NSW RECONSTRUCTION AUTHORITY

HAWKESBURY-NEPEAN RIVER FLOOD STUDY TECHNICAL VOLUME 6: WALLACIA FLOOD FREQUENCY ANALYSIS

FINAL REPORT

Wallacia during 1964 flood. Photo courtesy of Roads and Maritime Services

wma water

MAY 2024

Level 2, 160 Clarence Street
Sydney, NSW, 2000

Tel: (02) 9299 2855
Fax: (02) 9262 6208
Email: wma@wmawater.com.au
Web: www.wmawater.com.au

HAWKESBURY-NEPEAN RIVER FLOOD STUDY TECHNICAL VOLUME 6: WALLACIA FLOOD FREQUENCY ANALYSIS

FINAL REPORT

MAY 2024

Project Hawkesbury-Nepean River Flood Study Technical Volume 6: Wallacia Flood Frequency Analysis	**Project Number** 113031-15
Client NSW Reconstruction Authority	**Client's Representative** Stephen Yeo
Project Manager Mark Babister	

Revision History

Revision	Description	Distribution	Authors	Reviewed by	Verified by	Date
0	Draft Report	Internal	Mark Babister Mikayla Ward	Monique Retallick		JUL 2021
1	Draft Report	INSW	Mark Babister Mikayla Ward	Monique Retallick	Mark Babister	FEB 2022
2	Draft Final Report	INSW	Mark Babister Jayden Fraser	Monique Retallick	Mark Babister	SEP 2023
3	Final Report	NSW RA	Mark Babister Jayden Fraser	Monique Retallick	Mark Babister	MAY 2024

Acknowledgement of Country

The NSW Reconstruction Authority and WMAwater 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We advise this resource may contain images, or names of deceased persons in photographs or historical content.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. Any references to INSW should be read as referring to the Authority.

HAWKESBURY-NEPEAN RIVER FLOOD STUDY TECHNICAL VOLUME 6: WALLACIA FLOOD FREQUENCY ANALYSIS

TABLE OF CONTENTS

PAGE

LIST OF TABLES

APPENDIX B:

LIST OF FIGURES

LIST OF DIAGRAMS

LIST OF ACRONYMS

AEP	Annual Exceedance Probability
ARI	Average Recurrence Interval
ARR	Australian Rainfall and Runoff
BOM	Bureau of Meteorology
H14	Gate operating rules for Warragamba Dam
m AHD	metres above Australian Height Datum
PMF	Probable Maximum Flood
RORB	Runoff routing Software
TUFLOW	one-dimensional (1D) and two-dimensional (2D) flood and tide simulation software (hydraulic model)
WBNM	Watershed Bounded Network Model (hydrologic model)

ADOPTED TERMINOLOGY

Australian rainfall and runoff – A guide to flood estimation (ARR) (Pilgrim, 1987) is a national guideline document, data and software suite that can be used for the estimation of design flood characteristics in Australia. The fourth edition of ARR was published by the Commonwealth of Australia in 2019 (ARR 2019) (Ball et al., 2019). Geoscience Australia supports ARR as part of its role to provide authoritative, independent information and advice to the Australian Government and other stakeholders to support risk mitigation and community resilience.

ARR 2019 recommends flood frequency terminology that is not misleading to the public and stakeholders. Flood events are described in terms of the chance of occurrence in any one year, with this probability normally assigned to a flood based on its peak level. While there is a very high correlation between peak flow and peak level, individual floods show considerable variability in terms of flood volume, rate of rise and duration of inundation. This variability is caused by how wet the catchment is prior to an event and when, where and how much rain falls on the catchment. Floods occur randomly, so one flood event does not change the chance of a subsequent flood occurring. Rare events may occur in clusters: two floods with approximately a one per cent chance per year occurred in Kempsey in 1949 and 1950; the two largest floods in Brisbane occurred two weeks apart in 1893. Therefore, the use of terms such as ‘recurrence interval’, ‘return period’, and even ‘average recurrence interval’ (ARI), are no longer recommended as they imply that a given event magnitude is only exceeded at regular intervals such as every 100 years.

ARR 2019 recommends the use of Annual Exceedance Probability (AEP) to describe flood probabilities or frequency. Annual Exceedance Probability (AEP) is the probability of an event being equalled or exceeded within a year. AEP may be expressed as either a percentage (%) or 1 in X. Floodplain management typically uses the percentage form of terminology. Therefore a 1% AEP event or 1 in 100 AEP has a one per cent chance of being equalled or exceeded in any year. This report adopts the terminology of 1 in 100 AEP.

ARI and AEP are often mistaken as being interchangeable for events equal to or more frequent than 10% AEP. The table below describes how they are subtly different. It categorises flood events according to the ARR 2019 classification.

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*, 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 Bureau of Meteorology (BoM) and NSW State Emergency Service (NSW SES) use the terms 'minor', 'moderate' and 'major' to describe floods. These terms do not relate to a particular probability at any location but are assigned based on local consequences. For this reason, they vary in probability and severity at different locations along the rivers. For example, at Windsor gauge, minor floods are those between 5.8 and 7.0 metres, moderate floods are between 7.0 and 12.2 metres, and major floods exceed 12.2 metres.

Design event quantiles such as a 1 in 100 AEP are used to refer to standard probabilities of events used in design flood estimation for example those listed in the table below.

Frequency Descriptor	EY	AEP (%)	AEP (1 in x)	ARI
Very Frequent	12			
	6	99.75	1.002	0.17
	4	98.17	1.02	0.25
	3	95.02	1.05	0.33
	2	86.47	1.16	0.5
	1	63.21	1.58	1
Frequent	0.69	50	2	1.44
	0.5	39.35	2.54	2
	0.22	20	5	4.48
	0.2	18.13	5.52	5
	0.11	10	10	9.49
Rare	0.05	5	20	19.5
	0.02	2	50	49.5
	0.01	1	100	99.5
Very Rare	0.005	0.5	200	199.5
	0.002	0.2	500	499.5
	0.001	0.1	1000	999.5
	0.0005	0.05	2000	1999.5
Extreme	0.0002	0.02	5000	4999.5
			↓	
			PMP/ PMP Flood	

Note: EY = Exceedances per Year; AEP = Annual Exceedance Probability; ARI = Average Recurrence Interval
Source: adapted from ARR 2019 (Ball et al., 2019)

ACKNOWLEDGEMENTS

WMAwater acknowledges the contributions of the Hawkesbury-Nepean Valley Flood Risk Management Directorate and Penrith City Library for their assistance in generating historical flood records in this study.

EXECUTIVE SUMMARY

This Technical Volume describes a component of work completed as part of the 2024 Hawkesbury-Nepean River Flood Study, which updates and builds on the Hawkesbury-Nepean Valley Regional Flood Study completed in 2019 (WMAwater, 2019). The 2024 Flood Study includes a refined hydrologic model (WBNM) for all catchments other than the Warragamba catchment (**Technical Volume 2**), and a new two-dimensional hydraulic model (TUFLOW) (**Technical Volume 3**). This Technical Volume describes a detailed flood frequency analysis for Wallacia, which shapes the selection of appropriate representative design events from the Monte Carlo framework (**Technical Volume 7**), for detailed modelling using TUFLOW (**Technical Volume 11)**.

The Hawkesbury-Nepean Valley consists of a sequence of floodplains interspersed with incised sandstone gorges. Wallacia is located on a floodplain, upstream of where the Nepean River joins the Warragamba River to discharge into another floodplain at Penrith and Emu Plains.

Flood levels in the Wallacia floodplain have been well studied but estimates have historically varied over a 2-metre range. This is because in small events, flood levels are dominated by flows down the Nepean River while in very large events, the flood levels are dominated by backwatering of flows from large Warragamba Dam outflows. In between, there can be a mix of the two mechanisms.

This study collected data from a range of historical sources including the gauge records and newspaper sources for flood events prior to the 20th Century. These historical records were then carefully adjusted to different historical catchment conditions including prior to Warragamba Dam construction and prior to the construction of the four Nepean Dams. This was undertaken based on whether flood levels were influenced by the Warragamba or Upper Nepean flows.

The ranking of events and influence of the Warragamba or Upper Nepean catchments was confirmed by examining the equivalent event rankings at the Camden, Penrith and Windsor gauges. An event which ranked highly at Camden and Wallacia, but not at Penrith indicated an event at Wallacia that was dominated by Nepean River flows. Conversely if the event did not rank highly at Camden but did at Wallacia and Penrith, the levels at Wallacia in that event were likely generated by backwater from the Warragamba catchment outflows. Some events were assessed as ‘neutral’ because rankings were similar across the gauges.

This work resulted in two annual series that represented the pre- and post-Warragamba Dam scenarios. The pre-Warragamba Dam annual maximum series contains observed data for the years between 1860 and 1906, and adjusted values between the years 1907 and 1960 depending on the contribution of the Upper Nepean dams. For the years 1961 and onwards, the observed levels were converted into pre-Warragamba Dam levels and adjusted based on the contribution of the four Upper Nepean Dams.

Similarly, the post-Warragamba Dam annual maximum series contains observed data for the years 1961 to 2022. For the years prior to 1961, the observed levels were converted into post-Warragamba Dam levels and adjusted based on the contribution of the four upper Nepean Dams.

Diagram 1 plots the resulting pre- and post-Warragamba Dam annual maximum series with the updated Monte Carlo results (refer to **Technical Volume 7**). The error bars represent the range of possible levels at Wallacia after adjusting for the impact of Warragamba Dam. The ranges were calculated by assuming the degree of Warragamba or Nepean River dominance for each event was over or underestimated. There is a good fit to the historical data for events up to the 10% AEP and fair for events up to the 1% AEP. The pre-dam Monte Carlo curve sits mid-way between the two largest historical events. Given the shape of the observed data, this is a reasonable fit and the model is considered fit for purpose at Wallacia.

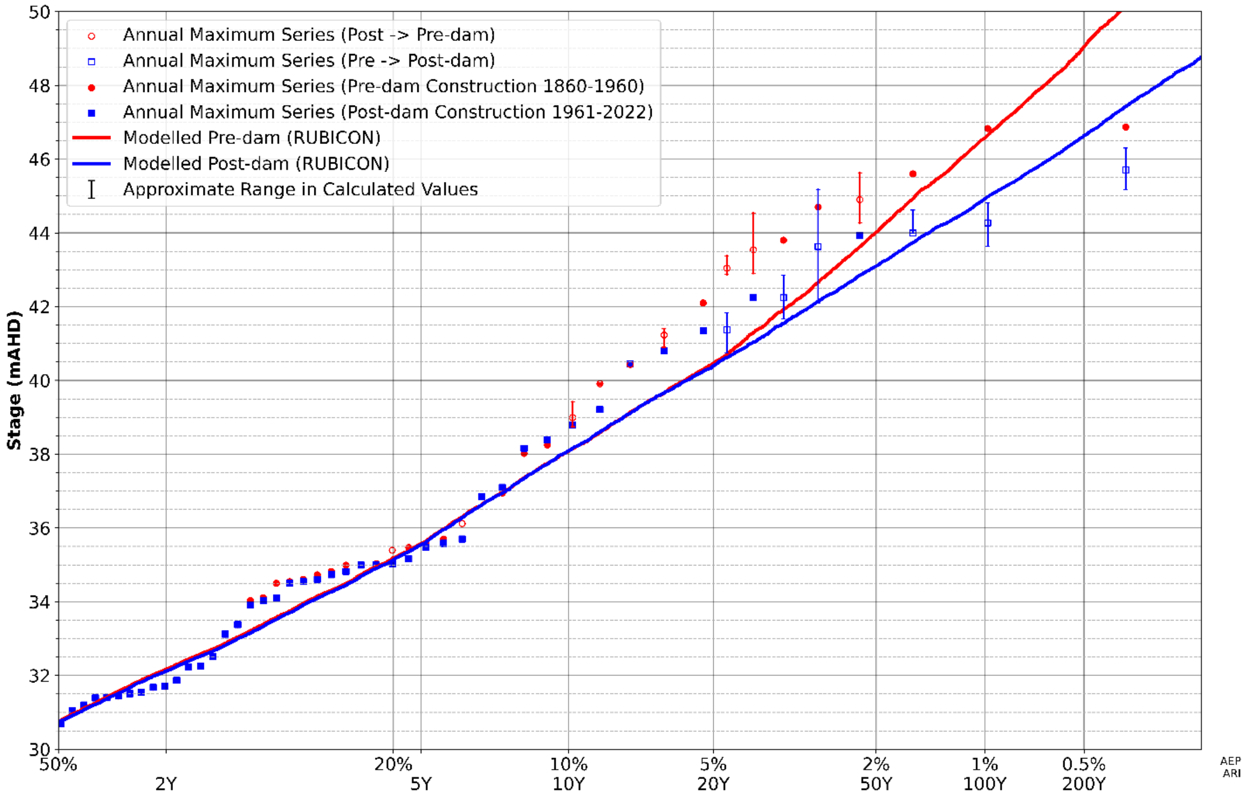


Diagram 1: Annual Series at Wallacia Weir

Table 1 compares the results provided by the updated modelling to previous estimates. Levels between the 1 in 5 AEP and the 1 in 200 AEP events have increased when compared with the Hawkesbury-Nepean Valley Regional Flood Study (WMAwater, 2019) results.

Table 1: Wallacia Weir design levels and comparison to previous estimates

AEP (1 in X)	1995 Upper Nepean River Flood Study Level (m AHD)[1]	2019 Hawkesbury-Nepean Valley Regional Flood Study Level (m AHD)	This study Monte Carlo results - Post-Dam Quantile Level (m AHD)[2]
2	-	31.10	30.72
5	36.5	34.81	35.14
10	-	36.94	38.09
20	42.3	39.23	40.4
50	-	42.50	43.1
100	45.7	44.60	44.92
200	47.1	46.46	46.63
500	-	48.91	48.84

[1] Levels from Table 6.9 of the Upper Nepean River Flood Study (1995)

[2] Levels from the RUBICON Monte Carlo model framework. Refer to **Technical Volume 11** for official results from the TUFLOW Model.

The RUBICON model and Monte Carlo framework are used to develop representative events for detailed modelling using TUFLOW (discussed further in **Technical Volumes 7** and **11**). The final design levels are determined by the TUFLOW model, and while the RUBICON and TUFLOW models produce similar levels at Wallacia in calibration events, the models diverge in larger events. For larger events, the TUFLOW model is considered more reliable.

1. INTRODUCTION

Wallacia is a small town located on the Nepean River 4.3 km upstream of its junction with the Warragamba River. Flooding at Wallacia is particularly complex. The Wallacia floodplain is located between Bents Basin and Wallacia Weir in its own 'bathtub'. A narrow gorge upstream of Bents Basin throttles Nepean River flows entering the Wallacia floodplain, and the gorge between Wallacia Weir and Penrith throttles flows leaving the Wallacia floodplain. In addition, the mechanism of flooding is highly variable, with small floods dominated by the Nepean River flows and large floods typically generated by Warragamba Dam outflows or a combination of both the Nepean and Warragamba flows. Whilst this complex flood behaviour is well documented, the current design levels at Wallacia produce flood levels from various assessments that have a range of over 2m.

