Hawkesbury-Nepean River Flood Study

Flood Study Report

Final Report

NSW Reconstruction Authority | RR-01-1297 | May 2024

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Cover image – View across South Creek, 26 March 2021

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Acknowledgement of Country

The NSW Reconstruction Authority, Rhelm and Catchment Simulation Solutions acknowledge the Traditional Custodians of the lands where we work and live. We celebrate the diversity of Aboriginal peoples and their ongoing cultures and connections to the lands and waters of NSW.

We pay our respects to Elders past, present and emerging and acknowledge the Aboriginal and Torres Strait Islander people that contributed to the development of this report.

We advise this resource may contain images, or names of deceased persons in photographs or historical content.

Note

In July 2023, the Hawkesbury-Nepean Valley Flood Risk Management Directorate transitioned from Infrastructure NSW (INSW) to the NSW Reconstruction Authority (RA). Any references to INSW should be read as referring to RA.

Executive Summary

Objectives

The Hawkesbury-Nepean Valley has one of the most significant flood risk exposures in NSW[1]. Having up-to-date technical information is essential for community safety, evacuation and emergency management, and land use and infrastructure planning.

To provide contemporary flood information, the NSW Government, through the Hawkesbury-Nepean Valley Flood Risk Management Directorate, commissioned Rhelm Pty Ltd and Catchment Simulation Solutions Pty Ltd, with input from WMAwater Pty Ltd and Baird, to develop the **Hawkesbury-Nepean River Flood Study** (described here as the **2024 Flood Study**). It builds on the foundations laid by the Hawkesbury-Nepean Valley Regional Flood Study (or 2019 Flood Study).

The 2024 Flood Study uses best practice and the latest technology in flood estimation to define flood behaviour along the Hawkesbury-Nepean River and its large floodplain located in Sydney's west and north. The study area extends from Bents Basin near Wallacia to Brooklyn, intersecting 8 local government areas: Penrith, Hawkesbury, Blacktown, The Hills, Central Coast, Hornsby, Liverpool and Wollondilly.

The key objective of the Hawkesbury-Nepean River Flood Study is to improve the understanding of flood behaviour and better inform management of flood risk in the study area, considering available information, together with the relevant standards and guidelines.

This report summarises the outcomes of the 2024 Flood Study. The extensive work undertaken to develop the study is detailed in 12 Technical Volumes.

Approach & Methodology

The following steps were taken:

a) Compiling and reviewing all available flood-related information
b) Updating and refining a hydrologic model to reflect contemporary catchment conditions
c) Developing a new, detailed 2-dimensional hydraulic flood model of the Hawkesbury-Nepean River, major tributaries and adjoining floodplain areas
d) Calibrating and validating the hydrologic and hydraulic computer models against information from 11 historical floods, including the 2020, 2021 and 2022 flood events
e) Updating the Monte Carlo model framework described in the 2019 Flood Study to reflect learnings from the 2-dimensional hydraulic flood model and the recent floods
f) Using the calibrated models to simulate flood behaviour for a range of design floods up to and including the probable maximum flood (PMF)
g) Completing various sensitivity and climate change simulations to gain an understanding of how modelling uncertainty and climate change may impact on the results produced by the models.

Further details on the modelling approach are provided in Section 3.

[1] *Taskforce Options Assessment Report* (INSW, 2019)

Outputs

Design flood modelling was undertaken for 12 flood likelihoods/sizes, from frequent/small to extreme: the 1 in 2, 5, 10, 20, 50, 100, 200, 500, 1000, 2000 and 5000 annual exceedance probability (AEP) floods, as well as the PMF. The hydraulic model simulations produced continuous surfaces of flood information for each design flood. The outputs from each of the design flood simulations were processed and provided in a variety of formats including maps (presented in a separate Map Book) and geographic information system (GIS) data. The outputs from this study include:

- Peak flood levels, depths and velocities
- Flood extents
- Flood hazard categories
- Flood function categories
- Information to support emergency services and evacuation.

In addition to the existing climatic conditions, an assessment was also undertaken on the potential influence of climate change, as well as influence of potential changes to the catchment through development.

The design flood levels produced by this 2024 Flood Study have changed in some locations relative to the 2019 Flood Study and earlier investigations. This is most evident in very large floods (i.e., larger than the 1 in 100 AEP flood), where the new hydraulic model provides a more detailed representation of the storage and conveyance across the river system including a better representation of hydraulic losses during high flow events around the tight bends in the lower river.

Further details on the flood study outputs are provided in Section 4.

Flood Behaviour

Flood extents across the study area are shown in Figure i, and the range of flood depths is shown for 4 locations in Figure ii. Flood behaviour varies throughout this large area, and is considered across 4 distinctive floodplains: Wallacia, Penrith, Windsor/South Creek, and the Lower Hawkesbury. Flood behaviour in these areas is summarised below:

- Wallacia: During frequent floods, flood behaviour at Wallacia is largely controlled by the gorge downstream of Wallacia Weir. During large floods, backwater effects from the Warragamba River further reduce the ability of water to drain from the floodplain located upstream of Wallacia Weir. The combined impact of the gorge and Warragamba River produces a very large flood range, with peak PMF levels being more than 22 metres higher than the 1 in 100 AEP levels (see Figure ii).
- Penrith: Flooding at Penrith is largely driven by the peak flow along the river rather than the volume of flow. For floods up to the 1 in 50 AEP, floodwaters are largely contained in the Nepean River channel. Breakouts from the river through Emu Plains and the Peach Tree Creek floodplain commence in the 1 in 100 AEP event. Changes in vegetation along the river and floodplain downstream of Penrith have had a notable impact on design flood levels relative to previous flooding investigations.
- Windsor: Flooding at Windsor is largely driven by the volume of runoff rather than the peak flow. Extensive inundation is predicted in the vicinity of Windsor (including backwater inundation of South and Eastern creeks) and is strongly correlated to the capacity of the incised gorge downstream of Windsor. Once the outflow capacity of the gorge is exceeded the excess water “ponds” across

the Windsor basin resulting in significant water depths across a large area. In rare to extreme floods, this pushes floodwater to great depths, with peak PMF levels being more than 13 metres higher than the 1 in 100 AEP levels (see Figure ii).

- Lower Hawkesbury: The Lower Hawkesbury River is contained within a narrow, sandstone gorge along much of its length. This results in flood extents that are commonly confined near the main river channel, with high flood depths and velocities, although notable backwater inundation is predicted along tributaries draining into the river. Flooding downstream of Lower Portland is strongly influenced by the magnitude and timing of flow from the Colo River. Flooding of the lower reaches towards Brooklyn is influenced by coastal flooding processes.

Further details about flood behaviour are provided in Section 5.

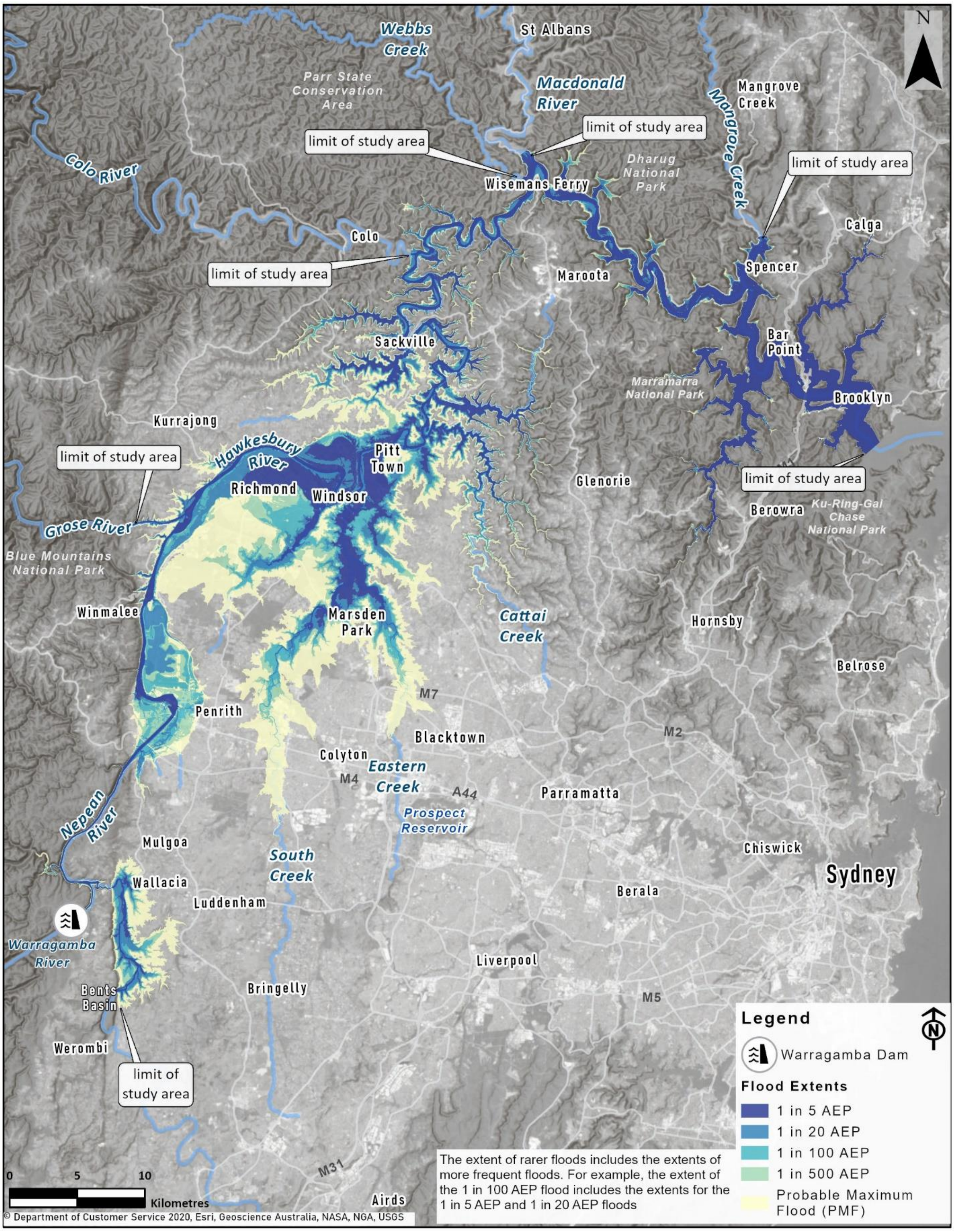

Figure i. Overview of Flood Extents

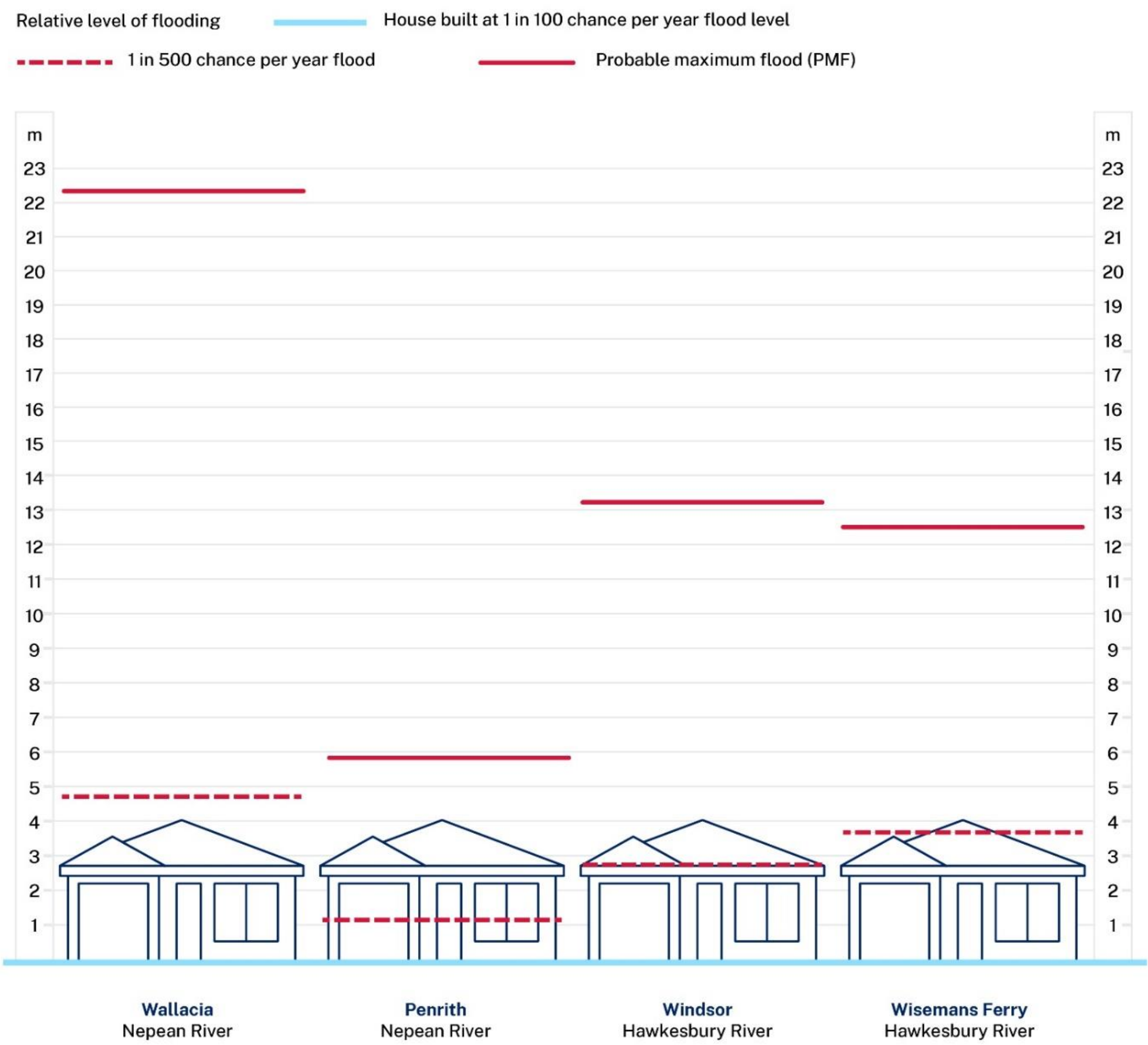

Figure ii. Flood depths in rare to extreme floods across the Hawkesbury-Nepean floodplain (source: NSW Reconstruction Authority)

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Acronyms

1D	One Dimensional
2D	Two Dimensional
AEP	Annual Exceedance Probability
AHD	Australian Height Datum
ARI	Average Recurrence Interval
ARF	Areal Reduction Factor
ARR	Australian Rainfall and Runoff
ARR87	Australian Rainfall and Runoff (Pilgrim et al, 1987)
ARR2019	Australian Rainfall and Runoff (Ball et al, 2019)
AWRC	Australian Water Resources Council
BoM	Bureau of Meteorology
DCCEEW	Department of Climate Change, Energy, the Environment and Water
DCP	Development Control Plan
DEM	Digital Elevation Model
DPE	Department of Planning and Environment
DPHI	Department of Planning, Housing and Infrastructure
IFD	Intensity Frequency Duration
FFA	Flood Frequency Assessment
FPL	Flood Planning Level
FRMP	Floodplain Risk Management Plan
FRMS	Floodplain Risk Management Study
FPRMSP	Floodplain Risk Management Study & Plan
GH	Gauge Height
HPC	Highly Parallelised Computer
ha	hectare
km	kilometres
km^2	Square kilometres
LEP	Local Environmental Plan
LGA	Local Government Area
LiDAR	Light Detection and Ranging
m	metre
m^2	Square metres
m^3	Cubic metres

mAHD	metres to Australian Height Datum
mm	millimetres
m/s	metres per second
m^3/s	cubic metres per second
ML	Megalitres
NSW	New South Wales
OSD	On-site Stormwater Detention
PMF	Probable Maximum Flood
PMP	Probable Maximum Precipitation
RA	NSW Reconstruction Authority
RL	Reduced Level
SES	State Emergency Service (NSW)
SRTM	Shuttle Radar Topography Mission
SGS	Sub Grid Sampling
SWC	Sydney Water Corporation
TUFLOW	Two-dimensional Unsteady FLOW
WBNM	Watershed Bounded Network Model

1 Introduction

1.1 Hawkesbury-Nepean Flood Strategy

The former NSW Government's *Resilient Valley, Resilient Communities: Hawkesbury–Nepean Valley Flood Risk Management Strategy* (2017) identified high flood risks in the Hawkesbury-Nepean Valley and recognised there is no simple solution to managing or reducing this risk. The NSW Government is building on the strategy to deliver a high-priority regional Disaster Adaptation Plan focused on managing flood risk, together with local councils, businesses and the community. The plan will be aligned with the State Emergency Management Plan and the National Strategy for Disaster Resilience to ensure the considerable flood risk across the Valley is appropriately managed. This includes the need for access to contemporary flood risk information.

The first stage of providing this information was through the Hawkesbury-Nepean Valley Regional Flood Study (2019 Flood Study) (WMAwater, 2019). The 2019 Flood Study used a fast-running, 1-dimensional hydraulic model[2] to simulate thousands of floods, to help understand the variability of flooding in the Valley.

A peer review of the 2019 Flood Study confirmed that, as part of the continuous improvement of providing contemporary flood risk information and to better assist land use and emergency response planning, a fully 2-dimensional model should be developed. Therefore, the second stage involved preparation of the Hawkesbury-Nepean River Flood Study (2024 Flood Study), which is the subject of this report. It builds on the 2019 Flood Study, taking advantage of modern, fully 2-dimensional flood modelling technology to further improve the understanding of flooding across the Hawkesbury-Nepean Valley and assist in better understanding the flood risk across the floodplain.

1.2 Study Area

The 2024 Flood Study accounts for flows from the entire 21,400 km^2 Hawkesbury-Nepean catchment, providing detailed flood information for the 190-km length of the Hawkesbury-Nepean River from Bents Basin near Wallacia through to Brooklyn, including backwater flooding up tributaries such as South and Eastern creeks. The study area falls mainly within the Penrith, Hawkesbury, Blacktown and The Hills Local Government Areas (LGAs) in western Sydney. Other LGAs impacted by flooding are Wollondilly, Liverpool, Hornsby and Central Coast (see Figure 1-1).

[2] Because the HNV 1-dimensional model includes some branches in the network, it is also described as a quasi-2-dimensional model.

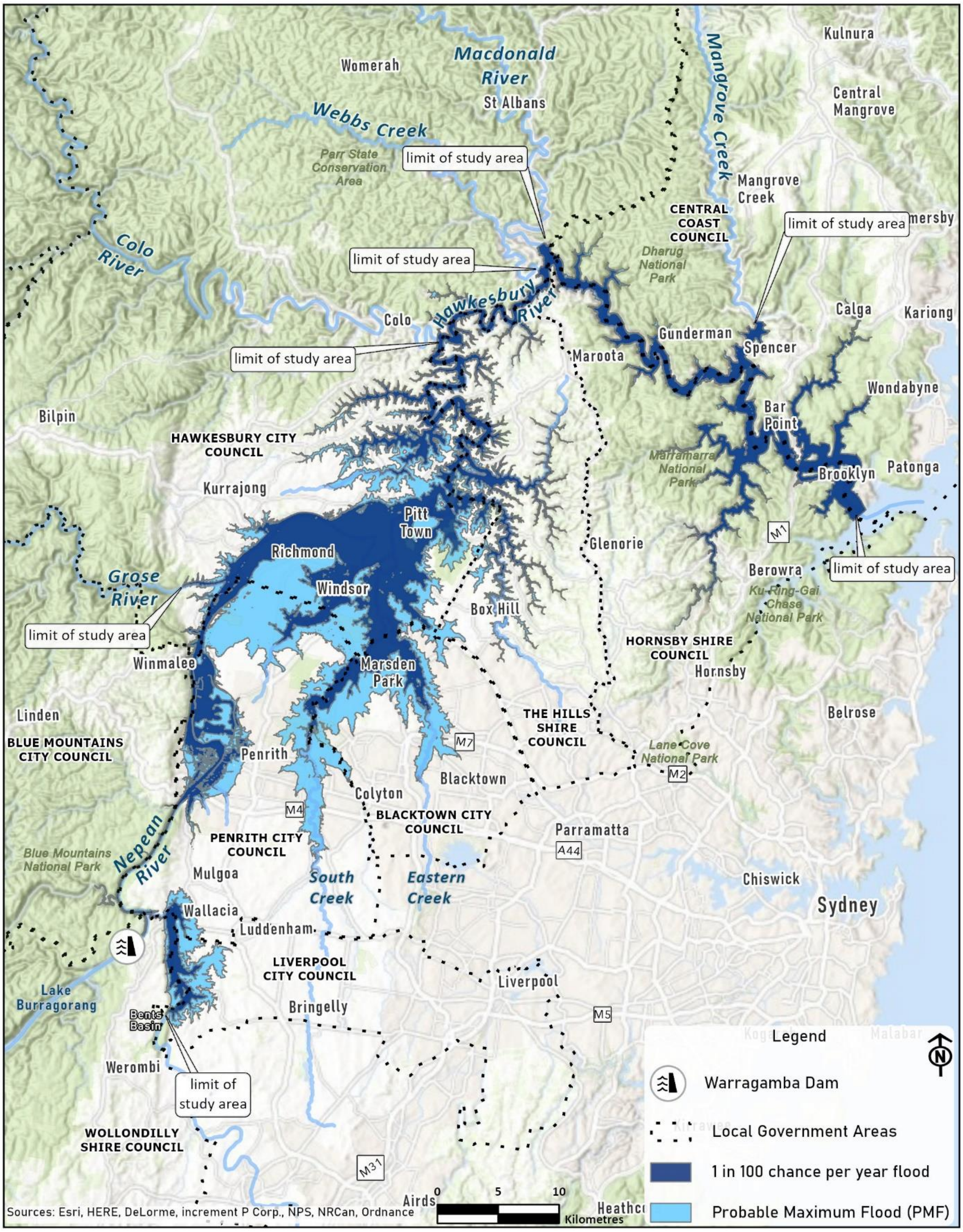


Figure 1-1. Study Area (source : NSW Reconstruction Authority)

1.3 Overview of Approach

The overall objective of the flood study was to provide a detailed understanding of flood behaviour along the Hawkesbury and Nepean rivers for contemporary floodplain conditions while assessing the potential future variations in flood behaviour associated with climate change. To achieve this overarching objective, the study was broken down into several stages, which are summarised below:

1. Collation and review of available data
2. Refinement and calibration of a WBNM hydrologic model
3. Development and calibration of a new 2-dimensional TUFLOW hydraulic model
4. Catchment/ocean level joint probability analysis
5. Lower Hawkesbury analysis
6. Wallacia flood frequency analysis
7. Monte Carlo analysis
8. March 2021 flood validation
9. March 2022 flood validation
10. July 2022 flood validation
11. Design flood modelling
12. Probable maximum flood (PMF) modelling.

The project was completed in accordance with modern best practice for flood estimation and flood risk management. This was largely informed by:

- 'Flood Risk Management Manual: the policy and manual for the management of flood liable land' (NSW Government, 2023)
- 'Australian Rainfall and Runoff: A guide to flood estimation' (Ball et al, 2019) and its associated revision project reports, most notably 'Project 15: Two Dimensional Modelling in Urban and Rural Floodplains' (Engineers Australia, 2012)
- 'Managing the Floodplain: a guide to best practice in flood risk management in Australia' (Australian Institute for Disaster Resilience, 2017).

In addition, guidelines and reports published by the NSW Department of Climate Change, Energy, Environment and Water (DCCEEW), Australian Institute for Disaster Resilience, and Intergovernmental Panel on Climate Change were also used as part of the project.

Further detailed information on the work completed as part of each stage of the project is contained in Technical Volumes, which are discussed further in Section 1.5.

1.4 Scope of this Report

This report serves as the main report for the Hawkesbury-Nepean River Flood Study. It provides a summary of the work completed as part of each stage of the project. This includes:

- Section 2 – Background : provides an overview of the study area from Bents Basin near Wallacia to Brooklyn, including past flooding investigations.
- Section 3 – Flood Modelling Approach: Documents the overall modelling approach including the hydrologic and hydraulic model development and calibration, joint probability assessments and Monte Carlo analysis.

- Section 4 - Design Event Modelling: Summarises the design flood, sensitivity and climate change simulations and discusses how the results compare with previous flooding investigations. It also discusses the potential flood impacts of future development.
- Section 5 – Flood Behaviour: provides a detailed description of flood behaviour at key locations throughout the study area.
- Section 6 - Conclusions: Summarises the overall outcomes of the study.

1.5 Technical Volumes

The Hawkesbury-Nepean River Flood Study represents a significant body of work. As a result, the outcomes of each stage of the project have been broken down into a number of separate Technical Volumes, as summarised below.

- Technical Volume 1: Data Collection & Review
- Technical Volume 2: Hydrologic Model Refinement and Calibration
- Technical Volume 3: Hydraulic Model Development and Calibration
- Technical Volume 4: Catchment/Ocean Level Joint Probability Assessment
- Technical Volume 5: Lower Hawkesbury Analysis
- Technical Volume 6: Wallacia Flood Frequency Analysis
- Technical Volume 7: Monte Carlo Analysis
- Technical Volume 8: March 2021 Flood Event Validation
- Technical Volume 9: March 2022 Flood Event Validation
- Technical Volume 10: July 2022 Flood Event Validation
- Technical Volume 11: Design Flood Modelling
- Technical Volume 12: Probable Maximum Flood (PMF) Modelling

The Technical Volumes provide support of the methodology and results documented in this Flood Study Report. If further detailed information is required on any stage of work, the reader is referred to the appropriate Technical Volume.

This flood study report is also supported with a separate Map Book. The Map Book provides a comprehensive set of maps providing design flood results across a range of the events and is discussed further in Section 4.1.

1.6 Review Processes

1.6.1 Independent Technical Review

The draft Hawkesbury-Nepean River Flood Study was reviewed by Associate Professor Fiona Johnson from the Water Research Centre, UNSW Sydney, checking the validity and accuracy of the data, method and results. Emeritus Professor Colin Apelt from the University of Queensland also assessed the hydraulic modelling.

1.6.2 Technical Working Group

To ensure the technical objectives of the study were consistently achieved, each stage of work was overseen by a Technical Working Group (TWG). The TWG comprised key project stakeholders and included representatives from the following organisations:

- State Government:
  - Hawkesbury-Nepean Valley Flood Risk Management branch, NSW Reconstruction Authority (formerly within Infrastructure NSW) (chair)
  - Department of Climate Change, Energy, Environment and Water – Biodiversity, Conservation and Science Group (DCCEEW - BCS), formerly the Department of Planning and Environment – Environment and Heritage Group (DPE - EHG)
  - Department of Planning, Housing and Infrastructure – Resilience and Urban Sustainability Division (DPHI - RUS), formerly the Department of Planning and Environment – Resilience and Urban Sustainability Group (DPE - RUS)
  - NSW State Emergency Service (NSW SES)
- Local Government:
  - Blacktown City Council
  - Central Coast Council
  - Hawkesbury City Council
  - Hornsby Shire Council
  - Liverpool City Council
  - Penrith City Council
  - The Hills Shire Council
  - Wollondilly Shire Council
- Commonwealth Government:
  - Bureau of Meteorology.

Presentations and information were provided to the TWG to outline each stage of work, and key feedback and comments were incorporated into the study. Draft reports on hydrologic and hydraulic model development, as well as calibration and verification, were also provided for review and comment A total of 15 TWG meetings were completed over the course of development of the 2024 Flood Study.

Image source: Adam Hollingworth, 21 March 2021

2 Background

2.1 Hawkesbury-Nepean Catchment

2.1.1 Catchment Description

The Hawkesbury-Nepean River Catchment covers 21,400 square kilometres, including the Warragamba and Nepean catchments, extending as far as Goulburn, Lithgow and Bowral, and downstream to Broken Bay. It represents one of the largest coastal catchments in New South Wales. The extent of the catchment is shown in Figure 2-1.

An overview of the key sub-catchments that make up the overall Hawkesbury-Nepean River Catchment is provided in Figure 2-2. As shown in Figure 2-2, the major subcatchments and their contributing catchment areas include:

- Warragamba River: 9,050 km^2
- Colo River: 4,640 km^2
- Macdonald River: 1,900 km^2
- Nepean River: 1,760 km^2
- Grose River: 670 km^2
- South Creek: 640 km^2
- Mangrove Creek: 430 km^2
- Webbs Creek: 350 km^2
- Cattai Creek: 290 km^2

The catchment includes extensive grazing areas in the southwest and large national parks in the Blue Mountains to the west and northwest. Urban development includes a number of country towns (e.g., Goulburn, Bowral and Lithgow) as well as many outer Sydney suburbs including Penrith, Richmond, and Windsor. The focus of the Hawkesbury-Nepean River Flood Study is the section of the catchment within the Sydney Basin, including much of the urban growth areas of western and north-western Sydney.

Within the Sydney Basin, the Hawkesbury-Nepean Valley comprises a sequence of floodplains that are linked by incised sandstone gorges. The upstream most floodplain is located on the Nepean River near Camden which drains through a narrow gorge between Theresa Park and Bents Basin and discharges into a floodplain near Wallacia. Another sandstone gorge runs between Wallacia and Regentville. Part way along this gorge, the Warragamba River joins the Nepean River. Flows from the Warragamba River are highly influenced by Warragamba Dam, which is discussed further in Section 2.1.2.

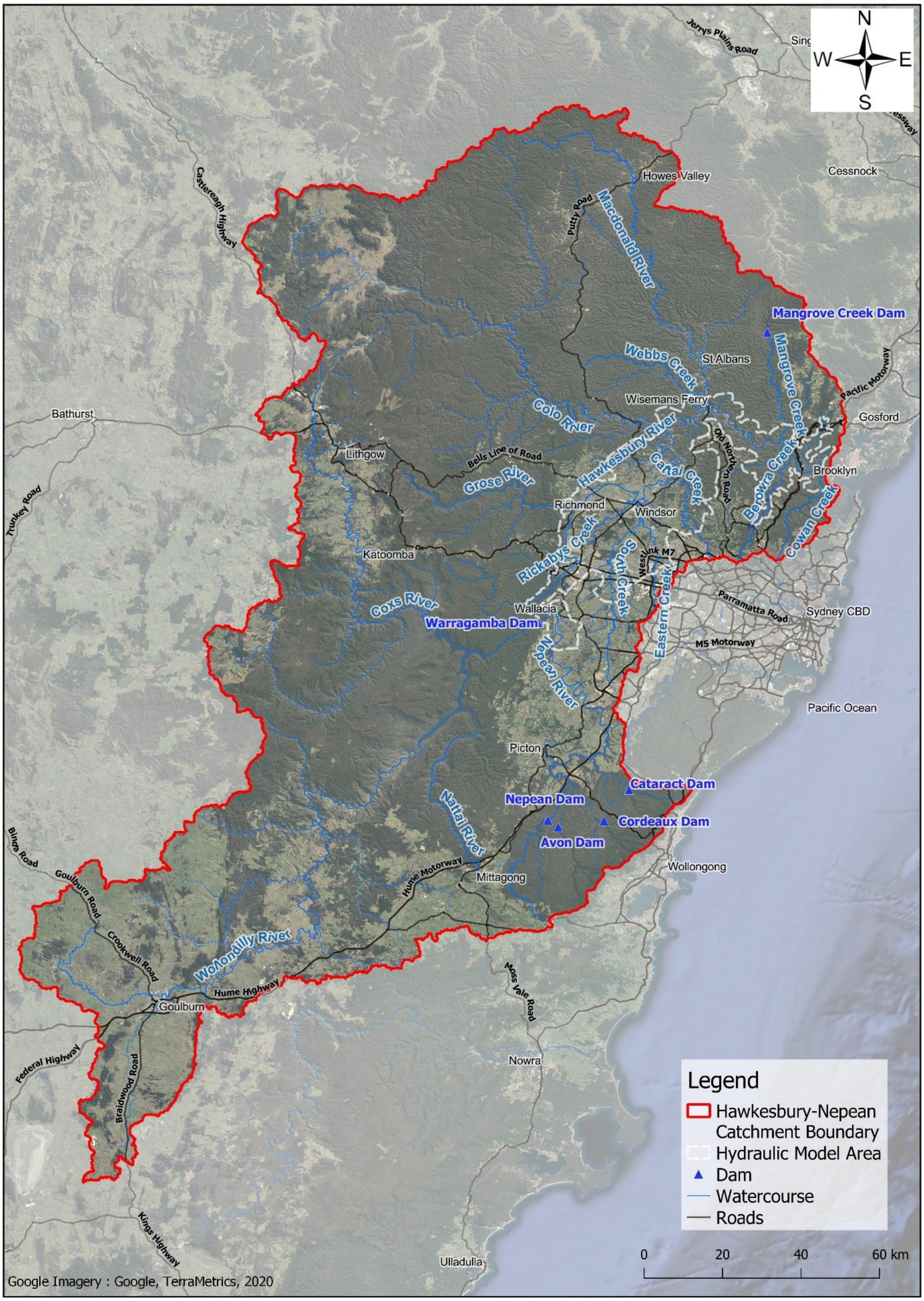
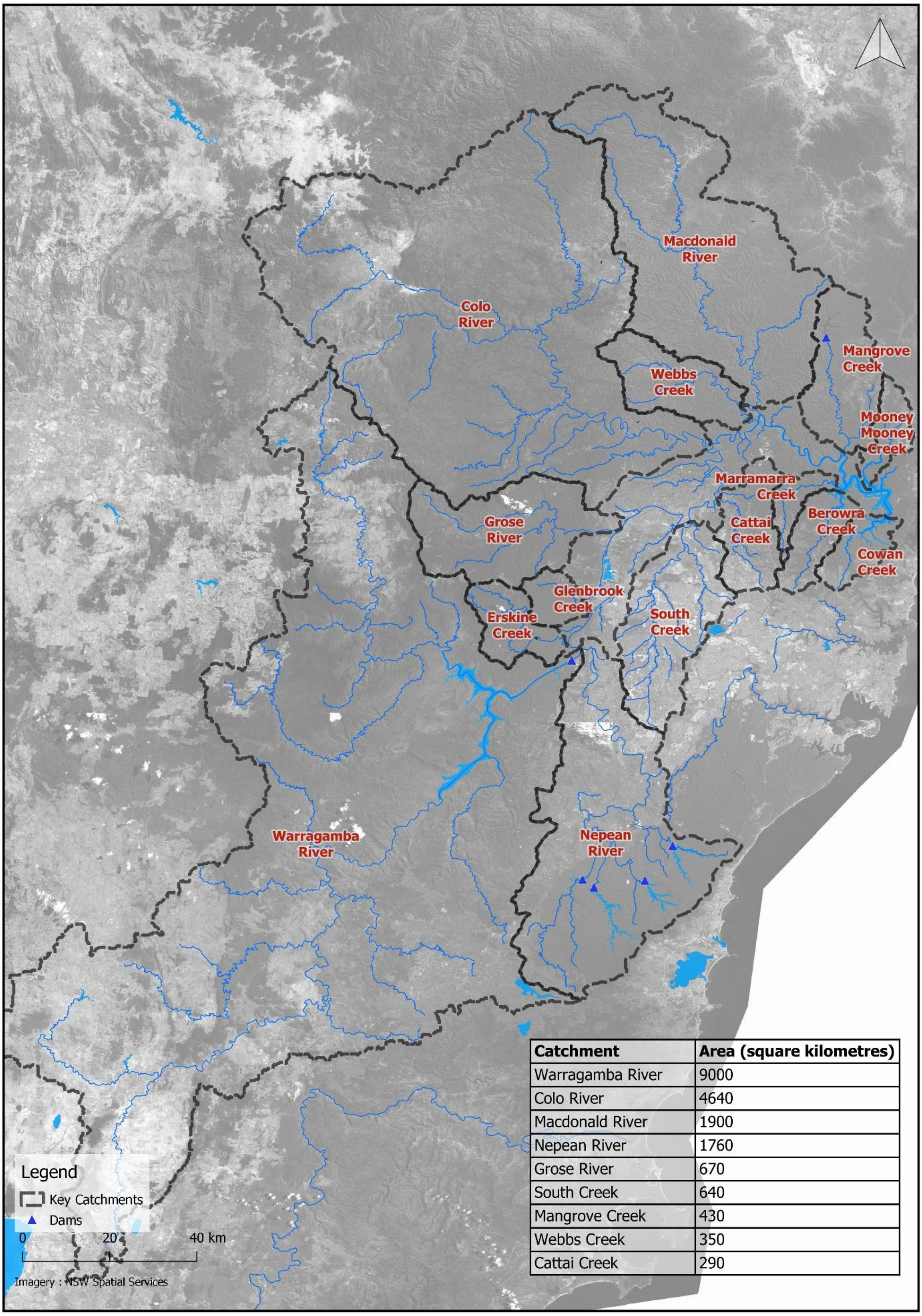


Figure 2-1. Hawkesbury-Nepean River Catchment



Catchment	Area (square kilometres)
Warragamba River	9000
Colo River	4640
Macdonald River	1900
Nepean River	1760
Grose River	670
South Creek	640
Mangrove Creek	430
Webbs Creek	350
Cattai Creek	290

Figure 2-2. Key Sub-Catchments

Downstream of Regentville, there is another floodplain that includes Penrith and Emu Plains which becomes constricted alongside Penrith Lakes/Castlereagh (although this constriction is not as significant as the other gorge areas with potential for water to break out from the river and into Penrith Lakes during medium and larger sized floods).

