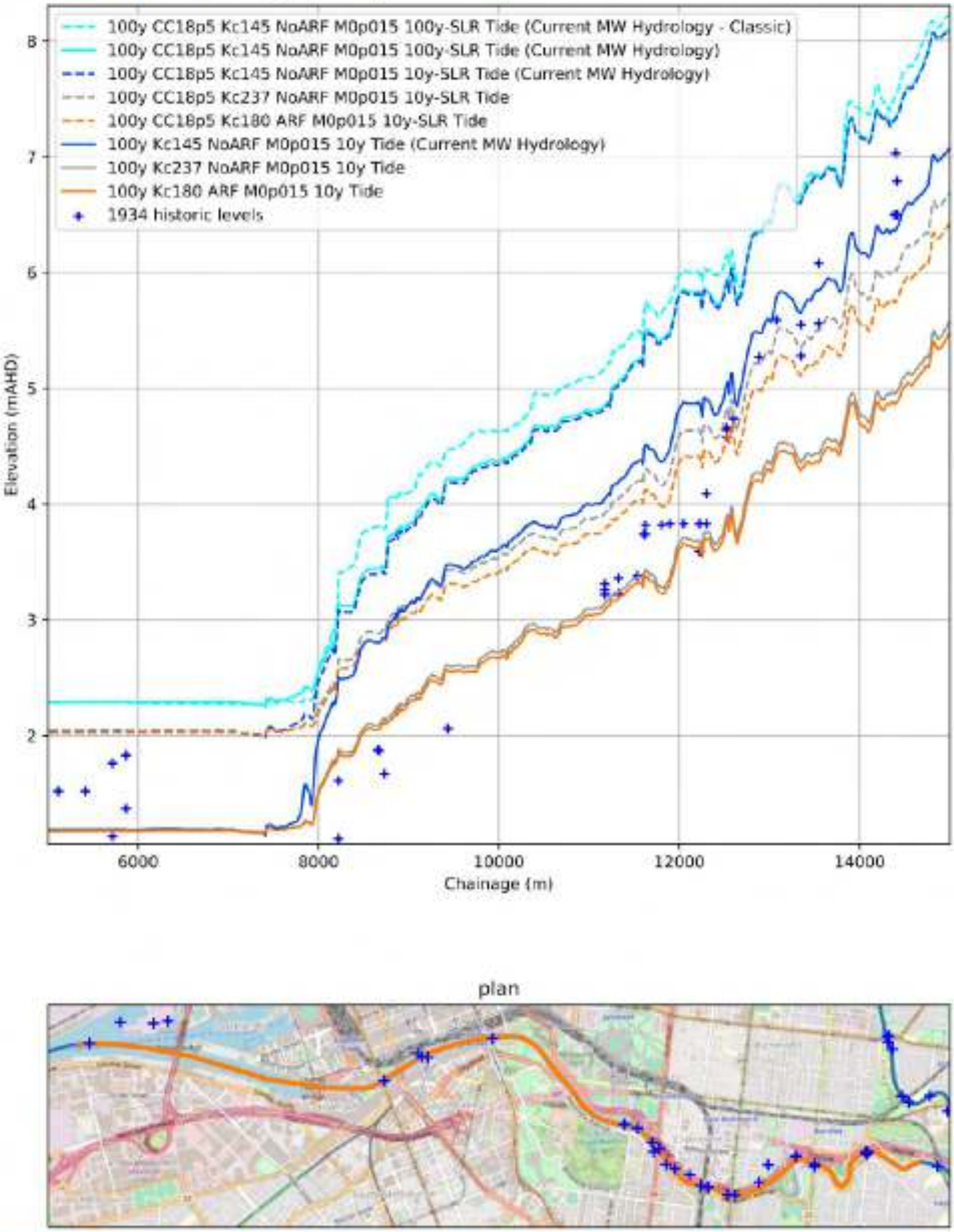


Figure 27 1% AEP Long-section along Yarra River comparing WSL along Yarra to historic levels - Impact of Kc & ARFs

2.4.2 Runs 7 to 12 - Varying Manning's 'n'

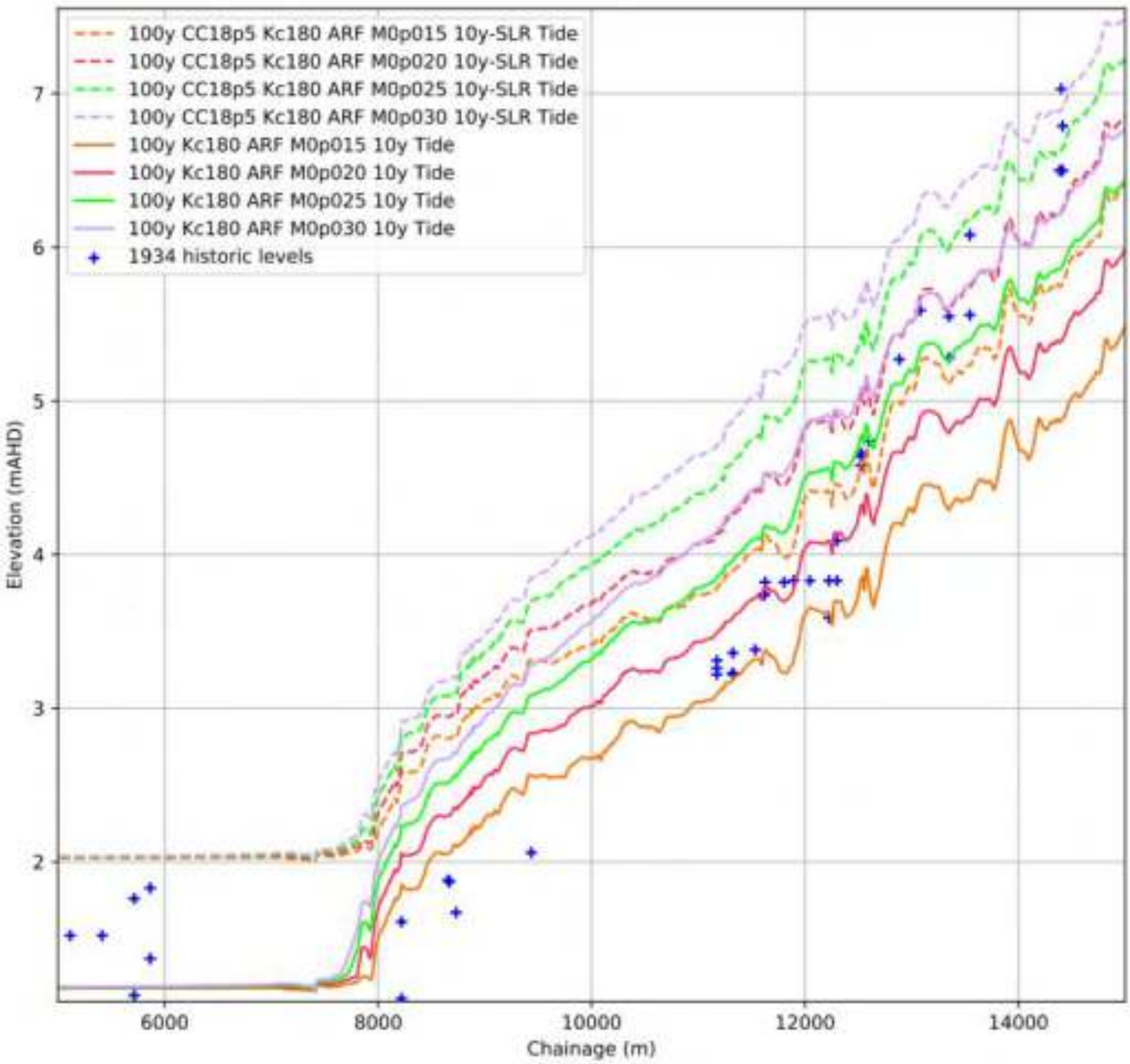
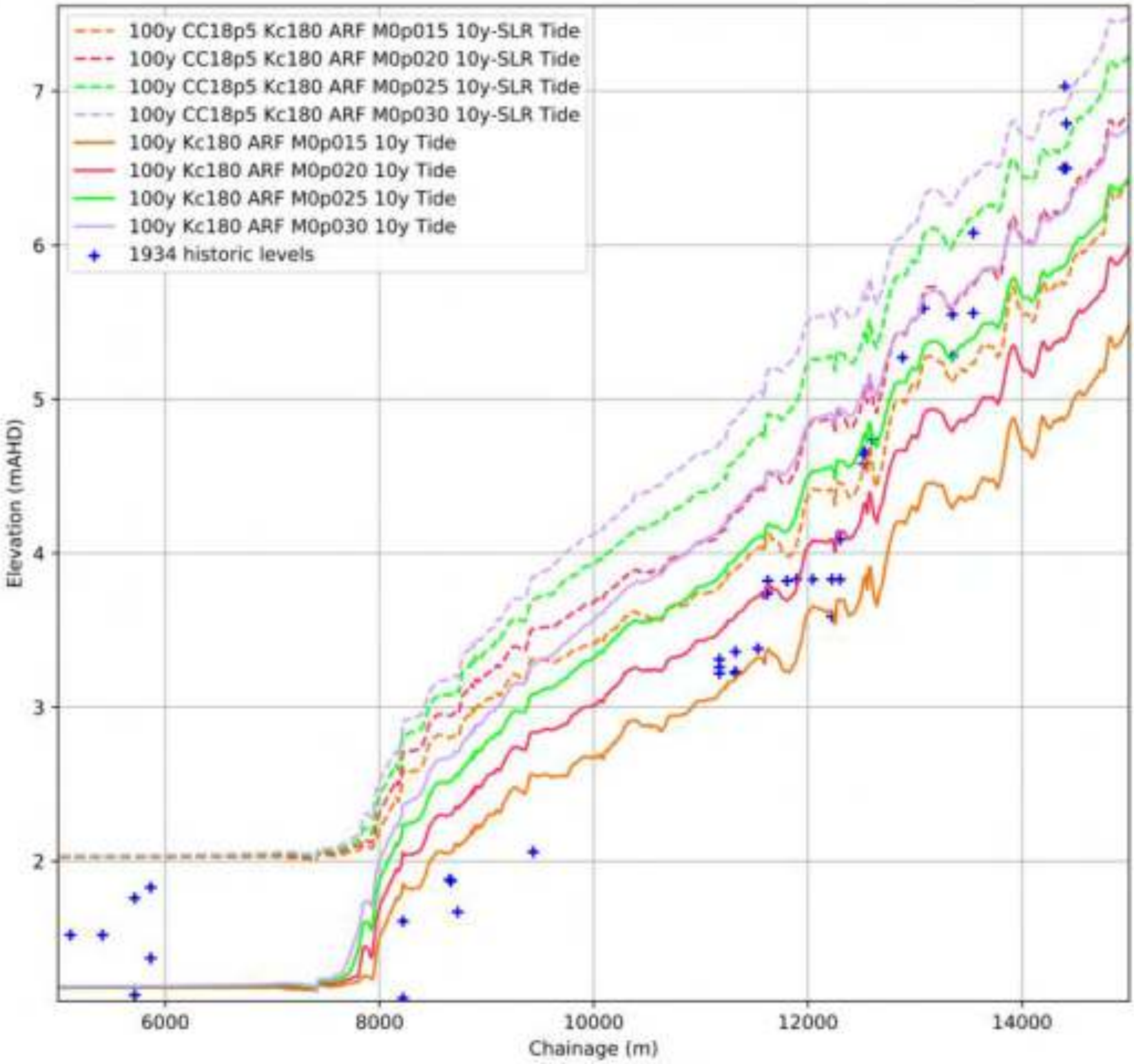


Figure 28 1% AEP Long-section along Yarra River comparing WSL along Yarra to historic levels - Impact of River Roughness

2.4.3 Runs 13 to 15 – Sensitivity of changes to 10 year ARI results provided to City of Melbourne



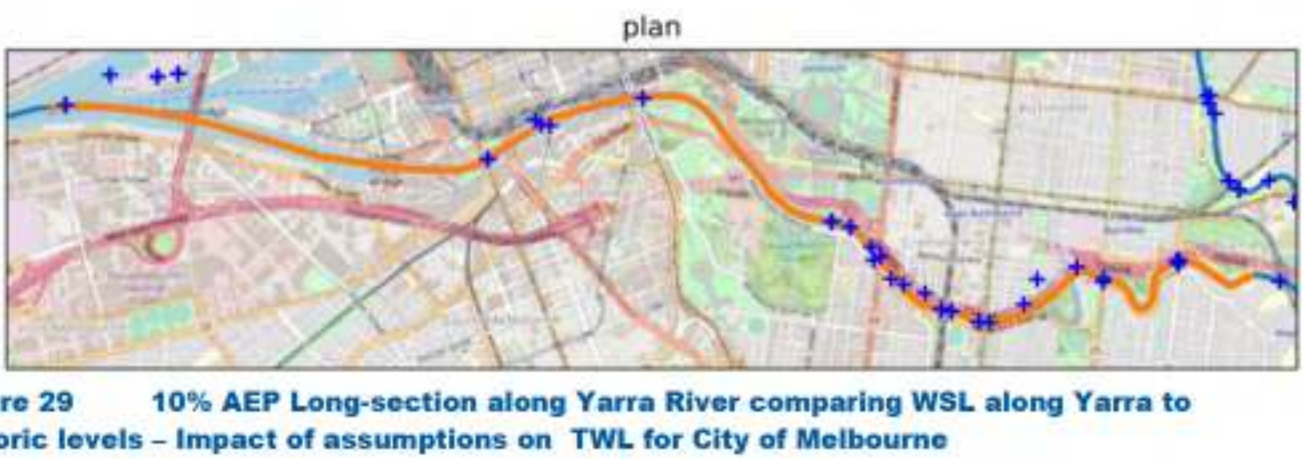


Figure 29 10% AEP Long-section along Yarra River comparing WSL along Yarra to historic levels – Impact of assumptions on TWL for City of Melbourne

2.5 Comparison Point Results – Overflow Refinement Area

Figure 30 Location of Comparison Points

2.5.1 Boundary Conditions Sensitivity (comparison of runs 1 to 6)

Table 3 Comparison Point Locations – Impact of Kc and ARFs

ID	Description	1% AEP w/ 1% AEP SLR Tide	1% AEP w/ 10% AEP Tide			1% AEP CC 18.5% w/ 10% AEP SLR Tide				
		Current [Classic] (Kc = 145 w/o ARFs & n = 0.015)	Current - Kc=145 w/o ARFs & n = 0.015	Kc=237 w/o ARFs & n = 0.015	Kc=180 w/ ARFs & n = 0.015	Current - Kc=145 w/o ARFs & n = 0.015	Kc=237 w/o ARFs & n = 0.015	Kc=180 w/ ARFs & n = 0.015	Fishbend	Southbank
1	Yarra River 1 (US)	4.48	3.48	2.60	2.55	4.19	3.43	3.31	-	2.14
2	Yarra River 2	3.80	2.81	2.10	2.06	3.40	2.89	2.81	-	2.14
3	Yarra River 3	2.29	1.24	1.20	1.20	2.09	2.06	2.05	-	2.14
4	Yarra River 4	2.27	1.19	1.18	1.18	2.04	2.03	2.03	-	-
5	Yarra River 5 (DS)	2.29	1.19	1.18	1.18	2.04	2.03	2.03	-	-
6	South Bank Pond	3.67	2.31	-	-	2.69	2.36	2.30	-	1.28
7	Sth Park St	3.68	-	-	-	2.58	-	-	-	-
8	Fwy\Montague St	2.36	-	-	-	2.08	1.80	1.79	1.82	-
9	Lorimer St \ Boundary St	2.27	-	-	-	2.03	1.83	1.83	1.82	-
10	Approx. Boundary St \ Gittus St	2.37	1.53	-	-	2.08	1.80	1.70	1.82	-
11	Approx. Buckhurst St \ George St	3.10	2.13	-	-	2.41	2.21	1.91	1.89	-
12	Approx. Heath St \ Raglan St	2.58	-	-	-	2.19	-	-	-	-
13	Edwards Park	2.53	-	-	-	2.18	-	-	-	-
14	Approx. St Vincent St \ Iffla St	2.53	-	-	-	2.18	-	-	-	-

2.5.2 Roughness Sensitivity (comparison of runs 7 to 12)

Table 4 Comparison Point Locations – Impact of Roughness

ID	Description	1% AEP w/ 10% AEP Tide					1% AEP CC 18.5% w/ 10% AEP SLR Tide				
		Current [HPC] (Kc = 145 w/o ARFs & n = 0.015)	Kc = 180 w/ ARF River Roughness n = 0.015	Kc = 180 w/ ARF River Roughness n = 0.020	Kc = 180 w/ ARF River Roughness n = 0.025	Kc = 180 w/ ARF River Roughness n = 0.030	Current [HPC] (Kc = 145 w/o ARFs & n = 0.015)	Kc = 180 w/ ARF River Roughness n = 0.015	Kc = 180 w/ ARF River Roughness n = 0.020	Kc = 180 w/ ARF River Roughness n = 0.025	Kc = 180 w/ ARF River Roughness n = 0.030
1	Yarra River 1 (US)	3.48	2.55	2.84	3.10	3.30	4.19	3.31	3.52	3.72	3.87
2	Yarra River 2	2.81	2.06	2.31	2.53	2.68	3.40	2.81	2.95	3.09	3.19
3	Yarra River 3	1.24	1.20	1.23	1.26	1.37	2.09	2.05	2.08	2.11	2.13
4	Yarra River 4	1.19	1.18	1.18	1.19	1.20	2.04	2.03	2.03	2.04	2.05
5	Yarra River 5 (DS)	1.19	1.18	1.18	1.18	1.19	2.04	2.03	2.03	2.03	2.04
6	South Bank Pond	2.31	-	1.65	2.03	2.20	2.69	2.30	2.40	2.48	2.55
7	Sth Park St	-	-	-	-	-	2.58	-	2.04	2.42	2.47
8	Fwy\Montague St	-	-	-	-	-	2.08	1.79	1.88	1.97	2.01
9	Lorimer St \ Boundary St	-	-	-	-	-	2.03	1.83	1.88	1.95	1.98
10	Approx. Boundary St \ Gittus St	1.53	-	-	-	-	2.08	1.70	1.88	1.97	2.01
11	Approx. Buckhurst St \ George St	2.13	-	-	-	-	2.41	1.91	2.25	2.29	2.33
12	Approx. Heath St \ Raglan St	-	-	-	-	-	2.19	-	-	2.09	2.13
13	Edwards Park	-	-	-	-	-	2.18	-	-	2.04	2.12
14	Approx. St Vincent St \ Iffla St	-	-	-	-	-	2.18	-	-	2.04	2.12

2.5.3 Effect on 10 year ARI levels (comparison of runs 13 to 15)

Table 5 Comparison Point Locations – Impact on TWL for City of Melbourne

ID	Description	10% AEP CC 18.5% w/ 10% AEP SLR Tide			
		Current [Classic] (Kc = 145 w/o ARFs & n = 0.015)	Current [HPC OR] (Kc = 145 w/o ARF & n = 0.015)	Kc = 180 w/ ARF & n = 0.020	Kc = 180 w/ ARF & n = 0.030
1	Yarra River 1 (US)	2.37	2.46	2.22	2.48
2	Yarra River 2	2.14	2.19	2.10	2.21
3	Yarra River 3	2.01	2.03	2.03	2.04
4	Yarra River 4	2.01	2.02	2.02	2.02
5	Yarra River 5 (DS)	2.01	2.02	2.01	2.01

2.6 Comparison with 1934 historic points

Figure 31 Location of 1934 Historic Flood Levels

Table 6 1934 Flood Level Comparison Points

ID	1934 Flood Level	1% AEP w/ 1% AEP SLR Tide	1% AEP w/ 10% AEP Tide						1% AEP w/ 10% AEP SLR Tide					
		Current (Kc=145) River Roughness n = 0.015	Current (Kc=145) River Roughness n = 0.015	Kc=237 River Roughness n = 0.015	Kc = 180 w/ ARF River Roughness n = 0.015	Kc = 180 w/ ARF River Roughness n = 0.020	Kc = 180 w/ ARF River Roughness n = 0.025	Kc = 180 w/ ARF River Roughness n = 0.030	Current (Kc=145) River Roughness n = 0.015	Kc=237 River Roughness n = 0.015	Kc = 180 w/ ARF River Roughness n = 0.015	Kc = 180 w/ ARF River Roughness n = 0.020	Kc = 180 w/ ARF River Roughness n = 0.025	Kc = 180 w/ ARF River Roughness n = 0.030
HL1	3.59	5.80	4.85	3.67	3.61	4.07	4.54	4.89	5.78	4.62	4.39	4.85	5.26	5.54
HL2	3.83	5.83	4.89	3.75	3.69	4.14	4.60	4.93	5.81	4.66	4.45	4.90	5.30	5.58
HL3	4.58	5.93	5.03	3.88	3.83	4.31	4.76	5.08	5.90	4.80	4.59	5.03	5.42	5.68
HL4	4.74	5.97	5.04	3.90	3.84	4.33	4.79	5.11	5.95	4.82	4.61	5.05	5.44	5.73
HL5	1.52	2.29	1.19	1.18	1.18	1.18	1.18	1.19	2.04	2.03	2.03	2.03	2.03	2.04
HL6	0.64	2.29	1.19	1.18	1.18	1.18	1.18	1.19	2.04	2.03	2.03	2.03	2.03	2.04
HL7	1.76	2.46	-	-	-	-	-	-	-	-	-	-	-	-
HL8	1.13	2.46	-	-	-	-	-	-	-	-	-	-	-	-
HL9	1.83	2.46	-	-	-	-	-	-	2.24	-	-	-	-	2.28
HL10	1.37	2.46	-	-	-	-	-	-	2.24	-	-	-	-	2.28
HL11	1.11	3.15	2.50	1.88	1.85	2.06	2.24	2.37	3.08	2.66	2.59	2.71	2.82	2.91
HL12	1.88	3.47	2.84	2.11	2.07	2.31	2.53	2.69	3.42	2.91	2.83	2.97	3.10	3.19
HL13	3.26	4.86	4.05	3.15	3.10	3.49	3.85	4.16	4.83	3.92	3.79	4.13	4.46	4.71
HL14	3.23	5.05	4.19	3.24	3.18	3.59	3.96	4.28	5.02	4.04	3.89	4.25	4.60	4.87
HL15	3.22	5.05	4.19	3.24	3.18	3.59	3.96	4.28	5.02	4.04	3.89	4.25	4.60	4.87
HL16	3.38	5.23	4.36	3.36	3.31	3.72	4.10	4.43	5.21	4.19	4.03	4.40	4.76	5.03
HL17	3.74	5.51	4.52	3.43	3.38	3.79	4.19	4.53	5.49	4.31	4.13	4.53	4.91	5.19
HL18	6.5	7.31	6.34	4.93	4.85	5.37	5.84	6.20	7.29	5.98	5.72	6.21	6.61	6.87
HL19	5.28	-	-	-	-	-	-	-	-	-	-	-	-	-
HL20	5.56	6.83	5.84	4.43	4.36	4.89	5.39	5.76	6.81	5.50	5.23	5.74	6.17	6.44
HL21	6.5	7.36	6.38	4.97	4.88	5.40	5.88	6.23	7.34	6.02	5.76	6.24	6.64	6.90
HL22	1.87	3.44	2.80	2.09	2.06	2.30	2.52	2.67	3.39	2.88	2.80	2.94	3.08	3.18
HL23	3.83	5.80	4.85	3.67	3.61	4.07	4.54	4.89	5.78	4.62	4.39	4.85	5.26	5.54
HL24	4.09	5.83	4.89	3.75	3.69	4.14	4.60	4.93	5.81	4.66	4.45	4.90	5.30	5.58
HL25	4.64	5.93	5.03	3.88	3.83	4.31	4.76	5.08	5.90	4.80	4.59	5.03	5.42	5.68
HL26	6.08	6.84	5.85	4.40	4.32	4.89	5.40	5.76	6.82	5.51	5.23	5.75	6.18	6.44
HL27	7.03	7.03	6.07	4.68	4.60	5.14	5.65	6.02	7.02	5.72	5.46	5.97	6.39	6.66
HL28	1.61	3.15	2.50	1.88	1.85	2.06	2.24	2.37	3.08	2.66	2.59	2.71	2.82	2.91
HL29	6.79	7.36	6.38	4.97	4.88	5.40	5.88	6.23	7.34	6.02	5.76	6.24	6.64	6.90
HL30	4.66	5.93	5.03	3.88	3.83	4.31	4.76	5.08	5.90	4.80	4.59	5.03	5.42	5.68
HL31	5.27	5.96	-	-	-	-	-	-	5.96	-	-	-	-	-
HL32	3.22	4.86	4.05	3.15	3.10	3.49	3.85	4.16	4.83	3.92	3.79	4.13	4.46	4.71
HL33	2.06	4.22	3.48	2.61	2.56	2.84	3.09	3.28	4.18	3.43	3.31	3.51	3.70	3.85
HL34	3.82	5.43	4.40	3.33	3.28	3.72	4.16	4.54	5.41	4.21	4.01	4.47	4.91	5.22
HL35	3.83	5.48	4.46	3.35	3.30	3.76	4.24	4.62	5.46	4.26	4.03	4.54	4.97	5.28
HL36	3.74	5.33	4.46	3.42	3.36	3.78	4.17	4.49	5.31	4.27	4.10	4.48	4.86	5.11
HL37	3.83	5.72	4.81	3.79	3.74	4.18	4.57	4.84	5.70	4.65	4.49	4.81	5.20	5.47
HL38	1.52	2.29	1.19	1.18	1.18	1.18	1.18	1.19	2.04	2.03	2.03	2.03	2.03	2.04
HL39	3.31	4.86	4.05	3.15	3.10	3.49	3.85	4.16	4.83	3.92	3.79	4.13	4.46	4.71
HL40	3.82	5.51	4.52	3.43	3.38	3.79	4.19	4.53	5.49	4.31	4.13	4.53	4.91	5.19
HL41	3.36	5.05	4.19	3.24	3.18	3.59	3.96	4.28	5.02	4.04	3.89	4.25	4.60	4.87
HL42	5.55	-	-	-	-	-	-	-	-	-	-	-	-	-

ID	1934 Flood Level	1% AEP w/ 1% AEP SLR Tide	1% AEP w/ 10% AEP Tide						1% AEP w/ 10% AEP SLR Tide					
		Current (Kc=145) River Roughness n = 0.015	Current (Kc=145) River Roughness n = 0.015	Kc=237 River Roughness n = 0.015	Kc = 180 w/ ARF River Roughness n = 0.015	Kc = 180 w/ ARF River Roughness n = 0.020	Kc = 180 w/ ARF River Roughness n = 0.025	Kc = 180 w/ ARF River Roughness n = 0.030	Current (Kc=145) River Roughness n = 0.015	Kc=237 River Roughness n = 0.015	Kc = 180 w/ ARF River Roughness n = 0.015	Kc = 180 w/ ARF River Roughness n = 0.020	Kc = 180 w/ ARF River Roughness n = 0.025	Kc = 180 w/ ARF River Roughness n = 0.030
HL43	1.67	3.45	2.83	2.15	2.12	2.36	2.56	2.71	3.40	2.90	2.82	2.96	3.10	3.20
HL44	5.59	6.84	5.88	4.58	4.50	4.97	5.41	5.73	6.82	5.57	5.32	5.77	6.15	6.40

2.7 Southbank City Link Tunnel Portal results

Table 7 Southbank City Link Tunnel Portal Flows & Volumes

Scenario	Kc & ARF	Hydrology	Tide	River Roughness (Manning's 'n')	Peak Flow (m^3/s)	Peak Volume (m^3)
1	Current (Kc=145 w/o ARFs)	1% AEP CC (18.5% increase rainfall intensity)	1% AEP SLR	0.015	-292.0	-51,296,280
2	Current (Kc=145 w/o ARFs)	1% AEP CC (18.5% increase rainfall intensity)	10% AEP SLR	0.015	-270.6	-46,754,266
3	Kc=237 w/o ARFs	1% AEP CC (18.5% increase rainfall intensity)	10% AEP SLR	0.015	-104.5	-14,283,613
4	Kc=180 w/ ARF	1% AEP CC (18.5% increase rainfall intensity)	10% AEP SLR	0.015	-36.2	-9,027,424
5	Current (Kc=145 w/o ARFs)	1% AEP Base Case	10% AEP	0.015	-87.4	-9,669,632
6	Kc=237 w/o ARFs	1% AEP Base Case	10% AEP	0.015	0.0	0
7	Kc=180 w/ ARF	1% AEP Base Case	10% AEP	0.015	0.0	0
4*	Kc=180 w/ ARF	1% AEP CC (18.5% increase rainfall intensity)	10% AEP SLR	0.015	-36.2	-9,027,424
8	Kc=180 w/ ARF	1% AEP CC (18.5% increase rainfall intensity)	10% AEP SLR	0.02	-120.2	-17,174,045
9	Kc=180 w/ ARF	1% AEP CC (18.5% increase rainfall intensity)	10% AEP SLR	0.025	-159.5	-26,489,967
10	Kc=180 w/ ARF	1% AEP CC (18.5% increase rainfall intensity)	10% AEP SLR	0.03	-194.9	-36,132,012
7*	Kc=180 w/ ARF	1% AEP Base Case	10% AEP	0.015	0.0	0
11	Kc=180 w/ ARF	1% AEP Base Case	10% AEP	0.02	-1.0	-84,797
12	Kc=180 w/ ARF	1% AEP Base Case	10% AEP	0.025	-29.5	-1,967,656
13	Kc=180 w/ ARF	1% AEP Base Case	10% AEP	0.03	-55.7	-6,188,394
14	Current (Kc=145 w/o ARFs)	10% AEP CC (18.5% increase rainfall intensity)	10% AEP SLR	0.015	0.0	0
15	Kc=180 w/ ARF	10% AEP CC (18.5% increase rainfall intensity)	10% AEP SLR	0.02	0.0	0
16	Kc=180 w/ ARF	10% AEP CC (18.5% increase rainfall intensity)	10% AEP SLR	0.03	0.0	0

3. Preliminary thoughts on scope of model extension for discussion.

The following are some preliminary thoughts on the extension of the Lower Yarra model to include the Banksia Street gauge. It is understood that this extension is primarily to enable a comparison of modelling parameters over a larger length of river to provide a greater understanding and confidence in the conclusions being made about the suitability of these modelling parameters.

3.1 RORB

3.1.1 Expected tasks

1. Modification to cat file to provide required inflows (no change to dav) and or use NELP RORB model.
2. Rerun hydrology with additional print out locations and required parameters

3.1.2 To be confirmed

Scenarios and parameters to be tested?

3.2 TUFLOW

It is anticipated that the extended model would be run in the latest version of HPC TUFLOW.

3.2.1 Model extents

The extent of the 'existing condition, models, are:

- Lower Yarra model extends for 13.9 kms of the Yarra River.
- NELP Yarra model extends for 31.6 kms extends upstream of Banksia Street Gauge to approximately Fran Court

The options for combined model length are as follows:

1. 42.4 km if extended to include Banksia St Heidelberg (229135A)
   a. may require minor changes to inflow hydrographs
   b. faster run time smaller extent
2. 48.8 km if including all and extending up to Fran Court
   a. No changes to boundary conditions
   b. Slightly longer run time
3. 68 km if extended to Forbes St Warrandyte Gauge (229200B) (also includes Fitzsimons Lane Templestowe 229142A)

3.2.2 Expected Tasks

1. Combine existing terrain models
2. Adopt a common loc line and grid:
   – Adopt loc line from Lower Yarra

- Check and revise NELP structure representation with new grids
  - Check and revise NELP terrain modifications with new grids

3. Merge materials layers
4. Add key structure and terrain between detailed sections of existing models
   - Details of additional structure to be provided by Melbourne Water
   - Level of detail for initial runs to be discussed and agreed.
     - Consider rough initial runs
     - Refine if required for current purpose
5. Debugging and refinement to enable running in latest version of HPC TUFLOW.
6. Identify additional reporting locations
7. Production runs
8. Checking results
9. Produce comparative tables and long sections between runs and 1934 historic flood levels
10. Discussions
11. Documentation

3.3 Current Exclusions

Current thinking has the following exclusions:

- No update for ARR2019.
- Modelling is not for flood mapping purpose.
- No significant iteration or calibration process allowed for at this stage.
- No modelling of historic events.
- No detailed assessment or survey of recorded flood levels.
- No flood frequency analysis at the gauges.
- Use existing terrain data in models no addition of additional bathymetric survey, structure survey or new Lidar sources.
- Checking and review to identify problems in commercial software packages.

Attachment 7

Phase 1 Model Extension Result Memo

Stage 1B –
Summary of results from TUFLOW Model Extension

Table of contents

Table index

Figure index

1. Project Diary

Table 1 summarises of the agreed model refinements carried out on the Lower Yarra River Flood Mapping TUFLOW model since the delivery of the 'Draft Deliverables' in February 2020.

Table 1 Progression of Model Refinement

Date	Time	Description\Outcome
23-04-2020	9:00 am	Skype meeting to discuss the Lower Yarra mapping limit
28-04-2020	5:29 pm	Emailed proposal $######
29-04-2020	8:30 am	Meeting to discuss scope for Lower Yarra
29-04-2020	12:58 pm	Revised proposal $######
29-04-2020	3:24 pm	MW accepted revised proposal
06-05-2020	10:19 pm	GHD provide Stage 1A results
07-05-2020	10:00 am	Discussion of stage 1A results
07-05-2020	3:30 pm	Meeting to discuss next steps
08-05-2020	10:07 am	Email to MW clarifying scope, fees and discussions with NELP
08-05-2020	2:50 pm	Emails back and forth, MW emailed NELP with formal request
08-05-2020	3:12 pm	MW confirm request for all 6 runs.
12-05-2020	2:57 pm	GHD provide results for the additional 6 runs
13-05-2020	8:30 am	Meeting to discuss results
13-05-2020	3:11 pm	GHD provided email to summarise revised scope
14-05-2020	3:21 pm	MW request information of the 10year tidal boundary time series
14-05-2020	3:45 pm	GHD referred MW to Appendix C of the report
15-05-2020	7:17 am	MW requested GHD to proceed in accordance with revised scope (13/5)
15-05-2020	3:58 pm	MW provide additional info on 1934 event
15-05-2020	4:10 pm	GHD advised that we had responded to NELP and expected that NELP would advise MW of their decision
18-05-2020	6:00 pm	NELP approve use of existing conditions TUFLOW and RORB models for MW
03-06-2020	**6:46 am**	**MW approve Lower Yarra model extension up to top of NELP 'existing' conditions model**

2. Preliminary Results for Discussion

2.1 Modelled Scenarios

Table 2 summarises the modelled scenarios completed since the initial overflow refinement modelling, which added terrain details from the Southbank and Fisherman's Bend TUFLOW models, a new boundary condition at the City Link portal in Southbank area, and a DS tidal boundary based on 10% AEP. We have now added a colum relating to scenarios run with the extended model

Table 2 Modelled Scenarios

Run ID	Hydrology	Yarra River Inflow (m^3/s)	Yarra River Inflow Volume (m^3)	DS TWL	River Roughness (Manning's 'n')	Plot Legend	Modelled with 4400_v24_OR? (refined version of 4400_v24)	Modelled with 4400_v26? (extended version of 4400_v24_OR)
1	Base 1% AEP (Kc=145 w/o ARFs)[1] [Solid blue line on Figure 1]	1475	517,000,000	10% AEP Tide	0.015	100y Kc145 NoARF M0p015 (Current)	Y	N
2	Base 1% (Kc=237 w/o ARFs)[2] [Solid orange line on Figure 1]	1115	517,000,000	10% AEP Tide	0.015	100y Kc237 NoARF M0p015	Y	N
3	Base 1% AEP (Kc=180 w/ ARFs)[3] [Solid green line on Figure 1]	1091	432,000,000	10% AEP Tide	0.015	100y Kc180 ARF M0p015	Y	N
4	CC 18.5% 1% AEP (Kc=145 w/o ARFs)[1] [Dashed blue line on Figure 1]	1792	621,000,000	10% AEP SLR Tide	0.015	100y CC18p5 Kc145 NoARF M0p015 (Current)	Y	N
5	CC 18.5% 1% AEP (Kc=237 w/o ARFs)[2] [Dashed green line on Figure 1]	1352	621,000,000	10% AEP SLR Tide	0.015	100y CC18p5 Kc237 NoARF M0p015	Y	N
6	CC 18.5% 1% AEP (Kc=180 w ARFs)[3] [Dashed green line on Figure 1]	1293	509,000,000	10% AEP SLR Tide	0.015	100y CC18p5 Kc180 ARF M0p015	Y	N
7	Base 1% AEP (Kc=180 w/ ARFs)[3]	-	-	10% AEP Tide	0.020	100y Kc180 ARF M0p020	Y	Y
8	Base 1% AEP (Kc=180 w/ ARFs)[3]	-	-	10% AEP Tide	0.025	100y Kc180 ARF M0p025	Y	Y
9	Base 1% AEP (Kc=180 w/ ARFs)[3]	-	-	10% AEP Tide	0.030	100y Kc180 ARF M0p030	Y	N

Run ID	Hydrology	Yarra River Inflow (m^3/s)	Yarra River Inflow Volume (m^3)	DS TWL	River Roughness (Manning's 'n')	Plot Legend	Modelled with 4400_v24_OR? (refined version of 4400_v24)	Modelled with 4400_v26? (extended version of 4400_v24_OR)
10	CC 18.5% 1% AEP (Kc=180 w ARFs)[3]	-	-	10% AEP SLR Tide	0.020	100y CC18p5 Kc180 ARF M0p020	Y	N
11	CC 18.5% 1% AEP (Kc=180 w ARFs)[3]	-	-	10% AEP SLR Tide	0.025	100y CC18p5 Kc180 ARF M0p025	Y	N
12	CC 18.5% 1% AEP (Kc=180 w ARFs)[3]	-	-	10% AEP SLR Tide	0.030	100y CC18p5 Kc180 ARF M0p030	Y	N
13	CC 18.5% 10% AEP (Kc=145 w/o ARFs)[1]	831	291,000,000	10% AEP SLR Tide	0.015	10y Kc145 NoARF M0p015 (Current)	Y	N
14	CC 18.5% 10% AEP (Kc=180 w ARFs)[3]	616	246,000,000	10% AEP SLR Tide	0.020	10y CC18p5 Kc180 ARF M0p020	Y	N
15	CC 18.5% 10% AEP (Kc=180 w ARFs)[3]	616	246,000,000	10% AEP SLR Tide	0.030	10y CC18p5 Kc180 ARF M0p030	Y	N
16	Base 1% AEP (Kc=145 w/o ARFs)[1] [Solid blue line on Figure 1]	1475	517,000,000	10% AEP Tide	0.020	100y Kc145 NoARF M0p020	N	Y
17	Base 1% AEP (Kc=145 w/o ARFs)[1] [Solid blue line on Figure 1]	1475	517,000,000	10% AEP Tide	0.025	100y Kc145 NoARF M0p025	N	Y

Note:

[1] indicates that the Kc parameter is based on calibration to flood levels using HEC-RAS from "2010 - SP Goh & Associates Study", which didn't use ARFs.

[2] indicates that the Kc parameter is based on calibration to gauge flows from "2010 - SP Goh & Associates Study" , which didn't use ARFs

[3] indicates that the Kc parameter is based on MW work prior to "2010 - SP Goh & Associates Study", but with the application of ARFs

2.2 Yarra River Boundary Conditions

Figure 2-1 and Figure 2-2 summarise the key boundary condition assumptions for the modelling presented in Section 2.1.