The Hawkesbury-Nepean Valley Regional Flood Study (WMAwater, 2019) recommended further investigation of the complex joint probability of Nepean and Warragamba rivers flooding as it impacts Wallacia. This Technical Volume fulfils that recommendation – providing a detailed analysis of flood behaviours and mechanisms in Wallacia by developing a record of historical floods back to 1860, flood frequency analysis, and Monte Carlo modelling. It forms part of the 2024 Hawkesbury-Nepean River Flood Study, as shown below:

- Technical Volume 1: Data Collection & Review
- Technical Volume 2: Hydrologic Model Refinement and Calibration
- Technical Volume 3: Hydraulic Model Setup 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 focus of this Technical Volume is the Nepean River between Bents Basin and its junction with the Warragamba River, though reference is also made to Camden, Penrith and Windsor, which have relatively long records of flooding. These locations are shown in Figure 1.

2. STUDY AREA

A joint probability problem exists at Wallacia where flood levels are influenced by either or both the Warragamba River and the Nepean River. As such, a range of cases must be considered at Wallacia:

- Warragamba River dominated events
- Nepean River dominated events
- Combination of Warragamba and Nepean River flows.

While most small events are dominated by the Nepean River flows, the *Upper Nepean River Flood Study* (Lyall and Macoun Consulting Engineers, 1995) demonstrated that the Warragamba River can impact flood levels at Wallacia even during small floods. While large flood events are influenced by Nepean River flows, Warragamba Dam has a significant influence on flood behaviour as most large floods are dominated by the discharge from Warragamba Dam. That is, for rarer floods approaching the design 1% AEP level, the Warragamba flow significantly influences the flood level at Wallacia. The other key aspect is to what extent the hydrographs on the two systems coincide.

The presence of Warragamba Dam alters several aspects of the flow behaviour and introduces further complexities to the Wallacia system. Dam outflows are heavily dependent on the storage capacity of the dam prior to the storm event. If the dam is drawn down sufficiently, smaller floods (such as the February 2020 event) can be successfully mitigated. The flood record shows multi-decadal wet (flood dominated) and dry (drought dominated) periods (WMAwater, 2021). These wet and dry periods mean that the dam tends to be relatively full during large events and results in a very small amount of mitigation.

The dam also changes the shape and timing of the dam discharge hydrograph. Lake Burragorang extends nearly 50 km from the dam wall to the lake's edge on the Wollondilly and Coxs rivers, where large parts of the lake are over 50 m deep. This causes the flood wave to pass through the lake in less than an hour as inflows in the upper reaches raise levels in the whole lake. The additional storage in the lake largely offsets this reduced travel time. In most flood events, the peak outflow time is similar. However, when storage is close to full supply level, peak discharges can occur earlier than if the dam was not present. The outflow hydrograph tends to be slightly mitigated and less peaky than the pre-dam outflow, but can arrive earlier as the peak is held for a sustained period when compared to the pre-dam hydrograph. As a result, flows close to the peak on both systems are more likely to coincide. In some circumstances where a gate opening is just tripped, the outflow from the dam can be higher.

For events larger than a 1 in 20 AEP at Wallacia, backwater flows from Warragamba catchment become more pronounced. Individual events vary considerably depending on the contribution from the Nepean and Warragamba and the timing of each.

This means that it is impossible to obtain a one-to-one relationship between level and flow at Wallacia. As such, a traditional flood frequency analysis based on flow is not possible.

3. PREVIOUS STUDIES

The following studies have been undertaken in the study area and have been used to inform the current study.

3.1. Upper Nepean River Flood Study - Lyall and Macoun Consulting Engineers (1995)

The Upper Nepean River Flood Study was prepared in 1995 for the NSW Department of Land and Water Conservation and the Wollondilly, Campbelltown, Camden, Liverpool and Penrith Councils. The study collated historical water level gauge data at Maldon Weir, Camden at Cowpasture Bridge, and Wallacia. The Study adopted a RORB hydrologic model which was calibrated at these three locations to 5 historical floods (1964, 1975, 1978, 1988, 1990). The MIKE 11 hydraulic model was calibrated at these three locations to stage hydrographs and observed peak flood levels for 3 historical floods (1964, 1978, 1988). Flood frequency analysis was undertaken at the same three locations. The collected data were used extensively in this study.

3.2. Upper Nepean River Floodplain Risk Management Study and Plan - SMEC (2001)

The Upper Nepean River Floodplain Risk Management Study and Plan - Floodplain Management Study was prepared in 2001 for Camden City Council. It adopted the design flood events generated in the 1995 study and other tributary studies. No further work was undertaken on the flood frequency analysis at Wallacia or Camden and as such it has not influenced this study.

3.3. Nepean River Flood Study - Worley Parsons (2015)

The Nepean River Flood Study was prepared in 2015 for Camden City Council. It provided updated design flood behaviour for the Nepean River within Camden LGA. While the hydraulic model extended down to the Warragamba River junction, it did not appear to include flood inflows from the Warragamba River and so is not suitable for setting design flood levels in the Wallacia floodplain. This study updated previous studies with an extended flood record at Wallacia and Camden. Parts of this extended flood record were used in this study, particularly in generating the post-dam flood record.

3.4. Hawkesbury-Nepean Valley Regional Flood Study - WMAwater (2019)

The Hawkesbury-Nepean Valley Regional Flood Study was prepared in 2019 for Infrastructure NSW. This study developed the Monte Carlo modelling framework which has been updated as part of the current study (refer to **Technical Volume 7**) and is used in the assessment of joint probability at Wallacia in this report.

4. APPROACH

While Wallacia has a long flood record, traditional flood estimation techniques cannot be used directly as flood levels are influenced by the interaction of Nepean flows and flow in the Warragamba River which joins the Nepean River 4.3 km downstream of Wallacia. Design estimation approaches need to consider the flows in both these systems and their timing. The backwater effects from the Warragamba mean that there is no simple high flow rating relationship.

While traditional flood estimation techniques cannot be used directly, a long stage flood record can be constructed, and Monte Carlo techniques can be used to understand the interaction of the Nepean and Warragamba systems. This can then be coupled with detailed two-dimensional flood modelling to produce traditional flood study outputs. This section outlines the complexities of the system and the approaches adopted.

4.1. Pre- and Post-Dam Stage Data Sets

While there is a long flood record at Wallacia, Warragamba Dam and the Upper Nepean Dams have changed flood behaviour. Homogeneous pre- and post-dam flood records have been constructed for comparison with other flood estimation techniques. A timeline of dam construction in the Hawkesbury-Nepean is provided in Diagram 2 and Table 2.

Warragamba Dam is a 142 m high and 351 m wide concrete gravity dam that retains 2065 gigalitres of water at its full water supply level. Construction of the dam began in late 1948 and was completed in 1960. As outlined above, a dam can significantly alter flood behaviour and as a result, a distinction was made between the Wallacia historical flood levels for pre- and post-dam construction. An additional distinction was made to account for the four Upper Nepean dams completed between 1907 and 1935. While minor compared to the Warragamba Dam, the Upper Nepean Dams still impact the flood behaviour at Wallacia (further discussed in Section 6.4).

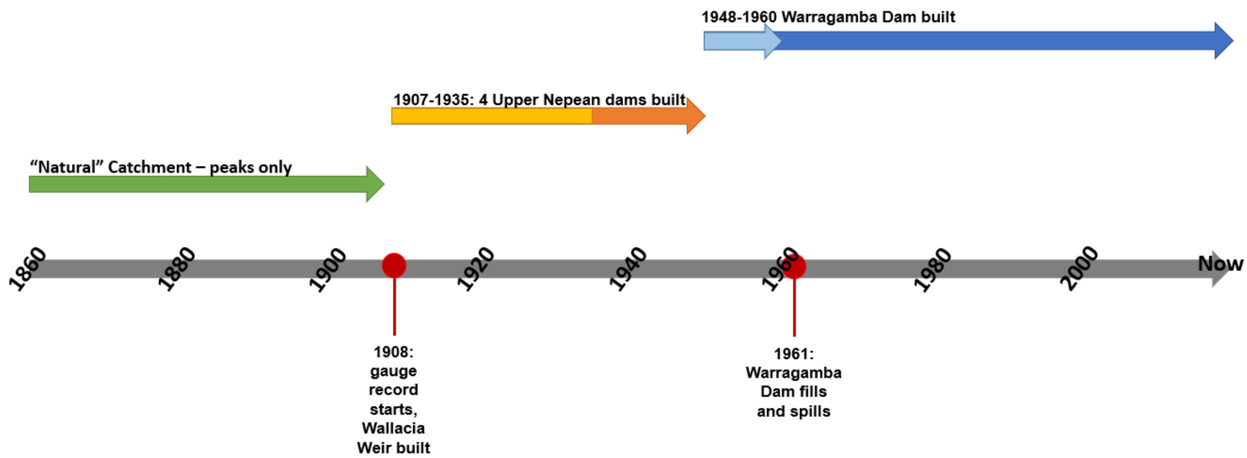


Diagram 2: Timeline of dam construction in the in Hawkesbury-Nepean.

Table 2: Hawkesbury - Nepean Dams

	Construction Commenced	Construction Completed
Cataract Dam	1902	1907
Cordeaux Dam	1918	1926
Avon Dam	1921	1927
Nepean Dam	1925	1935
Warragamba Dam	1948	1960

4.2. Monte Carlo

This study uses best practice techniques in defining flood behaviour in the Hawkesbury-Nepean Valley with a particular emphasis at Wallacia. The ‘Monte Carlo’ modelling framework is based on the 2019 Hawkesbury-Nepean Valley Regional Flood Study. This framework has been updated as described in **Technical Volume 7**, including to incorporate a WBNM hydrologic model and other changes to tides and timing. The RUBICON model was also recalibrated to historical events and the Flood Frequency Analysis (FFA) at Wallacia, Sackville, Lower Portland, and Wisemans Ferry which is in addition to the FFA for Warragamba, Penrith and Windsor described in the Regional Flood Study.

The ‘Monte Carlo’ framework generates thousands of potential events with variable inputs to mimic the observed variability of actual floods in the valley. Real flood events exhibit an enormous degree of variability, most of which is determined by where and when rain falls. Flood events are also influenced by how wet the catchment is before the event and, in the case of the Hawkesbury-Nepean floodplain, the levels in Warragamba Dam prior to an event. Understanding this variability is important for managing flood risk to life and property. To better account for this variability, design flood estimation in Australia is moving from a single event per quantile (i.e., 1 in 100 AEP) to Monte Carlo modelling.

For this study, the variability in each of the following key input variables was estimated from observed events, and the Monte Carlo framework was established to model flood events based on randomly sampling each variable from the range of possible inputs:

- Rainfall intensity and frequency
- Spatial pattern of rainfall (where)
- Temporal pattern of rainfall (when)
- Rainfall initial loss
- Rainfall pre-burst
- Warragamba Dam drawdown
- Relative timings of tributary inflows
- Ocean tide levels.

The updated framework is summarised in Diagram 3.

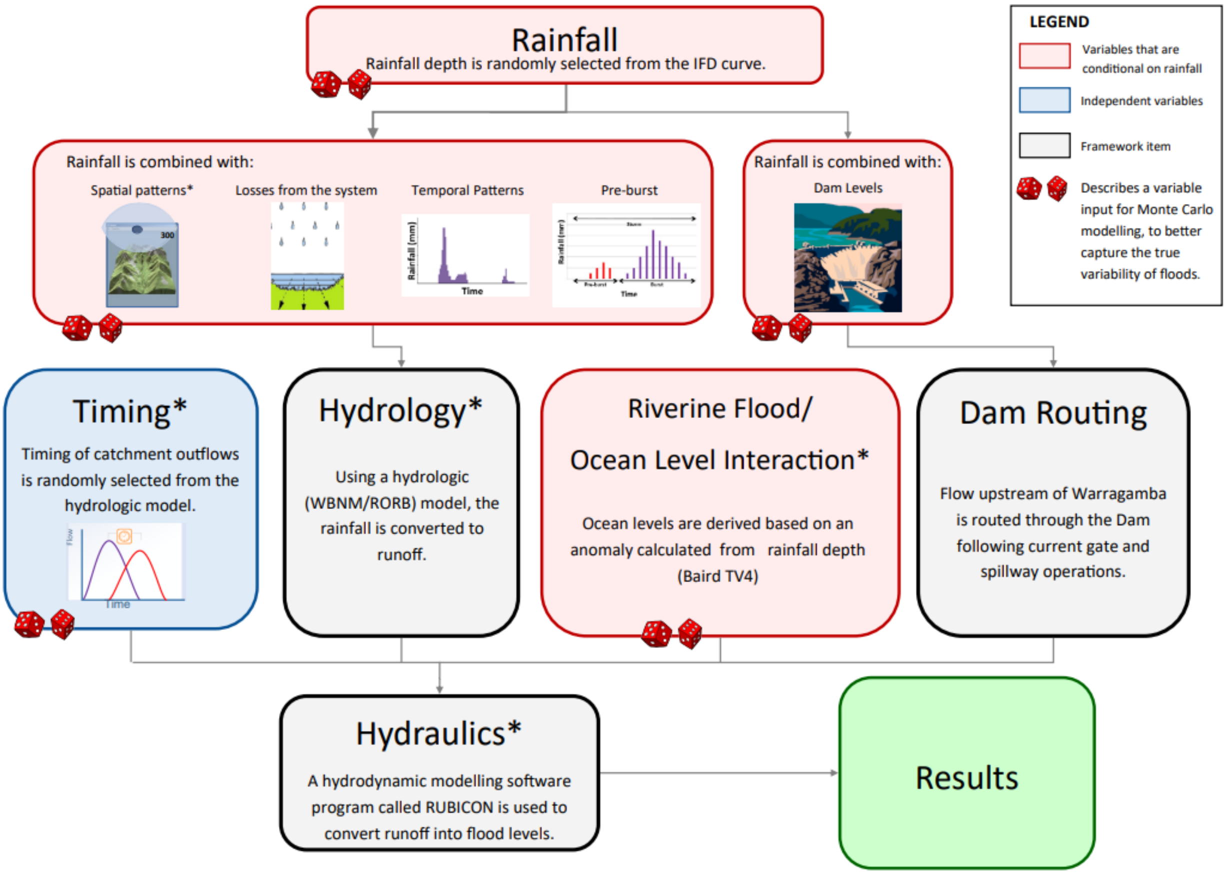


Diagram 3: Monte Carlo Modelling Methodology
* Indicates parts of the framework that have been updated for this study.

The variables from the Monte Carlo analysis were inputs to the updated hydrological model, and the resultant flows, together with the other variables were input into the updated RUBICON hydraulic model. This was used to assess flood behaviour.

4.3. Numerical Integration Techniques

Estimating design flood level at Wallacia is a complex joint probability problem. Classical numerical methods for solving a joint probability problem, such as Laurenson (1974), only work for two key flood drivers. For Wallacia the two key drivers are flow on the Warragamba and Nepean rivers, and the rainfall that causes these flows. If just these two factors are considered, the joint probability of flooding at Wallacia can be estimated using:

- The probability of the peak flow in both rivers
- The correlation between flow in both rivers, and
- How these flows combine to produce flood levels.