The Grose River joins the Nepean River near Yarramundi, forming the Hawkesbury River. This location also represents the start of the Richmond-Windsor floodplain which is the most substantial floodplain in the Hawkesbury-Nepean Valley extending from near North Richmond downstream towards Sackville. The area between Sackville and Brooklyn comprises another incised sandstone gorge with many sinuous river bends that stretch for over 100 kilometres before the river discharges into Broken Bay. This is highlighted by the digital terrain model shown in Figure 2-3.

As a result of this topography, major floods are characterised by significant inundation across the various floodplains. Significant water depths coupled with relatively low flow velocities are most typical across the floodplain areas. The gorges between floodplains are characterised by flooding that is confined near the main river, although flow velocities are much more significant. The water levels around Wallacia and Windsor are primarily determined by the flow volume entering the floodplain and the size of the downstream gorges which controls the release of floodwater from each floodplain (commonly referred to as the "bathtub effect"). The area around Penrith, by comparison, is driven more by the peak flow rather than the volume. A schematic view of the Hawkesbury-Nepean Valley and the associated gorges and floodplains/bathtubs is provided in Figure 2-4.

2.1.2 Warragamba Dam

Warragamba Dam is located about 65 kilometres west of Sydney in a narrow gorge on the Warragamba River. It represents the largest urban water supply in Australia and is one of the largest domestic water supply dams in the world (WaterNSW, 2022). Construction of Warragamba Dam commenced in 1948 and was completed in 1960. The dam wall is 142 metres high and holds back more than 2000 gigalitres of water (a volume 4 times larger than Sydney Harbour) (WaterNSW, 2022). The water body behind the dam wall is referred to as Lake Burragorang.

During the late 1980s, the dam wall was raised by 5 metres and strengthened to meet modern dam safety standards. In the early 2000s, an auxiliary spillway was installed to divert floodwaters around the dam wall in extreme floods, to protect the dam wall and ensure it remains safe during rare floods.

The Warragamba River represents the largest sub-catchment within the Hawkesbury-Nepean River catchment, comprising approximately 80% of the catchment draining to Penrith and 70% of the catchment draining to Windsor. Therefore, significant flows from Warragamba Dam have the greatest potential to impact on flooding along both the Nepean and Hawkesbury rivers.

During floods, there is an operational procedure (i.e., H14 Operational Protocol) for the various gates located near the top of the dam wall. The procedures are designed to manage the inflows and release of water from the dam during a flood.

It should be noted that Warragamba Dam was designed and is operated as a water supply dam and not a flood mitigation dam.

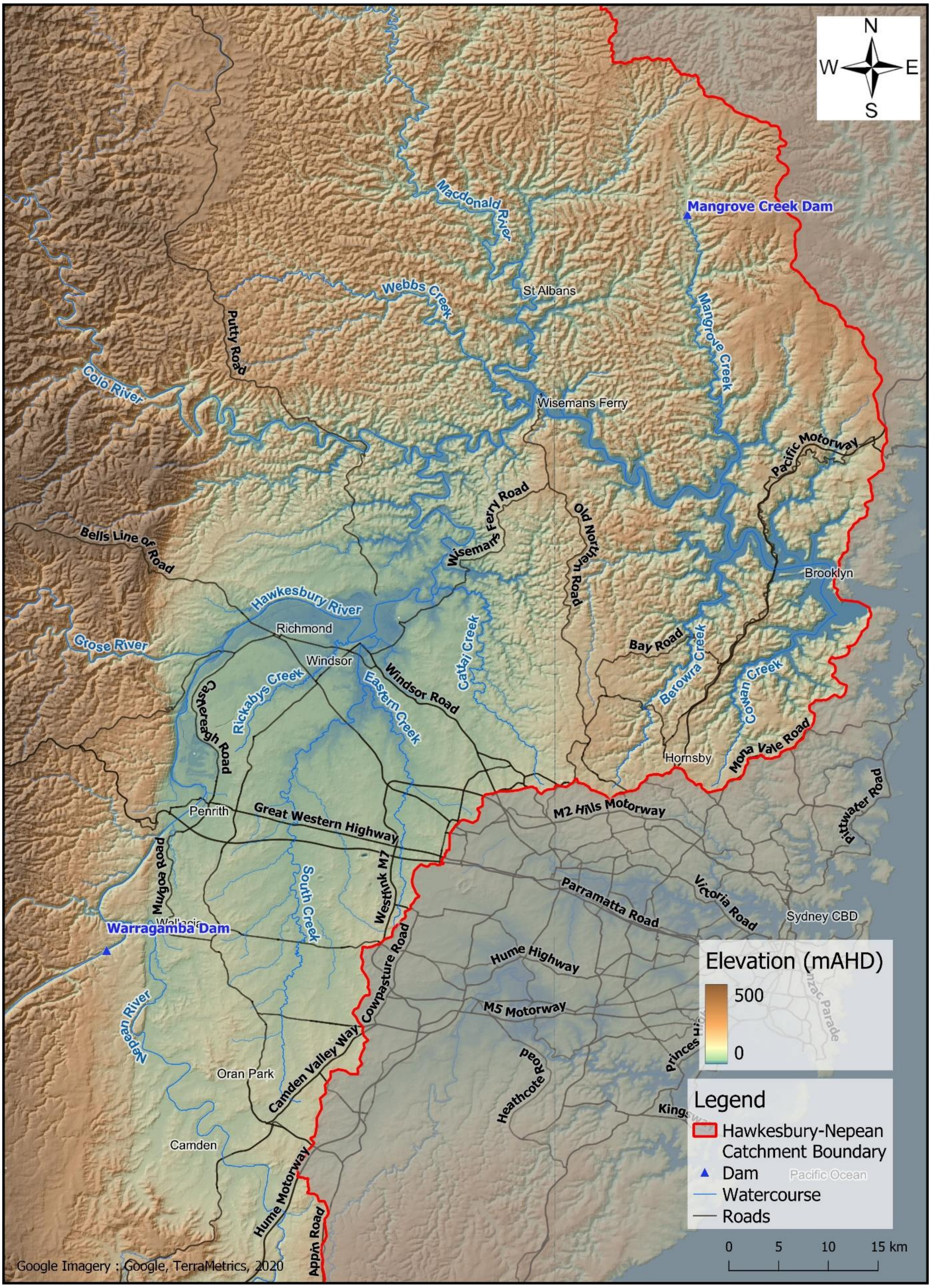


Figure 2-3. Variation in Terrain Across the Hawkesbury- Nepean Valley

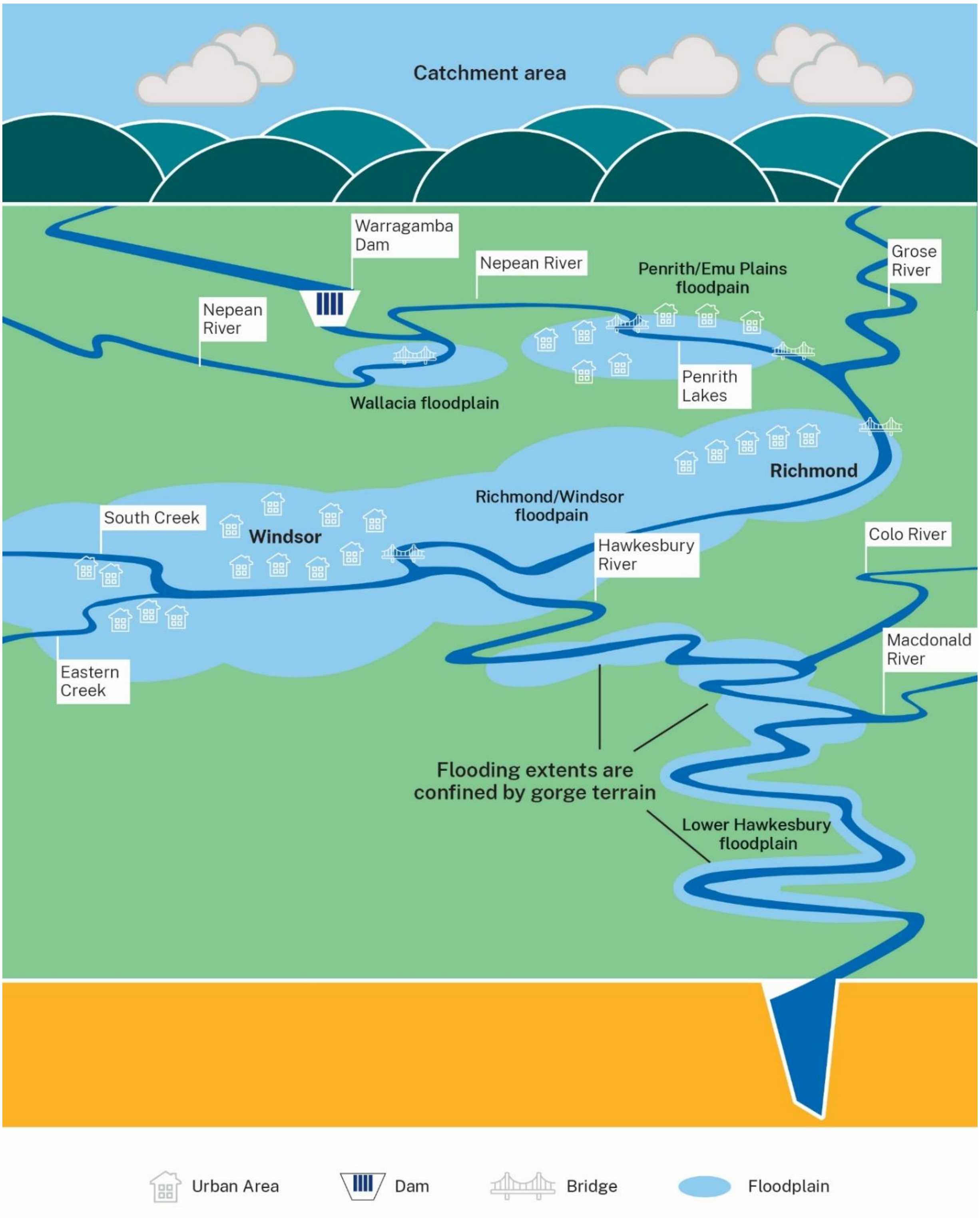


Figure 2-4. Schematic View Looking West Across the Hawkesbury- Nepean Valley Showing 'Bathtub' Effect (Source: NSW Reconstruction Authority)

2.1.3 Other Dams

The catchment incorporates several other water supply dams that are located within the Upper Nepean River catchment. This includes Nepean, Avon, Cordeaux and Cataract dams. The Wingecarribee Reservoir is located in the headwaters of the Wingecarribee River catchment which is a sub-catchment of the Warragamba River catchment. Key characteristics of each dam are summarised in Table 2-1.

Table 2-1. Properties of Major Dams in the Hawkesbury-Nepean River Catchment upstream of Penrith (WaterNSW, 2022)

Dam	Wall Height (m)	Storage Capacity (GL)	Catchment Size (km^2)
Avon	72	147	142
Cataract	56	97	130
Cordeaux	57	94	91
Nepean	82	68	320
Warragamba	142	2,027	9,051

As shown in Table 2-1, the catchments draining to each of these other dams is a small proportion of the overall Hawkesbury-Nepean catchment. As a result, the other dams have only a minor impact on flooding in areas downstream of Wallacia and Warragamba Dam.

Further downstream, Mangrove Creek Dam (188GL) is located in the upper Mangrove Creek catchment. With Mangrove Creek joining the Hawkesbury River at Spencer, this dam has a minor influence on flood behaviour in this lower part of the study area.

2.2 Terminology

Design floods are hypothetical floods that are commonly used for flood risk management investigations and are defined by their frequency or probability of occurrence. 'Australian Rainfall and Runoff: A Guide to Flood Estimation' (Ball et al., 2019) recommends that flood frequencies are expressed as an Annual Exceedance Probability (AEP). The AEP is the chance of a flood of a specific size being equalled or exceeded in any year and it can be expressed as a percentage or 1 in X. For example, the 1 in 100 AEP/1% AEP flood has a 1% (or 1 in 100) chance of being equalled or exceeded in any year. This report adopts the 1 in X AEP terminology for design floods ranging from the 1 in 2 AEP up to the 1 in 5000 AEP. A brief overview of the likelihood of different events, and the chance that they would be experienced in a typical lifetime, are summarised in Table 2-2.

The largest flood possible is called the probable maximum flood or PMF. It is an extremely rare and unlikely flood, however a number of historical floods in Australia have approached the scale of a PMF.

It should be noted that floods occur independently. Therefore, the occurrence of a large flood occurring in any 1 year does not alter the chance of an equivalent flood (or larger) occurring in subsequent years. This is evidenced by the occurrence of the February 2020, March 2021, March 2022 and July 2022 floods.

Table 2-2. Overview of Likelihood of Events

Likelihood	Chance of Occurring in Any Given Year AEP (%)	Chance of Occurring in Any Given Year AEP (1 in x)	Probability of Occurring at Least Once in an 80-year lifetime
Very High	20%	1 in 5	>99.9%
High	5%	1 in 20	98.3%
Medium	1%	1 in 100	55.3%
Low	0.2%	1 in 500	14.8%
Extremely Low	0.001%	1 in 100,000	< 0.1%

2.3 Flood History

The Hawkesbury-Nepean River (called Dyarubbin by First Nations people) has a long history of flooding. Documented reports of flooding date back to 1789 - the longest flood record in Australia. There have been over 130 moderate to major floods in that time (NSW Government, 2019). The largest flood in living memory at Windsor occurred in 1961 (14.95 mAHD peak flood level). The largest flood on record occurred in 1867 and reached a peak level of 19.7 mAHD at Windsor, 2.4m above the 1 in 100 chance per year flood on which the flood planning level is based.

First Nations people have lived along Dyarubbin for at least 50,000 years and have seen many floods. Reported oral traditions describe a flood at Windsor in around 1780 that was higher than the 1867 flood and swept away people taking refuge in tall trees. Geological evidence also points to flooding much higher than the 1867 flood, prior to European settlement (Saynor and Erskine, 1993).

Despite the random nature of flooding, the flood history of the Hawkesbury-Nepean River suggests flooding in the catchment can be cyclic. This includes periods of frequent and larger floods that can last for decades (including multiple floods within the same year). These can be followed by similar length periods of fewer and smaller floods. This pattern has been described as flood-dominated and drought-dominated regimes (Figure 2-5).

The most significant flood-dominated period extended from 1857 to 1900 and included nineteen floods that produced a peak level of at least 10 mAHD at Windsor, including the 1867 flood of record. This flood-dominated period was preceded by a drought-dominated period between 1820 and 1857 when no significant floods were recorded at Windsor.

It is not yet clear whether the cluster of floods from 2020 to 2022 marks the start of a new flood-dominated regime.

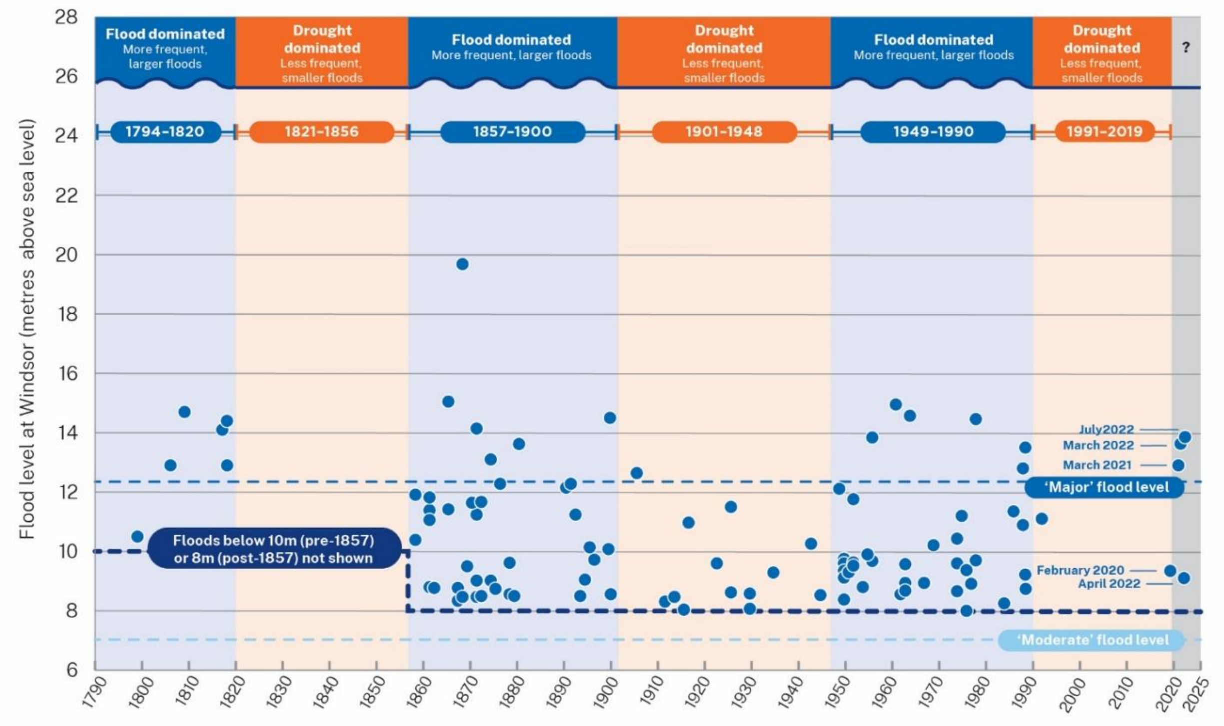


Figure 2-5. Hawkesbury River Floods at Windsor - 1791 to 2023

2.4 Previous Studies

A number of flooding investigations have been prepared in an effort to better understand the flood risk along different sections of the Hawkesbury-Nepean River system. Included below is a list of the most contemporary flooding investigations for the study area.

- Upper Nepean River Flood Study (DLWC, 1995) – relevant to the Wallacia floodplain
- Nepean River Flood Study (Advisian, 2018) – relevant to the Penrith floodplain
- Lower Hawkesbury River Flood Study (AWACS, 1997) – relevant to Sackville and downstream
- Hawkesbury-Nepean Valley Regional Flood Study (WMAwater, 2019) (2019 Flood Study).

2.4.1 Upper Nepean River Flood Studies

The Upper Nepean River Flood Study (DLWC, 1995) developed a RORB hydrologic model and a MIKE-11 hydraulic model to define Nepean River flooding between Menangle and the Warragamba River junction, including the Wallacia floodplain. Flood frequency analysis informed the work. The hydraulic model was calibrated to historical floods in 1964, 1978 and 1988. Design flood behaviour was modelled for the 1 in 5, 20, 100 and 200 AEP events, plus the PMF.

The Nepean River Flood Study (Worley Parsons, 2015) provided updated design flood behaviour for the Nepean River within Camden LGA. However, while the hydraulic model extended down to the Warragamba River junction, the 2015 Flood Study did not appear to include flood inflows from the Warragamba River, and so its results for the Wallacia floodplain are not comparable to the design flood behaviour being investigated as part of the current study. The record of historical flood levels at Wallacia described in the 2015 Flood Study formed part of the dataset used for the Wallacia flood frequency analysis described in **Technical Volume 6** of the current study.

2.4.2 Nepean River Flood Study (2018)

The Nepean River Flood Study (Advisian, 2018) developed an RMA-2 hydraulic model and used boundary conditions taken from an earlier version of the valley-wide RUBICON model to define Nepean River flooding between Glenbrook Creek and Yarramundi Bridge. The model was calibrated to historical floods in 1978, 1988 and 1990. Design flood behaviour was modelled for the 1 in 20, 50, 100, 200, 500, 1000 and 2000 AEP events, plus the PMF.

2.4.3 Lower Hawkesbury River Flood Study (1997)

The Lower Hawkesbury River Flood Study (AWACS, 1997) developed an RMA-2 hydraulic model and used adjusted inflows from an earlier version of the valley-wide RUBICON model to define Hawkesbury River flooding between Sackville and Broken Bay. The model was calibrated/verified to historical floods in 1978 and 1990. The joint probabilities of flooding from the Hawkesbury and Colo rivers, and of catchment flooding with ocean levels, were considered. Design flood behaviour was modelled for the 1 in 5, 20, 50 and 100 AEP events, plus the PMF.

2.4.4 HNV Regional Flood Study (2019)

The 2019 Flood Study represents the most recent flood study for the Hawkesbury-Nepean River in its entirety. It used a combination of a RORB model to define catchment hydrology and a quasi-2D RUBICON model to define flood hydraulics along the river and across the broader floodplain areas. This modelling system drew on earlier work that had been undertaken for the Warragamba Dam Auxiliary Spillway Environmental Impact Statement (Webb McKeown & Associates, 1996). This combination of fast-running models was particularly suited to the Monte Carlo methodology that was adopted as part of the 2019 Flood Study as it allowed for rapid assessment of the numerous parameters that fed into the Monte Carlo assessment. The Monte Carlo framework allowed an understanding of the variability of real floods across the large catchment, including key outputs such as rate-of-rise which is important for understanding evacuation constraints.

The 2019 Flood Study also provides information on flood levels throughout the study area; however, it has limited ability to provide fine scale (i.e. land parcel scale) descriptions of local flood behaviour, such as velocities and depths, across the large floodplain area. As a result, the 2019 Flood Study recommended that a fully 2-dimensional hydraulic model be developed for the next phase of flood modelling to provide a more detailed description of the spatial variation in flood hazard.

Image source: Adam Hollingworth, February 2020

3 Flood Modelling Approach

3.1 Overview

The Hawkesbury-Nepean River floodplain covered by this study is large and complex and is influenced by a range of hydrologic and hydraulic factors. To capture the variability of floods due to these various factors, a 'Monte Carlo' approach was used in the 2019 Regional Flood Study, which is considered to reflect best practice in flood estimation. This models flood variability by randomly combining the range of inputs that generate and influence flooding. This includes (WMAwater, 2019):

- rainfall intensity and frequency
- spatial pattern of rainfall
- temporal variation in rainfall
- pre-burst rainfall
- initial rainfall losses
- the timing of various tributary inflow
- tides
- water level in Warragamba Dam.

Using this approach, close to 20,000 possible flood events were simulated, which represents the range of floods that could be experienced over a 200,000-year period. As a result, the Monte Carlo approach provides the most rigorous means of deriving expected flood quantiles (Ball et al, 2019) while also providing a range of auxiliary information that is important for evaluating mitigation options and evacuation strategies (WMAwater, 2019).

This study builds on the Monte Carlo approach used in the 2019 Flood Study. Key advances are summarised below:

- A WBNM hydrologic model was updated and refined. The updated WBNM model was calibrated and was then incorporated into the Monte Carlo framework to improve the understanding of hydrologic processes for the catchment.
- A new, fully 2-dimensional (2D) hydraulic model of the study area was developed using the TUFLOW software and calibrated to observed floods. The 2D model provides greater resolution in flood behaviour across the floodplain relative to the 2019 Flood Study.
- The 1-dimensional (quasi-2-dimensional) RUBICON hydraulic model that was used for the 2019 Flood Study was refined to reflect learnings from the 2-dimensional flood modelling. This refined model was used to select a subset of the Monte runs referred to as "representative events" to represent floods of different frequencies (e.g. 1 in 100 AEP, 1 in 500 AEP etc), which are then run through the TUFLOW model.

- The Monte Carlo analysis was also refined as part of the current study to better understand flooding at key locations. This update was informed by joint probability analysis of flooding at Wallacia and the Lower Hawkesbury River, as well as ocean water levels.

A general overview of the modelling approach applied as part of the current study is provided in Figure 3-1. Further details of the modelling approach are included in Table 3-1, along with a summary of updates undertaken as a part of this study relative to the 2019 Flood Study. Further details and discussion on these models are provided in the following sections.

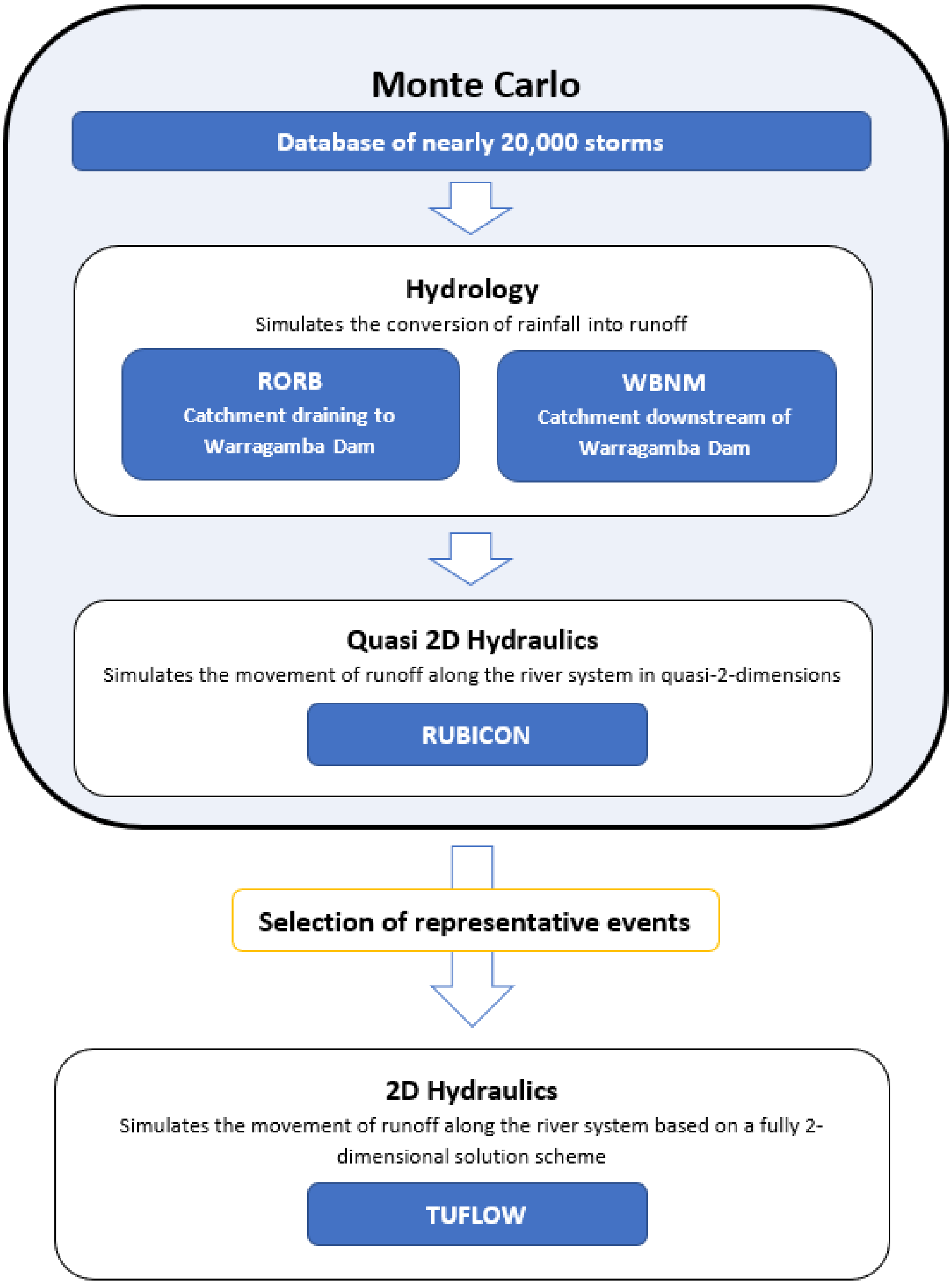


Figure 3-1. Conceptual Overview of Modelling Approach

Table 3-1. Summary of Modelling Approach and Key Updates

Model Component	Model Approach Summary	Key Updates and Refinements from 2019 Flood Study
Monte Carlo	The Monte Carlo model assesses flood variability by combining a range of hydrologic inputs that generate and influence flooding. The analysis uses the hydrologic and RUBICON hydraulic models to analyse nearly 20,000 different flood scenarios. The RUBICON model rather than the TUFLOW model is used for this analysis as it has significantly shorter computational model run times. Analysis of the RUBICON model allows for assessment of the different frequencies of flooding and identifies "representative" events for analysis in the TUFLOW model. These representative events are a short-list of events representing different frequencies from the Monte Carlo analysis (e.g., 1 in 100 AEP, 1 in 500 AEP etc).	Updates to the Monte Carlo assessment included an improved understanding of joint probability of flooding for the Nepean and Warragamba rivers (and the influence at Wallacia) as well as the Colo and Hawkesbury rivers. Analysis was undertaken of the ocean conditions that are likely to occur during a Hawkesbury-Nepean River flood. The recent flood events in 2021 and 2022, together with additional historic data collation, allowed for additional rainfall spatial patterns to be considered together with a validation of the model to flood frequency analysis at additional locations. Further details are provided in Section 3.6.
Hydrology	Hydrology is the study of how rainfall is converted into runoff from a catchment over time. It takes into account the rainfall (e.g., amount, timing and location) and ground conditions in the catchment. The RORB model developed and calibrated for the 2019 Flood Study was retained to describe the hydrology of the catchment draining to Warragamba Dam. A WBNM hydrologic model developed as part of the 'Hawkesbury Nepean Hydrologic Model Update' (WMAwater, 2018) was updated as part of the current study. It was used to describe the hydrology of catchments external to the Warragamba Dam catchment.	The WBNM hydrologic model was updated and refined for the catchments external to the Warragamba Dam catchment, including the Nepean River, Grose River, South Creek, Colo River and Macdonald River. The updates included greater spatial resolution in the model, and calibration and validation to more historical events. Further details are provided in Section 3.3.
RUBICON Hydraulic Model	A quasi-2-dimensional hydraulic model extending from Camden to the ocean. This hydraulic model provides information on the flow behaviour in the rivers and creeks and over floodplains. This model was used as the basis to estimate flood extents and flood depths across the floodplain in the 2019 Flood Study. In the current study, it was used to simulate flood behaviour for the large number of Monte Carlo simulations due to its fast run times.	The RUBICON model was refined to better represent the conveyance and storage characteristics of the river system and floodplain. This was achieved using outputs from the TUFLOW 2D model (discussed below). This ensures consistency when translating the hydraulic behaviour from the RUBICON to the more detailed TUFLOW 2D model. Further details are provided in Section 3.4.

Model Component	Model Approach Summary	Key Updates and Refinements from 2019 Flood Study
TUFLOW Hydraulic Model	The 2-dimensional (2D) model defines the flood behaviour between Bents Basin through to Juno Point, just downstream of Brooklyn. This model uses the latest bathymetry and terrain data to provide high resolution information on the flood behaviour throughout the study area. The model was used to simulate the range of representative events selected from the Monte Carlo analysis and produce detailed flooding information across the study area including floodwater levels, depths and velocities.	A new 2D model was created using the TUFLOW software. This model was calibrated and validated to a range of historical flood events, including the March 2021, March 2022 and July 2022 floods, to ensure it was providing a reliable description of flood behaviour. Further details are provided in Section 3.5.

3.2 Available Data

Several datasets were available to inform the 2024 Flood Study. A summary of each dataset is provided in Table 3-2. A more detailed description of each dataset, including quality review processes, is provided in **Technical Volume 1**.

3.3 Hydrologic Models

A hydrologic model is a computerised representation of the catchment and is used to simulate the conversion of rainfall into runoff. As outlined in Figure 3-1, 2 hydrologic models were used as part of the project:

- A RORB (Laurenson et al, 2010) model was used to define hydrologic processes for the catchment draining to Warragamba Dam
- A WBNM (Boyd et al, 2012) model was used to define hydrology for the balance of the catchment located outside of the Warragamba Dam catchment. This includes the Nepean River, Grose River, South Creek, Colo River and Macdonald River catchments.

The RORB model from the 2019 Flood Study was retained for the catchment draining to Warragamba Dam as the model underwent a significant calibration effort as part of the 2019 Flood Study with a particular focus on streamflow and rainfall records upstream of the dam. Therefore, there was considered limited opportunity to further improve on the performance of this existing model for Warragamba Dam catchment.

The WBNM model that was developed for the 'Hawkesbury Nepean Hydrologic Model Update' (WMAwater, 2018) formed the basis for defining hydrologic processes for the catchment areas external to Warragamba Dam. The WBNM model was adopted in preference to the RORB model as it was calibrated to additional locations outside of the Warragamba Dam catchment.

However, as a key outcome of the current study includes providing contemporary and detailed flood information, further updates and refinement of the WBNM model were completed as part of the current study. The key components of the update are as follows:

- Refinement of the model, providing greater resolution at sub-catchment scale, with an increase from 233 sub-catchments to 792 sub-catchments
- Detailed consideration of the imperviousness fraction of those sub-catchments within the model based on contemporary land uses

- Refinements of the representation of the Upper Nepean Dams and Mangrove Creek Dam storage relationships
- Calibration and validation of this refined hydrologic model, incorporating additional streamflow locations for areas external to the Warragamba Dam catchment, for a range of historical flood events including recent floods which were not available for the calibration of previous hydrologic models.

An overview of the refined catchment delineation and the extent of the WBNM model is shown in Figure 3-2.

Table 3-2. Summary of Available Dataset

Dataset	Description
Hydrologic Data	
Rain gauges	Rain gauge data for historical events was collected from various sources, including Bureau of Meteorology (BoM), Manly Hydraulics Laboratory (MHL) and Sydney Water. This was supplemented by radar data for more contemporary flood events.
Stream gauges	Stream gauge data were collected from BoM, MHL and WaterNSW.
Dam details	Details on the dams (Upper Nepean, Warragamba and Mangrove Creek), including stage-storage relationships, as well as the spillway details, were compiled from data from WaterNSW, the 2019 Flood Study and other reporting previously undertaken.
Land use	Land-use information was derived based on LiDAR point classification data, to assist in defining the catchment imperviousness in the more developed areas of the catchment.
Hydraulic Data	
Terrain Data	A combination of different LiDAR survey and ground survey was available for the establishment of the model terrain. This was further supplemented with information on current developments occurring in and adjacent to the floodplain.
Bathymetry	The bathymetry was derived from a composite of different bathymetry data sets that have been collected, including an infill survey commissioned for the 2024 Flood Study.
Surface Roughness	Land-use information was derived based on LiDAR classification data, together with other sources, to derive a “roughness” categorisation for the study area.
Hydraulic Structures	Data on hydraulic structures (bridges and culverts) was collated from a variety of sources, including TfNSW, councils, previous studies and available data.
Calibration and Validation Data	Data on historical events included water level gauge data as well as observations of flooding collated from previous reporting. For the most recent historical events of February 2020, March 2021, March 2022 and July 2022, significant datasets were captured, particularly for the last 3 events. In addition to gauging, aerial imagery, drone imagery, on-the-ground survey and various other sources of data were compiled to create a comprehensive library of data for each flood event. This was used to assist in the calibration and validation of the hydraulic model.