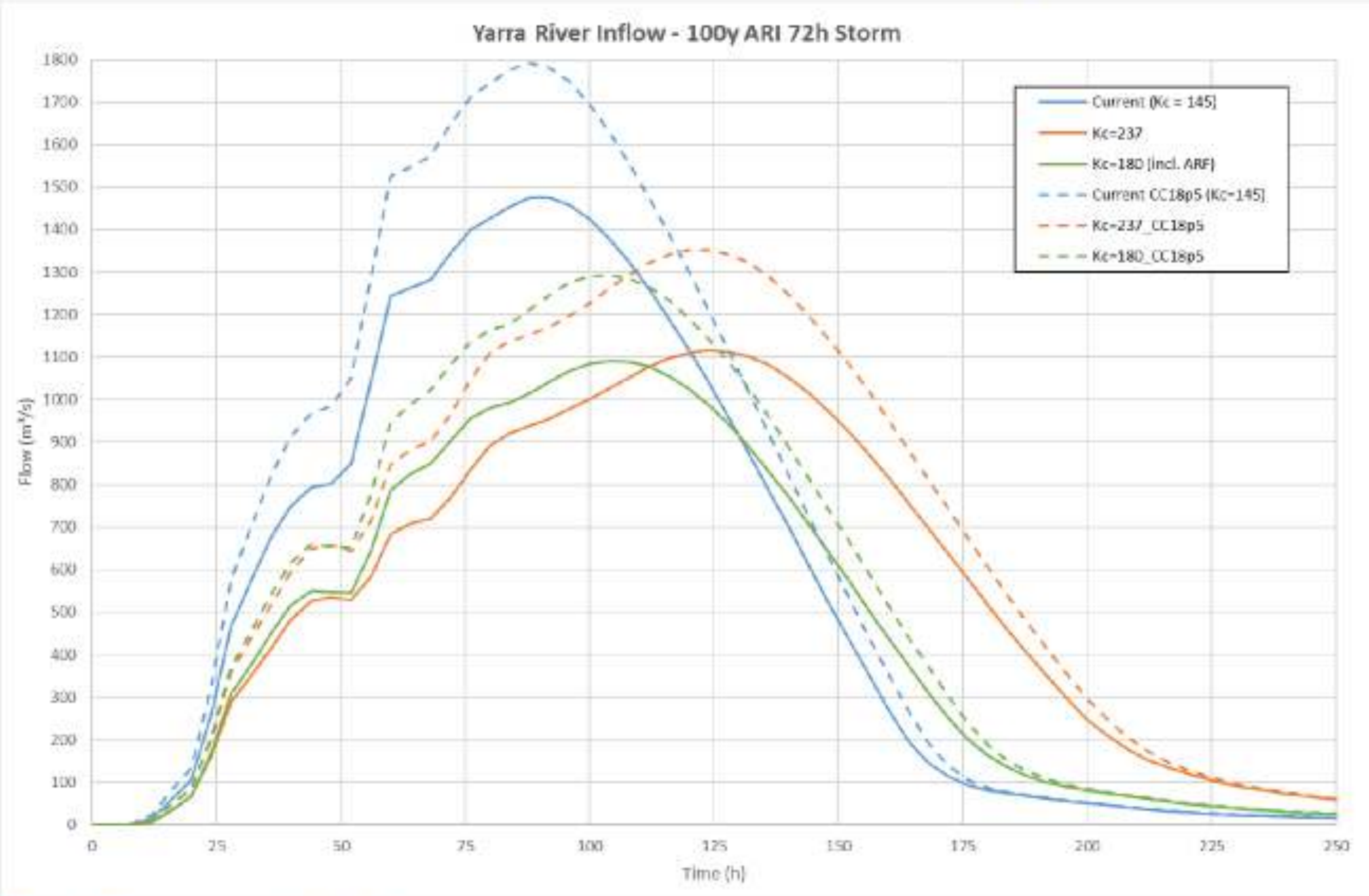


Figure 2-1 Comparison of Yarra Inflows

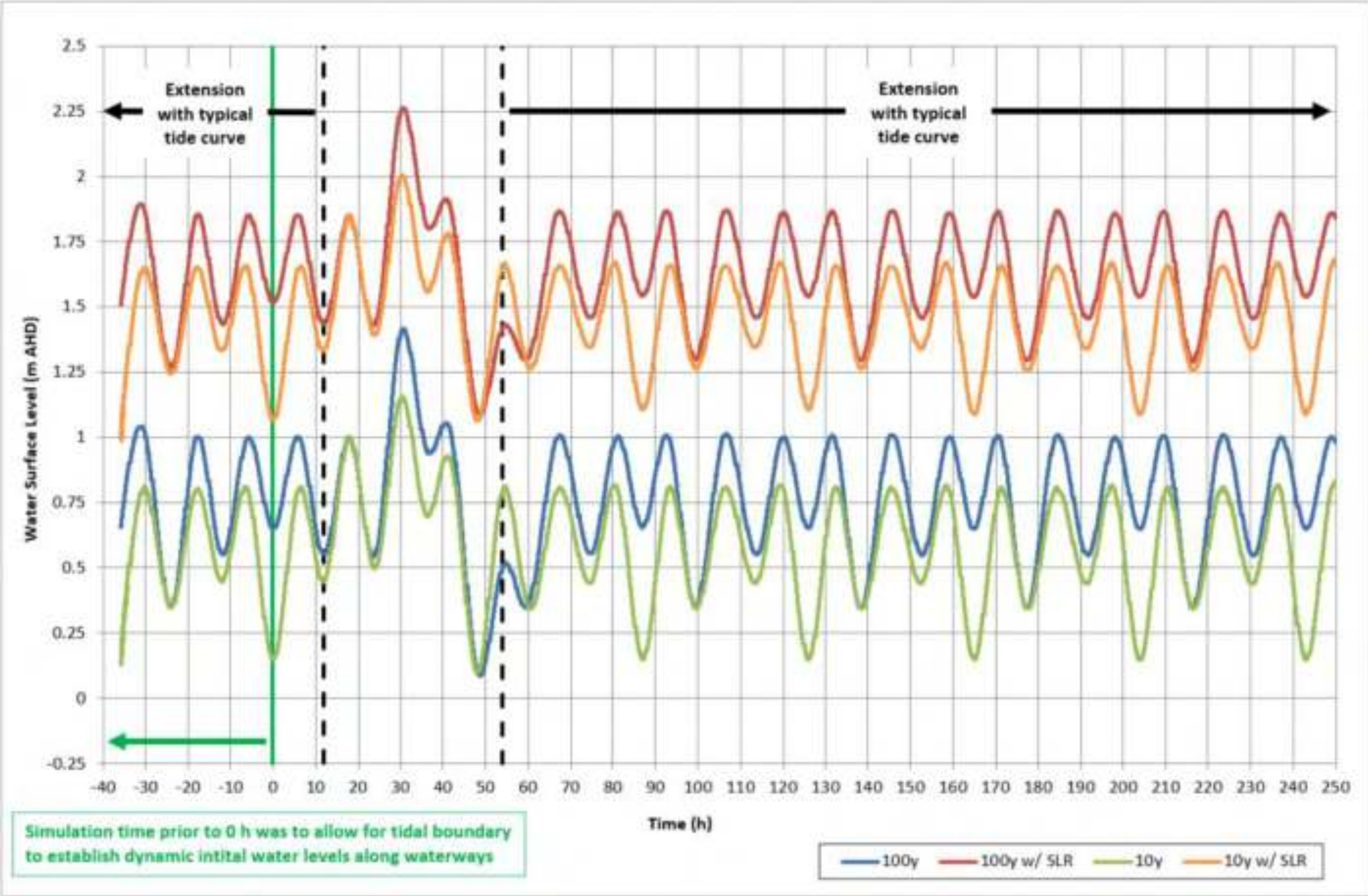


Figure 2-2 Adopted Yarra River DS Tidal Boundary Curves

2.3 Flood Extents (extended model results only)

2.3.1 Run 7

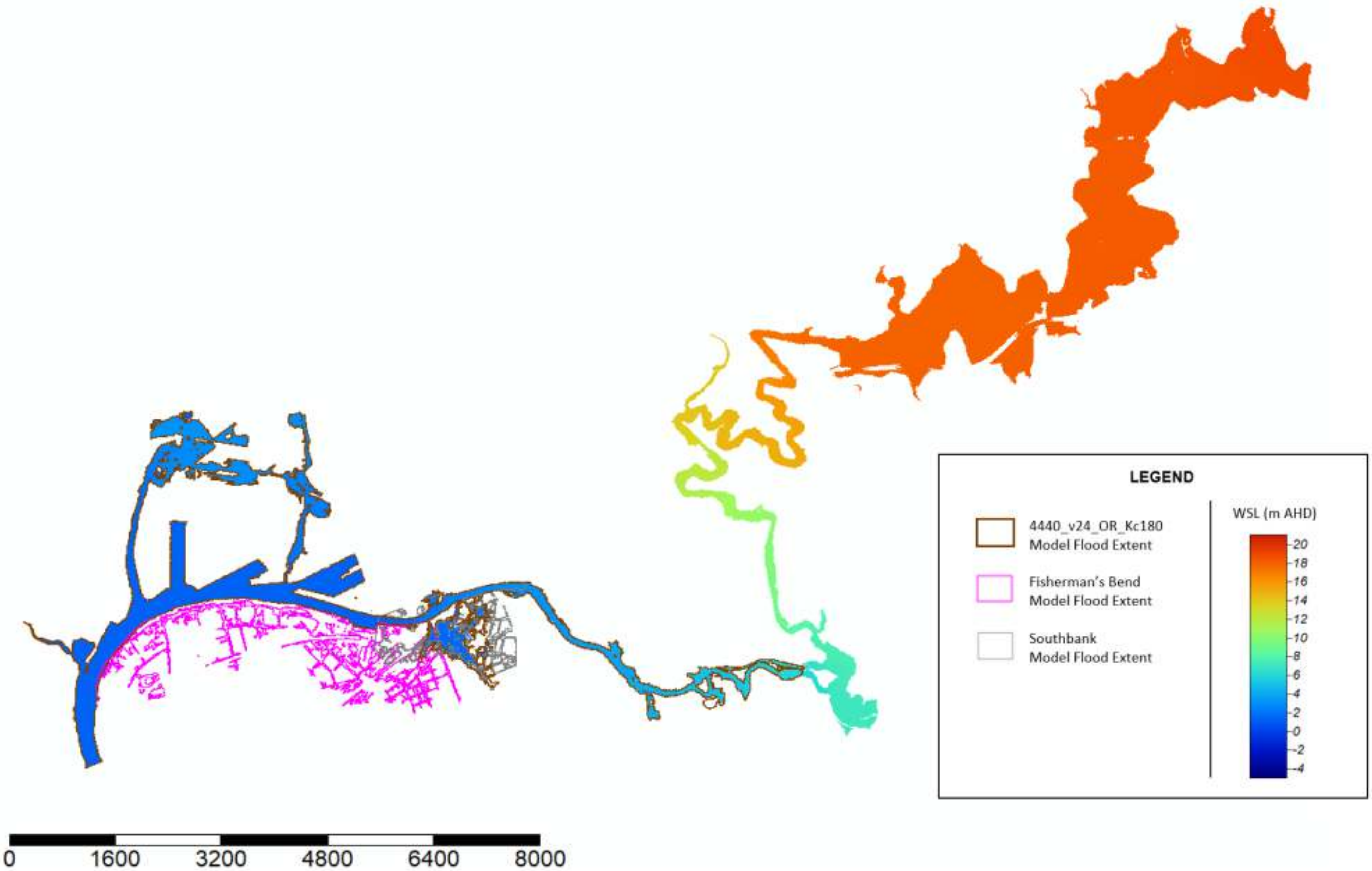


Figure 2-3 Peak 100y WSL Current (Kc=180 w/ ARFs, 10y Tide & River Manning's 'n' of 0.020)

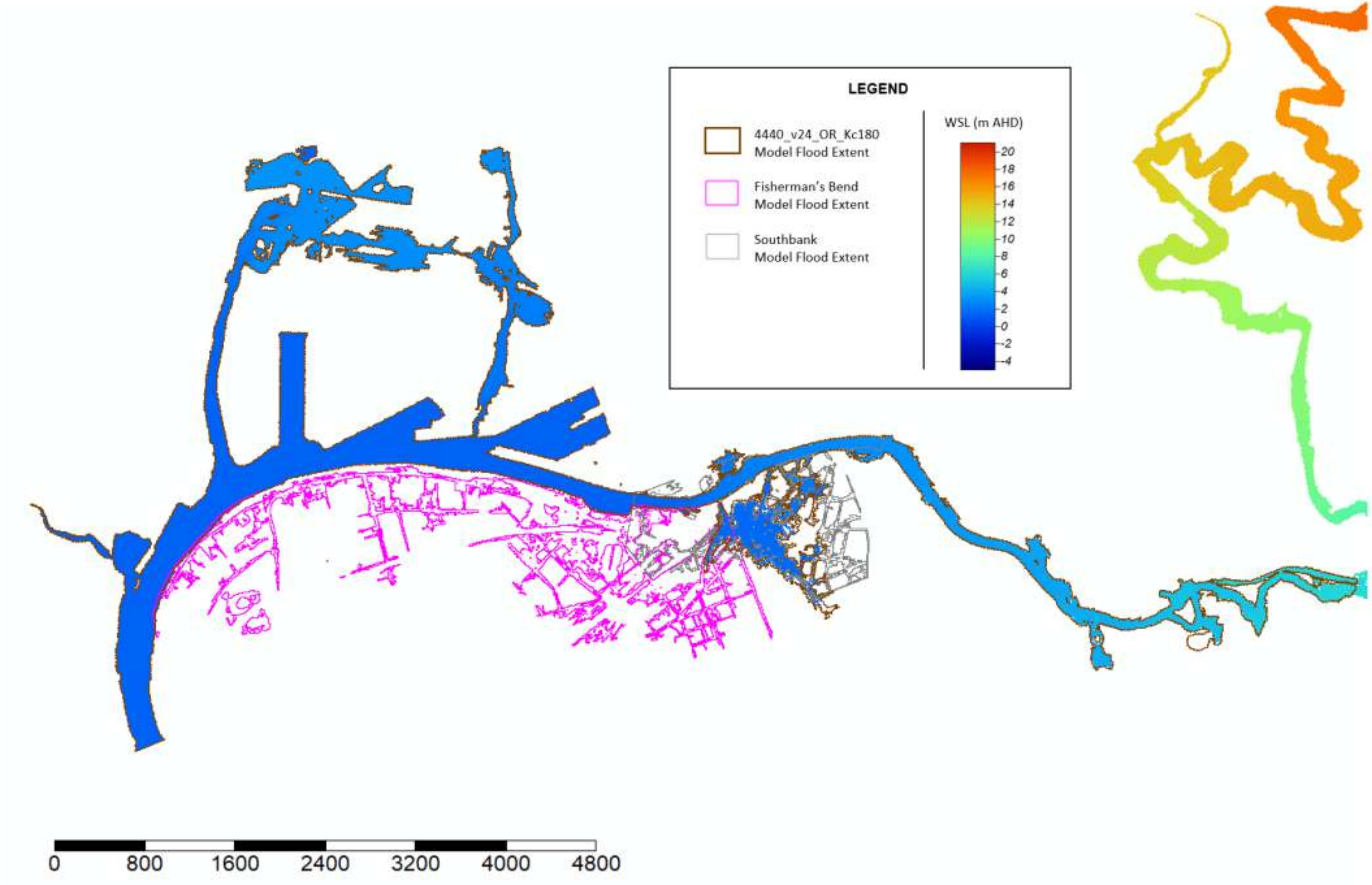


Figure 2-4 Peak 100y WSL Current (Kc=180 w/ ARFs, 10y Tide & River Manning's 'n' of 0.020– Zoomed to refinement area

2.3.2 Run 8

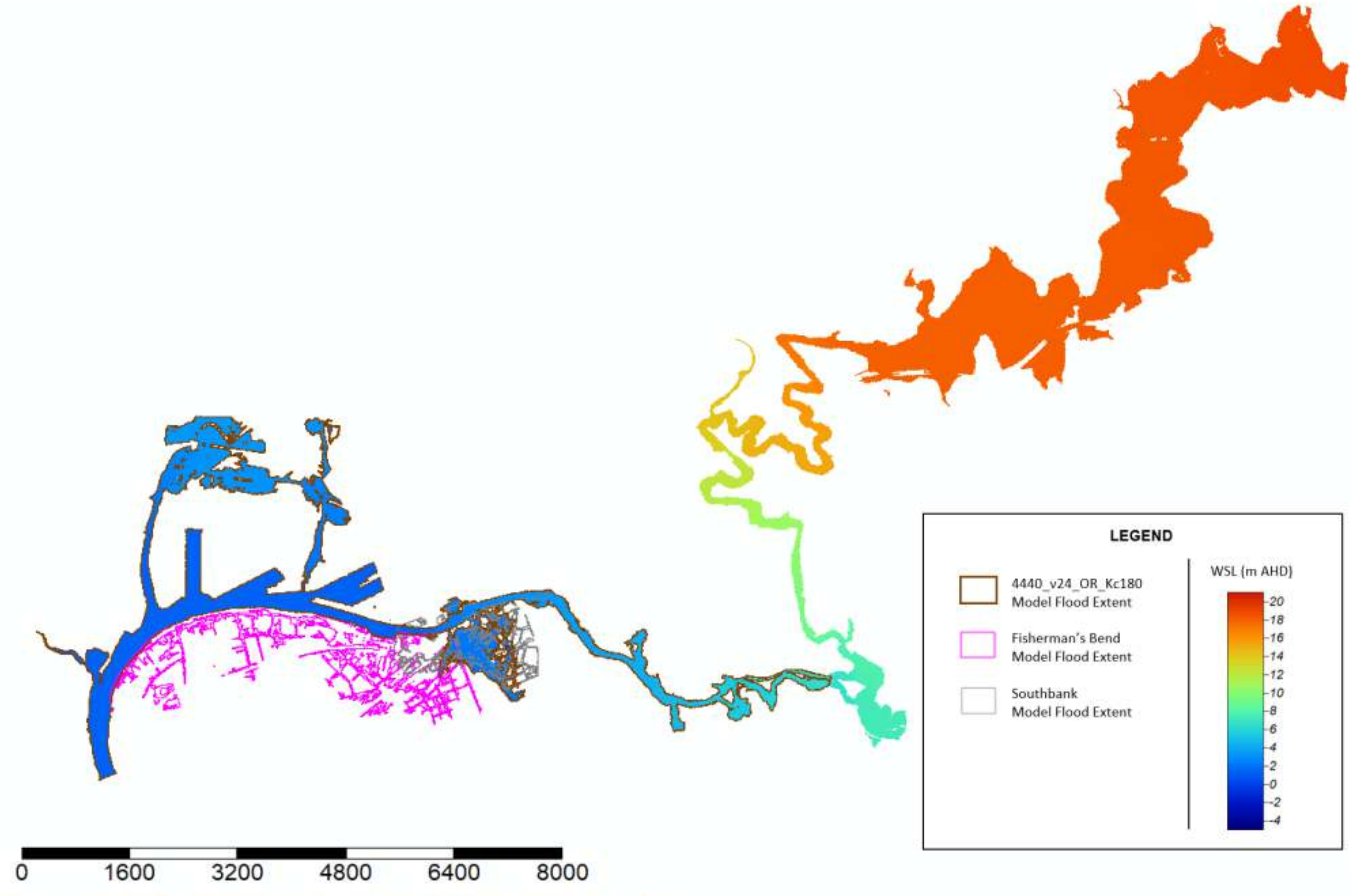


Figure 2-5 Peak 100y WSL Current (Kc=180 w/ ARFs, 10y Tide & River Manning's 'n' of 0.025)

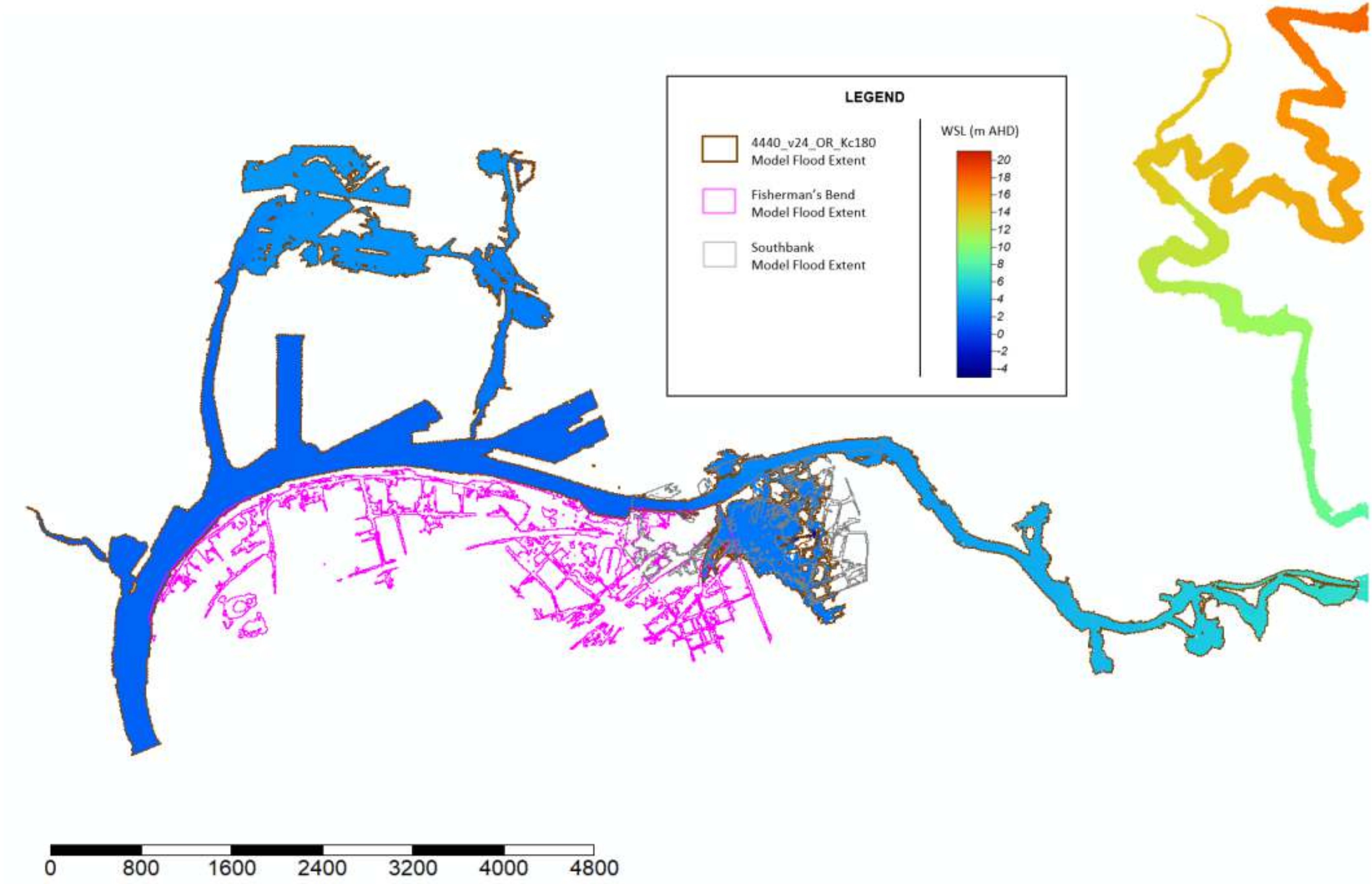


Figure 2-6 Peak 100y WSL Current (Kc=180 w/ ARFs, 10y Tide & River Manning's 'n' of 0.025) – Zoomed to refinement area

2.3.3 Run 16

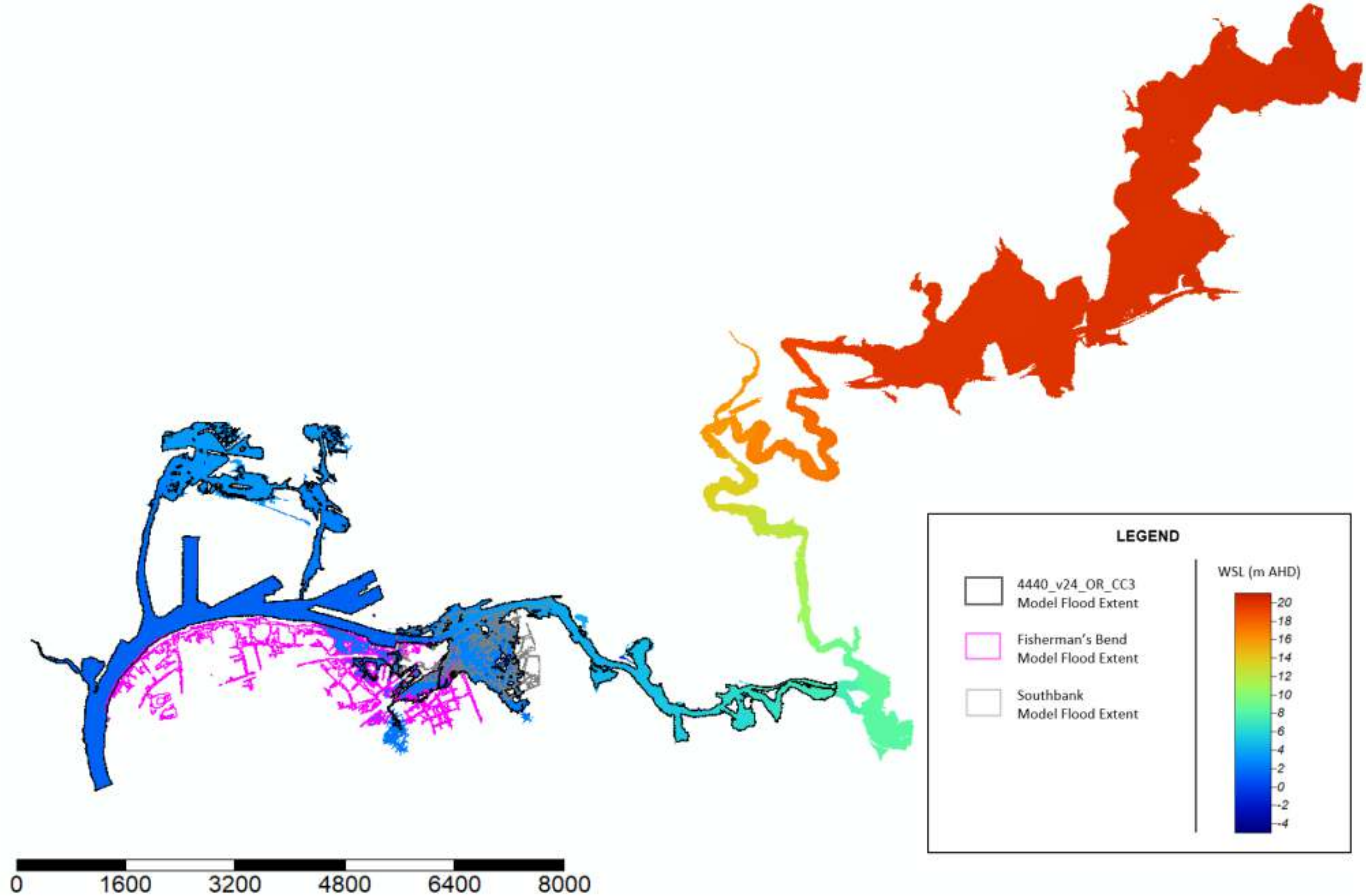


Figure 2-7 Peak 100y WSL Current (Kc=145 w/o ARFs, 10y Tide & River Manning's 'n' of 0.020)

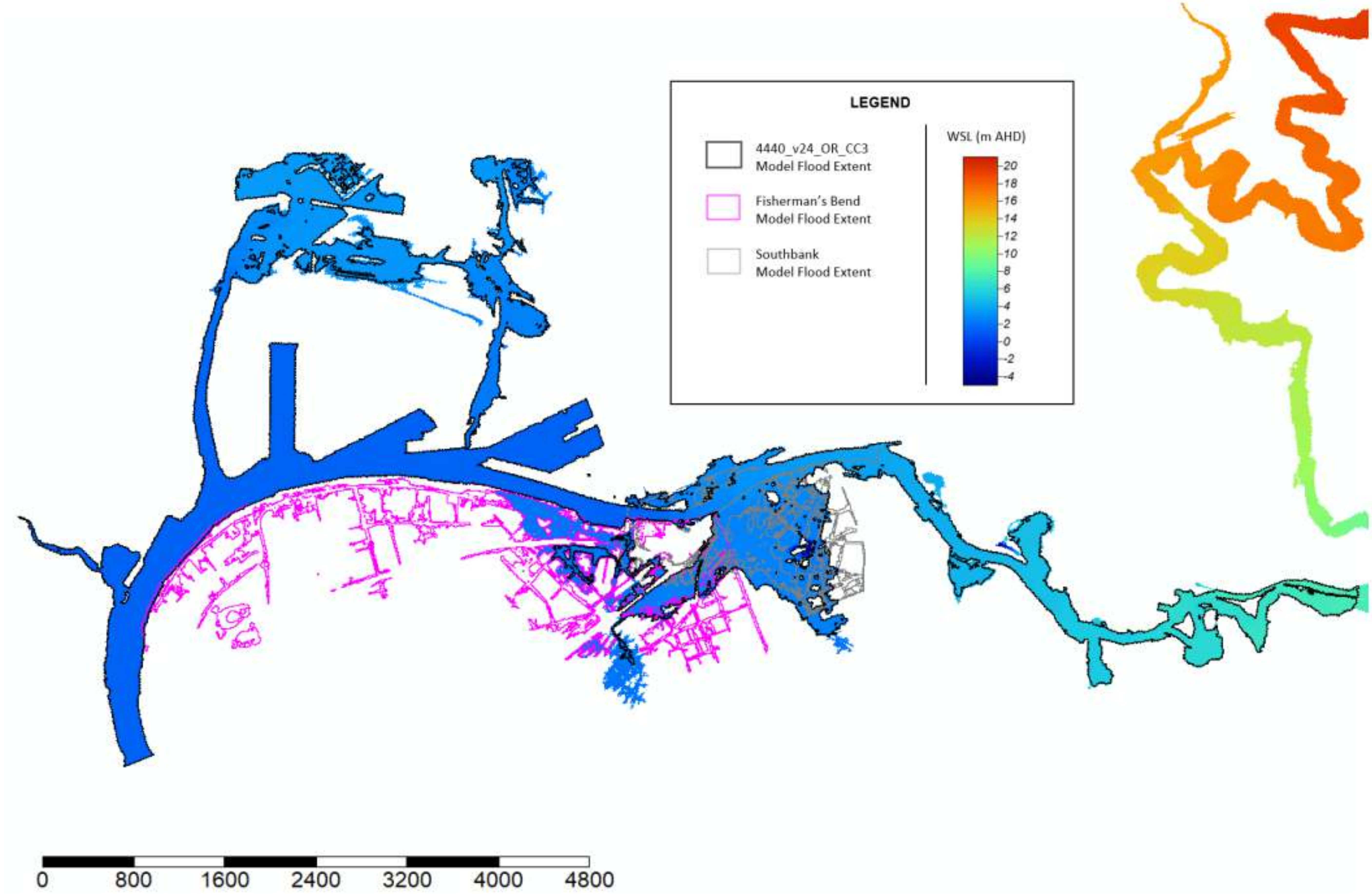


Figure 2-8 Peak 100y WSL Current (Kc=145 w/o ARFs, 10y Tide & River Manning's 'n' of 0.020) – Zoomed to refinement area

2.3.4 Run 17

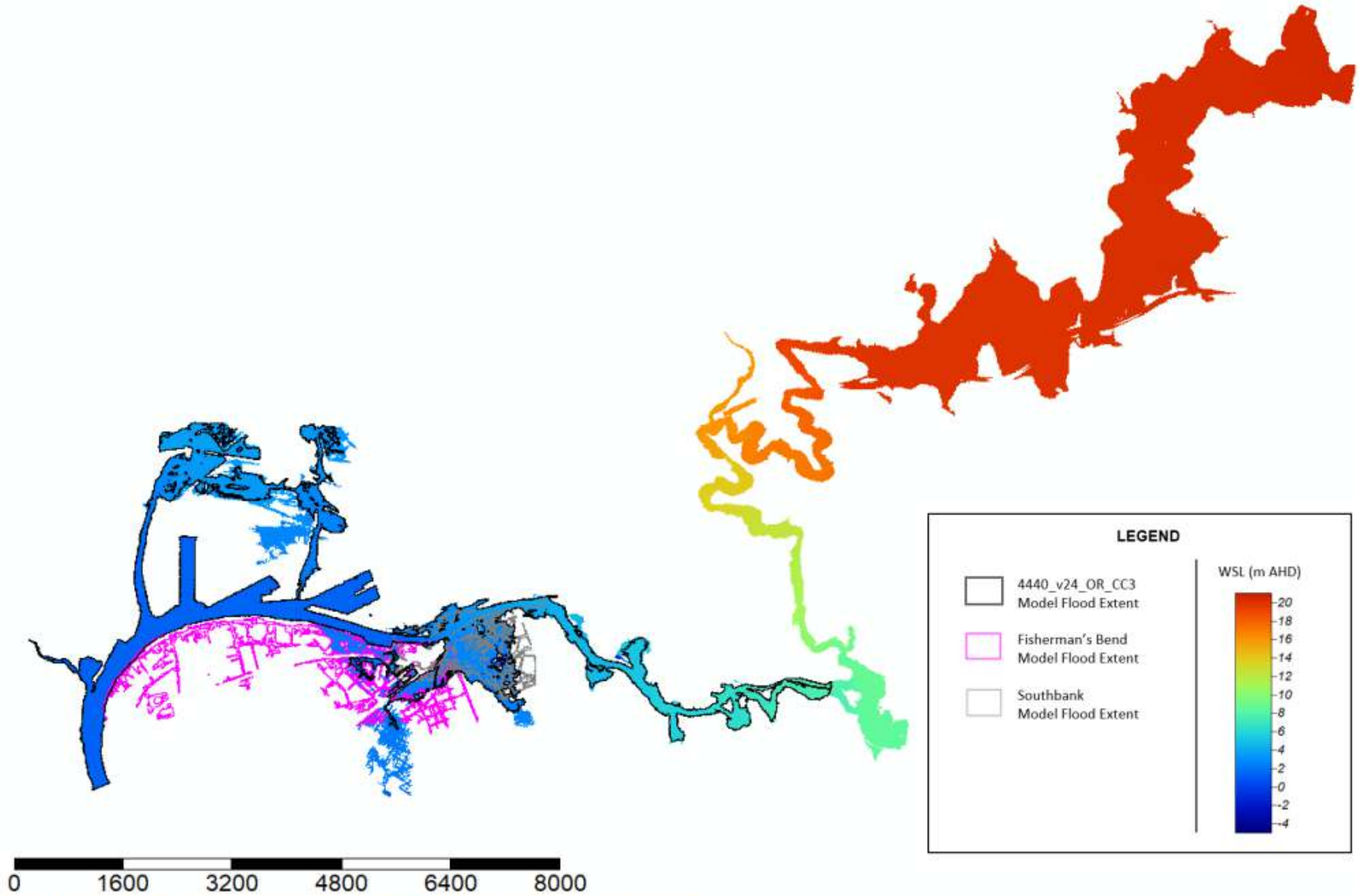


Figure 2-9 Peak 100y WSL Current (Kc=145 w/o ARFs, 10y Tide & River Manning's 'n' of 0.025)

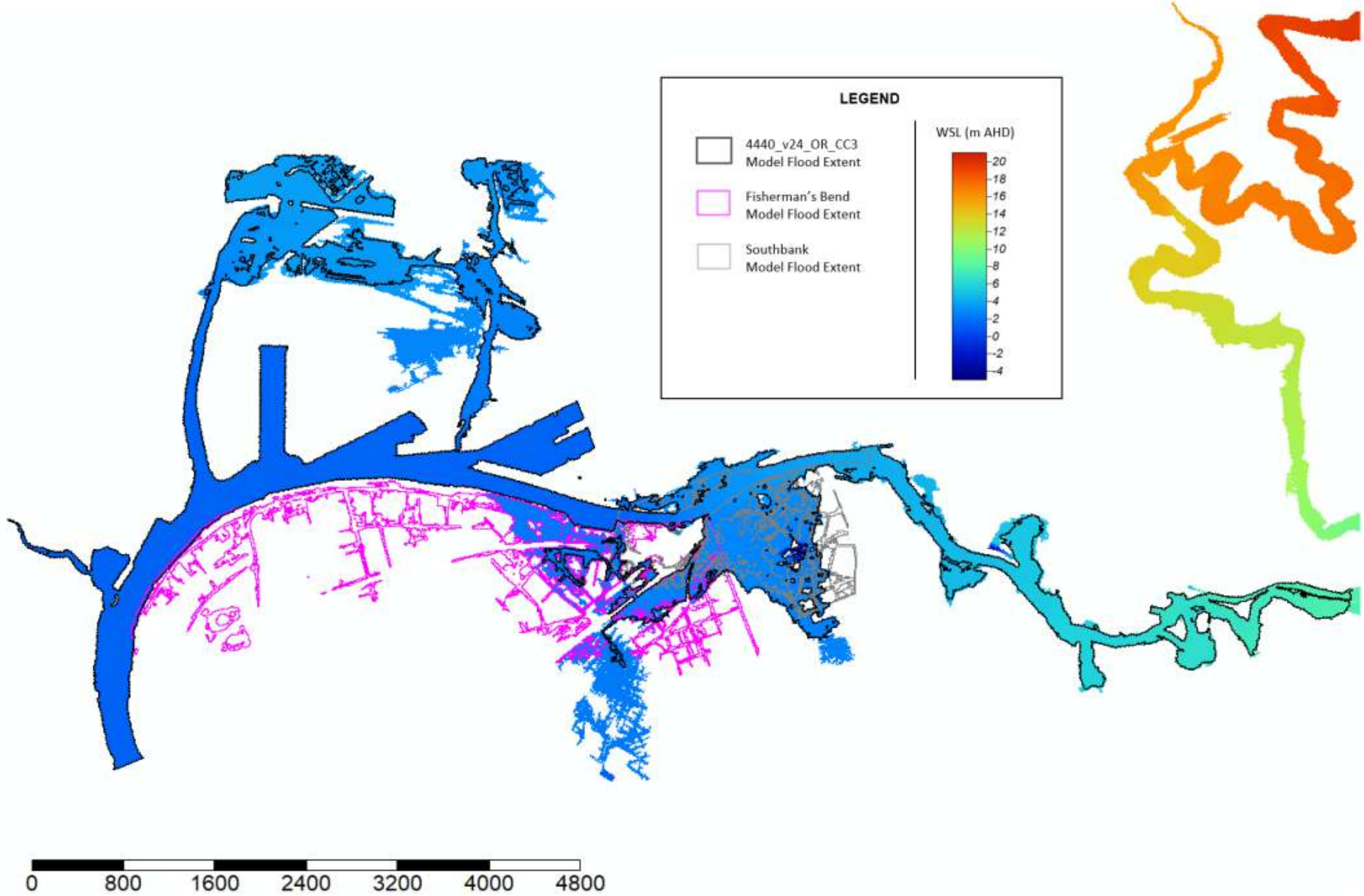
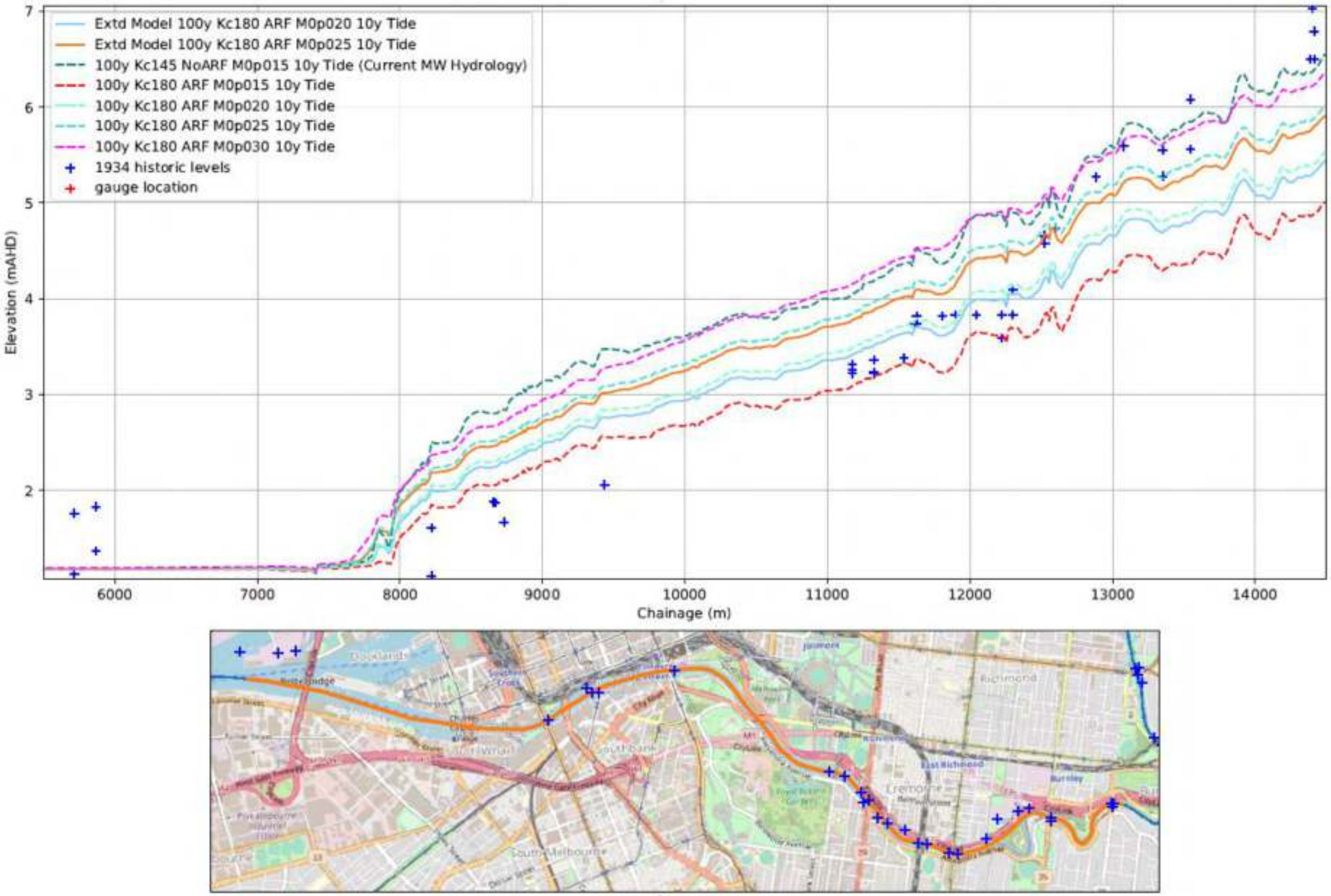