In order to use the Laurenson approach, other variables such as the dam level, hydrograph shape and timing need either to be assumed to be average, or the joint probability approach needs to be expanded beyond two inputs. Average values work well when the influence of the input is well behaved or symmetrical. That is, when the probability of it being a bit higher or lower and the influence on the resultant flood level is similar. Each additional input increases the complexity. The Laurenson method is easy to apply for two inputs as only a two-dimension matrix is required to calculate the conditional probability distribution. For this reason, when the number of significant inputs or drivers is more than two, Monte Carlo techniques are normally used.

A simple joint probability approach based on Laurenson (1974) was trialled but was discarded as the Monte Carlo approach showed that the timing of events and dam levels were quite important and the assumption about how much the peaks would overlap was critical to the final flood levels.

5. DATA

5.1. Historical Flood Levels

The Hawkesbury-Nepean catchment has a significant flood record, dating back to early European settlement. This section provides a summary of historical flood events at Wallacia Weir, located less than 2 km downstream of the town of Wallacia. In 1908 the current Wallacia Weir was constructed, with daily records from 1917 and continuous records from 1962. Large floods before 1917 are described in historical sources. In all, a reliable flood record can be constructed for the period 1860-2022. To construct a homogeneous record, it is necessary to adjust the events for the impact of Warragamba Dam.

The unmodified Wallacia Weir flood record is included as Table B1 in **Appendix B** along with sources. Only large floods are recorded from 1860 to 1916.

Extensive use was made of the National Library of Australia's 'Trove' database. Trove has significantly simplified the task of searching government and newspaper records. This database was helpful in obtaining and verifying early record data (1860, 1864, 1867, 1870, 1873, 1900, 1916, 1925). While the 1857 flood is also mentioned as damaging property at Wallacia, it is not possible to determine a level, though it appears to be lower than the 4 events in the 1860s and 1870s, which is consistent with the limited data at Penrith.

5.2. Previous Data Sets

Most of the data discussed within this section is described in the Hawkesbury-Nepean Valley Regional Flood Study (WMAwater, 2019). This study combined more recent data with the extensive data set collected in the Upper Nepean River Flood Study (Lyall Macoun Consulting Engineers, 1995). Post 1995 data was supplemented from the Nepean River Flood Study (Worley Parsons, 2015). The Wallacia records were also cross checked with the WaterNSW HYSTRA records.

5.3. Hydrographic Records

Flood information from historical sources and previous data sets was supplemented by stream records for Wallacia Weir obtained from WaterNSW (gauge number 212202). Wallacia Weir has an existing gauge zero of 26.596 m AHD (source: WaterNSW). This has not been consistent throughout the record with some variation as shown in Table 3.

Table 3: Historical changes to gauge zero at Wallacia Weir

Gauge Zero (m AHD)	Year
23.90	1908-1917
23.06	1917-1925
26.49	1925-1980
26.596	Current[1]

[1]The date the gauge was updated between 1980 and 2020 is unknown.

5.4. History of Blaxlands Crossing and Wallacia Weir

In order to derive a longer record it is necessary to combine data from Blaxlands Crossing and Wallacia Weir. Blaxlands Crossing is at Silverdale Road Bridge located approximately 2 kilometres upstream of the weir (see Figure 2). There are also some flood levels that were recorded at several properties upstream of Wallacia on either side of the river from the 1800's.

In 1813, Governor Macquarie granted land to John Blaxland, which encompasses most of the present-day suburbs of Luddenham and Wallacia. Here, Blaxland built a flour mill, which operated from the 1830s, a brewery (known to have been one of the first in the colony) and a homestead. Originally a ford consisting of consolidated river pebbles, Blaxlands Crossing is named after John Blaxland who was known to have regularly used the river ford when crossing the Nepean River to access his property on the western bank (Heritage NSW, 2021). The current road bridge is constructed in this location.

Wallacia Weir was constructed in 1908 (Department of Primary Industries, 2016). As a result, the flood records at Blaxlands Crossing have a longer history than those at Wallacia Weir. The gauging station at Wallacia Weir commenced operation in 1908 with the completion of the weir, and a record of flood peaks is available for the period 1917 to date. Digitised continuous records became available for most years since 1962.

5.5. Relationship Between Blaxlands Crossing and Wallacia Weir

Downstream of Wallacia Weir, the Nepean River rapidly descends through a series or narrow gorges and basins to Warragamba Junction. The weir pool extends upstream past Wallacia and Blaxlands Crossing. During very low flows the levels at the weir and Blaxlands Crossing are the same. A slight gradient exists during higher flows. During higher Nepean flows, the gorge chokes the flow creating a relatively flat gradient. Backwater effects from Warragamba Dam can create the same effect for large Warragamba flows. The gradient is dependent on the flow and backwater effects. By understanding the hydraulic behaviour, it is possible to combine records at Blaxlands Crossing and Wallacia Weir to form a long record.

A hydrologic (WBNM) model was developed by WMAwater in the *Hawkesbury Nepean Hydrologic Model Update Report* (WMAwater, 2018). As part of the current study, Rhelm and Catchment Simulation Solutions further developed and calibrated this model to eight historical events (**Technical Volume 2**). These hydrologic outputs were then used as the inputs to the new two-dimensional hydraulic (TUFLOW) model (**Technical Volume 3**).

Two of the larger historical events modelled with WBNM/TUFLOW have been used to analyse the relationship between Blaxlands Crossing and Wallacia Weir. Diagram 4 shows the rising and falling limb water levels at Blaxlands Crossing and Wallacia Weir for the 1964 and 1990 calibration events along with a 1:1 line. These events show near identical rising limb behaviour and a similar falling limb other than within a few metres of the peak. The difference between these events and the 1:1 line is indicative of the gradient between Blaxlands Crossing and Wallacia Weir. This gradient starts decreasing above 37m AHD. This can be used as a base for adjusting the earlier floods recorded at Blaxlands Crossing only. For larger floods the adjustment is small.

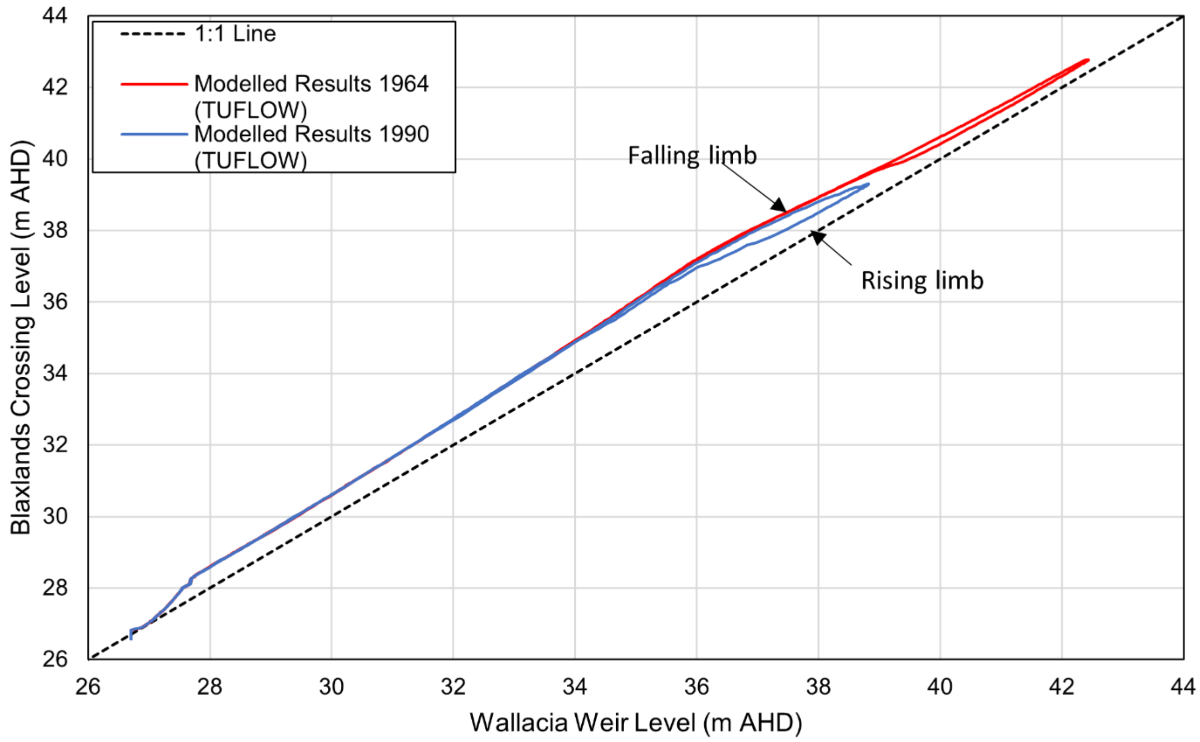


Diagram 4: Relationship between flood levels at Wallacia Weir and Blaxlands Crossing, demonstrated by 1964 and 1990 floods

5.6. Corresponding data at Camden, Warragamba Dam, Penrith and Windsor

Due to the complex nature of flooding at Wallacia, flood records at Camden, Penrith, Warragamba Dam and Windsor were used to assist in categorising events into Warragamba or Nepean dominated events. These are presented in Table B2 in **Appendix B**. Additionally, these records were used to validate data with questionable or conflicting values (refer to Section 6 for detailed information regarding data adjustment).

5.7. Rating relationship

The WaterNSW rating as well as the observed gaugings from PINEENA (managed by WaterNSW) have been plotted in Diagram 5 alongside the existing peak flow and level Monte Carlo results for the dam and “no discharge from Warragamba Dam” scenarios. The no discharge (“blackhole dam”) scenario refers to Nepean-only floods with no outflows from the Warragamba Catchment. The flow versus level relationships for 1961, 1978 and 1990 historical event TUFLOW results are also plotted in Diagram 5. This graph shows a number of aspects of the Wallacia Weir rating relationship:

- The no dam discharge events (red) plot as a single line showing that there would be a single rating relationship at Wallacia Weir without the Warragamba backwatering
- The dam discharge events show a considerable scatter above this line which increases with event magnitude
- The TUFLOW results show that the relationship varies considerably between the rising and falling limb

- The 1978 event show that the gradient reversal around 35m AHD which is a result of backwater effects from Warragamba Dam finishing
- The WaterNSW rating follows the rising limb gaugings
- Above 34m AHD, Warragamba can influence levels at Wallacia Weir and this starts to become significant above 37m AHD
- Above 2000 m^3/s on the Nepean, the Warragamba discharge can change flood levels by several metres.

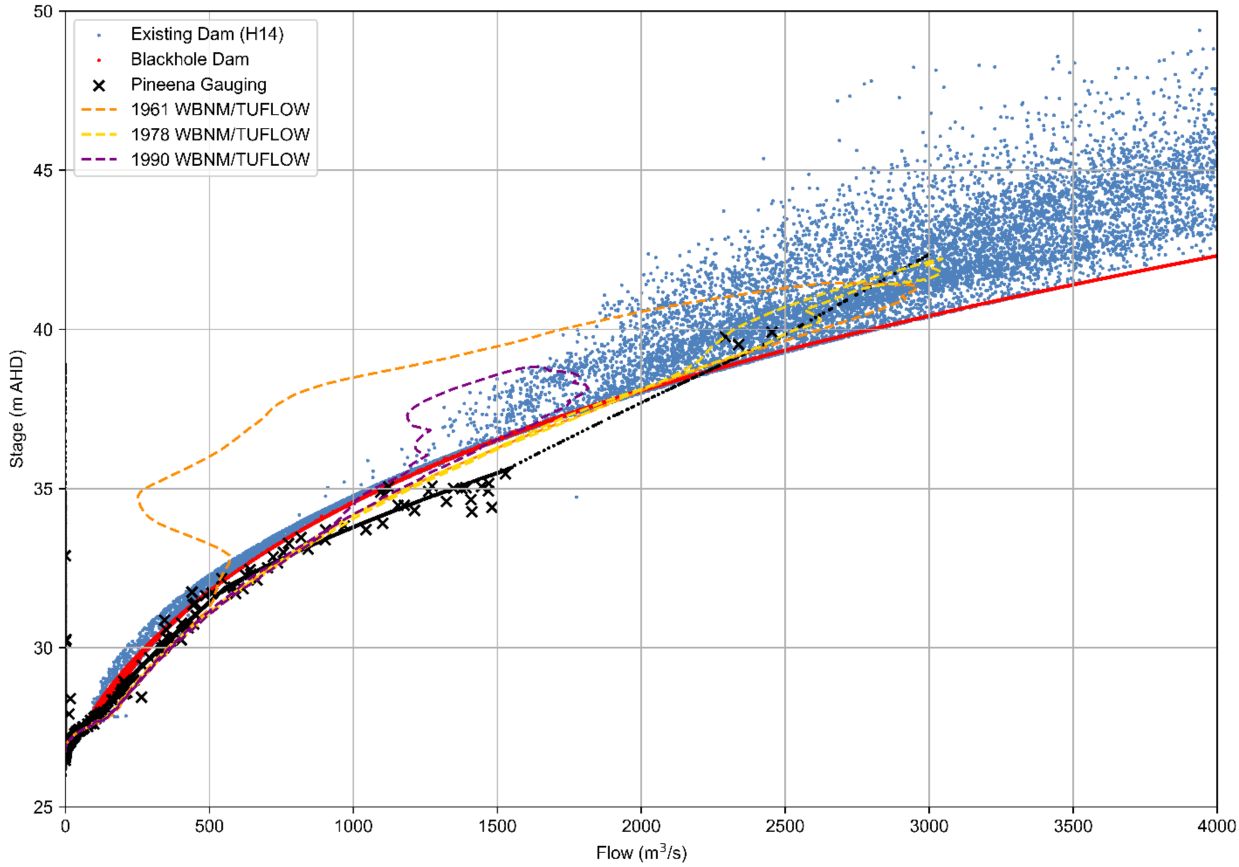


Diagram 5: Wallacia Weir Stage Flow Curve

Diagram 6 shows the influence of Warragamba Dam outflows on levels at Wallacia Weir. The x-axis represents the modelled outflow for each of the Monte Carlo events, and the y-axis represents the increase in level compared to a zero-dam discharge at Wallacia Weir. Given the dam has a series of fixed gate-openings between 1500 and 7000 m^3/s, the results are clustered around these openings. For smaller discharges, the difference is between 0-1 m, while for larger discharges where the gates are completely open, the change in level is approximately linear. The diagram also shows that high discharges affect most Wallacia levels, though there are some events where there is a small impact.