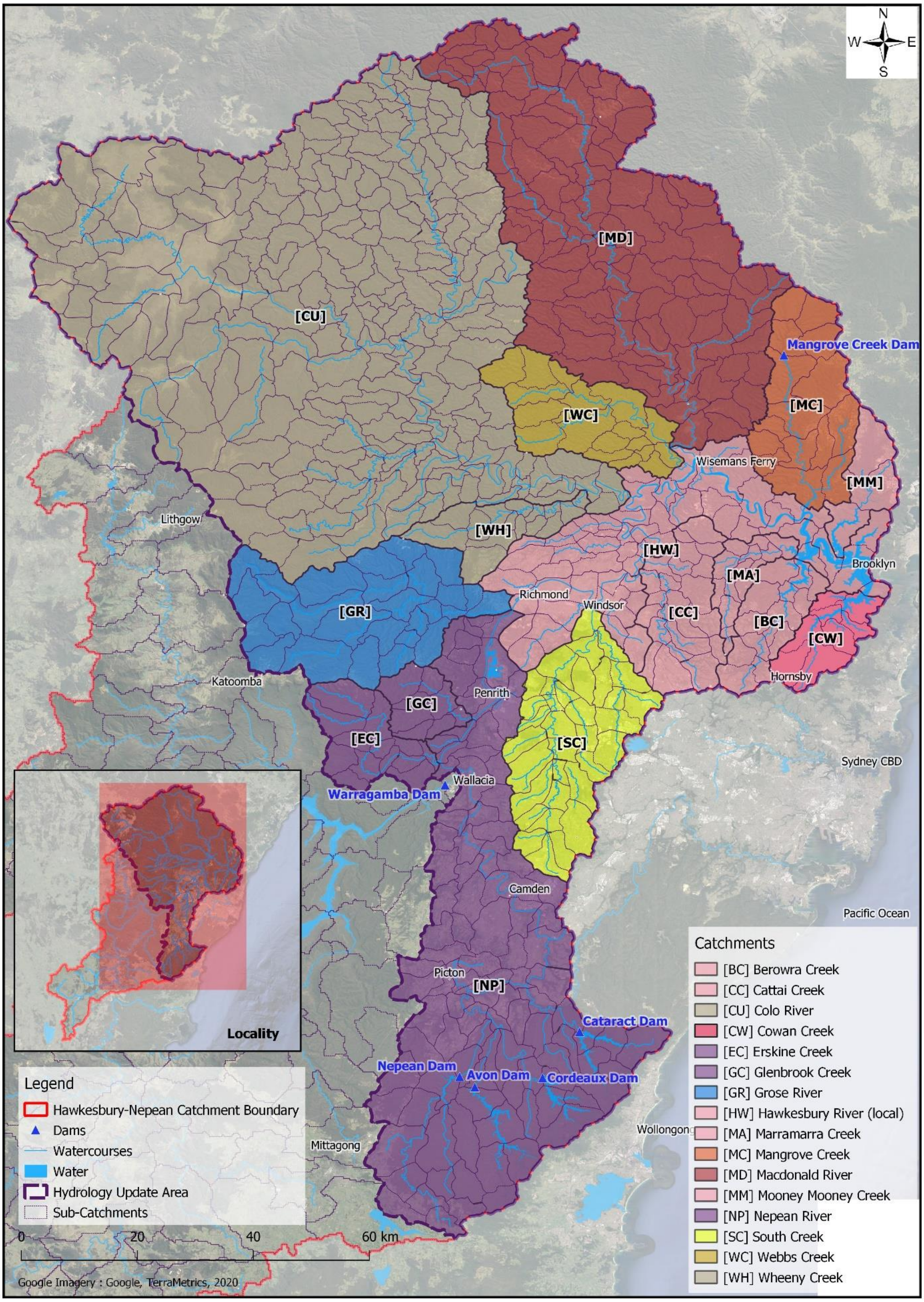


Figure 3-2. Overview of Updated Hydrologic Model Sub-Catchment Delineation

Following refinement of the hydrologic model, it was calibrated against 8 historical flood events that have occurred within the Hawkesbury-Nepean catchment, using data from 15 streamflow gauges:

- June 1964
- June 1975
- March 1978
- August 1986
- April/May 1988
- August 1990
- August 1998
- February 2020.

An overview of the streamflow gauge locations used for calibration is provided in Figure 3-3.

At the commencement of the calibration process, parameters were initially adopted consistent with the WMAwater (2018) configuration. Then, an iterative approach was adopted, to modify the model parameters to best fit the overall flow gauge data. This iterative approach involved:

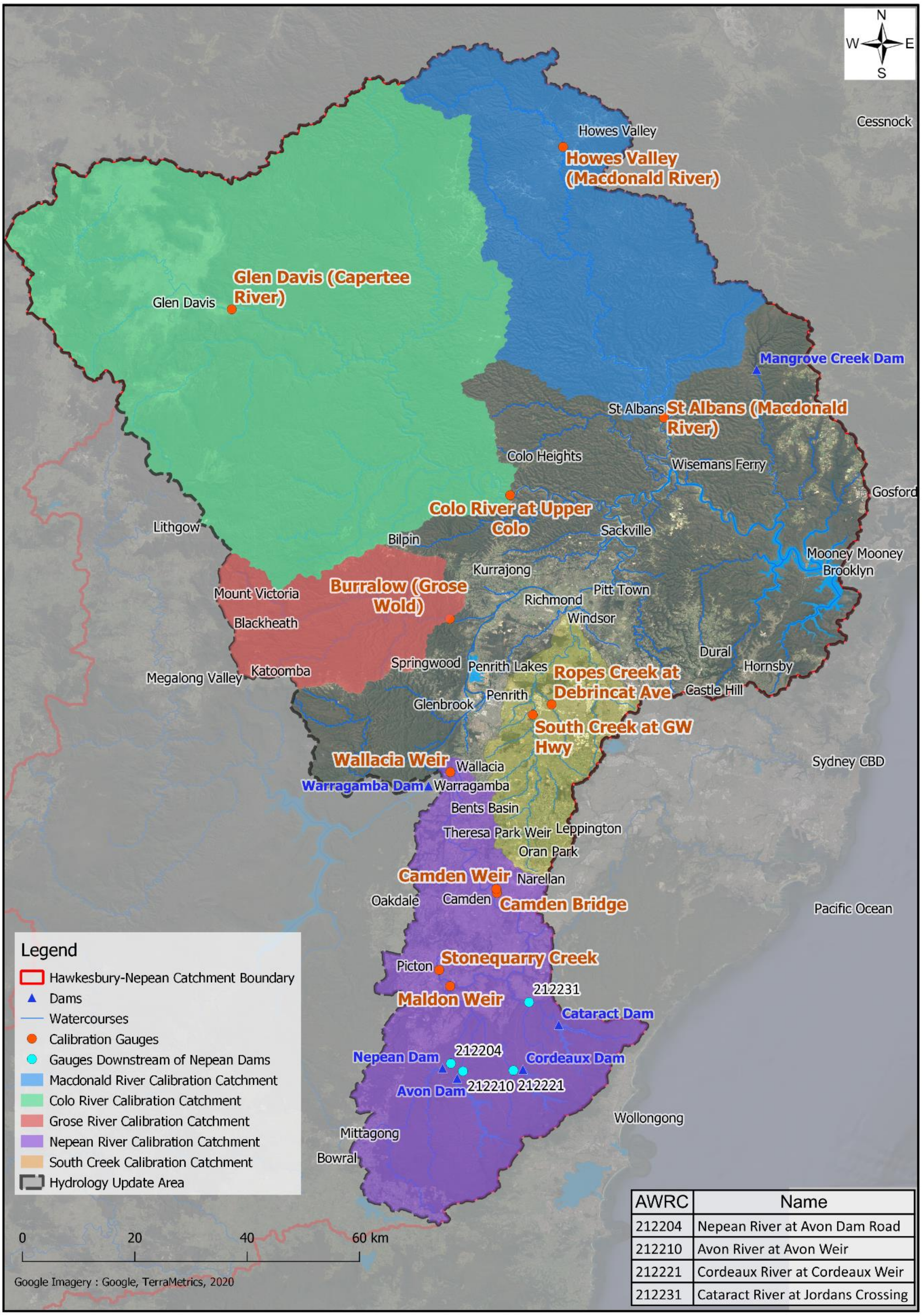
- Testing of alternative WBNM lag routing parameter values, to ensure that the flow hydrographs were representative of the timing and shape associated with each of the historical events
- Modification of the initial and continuing losses for each storm event to represent the appropriate condition for each flood event.

This process was undertaken in the context of the overall accuracy of both the input data for the model, particularly the rainfall information, and the accuracy of the different streamflow records. The calibration focused on both the representation of the peak flows, as well as the shape and timing of the hydrograph. The model results show a good comparison to the observed streamflow records in the various catchments. Examples of the calibration hydrographs are shown in Figure 3-4.

Further details on the development and calibration of this WBNM model are provided in **Technical Volume 2.**

Following the initial model calibration, significant floods occurred in March 2021, March 2022 and July 2022. These events provided an opportunity to collect additional data to further validate the WBNM model performance. Further discussion on the outcomes of the model validation is provided in:

- March 2021 Validation: **Technical Volume 8.**
- March 2022 Validation: **Technical Volume 9**.
- July 2022 Validation: **Technical Volume 10**.



AWRC	Name
212204	Nepean River at Avon Dam Road
212210	Avon River at Avon Weir
212221	Cordeaux River at Cordeaux Weir
212231	Cataract River at Jordans Crossing

Figure 3-3. Streamflow Gauges and Catchments for Calibration

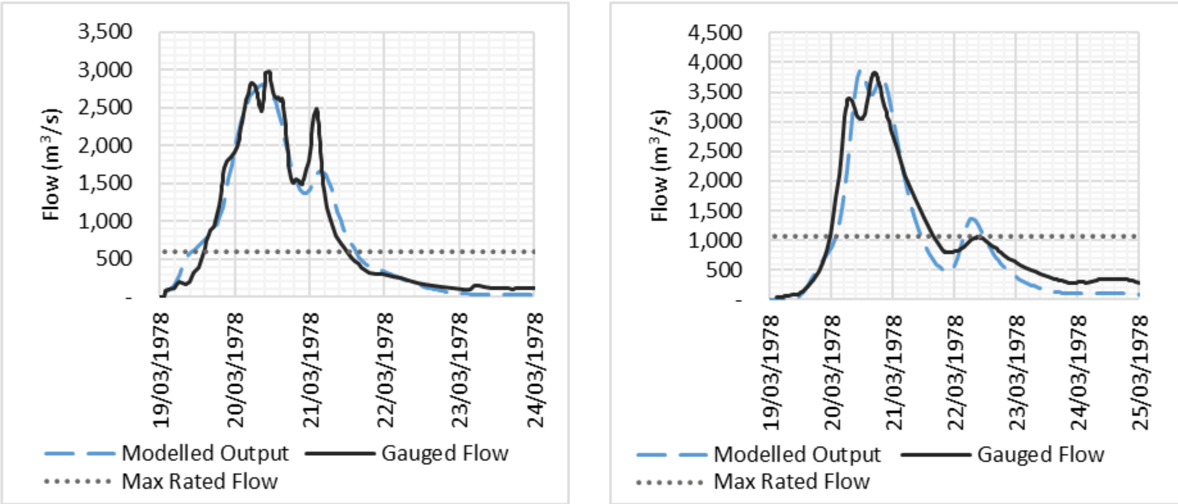


Figure 3-4. Example WBNM Calibration Flow Hydrographs for 1978 Flood - Nepean River at Maldon Weir (left) and Colo River at Upper Colo (right)

3.4 RUBICON Hydraulic Model

The RUBICON hydraulic model was developed as a part of the 2019 Flood Study. It is referred to as a quasi-2D model, as it incorporates a number of branches and flowpaths within the one-dimensional domain in order to represent the complex overbank flowpaths and storages. This is a fast running model that is suitable for use with a Monte Carlo framework (Section 3.6) and it underwent extensive calibration and verification as a part of the 2019 Flood Study.

This model was further refined as a part of the 2024 Flood Study. This included extending the calibration of the model to Wallacia, based on the joint probability assessment in **Technical Volume 6.** Similarly, additional calibration was undertaken at Sackville Ferry, Colo Junction and Webbs Creek Ferry based on stage frequency analyses undertaken in those locations. This assisted in informing the initial and continuing losses in the Monte Carlo framework, together with the timing of inflows on the Colo River and downstream tributaries.

Further verification and modification of the model was undertaken to align it with the TUFLOW model (Section 3.5), to ensure that the RUBICON would provide suitable outputs from the Monte Carlo framework.

Further details on the refinement of the RUBICON model are provided in **Technical Volume 7.**

3.5 TUFLOW Hydraulic Model

3.5.1 Model Setup

The Hawkesbury-Nepean River system includes an array of features that influence the movement of floodwaters. Each of these features needs to be represented in the model in sufficient detail to ensure a reliable description of flood behaviour is provided. However, this is a challenging task as the hydraulic model area is large (i.e., more than 1,500 km^2) which can limit the detail that can be incorporated in the model without encountering extensive simulation run times and/or computer memory limitations.

The TUFLOW Highly Parallelised Computer (HPC) software[3] was selected to develop the new hydraulic computer model of the Hawkesbury-Nepean River system as part of the project. The TUFLOW HPC

[3] TUFLOW Version 2020-1-AB was used for all hydraulic simulations (BMT, 2020)

software was selected due to its widespread use in the industry, significant research on its application in similar environments, and its allowance for a 2D representation of the movement of floodwater. The HPC version of the software takes advantage of the additional processing power of graphics cards to provide expedited simulation times. This allows the model simulations to be completed within reasonable timeframes (days).

The goal of the 2024 Flood Study is to define mainstream flood behaviour for the Hawkesbury-Nepean River system. Although the hydraulic model incorporates a number of tributaries, the scale/resolution of the model does not permit a detailed description of local catchment flood behaviour along each of these smaller/narrower watercourses. However, the backwater storage volume from the Hawkesbury-Nepean River afforded by these tributaries is represented. The reader should refer to specific, detailed flood studies for each of these tributaries that may be available from local councils for the most contemporary description of local flood behaviour.

A detailed description of the TUFLOW model setup is provided in **Technical Volume 3** and a summary of key model inputs and features is provided in Table 3-3.

Table 3-3. Summary of TUFLOW Model Configuration

Key Features	Description
Model Extent	The TUFLOW model was developed to provide a reliable description of flood behaviour within the defined study area extent (i.e., from Bents Basin downstream to Juno Point). However, the model was subsequently extended further upstream during the model calibration as it was determined the floodplain storage in the vicinity of Camden has a notable impact on flood behaviour in the vicinity of Wallacia. Therefore, the final model extends upstream to Cowpasture Bridge at Camden. The model also includes the lower reaches of major tributaries such as the Grose River and Colo River as well as all backwater storage areas such as South Creek and Eastern Creek. The extent of the TUFLOW model is shown in Figure 3-5.
Grid Size	The TUFLOW software uses a grid to define key features of the study area including the topography and hydraulic roughness. Therefore, the grid cell size of the model defines the level of detail, or resolution, of the model. A finer resolution can provide for more detailed representation of hydraulic features but will encounter extended run times and, potentially, computer memory limitations. A 15 metre grid size was adopted for all final calibration and design flood simulations (the model was also set up to allow use of a 20 metre grid size for initial model simulations with expedited run times). In addition, sub grid sampling was employed to enable a more detailed representation of features at the sub-grid level. A 5 metre sub grid sampling interval was adopted across the broader model area and a 2 metre sampling interval was adopted across more urbanised areas.
Terrain and Bathymetry	The floodplain topography in the TUFLOW model was defined based on contemporary data sets, including the most recent LiDAR terrain data, supplemented with representations of recent developments in the study area. This results in a floodplain terrain representative of mid-2020 conditions. The channel bathymetry (i.e., areas located below the permanent water surface and therefore, absent from LiDAR datasets) has been sourced from the most up to date hydrographic survey data throughout the Hawkesbury and Nepean Rivers, providing a continuous and detailed description of the conveyance capacity of the main watercourses at a resolution not previously available.

Key Features	Description
Hydraulic Roughness	The hydraulic roughness (i.e., Manning's 'n') refers to the resistance to flow afforded by different land uses/obstructions (e.g., trees, buildings, grass). The spatial variation in roughness was defined using remote sensing land use information which is described in **Technical Volume 2**. This land use information was further updated and refined using recent aerial imagery as well as the outcomes of site visits. The roughness coefficients assigned to each land use were initially assigned based on values quoted in literature. The coefficients were subsequently refined as part of the model calibration process.
Bridges and Culverts	A representation of all bridges and major culverts located within the Hawkesbury-Nepean floodplain was included in the TUFLOW model. The individual spans of "mainstream" hydraulic structure (i.e., major bridges located on the Hawkesbury and Nepean Rivers) were represented as 2-dimensional structures. This allows the differing blockage potential of individual bridge spans to be represented. Structures subject to "overbank" and "backwater" inundation were incorporated as either 2-dimensional structures (for larger bridges) or 1-dimenstional structures (for smaller culverts). Blockage was assigned to each mainstream hydraulic structure as well as overbank structures in the Emu Plains and Peach Tree Creek floodplains for all design flood simulations based on recommendations in 'Australian Rainfall and Runoff: A Guide to Flood Estimation' (Ball et al., 2019).
Weirs	A representation of weirs located within the study area was also incorporated in the model. The river area located behind each weir was "filled" with water that was set to the top of each weir elevation. That is, it was assumed that the river areas contained behind each weir were "full" for each flood simulation.
Model Boundary Conditions	Hydraulic computer models such as TUFLOW require suitable boundary conditions to define where water enters and leaves the model area. The upstream model boundaries (representing where flows enter the TUFLOW model area) were defined using flow hydrographs produced by the hydrology models. The flow hydrographs for smaller tributaries (e.g., Cattai Creek) were applied directly to the Hawkesbury and Nepean Rivers. Flow hydrographs for major tributaries (e.g., Colo River) were applied at the upstream model boundaries. Therefore, the "routing" of flows along minor tributaries was represented in the hydrology model and the routing of flow along major tributaries was represented in the TUFLOW model. The downstream boundary (defining where water leaves the model) was defined as a time varying ocean water level (i.e., tide).

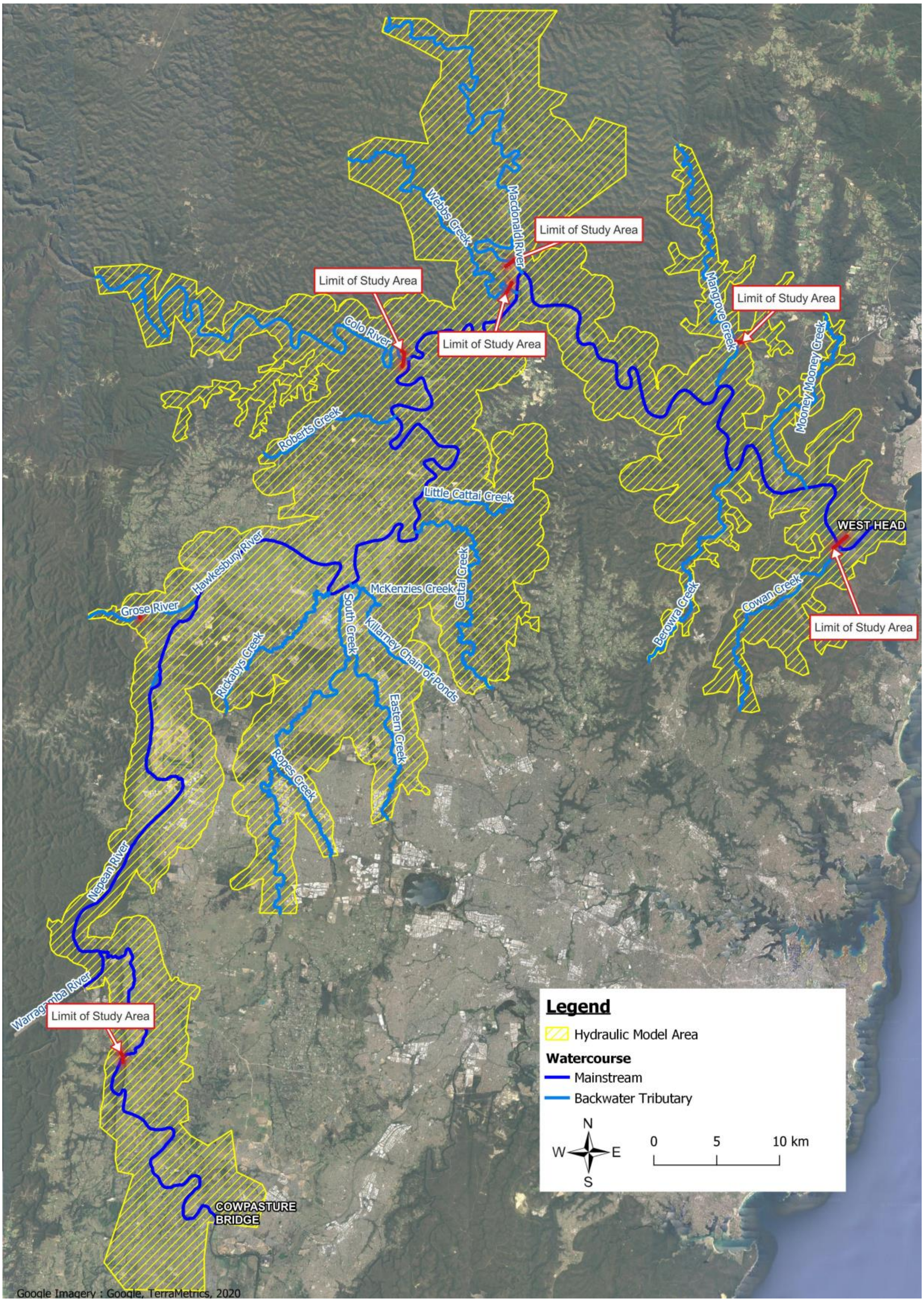


Figure 3-5. Hydraulic Model Area

3.5.2 Calibration

Calibration of the new TUFLOW model was completed to ensure the model setup was providing a reliable representation of flood behaviour across the study area. This involved comparing simulated flood levels generated by the model against recorded water levels at stream gauge locations as well as surveyed flood mark elevations for the following historical floods:

- November 1961
- June 1964
- June 1975
- March 1978
- August 1986
- May 1988
- August 1990
- February 2020.

The location of active stream gauges that were used as part of the calibration is shown in Figure 3-6.

Inflows to the TUFLOW model were defined based on flow hydrographs produced by the calibrated hydrology models. Calibration was then completed by adjusting the TUFLOW model parameters (mainly hydraulic roughness) to minimise differences/achieve the best possible correlation between simulated and recorded flood levels while keeping parameters within reasonable bounds.

Following the initial model calibration, significant floods occurred in March 2021, March 2022 and July 2022. These floods provided an opportunity to collect additional data to further validate the TUFLOW model performance. This included extensive data collection efforts in the Lower Hawkesbury River where only sparse amounts of historical flood information were previously available.

The calibration and validation focused on both the representation of the peak flood levels (for locations with surveyed peak flood levels), as well as the time variation in water levels (for stream gauge locations). The model results provide a good reproduction to the gauge records along the Nepean and Hawkesbury Rivers. Examples of the stage hydrographs for the March 2021 flood are shown in Figure 3-4.

Further details on the calibration of the TUFLOW model are described in **Technical Volume 3** and information on the validation of the TUFLOW model to the recent floods are provided in**:**

- March 2021 Validation: **Technical Volume 8**.
- March 2022 Validation: **Technical Volume 9**.
- July 2022 Validation: **Technical Volume 10**.

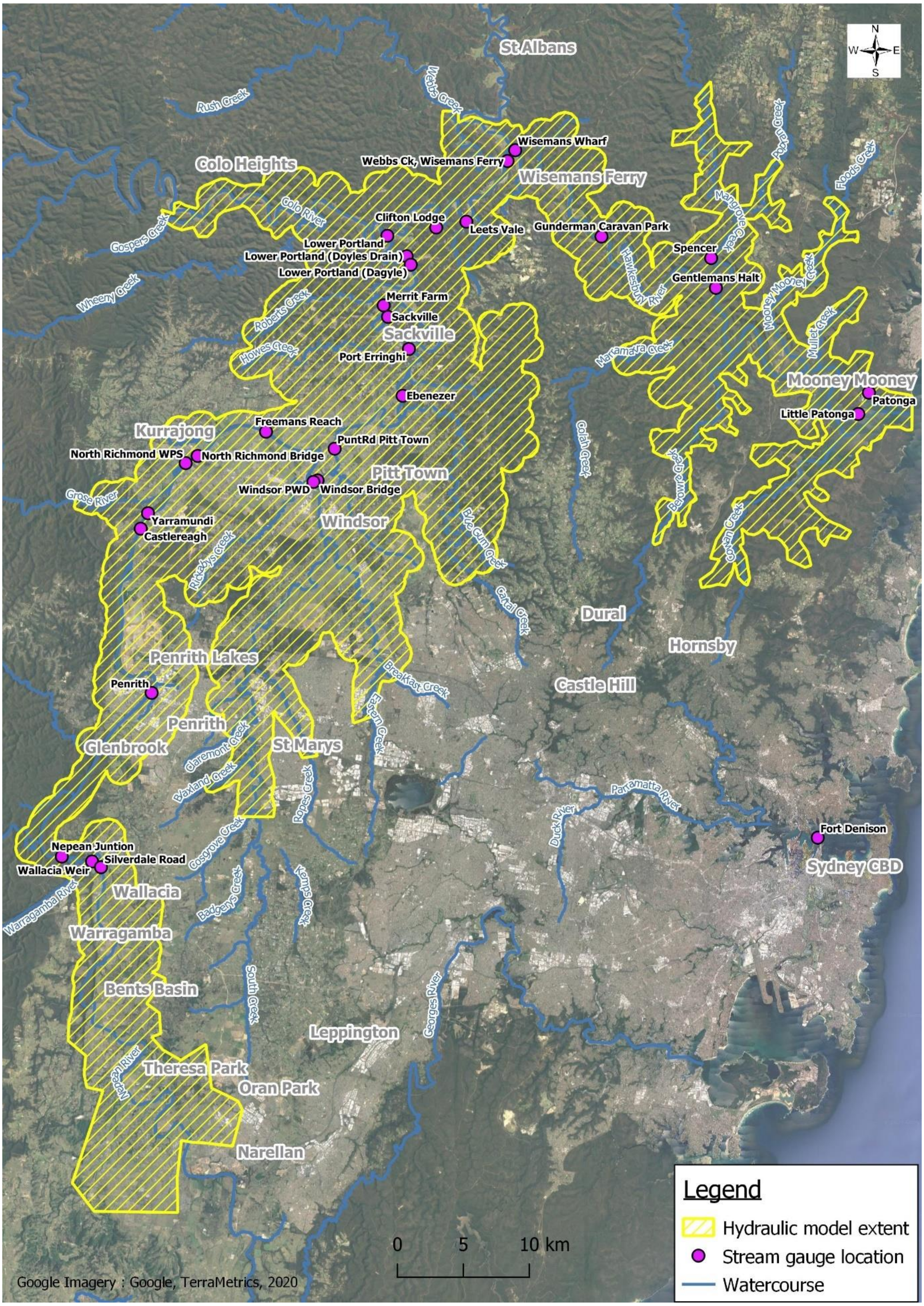


Figure 3-6. Location of water level gauges for hydraulic model calibration floods

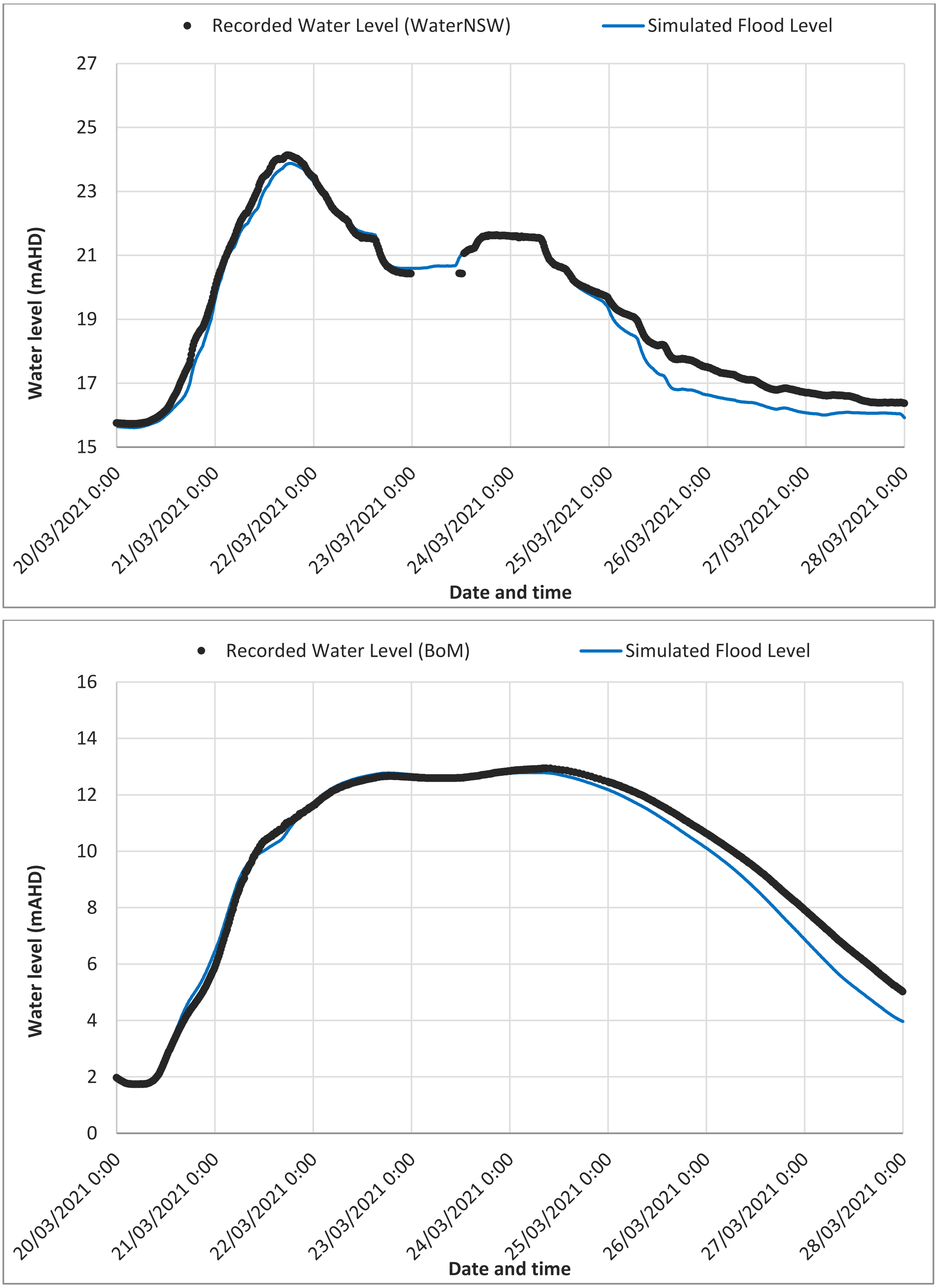


Figure 3-7. Example TUFLOW Calibration Hydrographs for March 2021 Flood at Penrith (top) and Windsor (bottom)

3.6 Monte Carlo Analysis

To best capture the observed variability of floods, a 'Monte Carlo' approach that was originally developed as part of the 2019 Flood Study was adopted and updated as part of the 2024 Flood Study to analyse potential flooding. This Monte Carlo model applies a range of variable hydrologic inputs (e.g., antecedent rainfall conditions, intensity and distribution of rainfall, Warragamba Dam levels) to develop a library of nearly 20,000 potential storms. The variables applied in developing the storm database for the Monte Carlo approach are summarised in Figure 3-8.

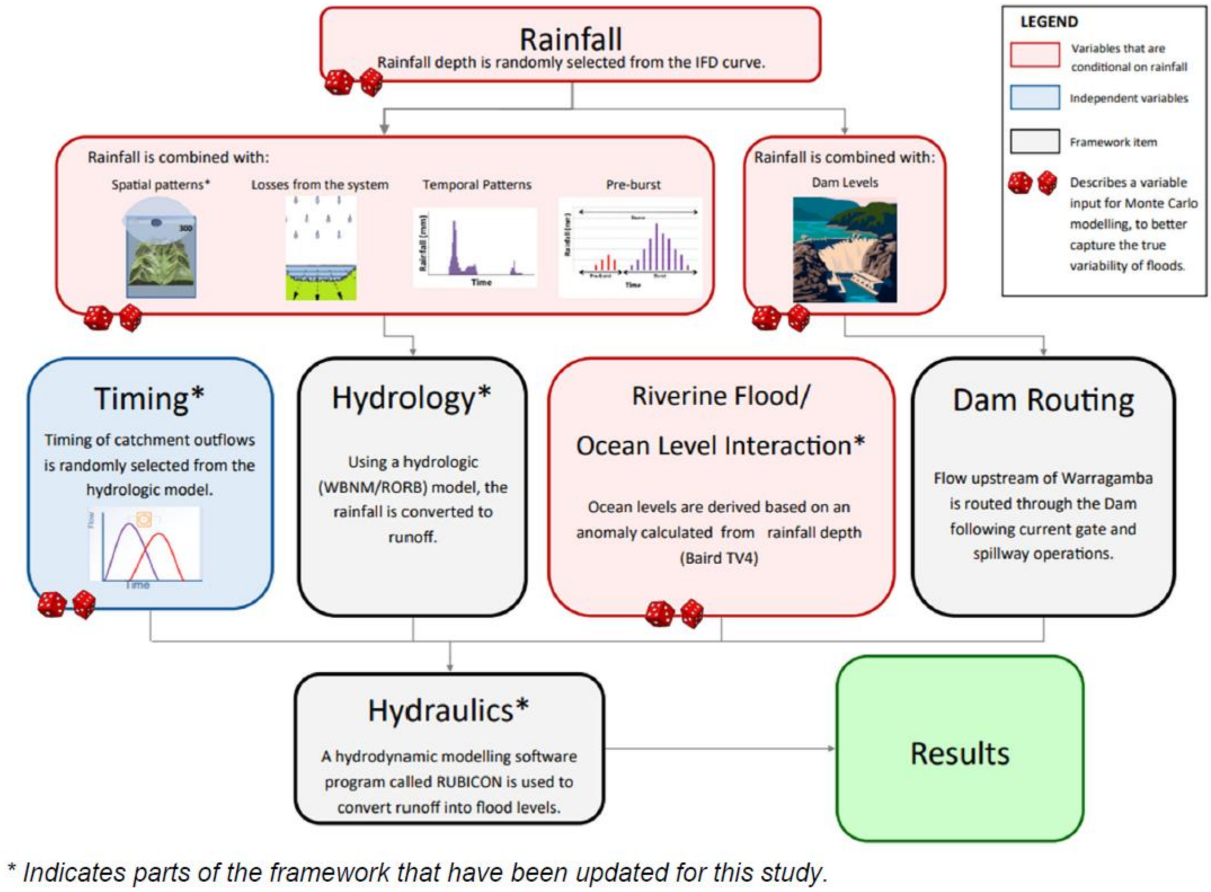


Figure 3-8. Monte Carlo Approach

The storms were applied to the 2 hydrologic models (RORB and WBNM, as per Section 3.3) used to simulate the conversion of rainfall into runoff for each storm and define the inflows from all watercourses within the catchment. The RUBICON hydraulic model (Section 3.4) was then used to combine the flows from the hydrologic models with other hydraulic variables (e.g., ocean water levels) to analyse the flood characteristics within the rivers, creeks and floodplain (e.g., peak flood levels).