Figure 2-10 Peak 100y WSL Current (Kc=145 w/o ARFs, 10y Tide & River Manning's 'n' of 0.025)– Zoomed to refinement area

2.4 Long Sections

2.4.1 Runs 7 & 8 – Impact of Model Extension and varying Manning's 'n'



Plan

Figure 2-11 1% AEP Long-section along Yarra River comparing WSL along Yarra to historic levels - Impact of Model Extension

2.4.2 Runs 7, 8, 16 & 17 – Impact of Hydrology and varying Manning's 'n'

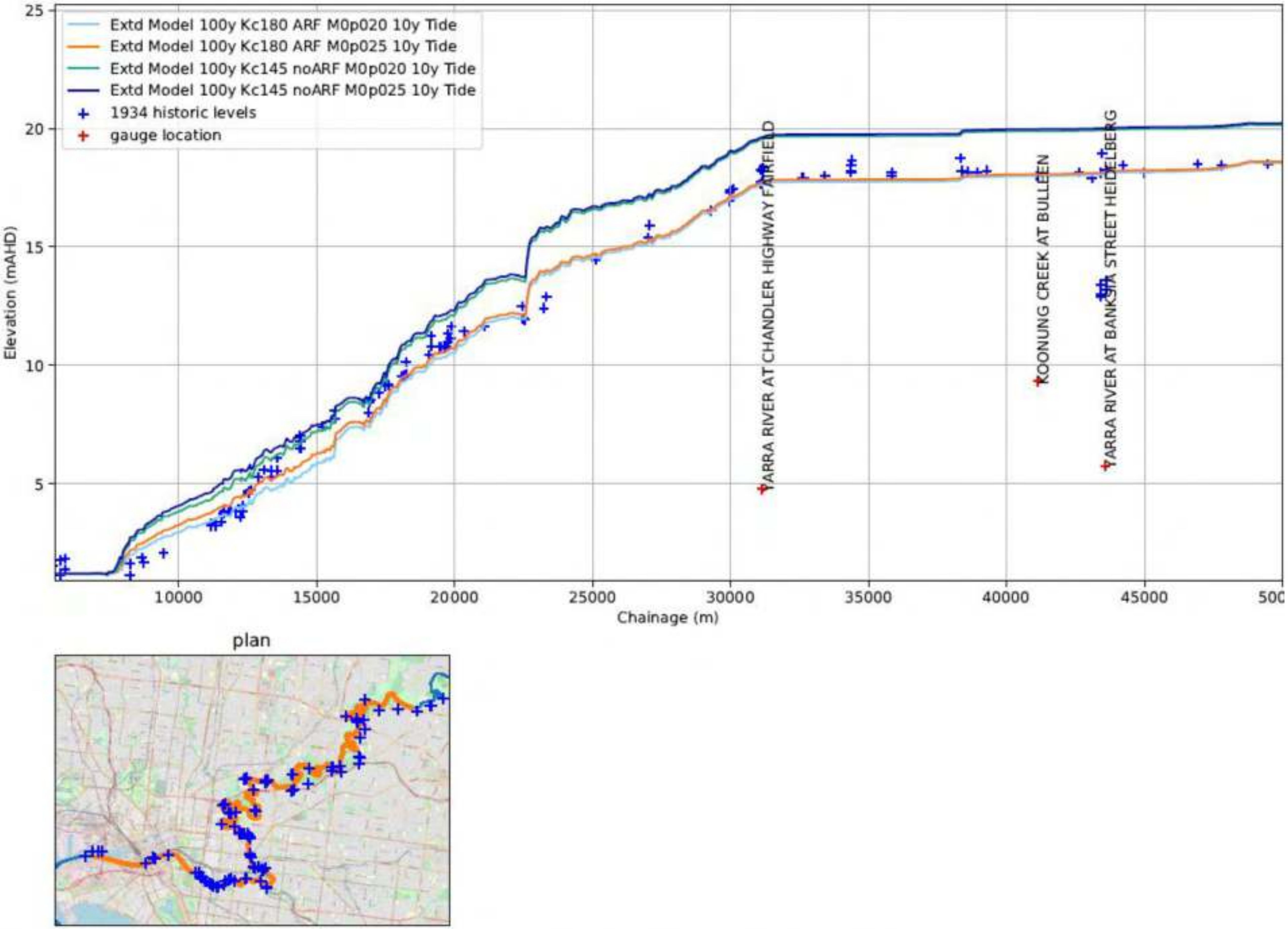


Figure 2-12 1% AEP Long-section along Yarra River comparing WSL along Yarra to historic levels - Impact of River Roughness

2.5 Comparison Point Results – Overflow Refinement Area

Figure 2-13 Location of Comparison Points

Table 3 Comparison Point Locations – Impact of model extension and varying roughness on 1% AEP

ID	Description	Southbank Model 1% AEP CC (18.5%) Flows w/ 10% AEP SLR Tide	Fisherman's Bend Model 1% AEP Flows w/ 10% AEP Tide	4400_v24_OR Model (refined version of Lower Yarra River flood mapping model) 1% AEP Flows w/ 10% AEP Tide				4400_v26 Model (extended version of 4400_v24_OR model) 1% AEP Flows w/ 10% AEP Tide			
				Current - Kc=145 w/o ARFs & n = 0.015	Kc=180 w/ ARFs & n = 0.015	Kc=180 w/ ARFs & n = 0.020	Kc=180 w/ ARFs & n = 0.025	Current - Kc=145 w/o ARFs & n = 0.020	Kc=180 w/ ARFs & n = 0.020	Current - Kc=145 w/o ARFs & n = 0.025	Kc=180 w/ ARFs & n = 0.025
1	Yarra River 1 (US)	2.14	-	3.48	2.55	2.84	3.10	3.62	2.77	3.82	3.03
2	Yarra River 2	2.14	-	2.81	2.06	2.31	2.53	2.92	2.25	3.07	2.47
3	Yarra River 3	2.14	-	1.24	1.20	1.23	1.26	1.31	1.23	1.45	1.27
4	Yarra River 4	-	-	1.19	1.18	1.18	1.19	1.19	1.18	1.21	1.19
5	Yarra River 5 (DS)	-	-	1.19	1.18	1.18	1.18	1.19	1.18	1.20	1.18
6	South Bank Pond	1.28	-	2.31	-	1.65	2.03	2.38	1.44	2.47	1.96
7	Sth Park St	-	-	-	-	-	-	-	-	2.41	-
8	Fwy \ Montague St	-	1.82	-	-	-	-	1.80	-	1.96	-
9	Lorimer St \ Boundary St	-	1.82	-	-	-	-	1.80	-	1.94	-
10	Approx. Boundary St \ Gittus St	-	1.82	1.53	-	-	-	1.80	-	1.96	-
11	Approx. Buckhurst St \ George St	-	1.89	2.13	-	-	-	2.24	-	2.28	-
12	Approx. Heath St \ Raglan St	-	-	-	-	-	-	-	-	2.09	-
13	Edwards Park	-	-	-	-	-	-	-	-	2.02	-
14	Approx. St Vincent St \ Iffla St	-	-	-	-	-	-	-	-	2.02	-

2.6 Comparison with 1934 historic points

Figure 2-14 Location of 1934 Historic Flood Levels

Table 4 1934 Flood Level Comparison Points

ID	1934 Flood Level	4400_v24_OR Model (refined version of Lower Yarra River flood mapping model)				4400_v26 Model (extended version of 4400_v24_OR model)			
		Current - Kc=145 w/o ARFs & n = 0.015	Kc=180 w/ ARFs & n = 0.015	Current - Kc=145 w/o ARFs & n = 0.020	Kc=180 w/ ARFs & n = 0.025	Current - Kc=145 w/o ARFs & n = 0.020	Kc=180 w/ ARFs & n = 0.020	Current - Kc=145 w/o ARFs & n = 0.025	Kc=180 w/ ARFs & n = 0.025
HL1	3.59	4.85	3.61	4.07	4.54	5.19	3.98	5.55	4.43
HL2	3.83	4.89	3.69	4.14	4.60	5.23	4.04	5.59	4.49
HL3	4.58	5.03	3.83	4.31	4.76	5.36	4.21	5.69	4.66
HL4	4.74	5.04	3.84	4.33	4.79	5.39	4.24	5.74	4.68
HL5	1.52	1.19	1.18	1.18	1.18	1.19	1.18	1.19	1.18
HL6	0.64	1.19	1.18	1.18	1.18	1.19	1.18	1.19	1.18
HL7	1.76	-	-	-	-	-	-	-	-
HL8	1.13	-	-	-	-	-	-	-	-
HL9	1.83	-	-	-	-	-	-	-	-
HL10	1.37	-	-	-	-	-	-	-	-
HL11	1.11	2.50	1.85	2.06	2.24	2.60	2.01	2.72	2.19
HL12	1.88	2.84	2.07	2.31	2.53	2.94	2.25	3.08	2.48
HL13	3.26	4.05	3.10	3.49	3.85	4.34	3.42	4.65	3.78
HL14	3.23	4.19	3.18	3.59	3.96	4.50	3.51	4.83	3.88
HL15	3.22	4.19	3.18	3.59	3.96	4.50	3.51	4.83	3.88
HL16	3.38	4.36	3.31	3.72	4.10	4.67	3.64	5.00	4.01
HL17	3.74	4.52	3.38	3.79	4.19	4.84	3.71	5.19	4.10
HL18	6.5	6.34	4.85	5.37	5.84	6.66	5.27	6.97	5.74
HL19	5.28	-	-	-	-	-	-	-	-
HL20	5.56	5.84	4.36	4.89	5.39	6.20	4.79	6.52	5.28
HL21	6.5	6.38	4.88	5.40	5.88	6.72	5.31	7.01	5.79
HL22	1.87	2.80	2.06	2.30	2.52	2.91	2.25	3.06	2.47
HL23	3.83	4.85	3.61	4.07	4.54	5.19	3.98	5.55	4.43
HL24	4.09	4.89	3.69	4.14	4.60	5.23	4.04	5.59	4.49
HL25	4.64	5.03	3.83	4.31	4.76	5.36	4.21	5.69	4.66
HL26	6.08	5.85	4.32	4.89	5.40	6.20	4.78	6.52	5.28
HL27	7.03	6.07	4.60	5.14	5.65	6.45	5.05	6.77	5.57
HL28	1.61	2.50	1.85	2.06	2.24	2.60	2.01	2.72	2.19
HL29	6.79	6.38	4.88	5.40	5.88	6.72	5.31	7.01	5.79
HL30	4.66	5.03	3.83	4.31	4.76	5.36	4.21	5.69	4.66
HL31	5.27	-	-	-	-	-	-	-	-
HL32	3.22	4.05	3.10	3.49	3.85	4.34	3.42	4.65	3.78
HL33	2.06	3.48	2.56	2.84	3.09	3.61	2.76	3.80	3.02
HL34	3.82	4.40	3.28	3.72	4.16	4.78	3.64	5.19	4.07
HL35	3.83	4.46	3.30	3.76	4.24	4.84	3.68	5.25	4.13
HL36	3.74	4.46	3.36	3.78	4.17	4.75	3.70	5.09	4.08
HL37	3.83	4.81	3.74	4.18	4.57	5.12	4.09	5.47	4.49
HL38	1.52	1.19	1.18	1.18	1.18	1.19	1.18	1.19	1.18
HL39	3.31	4.05	3.10	3.49	3.85	4.34	3.42	4.65	3.78
HL40	3.82	4.52	3.38	3.79	4.19	4.84	3.71	5.19	4.10
HL41	3.36	4.19	3.18	3.59	3.96	4.50	3.51	4.83	3.88
HL42	5.55	-	-	-	-	-	-	-	-
HL43	1.67	2.83	2.12	2.36	2.56	2.94	2.30	3.08	2.51
HL44	5.59	5.88	4.50	4.97	5.41	6.17	4.87	6.48	5.29

2.7 Southbank City Link Tunnel Portal results

Table 5 Southbank City Link Tunnel Portal Flows & Volumes

					Southbank Portal		Burnley Exit		Domain Entry	
Scenario	Kc & ARF	Hydrology	Tide	River Roughness (Manning's 'n')	Peak Flow (m^3/s)	Peak Volume (m^3)	Peak Flow (m^3/s)	Peak Volume (m^3)	Peak Flow (m^3/s)	Peak Volume (m^3)
5*	Current (Kc=145 w/o ARFs)	1% AEP Base Case	10% AEP	0.015	-87.4	-9,669,632	0.0	0	0.0	0
3*	Kc=180 w/ ARF	1% AEP Base Case	10% AEP	0.015	0.0	0	0.0	0	0.0	0
7*	Kc=180 w/ ARF	1% AEP Base Case	10% AEP	0.02	-1.0	-84,797	0.0	0	0.0	0
7	Kc=180 w/ ARF	1% AEP Base Case	10% AEP	0.02	0.0	0	0.0	0	0.0	0
15	Kc=145 w/o ARFs	1% AEP Base Case	10% AEP	0.02	-112.4	-15,163,951	-0.5	-21094.4	-0.5	-18849.8
8*	Kc=180 w/ ARF	1% AEP Base Case	10% AEP	0.025	-29.5	-1,967,656	0.0	0	0.0	0
8	Kc=180 w/ ARF	1% AEP Base Case	10% AEP	0.025	-20.5	-1,441,442	0.0	0	0.0	0
16	Kc=145 w/o ARFs	1% AEP Base Case	10% AEP	0.025	-151.8	-23,672,279	-14.5	-1203657.8	-2.3	-196330.8

Note:
* indicates that these runs were from the shorter model (4400_v24_OR)

2.8 Georeferenced Flood Extent

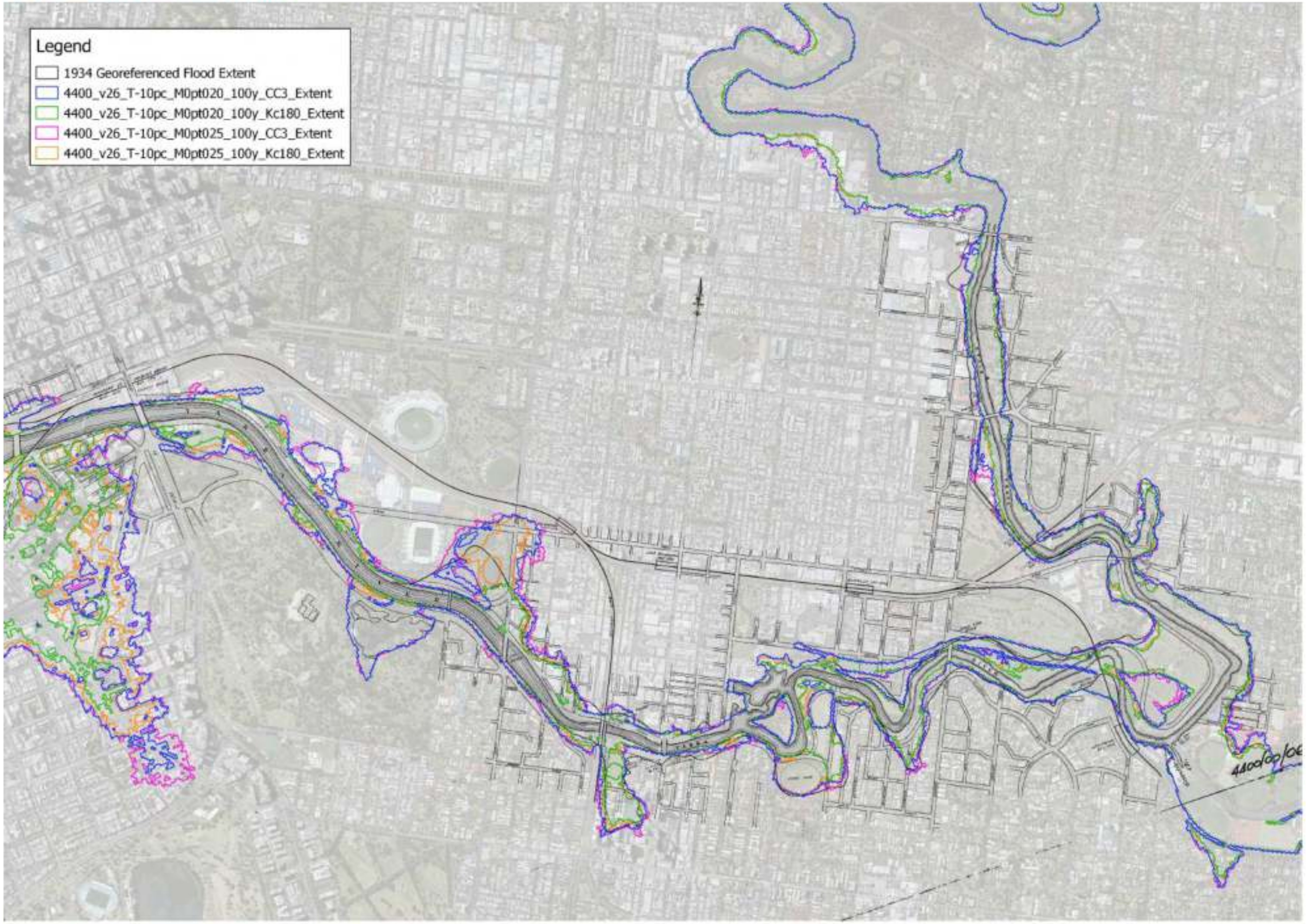
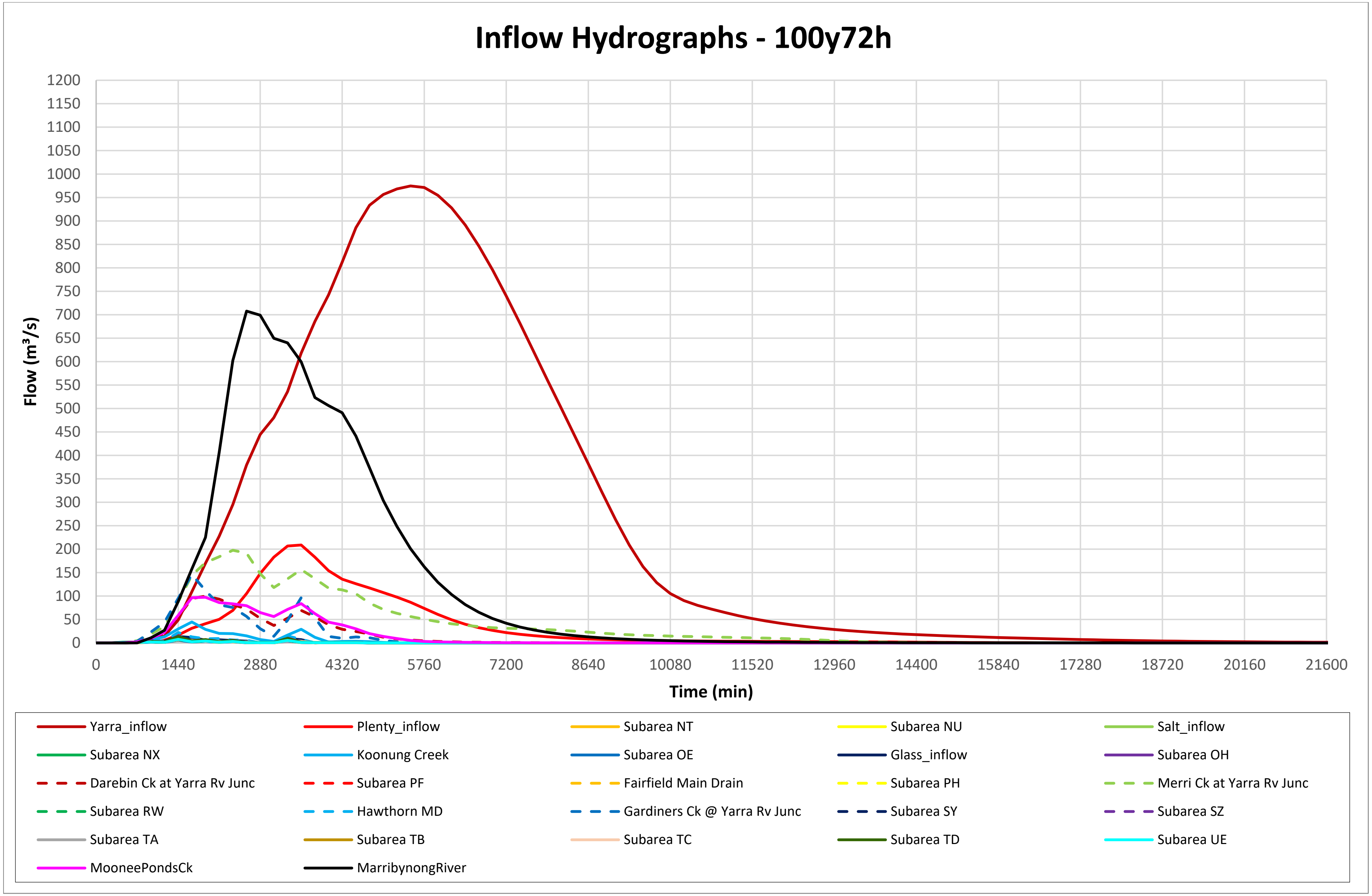
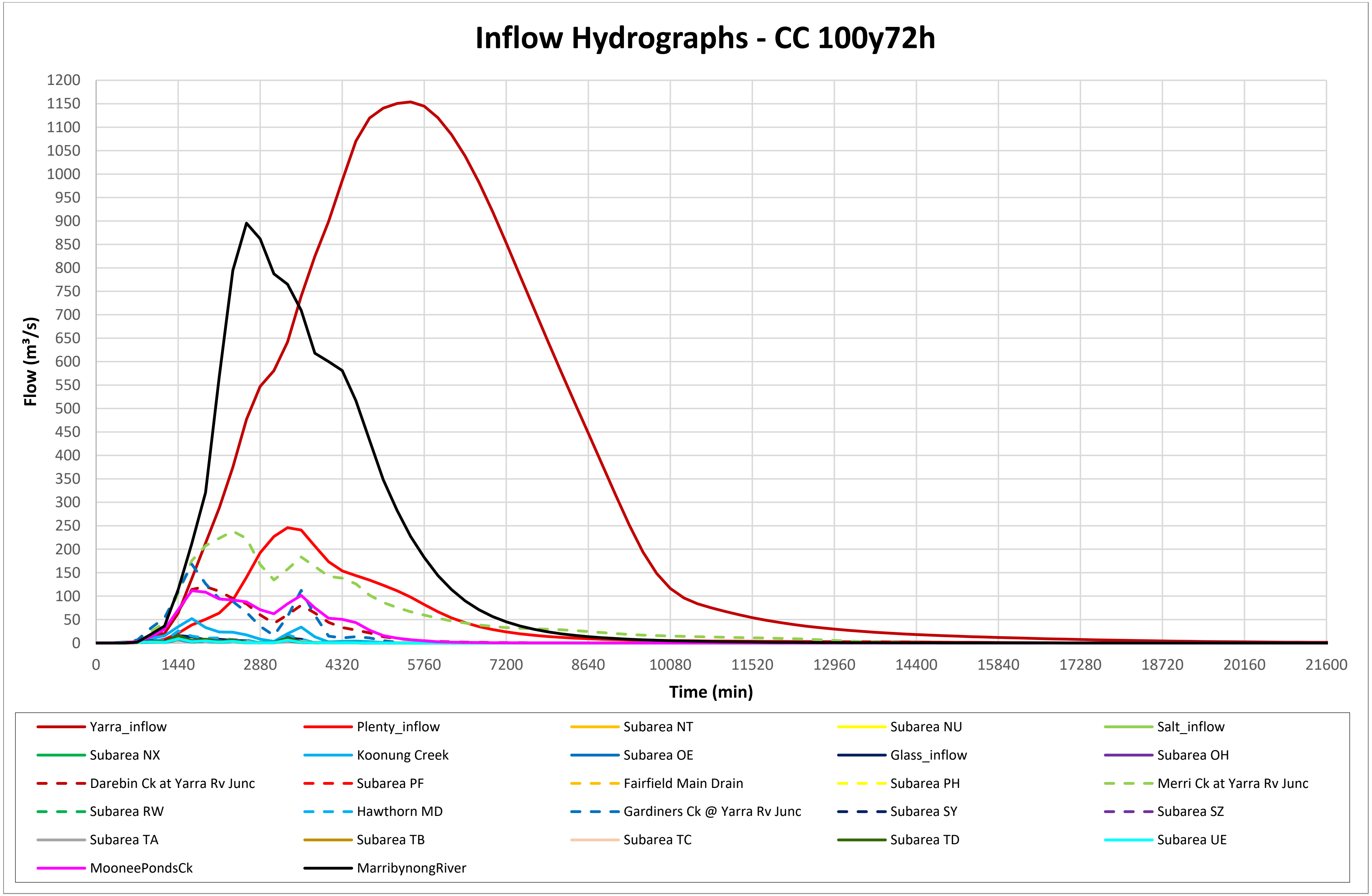


Figure 2-15 Flood Extent Comparison to georeferenced 1934 Flood Extent – St Kilda Road to Victoria Street

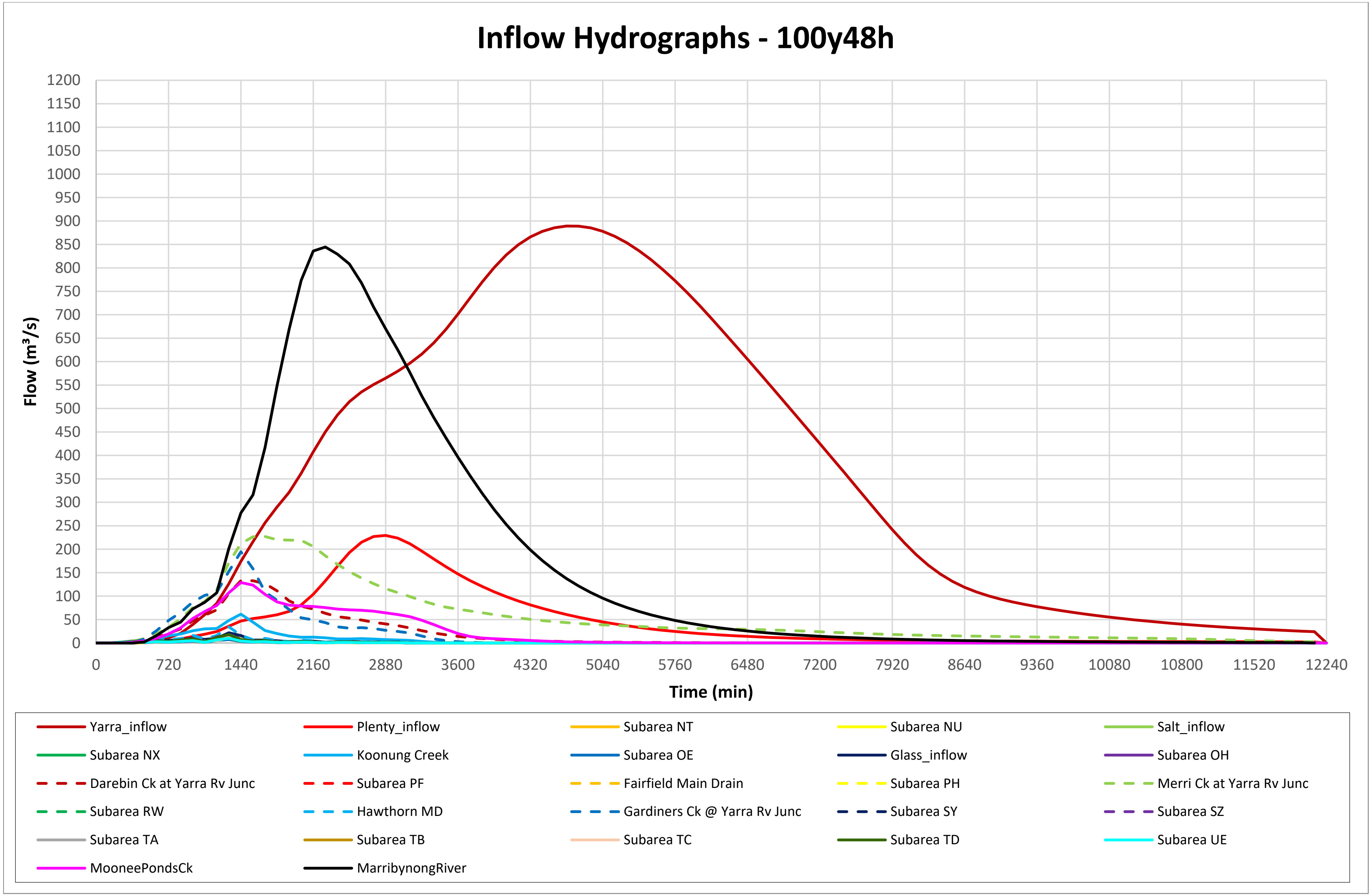
Appendix B – Inflow Hydrographs

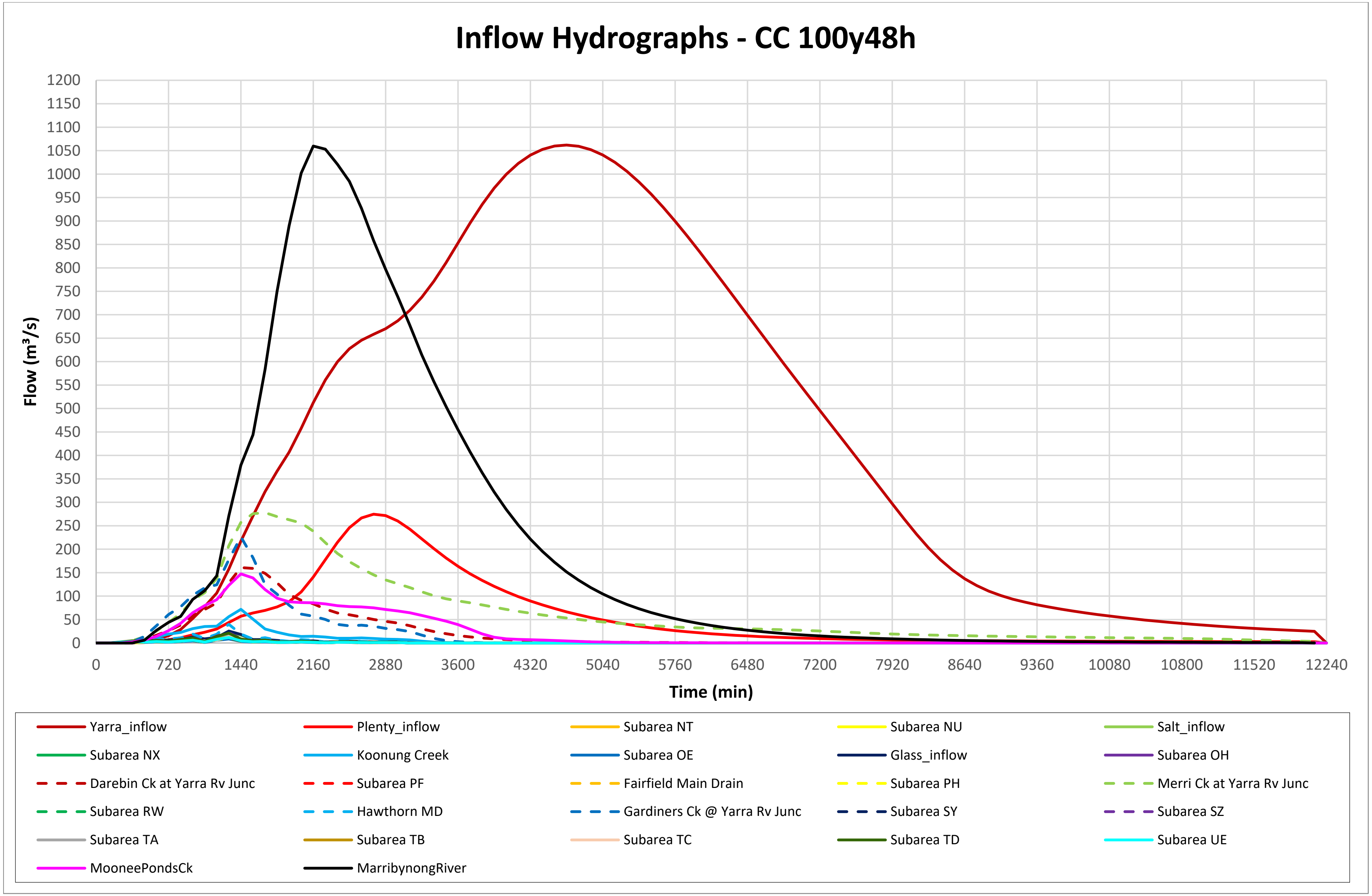


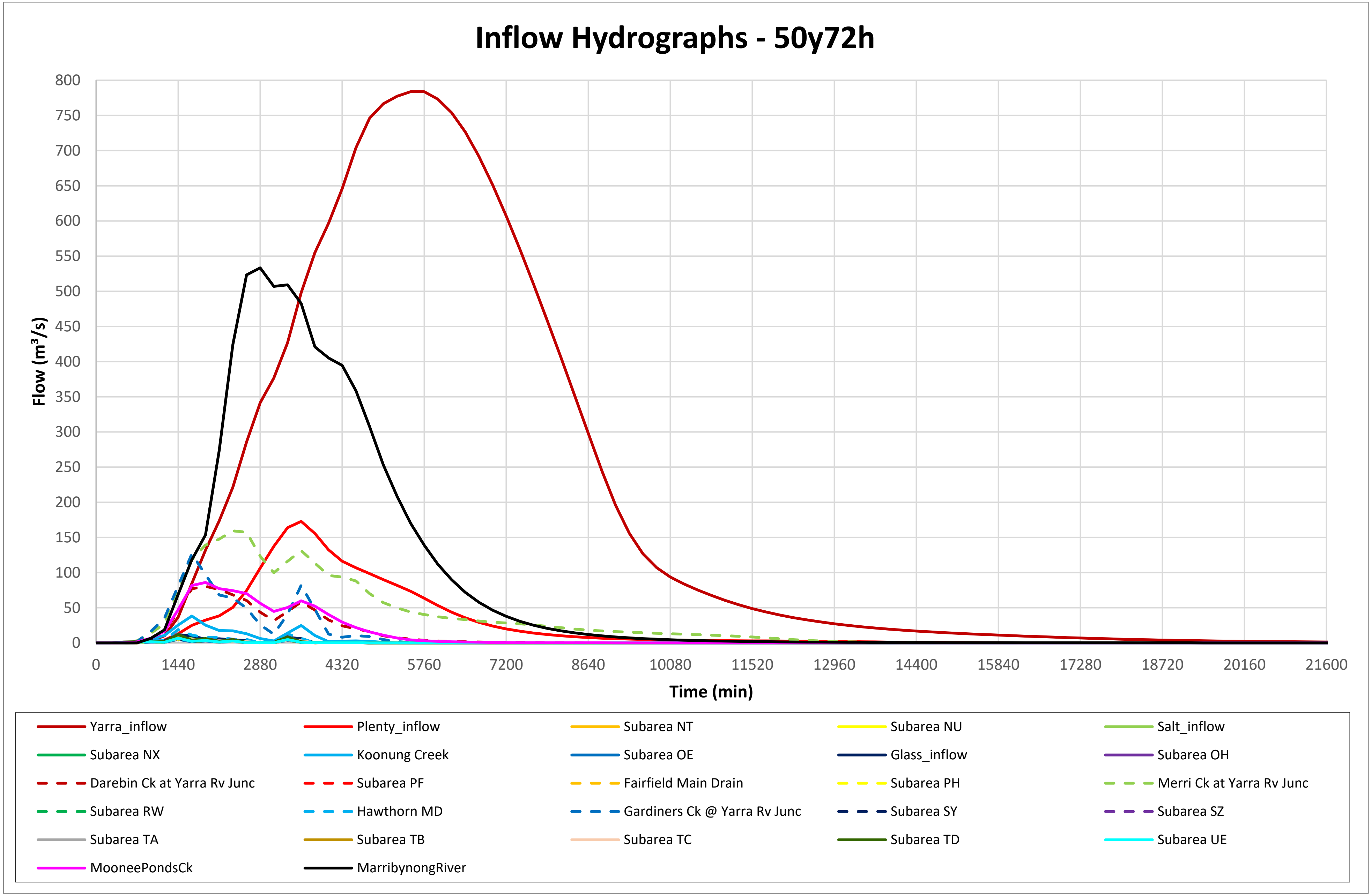
Inflow Hydrographs - 100y72h
Flow (m³/s)
1200
1150
1100
1050
1000
950
900
850
800
750
700
650
600
550
500
450
400
350
300
250
200
150
100
50
0
0
1440
2880
4320
5760
7200
8640
10080
11520
12960
14400
15840
17280
18720
20160
21600
Time (min)
Yarra_inflow
Plenty_inflow
Subarea NT
Subarea NU
Salt_inflow
Subarea NX
Koonung Creek
Subarea OE
Glass_inflow
Subarea OH
Darebin Ck at Yarra Rv Junc
Subarea PF
Fairfield Main Drain
Subarea PH
Merri Ck at Yarra Rv Junc
Subarea RW
Hawthorn MD
Gardiners Ck @ Yarra Rv Junc
Subarea SY
Subarea SZ
Subarea TA
Subarea TB
Subarea TC
Subarea TD
Subarea UE
MooneePondsCk
MarribynongRiver