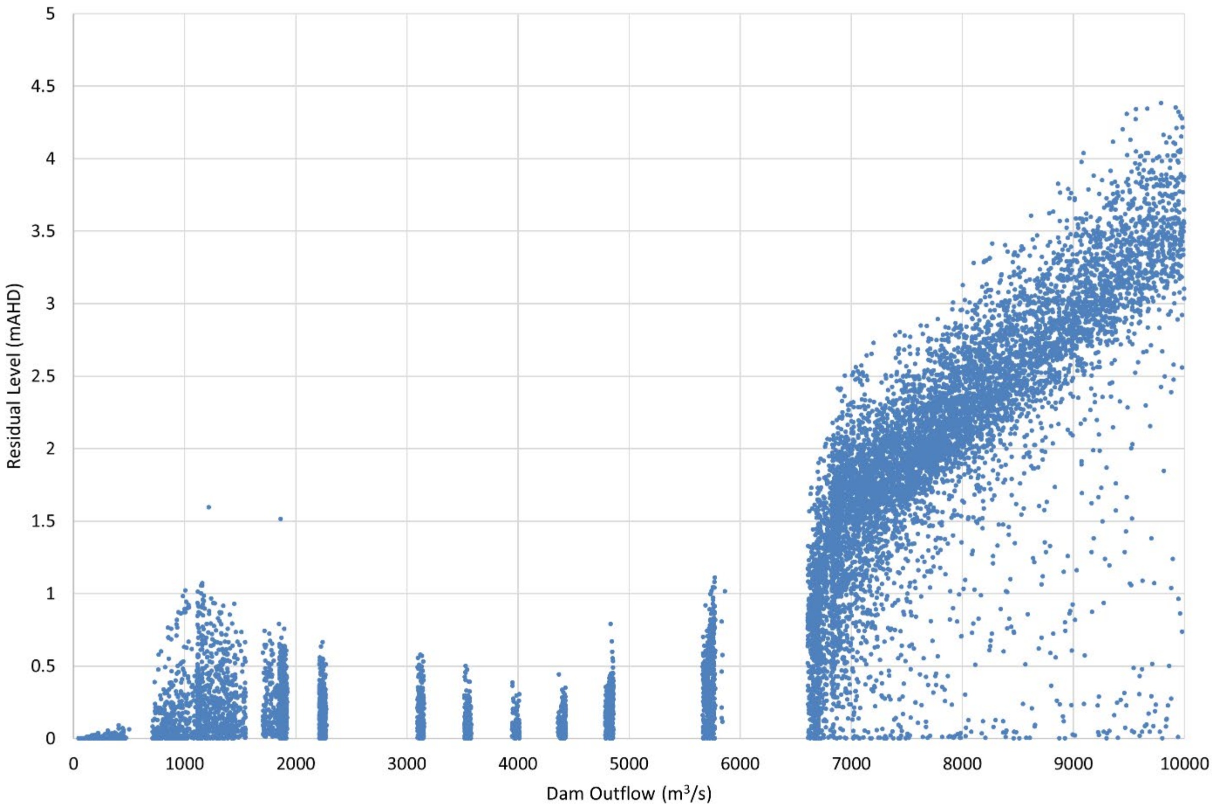


Diagram 6: Residual Level (Existing Dam minus Blackhole Dam) at Wallacia Weir plotted against Warragamba Dam outflow for the Monte Carlo runs.

6. DATA ANALYSIS

6.1. Approach summary

The following approach was taken to calculate the design levels at Wallacia:

1. Produce a homogeneous pre- and post-dam flood record at Wallacia, maximising the use of the available data. This involved:
   a. Collecting available historical flood data at Wallacia Weir (see Section 5)
   b. Classifying historical events as Nepean Dominated, Warragamba Dominated or Neutral based on their relative rank at Camden, Wallacia, and Windsor
   c. Correcting any potentially erroneous values in the pre- and post-dam datasets
   d. Estimating pre-dam and post-dam flood levels at Wallacia by first adjusting for the impact of Warragamba Dam (using the classifications in step b.), and then homogenising the dataset based on the impact of the four Upper Nepean Dams

2. Calibrate the RUBICON model and updated Monte Carlo framework to adequately fit the pre- and post-dam datasets at Wallacia

3. The Laurenson (1975) method was trialled but discarded due to complexity in the system.

6.2. Categorisation of events

To create a homogeneous pre- and post-dam flood record it is necessary to adjust events for the influence of the Warragamba and Upper Nepean Dams. While the recent events can be adjusted directly using modelling, the early historical events need to be adjusted based on our understanding from these events and the synthetic Monte Carlo events. To adjust the early events and the smaller recent events that have not been modelled, it is necessary to understand how much of the flood behaviour is caused by Warragamba and Nepean flows.

To identify the characteristics of historical flood events, the rare flood records were categorised depending on the relative influence of the Nepean River versus the Warragamba River. To do this, the flood behaviour at Wallacia Weir, Camden (Cowpasture Bridge) and downstream locations was analysed. This was done in two steps, first by comparing the levels at Camden and Wallacia Weir, and then by comparing levels and ranks at downstream locations.

6.2.1. Camden – Wallacia Weir Analysis

Diagram 7 compares the levels at Camden and Wallacia Weir for historical events up to 1990, showing there is considerable variation in level between these two sites. A second-degree polynomial (purple dashed line) was fit through the pre-dam data from 1860-1960, representing the expected stage-relationship between the two sites under natural catchment conditions. The yellow and blue dashed lines on either side of the polynomial are an approximate envelope of the Warragamba and Nepean dominated events respectively, constructed by fitting a first- or second-degree regression through the events with their label coloured in the respective colours. Events were visually classified as Nepean dominated (blue) or Warragamba dominated (yellow) based on their proximity to these respective regression relationships.

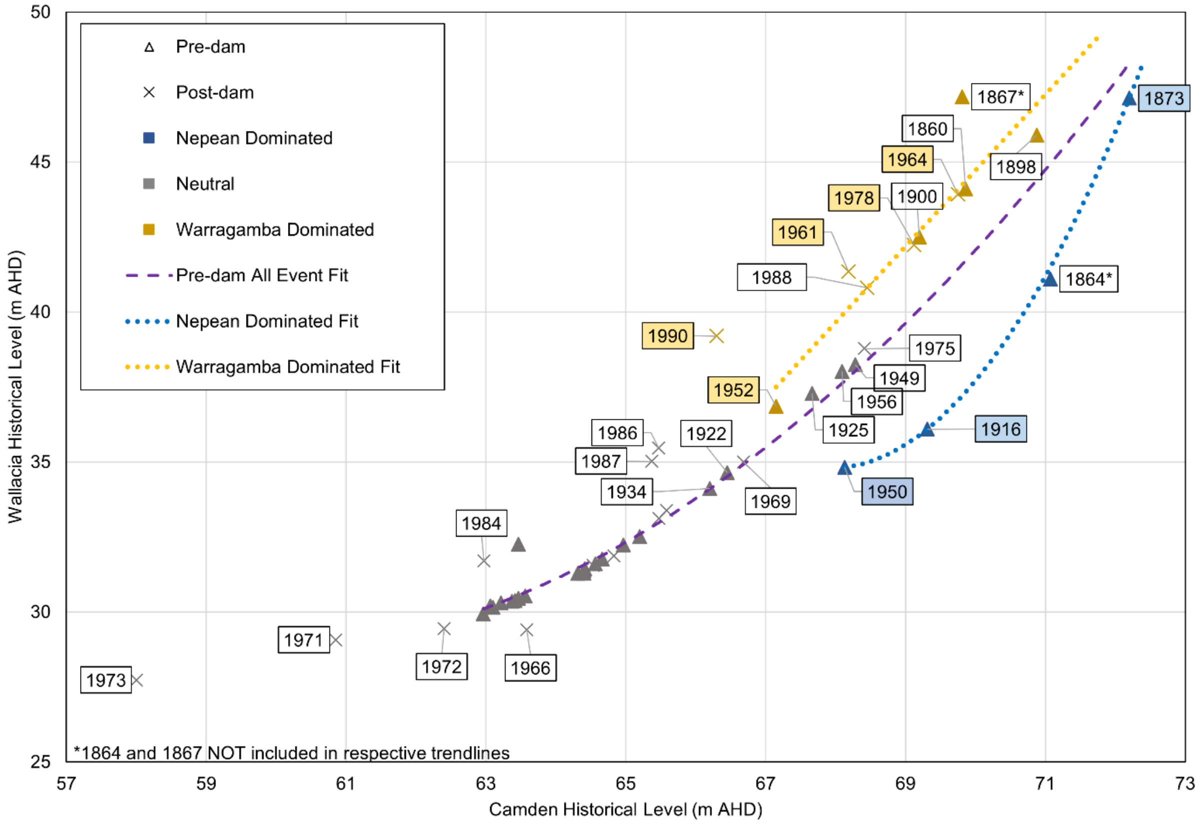


Diagram 7: Wallacia Weir Level vs Camden Historical Level Plot

6.2.2. Rank Analysis

Some historical events such as 1873 have a very high flood rank on the upper Nepean at Camden and a much lower rank downstream at Penrith and Windsor. This indicates they were larger events on the Nepean than they were elsewhere. Conversely, other historical events such as 1867 show the reverse. This effect is summarised visually in Diagram 8 for the nine largest events at Wallacia, showing the corresponding rank at Camden and Windsor (where we have complete flood records).

Events at Wallacia Weir were further categorised depending on the influence of the Warragamba Dam. As discussed, flood levels at Wallacia can be driven by backwater from Warragamba River, flows from the Nepean River catchment, or a combination of both. To illustrate this point, the top 9 ranked events at Wallacia Weir were extracted with peak flood level values tabulated at Camden, Wallacia, Penrith, Windsor, and Warragamba Dam (Table 4). The Nepean dominated events have much lower ranks downstream while the Warragamba dominated events have much higher ranks downstream. The more neutral events have relatively even ranks.

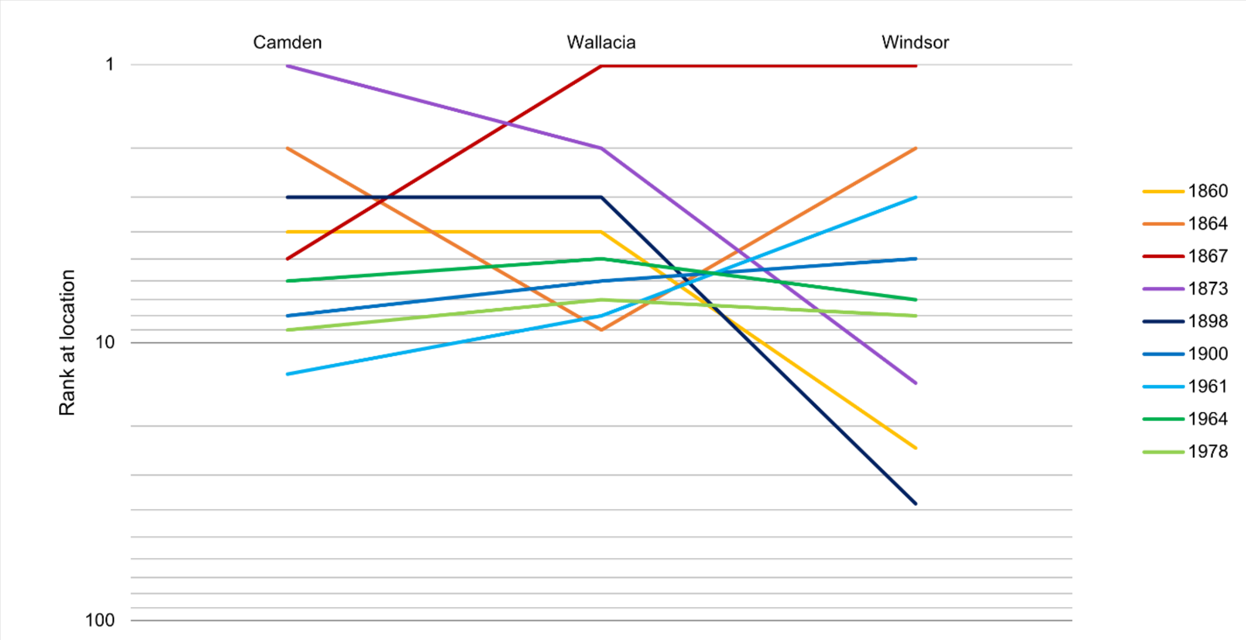


Diagram 8: Historical Flood Ranks at Camden, Wallacia and Windsor

Table 4: Top 9 ranked events at Wallacia

Event	Peak Levels – m AHD (rank)				Peak Flow - m³/s (rank) adjusted to Pre-dam	Dominant Mechanism
	Camden	Wallacia	Penrith	Windsor	Warragamba Dam	
1867	69.81 (5)	47.17 (1)	27.5 (1)	19.68 (1)	14600 (1)	Warragamba
1873	72.20 (1)	47.13 (2)	-	13.13 (14)	-	Nepean
1898	70.88 (3)	45.90 (3)	21.42 (>14)	10.07 (38)	-	Nepean
1860	69.86 (4)	44.10 (4)	-	11.85 (24)	-	Nepean
1964	69.75 (6)	43.93 (5)	23.74 (7)	14.48 (7)	7940 (5)	Neutral
1900	69.20 (8)	42.50 (6)	25.28 (3)	14.53 (5)	9500 (3)	Warragamba
1978	69.12 (9)	42.24 (7)	23.35 (9)	14.46 (8)	7580 (7)	Neutral
1961	68.18 (13)	41.35 (8)	23.89 (5)	14.94 (3)	9010 (4)	Warragamba
1864	71.07 (2)	41.10 (9)	- (2)	15.08 (2)	11700 (2)	Neutral

6.2.3. Combined Analysis

The 1860 and 1898 events demonstrate the imperfect nature of a level analysis between Camden and Wallacia (Section 6.2.1). This analysis suggests both events are Warragamba dominated, but when Windsor is included in the Rank Analysis (Section 6.2.2), they would be considered to be Nepean dominated. For this reason, they have been assigned a neutral mechanism.

The final adopted mechanism for each event, including an explanation for the selection, is provided in Table 5.

Table 5: Final adopted mechanism for each event.

Event	Camden-Wallacia Analysis	Rank Analysis	Assigned Mechanism for pre/post dam adjustment.	Explanation
1860	Warragamba	Nepean	Neutral	Methods disagree on the two extremes. Assume a neutral mechanism.
1864	Nepean	Neutral	Neutral	Nepean dominated is unlikely based on the rank of this event at Penrith and Windsor.
1867	Warragamba	Warragamba	Warragamba	Methods agree
1873	Nepean	Nepean	Nepean	Methods agree
1898	Warragamba	Nepean	Neutral	Methods disagree on the two extremes. Assume a neutral mechanism.
1900	Warragamba	Warragamba	Warragamba	Methods agree
1925	Neutral	-	Neutral	Not enough information to assign a different mechanism. The final level is supplemented with modelling.
1949	Neutral	-	Neutral	
1956	Neutral	-	Neutral	
1961	Warragamba	Warragamba	Warragamba	Methods agree
1964	Warragamba	Neutral	Warragamba	Assuming Warragamba dominated as it provides a more conservative (higher) correction. The final pre-dam level is supplemented with modelling.
1975	Neutral	-	Neutral	Not enough information to assign a different mechanism. The final pre-dam level is supplemented with modelling.
1978	Warragamba	Neutral	Warragamba	Assuming Warragamba dominated provides a more conservative (higher) correction. The final pre-dam level is supplemented with modelling.
1988	Warragamba	-	Warragamba	Camden-Wallacia analysis suggests Warragamba dominated. The final pre-dam adjustment is supplemented with modelling.
1990	Warragamba	-	Warragamba	

Diagram 7, Diagram 8, and Table 4 also highlight some potential anomalies in the data which are discussed in **Appendix C**.

6.3. Dam adjustment for effect of Warragamba Dam

The 20,000 Monte Carlo events can be used to provide an estimate of how much Warragamba Dam is likely to change individual events. Diagram 9 compares how each of the Monte Carlo events changes in level from pre-dam to post-dam. The graph shows considerable scatter with the dam generally lowering levels though there are some events where the dam raises level. Pre-dam is plotted as a single line, representing the Stage-Frequency analysis from Monte Carlo, and the corresponding post-dam levels plotted as scatter points which have 10, 25, 50, 75 and 90 percentile lines fitted through the scatter points.