Using this approach, close to 20,000 possible flood events were simulated, which represents the range of floods that could be experienced over a 200,000-year period and provides a detailed basis for undertaking a flood frequency analysis at key locations across the study area.

To validate the Monte Carlo approach, flood frequency analyses were conducted at seven locations along the river. A flood frequency analysis is a technique using historical flood peaks to relate the magnitude of floods to their frequency of occurrence using probability distribution functions. The validation found generally good matches between the peak flows or peak heights of floods using the Monte Carlo model and the flood frequency analyses, confirming the suitability of the approach.

The Monte Carlo analysis is further discussed in **Technical Volume 7**.

To further improve the Monte Carlo analysis that was developed as part of the 2019 Flood Study, further analysis was undertaken to understand the joint probabilities of flooding at 3 key areas: Wallacia, the Lower Hawkesbury and Broken Bay (ocean water levels). These are discussed further below.

3.6.1 Wallacia Joint Probability

Flood levels at Wallacia can vary significantly. This is due to the gorge downstream of Wallacia which restricts outflow from the Wallacia floodplain as well as the interaction between flooding on the Nepean River and Warragamba River (downstream of Warragamba Dam) which can result in backwater influences that extend upstream to the Wallacia floodplain during larger floods. This means that flooding at Wallacia can be the result of different combinations of Nepean River and Warragamba River flooding.

To better understand the potential for interaction of flooding in the Nepean River and Warragamba River, a joint probability assessment was completed for Wallacia. The assessment was completed using data from a range of historical sources including the gauge records and newspaper sources for flood events prior to the 20^{th} Century. The historical events were adjusted to different historical catchment conditions (reflecting pre and post Warragamba Dam scenarios). The adjusted events were ranked and sorted according to the influence of the Nepean and Warragamba River, which was informed by looking at event rankings away from Wallacia (i.e., at Camden and Penrith).

The adjusted flood level information was used to complete a water level frequency analysis for the Wallacia floodplain. The water level frequency analysis results formed the basis for updates to the Monte Carlo framework (i.e., ensuring the Monte Carlo frequency results correlated with the Wallacia frequency results).

The results provided by the updated Monte Carlo assessment indicates higher flood levels at Wallacia between the 1 in 5 AEP and the 1 in 200 AEP when compared with the 2019 Flood Study results, with results converging as the events get rarer.

Further details of the Wallacia joint probability analysis are provided in **Technical Volume 6**.

3.6.2 Lower Hawkesbury

The flood behaviour of the Lower Hawkesbury River, generally downstream of Sackville, is influenced not only by the Hawkesbury River flows from upstream, but also by inflows from the Colo River and, further downstream, Macdonald River.

Not only are the Colo River and Macdonald River systems relatively large, the rainfall that falls over these 2 catchments can be very different in terms of both magnitude and timing to that which falls over the Warragamba River and Nepean River catchments, upstream of Windsor. This can lead to very different behaviours on these 3 key inflows to the Lower Hawkesbury.

The peak levels in the Lower Hawkesbury are influenced not only by the peak flows on the Hawkesbury, Colo and Macdonald rivers, but also by the timing of the peaks and shapes of the hydrographs. A peak flow that occurs much earlier in the Colo River than in the Hawkesbury River at Windsor will not be as influential as a scenario for the Lower Hawkesbury as when the 2 peak flows coincide.

Examples of the influence of the Colo River on estimated flows downstream of Colo Junction are shown for the March 1978 and July 2022 events in Figure 3-9 and Figure 3-10, respectively. In 1978, the peak flows from the Colo River occurred around a day and a half earlier than the peak flows in the Hawkesbury River downstream of Windsor, compared with the July 2022 event when the peak flows were more closely aligned. Even though the peak flow in the Colo River in July 2022 was lower than the 1978 event, it contributed greater flow (around 2000m^3/s) to the Hawkesbury River at its peak.

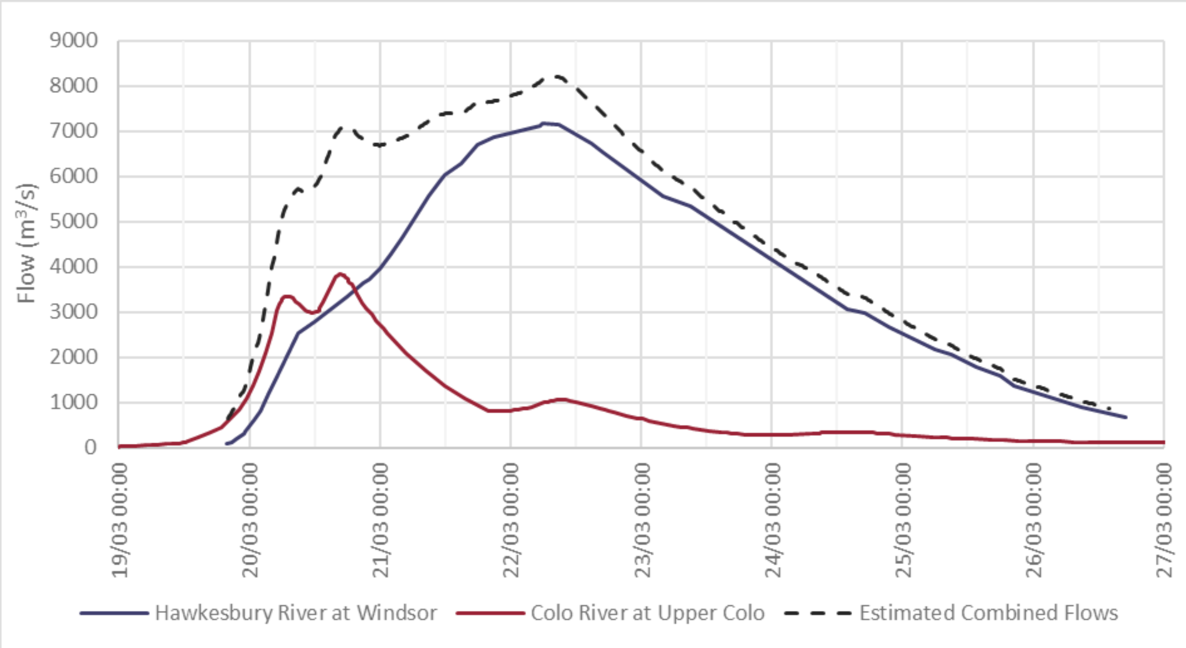


Figure 3-9. March 1978 Flows – Estimate of the Combined Flows Downstream of Colo Junction

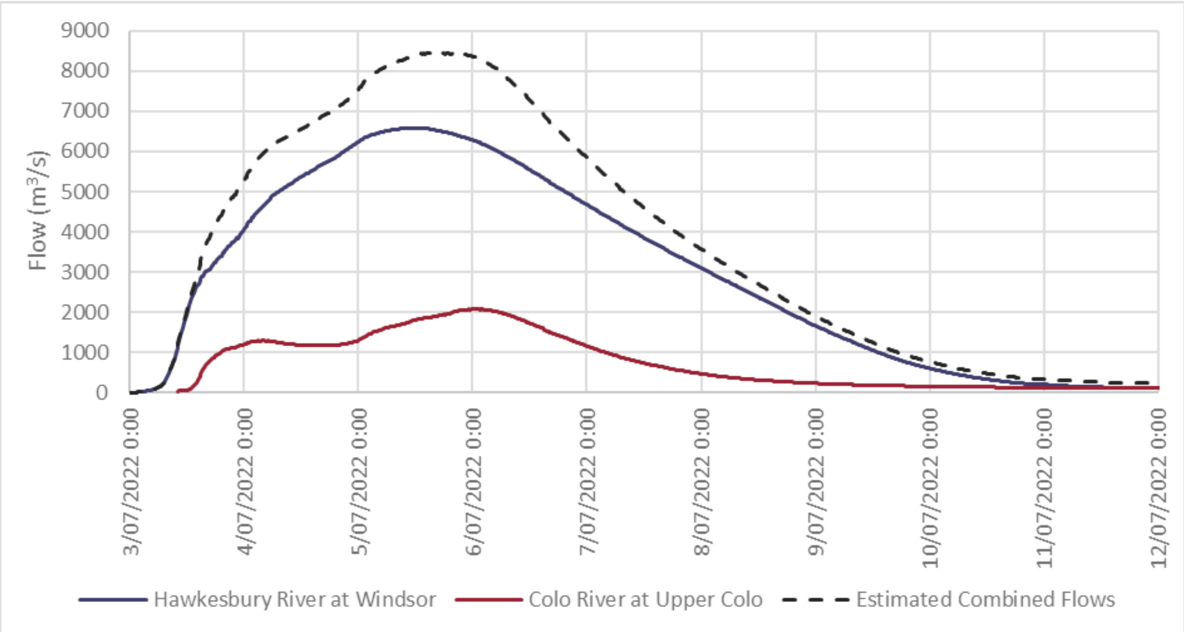


Figure 3-10. July 2022 Flows – Estimate of the Combined Flows Downstream of Colo Junction

An analysis was undertaken on the Lower Hawkesbury River, drawing on recent data collated from the 2021 and 2022 flood events, as well as a collation of earlier historical records (**Technical Volume 5**). The outcome was a compiled historical record for the Lower Hawkesbury. Analysis was undertaken on this record to understand the relative contribution to the peak flows and levels in the Lower Hawkesbury River from the Colo River and Macdonald River.

Figure 3-11 shows a summary of the relative contribution of the Colo and Macdonald rivers to the peak level at Webbs Creek (Wisemans Ferry). The 'residual' level on the graph shows the approximate contribution (in metres) to the peak level at Wisemans Ferry from the Colo and Macdonald rivers. For example, for the 1949 event, it is estimated that the Colo and Macdonald rivers contributed nearly 3 metres to the 5.5m AHD peak at Webbs Creek (Wisemans Ferry).

The analysis also considers the relative timing of the peak flows from the Hawkesbury-Nepean River with those of the Colo and Macdonald rivers (Figure 3-12). This information was used to establish a probability distribution based on the historical data set. This probability distribution provides a key input to the Monte Carlo modelling.

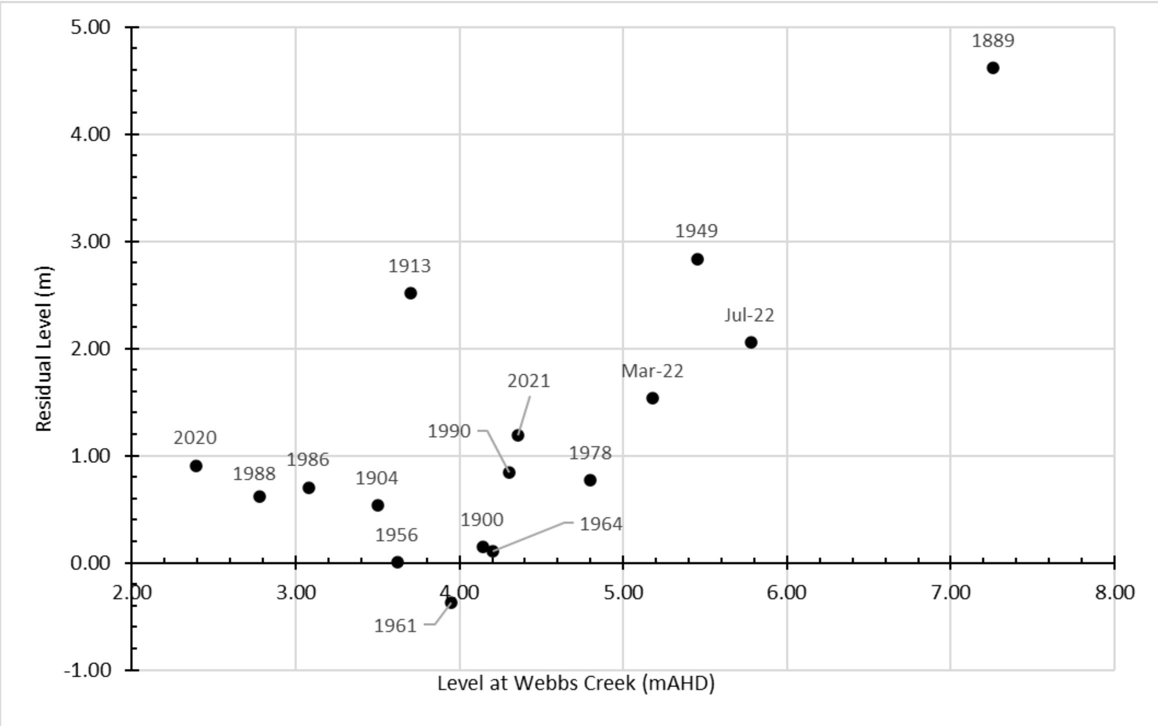


Figure 3-11. Estimated Residual Level vs Recorded Level at Webbs Creek[4]

[4] Note that this graph excludes events where Webbs Creek is below 2.5m AHD, given likely uncertainties in the flow level relationship at that level with the influences of the tide.

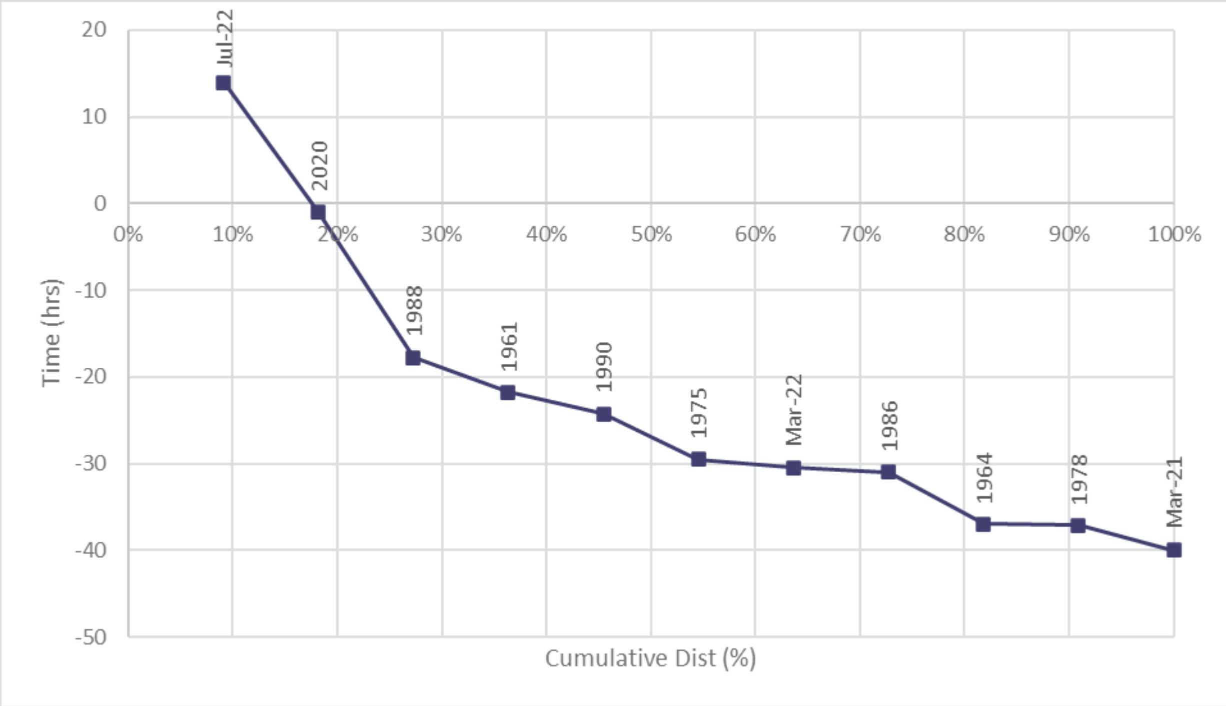


Figure 3-12. Time Difference between Hawkesbury River at Windsor Peak and Colo River at Upper Colo Peak[5]

3.6.3 Coastal Joint Probability

The joint occurrence of a coastal ocean event, together with a Hawkesbury-Nepean River flood, can influence the peak flood levels in the Lower Hawkesbury. The level of influence is a factor of both the likelihood of a coastal event occurring, together with the timeframe over which that coastal event occurs.

Through an analysis of historical storms over the Hawkesbury-Nepean River catchment and coastal water levels, a joint probability relationship was derived between catchment rainfall and elevated coastal water levels. Further analysis was undertaken through a coastal Monte Carlo analysis (separate to the overall Monte Carlo analysis) using a larger sample of synthetic storm events. A summary of this relationship is provided in Figure 3-13. The derived model has a weak positive linear trend between coastal residual water level (excluding astronomical tide) and rainfall across the Hawkesbury-Nepean River catchment.

[5] Negative values represent where the peak at Colo River occurs before the peak at Windsor.

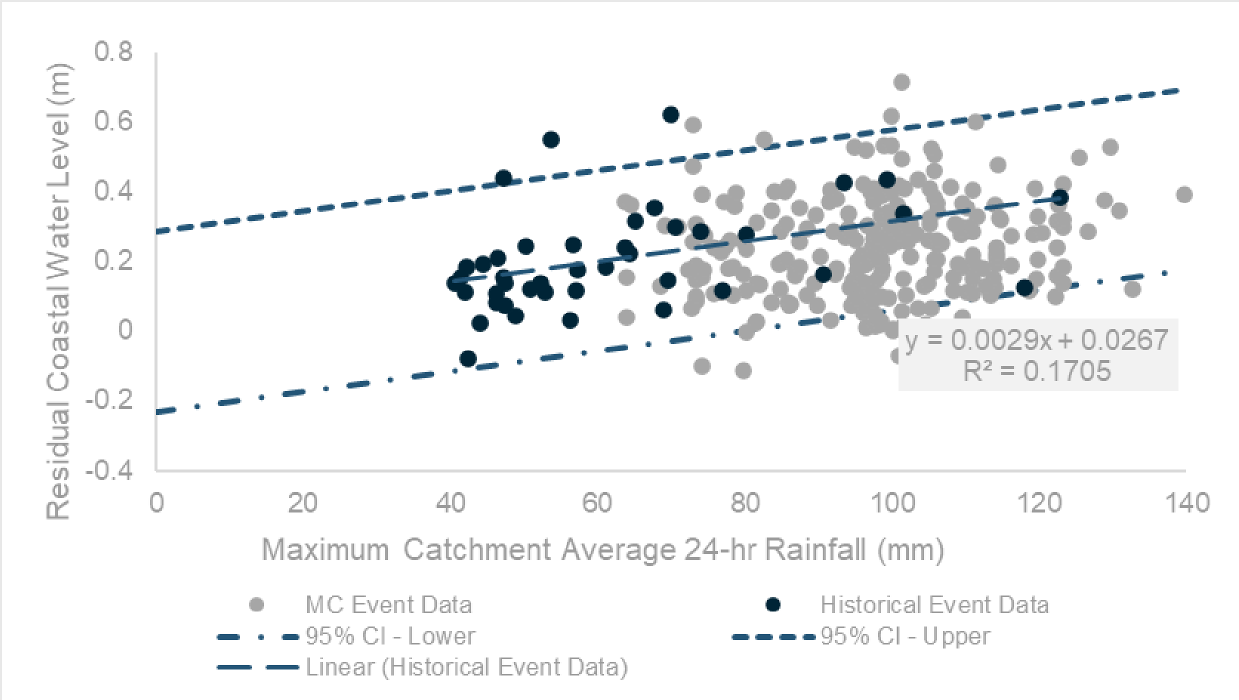


Figure 3-13. Joint Correlation between Maximum Daily Rainfall in the Hawkesbury-Nepean Catchment and Maximum Daily Coastal Residual Water Level

Analysis of historical hydrograph flow data at Windsor and Upper Colo determined that maximum flow rates rarely coincided with the timing of the maximum residual coastal water level, with the latter tending to occur first. A coastal water level time series was generated that follows the typical residual response of larger rainfall events from the period of 1970 to 2016. The residual coastal water level tends to peak earlier than the river flow, then the residual coastal water level decreases slowly to normal conditions once storm conditions ease.

The relationship between catchment rainfall and elevated coastal water level was used as one of the inputs to the Monte Carlo analysis.

Further details on this assessment are provided in **Technical Volume 4**.

The Monte Carlo modelling approach takes account of a range of hydrologic and hydraulic variables including the timing and spatial distribution of rainfall patterns, as well as the ocean level boundary. Because of the stochastic nature of the selection process for each of these variables, the ocean level boundary for the representative event may not necessarily correspond to the equivalent AEP for the ocean level event. Therefore, a peak ocean level only event (i.e., no catchment runoff) was also included in the flood envelope for each design flood to ensure a suitable peak design level was represented in the hydraulic model outputs for the estuarine sections of the river.

It is important to note that the ocean level adopted for this study represents the still water level, and does not include a dedicated allowance for storm surge, wave runup etc. For the lower portions of the study area, cross reference should be made with available coastal studies, including the recently completed *Hawkesbury River Coastal Inundation Study – Coastal Management Program Stage 2* (Rhelm & Baird, 2023), to understand the influence of these components during coastal-dominated events.

3.7 Selection of Representative Events

As discussed, a Monte Carlo assessment was completed as part of the study to provide a detailed understanding of the frequency of flooding across the study area. This involved the simulation of close to 20,000 flood events via the hydrologic models and the RUBICON hydraulic model. The ability to simulate such a large number of floods in the RUBICON model is a result of the short computation times of this model (i.e., run times of less than 1 minute). The fully 2D TUFLOW hydraulic model includes a more complex solution scheme that takes much longer to run (i.e., in the order of 1-2 days). Therefore, it is not possible to simulate all Monte Carlo floods in the TUFLOW model. For this reason, a reduced number of floods was selected from the results of the Monte Carlo assessment and applied to the TUFLOW model. These events are referred to as "Representative Events".

The Monte Carlo outputs provide a reliable description of design flood levels along the full length of the river. When identifying representative events, the goal of the process was to select a smaller number of events (targeting 4 or 5 event for each AEP) that, when combined, would reproduce the Monte Carlo levels to within ±0.1m. This was interrogated in the form of a design flood level difference profile (an example of such a profile is provided in Figure 3-14).

If, for example, the "RD01158" event was selected in isolation to represent the 1 in 100 AEP flood, it would provide a good reproduction of the Monte Carlo design flood levels between Wallacia and Windsor (i.e., design levels would be reproduced to within ±0.1 metres), but it would underrepresent the 1 in 100 AEP design levels across downstream areas. This is reflective of the different flooding mechanisms that influence flood levels along different parts of the river valley. Therefore, it is necessary to apply several different representative floods to ensure the design flood levels are reliably reproduced along the full length of the river. In this regard, when the peak flood levels from each of 5 identified representative profiles in Figure 3-14 are enveloped/combined (i.e., the maximum flood level is adopted from all of the available representative events) it will produce a final profile that is no greater than 0.1 metres from the "true" design flood levels along the full length of the river (the green area in Figure 3-14 representing the ±0.1m tolerance band).

Further details on the Monte Carlo analysis and the selection of representative events are provided in **Technical Volume 7**.

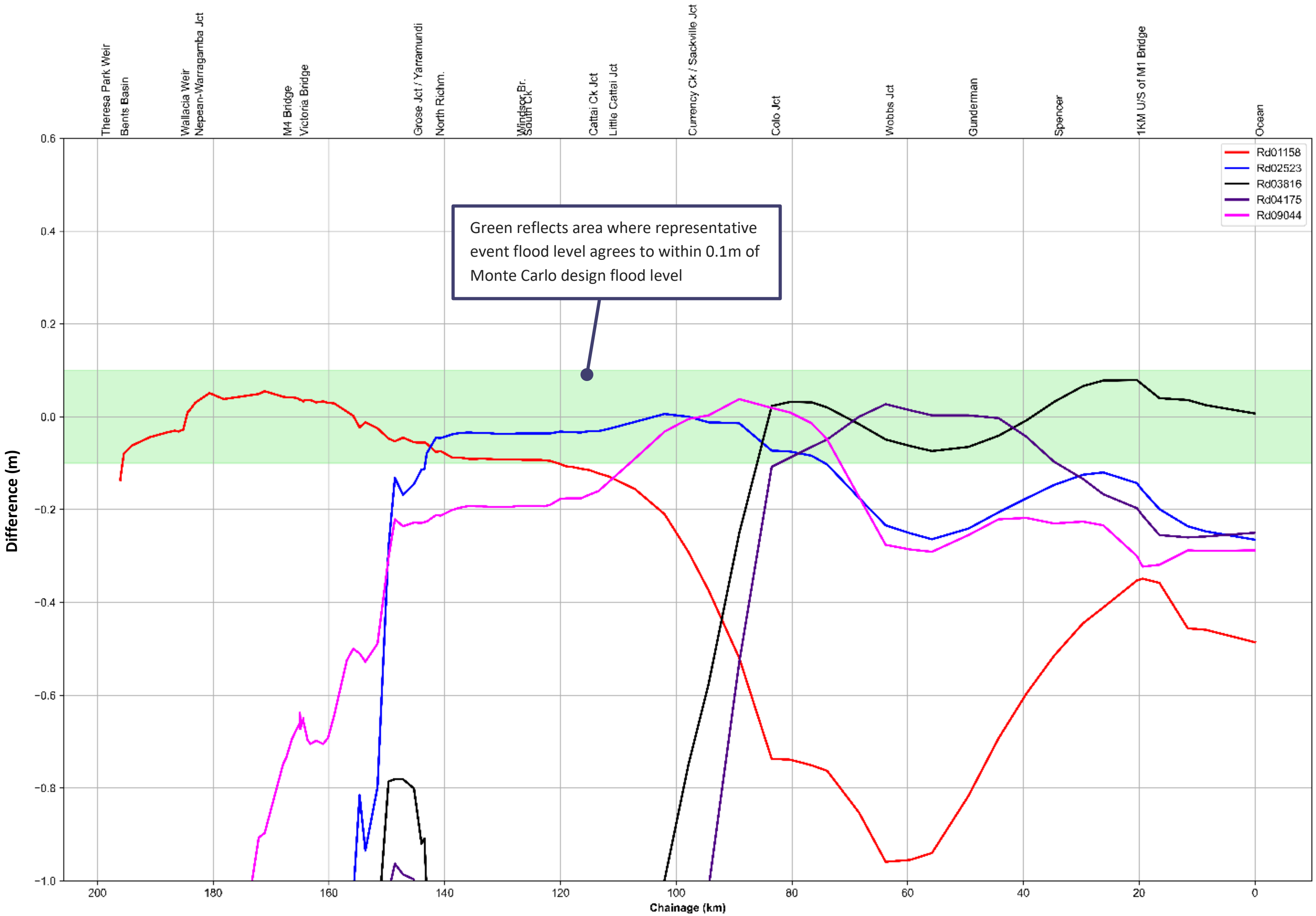


Figure 3-14. Example of Flood Profile Difference Plot for 1 in 100 AEP flood

3.8 Probable Maximum Flood

The probable maximum flood (PMF) is the largest flood that could reasonably be expected to occur for a catchment. For the purposes of floodplain management, and consistent with the NSW Government's *Flood Risk Management Manual* (NSW Government, 2023), the PMF is estimated using the probable maximum precipitation (PMP) and a single temporal pattern. Due to the conservativeness applied to other factors influencing flooding, a PMP does not translate to a PMF of the same probability. But for the purposes of floodplain management, the probability of the PMP may be assigned to the PMF.

The probable maximum precipitation (PMP) is the 'greatest depth of precipitation for a given duration meteorologically possible over a given size storm area at a particular location at a particular time of the year' (NSW Government, 2023).

Due to the size of the catchment, the PMP rainfall was estimated for several different points within the catchment:

- Wallacia
- Warragamba
- Penrith
- Sackville
- Wisemans Ferry.

Using the Generalised Southeast Australia Method (GSAM) (BOM, 2006), the PMP rainfall is estimated for the catchment contributing to these locations.

The PMP rainfalls were then applied to the hydrologic model to estimate the peak PMF flows throughout the catchment. These were then applied to the RUBICON model to understand the resulting peak water levels in the floodplain.

By comparing the peak water levels from the different PMF events, 3 PMF events were selected for analysis in the TUFLOW Model, the Wallacia 24-hour, the Penrith 72-hour and the Sackville 96-hour events.

Further details on this assessment are provided in **Technical Volume 12**.

Image source: Adam Hollingworth, February 2020

4 Design Event Modelling

4.1 Design Events Considered

Design floods are hypothetical floods that are commonly used for floodplain management investigations and defined by their probability of occurrence. Design flood modelling was undertaken by simulating each representative flood (refer Section 3.7) from the 1 in 2 AEP up to the 1 in 5000 AEP. The probable maximum flood (PMF) was also simulated (refer Section 3.8). **Technical Volume 11** provides details on the model results, while a discussion on the flood behaviour informed by the model results is provided in Section 5 of this report.

The Map Book provides a comprehensive set of maps for design flood results across the range of events. A summary of the flood maps for the design flood model results is provided in Table 4-1. Spatial datasets have also been prepared, including for peak flood velocities.

The outputs from this flood study will be used by a variety of stakeholders for different purposes, such as evacuation and emergency management, and land use and infrastructure planning. A summary of the key model outputs is provided in Table 4-2.

Table 4-1. Design Event Result Map Book Summary

AEP	Peak Depth and Water Levels	Flood Hazard	Flood Function
1 in 2	Map-EXT01-2-01 to 17	Map-HAZ01-2-01 to 13	
1 in 5	Map-EXT02-5-01 to 17	Map-HAZ02-5-01 to 13	
1 in 10	Map-EXT03-10-01 to 17	Map-HAZ03-10-01 to 13	
1 in 20	Map-EXT04-20-01 to 17	Map-HAZ04-20-01 to 13	Map-FLF01-20-01 to 13
1 in 50	Map-EXT05-50-01 to 17	Map-HAZ05-50-01 to 13	
1 in 100	Map-EXT06-100-01 to 17	Map-HAZ06-100-01 to 13	Map-FLF02-100-01 to 13
1 in 200	Map-EXT07-200-01 to 17	Map-HAZ07-200-01 to 13	Map-FLF03-200-01 to 13
1 in 500	Map-EXT08-500-01 to 17	Map-HAZ08-500-01 to 13	Map-FLF04-500-01 to 13
1 in 1,000	Map-EXT09-1000-01 to 17	Map-HAZ09-1000-01 to 13	
1 in 2,000	Map-EXT10-2000-01 to 17	Map-HAZ10-2000-01 to 13	Map-FLF05-2000-01 to 13
1 in 5,000	Map-EXT11-5000-01 to 17	Map-HAZ11-5000-01 to 13	
PMF	Map-EXT12-PMF-01 to 17	Map-HAZ12-PMF-01 to 13	

Table 4-2. Summary of Model Outputs

Output Type	Description
Peak Flood Extents, Levels and Depths	The "enveloped" maximum of the results from the representative events for a particular AEP event. In addition to providing these as a series of maps for the flood study, these results have been provided in a GIS format to the NSW Reconstruction Authority.
Peak Flood **Velocities**	The "enveloped" maximum of the results from the representative events for a particular AEP event. These results have been provided in a GIS format to the NSW Reconstruction Authority.
Peak Hazard	Flood hazard defines the potential impact that flooding will have on vehicles, people, and buildings across different sections of the floodplain. The mapping follows categories defined in AIDR [2] (2017). Flood hazard is calculated from the maximum depth, maximum velocity or maximum depth/velocity product, whenever they occur during a flood. The peak flood hazard is derived from the maximum of the representative events for a particular AEP. In addition to providing these as a series of maps for the flood study, these results have been provided in a GIS format to the NSW Reconstruction Authority.
Flood Function	Flood function includes the definition of floodway, flood storage and flood fringe. These are a key input to strategic planning, and are defined in accordance with the Flood Risk Management Manual (NSW Government, 2023). In addition to providing these as a series of maps for the flood study, these results have been provided in a GIS format to the NSW Reconstruction Authority.
Preliminary Flood Planning Area	Flood Planning Levels (FPLs) are an important tool in the management of flood risk and are derived by adding a freeboard to the planning flood level. The FPLs can then be combined with topographic information to establish the Flood Planning Area (FPA). FPAs can vary from council to council depending on the flood planning controls. For the purposes of this study, two indicative FPAs have been defined. These were derived from a FPL based upon the 1 in 100 AEP flood level plus a 0.5 metre freeboard (for the broader study area) and a 1 metre freeboard (for the Penrith Lakes area, consistent with the FPA definition in the Penrith Lakes DCP). These are intended to provide an understanding of what the FPA might look like for the study area, based on what has been commonly adopted. They are not, however, intended to actually define the flood planning area. Reference should be made to the respective council policies and planning requirements to understand the specific requirements for each LGA. In addition to providing these as a series of maps for the flood study, these results have been provided in a GIS format to the NSW Reconstruction Authority.
Time Series Outputs at Key Locations	Time series outputs have also been prepared as a part of this study. These results, presented in electronic format, include peak water levels, depths and flows for each of the representative events, and have been provided to the NSW Reconstruction Authority.
Raw Model 2D results	The peak 2D model results are in GIS readable format. This allows for direct interrogation of the model results, including water levels, depths and velocities.
waterRIDE	Provides the full time series of 2D model results. This allows the variation in model outputs (e.g., depth, velocity) to be extracted at any point in the design flood simulation.
Flood Impacts	A range of additional flood simulations were completed to understand the impact of modelling uncertainty (e.g., blockage of hydraulic structures), climate change and future catchment development on existing flood behaviour. The outputs from these simulations are provided in the form of flood level difference (i.e., afflux) mapping which have been provided in a GIS format to the NSW Reconstruction Authority.
Flood Models	In addition to the above, the flood models have also been provided to the NSW Reconstruction Authority for future analysis and interrogation.

4.2 Overview of Model Results

A summary of the peak design flood levels for key reporting locations for a selection of the design events is provided in Table 4-3, with these locations shown in Figure 4-1. A more detailed discussion on peak flood levels and flooding characteristics at key locations is provided in Section 5.