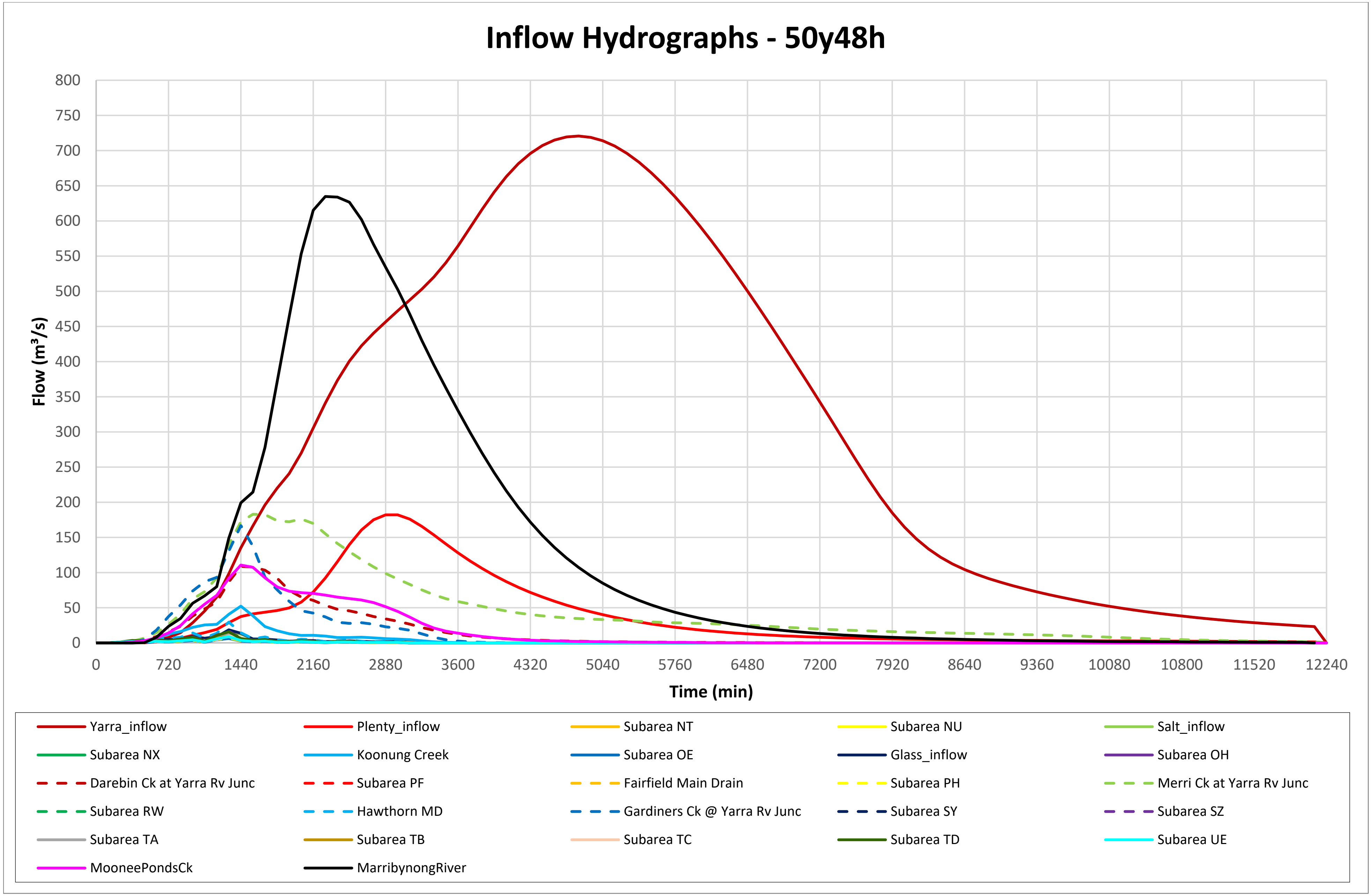


Inflow Hydrographs - CC 100y72h
Flow (m³/s)
1200
1150
1100
1050
1000
950
900
850
800
750
700
650
600
550
500
450
400
350
300
250
200
150
100
50
0
0
1440
2880
4320
5760
7200
8640
10080
11520
12960
14400
15840
17280
18720
20160
21600
Time (min)
Yarra_inflow
Plenty_inflow
Subarea NT
Subarea NU
Salt_inflow
Subarea NX
Koonung Creek
Subarea OE
Glass_inflow
Subarea OH
Darebin Ck at Yarra Rv Junc
Subarea PF
Fairfield Main Drain
Subarea PH
Merri Ck at Yarra Rv Junc
Subarea RW
Hawthorn MD
Gardiners Ck @ Yarra Rv Junc
Subarea SY
Subarea SZ
Subarea TA
Subarea TB
Subarea TC
Subarea TD
Subarea UE
MooneePondsCk
MarribynongRiver

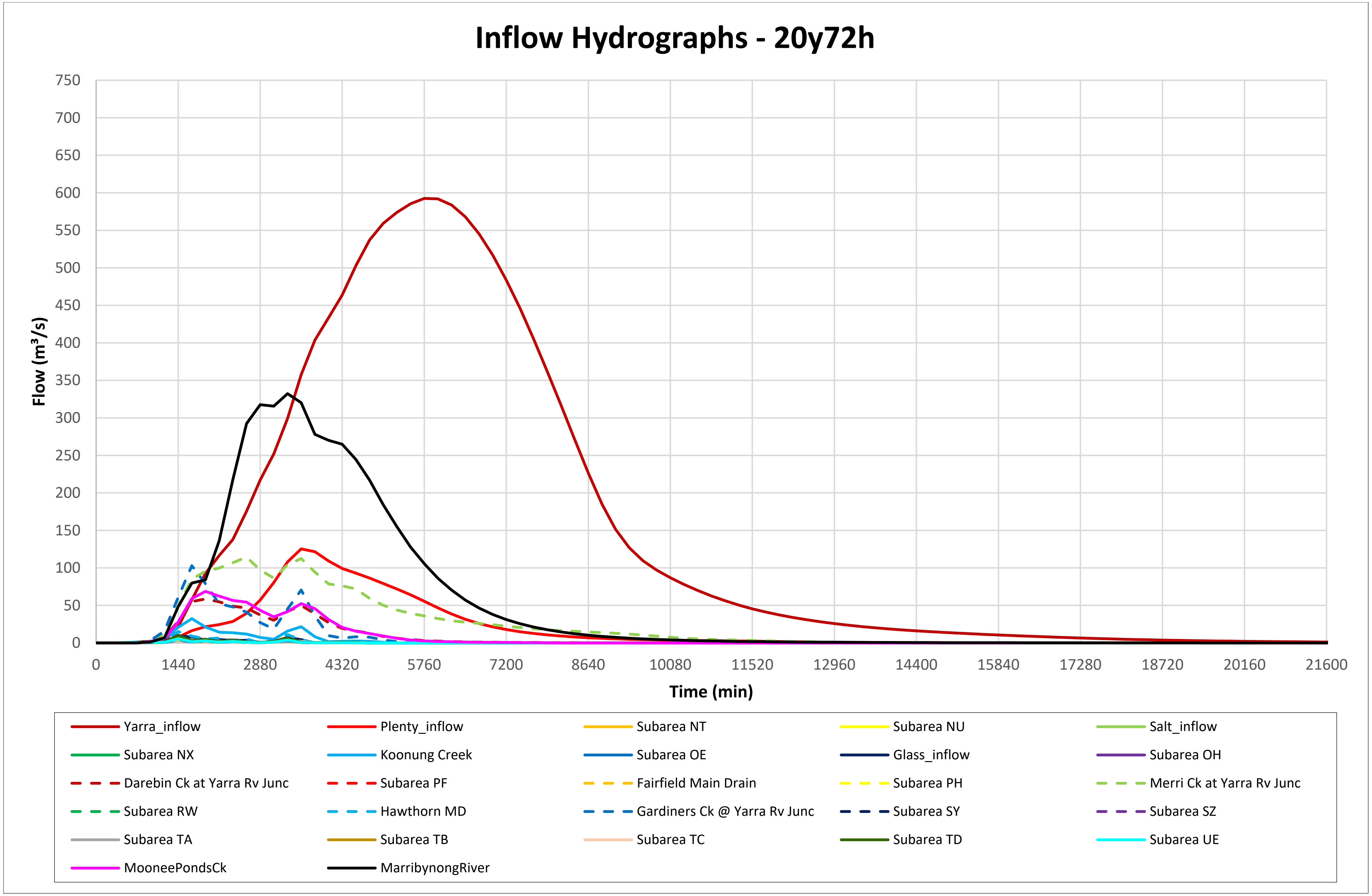

Inflow Hydrographs - 100y48h
Flow (m³/s)
1200
1150
1100
1050
1000
950
900
850
800
750
700
650
600
550
500
450
400
350
300
250
200
150
100
50
0
0
720
1440
2160
2880
3600
4320
5040
5760
6480
7200
7920
8640
9360
10080
10800
11520
12240
Time (min)
Yarra_inflow
Plenty_inflow
Subarea NT
Subarea NU
Salt_inflow
Subarea NX
Koonung Creek
Subarea OE
Glass_inflow
Subarea OH
Darebin Ck at Yarra Rv Junc
Subarea PF
Fairfield Main Drain
Subarea PH
Merri Ck at Yarra Rv Junc
Subarea RW
Hawthorn MD
Gardiners Ck @ Yarra Rv Junc
Subarea SY
Subarea SZ
Subarea TA
Subarea TB
Subarea TC
Subarea TD
Subarea UE
MooneePondsCk
MarribynongRiver


Inflow Hydrographs - CC 100y48h
Flow (m³/s)
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
750
800
850
900
950
1000
1050
1100
1150
1200
0
720
1440
2160
2880
3600
4320
5040
5760
6480
7200
7920
8640
9360
10080
10800
11520
12240
Time (min)
Yarra_inflow
Plenty_inflow
Subarea NT
Subarea NU
Salt_inflow
Subarea NX
Koonung Creek
Subarea OE
Glass_inflow
Subarea OH
Darebin Ck at Yarra Rv Junc
Subarea PF
Fairfield Main Drain
Subarea PH
Merri Ck at Yarra Rv Junc
Subarea RW
Hawthorn MD
Gardiners Ck @ Yarra Rv Junc
Subarea SY
Subarea SZ
Subarea TA
Subarea TB
Subarea TC
Subarea TD
Subarea UE
MooneePondsCk
MarribynongRiver

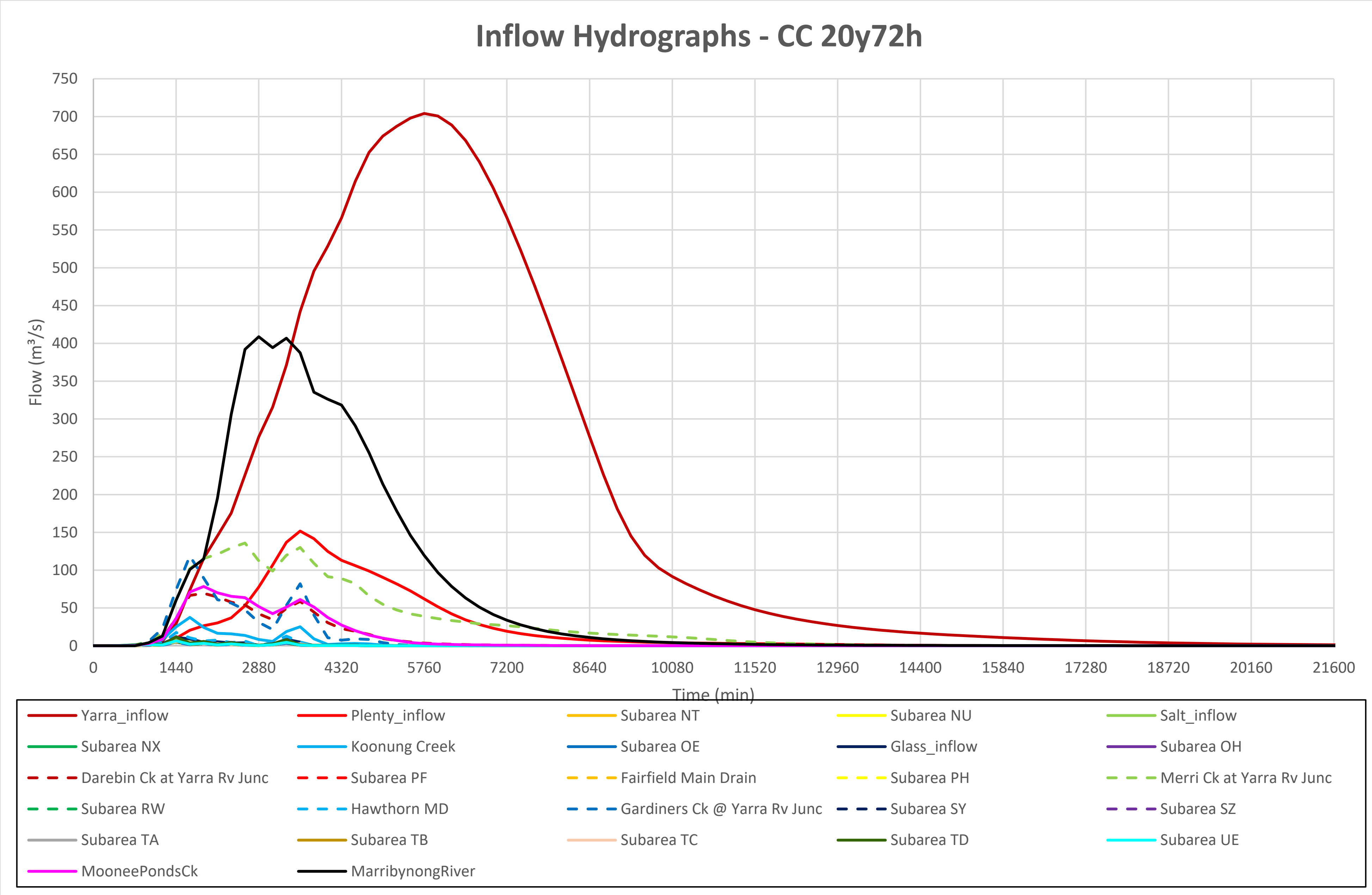

Inflow Hydrographs - 50y72h
Flow (m³/s)
800
750
700
650
600
550
500
450
400
350
300
250
200
150
100
50
0
0
1440
2880
4320
5760
7200
8640
10080
11520
12960
14400
15840
17280
18720
20160
21600
Time (min)
Yarra_inflow
Plenty_inflow
Subarea NT
Subarea NU
Salt_inflow
Subarea NX
Koonung Creek
Subarea OE
Glass_inflow
Subarea OH
Darebin Ck at Yarra Rv Junc
Subarea PF
Fairfield Main Drain
Subarea PH
Merri Ck at Yarra Rv Junc
Subarea RW
Hawthorn MD
Gardiners Ck @ Yarra Rv Junc
Subarea SY
Subarea SZ
Subarea TA
Subarea TB
Subarea TC
Subarea TD
Subarea UE
MooneePondsCk
MarribynongRiver



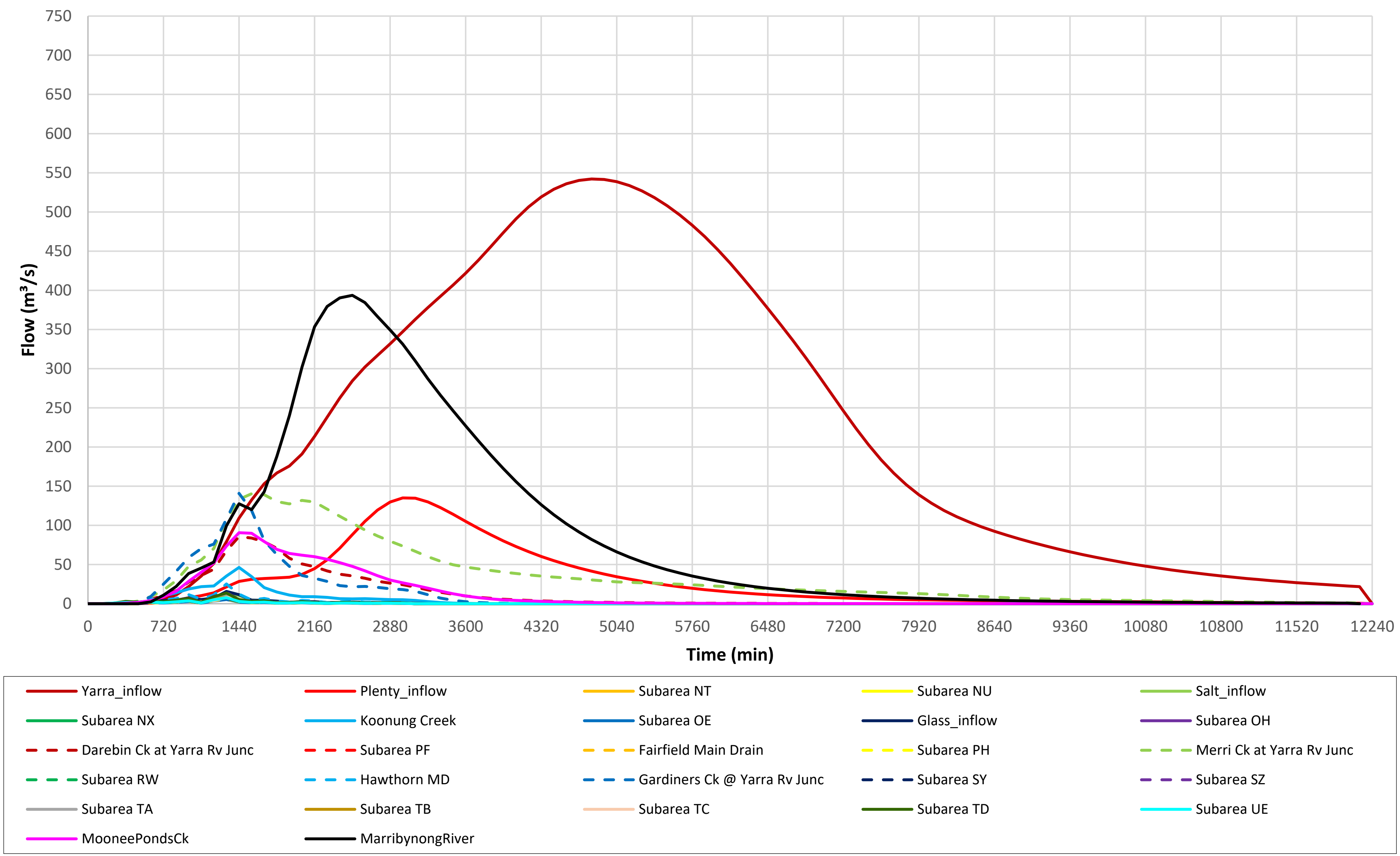
Inflow Hydrographs - 50y48h
Flow (m³/s)
800
750
700
650
600
550
500
450
400
350
300
250
200
150
100
50
0
0
720
1440
2160
2880
3600
4320
5040
5760
6480
7200
7920
8640
9360
10080
10800
11520
12240
Time (min)
Yarra_inflow
Plenty_inflow
Subarea NT
Subarea NU
Salt_inflow
Subarea NX
Koonung Creek
Subarea OE
Glass_inflow
Subarea OH
Darebin Ck at Yarra Rv Junc
Subarea PF
Fairfield Main Drain
Subarea PH
Merri Ck at Yarra Rv Junc
Subarea RW
Hawthorn MD
Gardiners Ck @ Yarra Rv Junc
Subarea SY
Subarea SZ
Subarea TA
Subarea TB
Subarea TC
Subarea TD
Subarea UE
MooneePondsCk
MarribynongRiver

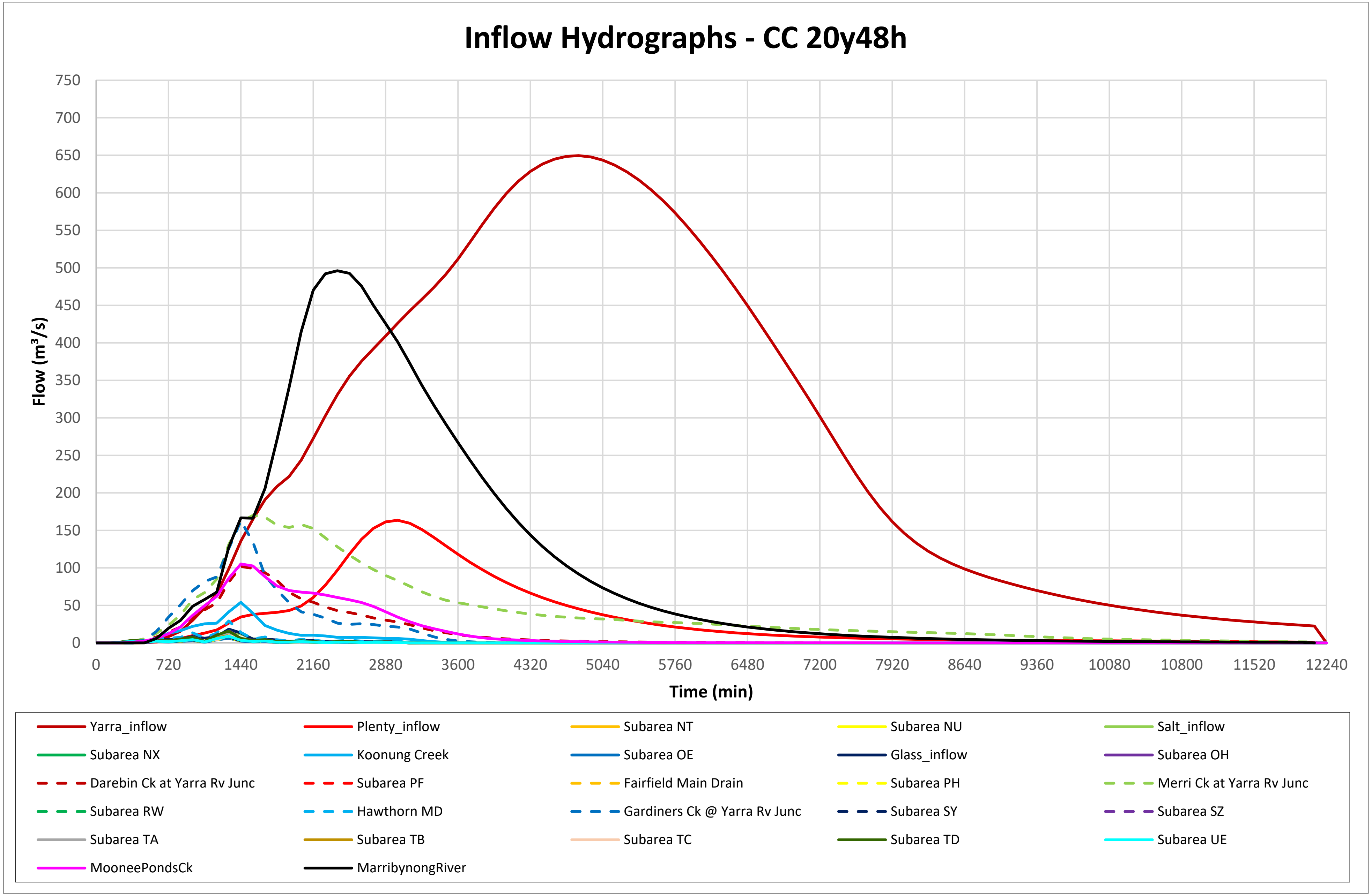


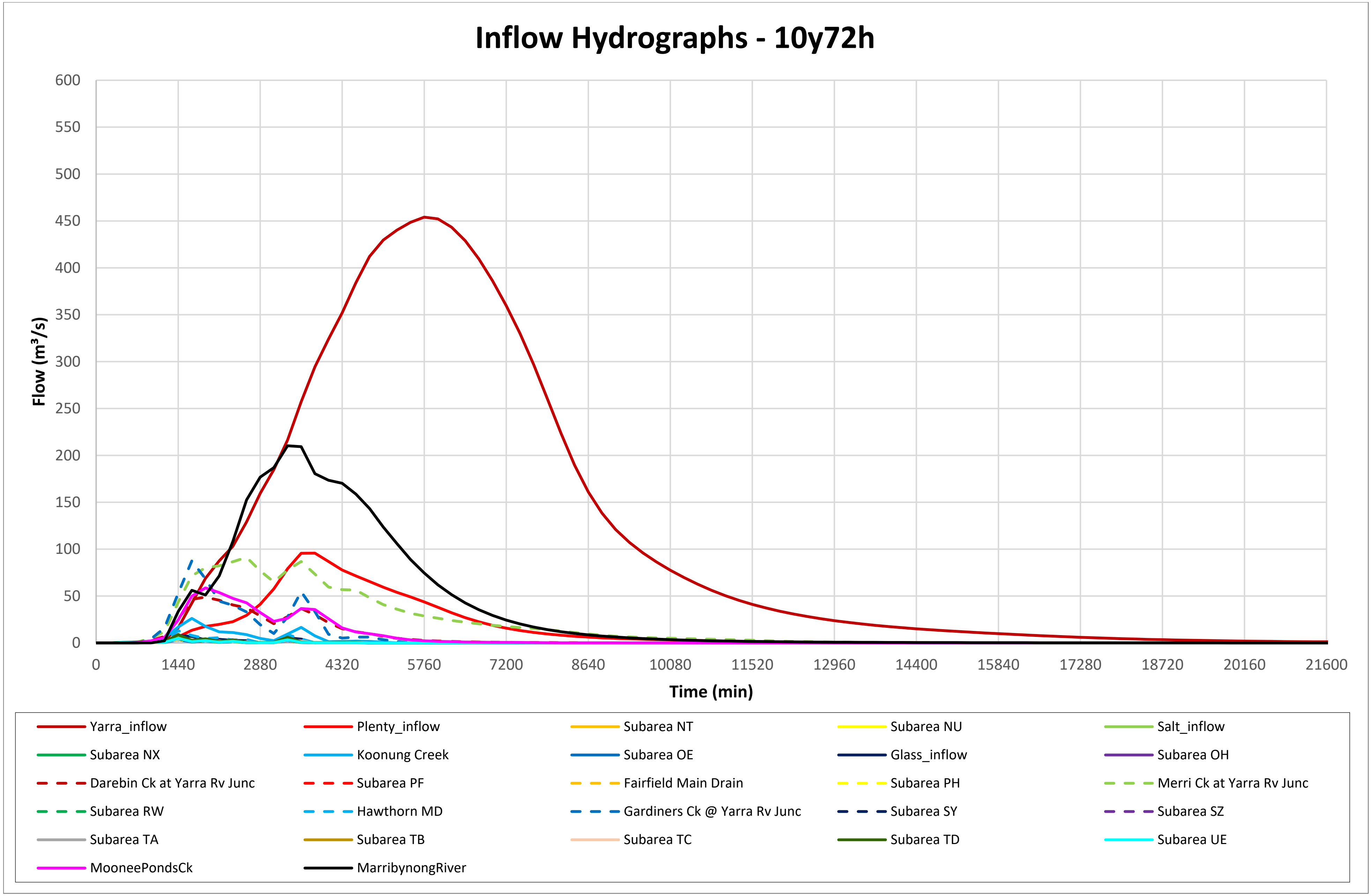
Inflow Hydrographs - 20y72h
Flow (m³/s)
750
700
650
600
550
500
450
400
350
300
250
200
150
100
50
0
0
1440
2880
4320
5760
7200
8640
10080
11520
12960
14400
15840
17280
18720
20160
21600
Time (min)
Yarra_inflow
Plenty_inflow
Subarea NT
Subarea NU
Salt_inflow
Subarea NX
Koonung Creek
Subarea OE
Glass_inflow
Subarea OH
Darebin Ck at Yarra Rv Junc
Subarea PF
Fairfield Main Drain
Subarea PH
Merri Ck at Yarra Rv Junc
Subarea RW
Hawthorn MD
Gardiners Ck @ Yarra Rv Junc
Subarea SY
Subarea SZ
Subarea TA
Subarea TB
Subarea TC
Subarea TD
Subarea UE
MooneePondsCk
MarribynongRiver


Inflow Hydrographs - CC 20y72h
Flow (m³/s)
750
700
650
600
550
500
450
400
350
300
250
200
150
100
50
0
0
1440
2880
4320
5760
7200
8640
10080
11520
12960
14400
15840
17280
18720
20160
21600
Time (min)
Yarra_inflow
Plenty_inflow
Subarea NT
Subarea NU
Salt_inflow
Subarea NX
Koonung Creek
Subarea OE
Glass_inflow
Subarea OH
Darebin Ck at Yarra Rv Junc
Subarea PF
Fairfield Main Drain
Subarea PH
Merri Ck at Yarra Rv Junc
Subarea RW
Hawthorn MD
Gardiners Ck @ Yarra Rv Junc
Subarea SY
Subarea SZ
Subarea TA
Subarea TB
Subarea TC
Subarea TD
Subarea UE
MooneePondsCk
MarribynongRiver

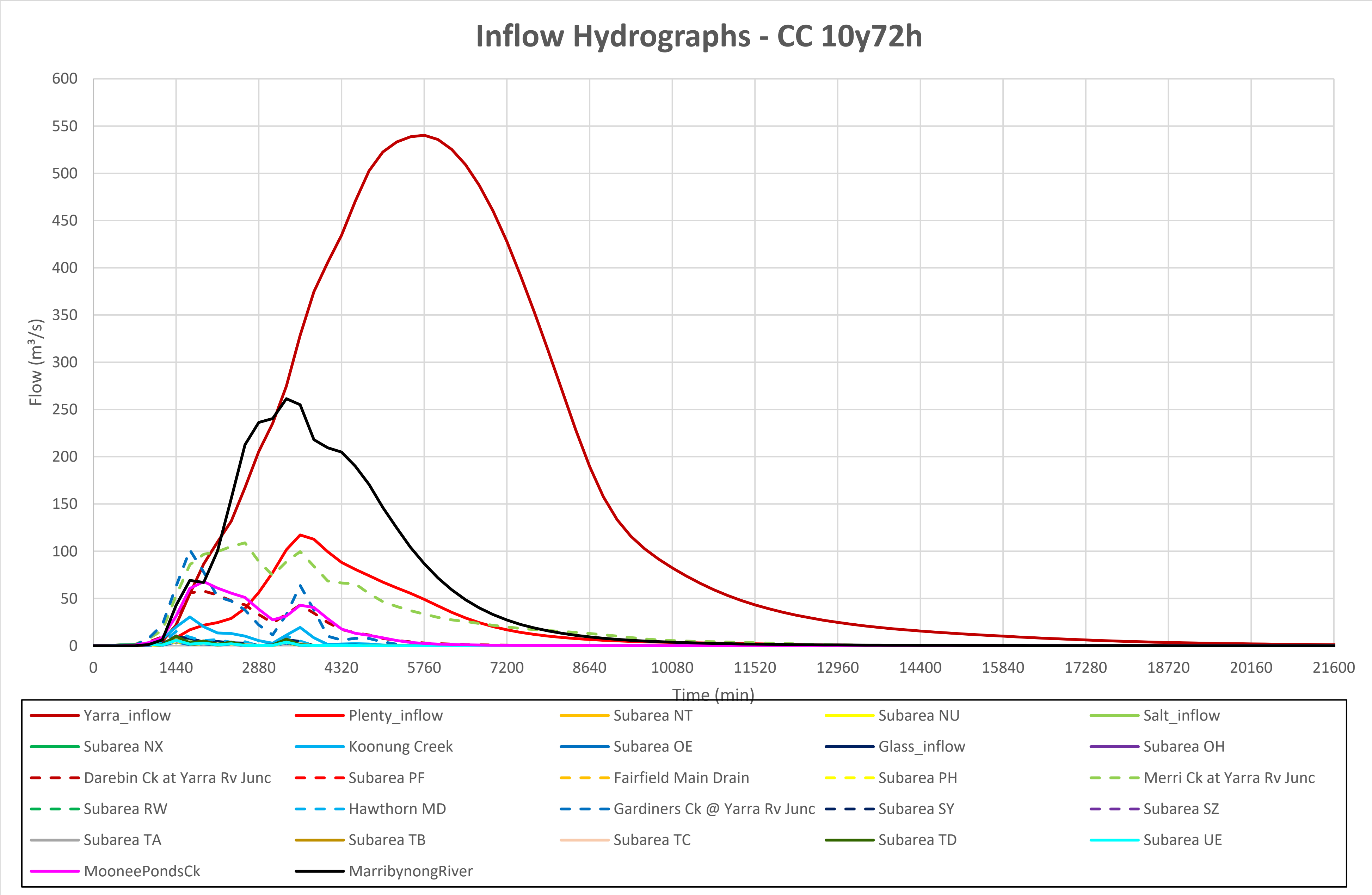
Inflow Hydrographs - 20y48h



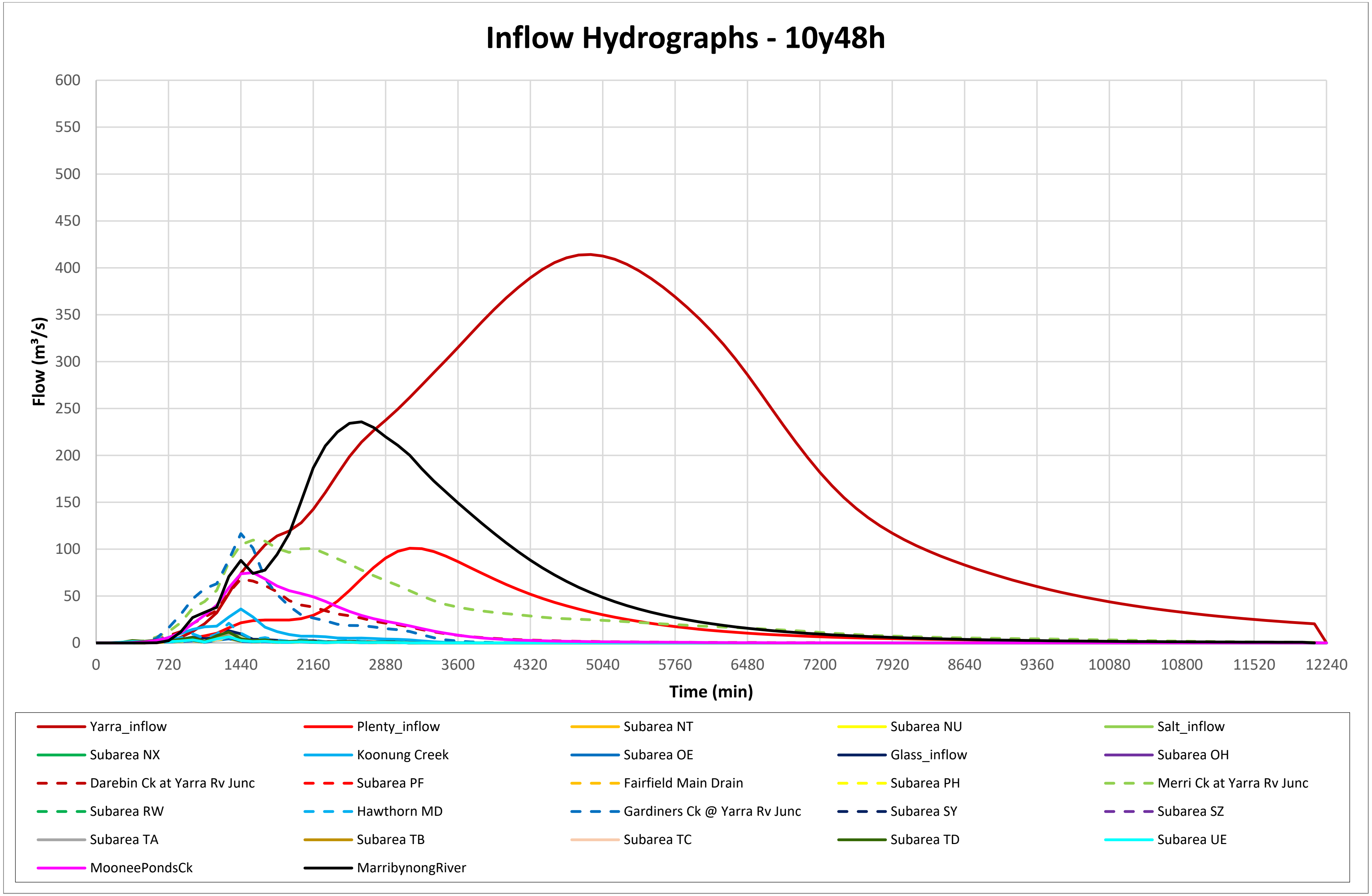

Inflow Hydrographs - CC 20y48h
Flow (m³/s)
750
700
650
600
550
500
450
400
350
300
250
200
150
100
50
0
0
720
1440
2160
2880
3600
4320
5040
5760
6480
7200
7920
8640
9360
10080
10800
11520
12240
Time (min)
Yarra_inflow
Plenty_inflow
Subarea NT
Subarea NU
Salt_inflow
Subarea NX
Koonung Creek
Subarea OE
Glass_inflow
Subarea OH
Darebin Ck at Yarra Rv Junc
Subarea PF
Fairfield Main Drain
Subarea PH
Merri Ck at Yarra Rv Junc
Subarea RW
Hawthorn MD
Gardiners Ck @ Yarra Rv Junc
Subarea SY
Subarea SZ
Subarea TA
Subarea TB
Subarea TC
Subarea TD
Subarea UE
MooneePondsCk
MarribynongRiver