Table 6 shows the level of the pre-1960 events using each percentile. For the smaller events the changes are relatively small in the order of less than 1m, but larger events can change by over 3m. The magnitude of these potential changes make it hard to accurately adjust these events but it is possible to provide an estimate and the likely range. The Warragamba dominated events have adopted the 25 percentile with the 50 percentile as the upper estimate and the 10 percentile as the lower estimate. The neutral events have adopted the 50 percentile with 75 percentile and 25 percentile as the upper and lower bounds, respectively. The Nepean events have adopted the 75 percentile with the 90 percentile and 50 percentile as the upper and lower bounds, respectively. The green shading in Table 6 is the adopted percentile for each event.

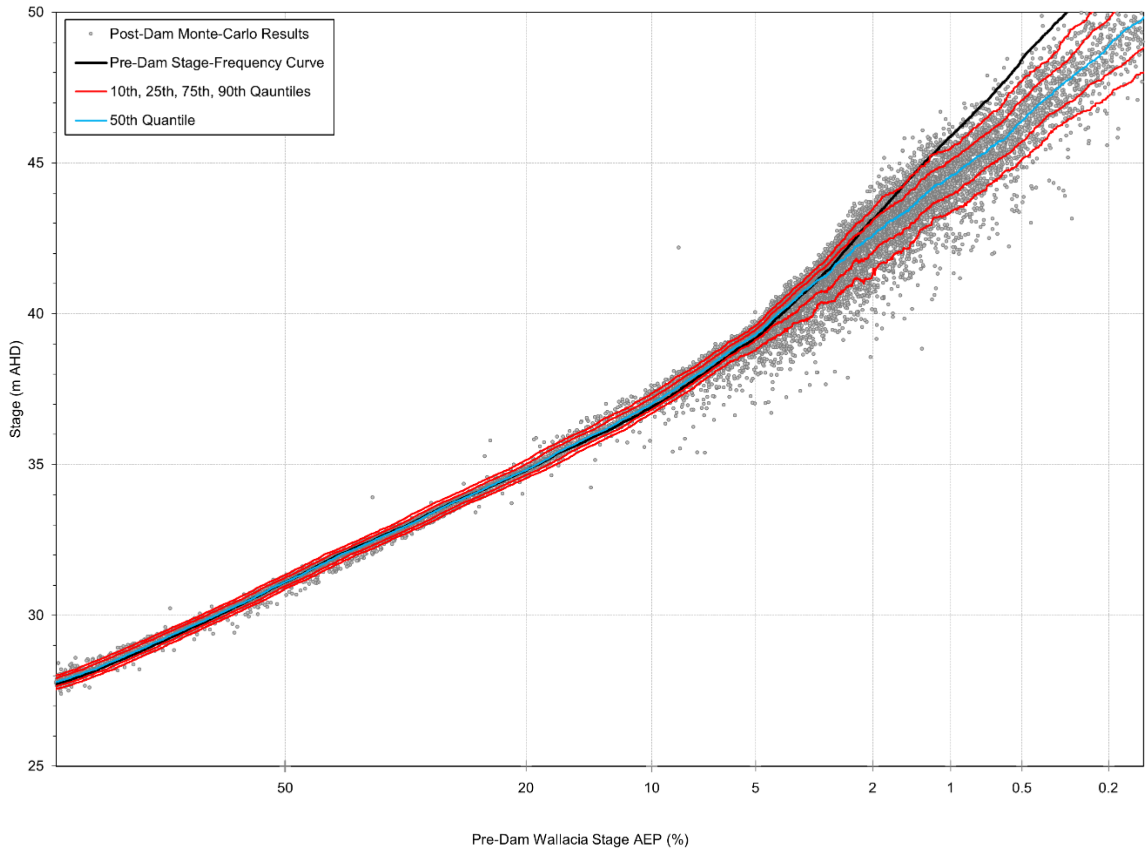


Diagram 9: Pre-Dam to Post-Dam Level Percentiles

Table 6: Pre-Dam to Post-Dam level percentiles at Wallacia Weir

Year	Level (Pre-Dam)	10% (Post-Dam) Very Warragamba Dominated	25% (Post-Dam) Warragamba Dominated	50% (Post-Dam) Neutral	75% (Post-Dam) Nepean Dominated	90% (Post-Dam) Very Nepean Dominated
1860	44.10	42.07	42.64	43.25	43.73	44.14
1864	45.00	42.85	43.40	43.93	44.48	44.91
1867	47.17	44.29	44.92	45.50	46.04	46.60
1873	47.13	44.28	44.91	45.48	46.01	46.60
1898	45.90	43.40	43.94	44.57	45.11	45.50
1900	42.50	41.15	41.77	42.23	42.60	42.98
1925	37.28	37.09	37.22	37.43	37.62	37.78
1949	38.25	38.03	38.20	38.39	38.55	38.72
1956	38.02	37.83	37.98	38.16	38.33	38.47

Similarly, Diagram 10 compares how each of the Monte Carlo events change in level from post-dam to pre-dam at Wallacia Weir. The line is the post-dam stage frequency curve, and the scatter points are the corresponding pre-dam event levels. Lines have been fit through the 10, 25, 50, 75 and 90 percentiles. Table 7 shows the adjusted pre-dam level of the post 1960 events using each of the quantiles, with the adopted quantile coloured in green.

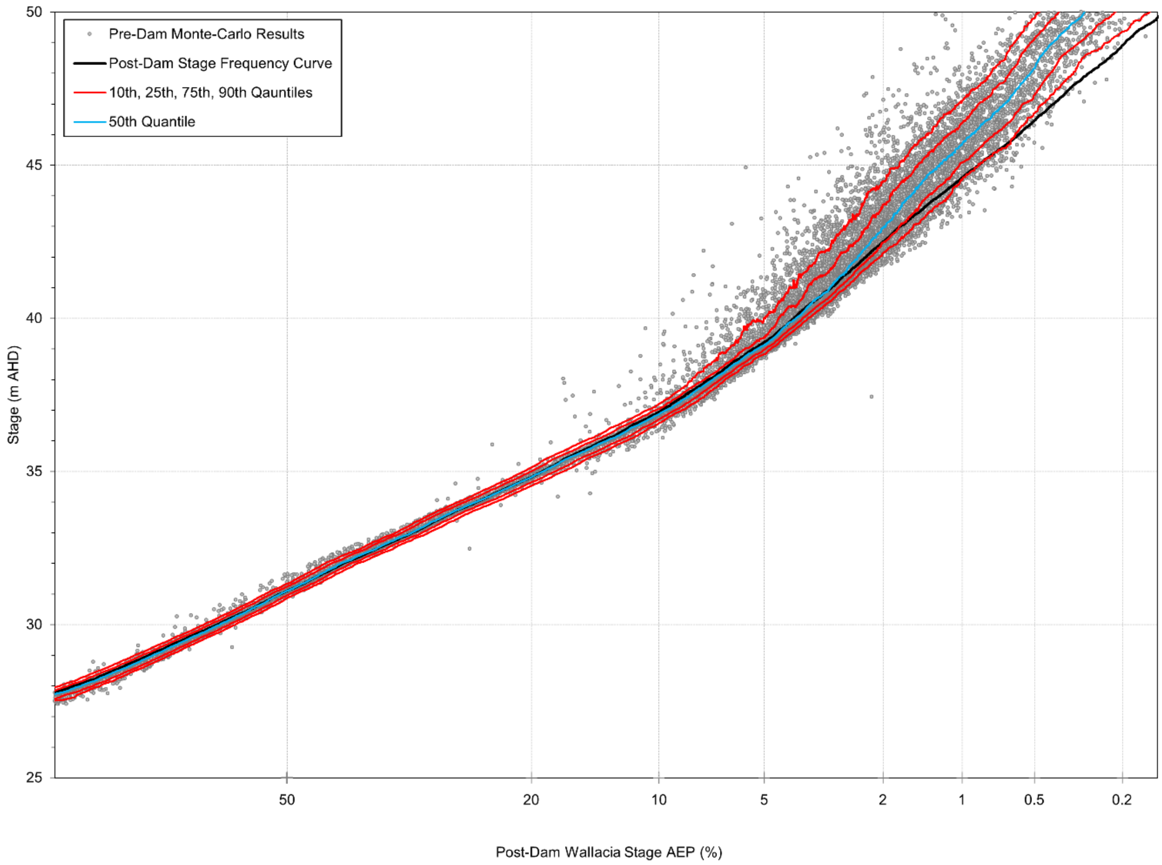


Diagram 10: Post-Dam to Pre-Dam Level Percentile

Table 7: Post-Dam to Pre-Dam level percentile at Wallacia Weir

Year	Level (Post Dam)	10% (Pre-Dam) Very Nepean Dominated	25% (Pre-Dam) Nepean Dominated	50% (Pre-Dam) Neutral	75% (Pre-Dam) Warragamba Dominated	90% (Pre-Dam) Very Warragamba Dominated
1961	41.35	40.91	41.10	41.42	42.16	42.90
1964	43.93	43.65	44.22	44.90	45.63	46.29
1975	38.79	38.45	38.56	38.74	38.99	39.74
1978	42.24	41.85	42.11	42.61	43.38	44.23
1988	40.81	40.38	40.54	40.81	41.40	42.17
1990	39.21	38.82	38.97	39.12	39.37	39.91

For post-dam levels, TUFLOW modelling was used to supplement the results displayed in Table 7. Outflows from Warragamba Dam were reverse routed to determine dam inflows. This is the process of applying the standard level-pool routing equations in reverse to generate an inflow hydrograph to the dam from the observed outflow hydrograph. There are various ways described in the literature aimed to minimise oscillations in the inflow hydrograph. These inflows were then routed from the upper reaches of the lake back to the dam site under pre-dam conditions. When this was combined with the downstream modelling, downstream flows and levels could be estimated. This modelling was carried out for the November 1961, June 1964, June 1975, March 1978, August 1986, April/May 1988 and August 1990 floods (the 1986 event was not included in the above analysis as it was not a large enough event for Warragamba Dam to have an impact).

The final adopted pre-dam level for these six events was taken as the average of the estimate from the Monte Carlo quantiles in Table 7, the modelled difference between the pre-dam and post-dam levels, and the difference between the modelled pre-dam level and the observed level at Wallacia. These differences and the adopted pre-dam level are presented in Table 8.

Table 8: Adopted pre-dam levels, Wallacia Weir (m AHD)

Year	Post dam level (m AHD)	Adjustment			Adopted adjustment (m) (average)	Pre dam level (m AHD)
		Table 7 estimate	Modelled difference (m)	Difference between modelled pre dam and observed (m)		
1961	41.35	1.55	1.83	3.19	2.19	43.54
1964	43.93	1.70	0.34	0.86	0.97	44.9
1975	38.79	-0.05	0.02	0.63	0.20	38.99
1978	42.24	1.14	0.63	0.63	0.80	43.04
1988	40.81	0.59	0.09	0.57	0.42	41.23
1990	39.21	0.70	0.67	0.72	0.70	39.91

During the preparation of the report, four events occurred between 2020 and 2022. For these events, the RUBICON differences were used as the results from the new TUFLOW model were not available at the time of analysis.

6.4. Upper Nepean Dams Influence

The Cataract, Cordeaux, Avon and Nepean dams make up the four dams that exist on the Upper Nepean catchment. These dams control a small proportion of the total catchment, but occupy the highest rainfall area in the catchment. The storage within the dams is relatively small compared to the rainfall and they tend to fill very quickly. In larger events temporary flood storage does reduce flood levels downstream.

To ensure a credible flood series, adjustments were made to flood records prior to dam construction based on Monte Carlo modelling results. The Monte Carlo framework was run with and without all of the Nepean dams, and a range of events between a nominal magnitude of 1 in 5 AEP and 1 in 100 AEP determined the contribution of each dam. The change in level at Wallacia was attributed to the average percentage change in discharge from the dams as noted in Table 9. This adjustment was applied to the years between 1907 and 1934 based on the cumulative percentage as outlined in Table 10.

The contribution of the four Upper Nepean dams was assessed based on comparing the peak flows of the representative 20% to 1% AEP events for the pre and post Nepean Dams scenarios and is tabulated in Table 9.

Table 9: Percentage flow contribution of each dam for Representative Events

Dam	1 in 5 AEP	1 in 10 AEP	1 in 20 AEP	1 in 50 AEP	1 in 100 AEP	Average Contribution
Cataract	32%	33%	37%	31%	33%	33%
Cordeaux	27%	30%	31%	33%	30%	30%
Avon	30%	23%	27%	27%	26%	26%
Nepean	12%	14%	5%	9%	11%	10%

Table 10: Percentage flow contribution of each dam to the sum of the four dams

Period	Cataract	Cordeaux	Avon	Nepean	Percent Adjustment (full adjustment based on outflows)
pre-1907	-	-	-	-	0%
1907 - 1925	yes	-	-	-	33%
1926 - 1927	yes	yes	-	-	63%
1928 - 1934	yes	yes	yes	-	90%
1935 - present	yes	yes	yes	yes	100%
percent flow reduction of total	33%	30%	26%	10%	

Table 11 is a summary of the reduction adopted for the conversion of water levels at Wallacia between the scenarios that (1) include the Upper Nepean Dams and (2) exclude the dams. For floods that occurred between 1907 and 1935 the impact of the Upper Nepean dams was adjusted by the percentage contribution calculated in Table 10. For larger floods there is a diminishing impact due to the Upper Nepean Dams. The exception to this is for very small events or freshes. This is because the mechanism driving water levels of this magnitude is highly variable.

Table 11: Average reduction in level at Wallacia Weir for all Upper Nepean Dams

Water Level at Wallacia Weir (m AHD)	28	30	32	34	36	38	40	42	44	46	48
Adjustment for without Nepean Dams (m)	0.3	0.8	0.9	0.9	0.7	0.5	0.4	0.4	0.3	0.3	0.3

6.5. Final Annual Maximum Series

Taking into consideration the impact of Warragamba Dam as well as the four Upper Nepean dams, an annual series was constructed for the pre-Warragamba dam scenario as well as the post-Warragamba dam scenario.

The pre-Warragamba Dam annual maximum series contains observed data for the years between 1860 and 1906, with values between the years 1907 and 1960 adjusted for which of the Upper

Nepean dams were completed and their relative contribution. For the years 1961 and onwards, the observed levels have been converted into pre-Warragamba Dam levels and adjusted based on the contribution of the four Upper Nepean Dams.

Similarly, the post-Warragamba Dam annual maximum series contains observed data for the years 1961 to 2020. For the years prior to 1961, the observed levels have been converted into post-Warragamba dam levels and adjusted based on the contribution of the four Upper Nepean Dams. These are presented in Diagram 11. The upper part of this series is influenced by the 1867 and 1873 flood levels which are nearly identical. The series would look very different if either the 1867 or 1873 floods was found to be in error.

Annual Exceedance Probabilities were calculated for the annual maximum series based on the following Cunnane Plotting Positions formula (Cunnane, 1978):

$$\frac{r - 0.4}{n + 0.2}$$

r = weighted rank n = sample size

The resulting pre- and post-Warragamba Dam annual maximum series have been plotted with the updated Monte Carlo results (refer to Diagram 11).