Table 4-3. Peak Flood Levels at Key Reporting Locations (m AHD)

Location	River/Creek	1 in 5 AEP	1 in 20 AEP	1 in 100 AEP	1 in 500 AEP	PMF
M1 Bridge, Brooklyn	Hawkesbury River	1.3	1.4	1.5	1.9	4.4
Spencer (gauge)	Hawkesbury River	1.3	1.6	2.3	3.9	9.5
Singletons Mill	Hawkesbury River	1.6	2.5	4.2	7.3	15.8
Gunderman Caravan Park (gauge)	Hawkesbury River	1.6	2.7	4.3	7.4	15.9
Webbs Creek (Wisemans Ferry) (gauge)	Hawkesbury River	2.3	4.3	6.5	10.2	19.1
Leets Vale (gauge)	Hawkesbury River	2.7	5.2	7.8	11.5	21.2
Colo Junction (Lower Portland) (gauge)	Hawkesbury River	4.0	7.6	11.0	15.0	26.6
Sackville (gauge)	Hawkesbury River	5.6	10.3	14.0	17.5	29.4
Ebenezer (gauge)	Hawkesbury River	7.4	12.8	16.6	19.7	30.5
Gronos Point	Hawkesbury River	7.8	13.3	17.1	20.0	30.5
Richmond Road	South Creek	9.8	13.8	17.3	20.2	30.6
Windsor PWD (gauge)	Hawkesbury River	9.9	13.8	17.3	20.2	30.6
Blacktown Road	Rickabys Creek	9.6	13.8	17.4	20.2	30.6
North Richmond Bridge (gauge)	Hawkesbury River	12.3	15.6	17.5	20.2	30.6
North Richmond WPS (gauge)	Hawkesbury River	12.5	15.9	17.5	20.3	30.6
Yarramundi Bridge	Nepean River	13.0	16.9	18.0	20.5	30.6
Victoria Bridge Penrith (gauge)	Nepean River	20.9	25.2	26.8	27.9	32.7
Wallacia Weir (gauge)	Nepean River	34.9	40.9	46.0	50.7	68.2
Blaxlands Crossing (Silverdale Road)	Nepean River	36.0	41.3	46.2	50.8	68.3

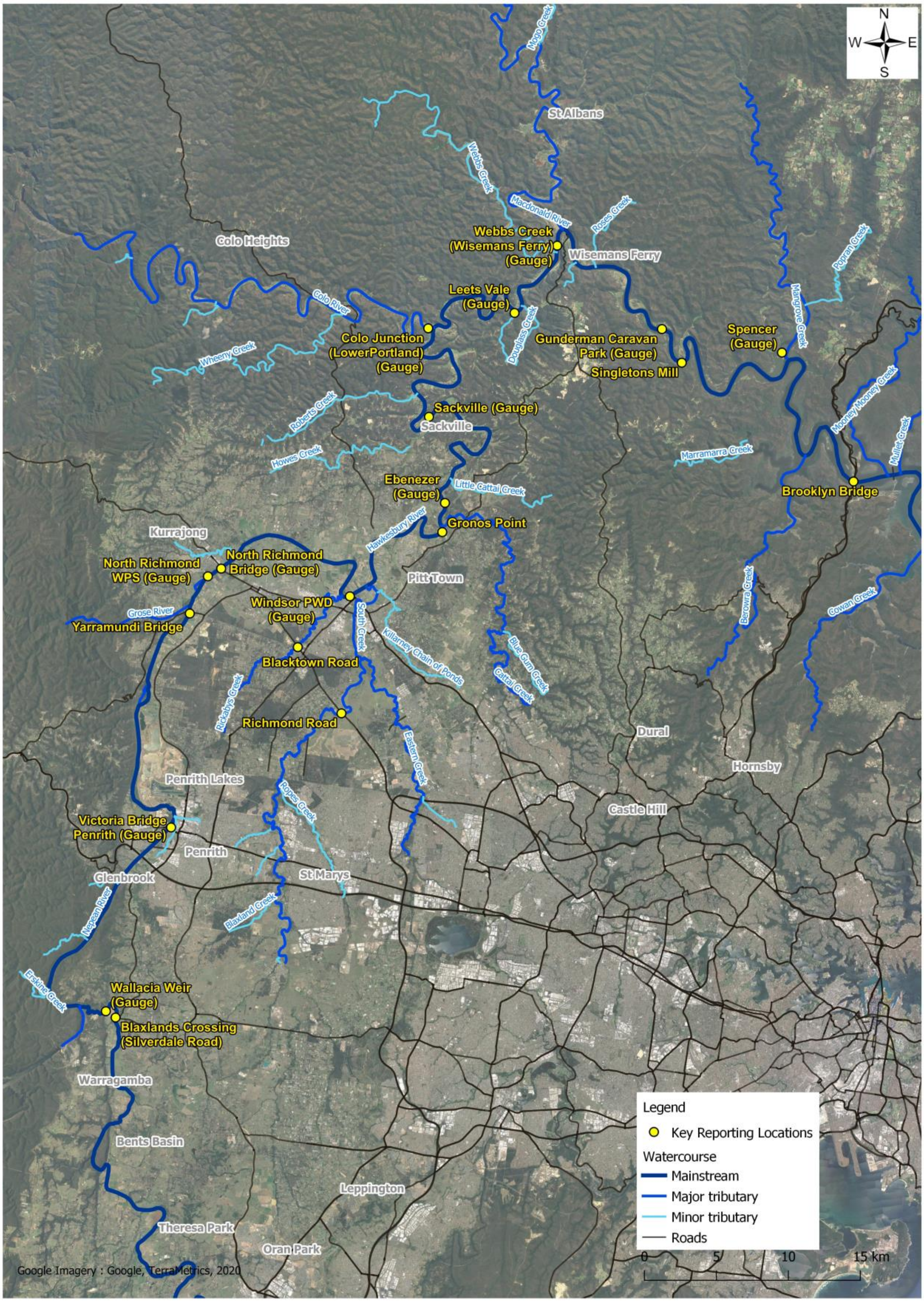


Figure 4-1. Key Flood Level Reporting Locations

4.3 Comparison with 2019 Regional Flood Study

The updated modelling approach has resulted in refinements to the representation of the hydrology and the hydraulics for the study area. This has led to some changes from previous estimates of peak flood levels.

To understand these changes, a comparison of peak flood levels is shown in Table 4-4. This lists peak flood level estimates for the RUBICON model developed for the 2019 Flood Study, the updated RUBICON Monte Carlo analysis undertaken for the current study, and the TUFLOW 2D model also undertaken for the current study.

The peak levels estimated in the current flood study are largely consistent with the 2019 Flood Study up to the 1 in 100 AEP event (Table 4-4). However, in rarer floods, the current flood study estimates higher flood levels. While there have been a number of changes as a part of the current flood study, some of the key changes influencing these levels include:

- An improved representation of the storage in the Windsor floodplain for larger, rarer events. This has been updated in both the revised RUBICON model as well as represented within the TUFLOW model. It is noted that the TUFLOW model can characterise these storage effects to a greater detail than the RUBICON model.
- Further, in more extreme events, significant storage is located in the backwater areas of South Creek and Eastern Creek. The representation of the travel lag for this storage is difficult to directly represent in a quasi-2D model like RUBICON.
- More detailed bathymetric and topographic information to better define storage characteristics across the floodplains and the conveyance capacity through the gorge areas in the TUFLOW model relative to the more sparsely located cross sections used in the RUBICON model.
- Access to detailed flood information for 4 contemporary floods (February 2020, March 2021, March 2022, and July 2022). This has demonstrated how changes across the catchment (e.g., vegetation density) have modified flood behaviour relative to 1990 which was the most recent flood available for calibration of the 2019 Flood Study RUBICON model.
- A detailed assessment of flooding in the Lower Hawkesbury was completed as part of the current study to better understand the interaction of flooding of the Colo and Macdonald rivers with the Hawkesbury River, which has a strong influence on flooding in the Lower Hawkesbury River (**Technical Volume 5**).
- An analysis was undertaken for the Nepean and Warragamba rivers, to derive a flood frequency at Wallacia based on historical data (**Technical Volume 6**).
- An improved understanding of the hydraulic behaviour of the Lower Hawkesbury River. This includes the hydraulic gradient in lower flow events, as well as the representation of bend losses in rarer events. This is discussed further in Section 5.4.3 and **Technical Volume 12**.
- For the PMF event, there have been updates to the way in which the PMF has been estimated for this flood study, as outlined in **Technical Volume 12**. This has resulted in some changes to the flows in the floodplain.

A notable difference is also observed at Victoria Bridge, and Penrith in general. This is largely driven by the changes in the floodplain in that area, as discussed in Section 5.2.2.

Table 4-4. Comparison of TUFLOW and RUBICON Peak Flood Levels (m AHD)

Location	River/ Creek	1 in 20 AEP			1 in 100 AEP			PMF*		
		2019 Flood Study (RUBICON)	2024 Flood Study		2019 Flood Study (RUBICON)	2024 Flood Study		2019 Flood Study (RUBICON)	2024 Flood Study	
			RUBICON	TUFLOW		RUBICON	TUFLOW		RUBICON	TUFLOW
Spencer	Hawkesbury River	2.0	1.8	1.6	2.7	2.6	2.3	6.8	9.2	9.4
Wisemans Ferry	Hawkesbury River	4.7	4.2	4.2	7.1	6.2	6.5	14.4	16.3	19.3
Leets Vale	Hawkesbury River	6.5	5.9	5.5	9.2	8.5	8.3	17.3	19.8	22.0
Lower Portland	Hawkesbury River	8.2	7.6	7.5	11.1	10.4	10.9	20.2	23.0	26.5
Sackville	Hawkesbury River	10.1	9.8	10.1	13.2	13.0	13.9	23.6	26.5	29.4
Windsor	Hawkesbury River	13.7	13.9	13.8	17.3	17.3	17.3	26.7	28.9	30.6
North Richmond	Hawkesbury River	15.4	15.6	15.4	17.6	17.5	17.4	26.8	28.9	30.6
Yarramundi	Nepean River	16.4	16.7	16.8	18.2	18.0	18.0	27.1	29.0	30.6
Penrith	Nepean River	23.3	23.7	25.1	25.8	25.9	26.8	32.8	32.9	32.6
Blaxlands Crossing (Silverdale Road)	Nepean River	39.4	40.5	41.3	44.7	45.0	46.2	66.3	66.4	68.3
Richmond Road	South Creek	13.7	13.8	13.8	17.3	17.3	17.3	26.7	28.9	30.6
Blacktown Road	Rickabys Creek	13.8	13.9	13.8	17.4	17.4	17.4	26.7	28.9	30.6

NOTE: * The 2019 Flood Study adopted a single PMF storm duration (72 hour storm to Penrith). The 2024 Flood Study adopted an envelope of 3 separate PMF storms (24 hours to Wallacia, 72 hour to Penrith, 96 hour to Sackville), as discussed below.

4.3.1 PMF Event

The differences between the 2019 Flood Study and the current TUFLOW model become more significant for rare and extreme events, including the PMF. For the upstream areas of the floodplain, the differences are less pronounced. For Wallacia, there is an increase of approximately 1.6 metres, while for Victoria Bridge at Penrith, the current estimate is 0.2 metres lower than the 2019 Flood Study.

The largest differences occur in the Windsor floodplain and into the Lower Hawkesbury River. In the Windsor floodplain, the 2024 Flood Study PMF is nearly 4 metres higher than the 2019 Flood Study PMF. There are several key drivers of this change:

- The use of multiple PMFs including a Sackville-focused 96 hour PMF event (**Technical Volume 12**), whereas the 2019 Flood Study used only a singular 72 hour Penrith-focused PMF event. While the peak flow for the Sackville 96 hour PMF is lower, the volume is larger than the 72 hour Penrith PMF.

The TUFLOW model estimates a peak level at Windsor from the Sackville 96 hour PMF event that is approximately 0.6 metres higher than the Penrith 72 hour PMF event.

- The representation of the Windsor floodplain and its storage has been significantly improved through the use of the most up to date terrain data and the use of the TUFLOW 2D model. Further, there is a better understanding of the outflow characteristics of the Sackville gorge under higher flows. Figure 4-2 compares the PMF flows (for the Penrith 72 hour event) at the M4 Bridge in Penrith (representative of upstream flows to Windsor) with the flows at Sackville, for the TUFLOW model, the current RUBICON model and the 2019 Flood Study RUBICON model. The 2019 model suggests much higher outflows through Sackville compared with the 2024 Flood Study, demonstrating the change in the representation of storage and outflow characteristics.
- The losses through the bends in the Lower Hawkesbury River are better understood and represented in the TUFLOW model (Section 5.4.3). These confined bends throughout the gorge have a significant impact on the flow behaviour, particularly under rare and extreme events (example of the Singletons Mill Bend is shown in Figure 4-3).

Further discussion of these differences is provided in **Technical Volume 12**.

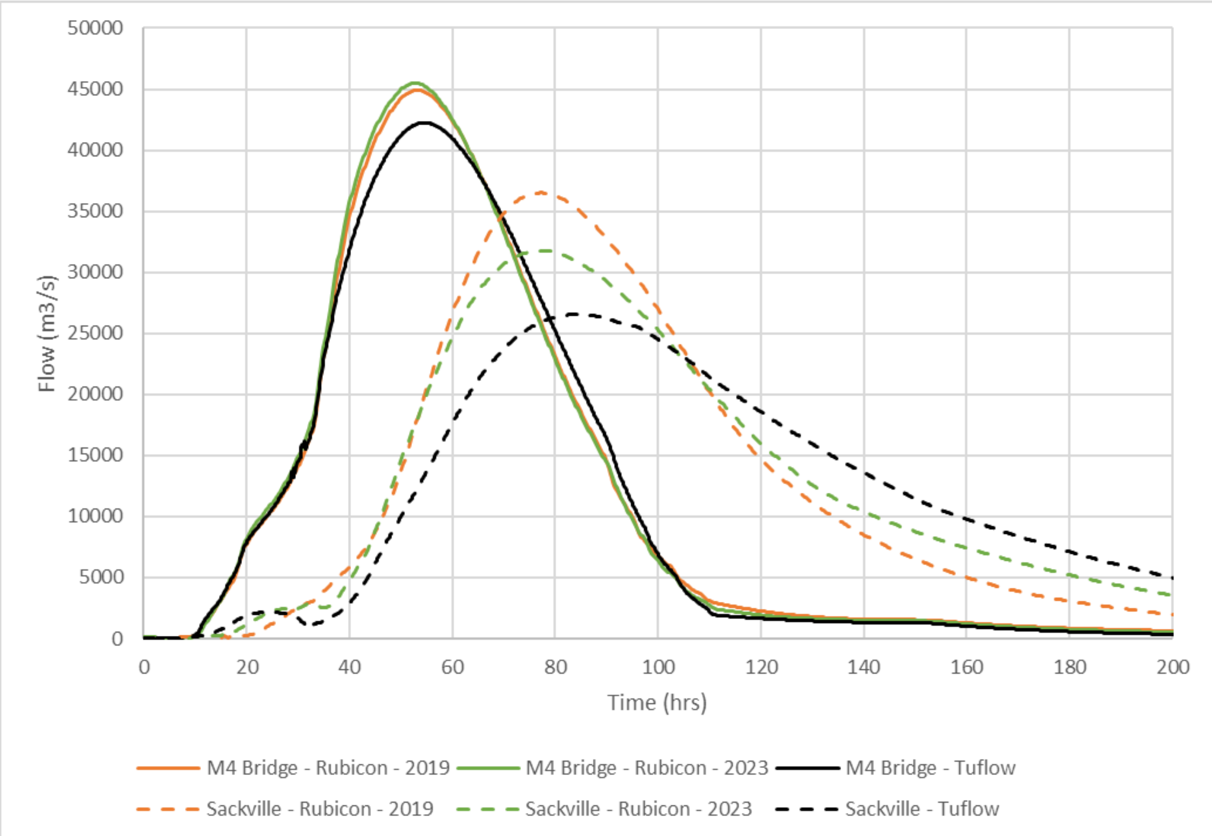


Figure 4-2. PMF Flows Comparison – Penrith 72 hour event - M4 Bridge and Sackville

Figure 4-3. Oblique View of Singletons Mill Bend - March 2021 Flood (26 March 2021, source: Adam Hollingworth)

4.4 Sensitivity Analysis

Hydraulic models require the specification of several parameters that can have a degree of uncertainty. Each of these parameters can impact on the results generated by the model.

The 2D hydraulic model developed as part of the 2024 Flood Study was calibrated against recorded historical flood information to ensure the adopted parameters were generating realistic estimates of flood behaviour. The outcomes of the calibration and validation of the hydraulic model confirmed that the model was providing realistic descriptions of flood behaviour at locations where historical flood information was available.

Nevertheless, it is important to understand how any uncertainties in model input parameters may impact the results produced by the model, particularly for floods that are beyond the magnitude of the historical events used for calibration purposes. Therefore, a sensitivity analysis was completed to establish the sensitivity of the results generated by the hydraulic model to changes in model input parameter values. The 1 in 100 AEP flood was selected for the sensitivity simulations.

The sensitivity analyses focussed on the following hydraulic model variables:

- Hydraulic roughness
- Blockage of hydraulic structures
- Hydraulic structure loss coefficients
- Ocean water levels
- Changes in bathymetry following the 2021-22 floods.

The outcomes of the sensitivity simulations are discussed in Section 5.

4.5 Climate Change

Climate change refers to a significant and lasting change in weather patterns arising from both natural and human induced processes. In 2021, the Intergovernmental Panel for Climate Change (IPCC) released the Working Group I contribution to its sixth assessment report (AR6) (IPCC, 2021). The key findings are:

- It is unequivocal that human influence has warmed the atmosphere, ocean and land. Widespread and rapid changes in the atmosphere, ocean, cryosphere and biosphere have occurred.
- Continued global warming is projected to further intensify the global water cycle, including its variability, and the severity of wet and dry events.
- It is very likely to virtually certain[6] that regional mean relative sea level rise will continue throughout the 21st century. Due to relative sea level rise, extreme sea level events that occurred once per century in the recent past are projected to occur at least annually at more than half of all tide gauge locations by 2100 (high confidence). Relative sea level rise contributes to increases in the frequency and severity of coastal flooding in low-lying areas and to coastal erosion along most sandy coasts.

It is therefore important to provide an assessment of the potential impact that climate change may have on the flood risk across the study area.

The 'NSW Coastal Planning Guideline: Adapting to Sea Level Rise' (Department of Planning, 2010) provides guidance on the expected impacts that climate change may have on sea levels. The 'NSW Sea Level Rise Policy Statement' (Department of Environment and Climate Change, 2009) states that ocean level increases of 0.4 metres could be expected by 2050 and a 0.9 metre increase could occur by 2100.

IPCC (2021) medium confidence projections of sea level rise for Fort Denison range from 0.39 m (+/- 0.19m) to 0.78 m (+/- 0.28) by 2100 (relative to a baseline of 1995-2014)[7]. These values are generally in the range of the DECC (2009) advice.

The interim climate change factors published on the Australian Rainfall and Runoff Data Hub (Ball et al, 2019) were used to undertake an assessment of the potential impacts of rainfall intensity increases on existing flood behaviour. The interim climate change factors indicate that a 9.5% increase in rainfall is the best estimate of likely rainfall intensity increases by 2090 under Representative Concentration Pathway scenario 4.5 (RCP4.5) (i.e., greenhouse gas emissions increase to 2040 and then reduce to 2100). Under RCP 8.5 conditions (i.e., current greenhouse gas emissions increase in the future), rainfall intensities are predicted to increase by 19.7% by 2090[8].

These sea level rise and rainfall projections were tested on the 1 in 20 AEP, 1 in 100 AEP and 1 in 500 AEP design flood simulations. The climate change assessment considered the following scenarios:

- sea level rises by 0.4m and 0.9m

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[6] Very Likely refers to a probability of 90 – 100% , while Virtually Certain refers to a 99 – 100% probability (IPCC, 2010)

[7] https://sealevel.nasa.gov/ipcc-ar6-sea-level-projection-tool?psmsl_id=65, accessed 3 February 2022

[8] Note that under AR6 (IPCC 2021), the concept of Representative Concentration Pathways (RCP) has been further developed and is instead referred to as Shared Socio-economic Pathways (SSP). However, at the time of the current study, updates to the interim factors from the ARR2019 Data Hub had not been completed to allow for any transition from those interim factors under various RCPs to an equivalent SSP.

- rainfall intensity increases by 9.5% and 19.7%
- a combination of increased rainfall intensity and increased sea level (0.4m and 9.5%; 0.9m and 19.7%).

The results of the climate change simulations are discussed in Section 5.

4.6 Cumulative Development Assessment

It's important to understand how future development in the Hawkesbury-Nepean catchment could potentially impact flood conditions and flood risk in the Valley. Therefore, a preliminary, regional assessment of future catchment development was undertaken to understand the potential changes to flood behaviour as a result of development within the catchment as well as changes to the floodplain itself. The assessment involved testing:

- Increases in development in the catchment, leading to increased imperviousness. Conservative assumptions were made on the spatial extent, and density of development, likely to occur in the catchment. Most of the development was anticipated to occur in the Nepean River and South Creek catchments.
- Filling within the floodplain to facilitate development. Testing was undertaken by assuming that areas zoned for residential development between the 1 in 100 AEP and 1 in 200 AEP were filled to the 1 in 200 AEP flood level. This assessment focused on areas of the floodplain around Windsor and South Creek that are zoned for urban uses but are yet to be developed.

It is important to note that the assessment undertaken does not necessarily represent approved development landforms or densities. This assessment has been undertaken on a regional scale to provide an understanding of the potential influence/sensitivity of development on flooding. Further details on the assumptions that were adopted as part of the cumulative development assessment are provided in **Technical Volume 11**.

Changes to catchment imperviousness as a result of increases in development suggest relatively minor changes in flood levels. In the 1 in 100 AEP event, the highest increase in peak flood level in the study area is modelled for Colo Junction (0.12m), with an increase of 0.05m at Windsor. Increases of around 0.1m are modelled for the Windsor floodplain in the 1 in 5 AEP event.

The assessment of the impact of filling suggests that there would be no increases in peak flood levels.

It should be noted that the assessment assumed there would be no mitigation measures implemented (e.g., construction of detention basins). Development consent would typically require developments to demonstrate no increases in existing design flows and/or adverse flood level impacts. Therefore, the reported flood impacts are considered to be conservative.

Further, as with the overall flood study, the focus of the study is on flood behaviour in the Hawkesbury-Nepean floodplain including backwater flooding. Development may have different influences on the various tributaries (such as South Creek), and these are not represented here. An assessment of the impacts of possible development scenarios in the South Creek Catchment on local catchment flooding in the South Creek floodplain was published in January 2023 (Advisian, 2023).

Further details are provided in **Technical Volume 11**.

4.7 Evacuation Events

The focus of the flood study is defining mainstream flooding along the Hawkesbury and Nepean rivers. For smaller watercourses/tributaries that are not the focus of the current study, flows from the hydrologic model were generally applied to the hydraulic model at the location where each watercourse joins the Hawkesbury and Nepean rivers.

However, to assist in evacuation planning, emergency management agencies such as the NSW State Emergency Service (SES) require an understanding of the overtopping behaviour of key roads, bridges and culverts, which limits or hinders evacuation from certain areas. In this regard, on a number of tributaries, there is the potential for local flooding in these tributaries to cut off access or isolate areas for a period of time. This local catchment flooding may occur earlier than the main river flood and, therefore, it is important to understand the available warning time on these tributaries to assist with emergency response planning.

Therefore, a modified "Evacuation Route" hydraulic model was developed. This model adopted the base hydraulic model described in **Technical Volume 11** (including the updates described in preceding sections of this chapter). However, the inflow boundaries were relocated further upstream within key tributaries.

This Evacuation Route hydraulic model was established to assess a specific set of representative events from the Monte Carlo analysis. These representative events include both Hawkesbury-Nepean riverine flood events as well as flood events for the key tributaries to provide an understanding of access and evacuation issues. The outputs from this model have been provided electronically to NSW SES to assist with emergency management planning.

5 Flood Behaviour

Given its extensive nature, the flood behaviour varies throughout the study area. For the purposes of this report, the study area has been discussed according to 4 main areas: Wallacia, Penrith, Windsor/ South Creek and Lower Hawkesbury. A summary of the flood behaviour in these areas is provided in the following sections.

It is noted that the flood descriptions here make reference to “small”, “medium” and “large” floods. These flood descriptors reflect the full range of potential flood sizes and are not consistent with the Bureau of Meteorology’s “minor”, “moderate” and “major” flood consequence categories. This is because the Bureau of Meteorology’s categories do not fully describe the consequences associated with the full range of potential floods within the Hawkesbury-Nepean Valley.

5.1 Wallacia

5.1.1 Flood Behaviour

The Wallacia floodplain is located between Bents Basin upstream and Wallacia Weir downstream. An overview of the floodplain, for a range of flood events, is shown in Figure 5-1.

The Nepean River, which emerges from a gorge into Bents Basin, is the main driver of flooding in smaller flood events. For these smaller flood events, flooding across the Wallacia floodplain is largely controlled by the capacity of the gorge downstream of Wallacia Weir. Once the outflow capacity of the gorge is exceeded, the excess water “builds up” behind the gorge creating what is referred to as a “bathtub” effect (i.e., the gorge effectively functions as the drain to the Wallacia bathtub). An overview of the key features is shown in Figure 5-2 and Figure 5-3.

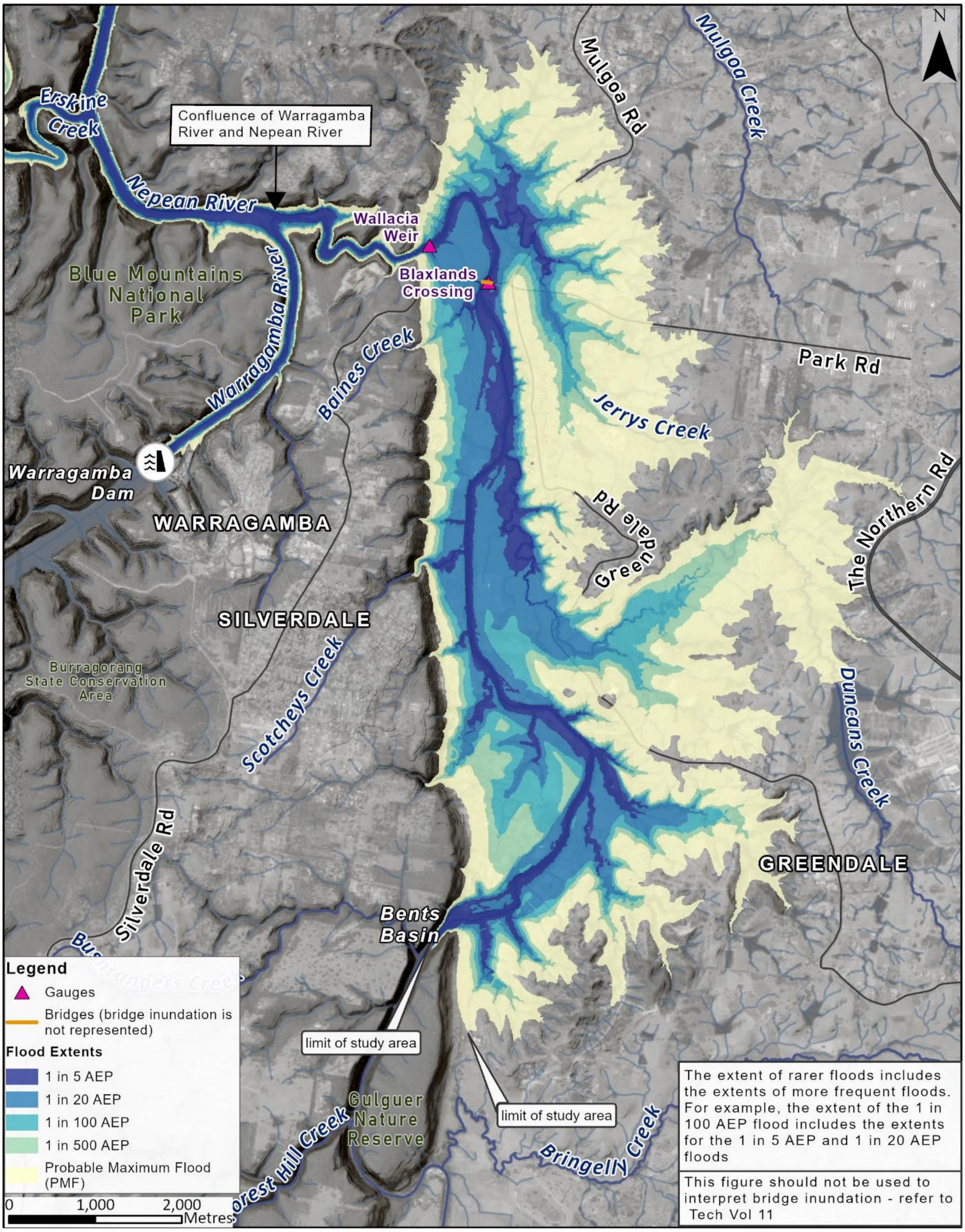

Figure 5-1. Wallacia Flood Extents

Figure 5-2. View of Bents Basin and the Gorge Upstream (Left), Norton Basin and the gorge downstream of Wallacia Weir (right) (26 March 2021)

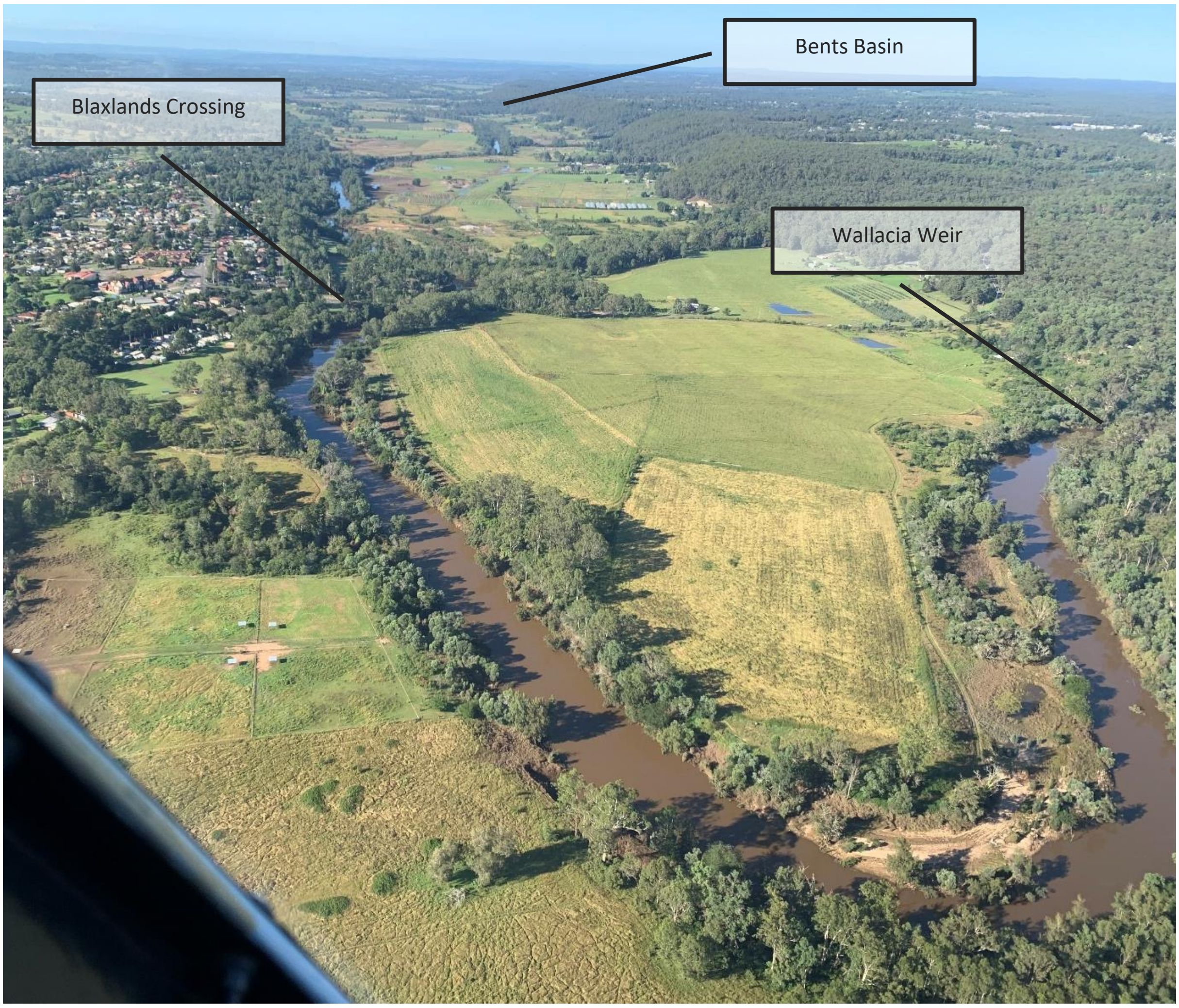

Figure 5-3. General Overview of Wallacia (26 March 2021)

Figure 5-4 shows flood behaviour at Wallacia for a 1 in 200 AEP event. There are high velocities downstream of Wallacia Weir as flows are "choked" in the gorge. However, upstream of the gorge itself, velocities are significantly lower, generally less than 2m/s. This illustrates that although the velocities within the channel are lower than the gorge, they are still important for the conveyance of flood flows. Away from the main channel, such as the backwater areas on Jerrys Creek, velocities drop below 0.5m/s.

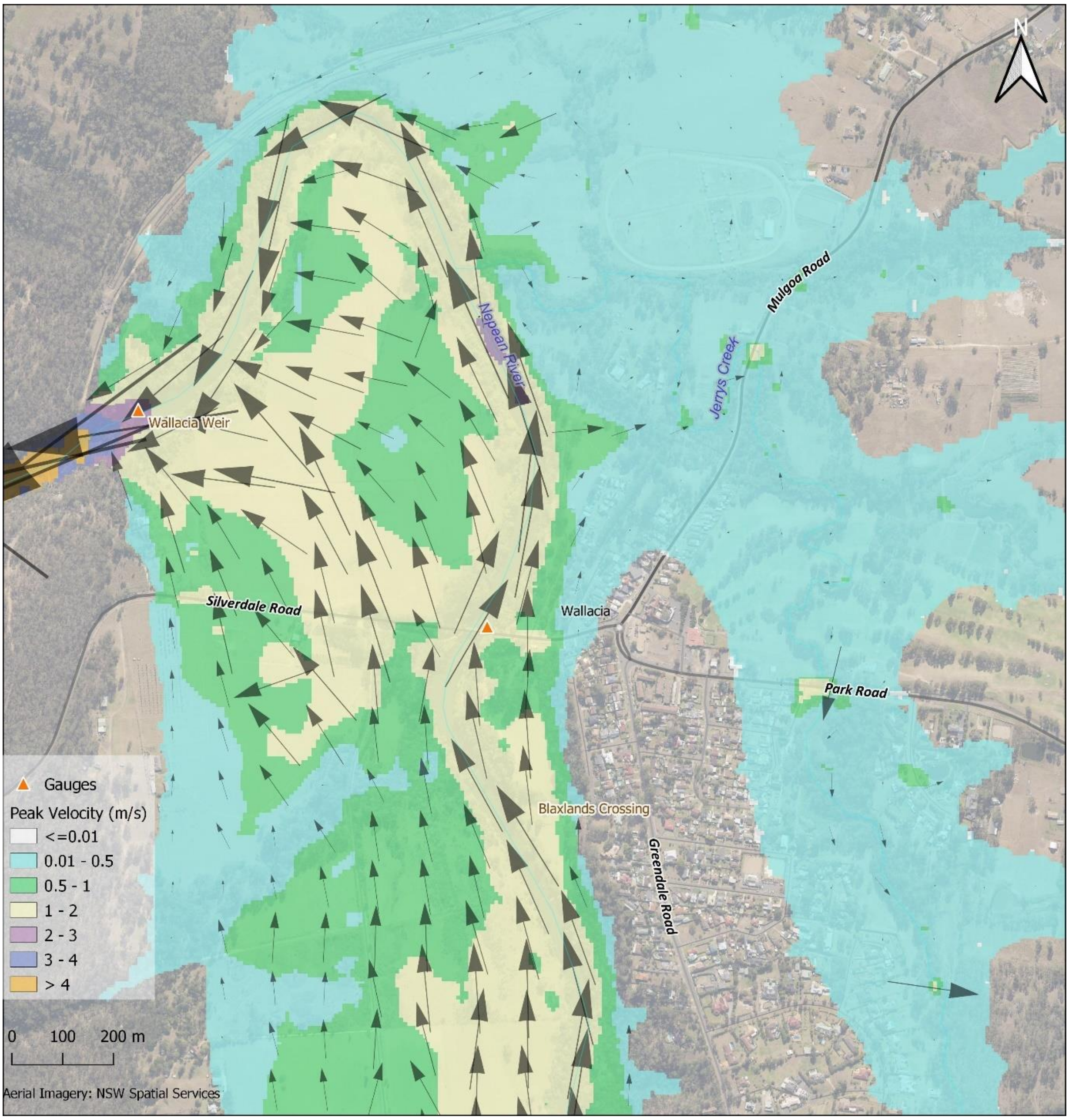

Figure 5-4. 1 in 200 AEP Peak Velocity at Wallacia[9]

In very large, less frequent flood events, large Warragamba Dam outflows become sufficiently constrained in the gorge downstream of the Nepean River and Warragamba River junction to create a backwater effect on the Wallacia floodplain. This can be seen in the flood profiles (Figure 5-5) where

[9] Arrows represent the direction of flow, with the size representative of the magnitude of the velocity.

the water level gradient between Wallacia Weir and Warragamba Junction reduces for larger events. This backwater influence further limits the amount of water that can flow downstream of Wallacia Weir. As outlined in Section 3.6.1, the interaction of flooding from the Nepean and Warragamba rivers was assessed as part of the Wallacia joint probability assessment and the outcomes of this assessment were used to inform the Monte Carlo assessment to ensure reliable flood estimates were provided for Wallacia.