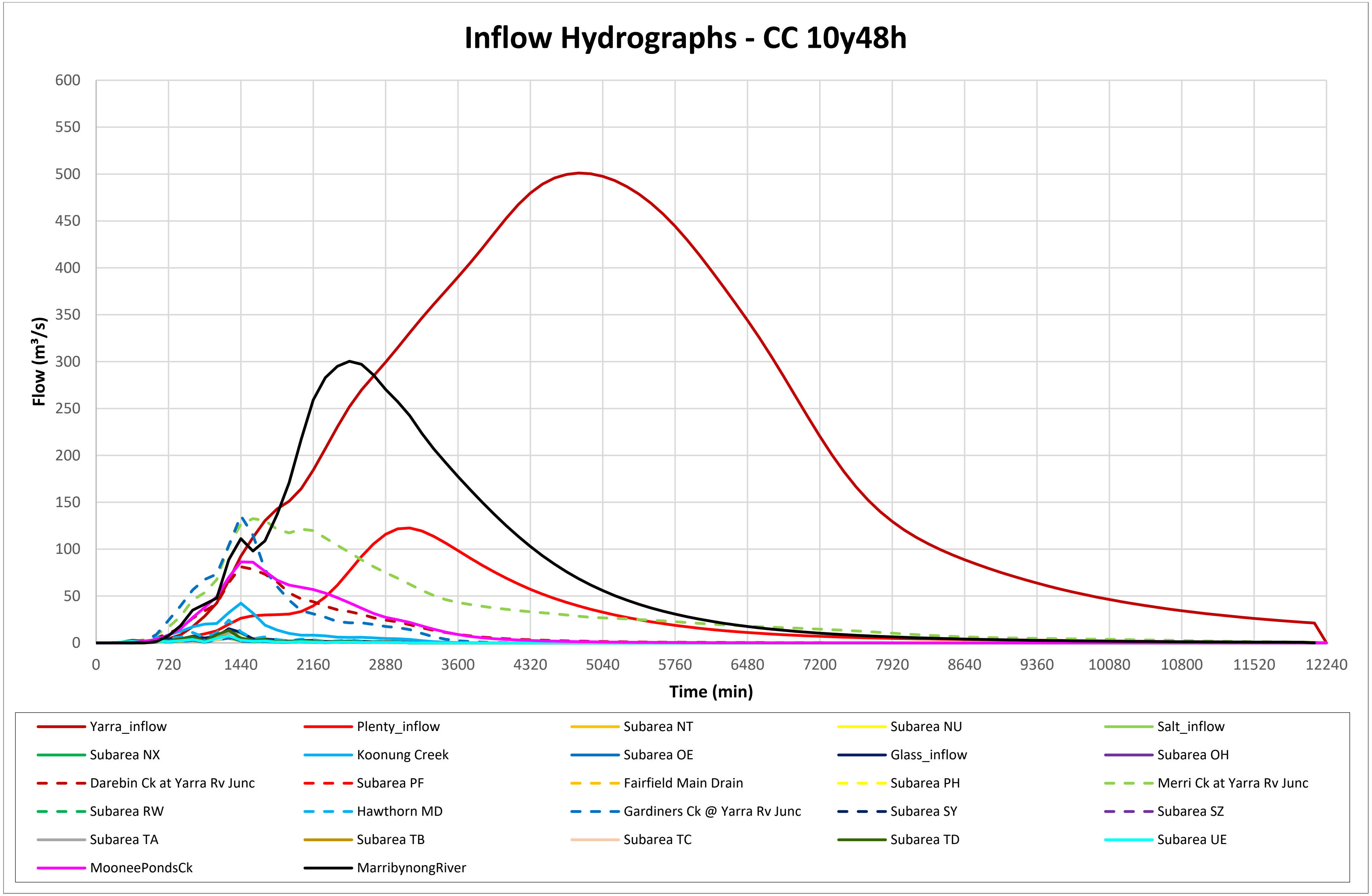
Inflow Hydrographs - 10y72h
Flow (m³/s)
600
550
500
450
400
350
300
250
200
150
100
50
0
0
1440
2880
4320
5760
7200
8640
10080
11520
12960
14400
15840
17280
18720
20160
21600
Time (min)
Yarra_inflow
Plenty_inflow
Subarea NT
Subarea NU
Salt_inflow
Subarea NX
Koonung Creek
Subarea OE
Glass_inflow
Subarea OH
Darebin Ck at Yarra Rv Junc
Subarea PF
Fairfield Main Drain
Subarea PH
Merri Ck at Yarra Rv Junc
Subarea RW
Hawthorn MD
Gardiners Ck @ Yarra Rv Junc
Subarea SY
Subarea SZ
Subarea TA
Subarea TB
Subarea TC
Subarea TD
Subarea UE
MooneePondsCk
MarribynongRiver



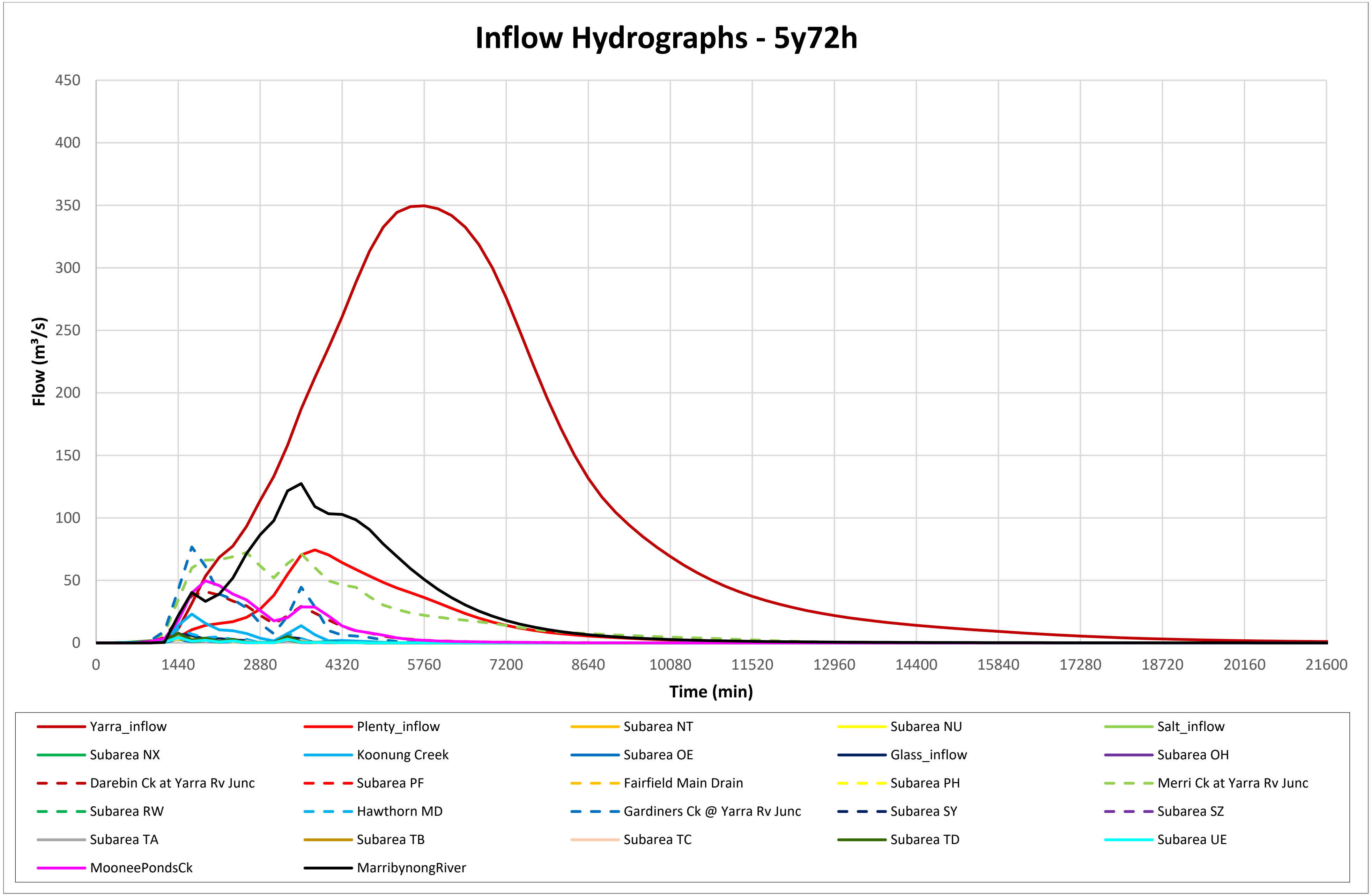
Inflow Hydrographs - CC 10y72h
Flow (m³/s)
600
550
500
450
400
350
300
250
200
150
100
50
0
0
1440
2880
4320
5760
7200
8640
10080
11520
12960
14400
15840
17280
18720
20160
21600
Time (min)
Yarra_inflow
Plenty_inflow
Subarea NT
Subarea NU
Salt_inflow
Subarea NX
Koonung Creek
Subarea OE
Glass_inflow
Subarea OH
Darebin Ck at Yarra Rv Junc
Subarea PF
Fairfield Main Drain
Subarea PH
Merri Ck at Yarra Rv Junc
Subarea RW
Hawthorn MD
Gardiners Ck @ Yarra Rv Junc
Subarea SY
Subarea SZ
Subarea TA
Subarea TB
Subarea TC
Subarea TD
Subarea UE
MooneePondsCk
MarribynongRiver



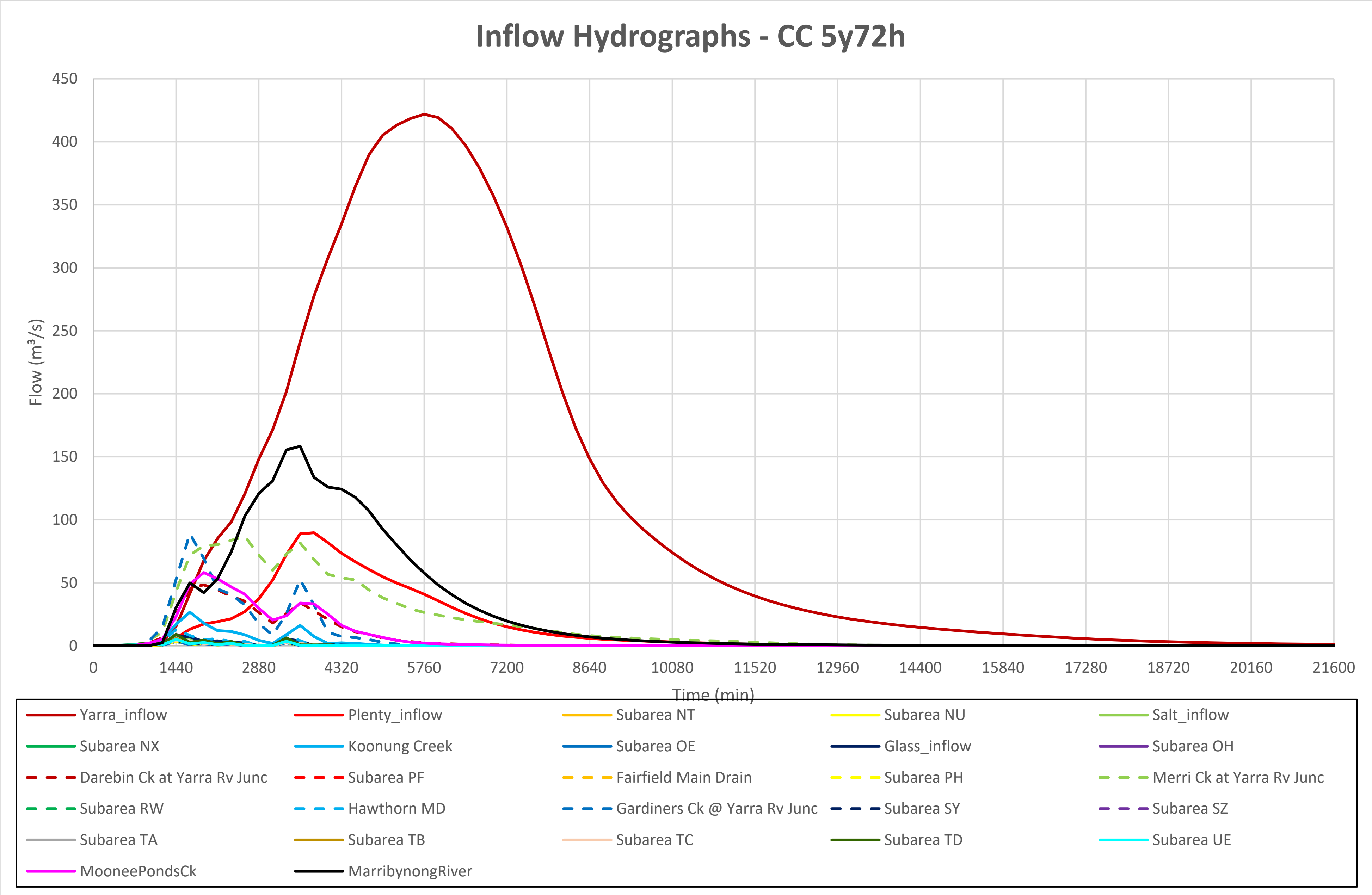
Inflow Hydrographs - 10y48h
Flow (m³/s)
600
550
500
450
400
350
300
250
200
150
100
50
0
0
720
1440
2160
2880
3600
4320
5040
5760
6480
7200
7920
8640
9360
10080
10800
11520
12240
Time (min)
Yarra_inflow
Plenty_inflow
Subarea NT
Subarea NU
Salt_inflow
Subarea NX
Koonung Creek
Subarea OE
Glass_inflow
Subarea OH
Darebin Ck at Yarra Rv Junc
Subarea PF
Fairfield Main Drain
Subarea PH
Merri Ck at Yarra Rv Junc
Subarea RW
Hawthorn MD
Gardiners Ck @ Yarra Rv Junc
Subarea SY
Subarea SZ
Subarea TA
Subarea TB
Subarea TC
Subarea TD
Subarea UE
MooneePondsCk
MarribynongRiver



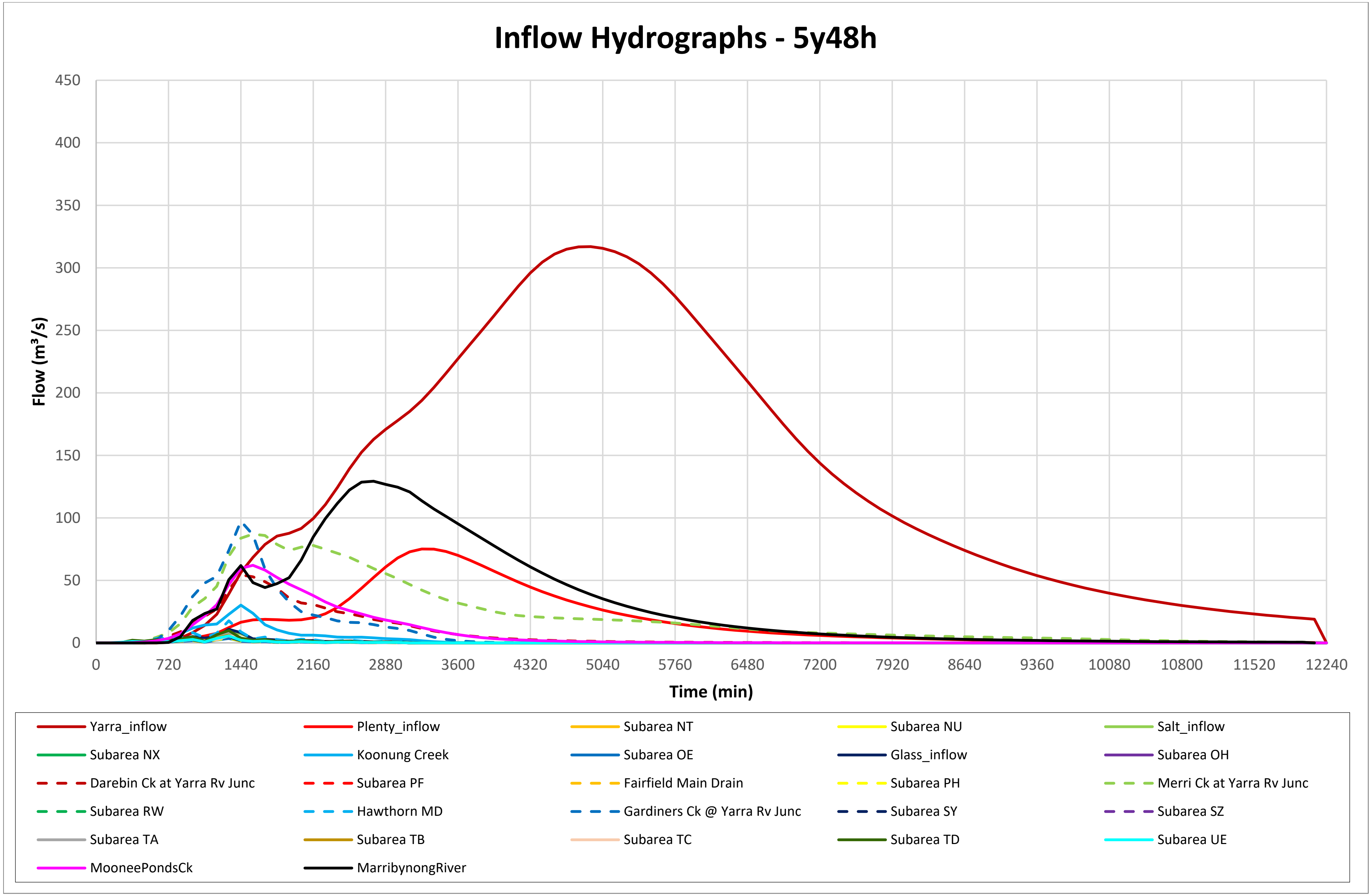
Inflow Hydrographs - CC 10y48h
Flow (m³/s)
600
550
500
450
400
350
300
250
200
150
100
50
0
0
720
1440
2160
2880
3600
4320
5040
5760
6480
7200
7920
8640
9360
10080
10800
11520
12240
Time (min)
Yarra_inflow
Plenty_inflow
Subarea NT
Subarea NU
Salt_inflow
Subarea NX
Koonung Creek
Subarea OE
Glass_inflow
Subarea OH
Darebin Ck at Yarra Rv Junc
Subarea PF
Fairfield Main Drain
Subarea PH
Merri Ck at Yarra Rv Junc
Subarea RW
Hawthorn MD
Gardiners Ck @ Yarra Rv Junc
Subarea SY
Subarea SZ
Subarea TA
Subarea TB
Subarea TC
Subarea TD
Subarea UE
MooneePondsCk
MarribynongRiver



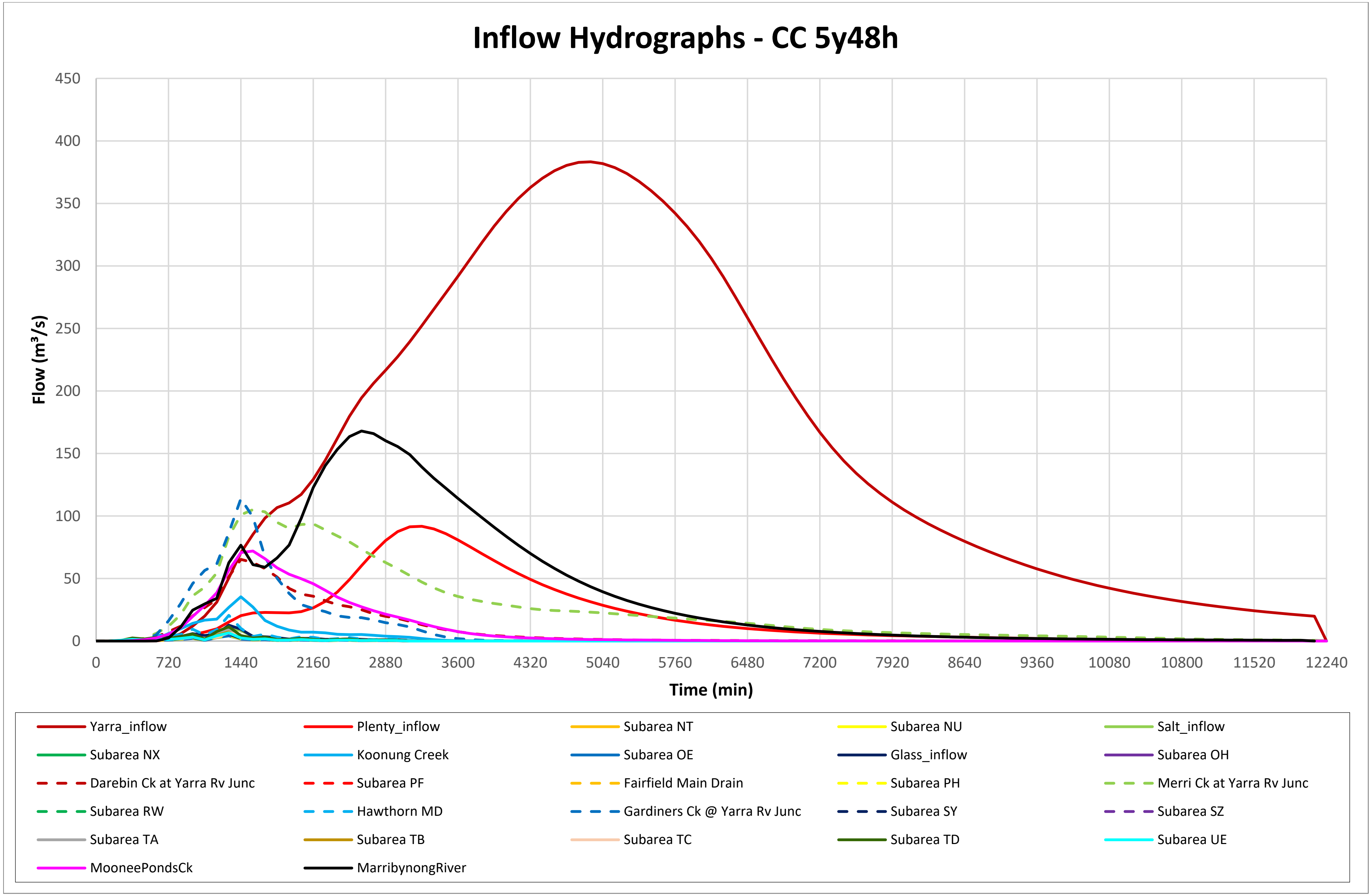
Inflow Hydrographs - 5y72h
Flow (m³/s)
0
50
100
150
200
250
300
350
400
450
Time (min)
0
1440
2880
4320
5760
7200
8640
10080
11520
12960
14400
15840
17280
18720
20160
21600
Yarra_inflow
Plenty_inflow
Subarea NT
Subarea NU
Salt_inflow
Subarea NX
Koonung Creek
Subarea OE
Glass_inflow
Subarea OH
Darebin Ck at Yarra Rv Junc
Subarea PF
Fairfield Main Drain
Subarea PH
Merri Ck at Yarra Rv Junc
Subarea RW
Hawthorn MD
Gardiners Ck @ Yarra Rv Junc
Subarea SY
Subarea SZ
Subarea TA
Subarea TB
Subarea TC
Subarea TD
Subarea UE
MooneePondsCk
MarribynongRiver



Inflow Hydrographs - CC 5y72h
Flow (m³/s)
450
400
350
300
250
200
150
100
50
0
0
1440
2880
4320
5760
7200
8640
10080
11520
12960
14400
15840
17280
18720
20160
21600
Time (min)
Yarra_inflow
Plenty_inflow
Subarea NT
Subarea NU
Salt_inflow
Subarea NX
Koonung Creek
Subarea OE
Glass_inflow
Subarea OH
Darebin Ck at Yarra Rv Junc
Subarea PF
Fairfield Main Drain
Subarea PH
Merri Ck at Yarra Rv Junc
Subarea RW
Hawthorn MD
Gardiners Ck @ Yarra Rv Junc
Subarea SY
Subarea SZ
Subarea TA
Subarea TB
Subarea TC
Subarea TD
Subarea UE
MooneePondsCk
MarribynongRiver



Inflow Hydrographs - 5y48h
Flow (m³/s)
450
400
350
300
250
200
150
100
50
0
0
720
1440
2160
2880
3600
4320
5040
5760
6480
7200
7920
8640
9360
10080
10800
11520
12240
Time (min)
Yarra_inflow
Plenty_inflow
Subarea NT
Subarea NU
Salt_inflow
Subarea NX
Koonung Creek
Subarea OE
Glass_inflow
Subarea OH
Darebin Ck at Yarra Rv Junc
Subarea PF
Fairfield Main Drain
Subarea PH
Merri Ck at Yarra Rv Junc
Subarea RW
Hawthorn MD
Gardiners Ck @ Yarra Rv Junc
Subarea SY
Subarea SZ
Subarea TA
Subarea TB
Subarea TC
Subarea TD
Subarea UE
MooneePondsCk
MarribynongRiver



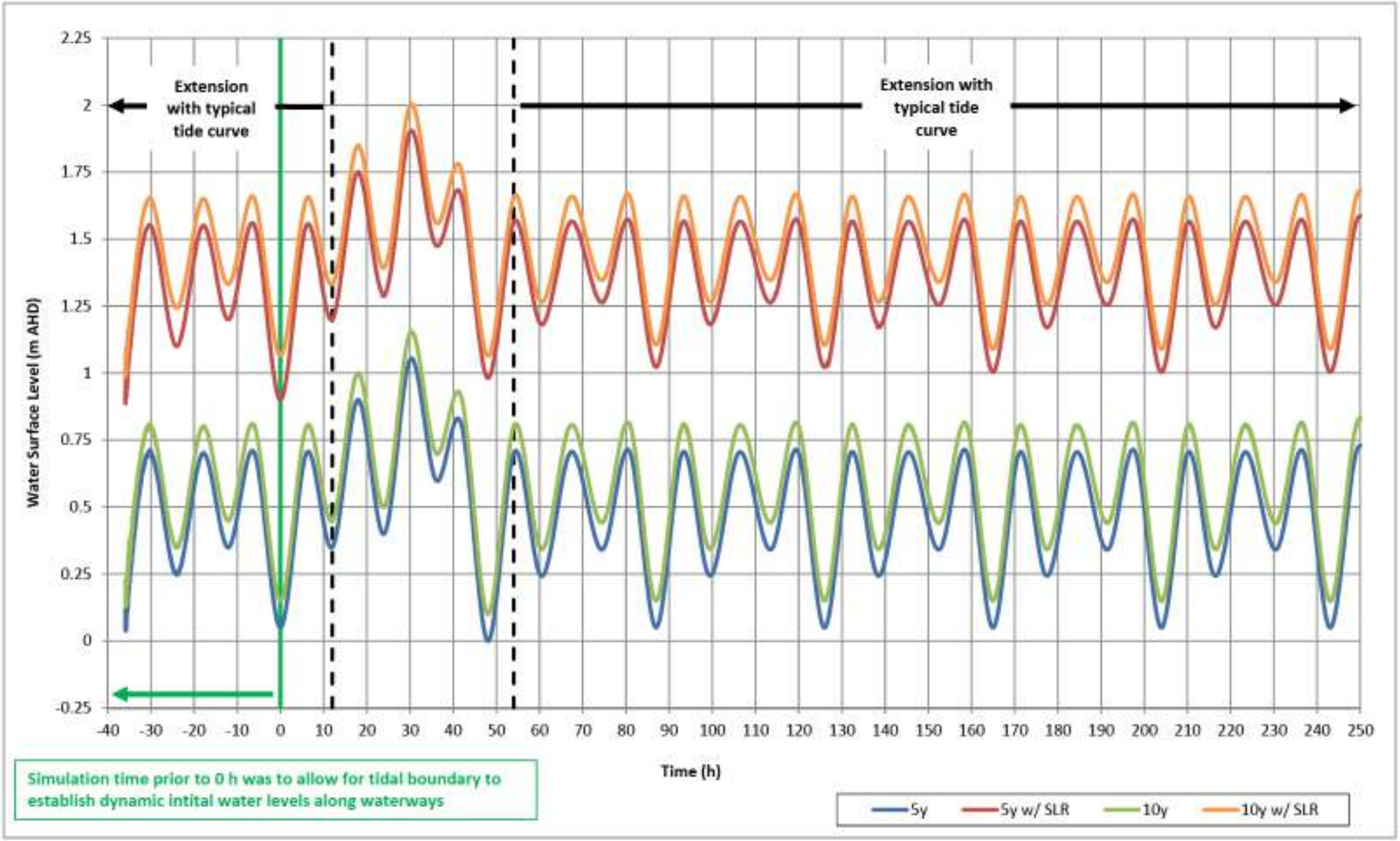
Inflow Hydrographs - CC 5y48h
Flow (m³/s)
450
400
350
300
250
200
150
100
50
0
0
720
1440
2160
2880
3600
4320
5040
5760
6480
7200
7920
8640
9360
10080
10800
11520
12240
Time (min)
Yarra_inflow
Plenty_inflow
Subarea NT
Subarea NU
Salt_inflow
Subarea NX
Koonung Creek
Subarea OE
Glass_inflow
Subarea OH
Darebin Ck at Yarra Rv Junc
Subarea PF
Fairfield Main Drain
Subarea PH
Merri Ck at Yarra Rv Junc
Subarea RW
Hawthorn MD
Gardiners Ck @ Yarra Rv Junc
Subarea SY
Subarea SZ
Subarea TA
Subarea TB
Subarea TC
Subarea TD
Subarea UE
MooneePondsCk
MarribynongRiver

REMAINING FIGURES WILL BE ADDED IN A FUTURE REVISION.

Appendix C – Tidal Curves

Content

10y & 5y Tidal Boundary



Extension with typical tide curve
Extension with typical tide curve
Water Surface Level (m AHD)
Time (h)
Simulation time prior to 0 h was to allow for tidal boundary to establish dynamic intital water levels along waterways
5y
5y w/ SLR
10y
10y w/ SLR

Appendix D – Bridge Modelling Approach

1. Introduction

1.1 Background

Following previous investigation by GHD, a refined bridge modelling approach was developed to better represent bridges in TUFLOW that cross waterways. Due to the hydraulic importance of bridge structures in the Lower Yarra River model, this modelling approach has been adopted for this project for such structures within the Study Area. Outside the Study Area, a slightly less detailed approach was adopted to represent the more significant structures given that these were an extension of the model for “verification” and not flood mapping purposes.

1.2 Purpose

This appendix provides:

- An explanation of the need for the refined methodologies for modelling bridge losses,
- The basis of separate deck and pier polygons within the Study Area,
- FLC weighting options and adopted approach in TUFLOW, and
- An overview of the methodology for estimating an adjusted FLC parameter.

2. Refinement of Existing Bridge Modelling Techniques

2.1 Need for refinement of hydraulic analysis

The TUFLOW model is well suited to flood mapping of the Lower Yarra River. It is however limited in its ability to explicitly model bridge losses, relying on parameters and approaches investigated and documented by the Federal Highway Administration and several Universities and road authorities in the publication Hydraulics of Bridge Waterways (Bradley 1978).

Given that bridge losses are a significant aspect of this investigation, their estimation is an important outcome and it was decided that the approach warranted a refined approach. The methodology documented below improves the representation of these characteristics relative to coarser more conventional approaches and is thus better able to represent existing bridge structures.

2.2 The basis of separate deck and pier polygons

The modelling approach taken to represent bridges crossing the waterways was determined in previous projects by testing the relative effectiveness of several different modelling approaches. These approaches included modelling:

- a cross-section averaged bridge with form loss and blockage calculated for the entire bridge span and
- a bridge split up to represent pier and deck polygons individually with application of blockage and form losses varied between different scenarios.

References such as the TUFLOW manual, *Modelling Bridge Piers in 2D using TUFLOW* (TUFLOW 2013) and *Cell Based Modelling of Bridge Piers Using TUFLOW* (Vienot, Sexton and McNulty 2011) were considered and discussed in determining our approach. Both methods can provide a reasonable representation when applied correctly. The split pier and deck polygon approach was adopted within the Mapping limit and upstream of this the slightly simpler cross-sectional average approach was applied.

The more detailed approach was adopted within the Mapping Limit as it provided a good match to Bradley with the added advantage of a more realistic flow and velocity distribution within the bridge leading to more confidence in the representation of effects such as pier shielding and the understanding of scour potential. Although it was found that for pier losses the best representation (relative to Bradley) was achieved using both FLC and blockage factors (consistent with Vienot, Sexton and McNulty 2011 and contrary to TUFLOW 2013) this finding may not be universal or significant since, for most bridges, a low blockage factor is typically applied.

Section 13.1 of Bradley reviews the applicability of the Bradley relationships, several of these numbered points can be related to the current context, sometimes directly and sometimes with a little extrapolation. Some of the more relevant aspects are briefly discussed below:

- Point 1 states that the method of computing backwater is intended to be used for relatively straight reaches. While the Lower Yarra River does meander this characteristic is relatively true.
- Point 10 in Section 13.1 of Bradley essentially states that the method is valid for multiple bridges (hydraulically parallel waterway openings) provided that the flow is properly divided between bridges. While it is a leap to extend this concept to individual cells the logic is somewhat consistent and supported by our testing and that of Vienot, Sexton and McNulty 2011.

2.3 Application of Form Loss Coefficients (FLC) in TUFLOW

As of version 2016-03 AA released on April 4th 2016, TUFLOW provides two methods with which to apply an FLC within layered flow constrictions, the ‘Cumulate’ method and the ‘Portion’ method.

- The ‘Cumulate’ method, which was the only method available in TUFLOW prior to version 2016, effectively sums the FLC of each layer depending on the depth of water within each layer relative to the depth of that layer as shown in Equation 1. This method works well for low flows but fails to reduce the effective FLC when a structure becomes significantly drowned out.
- To address this limitation the ‘Portion’ method was developed (and is now the default in TUFLOW). It effectively calculates a depth weighted average FLC as shown in Equation 2.

Equation 1 'Cumulate' equation

$$\zeta_{total} = \zeta_1 + \zeta_2 \frac{y_2}{D_2} + \zeta_3 \frac{y_3}{D_3}$$

ζ_n = Layer n FLC

D_n = Depth of layer n

y_n = Layer n water depth (set to zero if dry and cannot exceed depth of layer, D)

ζ_{total} = Applied overall FLC

Equation 2 'Portion' equation

$$\zeta_{total} = \frac{(y_1\zeta_1 + y_2\zeta_2 + y_3\zeta_3)}{y_{total}}$$

$$y_{total} = y_1 + y_2 + y_3 + y_4$$

ζ_n = Layer n FLC

y_n = Layer n water depth (set to zero if dry and cannot exceed depth of layer)

ζ_{total} = Applied overall FLC

Combining either of these methods with the application of standard FLC values (as derived directly from Bradley) yields FLC values as applied by TUFLOW which can be significantly different to those that were intended to be applied. As a result, we looked at how the FLC values could be adjusted to achieve a target FLC at certain levels. A sample set of FLC parameters are defined in Table 2-1, with Figure 2-1 showing how the values are interpreted by TUFLOW. This figure shows the following (when FLCs in Table 2-1 are adopted):

- The 'Cumulate' method (using FLC values of 0.1, 1.5625 and 0 for layers 1, 2 and 3 respectively) perhaps best defines typical Industry Practice (until recently). It applies the desired FLCs up until the top of 'Layer 1'. Above this level the adopted FLC is overstated, but is similar to intended provided the 'Layer 1' FLC is small and that there is not significant overtopping.
- The 'Portion' method (using FLC values of 0.1, 1.5625 and 0) applies the intended FLC for 'Layer 1' only and in the absence of adjustment, applies a much lower than intended FLC for 'Layer 2' and higher.
- The 'Adjusted Cumulate' method (using FLC values of 0.1, 1.4625 and 0) generally results in the intended behaviour provided that there is not significant overtopping (since the applied FLC will never reduce with increasing depth above the top of Layer 2).
- The 'Adjusted Portion' method (using FLC values of 0.1, 7.4125 and 0) applies the desired FLCs up until the top of 'Layer 2', from which point it applies an FLC that diminishes with depth. The reduction of FLC with depth is consistent with a structure becoming more drowned out.

The 'Adjusted Portion' method gives FLCs closest to those intended, and as such this is the method that has been adopted for the Yarra River modelling. It effectively involves the use of the now default 'Portion' option with a higher 'Layer 2' FLC input value to achieve a more correct effective FLC when the deck is fully submerged (and reasonable approximations at other levels).

Table 2-1 Sample FLCs for comparison

FLC Layer	Applied Total FLC		
	Cumulate & Portion	Adjusted Cumulate	Adjusted Portion
1	0.1	0.1	0.1
2	1.5625	1.4625	7.4125
3	0	0	0

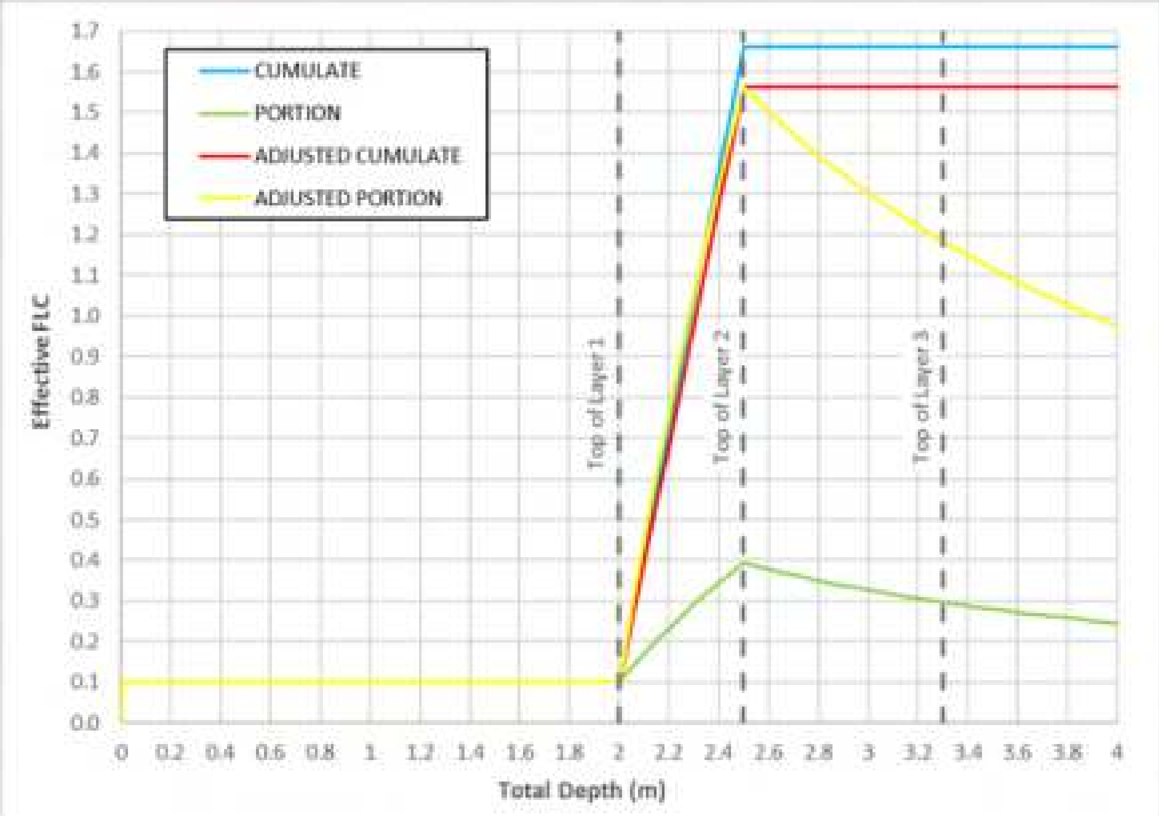


Figure 2-1 Effect of Averaging Method on Effective FLC

2.4 Adjusting FLC Values

This section provides an overview of how the FLC values derived from Bradley were adjusted for use with the default 'Portion' option on the discrete TUFLOW Layered Flow Constriction polygons defining the 'Deck' and 'Pier' sections within the Study Area.