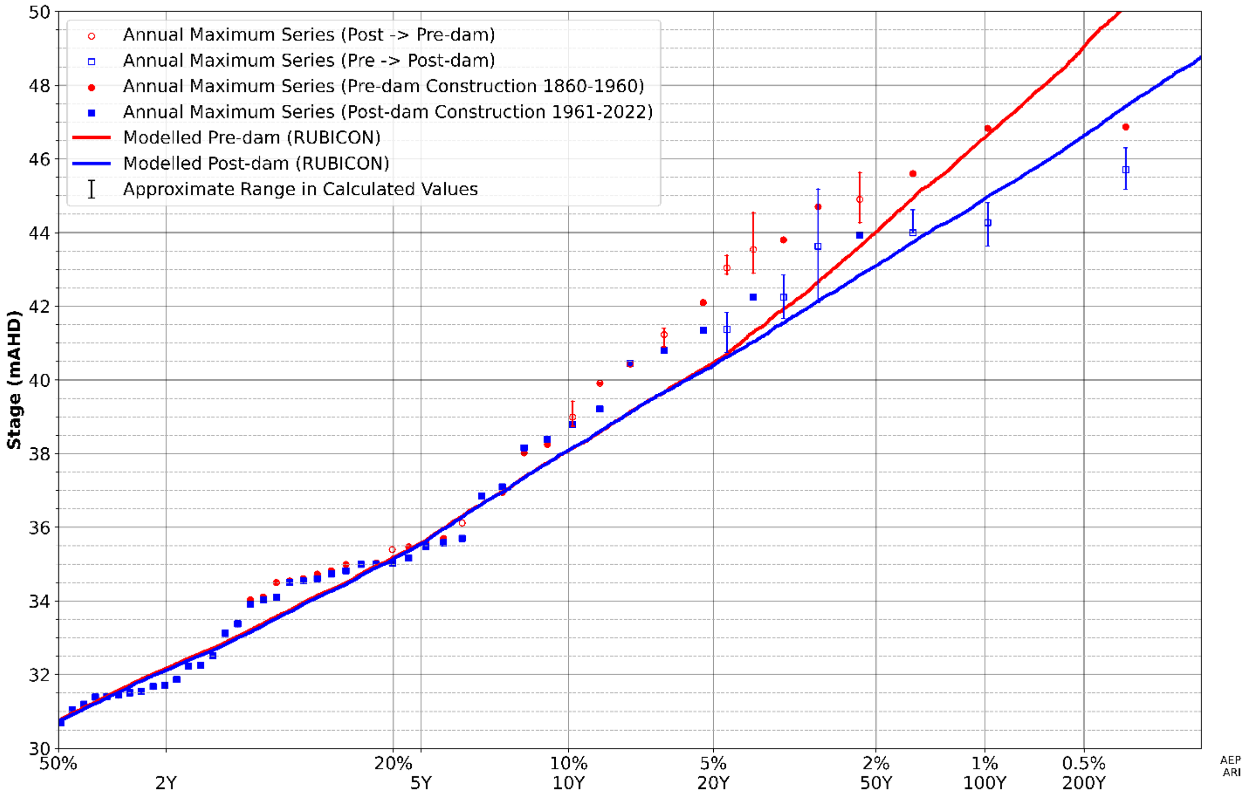


Diagram 11: Final Annual Series at Wallacia Weir

7. RESULTS

In order to determine the stage frequency at Wallacia Weir, the Monte Carlo results for pre and post Warragamba dam were compared to the final annual series shown in Diagram 11. There is a good match up to the 10% AEP but the annual series plots higher until the 1% AEP where the pre-Dam Monte Carlo results sit mid-way between the top two events and the annual series. This comparison would look substantially better if either the 1867 or 1873 floods was found to be an error (refer **Appendix C**).

The design event quantiles from the Monte Carlo results were then extracted and presented in Table 12 along with estimates from the Upper Nepean River Flood Study (Lyall & Macoun Consulting Engineers, 1995) and the Hawkesbury-Nepean Valley Regional Flood Study (WMAwater, 2019).

Flood levels at Wallacia Weir vary largely due to the constrictive effects of the Fairlight Gorge between Warragamba Dam and Penrith (i.e., 1 in 10 AEP event has a level of 38.09 m AHD in comparison to the 1 in 100 AEP event with a level of 44.92 m AHD). The results provided by the updated modelling as outlined in this report indicate increased levels between the 1 in 5 AEP and the 1 in 200 AEP when compared with the Hawkesbury-Nepean Valley Regional Flood Study results, with results converging as event frequency decreases for events rarer than the 1 in 200 AEP (refer to Diagram 12).

Table 12: Wallacia Monte Carlo levels and comparison to previous estimates

AEP (1 in X)	1995 Upper Nepean River Flood Study Level (m AHD)[1]	2019 Hawkesbury-Nepean Valley Regional Flood Study Level (m AHD)	This study Monte Carlo results - Post-Dam Quantile Level (m AHD)[2]
2	-	31.10	30.72
5	36.5	34.81	35.14
10	-	36.94	38.09
20	42.3	39.23	40.40
50	-	42.50	43.10
100	45.7	44.60	44.92
200	47.1	46.46	46.63
500	-	48.91	48.84

[1] Levels from Table 6.9 of the Upper Nepean River Flood Study (1995)

[2] Levels from RUBICON Monte Carlo model framework. Refer to **Technical Volume 11** for official results from the TUFLOW Model.

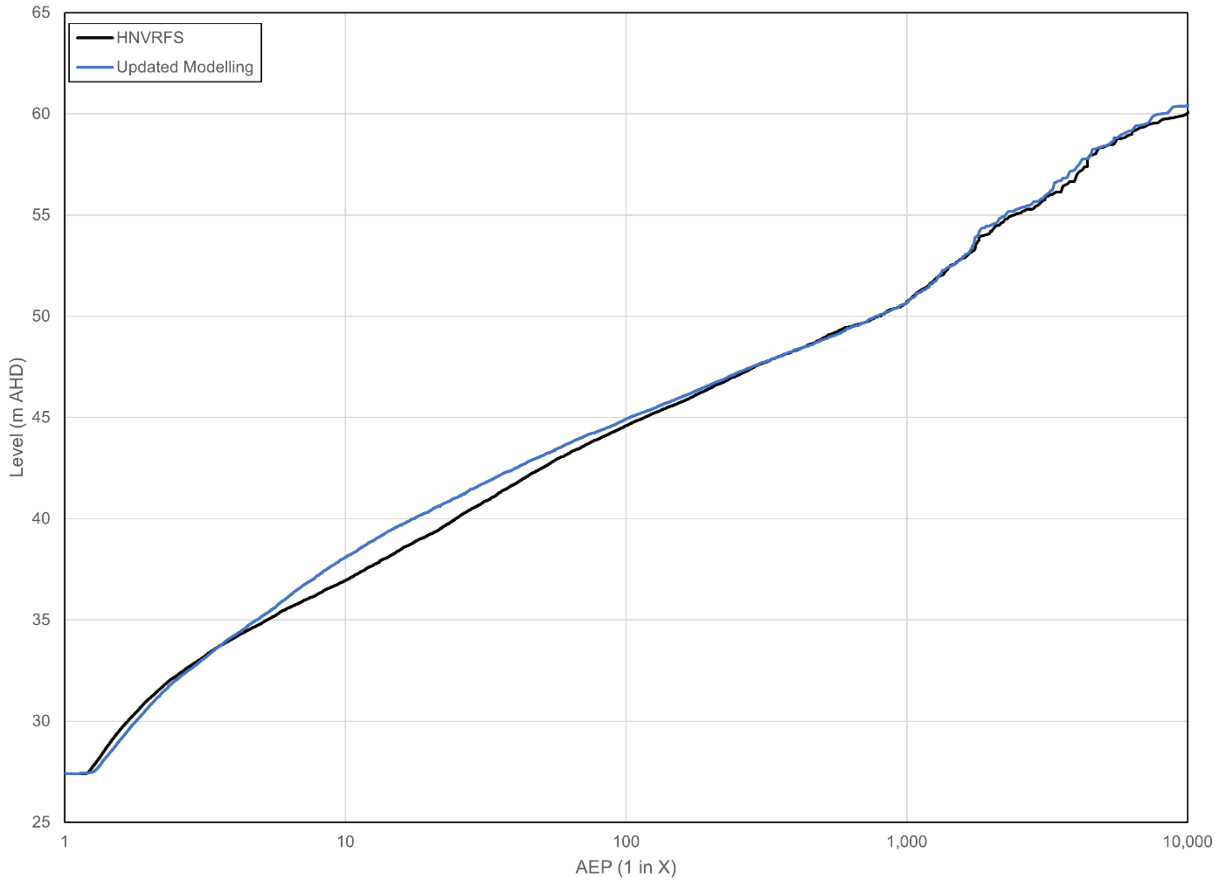


Diagram 12: Comparison between the current study modelling results and the Hawkesbury-Nepean Valley Regional Flood Study results
Note: Refer to **Technical Volume 11** for official TUFLOW-modelled peak flood levels

The RUBICON model and Monte Carlo framework are used to develop representative events for detailed modelling using TUFLOW (discussed further in **Technical Volumes 7** and **11**). The final design levels are determined by the TUFLOW model, and while the RUBICON and TUFLOW models produce similar levels at Wallacia in calibration events, the models diverge in larger events. For larger events, the TUFLOW model is considered more reliable.

8. CONCLUSIONS

This Technical Volume provides detailed analysis of flood behaviour and mechanisms in Wallacia by updating the modelling undertaken in the Hawkesbury-Nepean Valley Regional Flood Study (HNVRFS) (refer to WMAwater, 2019).

A traditional flood frequency analysis fits a distribution to flows. These are typically derived using a unique rating relationship to convert levels to flows. However, the inability to establish a unique relationship between stage and flows at Wallacia necessitates an analysis of the long-term water level records. This report outlines the methods undertaken to validate and adjust recorded levels to achieve a homogeneous pre- and post-dam data set. This approach allows the best use to be made of the long flood record which is dominated by large events from the 1860s - 1870s.

Annual maximum series were prepared for pre-Dam and post-Dam series, and compared to the updated Monte Carlo results. There is a good match up to the 1 in 10 AEP but the annual series plots higher until the 1 in 100 AEP. When compared with the Hawkesbury-Nepean Valley Regional Flood Study results, results from the updated Monte Carlo model are higher between the 1 in 5 AEP and the 1 in 200 AEP, with results converging as event frequency decreases for events rarer than the 1 in 200 AEP.

9. REFERENCES

Ball J, Babister M, Nathan R, Weeks W, Weinmann E, Retallick M, Testoni I, (Editors)
Australian Rainfall and Runoff: A Guide to Flood Estimation
Commonwealth of Australia, Australia, 2019

Cunnane, C.
Unbiased plotting positions—A review: Journal of Hydrology, v. 37, p. 205–222.
1978

Department of Primary Industries
Improved fish passage along the Nepean River as a result of retrofitting weirs with vertical-slot fishways
Fisheries Final Report Series No. 152, 2016

Lyall and Macoun Consulting Engineers
Upper Nepean River Flood Study
prepared for DLWC (Department of Land and Water Conservation) and Wollondilly, Campbelltown, Camden, Liverpool and Penrith Councils
September 1995

Laurenson, E.M.
Modeling of stochastic-deterministic hydrologic systems. Water Resources Research, 10(1), 955-961.
1974

Metropolitan Water Sewerage and Drainage Board
The 1867 Flood
1985

NSW Government
Floodplain Development Manual: The management of flood liable land
April 2005

Office of Environment & Heritage
Blaxland's Crossing at Nepean River
Accessed 7 January 2021,
<https://www.environment.nsw.gov.au/heritageapp/ViewHeritageItemDetails.aspx?ID=2690011>

WMAwater
Hawkesbury Nepean Hydrologic Model Update - Final Report
prepared for WaterNSW
January 2018

WMAwater
Hawkesbury-Nepean Valley Regional Flood Study
prepared for Infrastructure NSW
July 2019

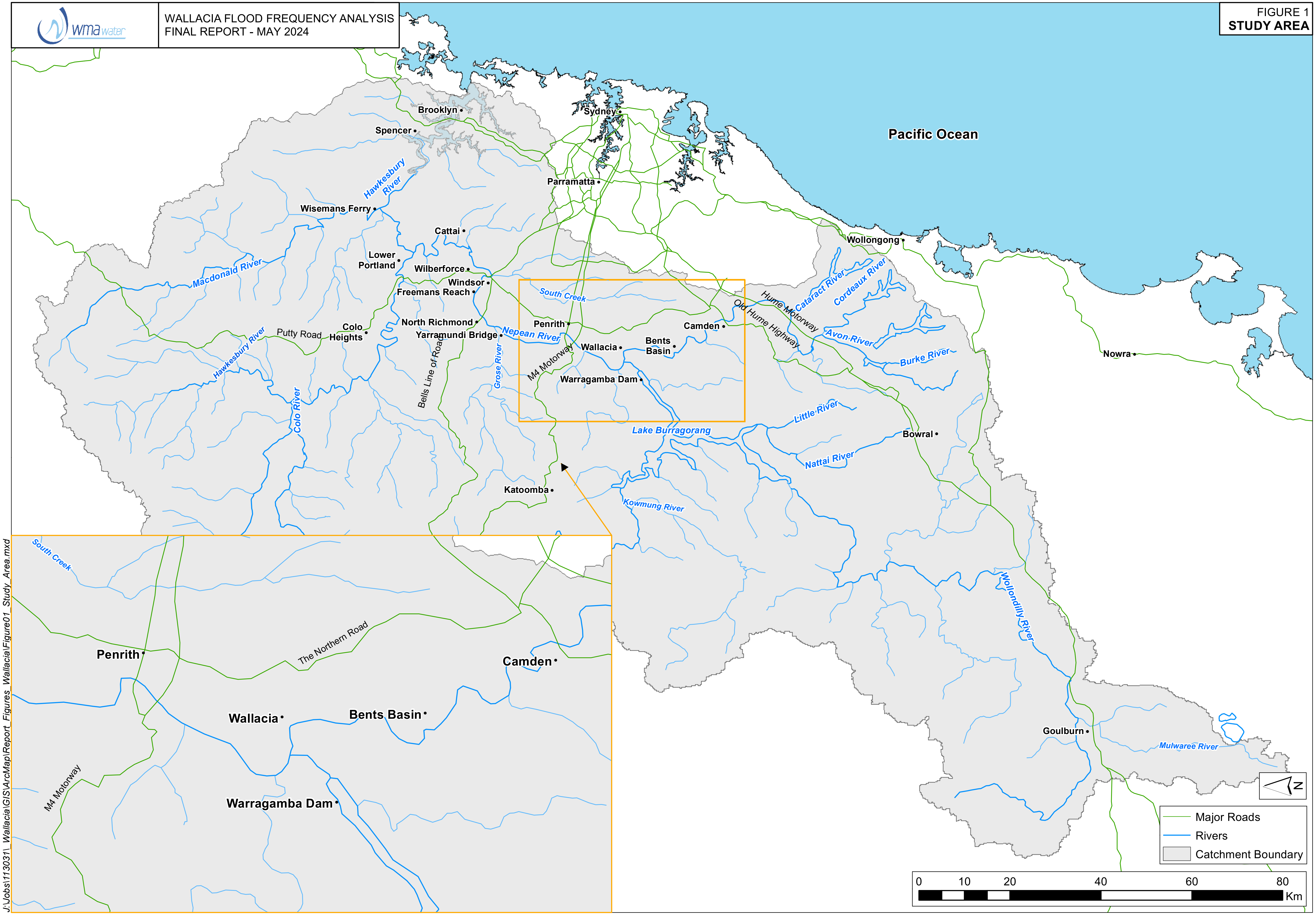
WMAwater
Climate Change and flooding effects on the Hawkesbury-Nepean
prepared for Infrastructure NSW
September 2021