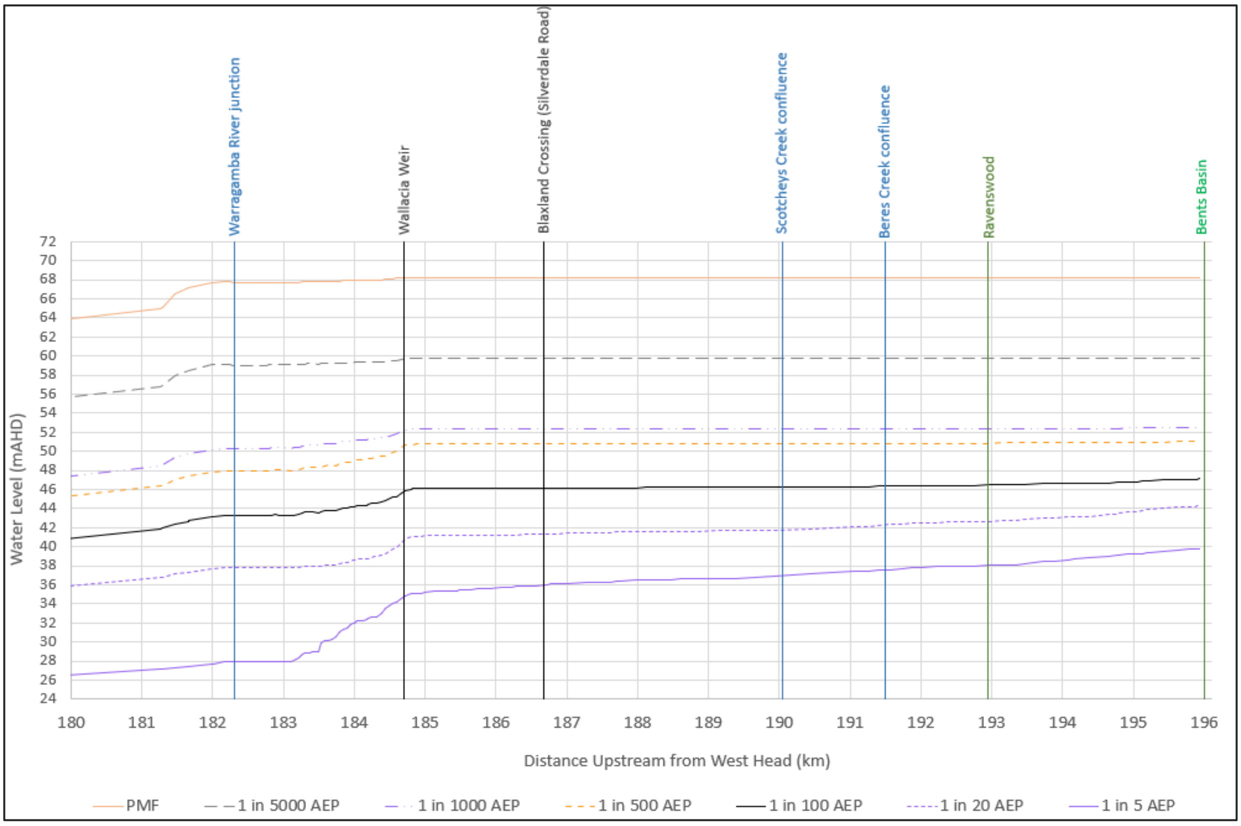

Figure 5-5. Flood Profile - Wallacia Floodplain

In large Warragamba River catchment events, there is potential for flows at the Nepean and Warragamba River junction to reverse, with flows travelling upstream along the Nepean River and spilling back into Wallacia. However, the potential for reverse flow can be tempered by flows in the Nepean River, with the combined momentum of flows from the Nepean and Warragamba rivers driving water in a downstream direction.

Due to the constraints of the downstream gorge, together with these backwater impacts from Warragamba Dam outflows, there is a very large range in peak design water levels at Wallacia. Peak water levels at Wallacia Weir and Blaxlands Crossing are shown in Table 5-1. Peak water levels between the 1 in 5 AEP and PMF events vary by more than 30 metres, with the PMF event over 20 metres higher than the 1 in 100 AEP.

Table 5-1. Peak Water Level Summary - Wallacia Weir

Design Event (AEP)	Peak Water Level			
	Wallacia Weir		Blaxlands Crossing (Silverdale Road)	
	m AHD	GH*	m AHD	GH*
1 in 2	30.0	3.4	30.5	4.1
1 in 5	35.0	8.4	36.0	9.6
1 in 10	38.3	11.7	39.1	12.7
1 in 20	40.9	14.3	41.3	14.9
1 in 50	44.2	17.6	44.4	18.0
1 in 100	46.0	19.4	46.2	19.8
1 in 200	48.1	21.5	48.2	21.8
1 in 500	50.7	24.1	50.8	24.4
1 in 1000	52.3	25.7	52.4	26.0
1 in 2000	55.7	29.1	55.7	29.3
1 in 5000	59.7	33.1	59.7	33.3
PMF	68.2	41.6	68.3	41.9

**GH – Gauge Height. Wallacia Weir gauge zero = 26.596m AHD, Blaxlands Crossing gauge zero = 26.44m AHD*

The gorge upstream of Bents Basin also serves as a significant control during large floods. The constrained capacity of the gorge results in floodwater during the PMF "building up" upstream of the gorge, backing up Bringelly Creek and then spilling north across existing farmland and re-joining the Nepean River at Bents Basin. This flowpath that is activated during the PMF is shown in Figure 5-6. (This PMF floodway was also identified in the Nepean River Flood Study [Worley Parsons, 2015]).

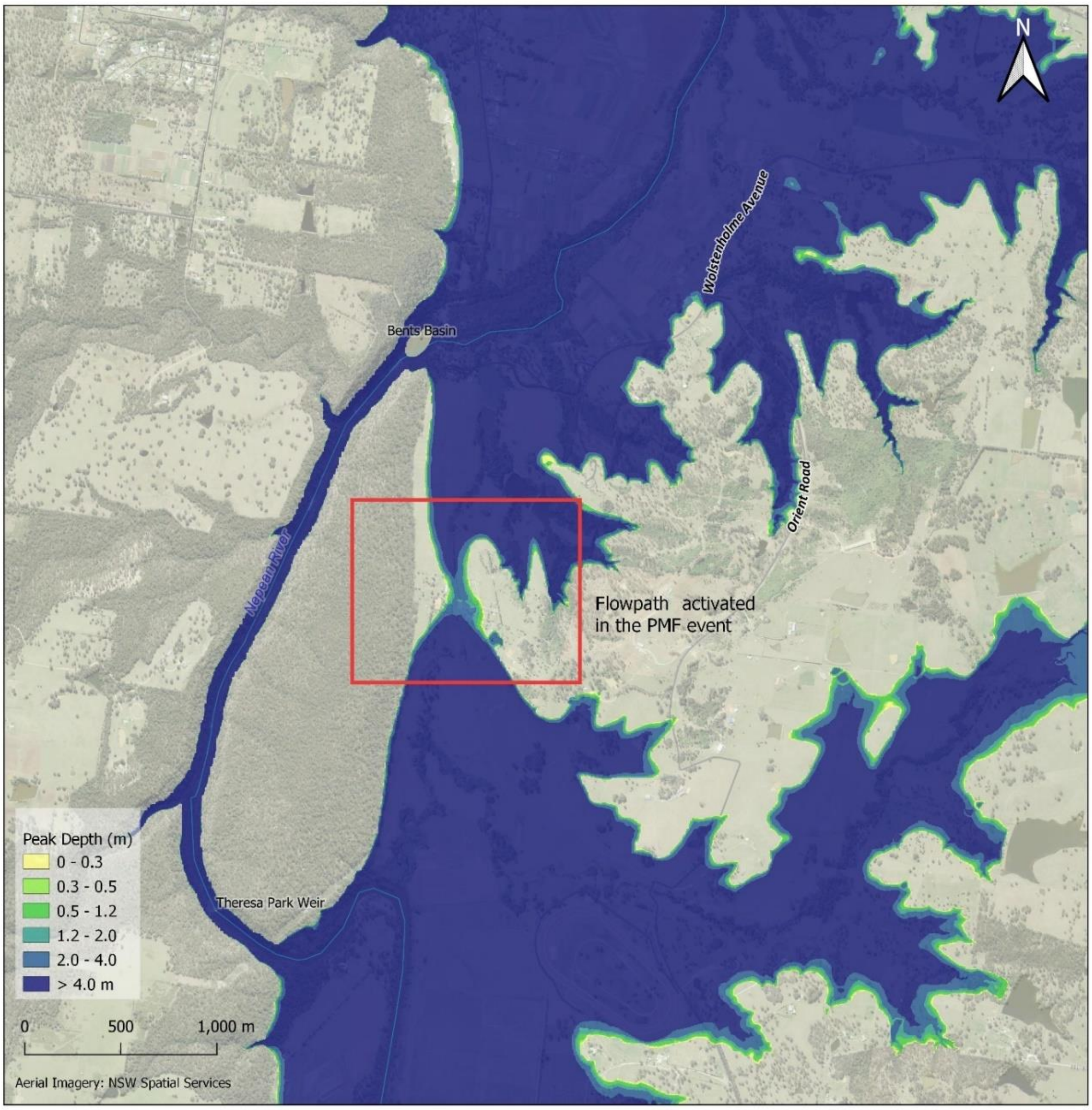

Figure 5-6. Flowpath through Greendale activated in PMF event

5.1.2 Model Sensitivities and Uncertainties

Flood behaviour at Wallacia is complex, being a function of the interaction in flows in both the Nepean and Warragamba rivers. Significant work has been undertaken in this study to understand this complex interaction, as summarised in **Technical Volume 6**. This has provided an improved understanding of the level and frequency of flooding based on historical flood data and has provided a key input to the subsequent flood analysis.

The Wallacia floodplain is not sensitive to assumptions on ocean water levels or hydraulic structure parameters (e.g., blockage). However, with its key control being the gorge downstream of Wallacia Weir, it is sensitive to the hydraulic characteristics of this gorge. Calibration and verification of the model were undertaken to ensure that the gorge characteristics were represented appropriately in the model. However, to understand the potential uncertainty in the model results, sensitivity testing of the model roughness was undertaken. This involved modifying the adopted roughness coefficients in the model to the upper and lower limits of suggested roughness ranges documented in Australian Rainfall and Runoff (Ball et al, 2019), and re-simulating the 1 in 100 AEP flood. The result of this assessment suggests a potential variance in peak 1 in 100 AEP flood levels in the order of ±1 – 1.5 metres.

5.1.3 Climate Change

Modelling was also undertaken to assess the potential influences of climate change on flooding around Wallacia.

While the Wallacia floodplain is not sensitive to sea level rise, it is influenced by potential changes in rainfall intensity. In the 1 in 100 AEP event, peak water levels increase by 1.4 metres for a 9.5% increase in rainfall and 2.9 metres for a 19.7% increase in rainfall. For the 1 in 500 AEP event, the peak water levels increase by up to 4.2 metres for a 19.7% increase in rainfall. Based on this assessment, a future 1 in 100 AEP event peak water level would be higher than the existing 1 in 200 AEP event.

5.2 Penrith

5.2.1 Flood Behaviour

The Penrith floodplain, for the purposes of this report, extends from upstream (south) of the M4 Motorway, where the Nepean River emerges from the gorge, to downstream (north) of Penrith Lakes. A general overview of the flood extents is shown in Figure 5-7, while Figure 5-8 and Figure 5-9 provide some aerial perspectives of the area.

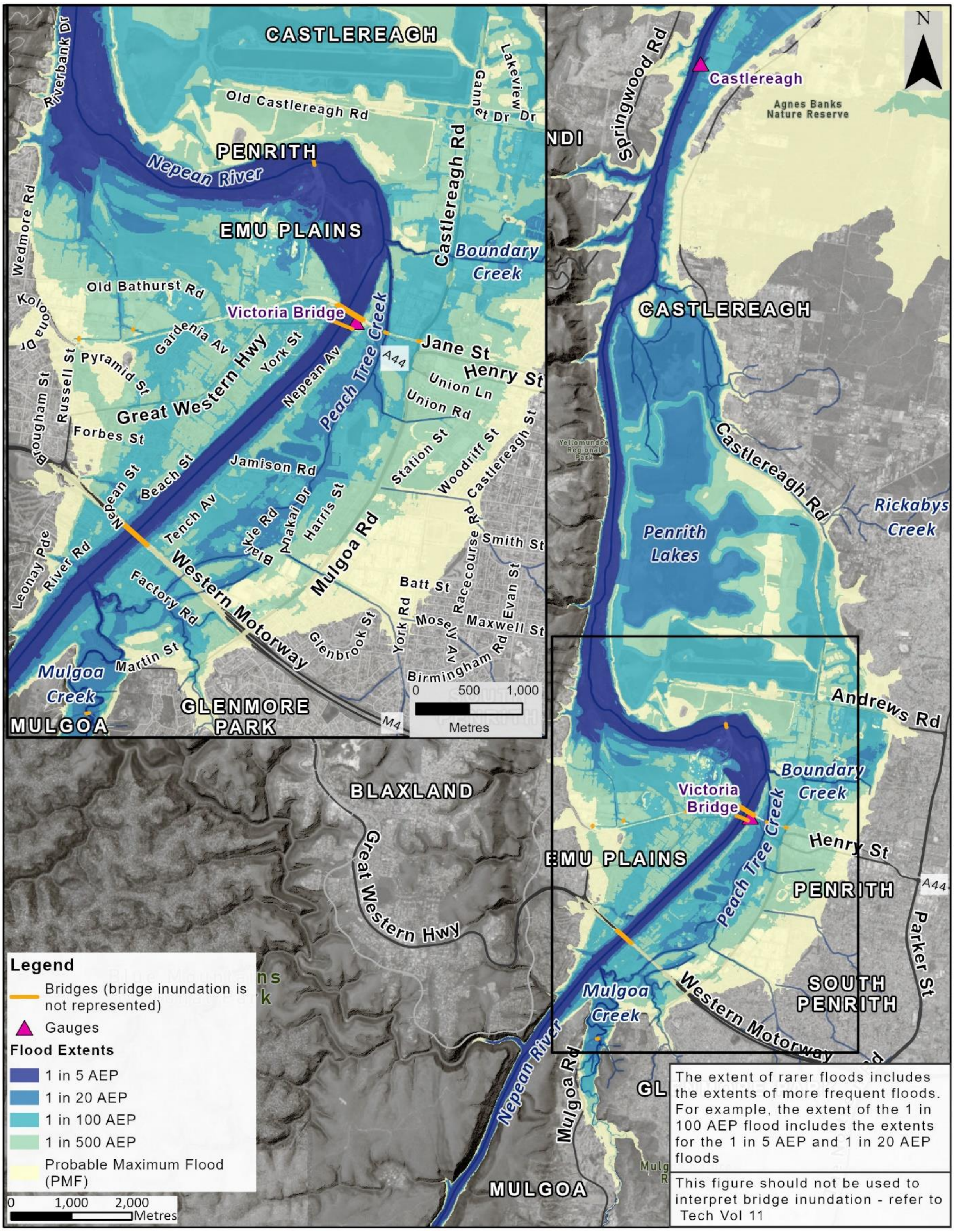

Figure 5-7. Penrith Flood Extents

Figure 5-8. Looking upstream toward M4 Bridge (left), looking downstream to Victoria Bridge and Penrith Lakes (right) (26 March 2021)

Figure 5-9. View from downstream looking toward Victoria Bridge and Penrith Weir (26 March 2021)

Unlike Windsor and Wallacia, the flooding in Penrith is largely driven by the conveyance capacity of the channel, rather than the 'bathtub' effect created by the downstream gorges. Therefore, the flood levels through this area are more closely correlated with peak flow rather than the volume of runoff during floods. Flooding in this area is primarily driven by a combination of Warragamba River and Nepean River flows, although Erskine Creek and Glenbrook Creek both contribute flow, with an appreciable contribution in smaller events like February 2020.

Larger flood events are generally dominated by Warragamba Dam spills into the Warragamba River. Figure 5-10 shows the modelled flows from the March 2021 event, together with the water level at the Victoria Bridge gauge. The flows arriving at Penrith in the March 2021 event were largely driven by Warragamba Dam outflows, with less than 20% of the peak flow from Nepean River. A similar pattern is observed for the 1 in 20 and 1 in 100 AEP critical events, shown in Figure 5-11 and Figure 5-12.

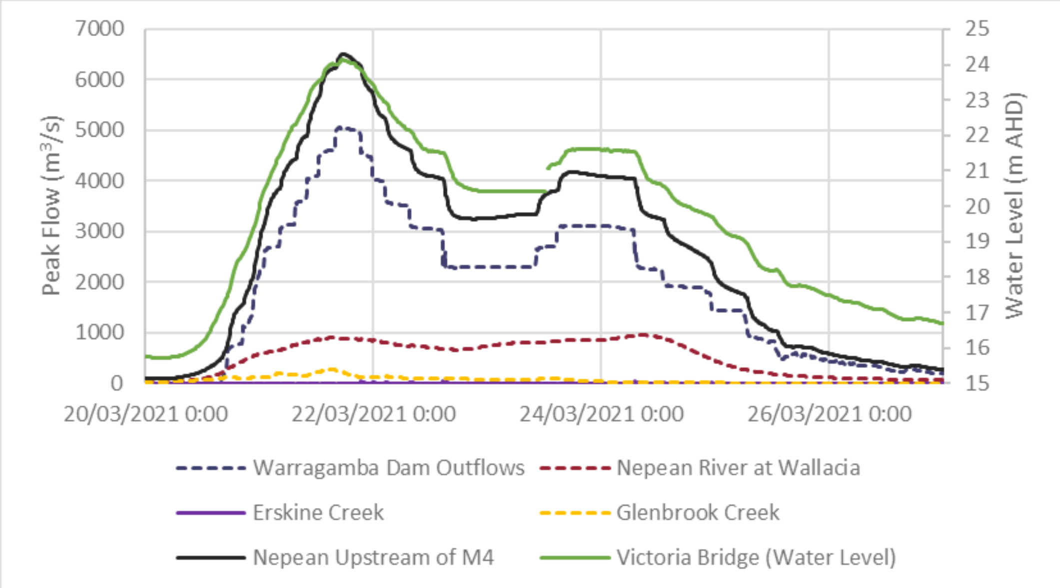

Figure 5-10. March 2021 Inflows and Peak Water Level at Victoria Bridge[10]

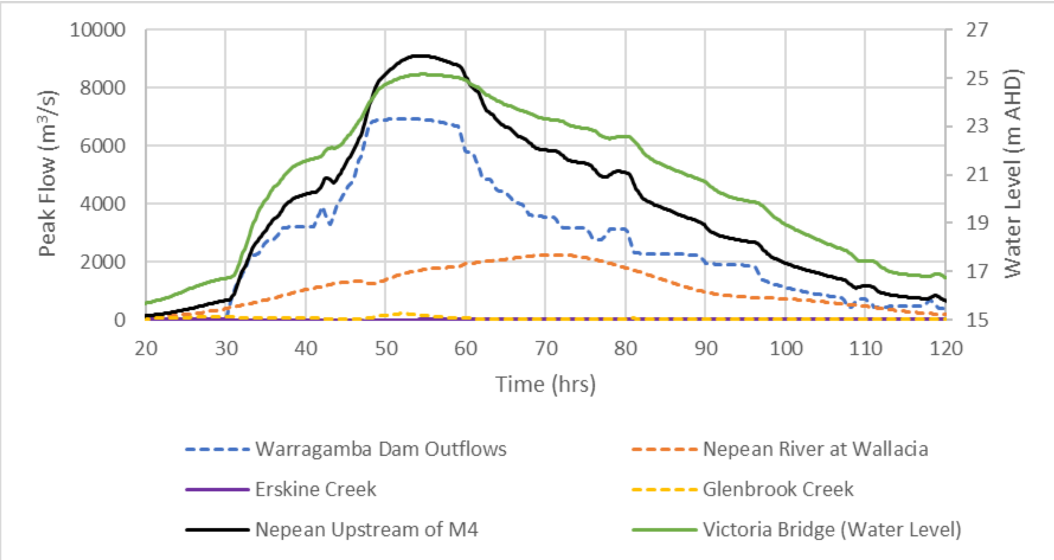

Figure 5-11. 1 in 20 AEP Inflows and Peak Water Level at Victoria Bridge

[10] Victoria Bridge water levels are based on gauge recordings.

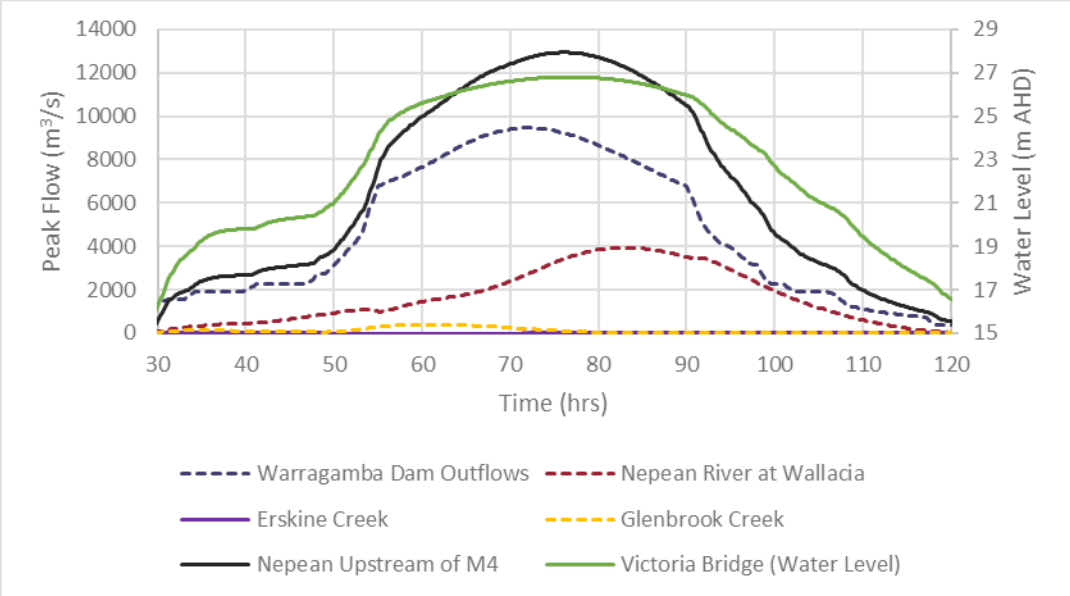

Figure 5-12. 1 in 100 AEP Inflows and Peak Water Level at Victoria Bridge

On the eastern side of the Nepean River floodplain, smaller flood events backwater up Mulgoa and School House creeks and flow through culverts under the M4. Floodwaters also backwater up Peach Tree Creek, resulting in inundation in the area between Mulgoa Road and the Nepean River. However, the Nepean riverbank itself does not overtop until events greater than the 1 in 50 AEP.

Further north, backwater flooding occurs up Boundary Creek, flowing toward Andrews Road in events between a 1 in 20 and 1 in 50 AEP event. In events larger than a 1 in 50 AEP, flow moves into the lakes on the eastern side of Penrith Lakes. This flow overtops into the main lake of Penrith Lakes between a 1 in 50 and 1 in 100 AEP event, along a dedicated flow path within the Penrith Lakes area.

On the western side of the floodplain, backwater up Jamison Creek near the M4 starts to inundate the Emu Plains floodplain in events of 1 in 50 AEP and greater. This flow then makes its way northward, controlled by the rail line across the floodplain. This inundation becomes widespread in events larger than the 1 in 100 AEP.

Figure 5-13 provides an overview of the 1 in 200 AEP peak velocity in the Peach Tree Creek and Emu Plains parts of the floodplain. During the 1 in 200 AEP event, more extensive overtopping of the riverbank occurs on both the western and eastern sides. This is demonstrated by the velocities shown in Figure 5-13, showing, for example, the higher overtopping velocities on Tench Avenue as the riverbank overtops more extensively.

Peak water levels at Victoria Bridge are summarised in Table 5-2.

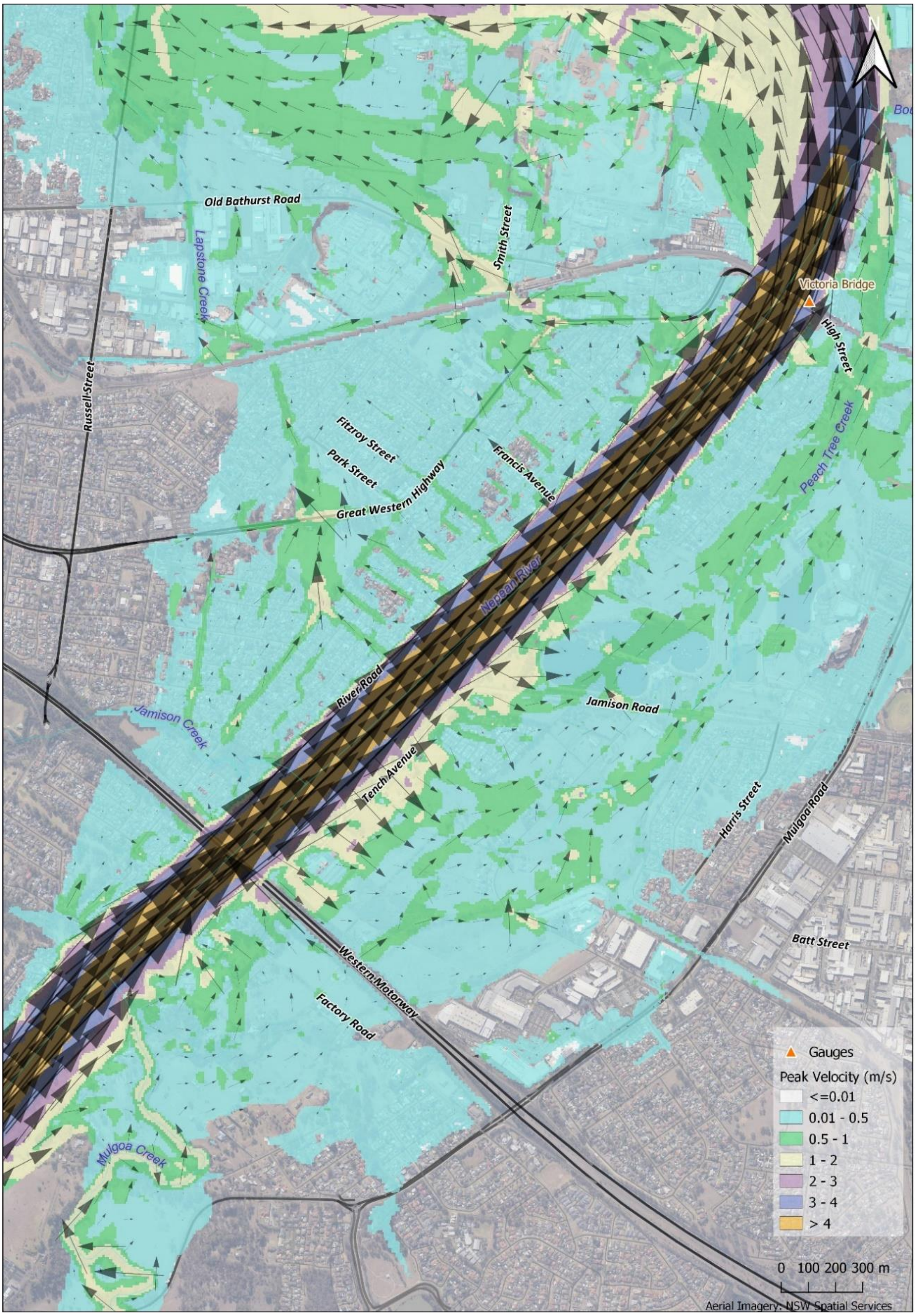

Figure 5-13. Peak 1 in 200 AEP Velocity - Penrith[11]

[11] Arrows represent the direction of flow, with the size representative of the magnitude of the velocity.

Table 5-2. Peak Water Level Summary – Victoria Bridge (Penrith)

Design Event	Victoria Bridge	
	m AHD	GH*
1 in 2	17.3	3.2
1 in 5	20.9	6.8
1 in 10	23.3	9.2
1 in 20	25.2	11.1
1 in 50	26.2	12.1
1 in 100	26.8	12.7
1 in 200	27.3	13.2
1 in 500	27.9	13.8
1 in 1000	28.3	14.2
1 in 2000	29.1	15.0
1 in 5000	30.0	15.9
PMF	32.7	18.6

**GH – Gauge Height. Penrith gauge zero = 14.139m AHD*

5.2.2 Changes in the Floodplain

The TUFLOW model adopts a vegetation condition in the area around Penrith that is generally representative of the conditions in early 2021, prior to the March 2021 event. The following provides a discussion on the changes up until 2021, and then the changes that have occurred as a result of the March 2021, March 2022 and July 2022 events.

Changes up to 2021

The vegetation in the area downstream of Victoria Bridge has changed dramatically over the last 80 years, with some of the most significant changes in the period from 1990 through to present day. These changes have resulted in an increase in the hydraulic roughness in this area particularly since 1990, resulting in higher flood levels especially in the area around Emu Plains and Penrith. An overview of the vegetation changes is shown in Figure 5-14 to Figure 5-16.

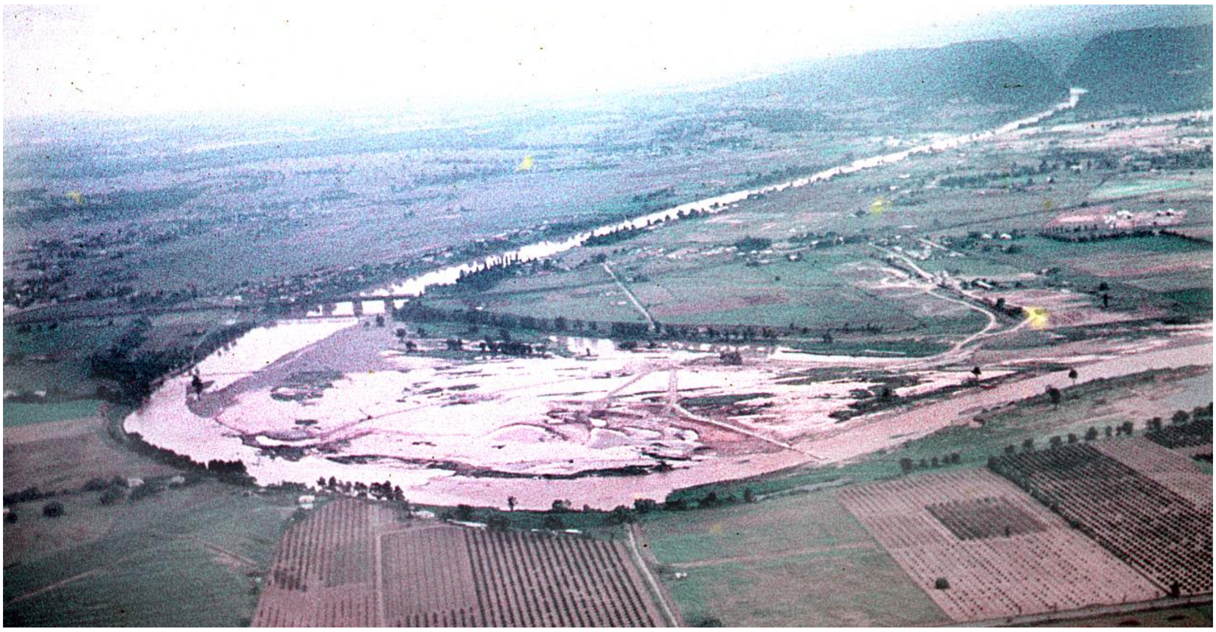

Figure 5-14. Oblique Aerial of Penrith Floodplain - 1962 (source : Penrith City Council Library)

Figure 5-15. Aerial Image of Penrith Floodplain – 1988 (source : Penrith City Council)

Figure 5-16. Aerial Image of Penrith Floodplain - October 2020 (source : Nearmap)

Comparisons between the more contemporary March 2021 and February 2020 floods, to the August 1990 flood and earlier, demonstrate this change. Figure 5-17 provides a comparison between the peak flows for each event with the peak levels at Victoria Bridge. Although March 2021 had a significantly lower peak flow than November 1961, the peak levels are relatively similar (the flooding in both of these events is shown in Figure 5-18). Similarly, the peak flows in June 1975 were similar to March 2021, however, the March 2021 event was nearly 2 metres higher. The second peak of the March 2021 event was a similar order of magnitude flow to the August 1986 event, yet the March 2021 event produced a peak water level that was over 1.5 metres higher.

The changes identified above are carried over to the design flood modelling results. Compared to the 2019 Flood Study, the current study produces flood levels that are approximately 1.8 metres higher in the 1 in 20 AEP event and 1.0 metre higher in the 1 in 100 AEP event. Similarly, compared to the 2018 Nepean River Flood Study, the current study produces flood levels that are 1.7 metres higher in the 1 in 20 AEP event and 0.5 metres higher in the 1 in 100 AEP event.

Modelling of a representation of the 1990 roughness was undertaken to understand the relative changes that have occurred in the floodplain. Consistent with the above analysis, this hydraulic assessment suggests that the 1 in 100 AEP level at Victoria Bridge is roughly 0.9 metres higher under 2021 vegetation conditions than it would be under 1990 vegetation conditions.

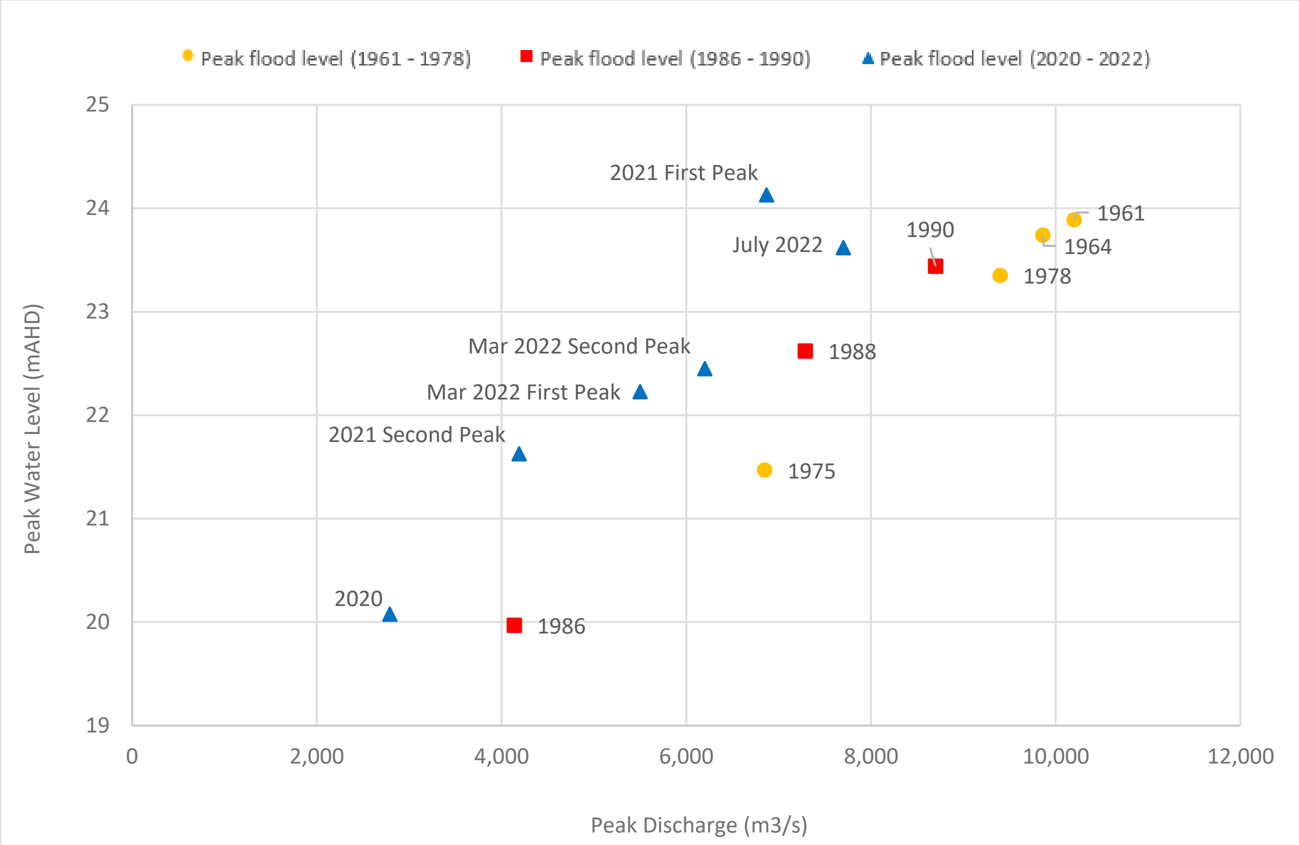

Figure 5-17. Comparison of Historical Peak Water Levels and Discharges at Victoria Bridge Gauge[12]

Figure 5-18. View of Flooding Downstream of Victoria Bridge (left : 1961[13], right : 2021[14])

Changes from 2021 to 2022

With 3 significant floods in a 15-month period, there was limited opportunity for the vegetation to recover between flood events. An example of the changes around McCanns Island downstream of Penrith is shown in Figure 5-19.