2.4.1 Methodology Overview

To apply the 'Adjusted Portion' method, the following steps were taken.

1. To begin, the 'Bradley FLC' values (i.e. the FLC values desired at the top of each layer within the layered flow constriction shapes) were estimated in accordance with Bradley. These targeted FLC values are outlined below.
   - Deck polygon: Layer 1 FLC of 0, Layer 2 FLC of 1.5625, Layer 3 FLC of 0.
   - Pier polygon: Layer 1 FLC values depending on pier type and dimensions, Layer 2 FLC of 1.5625, Layer 3 FLC of 0.

   For pier polygons the 'Bradley FLC' values within 'Layer 1' were scaled up by a factor equal to the number of cells across the span of the bridge (perpendicular to the direction of flow) that the pier is representing to give the 'Target FLC'. This factoring is required due to the pier related FLC being applied on only a small portion of the bridge while the 'Bradley FLC' value represents a cross-sectional average for the entire bridge. For example, given the pier polygon covered only one third of the span which it represented, the FLC on this section would be required to be scaled up three times to account for the FLC not being applied on the adjacent cells that they would otherwise be applied on.

2. The ‘Required FLC’ values that would achieve the ‘Target FLC’ values were next determined. The calculation of these required the average depth beneath each polygon to be determined as an input into the ‘Portion’ equation, with the ‘Required FLC’ of each layer then back-calculated by rearranging the ‘Portion’ equation. The ‘Portion’ equation is reproduced below.

$$\zeta_{total} = \frac{(y_1\zeta_1 + y_2\zeta_2 + y_3\zeta_3)}{y_{total}}$$

$$y_{total} = y_1 + y_2 + y_3 + y_4$$

ζ_n = Layer n FLC

y_n = Layer n water depth (set to zero if dry and cannot exceed depth of layer)

ζ_{total} = Applied overall FLC

3. The ‘Applied FLC’ values that were input into the layered flow constriction shape attributes were then derived. These were calculated by dividing the ‘Required FLC’ values by the product of the number of cell sides in the direction of flow of the deck/pier polygon and the cell size (i.e. attaining the FLC per metre in the direction of flow along the bridge over as many cells as the number of cell sides crossed by the polygon in the direction of flow).

3. Summary

Due to the hydraulic importance of bridge structures for the Lower Yarra model, a refined bridge modelling approach has been applied to represent the bridges crossing the Lower Yarra River. This approach is considered an improvement on the more traditional bridge modelling approaches and as such has been adopted for all bridges crossing the Lower Yarra River that may be intercepted by flood waters at the deck level (and as such require FLC adjustment).

Appendix E – Flood Maps

Content

Paper Size ISO A3

0 0.2 0.4 0.6 0.8

Kilometers

Map Projection: Transverse Mercator
Horizontal Datum: GDA 1994
Grid: GDA 1994 MGA Zone 55

Melbourne Water
Lower Yarra River Flood Mapping

Model Terrain

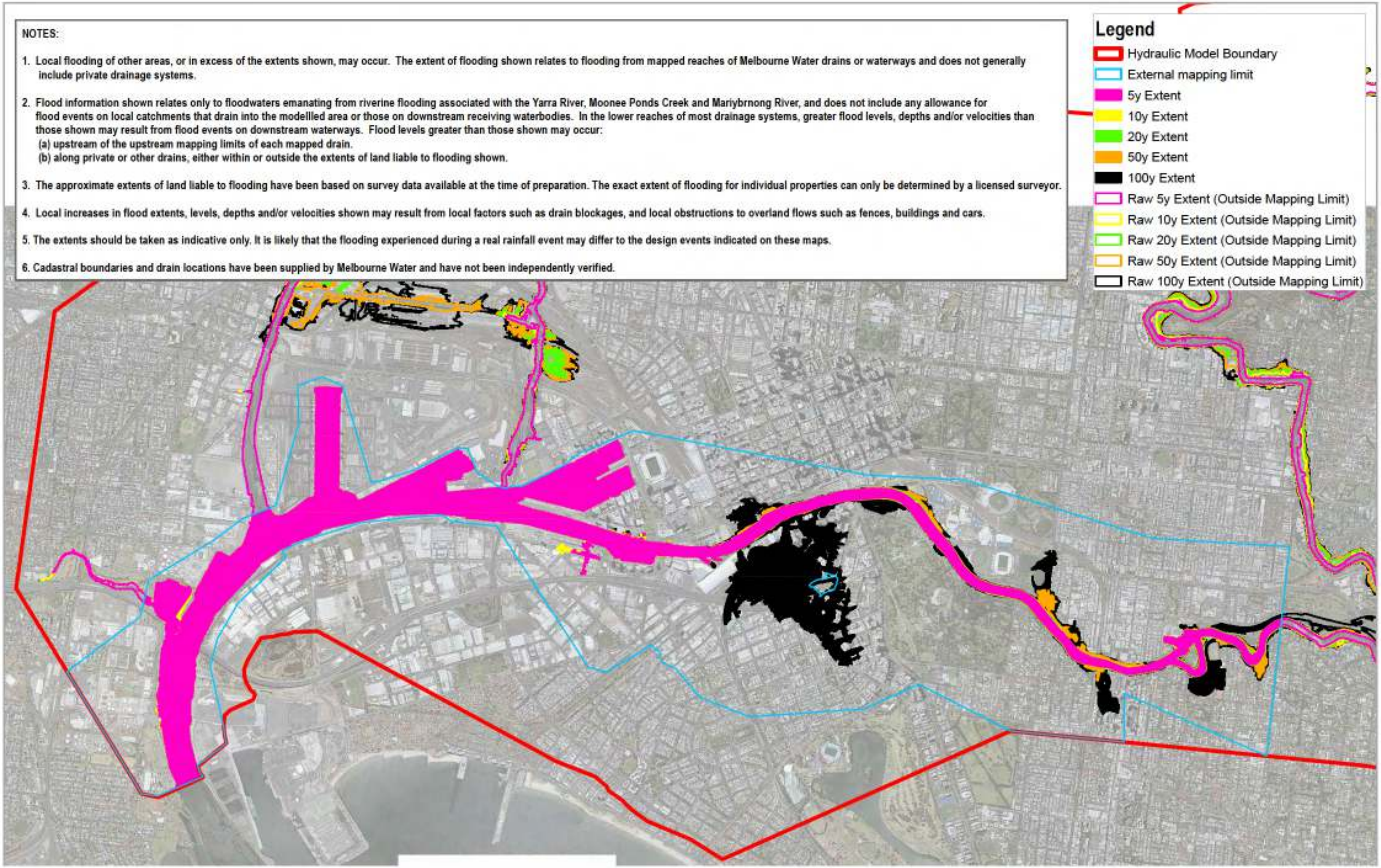
-

Project No. **31-35474**
Revision No. **0**
Date **31/08/2020**

Figure E1

NOTES:

1. Local flooding of other areas, or in excess of the extents shown, may occur. The extent of flooding shown relates to flooding from mapped reaches of Melbourne Water drains or waterways and does not generally include private drainage systems.
2. Flood information shown relates only to floodwaters emanating from riverine flooding associated with the Yarra River, Moonee Ponds Creek and Mariybrnong River, and does not include any allowance for flood events on local catchments that drain into the modellled area or those on downstream receiving waterbodies. In the lower reaches of most drainage systems, greater flood levels, depths and/or velocities than those shown may result from flood events on downstream waterways. Flood levels greater than those shown may occur:
   (a) upstream of the upstream mapping limits of each mapped drain.
   (b) along private or other drains, either within or outside the extents of land liable to flooding shown.
3. The approximate extents of land liable to flooding have been based on survey data available at the time of preparation. The exact extent of flooding for individual properties can only be determined by a licensed surveyor.
4. Local increases in flood extents, levels, depths and/or velocities shown may result from local factors such as drain blockages, and local obstructions to overland flows such as fences, buildings and cars.
5. The extents should be taken as indicative only. It is likely that the flooding experienced during a real rainfall event may differ to the design events indicated on these maps.
6. Cadastral boundaries and drain locations have been supplied by Melbourne Water and have not been independently verified.



This data should be read in conjunction with the latest revision of the document entitled "Lower Yarra River Flood Mapping" (Document No. 3135474-23531) and is subject to the assumptions and qualifications contained therein. If the report is yet to be released, these assumptions and qualifications must be confirmed by reference to GHD Pty Ltd.

Map Projection: Transverse Mercator
Horizontal Datum: GDA 1994
Grid: GDA 1994 MGA Zone 55

Melbourne Water
Lower Yarra River Flood Mapping

Flood Extents
Base Case Scenario

Project No. 31-35474
Revision No. 0
Date 31/08/2020

Figure E2

NOTES:

1. Local flooding of other areas, or in excess of the extents shown, may occur. The extent of flooding shown relates to flooding from mapped reaches of Melbourne Water drains or waterways and does not generally include private drainage systems.

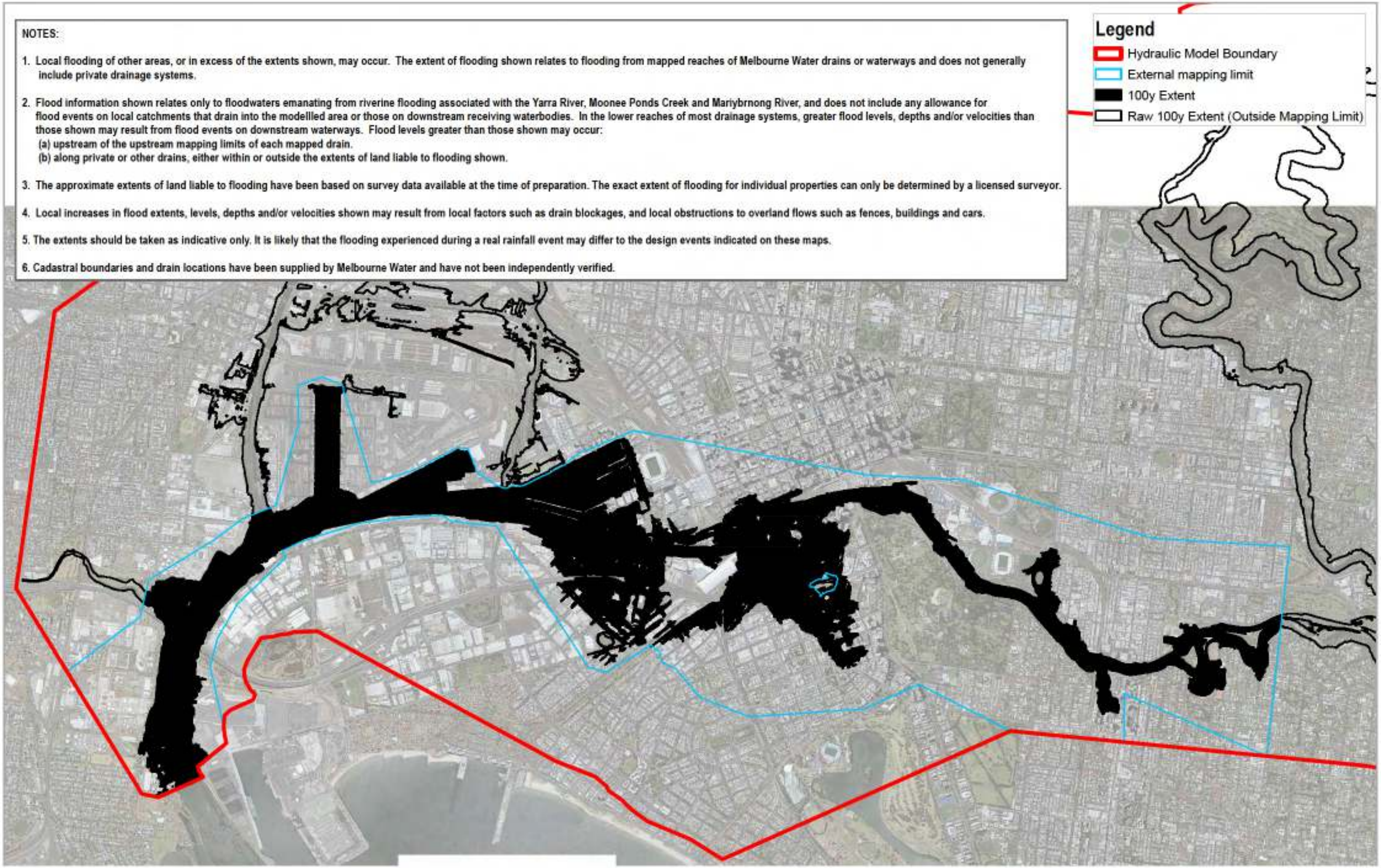
2. Flood information shown relates only to floodwaters emanating from riverine flooding associated with the Yarra River, Moonee Ponds Creek and Mariybrnong River, and does not include any allowance for flood events on local catchments that drain into the modellled area or those on downstream receiving waterbodies. In the lower reaches of most drainage systems, greater flood levels, depths and/or velocities than those shown may result from flood events on downstream waterways. Flood levels greater than those shown may occur:
   (a) upstream of the upstream mapping limits of each mapped drain.
   (b) along private or other drains, either within or outside the extents of land liable to flooding shown.

3. The approximate extents of land liable to flooding have been based on survey data available at the time of preparation. The exact extent of flooding for individual properties can only be determined by a licensed surveyor.

4. Local increases in flood extents, levels, depths and/or velocities shown may result from local factors such as drain blockages, and local obstructions to overland flows such as fences, buildings and cars.

5. The extents should be taken as indicative only. It is likely that the flooding experienced during a real rainfall event may differ to the design events indicated on these maps.

6. Cadastral boundaries and drain locations have been supplied by Melbourne Water and have not been independently verified.



This data should be read in conjunction with the latest revision of the document entitled "Lower Yarra River Flood Mapping" (Document No. 3135474-23531) and is subject to the assumptions and qualifications contained therein. If the report is yet to be released, these assumptions and qualifications must be confirmed by reference to GHD Pty Ltd.

Paper Size ISO A3
0 0.2 0.4 0.6 0.8
Kilometers

Map Projection: Transverse Mercator
Horizontal Datum: GDA 1994
Grid: GDA 1994 MGA Zone 55

N

Melbourne Water
Lower Yarra River Flood Mapping

Flood Extents
Climate Change 1 Scenario

Project No. 31-35474
Revision No. 0
Date 31/08/2020

Figure E3

NOTES:

1. Local flooding of other areas, or in excess of the extents shown, may occur. The extent of flooding shown relates to flooding from mapped reaches of Melbourne Water drains or waterways and does not generally include private drainage systems.

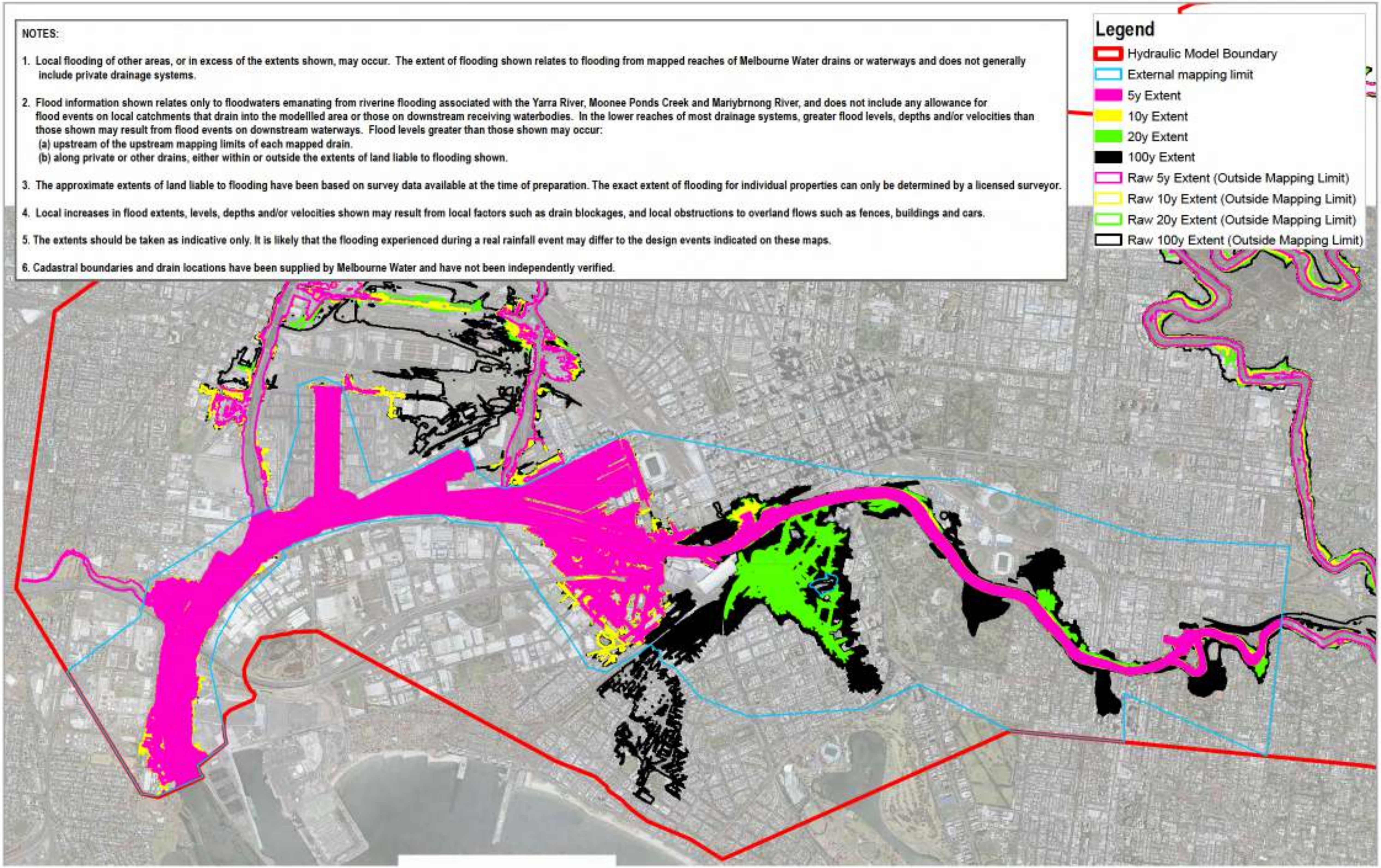
2. Flood information shown relates only to floodwaters emanating from riverine flooding associated with the Yarra River, Moonee Ponds Creek and Mariybrnong River, and does not include any allowance for flood events on local catchments that drain into the modellled area or those on downstream receiving waterbodies. In the lower reaches of most drainage systems, greater flood levels, depths and/or velocities than those shown may result from flood events on downstream waterways. Flood levels greater than those shown may occur:
   (a) upstream of the upstream mapping limits of each mapped drain.
   (b) along private or other drains, either within or outside the extents of land liable to flooding shown.

3. The approximate extents of land liable to flooding have been based on survey data available at the time of preparation. The exact extent of flooding for individual properties can only be determined by a licensed surveyor.

4. Local increases in flood extents, levels, depths and/or velocities shown may result from local factors such as drain blockages, and local obstructions to overland flows such as fences, buildings and cars.

5. The extents should be taken as indicative only. It is likely that the flooding experienced during a real rainfall event may differ to the design events indicated on these maps.

6. Cadastral boundaries and drain locations have been supplied by Melbourne Water and have not been independently verified.



Paper Size ISO A3
0 0.2 0.4 0.6 0.8
Kilometers

Map Projection: Transverse Mercator
Horizontal Datum: GDA 1994
Grid: GDA 1994 MGA Zone 55

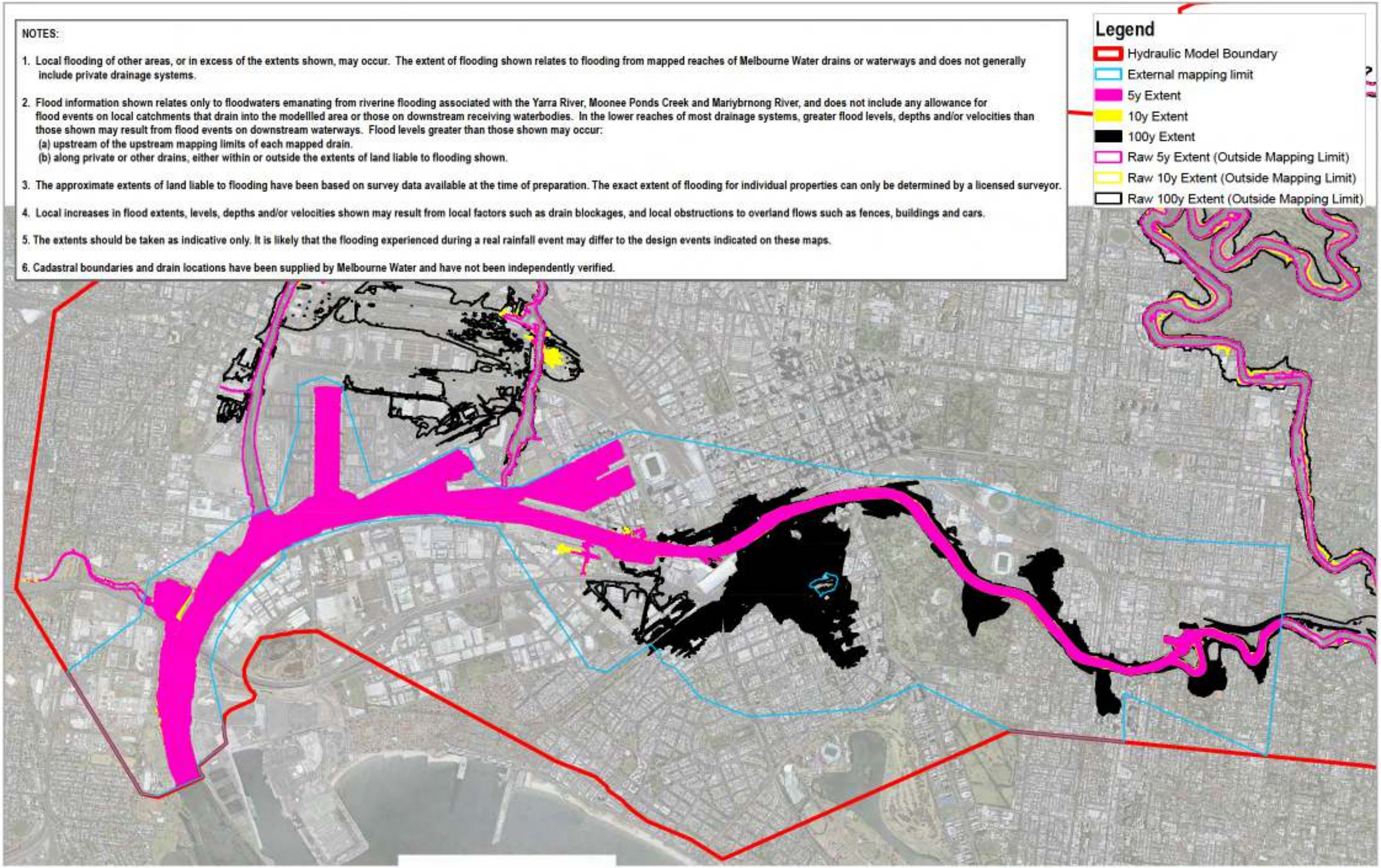
N

Melbourne Water
Lower Yarra River Flood Mapping

Flood Extents
Climate Change 2 Scenario

Project No. 31-35474
Revision No. 0
Date 31/08/2020

Figure E4



This data should be read in conjunction with the latest revision of the document entitled "Lower Yarra River Flood Mapping" (Document No. 3135474-23531) and is subject to the assumptions and qualifications contained therein. If the report is yet to be released, these assumptions and qualifications must be confirmed by reference to GHD Pty Ltd.

Paper Size ISO A3
0 0.2 0.4 0.6 0.8
Kilometers

Map Projection: Transverse Mercator
Horizontal Datum: GDA 1994
Grid: GDA 1994 MGA Zone 55

N

Melbourne Water
Lower Yarra River Flood Mapping

Flood Extents
Climate Change 3 Scenario

Project No. 31-35474
Revision No. 0
Date 31/08/2020

Figure E5

Paper Size ISO A3
0 0.2 0.4 0.6 0.8
Kilometres

Map Projection: Transverse Mercator
Horizontal Datum: GDA 1994
Grid: GDA 1994 MGA Zone 55

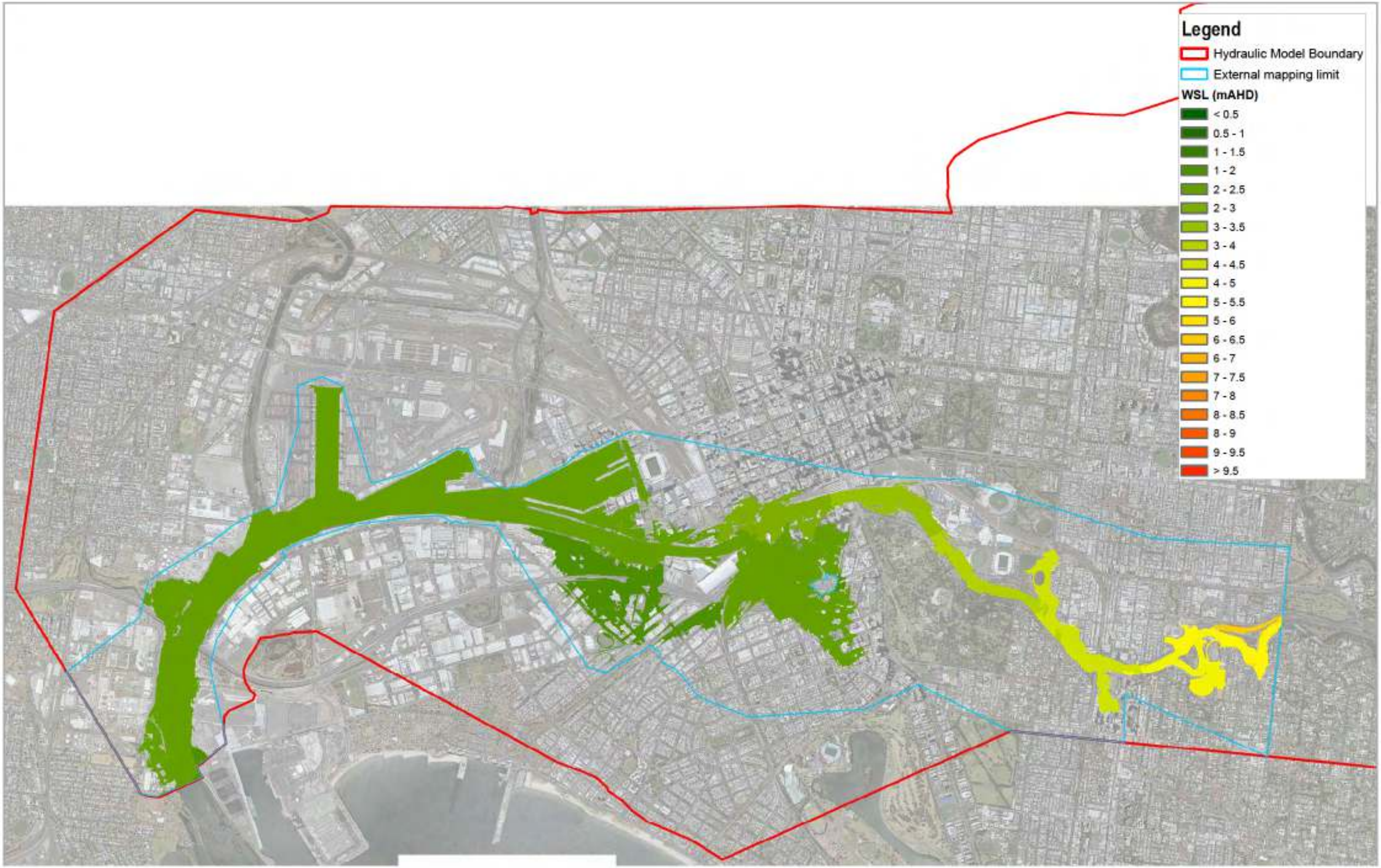
N

Melbourne Water
Lower Yarra River Flood Mapping

Peak WSL
100y ARI (Base Case Scenario)

Project No. **31-35474**
Revision No. **0**
Date **31/08/2020**

Figure E6



This data should be read in conjunction with the latest revision of the document entitled "Lower Yarra River Flood Mapping" (Document No. 3135474-23531) and is subject to the assumptions and qualifications contained therein. If the report is yet to be released, these assumptions and qualifications must be confirmed by reference to GHD Pty Ltd.

Melbourne Water
Lower Yarra River Flood Mapping

Peak WSL
100y ARI (Climate Change 1 Scenario)

Project No. **31-35474**
Revision No. **0**
Date **31/08/2020**

Figure E7

This data should be read in conjunction with the latest revision of the document entitled "Lower Yarra River Flood Mapping" (Document No. 3135474-23531) and is subject to the assumptions and qualifications contained therein. If the report is yet to be released, these assumptions and qualifications must be confirmed by reference to GHD Pty Ltd.

Paper Size ISO A3
0 0.2 0.4 0.6 0.8
Kilometres

Map Projection: Transverse Mercator
Horizontal Datum: GDA 1994
Grid: GDA 1994 MGA Zone 55

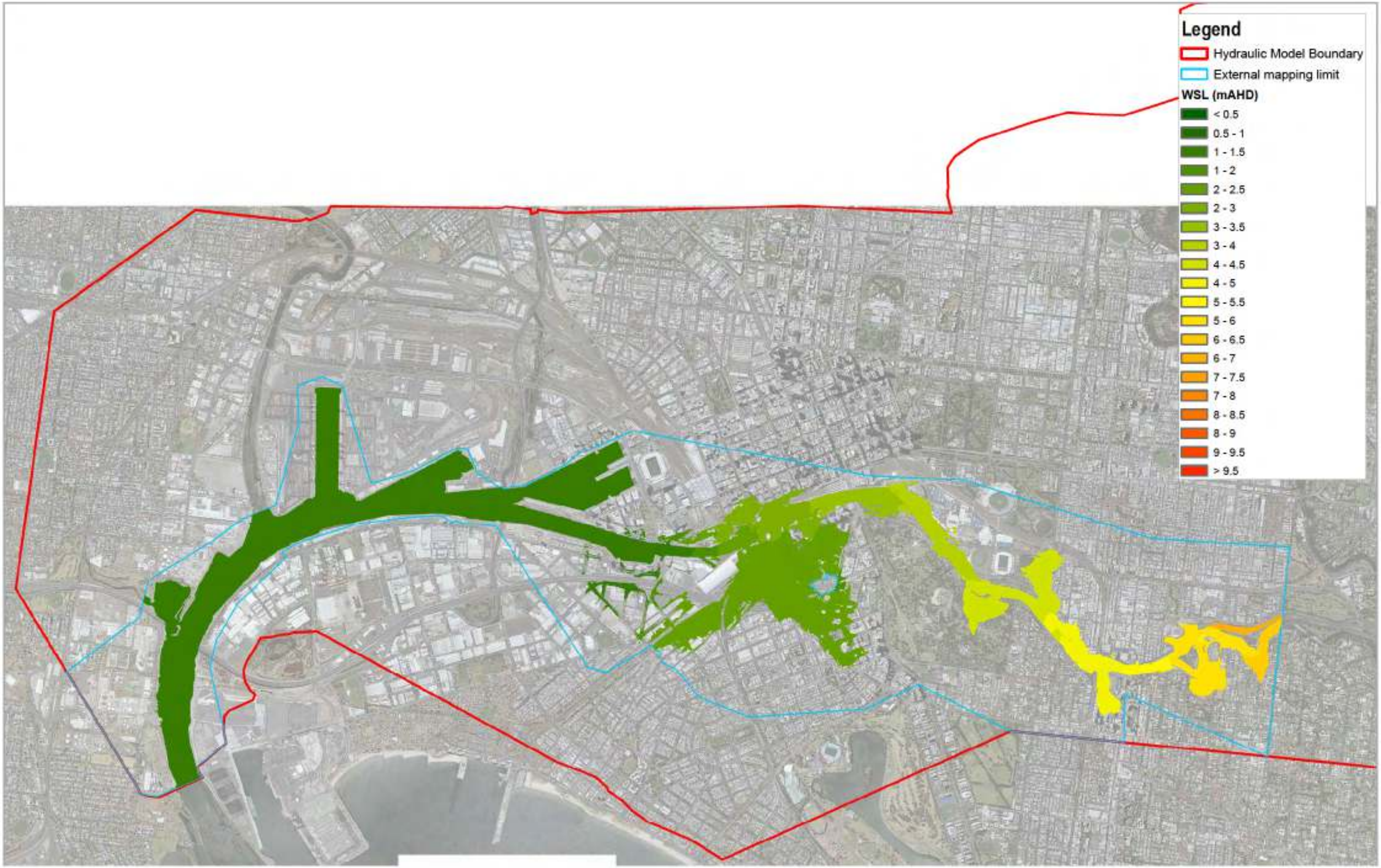
N

Melbourne Water
Lower Yarra River Flood Mapping

Peak WSL
100y ARI (Climate Change 2 Scenario)

Project No. 31-35474
Revision No. 0
Date 31/08/2020

Figure E8



This data should be read in conjunction with the latest revision of the document entitled "Lower Yarra River Flood Mapping" (Document No. 3135474-23531) and is subject to the assumptions and qualifications contained therein. If the report is yet to be released, these assumptions and qualifications must be confirmed by reference to GHD Pty Ltd.

Paper Size ISO A3
0 0.2 0.4 0.6 0.8
Kilometres

Map Projection: Transverse Mercator
Horizontal Datum: GDA 1994
Grid: GDA 1994 MGA Zone 55

N

Melbourne Water
Lower Yarra River Flood Mapping

Peak WSL
100y ARI (Climate Change 3 Scenario)

Project No. 31-35474
Revision No. 0
Date 31/08/2020

Figure E9

Paper Size ISO A3
0 0.2 0.4 0.6 0.8
Kilometres

Map Projection: Transverse Mercator
Horizontal Datum: GDA 1994
Grid: GDA 1994 MGA Zone 55

N

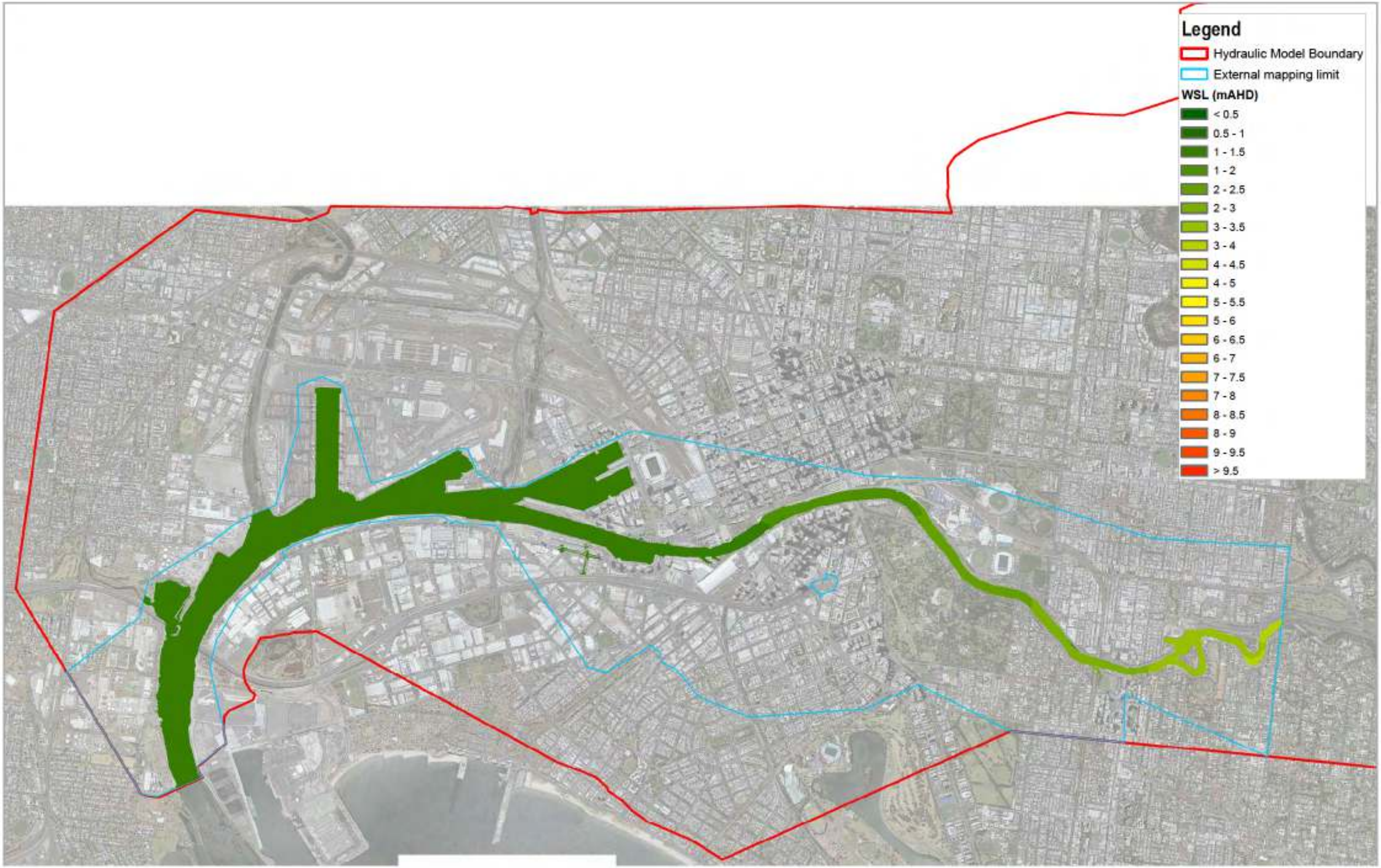
Melbourne Water
Lower Yarra River Flood Mapping

Peak WSL
50y ARI (Base Case Scenario)

Project No. **31-35474**
Revision No. **0**
Date **31/08/2020**

Figure E10

Data source: . Created by:



This data should be read in conjunction with the latest revision of the document entitled "Lower Yarra River Flood Mapping" (Document No. 3135474-23531) and is subject to the assumptions and qualifications contained therein. If the report is yet to be released, these assumptions and qualifications must be confirmed by reference to GHD Pty Ltd.