Worley Parsons
Nepean River Flood Study
prepared for Camden Council
April 2015

Zheng, F, Westra, S, Leonard, M.
Australian Rainfall and Runoff Project 18 Stage 3.
2014

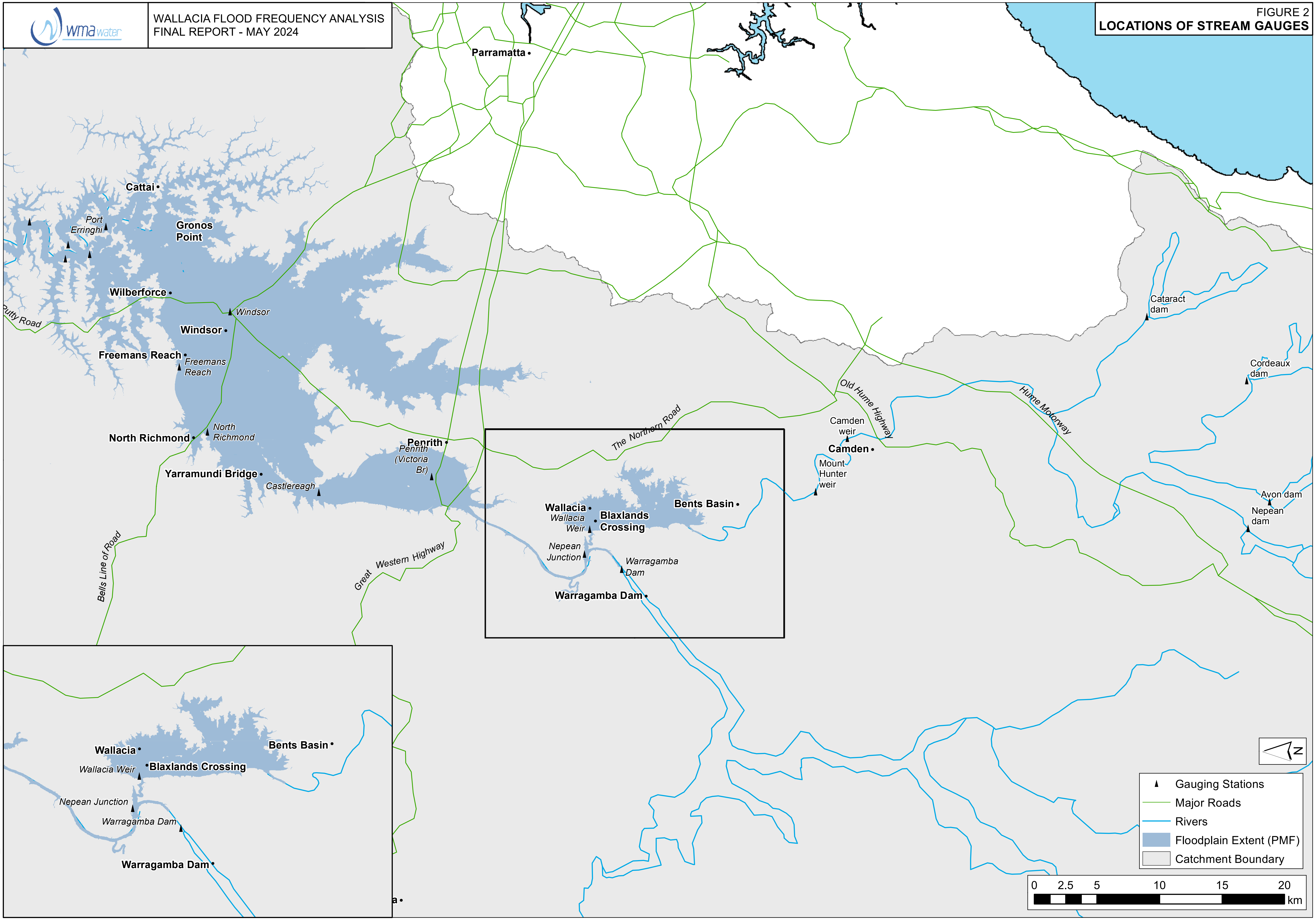
Figures

FIGURE 1
STUDY AREA



WALLACIA FLOOD FREQUENCY ANALYSIS
FINAL REPORT - MAY 2024

FIGURE 2
LOCATIONS OF STREAM GAUGES



J:\Jobs\113031_Wallacia\GIS\ArcMap\Report_Figures_Wallacia\Figure02_Studyarea_floodplain_area_261018.mxd

Appendix A

APPENDIX A. GLOSSARY

Taken from the Floodplain Development Manual (April 2005 edition)

acid sulfate soils — Are sediments which contain sulfidic mineral pyrite which may become extremely acid following disturbance or drainage as sulfur compounds react when exposed to oxygen to form sulfuric acid. More detailed explanation and definition can be found in the NSW Government Acid Sulfate Soil Manual published by Acid Sulfate Soil Management Advisory Committee.

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. For example, if a peak flood discharge of 500 m^3/s has an AEP of 5%, it means that there is a 5% chance (that is one-in-20 chance) of a 500 m^3/s or larger event occurring in any one year (see ARI).

Australian Height Datum (AHD) — A common national surface level datum approximately corresponding to mean sea level.

Average Annual Damage (AAD) — Depending on its size (or severity), each flood will cause a different amount of flood damage to a flood prone area. AAD is the average damage per year that would occur in a nominated development situation from flooding over a very long period of time.

Average Recurrence Interval (ARI) — The long term average number of years between the occurrence of a flood as big as, or larger than, the selected event. For example, floods with a discharge as great as, or greater than, the 20 year ARI flood event will occur on average once every 20 years. ARI is another way of expressing the likelihood of occurrence of a flood event.

caravan and moveable home parks — Caravans and moveable dwellings are being increasingly used for long-term and permanent accommodation purposes. Standards relating to their siting, design, construction and management can be found in the Regulations under the LG Act.

catchment — The land area draining through the main stream, as well as tributary streams, to a particular site. It always relates to an area above a specific location.

consent authority — The Council, government agency or person having the function to determine a development application for land use under the EP&A Act. The consent authority is most often the Council, however legislation or an EPI may specify a Minister or public authority (other than a Council), or the Director General of DIPNR, as having the function to determine an application.

development — Is defined in Part 4 of the Environmental Planning and Assessment Act (EP&A Act).

infill development: refers to the development of vacant blocks of land that are generally surrounded by developed properties and is permissible under the current zoning of the land. Conditions such as minimum floor levels may be imposed on infill development.

new development: refers to development of a completely different nature to that associated with the former land use. For example, the urban subdivision of an area previously used for rural purposes. New developments involve rezoning and typically require major extensions of existing urban services, such as roads, water supply, sewerage and electric power.

redevelopment: refers to rebuilding in an area. For example, as urban areas age, it may become necessary to demolish and reconstruct buildings on a relatively large scale. Redevelopment generally does not require either rezoning or major extensions to urban services.

disaster plan (DISPLAN)
A step by step sequence of previously agreed roles, responsibilities, functions, actions and management arrangements for the conduct of a single or series of connected emergency operations, with the object of ensuring the coordinated response by all agencies having responsibilities and functions in emergencies.

discharge
The rate of flow of water measured in terms of volume per unit time, for example, cubic metres per second (m^3/s). Discharge is different from the speed or velocity of flow, which is a measure of how fast the water is moving for example, metres per second (m/s).

ecologically sustainable development (ESD)
Using, conserving and enhancing natural resources so that ecological processes, on which life depends, are maintained, and the total quality of life, now and in the future, can be maintained or increased. A more detailed definition is included in the Local Government Act 1993. The use of sustainability and sustainable in this manual relate to ESD.

effective warning time
The time available after receiving advice of an impending flood and before the floodwaters prevent appropriate flood response actions being undertaken. The effective warning time is typically used to move farm equipment, move stock, raise furniture, evacuate people and transport their possessions.

emergency management
A range of measures to manage risks to communities and the environment. In the flood context it may include measures to prevent, prepare for, respond to and recover from flooding.

flash flooding
Flooding which is sudden and unexpected. It is often caused by sudden local or nearby heavy rainfall. Often defined as flooding which peaks within six hours of the causative rain.

flood
Relatively high stream flow which overtops the natural or artificial banks in any part of a stream, river, estuary, lake or dam, and/or local overland flooding associated with major drainage before entering a watercourse, and/or coastal inundation resulting from super-elevated sea levels and/or waves overtopping coastline defences excluding tsunami.

flood awareness
Flood awareness is an appreciation of the likely effects of flooding and a knowledge of the relevant flood warning, response and evacuation procedures.

flood education
Flood education seeks to provide information to raise awareness of the flood problem so as to enable individuals to understand how to manage themselves an their property in response to flood warnings and in a flood event. It invokes a state of flood readiness.

flood fringe areas
The remaining area of flood prone land after floodway and flood storage areas have been defined.

flood liable land
Is synonymous with flood prone land (i.e. land susceptible to flooding by the probable maximum flood (PMF) event). Note that the term flood liable land covers the whole of the floodplain, not just that part below the flood planning level (see flood planning area).

flood mitigation standard	The average recurrence interval of the flood, selected as part of the floodplain risk management process that forms the basis for physical works to modify the impacts of flooding.
floodplain	Area of land which is subject to inundation by floods up to and including the probable maximum flood event, that is, flood prone land.
floodplain risk management options	The measures that might be feasible for the management of a particular area of the floodplain. Preparation of a floodplain risk management plan requires a detailed evaluation of floodplain risk management options.
floodplain risk management plan	A management plan developed in accordance with the principles and guidelines in this manual. Usually includes both written and diagrammetic information describing how particular areas of flood prone land are to be used and managed to achieve defined objectives.
flood plan (local)	A sub-plan of a disaster plan that deals specifically with flooding. They can exist at State, Division and local levels. Local flood plans are prepared under the leadership of the State Emergency Service.
flood planning area	The area of land below the flood planning level and thus subject to flood related development controls. The concept of flood planning area generally supersedes the Aflood liable land@ concept in the 1986 Manual.
Flood Planning Levels (FPLs)	FPLs are the combinations of flood levels (derived from significant historical flood events or floods of specific AEPs) and freeboards selected for floodplain risk management purposes, as determined in management studies and incorporated in management plans. FPLs supersede the standard flood event in the 1986 manual.
flood proofing	A combination of measures incorporated in the design, construction and alteration of individual buildings or structures subject to flooding, to reduce or eliminate flood damages.
flood prone land	Is land susceptible to flooding by the Probable Maximum Flood (PMF) event. Flood prone land is synonymous with flood liable land.
flood readiness	Flood readiness is an ability to react within the effective warning time.
flood risk	Potential danger to personal safety and potential damage to property resulting from flooding. The degree of risk varies with circumstances across the full range of floods. Flood risk in this manual is divided into 3 types, existing, future and continuing risks. They are described below. **existing flood risk:** the risk a community is exposed to as a result of its location on the floodplain. **future flood risk:** the risk a community may be exposed to as a result of new development on the floodplain. **continuing flood risk:** the risk a community is exposed to after floodplain risk management measures have been implemented. For a town protected by levees, the continuing flood risk is the consequences of the levees being overtopped. For an area without any floodplain risk management measures, the continuing flood risk is simply the existence of its flood exposure.
flood storage areas	Those parts of the floodplain that are important for the temporary storage of floodwaters during the passage of a flood. The extent and behaviour of flood storage areas may change with flood severity, and loss of flood storage can

increase the severity of flood impacts by reducing natural flood attenuation. Hence, it is necessary to investigate a range of flood sizes before defining flood storage areas.

floodway areas Those areas of the floodplain where a significant discharge of water occurs during floods. They are often aligned with naturally defined channels. Floodways are areas that, even if only partially blocked, would cause a significant redistribution of flood flows, or a significant increase in flood levels.

freeboard Freeboard provides reasonable certainty that the risk exposure selected in deciding on a particular flood chosen as the basis for the FPL is actually provided. It is a factor of safety typically used in relation to the setting of floor levels, levee crest levels, etc. Freeboard is included in the flood planning level.

habitable room **in a residential situation:** a living or working area, such as a lounge room, dining room, rumpus room, kitchen, bedroom or workroom.

in an industrial or commercial situation: an area used for offices or to store valuable possessions susceptible to flood damage in the event of a flood.

hazard A source of potential harm or a situation with a potential to cause loss. In relation to this manual the hazard is flooding which has the potential to cause damage to the community. Definitions of high and low hazard categories are provided in the Manual.

hydraulics Term given to the study of water flow in waterways; in particular, the evaluation of flow parameters such as water level and velocity.

hydrograph A graph which shows how the discharge or stage/flood level at any particular location varies with time during a flood.

hydrology Term given to the study of the rainfall and runoff process; in particular, the evaluation of peak flows, flow volumes and the derivation of hydrographs for a range of floods.

local overland flooding Inundation by local runoff rather than overbank discharge from a stream, river, estuary, lake or dam.

local drainage Are smaller scale problems in urban areas. They are outside the definition of major drainage in this glossary.

mainstream flooding Inundation of normally dry land occurring when water overflows the natural or artificial banks of a stream, river, estuary, lake or dam.

major drainage Councils have discretion in determining whether urban drainage problems are associated with major or local drainage. For the purpose of this manual major drainage involves:

- the floodplains of original watercourses (which may now be piped, channelised or diverted), or sloping areas where overland flows develop along alternative paths once system capacity is exceeded; and/or

- water depths generally in excess of 0.3 m (in the major system design storm as defined in the current version of Australian Rainfall and Runoff). These conditions may result in danger to personal safety and property damage to both premises and vehicles; and/or

- major overland flow paths through developed areas outside of defined drainage reserves; and/or
- the potential to affect a number of buildings along the major flow path.

mathematical/computer models The mathematical representation of the physical processes involved in runoff generation and stream flow. These models are often run on computers due to the complexity of the mathematical relationships between runoff, stream flow and the distribution of flows across the floodplain.

merit approach The merit 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 well being of the States rivers and floodplains.

The merit approach operates at two 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 EPIs. At a site specific level, it involves consideration of the best way of conditioning development allowable under the floodplain risk management plan, local floodplain risk management policy and EPIs.

minor, moderate and major flooding Both the State Emergency Service and the Bureau of Meteorology use the following definitions in flood warnings to give a general indication of the types of problems expected with a flood:

minor flooding: causes inconvenience such as closing of minor roads and the submergence of low level bridges. The lower limit of this class of flooding on the reference gauge is the initial flood level at which landholders and townspeople begin to be flooded.

moderate flooding: low-lying areas are inundated requiring removal of stock and/or evacuation of some houses. Main traffic routes may be covered.

major flooding: appreciable urban areas are flooded and/or extensive rural areas are flooded. Properties, villages and towns can be isolated.

modification measures Measures that modify either the flood, the property or the response to flooding. Examples are indicated in Table 2.1 with further discussion in the Manual.

peak discharge The maximum discharge occurring during a flood event.