These changes have resulted in a change to the hydraulic behaviour around Penrith in each sequential flood. The rating curves estimated for Victoria Bridge from the TUFLOW model for March 2021, March

[12] Flows for 2021 estimated from gauging & cross checked against modelling. Flows for other events based on model estimates
[13] Source: Penrith City Library. Photo: Nepean Rowing Club
[14] Source: Infrastructure NSW. Photo: Adam Hollingworth

2022 and July 2022, as described in **Technical Volume 10**, are shown in Figure 5-20. These show that for a flow of 5000m^3/s, peak levels with the July 2022 vegetation conditions can be around 1.5 metres lower than the March 2021 vegetation conditions.

Post July 2022 Vegetation

There is evidence of some vegetation recovery in the 12 months following the July 2022 event. Comparisons of aerial imagery are provided in Figure 5-21 and Figure 5-22. This suggests that the roughness may progressively increase in coming years unless further flood events occur.

Design Event

The design event modelling has adopted the March 2021 conditions at Penrith to determine the design flood levels. This is intended to recognise the historical patterns of flood dominated and non-flood dominated regimes which accounts for extended periods with few floods which would permit vegetation to re-establish. However, it is important to note that flood levels could be lower in this area should flooding occur after numerous larger floods where vegetation densities are lower.

Conversely, the area has been subject to progressive vegetation re-establishment since the 1960s and 1970s, which is a result of improved land-use practices in this area. Should this longer term trend continue, together with a longer period of limited flooding, then there is the potential that vegetation could be denser than that which has been assumed, resulting in higher flood levels.

Further analysis of these changes in the Penrith floodplain is provided in **Technical Volume 11**.

5.2.3 Model Sensitivity and Uncertainty

As identified above, the Nepean floodplain is largely driven by conveyance. As outlined in the previous section, the changes in the channel vegetation over the last 30 years have resulted in reasonably large changes in flood levels, in the order of 0.9 metres in the 1 in 100 AEP event.

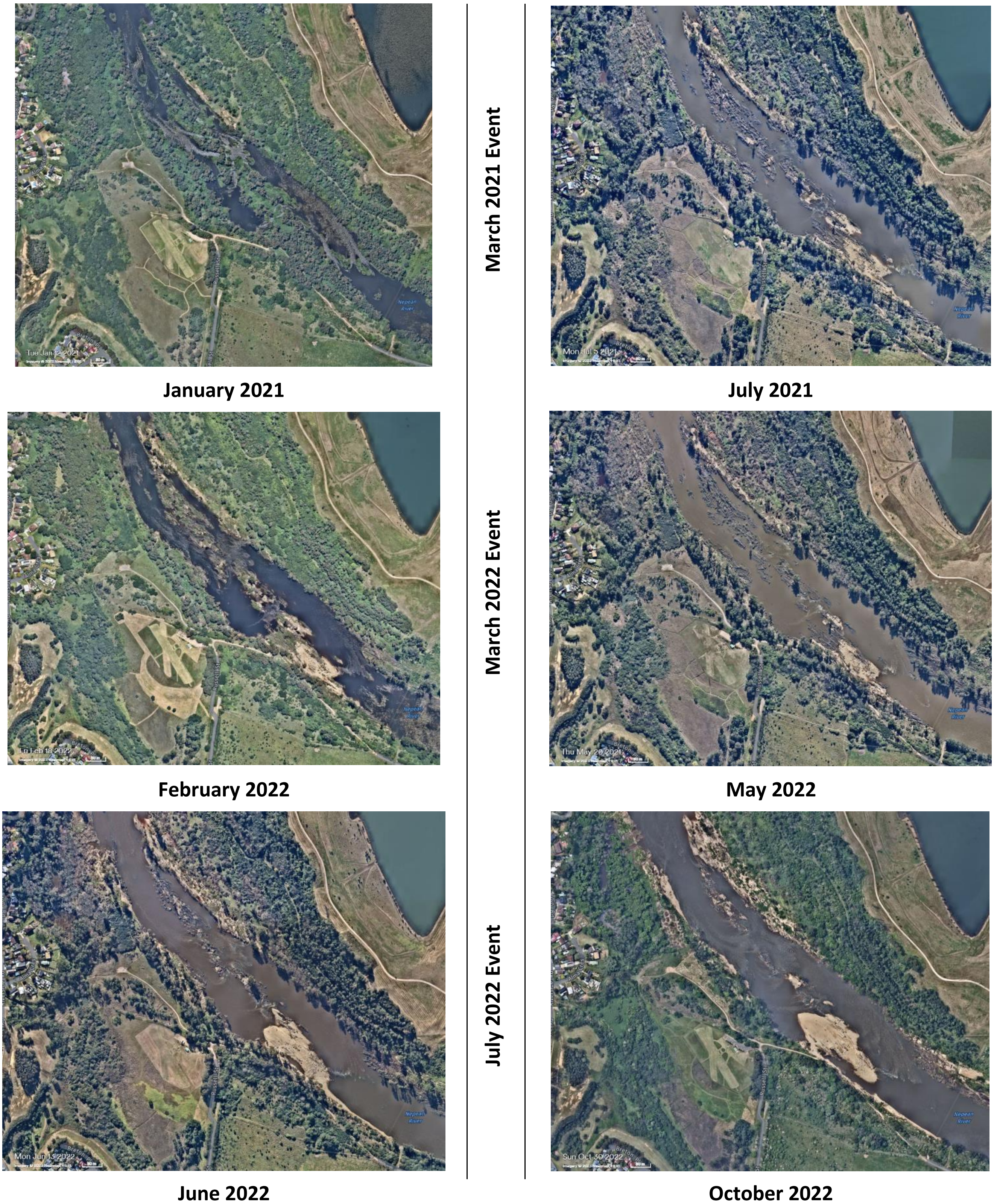

Figure 5-19. Changing Vegetation near McCanns Island at Penrith 2021 to 2022 (source : Nearmap)

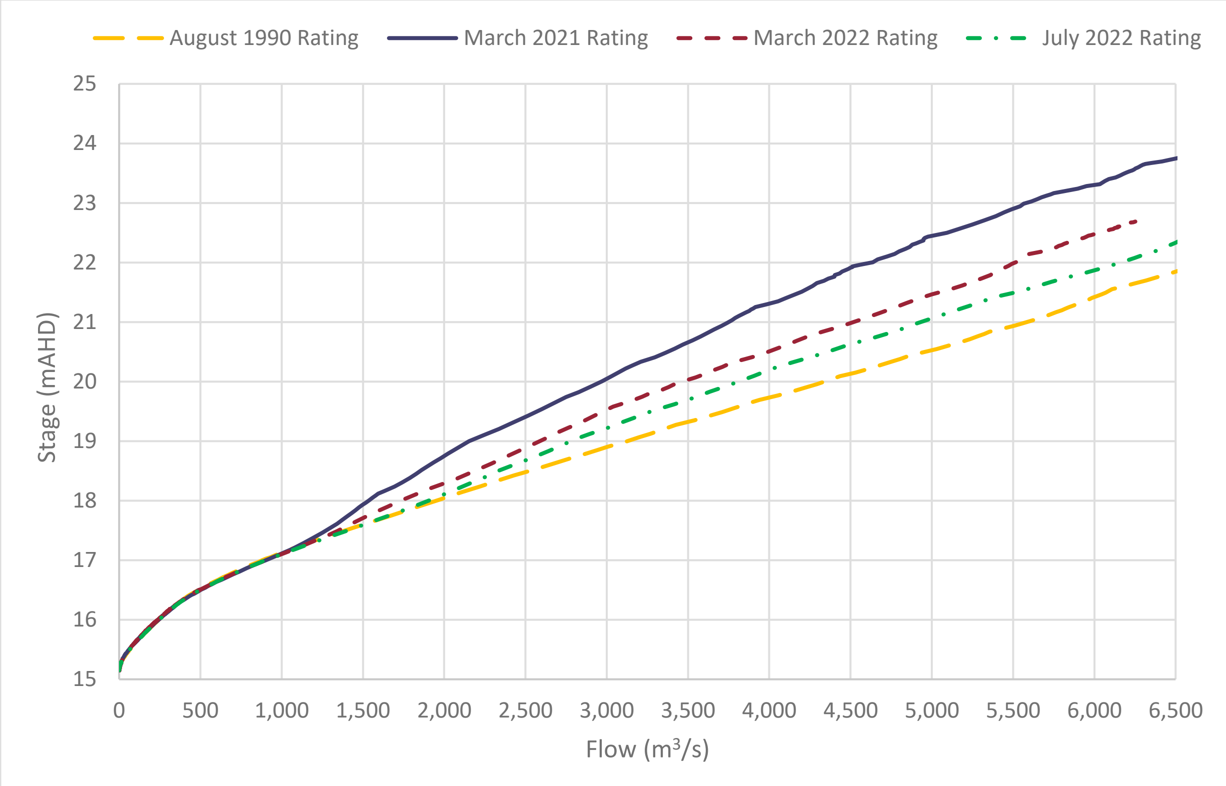

Figure 5-20. Comparison between August 1990, March 2021, March 2022 and July 2022 rating curves for Victoria Bridge gauge

Figure 5-21. Vegetation Changes near Penrith Weir (left : October 2022, right : June 2023) (source : Nearmap)

Figure 5-22. Vegetation Changes Downstream of Penrith Weir (left : October 2022, right : June 2023) (source : Nearmap)

5.2.4 Climate Change

Peak flood levels at Penrith are not sensitive to sea level rise but are influenced by changes in rainfall intensities.

The flood model suggests levels could increase by 0.4 metres at Victoria Bridge under a 9.5% rainfall increase, and around 0.6 metres under a 19.7% rainfall increase, in the 1 in 100 AEP. Based on these increases, under the higher 19.7% increase in rainfall, an existing 1 in 200 AEP event would be roughly equivalent to a 1 in 100 AEP event under climate change.

5.3 Windsor & South Creek

5.3.1 Flood Behaviour

Flooding at Richmond and Windsor is influenced by a combination of the large storage area on the floodplain, and the constriction downstream through the confined gorge that enters into the Lower Hawkesbury. This creates what is commonly referred to as the ‘bathtub’ effect. An overview of the flood extents is shown in Figure 5-23. General photos of the floodplain are shown in Figure 5-24 and Figure 5-25.

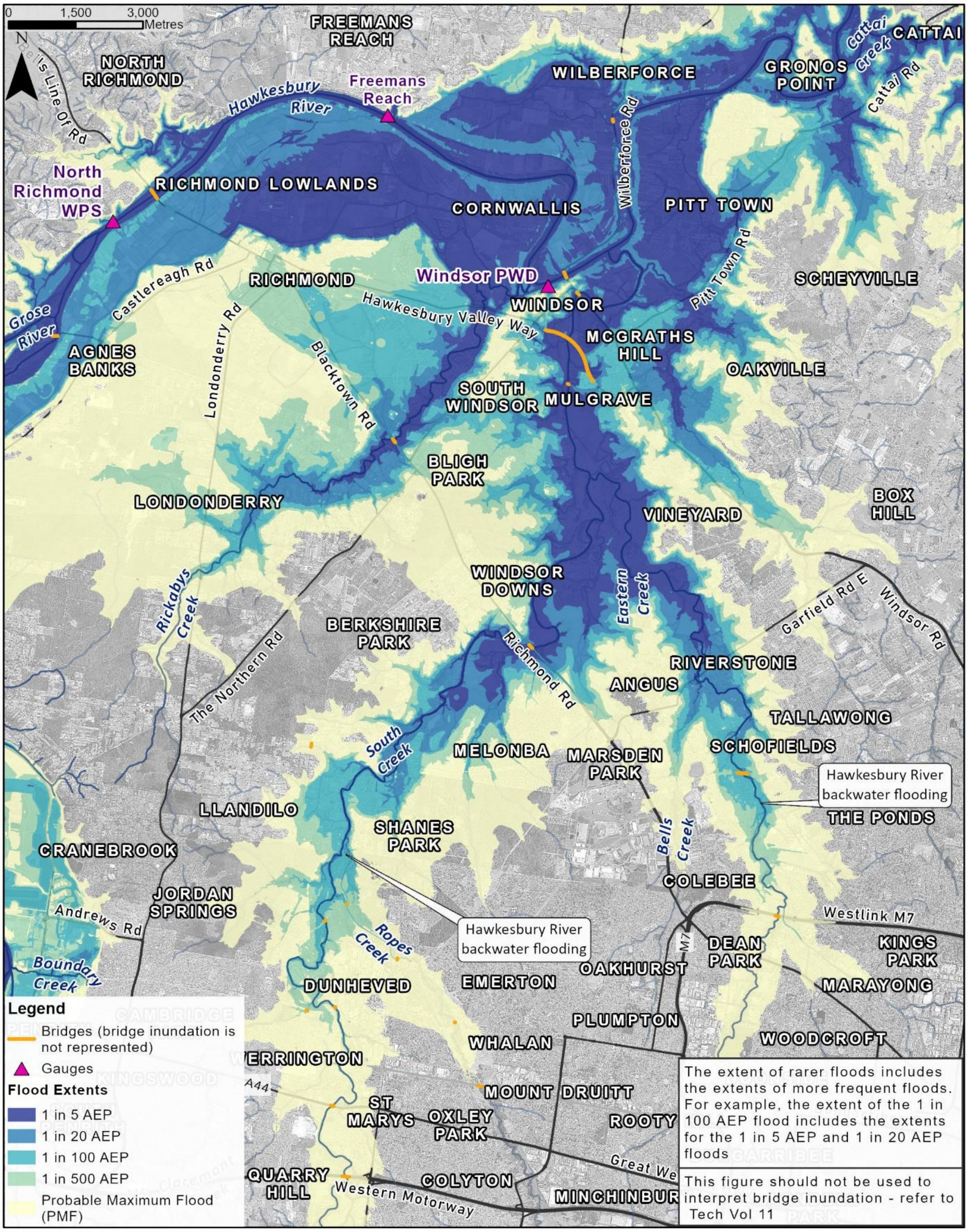

Figure 5-23. Windsor Flood Extents

Figure 5-24. View of the large floodplain storage on the Windsor floodplain – 26 March 2021 (Source: Infrastructure NSW. Photo: Adam Hollingworth)

Figure 5-25. View of the gorge downstream of Windsor, just upstream of Sackville (26 March 2021)

Unlike the Penrith floodplain, flooding at Windsor is largely driven by the volume of floodwaters entering the floodplain, rather than the peak flow. Figure 5-26 shows a comparison of the peak inflows (extracted from the model downstream of the Grose River Junction) with the water level at the Windsor PWD gauge for the March 2021 event. This shows the sustained peak at Windsor even after the peak inflows have reduced, reflective of it being influenced by the volume of inflow.

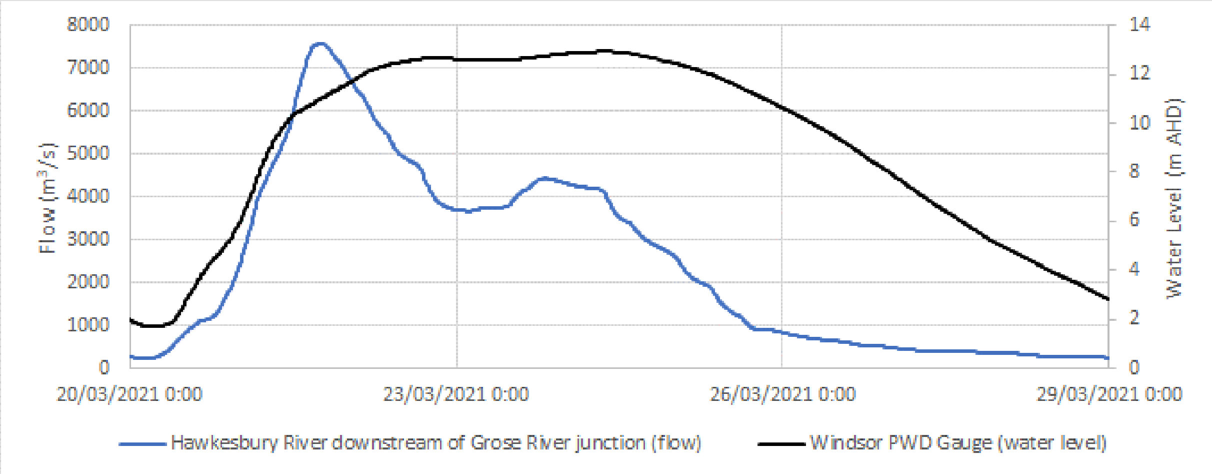

Figure 5-26. Windsor Floodplain Inflows and Peak Water Level - March 2021 Event

The Warragamba River tends to dominate this inflow volume for larger flood events, with smaller inflows from the Nepean River, Grose River and South Creek. An example of the cumulative inflow volumes for the March 2021 event is shown in Figure 5-27.

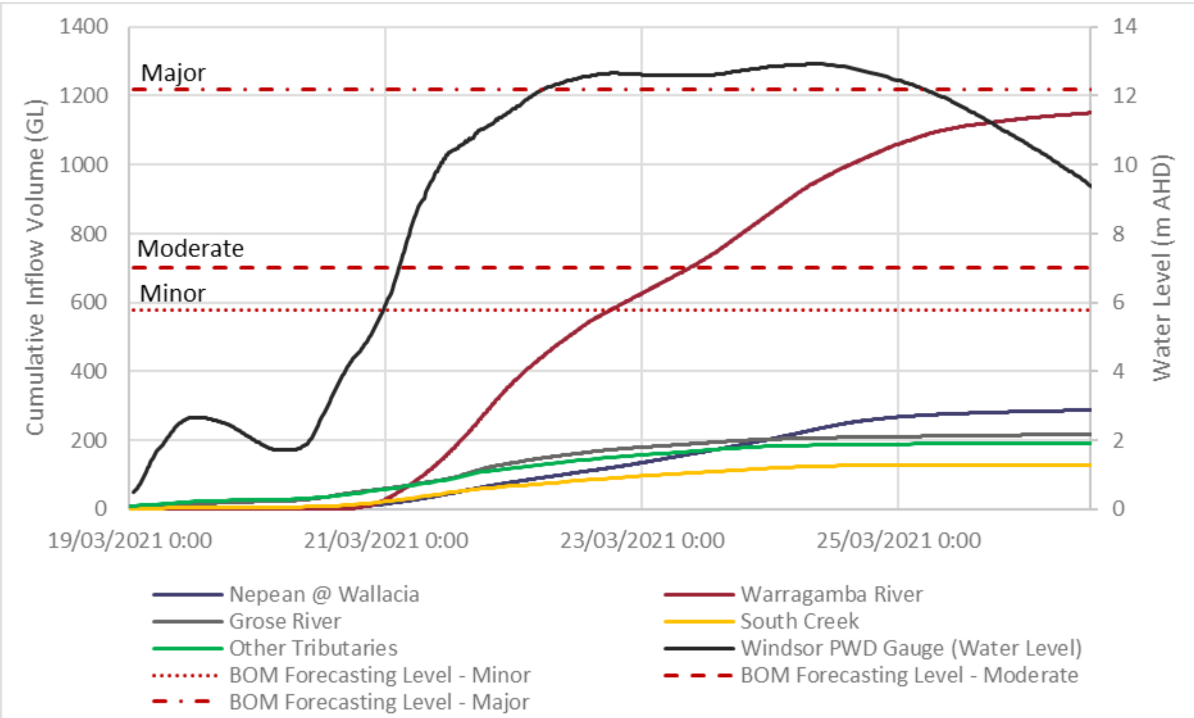

Figure 5-27. Cumulative Inflows for Windsor - March 2021 Event[15]

The flood level at North Richmond remains somewhat independent of the flood level at Windsor for frequent flood events. However, as the flood level rises in the Windsor floodplain, this creates a

[15] Volumes estimated based on the TUFLOW model results, and WBNM flows for South Creek and other tributaries. "Other Tributaries" represent an estimate of the inflow volumes from the remaining inflow tributaries to the Windsor floodplain, based on the WBNM flow estimates. Windsor PWD gauge represents recorded levels. 'Major', 'moderate' and 'minor' refer to Bureau of Meteorology flood categories describing general consequences, linked to flood levels.

backwater effect that results in increasing influence on the water levels at North Richmond and further upstream. Figure 5-28 shows the flood profile at Windsor and Richmond. The flood gradient between Windsor and North Richmond is present up to a 1 in 20 AEP event, but in the 1 in 100 AEP the flood level is largely constant between Windsor and North Richmond, as the storage within the floodplain fills.

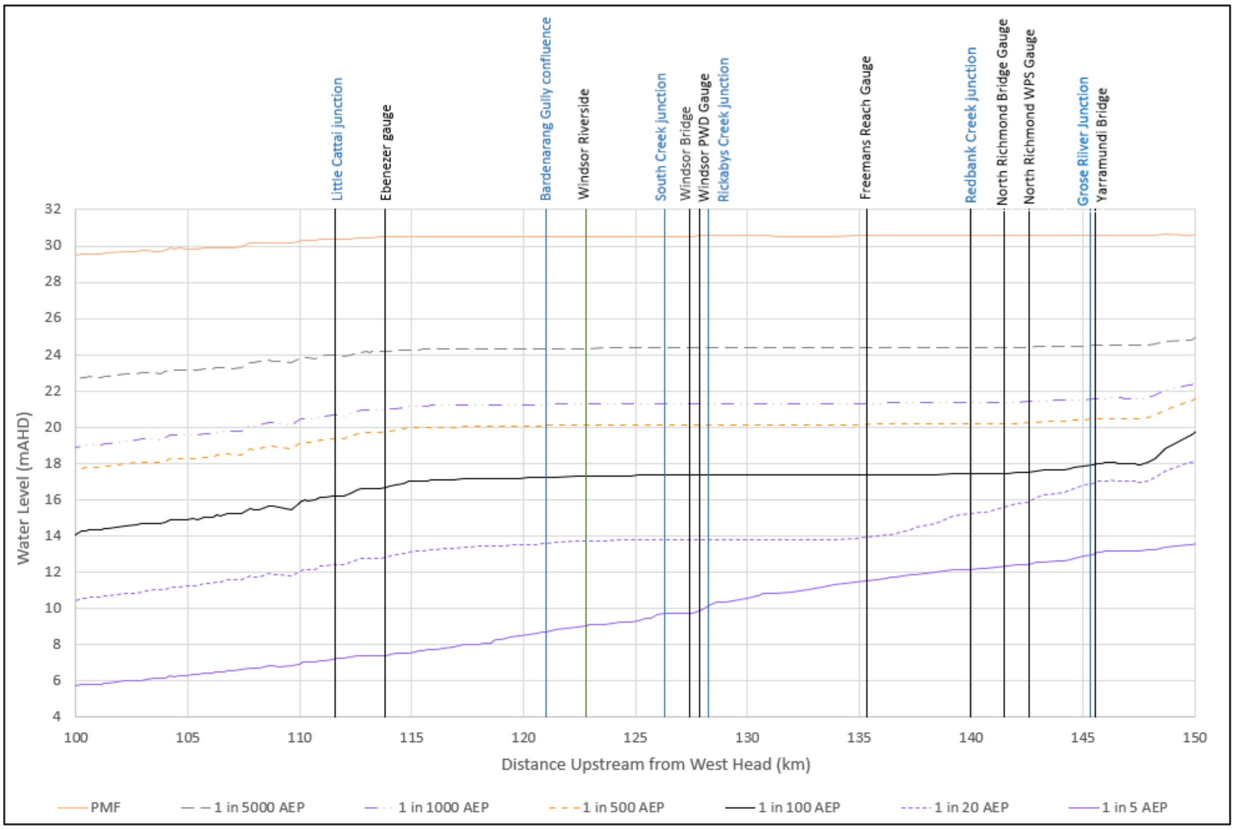

Figure 5-28. Flood Profile - Windsor Floodplain

As the floodplain fills in Windsor, this creates backwater and inundates tributaries such as South Creek, Eastern Creek and Rickabys Creek, and forms part of the storage area of the wider floodplain. In the 1 in 100 AEP event, backwater flooding extends upstream of Dunheved Road on South Creek and approximately 1 kilometre downstream of the M7 on Eastern Creek.

In the 1 in 5000 AEP event, backwater flooding extends upstream of the M4 on South Creek and the M7 on Eastern Creek.

The backwater effect in the floodplain results in reverse flows occurring up some of the tributaries and into the flood storage areas as flood levels rise. The peak 1 in 200 AEP velocities in Figure 5-29 demonstrate some of these reverse flows, for example, the reverse flows up Rickabys Creek, as well as the filling of the Richmond Lowlands. However, as noted in Section 4.7, the focus of the current study is mainstream flooding along the Hawkesbury and Nepean rivers. Therefore, when viewing the results of this study, local catchment flooding should also be considered. The relevant studies for South Creek, Eastern Creek and other tributaries (where available) should be reviewed to ensure all types of flooding are considered.

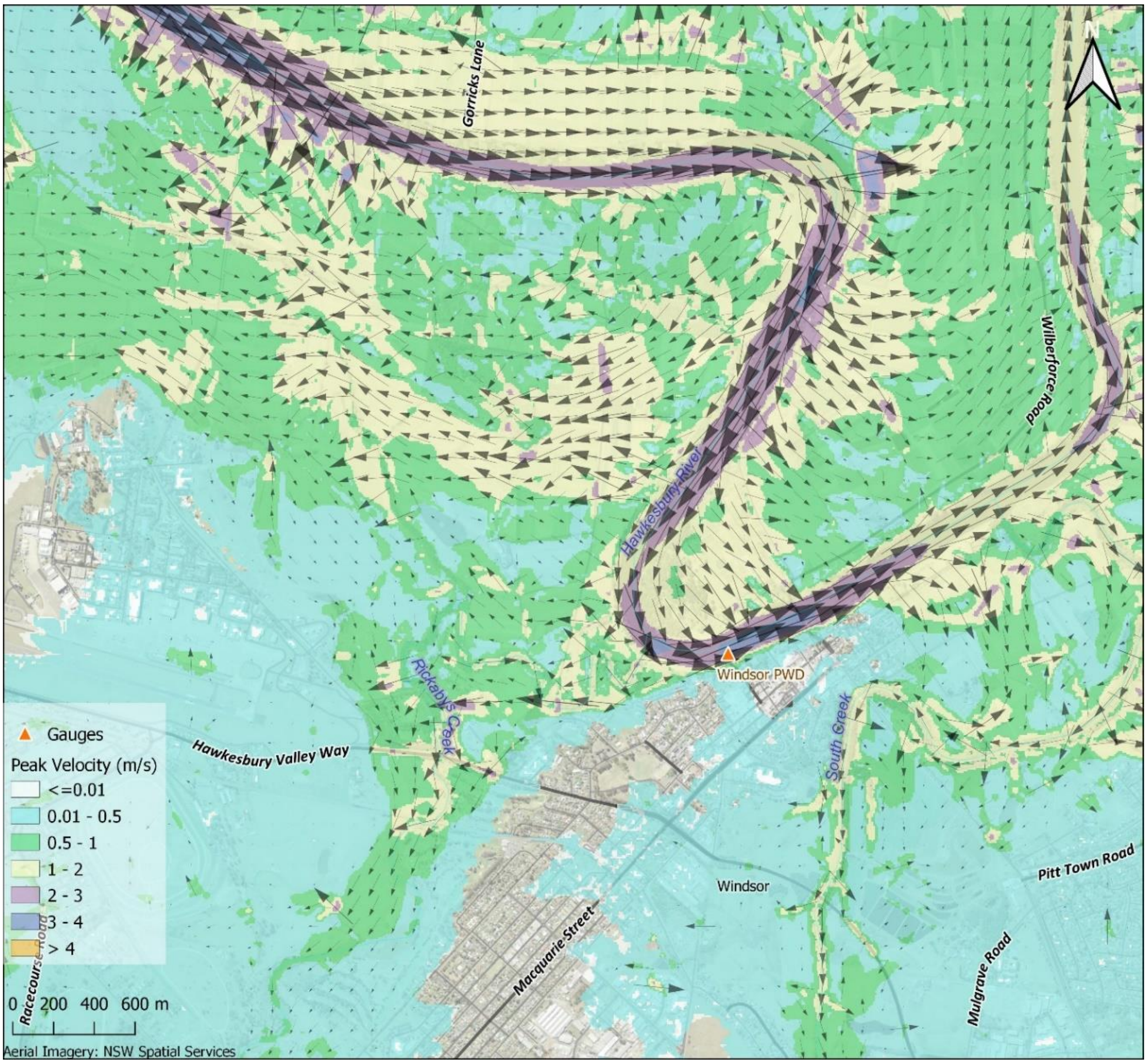

Figure 5-29. Peak 1 in 200 AEP Velocity - Windsor[16]

Peak water levels at Windsor and North Richmond are shown in Table 5-3. Peak water levels between the 1 in 5 AEP and PMF events vary by more than 18 metres, with the PMF event being more than 13 metres higher than the 1 in 100 AEP.

[16] Arrows represent the direction of flow, with the size indicative of the magnitude of velocity.

Table 5-3. Peak Water Level Summary – North Richmond and Windsor

Design Event	Peak Water Level		
	North Richmond (WPS)		Windsor (PWD)
	m AHD	GH*	m AHD
1 in 2	6.8	6.3	5.5
1 in 5	12.5	11.9	9.9
1 in 10	14.7	14.2	11.8
1 in 20	15.9	15.4	13.8
1 in 50	16.5	15.9	15.9
1 in 100	17.5	17.0	17.3
1 in 200	18.7	18.1	18.5
1 in 500	20.3	19.7	20.2
1 in 1000	21.4	20.9	21.3
1 in 2000	22.9	22.3	22.8
1 in 5000	24.4	23.9	24.4
PMF	30.6	30.0	30.6

**GH – Gauge Height. North Richmond WPS gauge zero = 0.529m AHD*

5.3.2 Model Sensitivity and Uncertainty

The flood model results for Windsor are not significantly impacted by changes in bathymetry, ocean level, structure loss coefficients or blockage of hydraulic structures. However, the flood levels are sensitive to the representation of the conveyance through the gorge downstream. Changes to roughness coefficients have the potential to change 1 in 100 AEP flood levels by around 0.6-0.7 metres.

The flood behaviour at Windsor is also influenced by hydraulics losses through the bends in the gorge downstream. This is further discussed in Section 5.4.3.

5.3.3 Climate Change

Peak flood levels at Windsor are not significantly influenced by sea level rise, with less than a 0.05m increase in 1 in 100 AEP flood levels at Windsor with a 0.9 metre increase in ocean levels. However, Windsor is affected by changes in rainfall intensities.

The flood model suggests 1 in 100 AEP levels could increase by 0.9 metres at Windsor (PWD) under a 9.5% rainfall increase and sea level rise of 0.4 metres, and around 1.9 metres under a 19.7% rainfall increase and sea level rise of 0.9 metres. Based on these increases, under the higher 19.7% increase in rainfall, an event of a similar magnitude to the existing 1 in 200 AEP event would be occur more frequently than a 1 in 100 AEP event under climate change.

5.4 Lower Hawkesbury

5.4.1 Flood Behaviour

The Lower Hawkesbury River is characterised by a relatively narrow sandstone gorge that generally confines inundation near to the main river channel. However, the confined nature of flooding produces deep and fast-moving floodwater. Peak water depths of at least 10 metres and flow velocities of more than 2 m/s are common during each design flood. During the PMF, water depths are predicted to exceed 30 metres and flow velocities are predicted to exceed 4 m/s along some sections of the lower river. An overview of flood extents is shown in Figure 5-30. Representative photos of the area are shown in Figure 5-31 to Figure 5-34.

As noted in Section 5.3.1, the gorge near Sackville controls the quantity of floodwater that can be released from the Windsor basin. Therefore, the gorge also serves to control the quantity of flow that can enter the Lower Hawkesbury. Although the Warragamba River tends to contribute the largest volume to the Windsor basin and therefore, flow rates in the lower river, the Lower Hawkesbury is joined by some major tributaries notably the Colo and Macdonald rivers. These 2 tributaries each incorporate a large catchment area that can contribute significant runoff rates and volumes to the lower river. The timing and magnitude of flow from the Colo and Macdonald rivers relative to the Hawkesbury River can have a considerable influence on flooding downstream of Lower Portland (Section 3.6.2).

The Lower Hawkesbury River is also characterised by many tight and confined river bends. The complex, dynamic movement of floodwaters around these bends creates numerous eddies and associated hydraulic losses. These losses become pronounced during very large floods where river depths and velocities are substantial (i.e., in events larger than the 1 in 100 AEP flood) and serve to increase flood levels within the Lower Hawkesbury. The elevated river levels also restrict the ability of flow to escape from the Windsor basin. That is, the hydraulic losses through the lower river impact on flood levels upstream beyond Windsor. These bend losses are discussed further in Section 5.4.3.

Across the downstream river sections, the prevailing ocean levels start to become more influential. That is, flood levels along the very downstream sections of the river are more strongly dominated by ocean water levels rather than the flow travelling along the river. The extent of the where the ocean levels dominate over the catchment flooding varies according to the size of the flood. For example:

- 1 in 2 AEP ocean level dominates to upstream of Spencer
- 1 in 20 AEP ocean level dominates to upstream of the M1 Bridge
- 1 in 100 AEP (and larger) ocean levels dominate only upstream to Little Wobby/Green Point.

As noted in Section 3.6.3, the flood levels in this study do not include allowance for coastal driven factors like wave runup and storm surge. Reference should be made to appropriate studies to understand these influences in coastal affected portions of the study area.

Peak water levels at Sackville, Lower Portland and Wisemans Ferry are shown in Table 5-4. Peak water levels between the 1 in 5 AEP and PMF events vary by around 25 metres, with the PMF event being more than 13 metres higher than the 1 in 100 AEP.