Melbourne Water
Lower Yarra River Flood Mapping

Peak WSL
20y ARI (Base Case Scenario)

Project No. **31-35474**
Revision No. **0**
Date **31/08/2020**

Figure E11

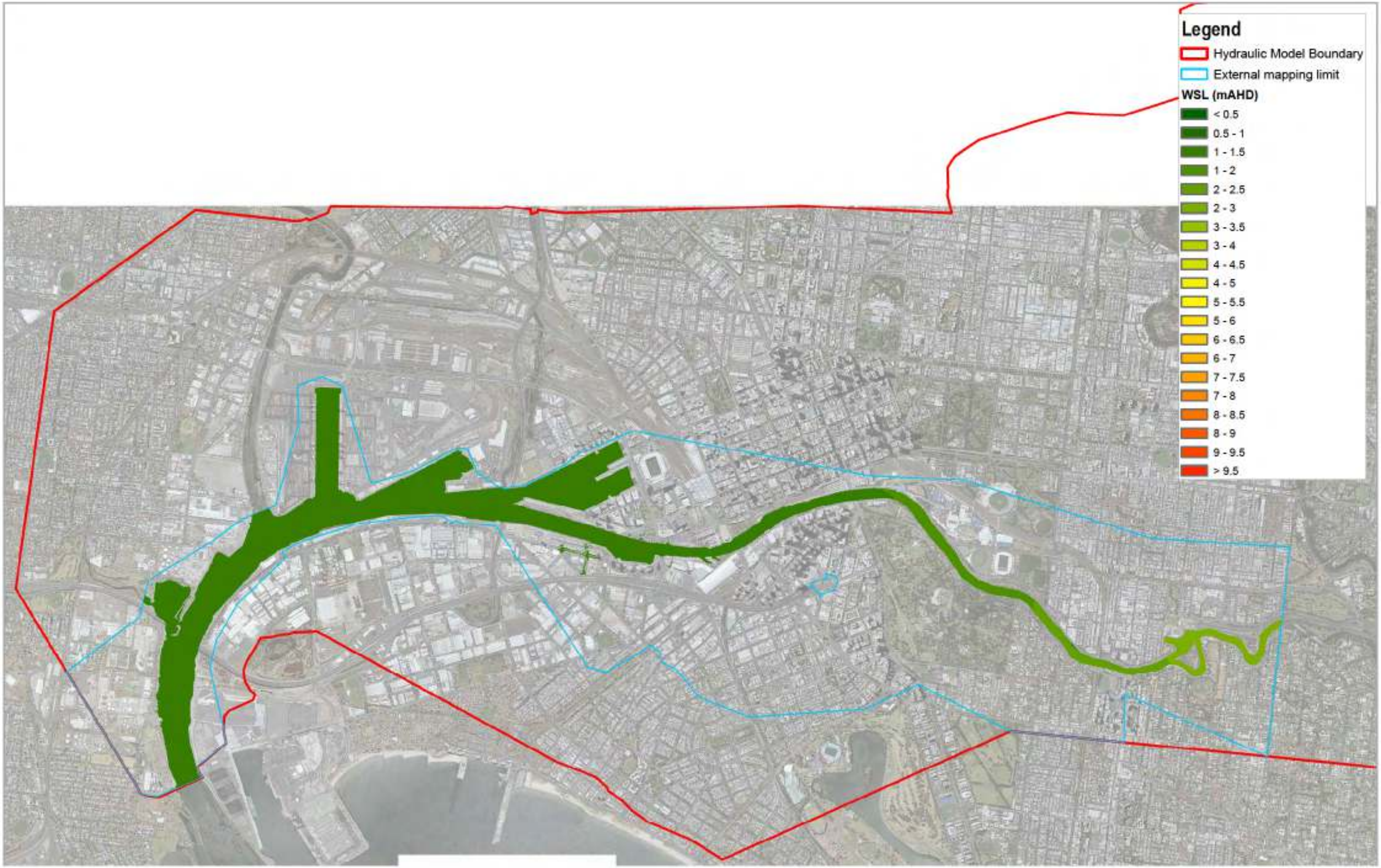
This data should be read in conjunction with the latest revision of the document entitled "Lower Yarra River Flood Mapping" (Document No. 3135474-23531) and is subject to the assumptions and qualifications contained therein. If the report is yet to be released, these assumptions and qualifications must be confirmed by reference to GHD Pty Ltd.

Melbourne Water
Lower Yarra River Flood Mapping

Peak WSL
20y ARI (Climate Change 2 Scenario)

Project No. **31-35474**
Revision No. **0**
Date **31/08/2020**

Figure E12



This data should be read in conjunction with the latest revision of the document entitled "Lower Yarra River Flood Mapping" (Document No. 3135474-23531) and is subject to the assumptions and qualifications contained therein. If the report is yet to be released, these assumptions and qualifications must be confirmed by reference to GHD Pty Ltd.

Paper Size ISO A3

0 0.2 0.4 0.6 0.8

Kilometres

Map Projection: Transverse Mercator
Horizontal Datum: GDA 1994
Grid: GDA 1994 MGA Zone 55

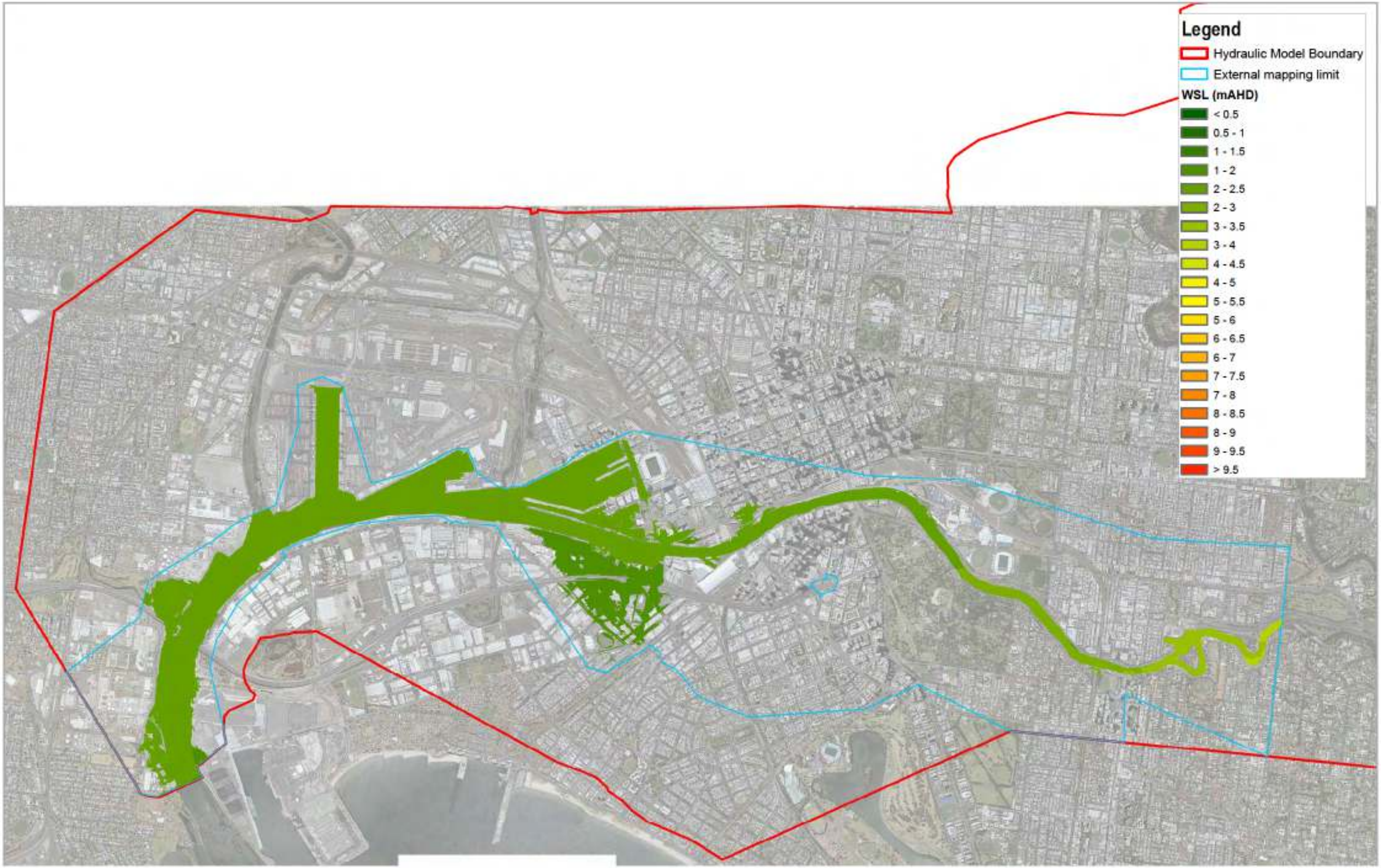
N

Melbourne Water
Lower Yarra River Flood Mapping

Peak WSL
10y ARI (Base Case Scenario)

Project No. **31-35474**
Revision No. **0**
Date **31/08/2020**

Figure E13



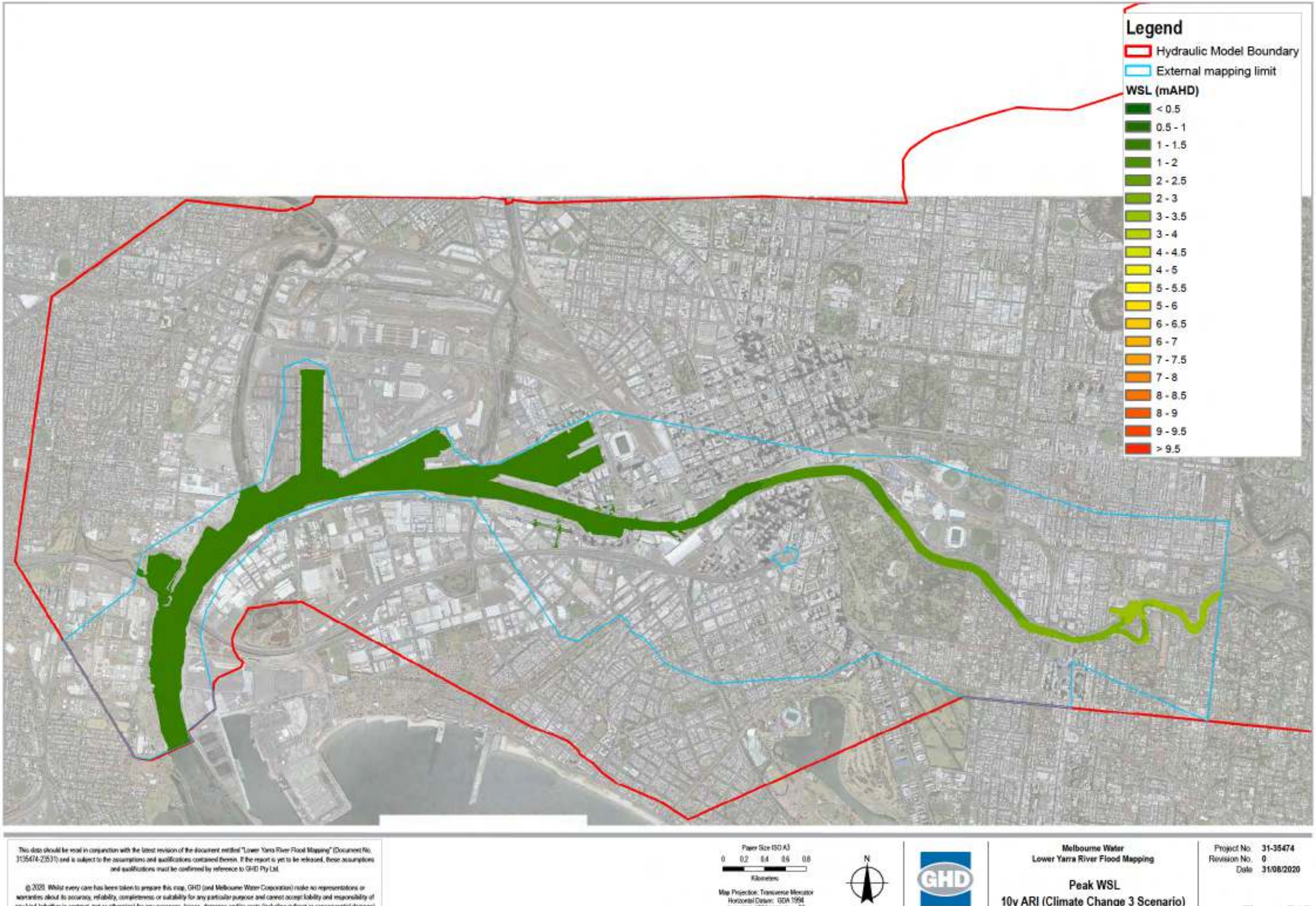
This data should be read in conjunction with the latest revision of the document entitled "Lower Yarra River Flood Mapping" (Document No. 3135474-23531) and is subject to the assumptions and qualifications contained therein. If the report is yet to be released, these assumptions and qualifications must be confirmed by reference to GHD Pty Ltd.

Melbourne Water
Lower Yarra River Flood Mapping

Peak WSL
10y ARI (Climate Change 2 Scenario)

Project No. **31-35474**
Revision No. **0**
Date **31/08/2020**

Figure E14



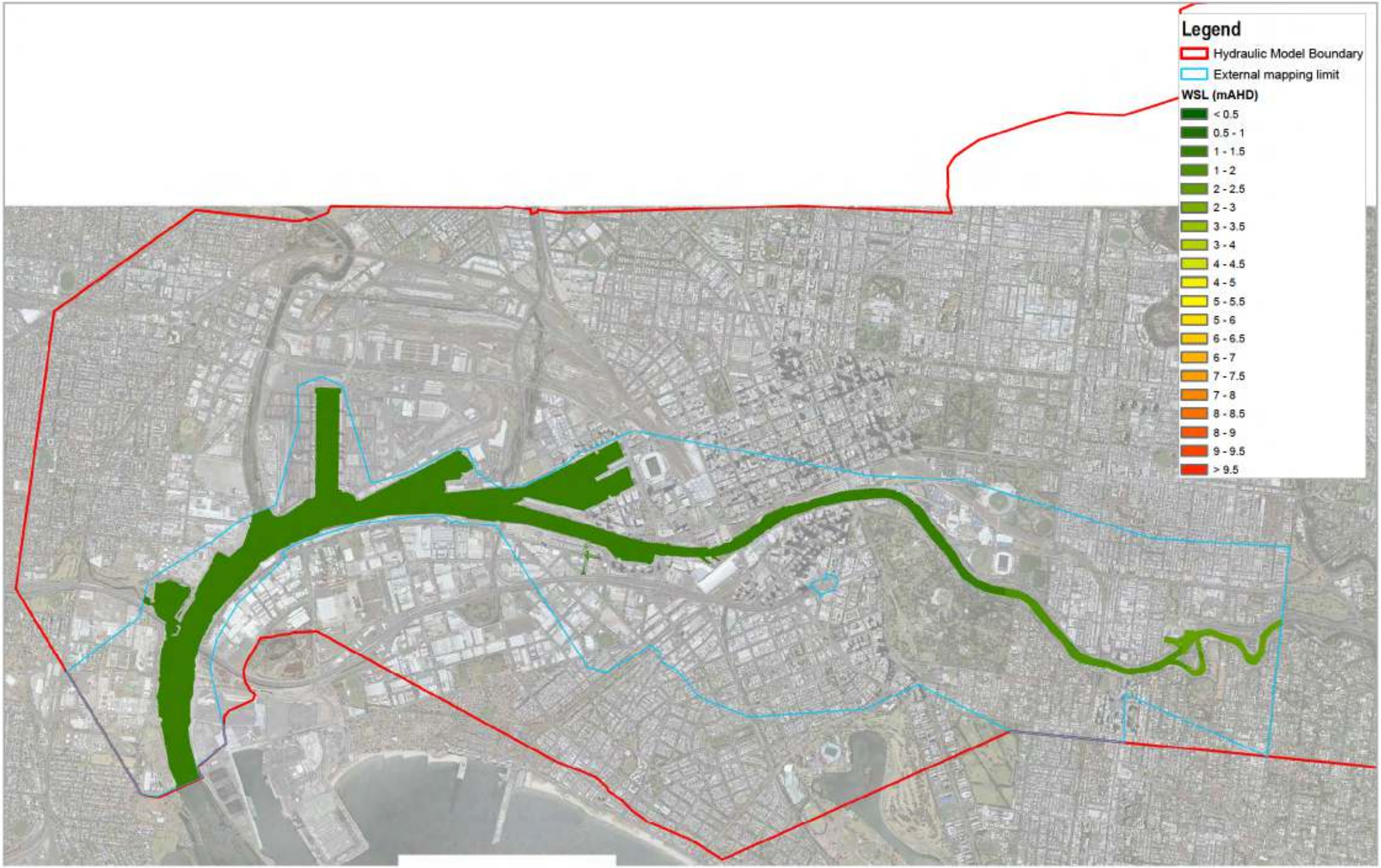
This data should be read in conjunction with the latest revision of the document entitled "Lower Yarra River Flood Mapping" (Document No. 3135474-23531) and is subject to the assumptions and qualifications contained therein. If the report is yet to be released, these assumptions and qualifications must be confirmed by reference to GHD Pty Ltd.

Melbourne Water
Lower Yarra River Flood Mapping

Peak WSL
10y ARI (Climate Change 3 Scenario)

Project No. **31-35474**
Revision No. **0**
Date **31/08/2020**

Figure E15



This data should be read in conjunction with the latest revision of the document entitled "Lower Yarra River Flood Mapping" (Document No. 3135474-23531) and is subject to the assumptions and qualifications contained therein. If the report is yet to be released, these assumptions and qualifications must be confirmed by reference to GHD Pty Ltd.

Paper Size ISO A3

0 0.2 0.4 0.6 0.8

Kilometers

Map Projection: Transverse Mercator
Horizontal Datum: GDA 1994
Grid: GDA 1994 MGA Zone 55

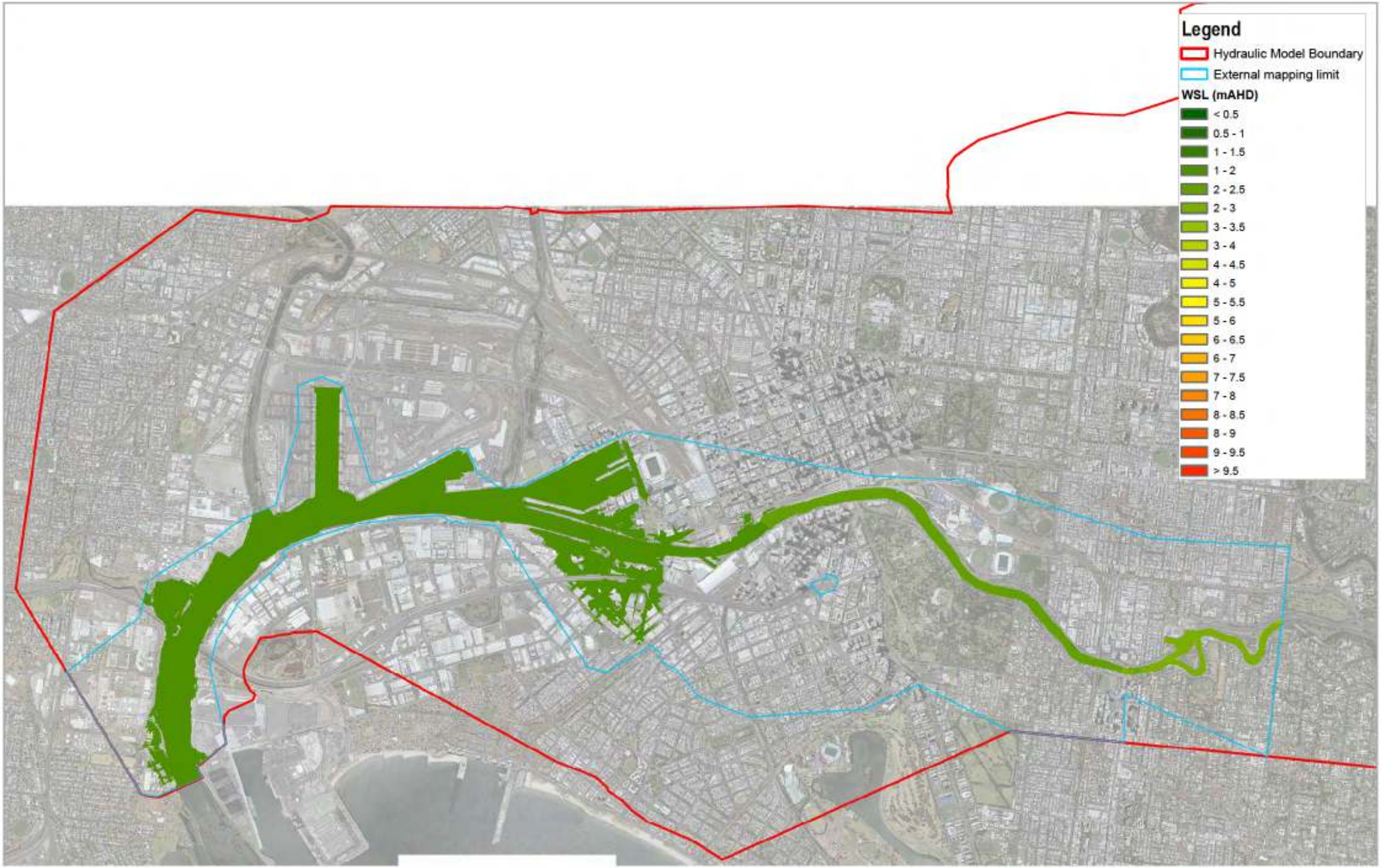
N

Melbourne Water
Lower Yarra River Flood Mapping

Peak WSL
5y ARI (Base Case Scenario)

Project No. **31-35474**
Revision No. **0**
Date **31/08/2020**

Figure E16



This data should be read in conjunction with the latest revision of the document entitled "Lower Yarra River Flood Mapping" (Document No. 3135474-23531) and is subject to the assumptions and qualifications contained therein. If the report is yet to be released, these assumptions and qualifications must be confirmed by reference to GHD Pty Ltd.

Paper Size ISO A3
0 0.2 0.4 0.6 0.8
Kilometres

Map Projection: Transverse Mercator
Horizontal Datum: GDA 1994
Grid: GDA 1994 MGA Zone 55

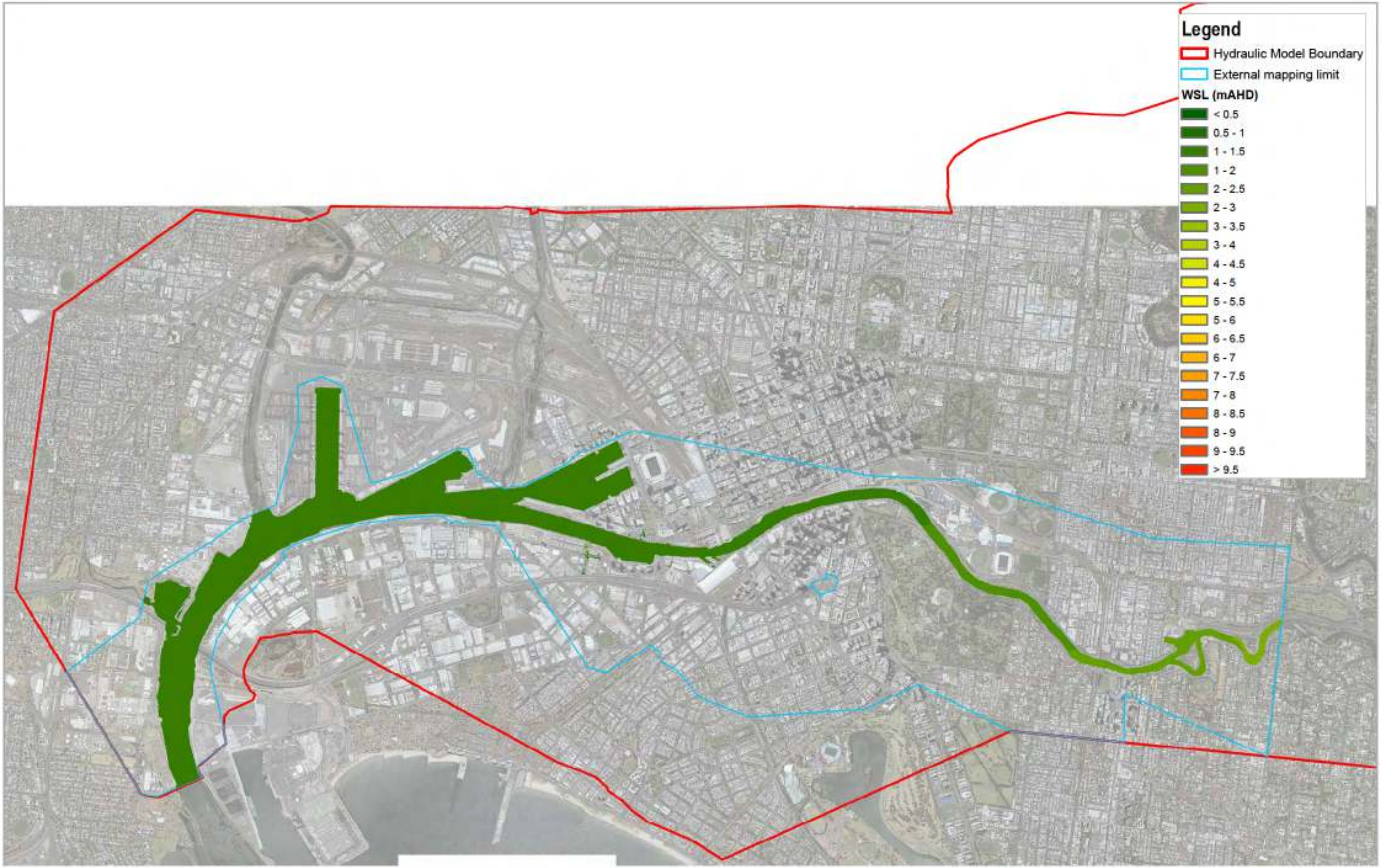
N

Melbourne Water
Lower Yarra River Flood Mapping

Peak WSL
5y ARI (Climate Change 2 Scenario)

Project No. 31-35474
Revision No. 0
Date 31/08/2020

Figure E17



Paper Size ISO A3

0 0.2 0.4 0.6 0.8

Kilometres

Map Projection: Transverse Mercator
Horizontal Datum: GDA 1994
Grid: GDA 1994 MGA Zone 55

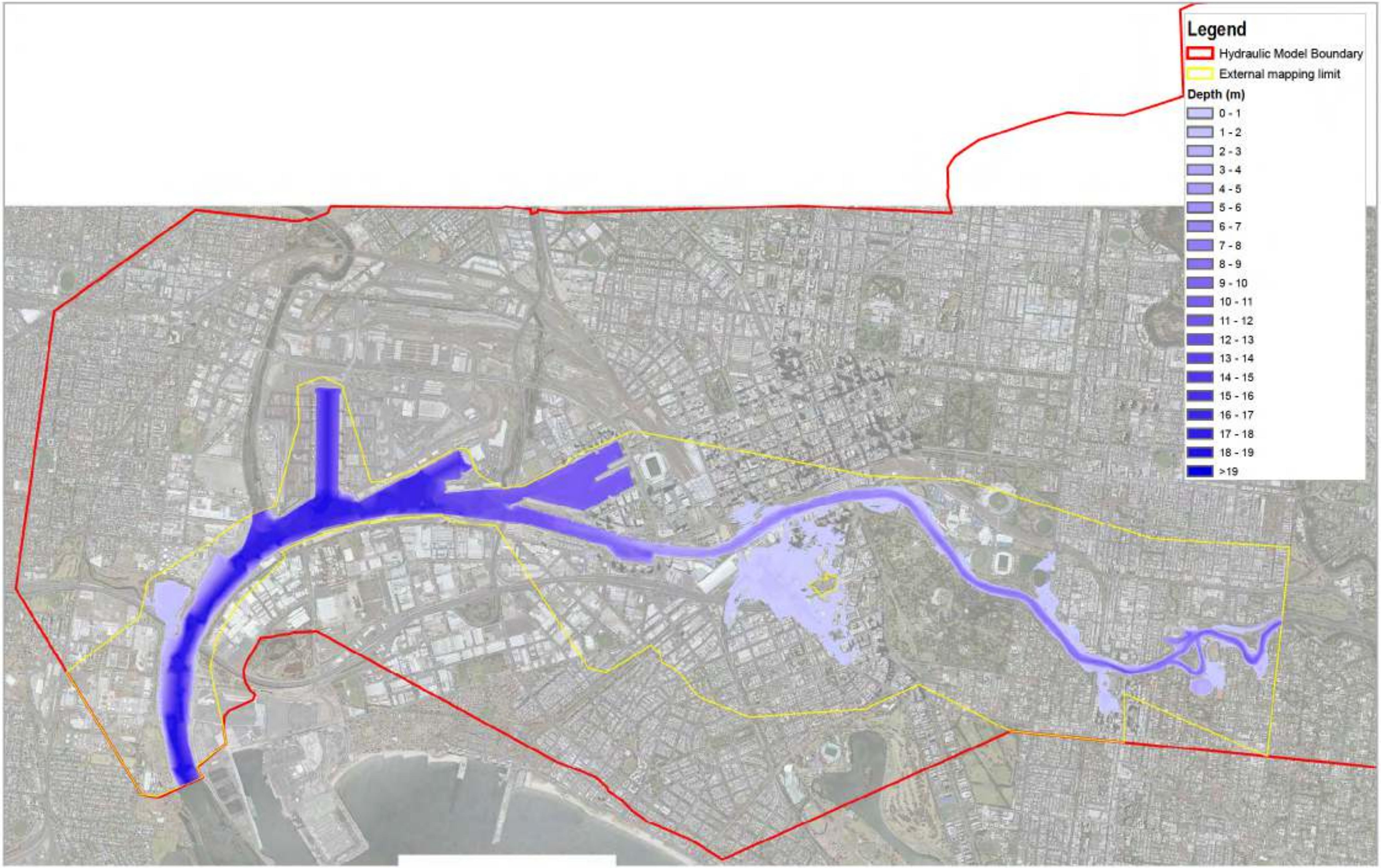
N

Melbourne Water
Lower Yarra River Flood Mapping

Peak WSL
5y ARI (Climate Change 3 Scenario)

Project No. **31-35474**
Revision No. **0**
Date **31/08/2020**

Figure E18



This data should be read in conjunction with the latest revision of the document entitled "Lower Yarra River Flood Mapping" (Document No. 3135474-23531) and is subject to the assumptions and qualifications contained therein. If the report is yet to be released, these assumptions and qualifications must be confirmed by reference to GHD Pty Ltd.

Paper Size ISO A3

0 0.2 0.4 0.6 0.8

Kilometres

Map Projection: Transverse Mercator
Horizontal Datum: GDA 1994
Grid: GDA 1994 MGA Zone 55

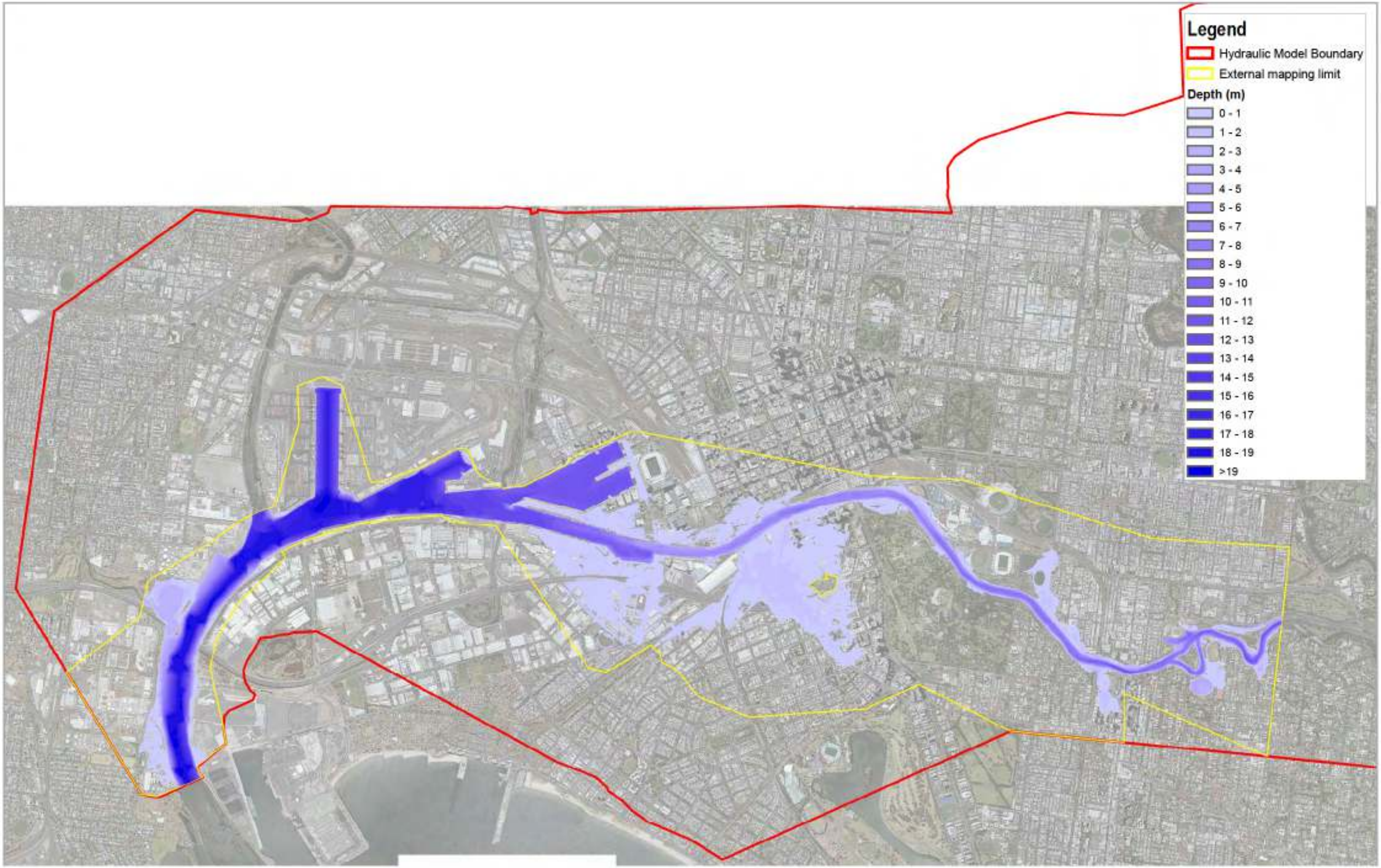
N

Melbourne Water
Lower Yarra River Flood Mapping

Peak Depth
100y ARI (Base Case Scenario)

Project No. 31-35474
Revision No. 0
Date 31/08/2020

Figure E19



This data should be read in conjunction with the latest revision of the document entitled "Lower Yarra River Flood Mapping" (Document No. 3135474-23531) and is subject to the assumptions and qualifications contained therein. If the report is yet to be released, these assumptions and qualifications must be confirmed by reference to GHD Pty Ltd.

Paper Size ISO A3

0 0.2 0.4 0.6 0.8

Kilometers

Map Projection: Transverse Mercator
Horizontal Datum: GDA 1994
Grid: GDA 1994 MGA Zone 55

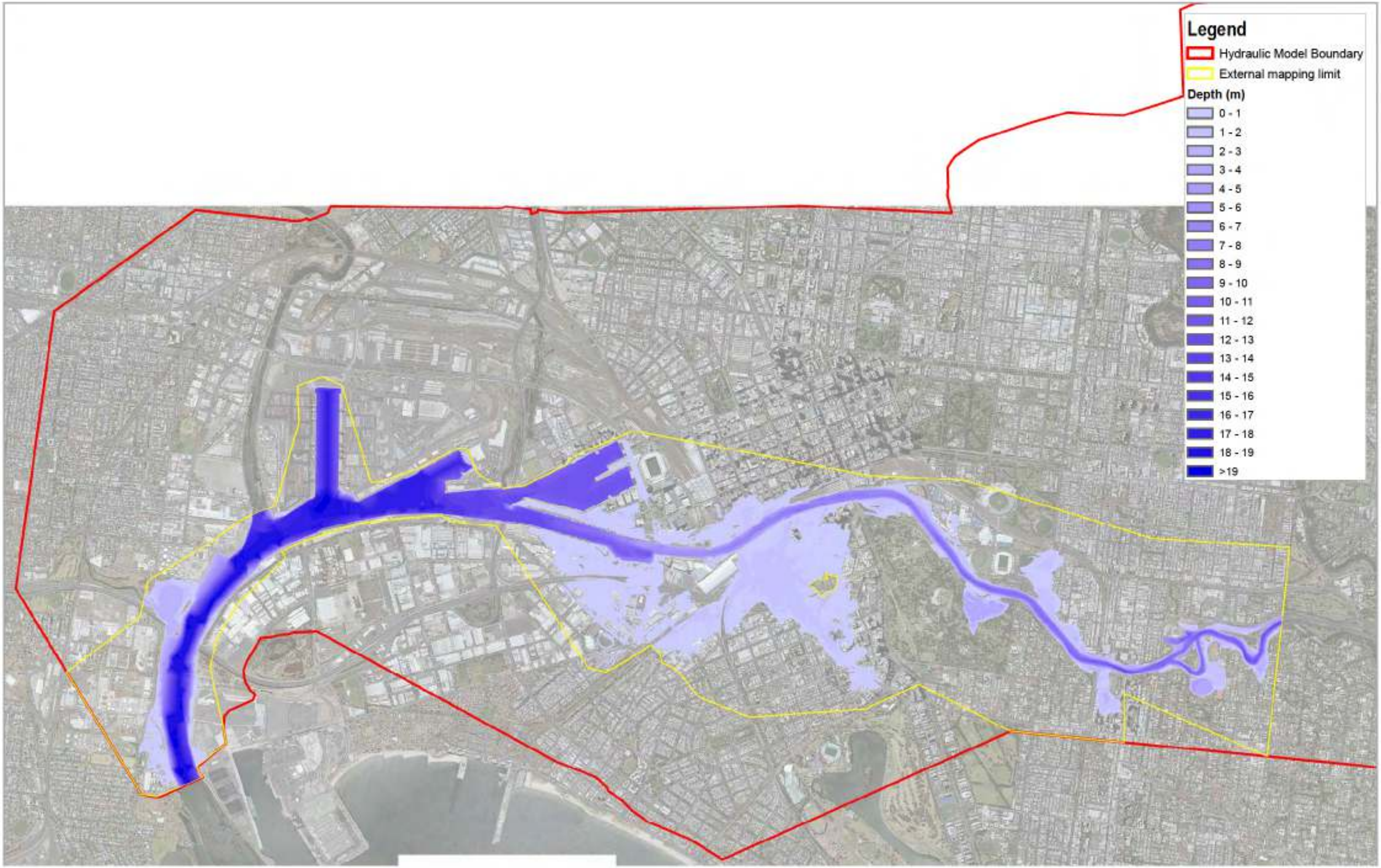
N

Melbourne Water
Lower Yarra River Flood Mapping

Peak Depth
100y ARI (Climate Change 1 Scenario)

Project No. 31-35474
Revision No. 0
Date 31/08/2020

Figure E20



This data should be read in conjunction with the latest revision of the document entitled "Lower Yarra River Flood Mapping" (Document No. 3135474-23531) and is subject to the assumptions and qualifications contained therein. If the report is yet to be released, these assumptions and qualifications must be confirmed by reference to GHD Pty Ltd.