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Catchment Simulation Solutions

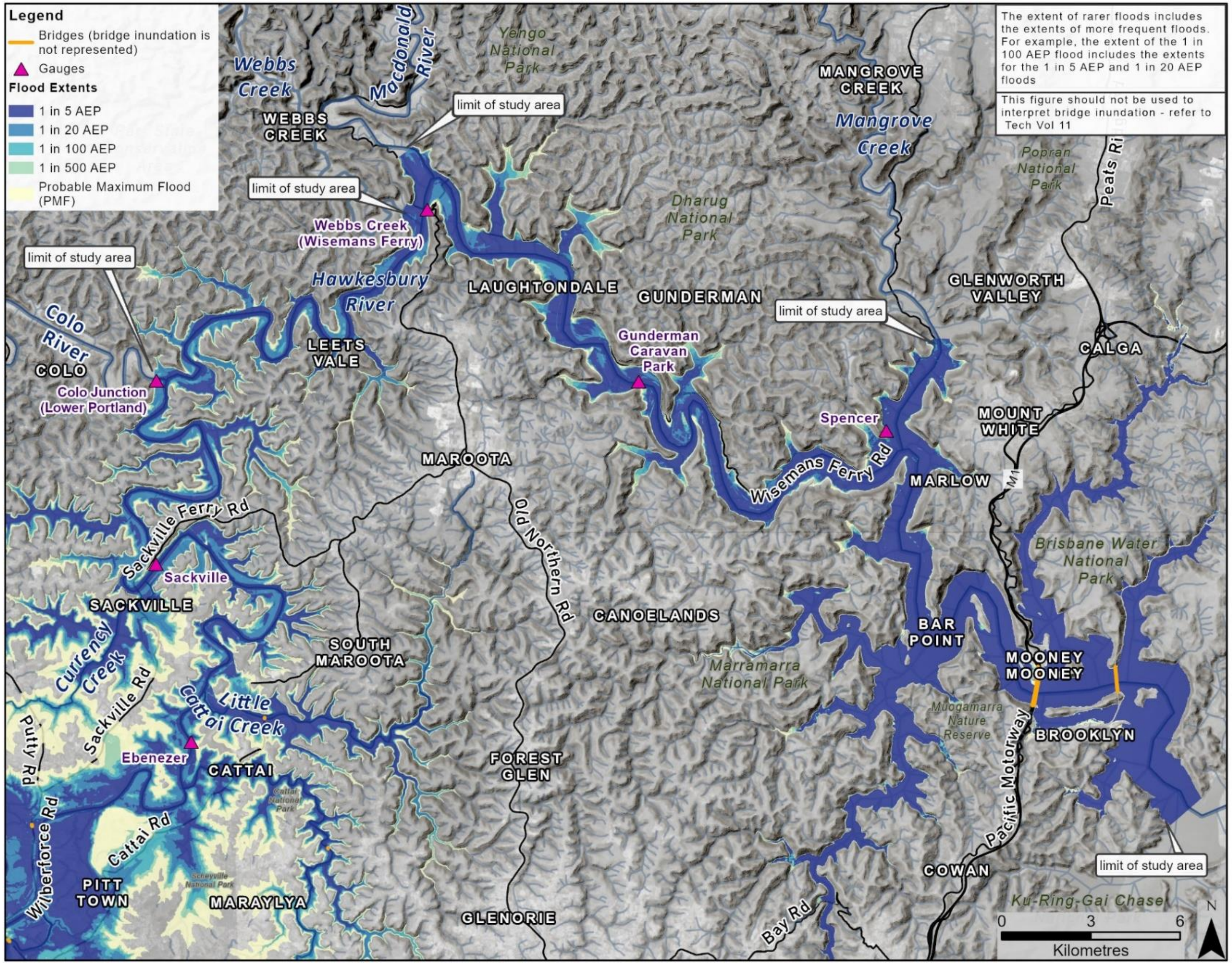

Figure 5-30. Lower Hawkesbury Flood Extents

Figure 5-31. View of the Colo River Junction (looking from the Colo River) – 26 March 2021 (Source: Infrastructure NSW. Photo: Adam Hollingworth)

Figure 5-32. View of the Hawkesbury River near Leets Vale, looking towards Wisemans Ferry in the distance – 26 March 2021 (Source: Infrastructure NSW. Photo: Adam Hollingworth)

Figure 5-33. View of the Hawkesbury River from Laughtondale (foreground) and Gunderman (opposite bank) looking downstream – 26 March 2021 (Source: Infrastructure NSW. Photo: Adam Hollingworth)

Figure 5-34. View of the Hawkesbury River looking toward M1 Bridge and Brooklyn – 26 March 2021 (Source: Infrastructure NSW. Photo: Adam Hollingworth)

Table 5-4. Peak Water Level Summary – Lower Hawkesbury

Design Event	Peak Water Level (m AHD)		
	Sackville	Lower Portland (Colo Junction)	Wisemans Ferry (Webbs Creek)
1 in 2	3.1	2.2	1.6
1 in 5	5.6	4.0	2.2
1 in 10	8.1	5.8	3.2
1 in 20	10.3	7.6	4.3
1 in 50	12.6	9.8	5.5
1 in 100	14.0	11.0	6.5
1 in 200	15.5	12.9	8.0
1 in 500	17.5	15.0	10.2
1 in 1000	18.8	17.0	11.5
1 in 2000	20.8	18.7	12.9
1 in 5000	22.6	20.3	14.2
PMF	29.4	26.6	19.1

5.4.2 Colo and Macdonald rivers

The influence of the Colo and Macdonald rivers on flows in the Lower Hawkesbury is a combination of the timing of the peak flow in each river, as well as the shape of the hydrograph itself (duration and volume). The Monte Carlo analysis (**Technical Volume 7**) incorporates variability in the timing of these tributaries, drawing on analysis of the Lower Hawkesbury River Probability Assessment documented in **Technical Volume 5**. This analysis was informed by available historical data in the Lower Hawkesbury (Section 3.6.2).

5.4.3 Bend Losses

The TUFLOW hydraulic model predicts peak flood levels that are higher in larger flood events compared with the RUBICON model in areas of the Lower Hawkesbury. Part of this difference can be attributed to the higher head losses[17] around the river bends of the Lower Hawkesbury in the TUFLOW model compared to the RUBICON model. This area of the river is characterised by a number of tight and confined bends which can influence the hydraulic loss behaviour (see example of Singletons Mill bend downstream of Gunderman in Figure 4-3). This complex flow behaviour is difficult to represent, particularly in a quasi 2-dimensional model such as RUBICON.

A review was undertaken to verify the hydraulic losses around river bends observed in the TUFLOW model and is documented in **Technical Volume 12**. The verification drew upon extensive data collected for the March 2021, March 2022 and July 2022 flood events, various model testing, and a comparison against the Brisbane River Catchment Flood Study's modelling of the Story Bridge bend. One of the

[17] Headloss for the river refers to the energy dissipated along its length. In lower velocity flows, the energy loss is primarily characterised by the change in water level. Therefore, a larger drop in water level represents a higher headloss.

large eddies observed in the March 2021 event near the St George Caravan Park is compared with the model results in Figure 5-35 and Figure 5-36.

In the absence of a very rare flood for calibration, the verification outcomes show that the hydraulic losses in the lower river are being reliably represented and the current modelling tools provide the best available representation of flood behaviour in the Lower Hawkesbury during an extreme flood.

5.4.4 Model Sensitivity and Uncertainty

The Lower Hawkesbury contains only a small number of major bridges. As a result, no significant changes in results are predicted due to changes in structure loss coefficients or structure blockage (flood level differences are not predicted to exceed 0.1 metres). Similarly, the assessed changes in bathymetry had a small impact on peak flood levels.

As discussed, flood levels in the very lower river are more strongly influenced by the prevailing ocean water levels. Therefore, changes in ocean water levels are predicted to have an impact on flood levels, however, the impacts are most significant in areas located downstream of the Wisemans Ferry. Changes in roughness can also alter peak flood levels, with the most significant impacts predicted in the vicinity of Sackville (differences of up to 0.9 metres are predicted at this location).

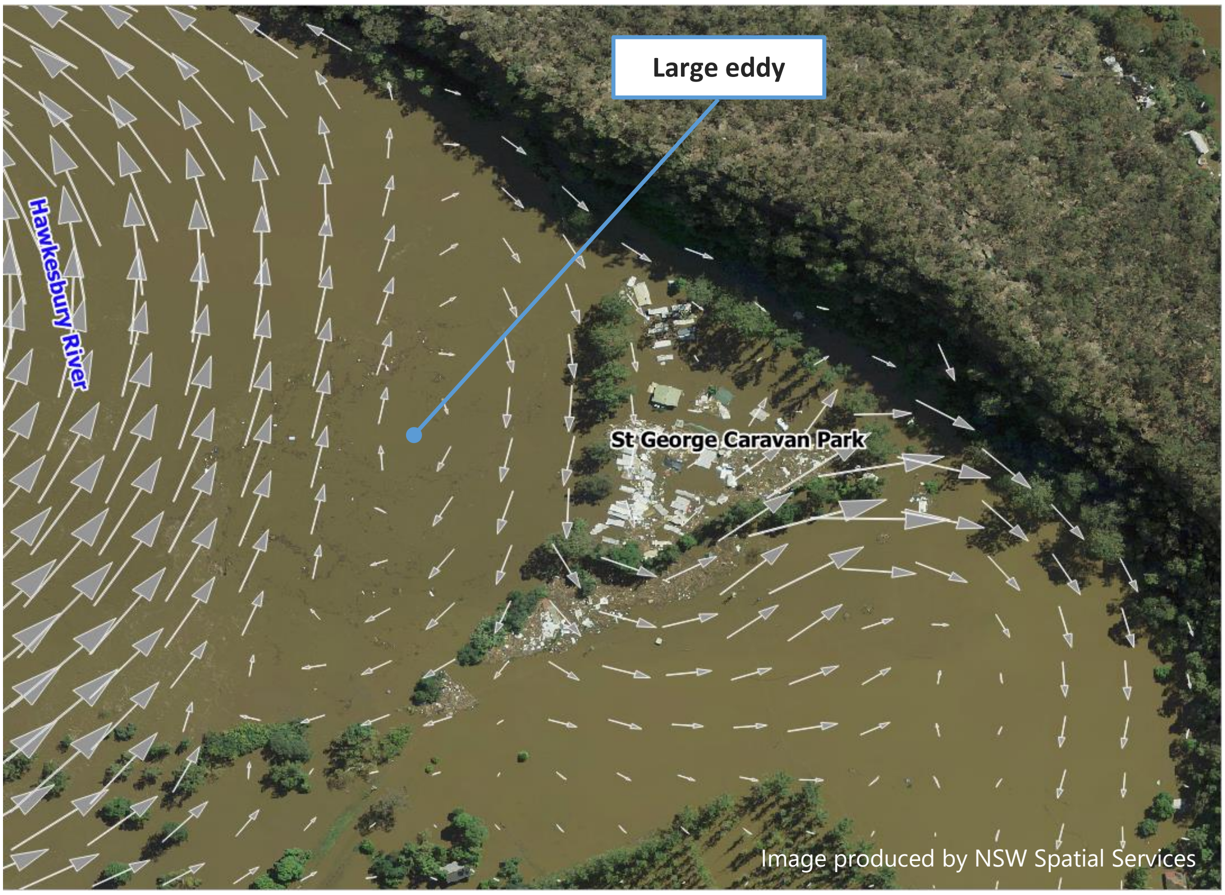

Figure 5-35. Simulated peak velocity vectors (where length represents magnitude of velocity) for March 2021 flood overlaid on March 2021 aerial imagery showing large eddy directly west of St George Caravan Park where substantial debris was deposited

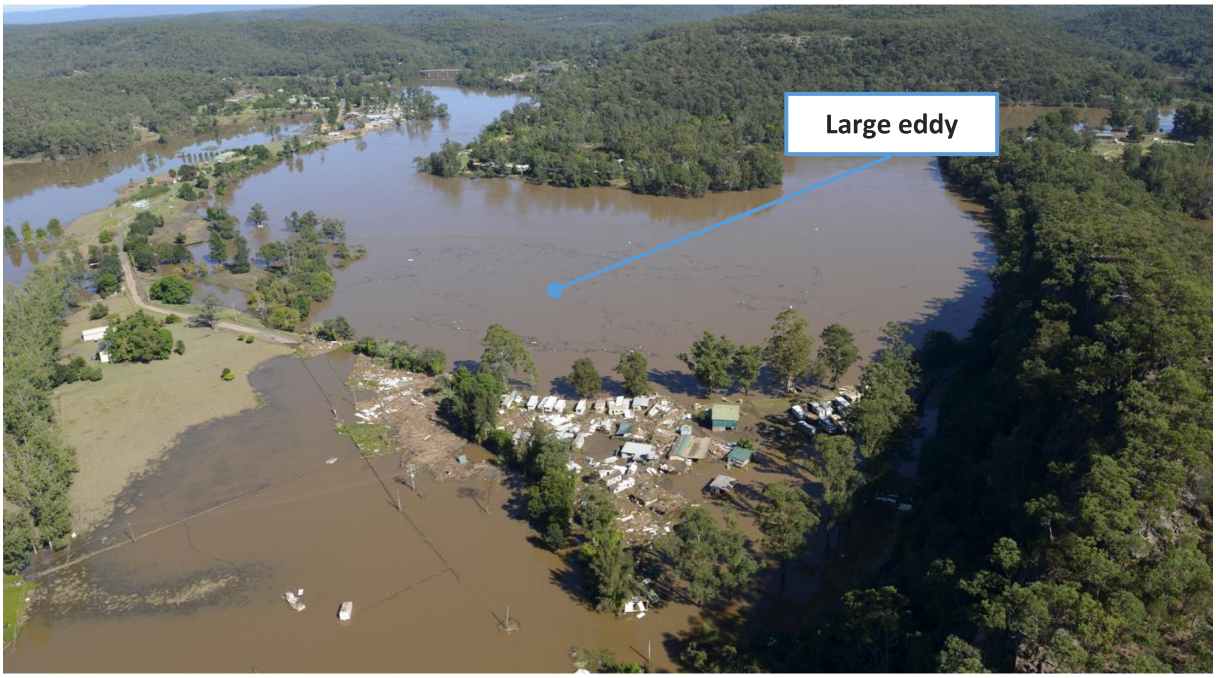

Figure 5-36. Oblique View of St George Caravan Park and Large Eddy (26 March 2021, Source: Adam Hollingworth)

5.4.5 Climate Change

Unlike other sections of the study area which are not significantly impacted by sea level rise, the Lower Hawkesbury can be impacted by both increased sea levels as well as increases in rainfall.

The most significant flood level increases associated with sea level rise occur downstream (i.e., east) of the M1 Motorway Bridge (e.g., a 0.9 metre increase in sea level will translate to a 0.9m increase in 1 in 100 AEP flood levels at the M1 Bridge). The flood level impacts start to diminish moving upstream from the M1 Bridge with flood levels predicted to be in the order of 0.3m higher at Wisemans Ferry under a 0.9m increase in sea level scenario.

The impacts of rainfall increases are most pronounced between Sackville and Wisemans Ferry, although increases in 1 in 100 AEP flood levels are predicted to extend as far downstream as Spencer. Under the 19.7% increase in rainfall scenario, peak 1 in 100 AEP flood levels at Wisemans Ferry are predicted to increase by around 1 metre while 1 in 100 AEP levels at Lower Portland are predicted to increase by approximately 1.5 metres.

Should sea levels increase by 0.9 metres and rainfall increase by 19.7%, significant flood level impacts are predicted along the full length of the Lower Hawkesbury. This ranges from 0.9m increases in 1 in 100 AEP flood levels downstream of the M1 Motorway Bridge to increases approaching 1.5 metres between Sackville and Gunderman.

Based on these increases, under the higher 19.7% increase in rainfall and 0.9 metre sea level rise, an existing 1 in 200 AEP event would be more frequent than a 1 in 100 AEP event under climate change at Colo Junction and Wisemans Ferry.

Image source: Adam Hollingworth, 26 March 2021

6 Conclusions

This report summarises the outcomes of the 2024 Hawkesbury-Nepean River Flood Study that was completed to improve the understanding of flood behaviour across the Hawkesbury-Nepean Valley. The flood study builds upon the 2019 Hawkesbury-Nepean Valley Regional Flood Study (WMAwater, 2019). The 2024 Flood Study provides updated information on design flood levels, depths, and velocities as well as hydraulic and flood hazard categories for a range of design floods for contemporary catchment and floodplain conditions while also considering the potential impacts of climate change.

The study uses best practice and the latest technology in flood estimation to define flood behaviour. This included the development of a new, fully 2-dimensional hydraulic model of the river system and floodplain. The hydraulic model was developed to provide a detailed representation of river and floodplain features that influence flood behaviour. The hydraulic model was calibrated against information for 8 historical floods and was also validated against the March 2021, March 2022 and July 2022 floods to ensure it was providing a reliable representation of flood behaviour along the river system.

The flood study also employed a Monte Carlo analysis to reflect the natural variability of observed floods. This approach provides the equivalent of roughly 200,000 years of flood events and provides a detailed basis for understanding the frequency of floods of different magnitudes occurring across different parts of the floodplain.

A subset of flood events from the Monte Carlo analysis was applied to the calibrated hydraulic model for a range of design floods. The hydraulic model was used to simulate the movement of water along the main Hawkesbury-Nepean River and across the adjoining floodplain for each design flood. The outputs from the hydraulic model simulations provide a continuous surface of flood information (e.g., water levels, depths and velocities) for a range of flood sizes and, therefore, provides a detailed understanding of the variability of flood behaviour across the floodplain. This flood information is presented as a series of flood maps in a separate map book.

The revised design flood levels have changed in some locations relative to the 2019 Flood Study and earlier investigations. This is most evident in very large floods (i.e., larger than the 1 in 100 AEP flood), where the new hydraulic model provides a more detailed representation of the storage and conveyance across the river system including a better representation of hydraulic losses during high flow events in the lower river.

The following conclusions can be drawn from the results of the study:

- Wallacia: During frequent floods, flood behaviour at Wallacia is largely controlled by the gorge downstream of Wallacia Weir. During large floods, backwater effects from the Warragamba River further reduce the ability of water to drain from the floodplain located upstream of Wallacia Weir.

The combined impact of the gorge and Warragamba River produces a very large flood range, with peak PMF levels being more than 30 metres higher than the 1 in 5 AEP levels.

- Penrith: During smaller to medium sized floods (i.e., up to 1 in 50 AEP), floodwaters are largely contained to the Nepean River channel. A breakout from the river through Emu Plains as well as the Peach Tree Creek floodplain commences in the 1 in 100 AEP. Changes in vegetation along the river and floodplain downstream of Penrith have had a notable impact on design flood levels relative to previous flooding investigations. The flooding at Penrith is largely driven by the peak flow along the river rather than the volume of flow.
- Windsor: Extensive inundation is predicted in the vicinity of Windsor (including backwater inundation of South and Eastern Creeks) and is strongly correlated to the capacity of the incised gorge downstream of Windsor. Once the outflow capacity of the gorge is exceeded the excess water “ponds” across the Windsor basin resulting in significant water depths across a large area. Unlike Penrith, flooding at Windsor is largely driven by the volume of runoff rather than the peak flow.
- Lower Hawkesbury: The Lower Hawkesbury is contained within a confined, sandstone gorge along much of its length. This results in flood extents that are commonly contained close to the main river channel, although notable backwater inundation is predicted along tributaries draining into the river. Flooding downstream of Lower Portland is strongly influenced by the magnitude and timing of flow from the Colo River.

The results of additional climate change simulations indicate that projected future increases in rainfall intensity and sea level would produce a notable increase in flood risk across all sections of the study area. This includes increases in 1 in 100 AEP flood levels of more than 1 metre between Gunderman and Windsor under certain climate change scenarios.

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8 Glossary[18]

Term	Shortened form	Definition	Context for use/additional information
Annual exceedance probability	AEP	The chance of a flood of a given or larger size occurring in any one year, usually expressed as a percentage	AEP is generally the preferred terminology. ARI is the historical way of describing a flood event, for example, a 1% AEP flood has a 1% or 1 in 100 chance of being reached or exceeded in any given year
Australian height datum	AHD	A common national surface level datum often used as a referenced level for ground, floor and flood levels	0.0 m AHD corresponds approximately to mean sea level
Average recurrence interval	ARI	The long-term average number of years between the occurrence of a flood equal to or larger in size than the selected event	ARI is the historical way of describing a flood event. AEP is generally the preferred terminology, for example, a 100-year ARI flood that has 1 in 100 chance of being reached or exceeded in any given year. It is equivalent to a 1% AEP flood
Catchment		The area of land draining to a specific location	It includes the catchment of the primary waterway as well as any tributary streams and flowpaths
Catchment flooding		Flooding due to prolonged or intense rainfall (e.g. severe thunderstorms, monsoonal rains in the tropics, tropical cyclones)	Types of catchment flooding include riverine, local overland and groundwater flooding
Chance		The likelihood of something happening that will have adverse or beneficial consequences	In FRM this generally relates to the adverse consequences of floods with chance being related to AEP, for example, 1% chance or 1 in 100 chance per year is equivalent to 1% AEP
Coastal inundation		Inundation due to tidal or storm-driven coastal events, including storm surges in lower coastal waterways. This can be exacerbated by wind-wave generation from storm events	
Consent authority		The authority or agency with the legislative power to determine the outcome of development and building applications	This may be the relevant local council or Minister
Consequence		The outcomes of an event or situation affecting objectives, expressed qualitatively or quantitatively	Consequences can be adverse (e.g. death or injury to people, damage to property and disruption of the community) or beneficial
Continuing flood risk		Risk to existing and future development that may be reduced by EM measures	Flood risk to the existing development and future development may be reduced by EM measures depending on flood constraints, however, these measures cannot remove all risk and a residual risk will remain

[18] Definitions from the Flood Risk Management Manual (2023)

Term	Shortened form	Definition	Context for use/additional information
Defined flood event	DFE	The flood event selected as a general standard for the management of flooding to development	Aims to reduce the frequency of flooding but does not remove all flood risk, for example, in selecting a 1% AEP flood as a DFE you are accepting that there is a 1 in 100 chance that a larger event will occur in any year. This risk is being built into the decision
Design flood		The flood selected as part of the FRM process that forms the basis for physical works to modify the impacts of flooding	The design flood may be considered the flood mitigation standard, for example, a levee may be designed to exclude a 2% AEP flood, which means that floods rarer than this may breech the structure and impact upon the protected area. In this case, the 2% AEP flood would not equate to the crest level of the levee, because this generally has a freeboard allowance, but it may be the level of the spillway to allow for controlled levee overtopping
Development		May be treated differently depending on the following categorisation: · **infill development**: the development of vacant blocks of land that are generally surrounded by developed properties and is permissible under current land zoning · **new development**: development of a completely different nature to that associated with the former land-use (e.g. the urban subdivision of a previously rural area) · **redevelopment**: rebuilding in an area (e.g. as urban areas age, it may become necessary to demolish and reconstruct buildings on a relatively large scale)	New developments involve rezoning and typically require major extensions of existing urban services, such as roads, water supply, sewerage and electric power. Redevelopment generally does not require either rezoning or major extensions to urban services
Development control plan	DCP	See *Environmental Planning and Assessment Act 1979*	
Emergency management	EM	A comprehensive approach to dealing with risks to the community arising from hazards. It is a systematic method for identifying, analysing, evaluating and managing these risks	May include measures to reduce flood frequency or consequences through prevention and mitigation measures, and preparation, as well as response and recovery should a flood occur (see PPRR)
Ecologically sustainable development	ESD	As outlined in the *Local Government Act 1993*	Principles of ESD are outlined in the *Local Government Act 1993*

Term	Shortened form	Definition	Context for use/additional information
Existing flood risk		The risk an existing community is exposed to as a result of its location on the floodplain	Existing flood risk may be reduced by existing or proposed FRM measures leaving a residual flood risk to the existing community. Residual flood risk may be further reduced by addressing continuing risk
Flood		A natural phenomenon that occurs when water covers land that is normally dry. It may result from coastal inundation (excluding tsunamis) or catchment flooding, or a combination of both	Flooding results from relatively high stream flow that overtops the natural or artificial banks in any part of a stream, river, estuary, lake or dam, and/or local overland flowpaths associated with major drainage, and/or oceanic inundation resulting from super-elevated ocean levels
Flood (hydrologic and hydraulic) modelling		Hydrologic and hydraulic computer models to simulate catchment processes of rainfall, run-off, stream flow and distribution of flows across the floodplain or similar	They typically involve consideration of the local flood history, available collected data, and the development of models that are calibrated and validated, where possible, against historic flood events and extended to determine the full range of flood behaviour
Flood affected land		Equivalent to flood prone land	See the definition of flood prone land
Flood awareness		An appreciation of the likely effects of flooding, and a knowledge of the relevant flood warning, response and evacuation procedures facilitating prompt and effective community response to a flood threat	In communities with a low degree of flood awareness, flood warnings may be ignored or misunderstood, and residents confused about what they should do, when to evacuate, what to take with them and where to go
Flood constraints		Key constraints that flooding place on land	These include flood function, flood hazard, flood range, and flood emergency response classification. These can be used to inform FRM including consideration of options such as mitigation works, EM and land-use planning
Flood damage		The tangible (direct and indirect) and intangible costs (financial, opportunity costs, clean-up) of flooding	Tangible costs are quantified in monetary terms (e.g. damage to goods). Intangible damages are difficult to quantify in monetary terms and include the increased levels of physical, emotional and psychological health problems suffered by flood affected people that are attributed to a flood
Flood education		Seeks to provide information to raise community awareness of flooding so as to enable individuals to understand how to manage themselves and their property in response to flood warnings	

Term	Shortened form	Definition	Context for use/additional information
Flood evacuation		The movement of people from a place of danger to a place of relative safety, and their eventual return	People are usually evacuated to areas outside of flood prone land with access to adequate community support. Livestock may be relocated to areas outside of the influence of flooding
Flood fringe areas		That part of the flood extents for the event remaining after the flood function areas of floodway and flood storage areas have been defined.	
Flood function		The flood related functions of floodways, flood storage and flood fringe within the floodplain	Flood function is equivalent to hydraulic categorisation
Flood hazard		A flood that has the potential to cause harm or conditions with the potential to result in loss of life, injury and economic loss	The degree of hazard varies with the severity of flooding and is affected by flood behaviour (extent, depth, velocity, isolation, etc.)
Flood impact and risk assessment	FIRA	A study to assess flood behaviour, constraints and risk, understand offsite flood impacts on property and the community resulting from the development, and flood risk to the development and its users	These studies are generally undertaken for development and are to be prepared by a suitably qualified engineer experienced in hydrological and hydraulic analysis for FRM
Flood liable land		Equivalent to flood prone land	See the definition of flood prone land
Flood plan (local or state)	Local (LFP)	A sub-plan of an EM plan that deals specifically with flooding; they can exist at state, zone and local levels	The NSW Government develops flood plans as a legislative responsibility to determine how best to respond to floods. These community-based plans describe the risk to the community, outline agency roles and responsibilities, the agreed community emergency response strategy and how floods will be managed
Flood planning area	FPA	The area of land below the FPL	The FPA is generally developed based on the FPL for typical residential development. Different types of development may have different FPLs applied within the FPA. In addition development controls will vary across the FPA due to varying flood constraints
Flood planning level	FPL	The combination of the flood level from the DFE and freeboard selected for FRM purposes	Different FPLs may apply to different types of development. Determining the FPL for typical residential development should generally start with a DFE of the 1% AEP flood plus an appropriate freeboard (typically 0.5 m). This assists in determining the FPA

Term	Shortened form	Definition	Context for use/additional information
Flood prone land		Land susceptible to flooding by the PMF event	Flood prone land is also known as the floodplain, flood liable land and flood affected land
Flood risk		Risk is based on the consideration of the consequences of the full range of flood behaviour on communities and their social settings, and the natural and built environment	See also risk. The degree of risk varies with circumstances across the full range of floods. It is affected by factors including flood behaviour and hazard, topography and EM difficulties
Flood risk management	FRM	The management of flood risk to communities	
Flood storage areas		Areas of the floodplain that are outside floodways which generally provide for temporary storage of floodwaters during the passage of a flood and where flood behaviour is sensitive to changes that impact on temporary storage of water during a flood	See also flood function, floodways and flood fringe areas
Flood study		A comprehensive technical investigation of flood behaviour undertaken in accordance with the principles in this manual and consistent with associated guidelines. A flood study defines the nature of flood behaviour and hazard across the floodplain by providing information on the extent, level and velocity of floodwaters, and on the distribution of flood flows considering the full range of flood events up to and including extreme events, such as the PMF	A flood study is undertaken in accordance with the FRM process outlined in this manual to support the understanding and management of flood risk. It is different from a flood impact and risk assessment (FIRA)
Flood warnings		Warnings issued when there is more certainty that flooding is expected, are more targeted and are issued for specific catchments	Flood warnings include more specific predictions of the severity of expected flooding and may give quantitative figures such as expected river water heights at gauge stations
Floodplain		Equivalent to flood prone land	See the definition of flood prone land

Term	Shortened form	Definition	Context for use/additional information
Floodways		Areas of the floodplain which generally convey a significant discharge of water during floods and are sensitive to changes that impact flow conveyance. They often align with naturally defined channels or form elsewhere in the floodplain	See also flood function, floodways and flood fringe areas. Floodways are sometimes known as flow conveyance areas
Flow		The rate of flow of water measured in volume per unit time, for example, cubic metres per second (m_3/s)	Flow is different from the speed or velocity of flow, which is a measure of how fast the water is moving
Freeboard		A factor of safety typically used in relation to the setting of minimum floor levels or levee crest levels	Freeboard aims to provide reasonable certainty that the risk exposure selected in deciding on a specific event for development controls or mitigation works is achieved. Freeboards for development controls and mitigation works will differ. In addition freeboards for development control may vary with the type of flooding and with the type of development
Frequency		The measure of likelihood expressed as the number of occurrences of a specified event in a given time	For example, the frequency of occurrence of a 20% AEP or 5-year ARI flood is once every 5 years on average
FRM measures		Measures that can reduce flood risk	FRM measures may include FRM, flood mitigation, EM and land-use planning measures
FRM options		The FRM measures that might be feasible for the management of a particular area of the floodplain	Preparation of an FRM plan requires a detailed evaluation of FRM options
FRM plan		A management plan developed in accordance with the principles in this manual and its supporting guidelines	Previously known as a floodplain risk management plan or floodplain management plan. It may describe how particular areas of flood prone land are to be used and managed to achieve defined objectives
FRM study		A management study developed in accordance with the principles in this manual and its supporting guidelines	Previously known as a floodplain risk management study or floodplain management study
Future flood risk		The risk future development and its users are exposed to as a result of its location on the floodplain	Future flood risk may be reduced by existing or proposed FRM measures and land-use planning controls that consider the flood constraints on the land. This leaves a residual flood risk to the new development and its users. This residual flood risk may be further reduced by addressing continuing flood risk

Term	Shortened form	Definition	Context for use/additional information
Gauge height		The height of a flood level at a particular water level gauge site related to a specified datum	The datum may or may not be the AHD
Hazard		A source of potential harm or conditions that may result in loss of life, injury and economic loss due to flooding	
Hydraulics		The study of water flow in waterways and flowpaths; in particular, the evaluation of flow parameters such as water level and velocity	
Hydrology		The study of the rainfall and run-off process; in particular, the evaluation of peak flows, flow volumes and the derivation of hydrographs for a range of floods	
Integrated planning and reporting framework	IP&R framework	The IP&R framework includes a suite of integrated plans that set out a vision and goals and strategic actions to achieve them. It involves a reporting structure to communicate progress to council and the community as well as a structured timeline for review to ensure the goals and actions are still relevant	Preparation of FRMS and plans and implementation and maintenance of works requires linkages to the IP&R framework
Likelihood		A qualitative description of probability and frequency	See also frequency and probability
Likelihood of occurrence		The likelihood that a specified event will occur	With respect to flooding, see also AEP and ARI
Local environmental plan	LEP	See *Environmental Planning and Assessment Act 1979*	
Local government area	LGA	The area serviced by the local government council	
Local overland flooding	LOF	Inundation by local run-off on its way to a waterway, rather than overbank flow from a waterway	
Local strategic planning statement	LSPS	Local strategic planning statements assist councils to implement the priorities set out in their community strategic plan and actions in regional and district plans	

Term	Shortened form	Definition	Context for use/additional information
Loss		Any negative consequence or adverse effect, financial or otherwise	
Merit-based approach		Weighs social, economic, ecological and cultural impacts of land-use options for different flood prone areas together with flood damage, hazard and behaviour implications, and environmental protection and wellbeing of the state's rivers and floodplains	The merit approach operates at 2 levels. At the strategic level it allows for the consideration of social, economic, ecological, cultural and flooding issues to determine strategies for the management of future flood risk, which are formulated into council plans, policy and environmental planning instruments At a site-specific level, it involves consideration of the merits of a development consistent with council LEPs, DCPs and local FRM policies, and consistent with FRM plans
NSW Floodplain Management Program	The program	The NSW Government's program of technical support and financial assistance to local councils to enable them to understand and manage their flood risk	The program, manual and FRM guides support the delivery of the policy through a partnership across governments
Prevention, preparedness, response and recovery	PPRR	Involves: · **prevention:** to eliminate or reduce the level of the risk or severity of emergencies · **preparedness:** enhances the capacity of agencies and communities to cope with the consequences of emergencies · **response:** to ensure the immediate consequences of emergencies to communities are minimised · **recovery:** measures that support individuals and communities affected by emergencies in the reconstruction of physical infrastructure and restoration of physical, emotional, environmental and economic wellbeing	In the flood context prevention involves FRM (including flood mitigation), EM and land-use planning measures
Probability		A statistical measure of the expected chance of a flood	For example, AEP

Term	Shortened form	Definition	Context for use/additional information
Probable maximum flood	PMF	The largest flood that could conceivably occur at a particular location, usually estimated from probable maximum precipitation (PMP), and where applicable, snow melt, coupled with the worst flood-producing catchment conditions	This is equivalent to the probable maximum precipitation flood in Australian Rainfall and Runoff (ARR). The PMF in ARR is used for estimating dam design floods
Probable maximum precipitation	PMP	The greatest depth of precipitation for a given duration meteorologically possible over a given size storm area at a particular location at a particular time of the year, with no allowance made for long- term climatic trends (World Meteorological Organization 1986)	PMP is the primary input to PMF estimation
Rainfall intensity		The rate at which rain falls, typically measured in millimetres per hour (mm/h)	Rainfall intensity varies throughout a storm in accordance with the temporal pattern of the storm
Residual flood risk		The risk to the existing and future community that remains with FRM, EM and land-use planning measures in place to address flood risk	FRM measures cannot remove all flood risk, but rather they reduce residual flood risk
Risk		'The effect of uncertainty on objectives' (ISO 2018)	See also flood risk. Note 4 of the definition in ISO31000:2018 also states that 'risk is usually expressed in terms of risk sources, potential events, their consequences and their likelihood'
Risk analysis		The systematic use of available information to determine how often specified (flood) events occur and the magnitude of their likely consequences	
Run-off		The amount of rainfall that ends up as streamflow, also known as rainfall excess	
Scenario		A scenario may relate to current, historical or assumed future floodplain, catchment and climate conditions	Flood behaviour varies over time with changes in key catchment and floodplain (such as the scale of development) and climatic conditions (including climate change), and due to the implementation of FRM measures. A range of scenarios are generally needed to understand and assess flood behaviour
Stage		Equivalent to water level; measured with reference to a specified datum	Measurement may relate to AHD, a local datum or a local water level gauge

Term	Shortened form	Definition	Context for use/additional information
Storm surge		The increases in coastal water levels above predicted astronomical tide level (i.e. tidal anomaly) resulting from a range of location-dependent factors	These factors may include the inverted barometer effect, wind and wave setup and astronomical tidal waves, together with any other factors that increase tidal water level
Velocity		The speed of floodwaters, measured in metres per second (m/s)	
Vulnerability		The degree of susceptibility and resilience of a community, its social setting, and the built environment to flooding	Vulnerability is assessed in terms of ability of the community and environment to anticipate, cope and recover from flood events

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