Paper Size ISO A3

0 0.2 0.4 0.6 0.8

Kilometres

Map Projection: Transverse Mercator
Horizontal Datum: GDA 1994
Grid: GDA 1994 MGA Zone 55

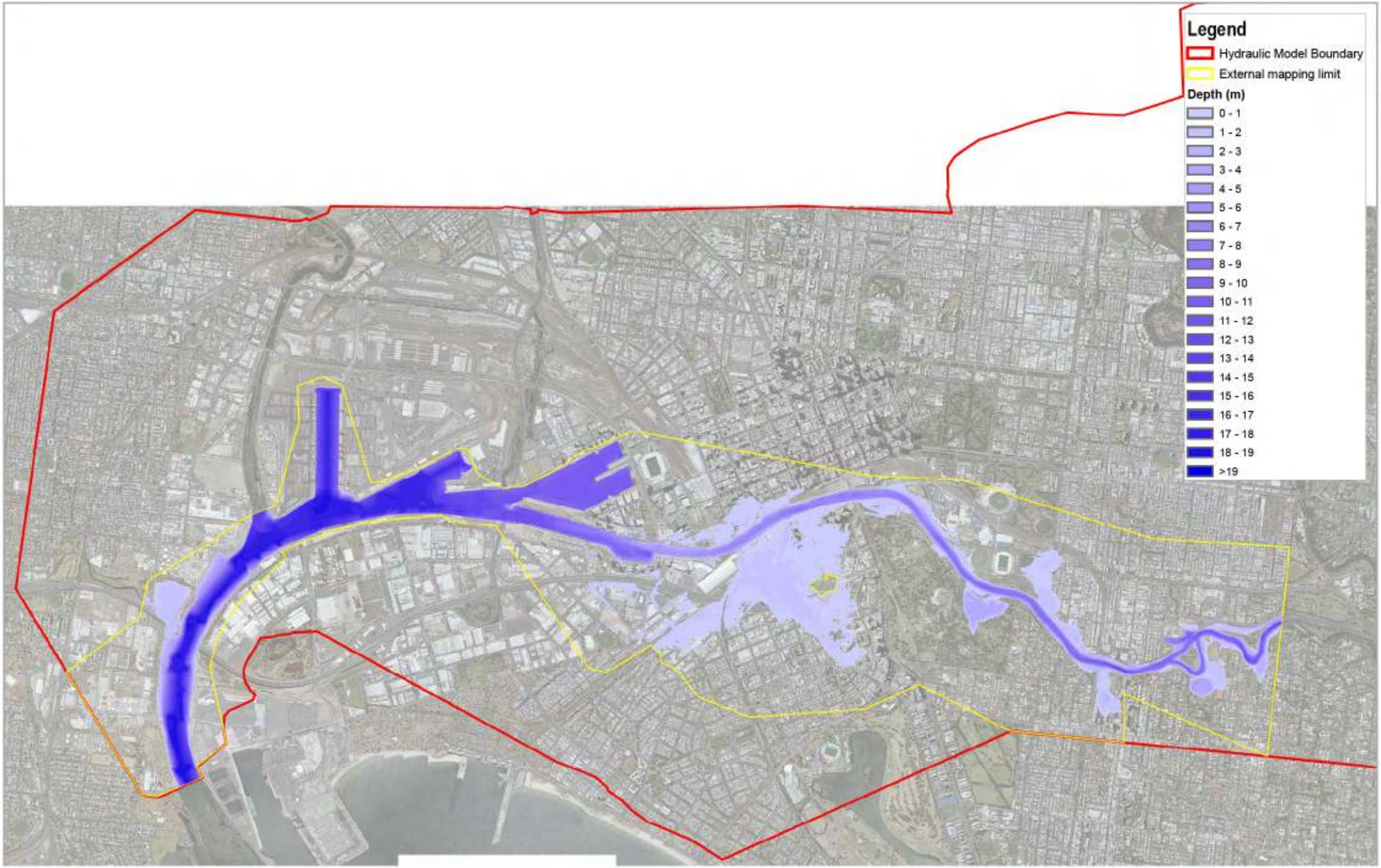
N

Melbourne Water
Lower Yarra River Flood Mapping

Peak Depth
100y ARI (Climate Change 2 Scenario)

Project No. 31-35474
Revision No. 0
Date 31/08/2020

Figure E21



This data should be read in conjunction with the latest revision of the document entitled "Lower Yarra River Flood Mapping" (Document No. 3135474-23531) and is subject to the assumptions and qualifications contained therein. If the report is yet to be released, these assumptions and qualifications must be confirmed by reference to GHD Pty Ltd.

Paper Size ISO A3
0 0.2 0.4 0.6 0.8
Kilometers

Map Projection: Transverse Mercator
Horizontal Datum: GDA 1994
Grid: GDA 1994 MGA Zone 55

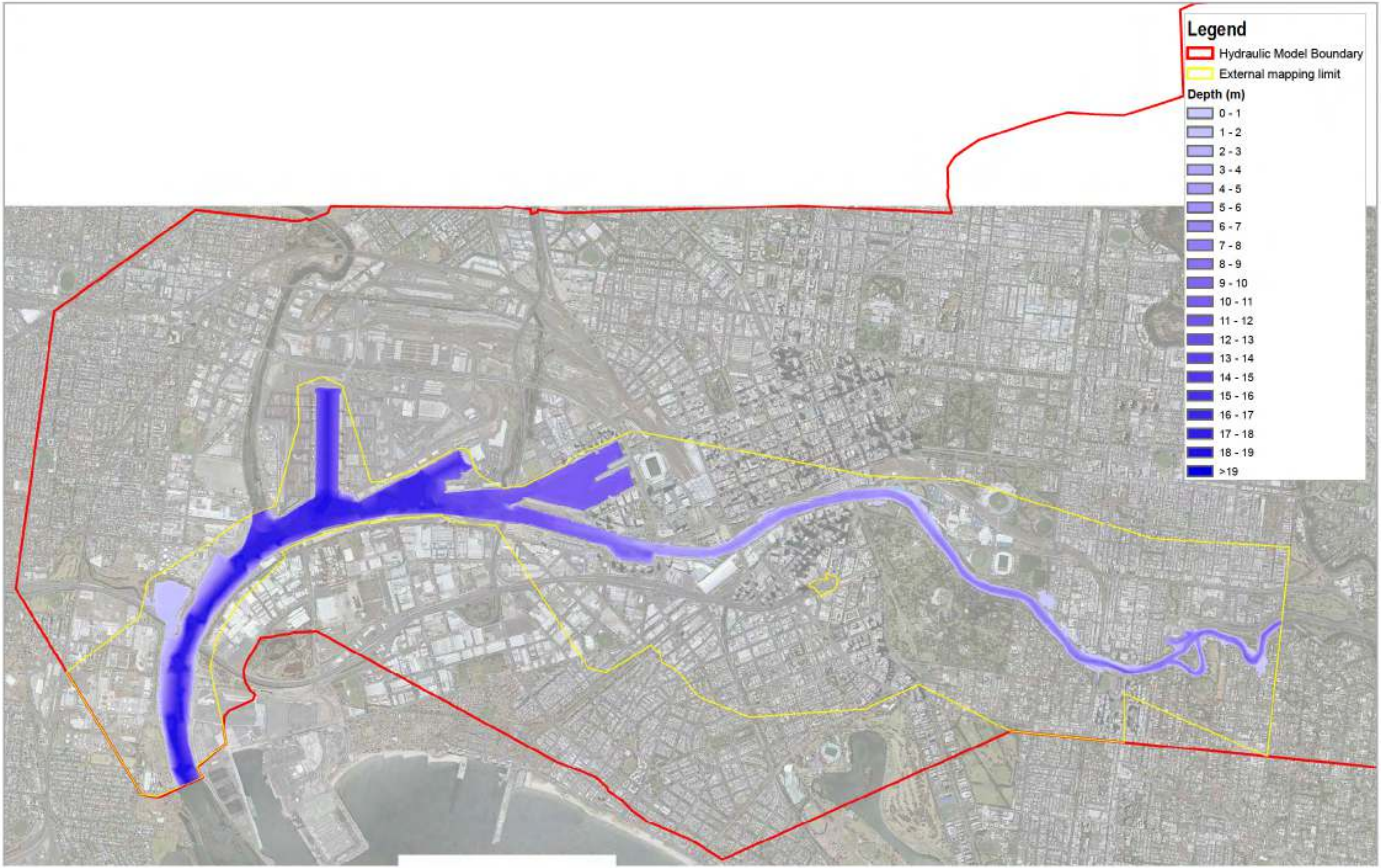
N

Melbourne Water
Lower Yarra River Flood Mapping

Peak Depth
100y ARI (Climate Change 3 Scenario)

Project No. **31-35474**
Revision No. **0**
Date **31/08/2020**

Figure E22

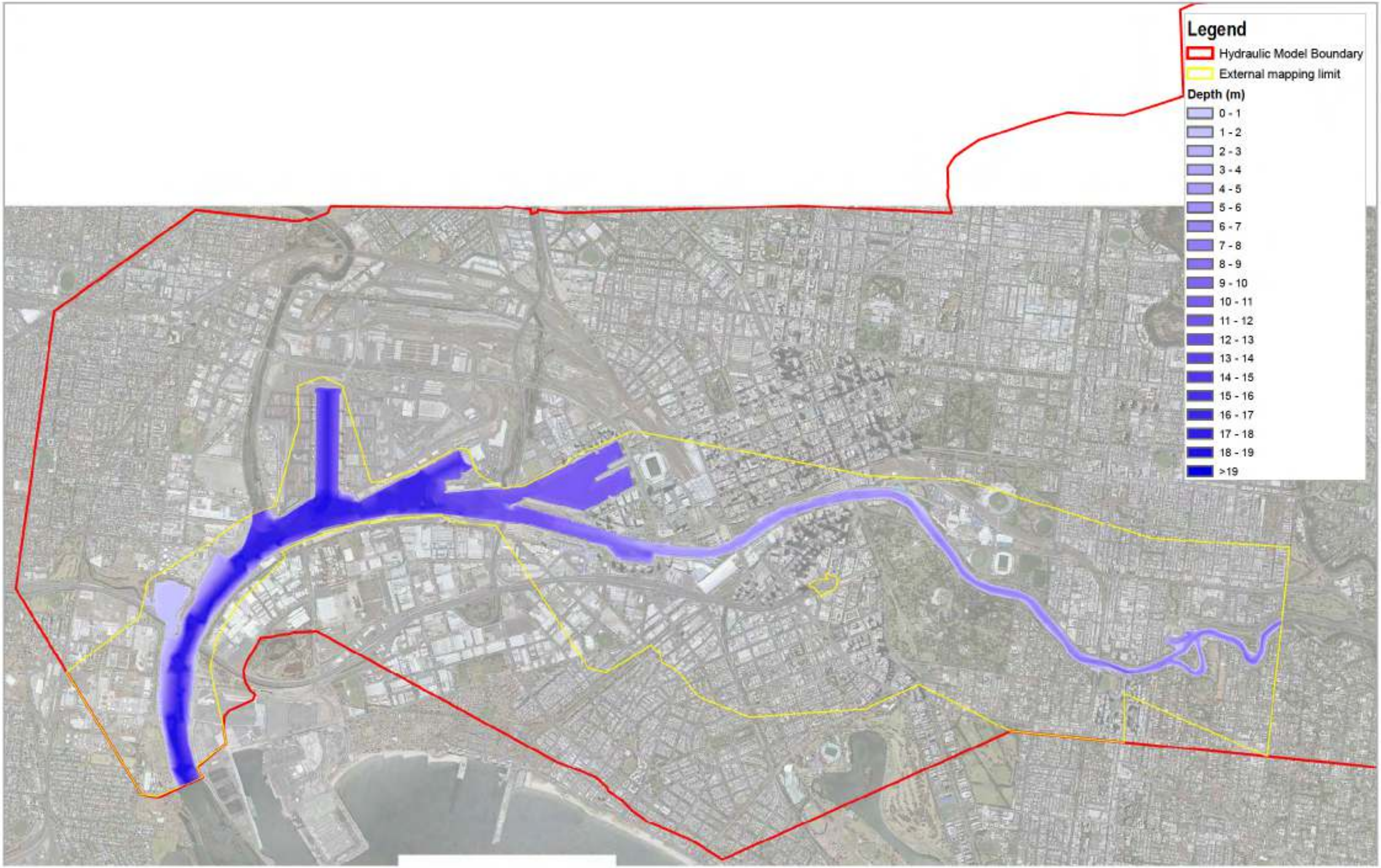


Melbourne Water
Lower Yarra River Flood Mapping

Peak Depth
50y ARI (Base Case Scenario)

Project No. **31-35474**
Revision No. **0**
Date **31/08/2020**

Figure E23



This data should be read in conjunction with the latest revision of the document entitled "Lower Yarra River Flood Mapping" (Document No. 3135474-23531) and is subject to the assumptions and qualifications contained therein. If the report is yet to be released, these assumptions and qualifications must be confirmed by reference to GHD Pty Ltd.

Paper Size ISO A3

0 0.2 0.4 0.6 0.8

Kilometres

Map Projection: Transverse Mercator
Horizontal Datum: GDA 1994
Grid: GDA 1994 MGA Zone 55

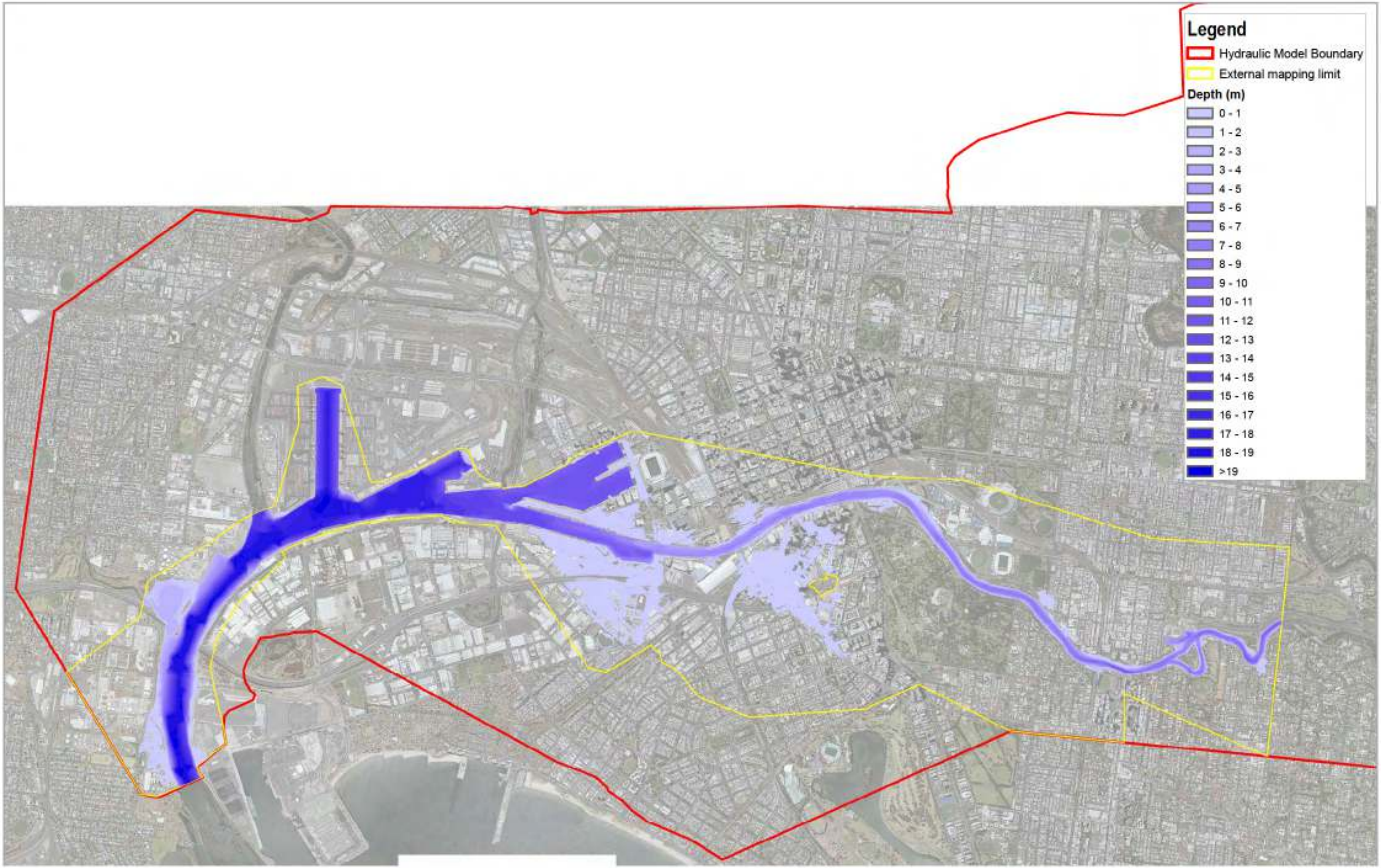
N

Melbourne Water
Lower Yarra River Flood Mapping

Peak Depth
20y ARI (Base Case Scenario)

Project No. **31-35474**
Revision No. **0**
Date **31/08/2020**

Figure E24



This data should be read in conjunction with the latest revision of the document entitled "Lower Yarra River Flood Mapping" (Document No. 3135474-23531) and is subject to the assumptions and qualifications contained therein. If the report is yet to be released, these assumptions and qualifications must be confirmed by reference to GHD Pty Ltd.

Paper Size ISO A3

0 0.2 0.4 0.6 0.8

Kilometers

Map Projection: Transverse Mercator
Horizontal Datum: GDA 1994
Grid: GDA 1994 MGA Zone 55

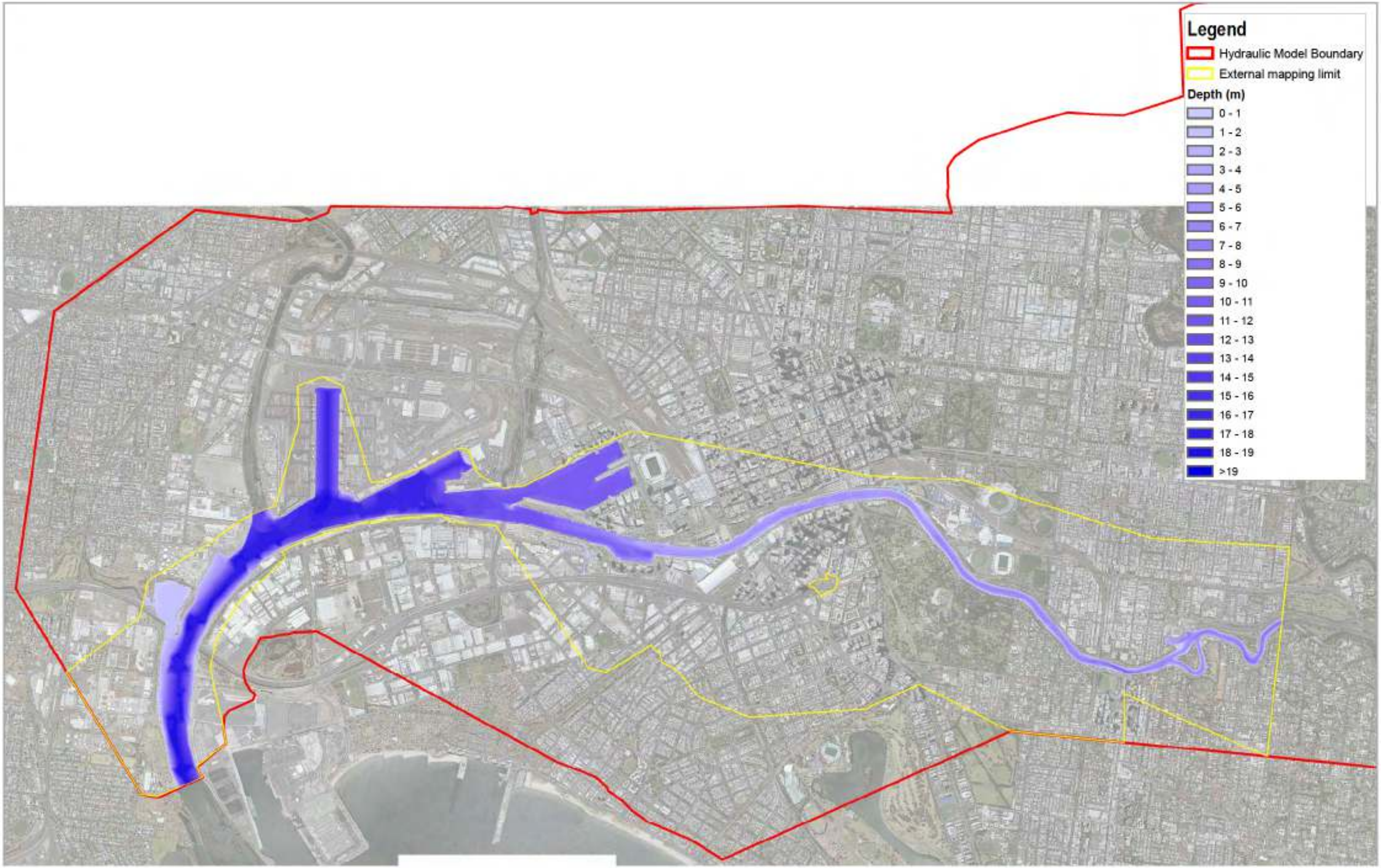
N

Melbourne Water
Lower Yarra River Flood Mapping

Peak Depth
20y ARI (Climate Change 2 Scenario)

Project No. 31-35474
Revision No. 0
Date 31/08/2020

Figure E25



Paper Size ISO A3
0 0.2 0.4 0.6 0.8
Kilometres

Map Projection: Transverse Mercator
Horizontal Datum: GDA 1994
Grid: GDA 1994 MGA Zone 55

N

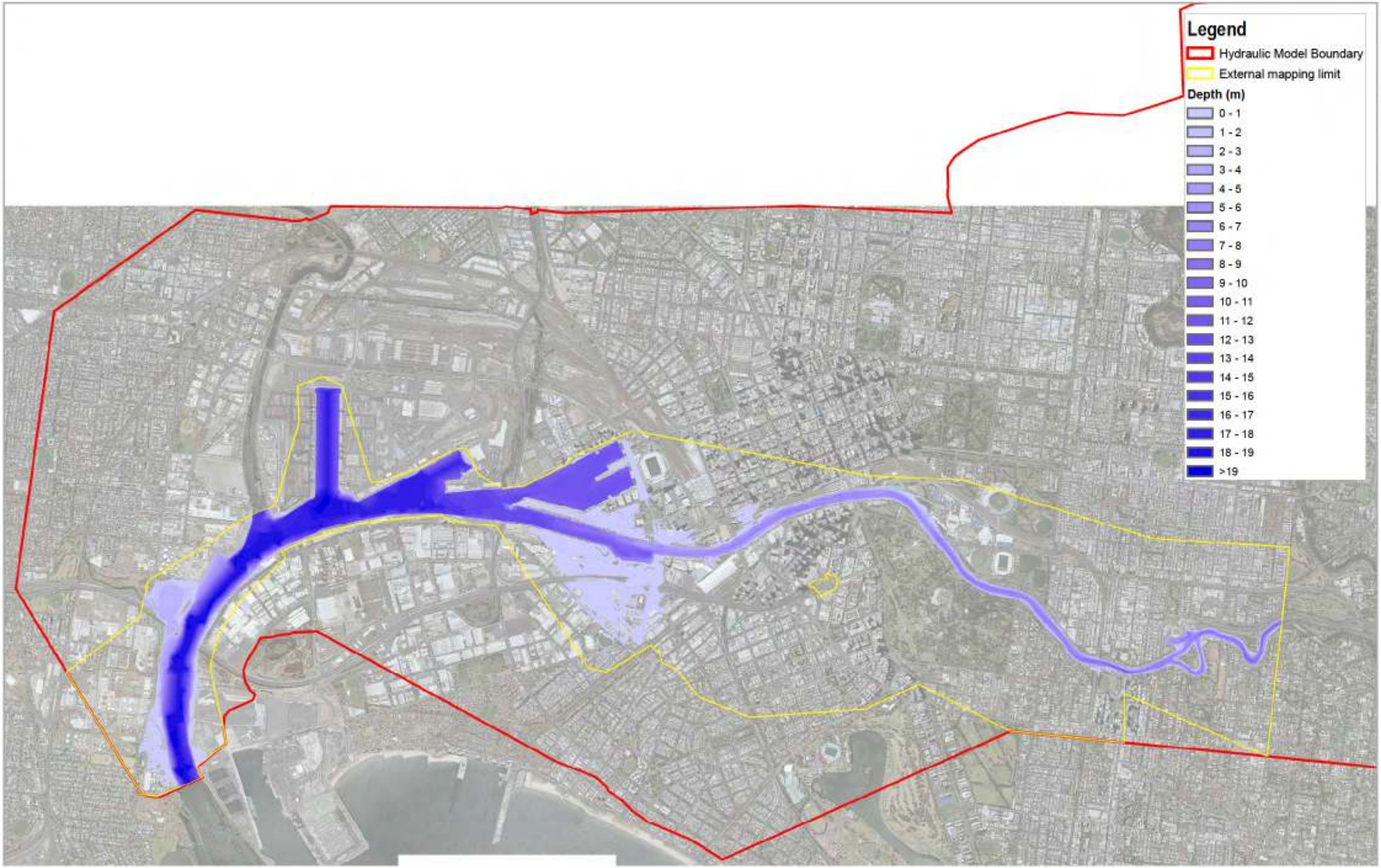
GHD

Melbourne Water
Lower Yarra River Flood Mapping

Peak Depth
10y ARI (Base Case Scenario)

Project No. **31-35474**
Revision No. **0**
Date **31/08/2020**

Figure E26



This data should be read in conjunction with the latest revision of the document entitled "Lower Yarra River Flood Mapping" (Document No. 3135474-23531) and is subject to the assumptions and qualifications contained therein. If the report is yet to be released, these assumptions and qualifications must be confirmed by reference to GHD Pty Ltd.

Paper Size ISO A3
0 0.2 0.4 0.6 0.8
Kilometres

Map Projection: Transverse Mercator
Horizontal Datum: GDA 1994
Grid: GDA 1994 MGA Zone 55

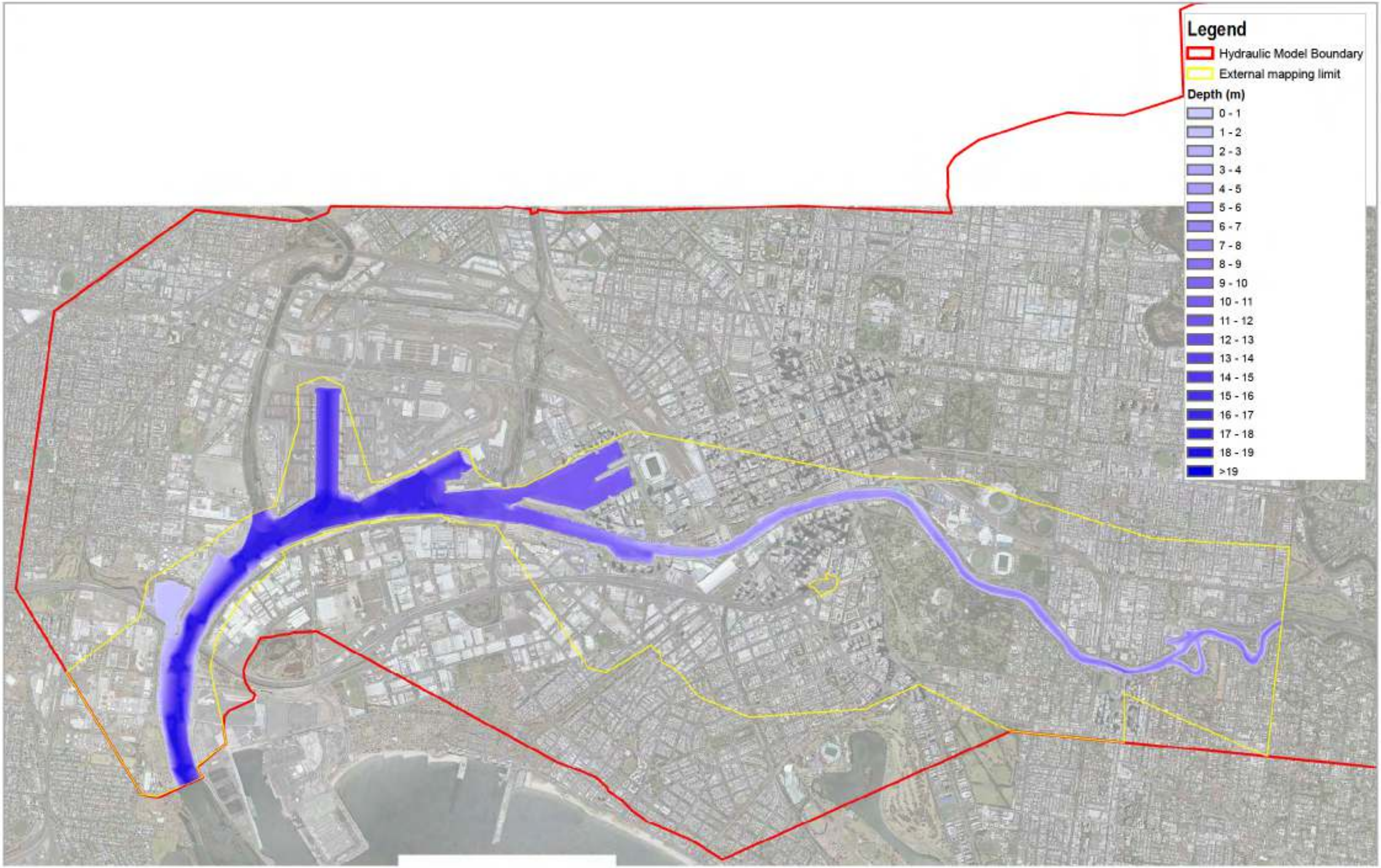
N

Melbourne Water
Lower Yarra River Flood Mapping

Peak Depth
10y ARI (Climate Change 2 Scenario)

Project No. 31-35474
Revision No. 0
Date 31/08/2020

Figure E27



Melbourne Water
Lower Yarra River Flood Mapping

Peak Depth
10y ARI (Climate Change 3 Scenario)

Project No. 31-35474
Revision No. 0
Date 31/08/2020

Figure E28

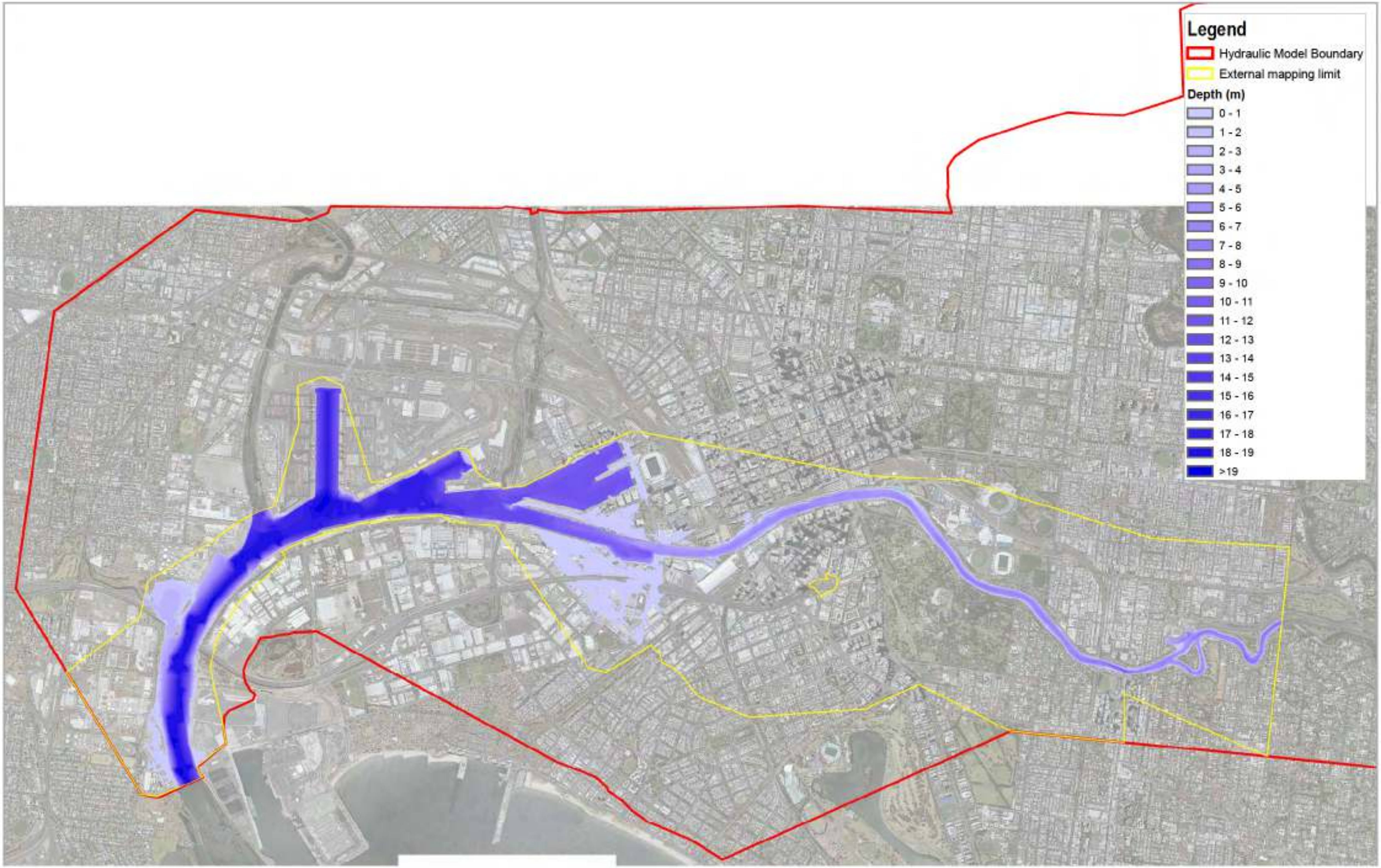
This data should be read in conjunction with the latest revision of the document entitled "Lower Yarra River Flood Mapping" (Document No. 3135474-23531) and is subject to the assumptions and qualifications contained therein. If the report is yet to be released, these assumptions and qualifications must be confirmed by reference to GHD Pty Ltd.

Melbourne Water
Lower Yarra River Flood Mapping

Peak Depth
5y ARI (Base Case Scenario)

Project No. 31-35474
Revision No. 0
Date 31/08/2020

Figure E29



This data should be read in conjunction with the latest revision of the document entitled "Lower Yarra River Flood Mapping" (Document No. 3135474-23531) and is subject to the assumptions and qualifications contained therein. If the report is yet to be released, these assumptions and qualifications must be confirmed by reference to GHD Pty Ltd.

Paper Size ISO A3
0 0.2 0.4 0.6 0.8
Kilometers

Map Projection: Transverse Mercator
Horizontal Datum: GDA 1994
Grid: GDA 1994 MGA Zone 55

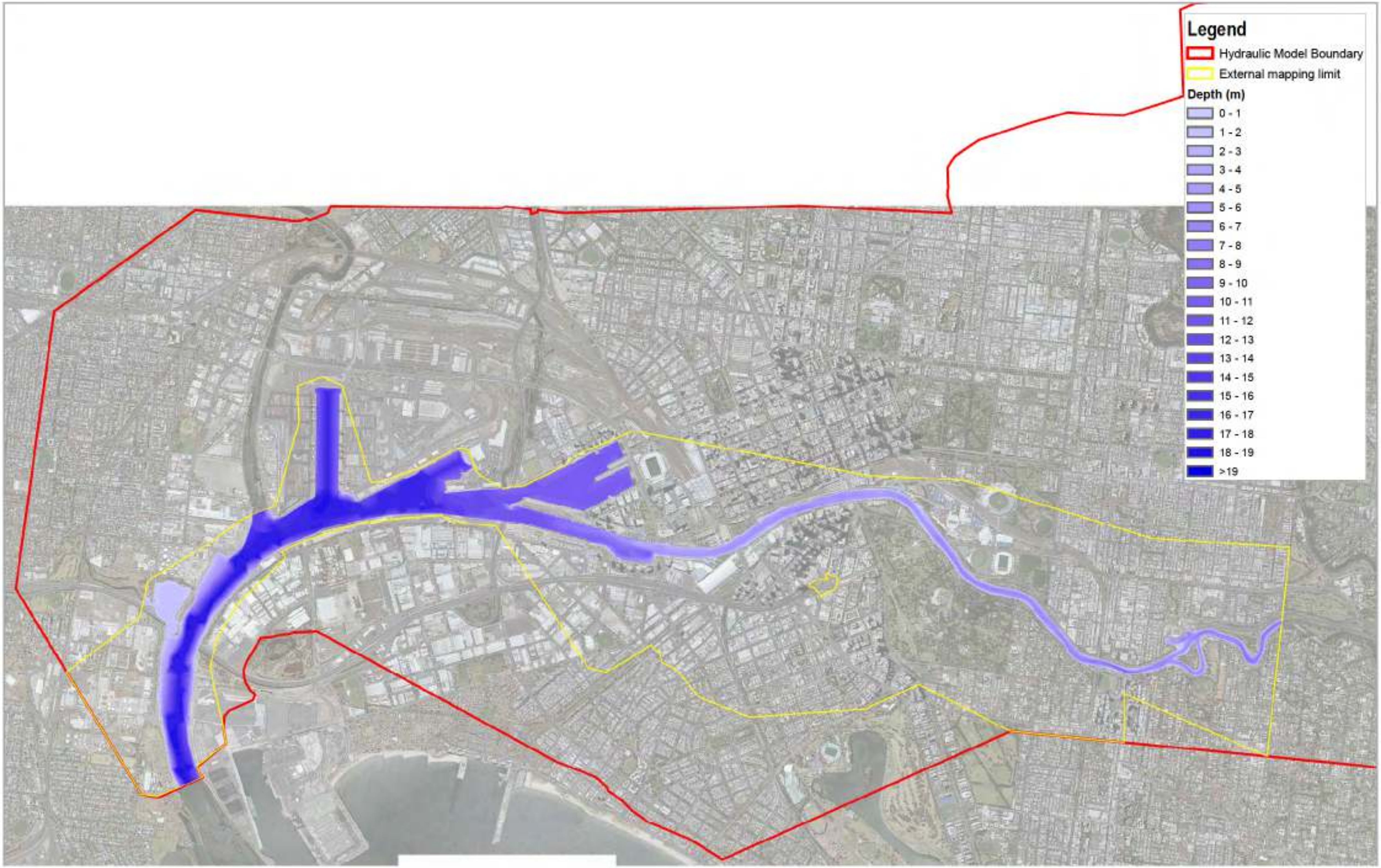
N

Melbourne Water
Lower Yarra River Flood Mapping

Peak Depth
5y ARI (Climate Change 2 Scenario)

Project No. **31-35474**
Revision No. **0**
Date **31/08/2020**

Figure E30



This data should be read in conjunction with the latest revision of the document entitled "Lower Yarra River Flood Mapping" (Document No. 3135474-23531) and is subject to the assumptions and qualifications contained therein. If the report is yet to be released, these assumptions and qualifications must be confirmed by reference to GHD Pty Ltd.

Map Projection: Transverse Mercator
Horizontal Datum: GDA 1994
Grid: GDA 1994 MGA Zone 55

Melbourne Water
Lower Yarra River Flood Mapping

Peak Depth
5y ARI (Climate Change 3 Scenario)

Project No. 31-35474
Revision No. 0
Date 31/08/2020

Figure E31

GHD

Level 18 180 Lonsdale Street
Melbourne VIC 3000
T: 61 3 8687 8000 F: 61 3 8687 8522 E: melmail@ghd.com

3135474-33979-22/https://projects.ghd.com/oc/Victoria/loweryarrariverflood/Delivery/Documents/3135474-REP-1-Lower Yarra River Flood Mapping Report.docx

Document Status

Revision	Author	Reviewer		Approved for Issue		
		Name	Signature	Name	Signature	Date
1	P.Woodman	G.Hay	Graeme Hay	G.Hay	Graeme Hay	01/09/2020

www.ghd.com