Probable Maximum Flood (PMF) The PMF is the largest flood that could conceivably occur at a particular location, usually estimated from probable maximum precipitation, and where applicable, snow melt, coupled with the worst flood producing catchment conditions. Generally, it is not physically or economically possible to provide complete protection against this event. The PMF defines the extent of flood prone land, that is, the floodplain. The extent, nature and potential consequences of flooding associated with a range of events rarer than the flood used for designing mitigation works and controlling development, up to and including the PMF event should be addressed in a floodplain risk management study.

Probable Maximum Precipitation (PMP) The 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, with no allowance made for long-term climatic trends (World Meteorological Organisation, 1986). It is the primary input to PMF estimation.

probability	A statistical measure of the expected chance of flooding (see AEP).
risk	Chance of something happening that will have an impact. It is measured in terms of consequences and likelihood. In the context of the manual it is the likelihood of consequences arising from the interaction of floods, communities and the environment.
runoff	The amount of rainfall which actually ends up as streamflow, also known as rainfall excess.
stage	Equivalent to water level. Both are measured with reference to a specified datum.
stage hydrograph	A graph that shows how the water level at a particular location changes with time during a flood. It must be referenced to a particular datum.
survey plan	A plan prepared by a registered surveyor.
water surface profile	A graph showing the flood stage at any given location along a watercourse at a particular time.
wind fetch	The horizontal distance in the direction of wind over which wind waves are generated.

Appendix B

APPENDIX B. FLOOD RECORD

Table B1: Wallacia Weir observed flood record, 1860-2022

Year*	Peak Flood Level (m AHD)	Data Source
1860	44.10	1995 Upper Nepean Flood Study
1864^	41.10	Flood Mark[1]
1867^	47.17	Trove/Nepean Times (Penrith 1882-1962)[1]
1873	47.13	1995 Upper Nepean Flood Study/Flood Mark[2]
1898	45.90	1995 Upper Nepean Flood Study
1900^	42.50	Trove/Sydney Morning Herald (1842-1954)[3]
1916	36.10	Trove/Nepean Times (Penrith 1882-1962)[4]
1917	28.06	1995 Upper Nepean Flood Study
1918	30.35	1995 Upper Nepean Flood Study
1919	31.29	1995 Upper Nepean Flood Study
1920	28.17	1995 Upper Nepean Flood Study
1921	31.29	1995 Upper Nepean Flood Study
1922	34.64	1995 Upper Nepean Flood Study
1923	27.78	1995 Upper Nepean Flood Study
1924	27.46	1995 Upper Nepean Flood Study
1925	37.28	1995 Upper Nepean Flood Study
1926	27.75	1995 Upper Nepean Flood Study
1927	31.37	1995 Upper Nepean Flood Study
1928	30.53	1995 Upper Nepean Flood Study
1929	31.60	1995 Upper Nepean Flood Study
1930	30.38	1995 Upper Nepean Flood Study
1931	31.29	1995 Upper Nepean Flood Study
1932	27.18	1995 Upper Nepean Flood Study
1933	31.77	1995 Upper Nepean Flood Study
1934	34.11	1995 Upper Nepean Flood Study
1935	27.23	1995 Upper Nepean Flood Study
1936	26.77	1995 Upper Nepean Flood Study
1937	27.33	1995 Upper Nepean Flood Study
1938	30.30	1995 Upper Nepean Flood Study
1939	27.15	1995 Upper Nepean Flood Study
1940	26.97	1995 Upper Nepean Flood Study
1941	26.87	1995 Upper Nepean Flood Study
1942	29.94	1995 Upper Nepean Flood Study
1943	32.51	1995 Upper Nepean Flood Study
1944	26.75	1995 Upper Nepean Flood Study
1945	30.20	1995 Upper Nepean Flood Study
1946	27.10	1995 Upper Nepean Flood Study
1947	27.38	1995 Upper Nepean Flood Study
1948	27.71	1995 Upper Nepean Flood Study
1949	38.25	1995 Upper Nepean Flood Study
1950	34.82	1995 Upper Nepean Flood Study
1951	32.23	1995 Upper Nepean Flood Study
1952	36.85	1995 Upper Nepean Flood Study
1953	30.45	1995 Upper Nepean Flood Study
1954	30.15	1995 Upper Nepean Flood Study
1955	32.26	1995 Upper Nepean Flood Study
1956	38.02	1995 Upper Nepean Flood Study
1957	27.15	1995 Upper Nepean Flood Study
1958	28.55	1995 Upper Nepean Flood Study

Year*	Peak Flood Level (m AHD)	Data Source
1959	31.44	1995 Upper Nepean Flood Study
1960	28.32	1995 Upper Nepean Flood Study
1961	41.35	1995 Upper Nepean Flood Study
1962	31.55	1995 Upper Nepean Flood Study
1963	34.99	1995 Upper Nepean Flood Study
1964	43.93	1995 Upper Nepean Flood Study
1965	26.92	1995 Upper Nepean Flood Study
1966	29.40	1995 Upper Nepean Flood Study
1967	33.12	1995 Upper Nepean Flood Study
1969	35.00	1995 Upper Nepean Flood Study
1970	27.46	1995 Upper Nepean Flood Study
1971	29.07	1995 Upper Nepean Flood Study
1972	29.44	1995 Upper Nepean Flood Study
1973	27.73	1995 Upper Nepean Flood Study
1974	34.73	1995 Upper Nepean Flood Study
1975	38.79	1995 Upper Nepean Flood Study
1976	31.87	1995 Upper Nepean Flood Study
1977	33.38	1995 Upper Nepean Flood Study
1978	42.24	1995 Upper Nepean Flood Study
1979	27.15	1995 Upper Nepean Flood Study
1980	27.26	WaterNSW Gauge Data
1981	27.74	1995 Upper Nepean Flood Study
1982	27.84	WaterNSW Gauge Data
1983	27.90	1995 Upper Nepean Flood Study
1984	31.70	1995 Upper Nepean Flood Study
1985	29.36	1995 Upper Nepean Flood Study
1986	35.47	1995 Upper Nepean Flood Study
1987	35.03	1995 Upper Nepean Flood Study
1988	40.81	1995 Upper Nepean Flood Study
1989	31.39	1995 Upper Nepean Flood Study
1990	39.21	1995 Upper Nepean Flood Study
1991	35.58	1995 Upper Nepean Flood Study
1992	34.50	1995 Upper Nepean Flood Study
1993	26.92	1995 Upper Nepean Flood Study
1998	27.40	WaterNSW Gauge Data
1999	34.61	WaterNSW Gauge Data
2001	27.11	WaterNSW Gauge Data
2002	27.08	WaterNSW Gauge Data
2003	27.20	WaterNSW Gauge Data
2005	26.97	WaterNSW Gauge Data
2011	27.48	WaterNSW Gauge Data
2012	27.94	WaterNSW Gauge Data
2013	29.87	WaterNSW Gauge Data
2014	31.41	WaterNSW Gauge Data
2015	28.37	WaterNSW Gauge Data
2016	29.63	WaterNSW Gauge Data
2017	34.54	WaterNSW Gauge Data
2018	28.82	WaterNSW Gauge Data
2019	27.12	WaterNSW Gauge Data
2020	33.92	WaterNSW Gauge Data
2021	35.16	WaterNSW Gauge Data
2022	40.44	WaterNSW Gauge Data (July 2022)

Notes
*Records prior to the construction of Wallacia Weir in 1908 were recorded at Blaxlands Crossing.
^ Indicates where there is uncertainty with regards to the datum used – the datum may have been a Standard Datum. If a datum adjustment is applied, these levels would reduce by 0.06m.
[1] MWS&DB (1985) and Nepean Times - Height of '67 Flood (05 Jun 1926)
[2] DWR gauge records place this at 47.12. The 1867 Flood report (MWS&DB, 1985) adopts 47.14m AHD (with datum adjustment). Upper Nepean River Study (1995) adopts 47.13m AHD.
[3] MWS&DB (1985) Table A6.1 with gauge zero of 26.58m AHD and Sydney Morning Herald - Flood in the Nepean (Sat 7 Jul 1900)
[4] Nepean Times - The Great Monsoonal Downpour (07 Oct 1916)

Table B2: Camden, Penrith, Warragamba Dam and Windsor-Sackville flow record

Year	Wallacia Weir Level (m AHD)	Camden Flow (m^3/s) [1]	Penrith Flow (m^3/s) [2]	Warragamba Flow (m^3/s)	Windsor-Sackville Flow (m^3/s) [3]
1799	-	-	-	-	3190
1806	-	-	-	-	4760
1807	-	-	-	-	1140
1808	-	-	-	-	1570
1809	-	-	-	-	6450
1816	-	-	-	-	5840
1817	-	-	-	-	6150
1819	-	-	-	-	4830
1857	-	-	-	-	4080
1860	44.10	4860	-	-	4020
1861	-	1500	-	-	2380
1864	41.10	7400	-	11700	6750
1866	-	1330	-		2380
1867	47.17	4390	-	14600	12970
1868	-	2720	-	-	2700
1869	-		-	-	3900
1870	-	5320	-	-	5810
1871	-	4280	-	-	3920
1872	-		-	-	1330
1873	47.13	10060	-	-	4940
1874	-	1550	-	-	2370
1875	-	4050	-	-	4320
1877	-	5320	-	-	2760
1878	-	1280	-	-	2290
1879	-	4860	-	-	5340
1889	-	3870	-	-	4240
1890	-	3760	-	-	4320
1891	-	1150	-	-	3620
1892	-	925	-	-	2290
1893	-	750	2260	-	2490
1894	-	1910	3280	-	3000
1895	-	2140	4140	-	2800
1896	-	450	975	-	-
1897	-	1060	1600	-	1930
1898	45.90	7170	4550	-	2950
1899	-	750	1790	-	2290
1900	42.50	6580	10600	9500	6180
1901	-	55	1060	-	-
1902	-	160	1030	-	-
1903	-	185	700	-	-
1904	-	3870	7230	-	4500

Year	Wallacia Weir Level (m AHD)	Camden Flow (m^3/s) [1]	Penrith Flow (m^3/s) [2]	Warragamba Flow (m^3/s)	Windsor-Sackville Flow (m^3/s) [3]
1905	-		440	-	-
1906	-	860	1140	-	1110
1907	-	1730	115	-	-
1908	-	415	1100	-	-
1909	-	10	240	115	-
1910	-	750	1870	850	1690
1911	-	1500	2180	940	2100
1912	-	2540	1510	340	1800
1913	-	900	1680	1100	2150
1914	-	1560	1910	1340	1850
1915	-	450	900	1350	2040
1916	36.10	3700	5420	4600	3470
1917	28.06	130	960	230	-
1918	30.35	460	709	500	-
1919	31.29	670	625	430	-
1920	28.17	145	1340	970	-
1921	31.29	670	510	650	-
1922	34.64	1530	335	2960	2730
1923	27.78	220	425	310	-
1924	27.46	70	115	65	-
1925	37.28	2250	9240	7140	3790
1926	27.75	100	325	215	-
1927	31.37	695	1290	960	-
1928	30.53	495	1930	1260	-
1929	31.60	740	1620	1350	-
1930	30.38	475	510	385	-
1931	31.29	660	975	990	-
1932	27.18	35	235	160	-
1933	31.77	765	889	690	-
1934	34.11	1410	3080	2630	2590
1935	27.23	45	230	175	-
1936	26.77	-	195	110	-
1937	27.33	50	595	420	-
1938	30.30	450	1910	1900	-
1939	27.15	35	135	80	-
1940	26.97	15	225	166	-
1941	26.87	10	150	135	-
1942	29.94	405	1310	1420	1980
1943	32.51	935	4040	5020	3050
1944	26.75	-	40	30	-
1945	30.20	415	1460	2000	-
1946	27.10	30	275	250	-
1947	27.38	60	960	1520	-
1948 – Warragamba Dam Construction Commences					
1948	27.71	100	820	850	-
1949	38.25	2780	4500	3930	4190
1950	34.82	2660	1710	3280	2730
1951	32.23	880	2170	2520	2500
1952	36.85	1970	7640	6300	3960
1953	30.45	485	875	370	-
1954	30.15	415	2570	1620	-

Year	Wallacia Weir Level (m AHD)	Camden Flow (m^3/s) [1]	Penrith Flow (m^3/s) [2]	Warragamba Flow (m^3/s)	Windsor-Sackville Flow (m^3/s) [3]
1955	32.26	890	4680	2990	2880
1956	38.02	2660	9480	6090	5500
1957	27.15	35	195	115	-
1958	28.55	185	875	720	-
1959	31.44	705	895	440	-
1960	28.32	160	275	75	-
1960 – Warragamba Dam Construction Complete					
1961	41.35	2720	10400	9010	6590
1962	31.55	720	3360	1930	2300
1963	34.99	1620	3550	2300	2720
1964	43.93	4510	10200	7940	6125
1965	26.92	-	100	235	-
1966	29.40	500	1170	0	1200
1967	33.12	1080	1810	1590	2440
1968	-	-	50	100	-
1969	35.00	1710	3590	2310	2890
1970	27.46	65	270	0	1040
1971	29.07	200	1140	1180	1440
1972	29.44	3030	355	1190	1840
1973	27.73	85	445	460	0
1974	34.73	1560	3640	1600	3140
1975	38.79	3030	6760	5980	3590
1976	31.87	190	2390	1950	2640
1977	33.38	1100	2020	2330	2430
1978	42.24	3580	9530	7580	6105
1979	27.15	-	690	55	-
1980	27.26	-	210	200	-
1981	27.74	-	445	865	-
1982	27.84	-	25	75	-
1983	27.90	-	709	0	1020
1984	31.70	400	3070	1550	1890
1985	29.36	-	340	218	-
1986	35.47	1080	4570	4080	3680
1987	35.03	1030	1280	215	-
1988	40.81	3050	7390	5020	4680
1989	31.39	-	2200	1880	-
1990	39.21	1500	8630	7590	5350
1991	35.58	1160	1800	1700	-
1992	34.50	990	3920	3500	3470
1993	26.92	-	-	60	-
1994	-	-	-	180	-
1995	-	305	480	790	-
1996	-	250	285	490	-
1997	-	-	405	630	-
1998	27.40	1140	1795	4600	1270
1999	34.61	525	645	980	-
2000	-	-	95	370	-
2001	27.11	-	160	160	-
2002	27.08	-	185	290	-
2003	27.20	-	60	100	-
2004	-	-	90	40	-

Year	Wallacia Weir Level (m AHD)	Camden Flow (m^3/s) [1]	Penrith Flow (m^3/s) [2]	Warragamba Flow (m^3/s)	Windsor-Sackville Flow (m^3/s) [3]
2005	26.97	-	60	200	-
2006	-	-	25	320	-
2007	-	475	840	930	-
2008	-	-	570	60	-
2009	-	-	45	170	-
2010	-	-	425	1900	-
2011	27.48	110	95	150	-
2012	27.94	280	1800	1700	1690
2013	29.87	-	-	-	-
2014	31.41	-	-	-	-
2015	28.37	-	-	-	-
2016	29.63	-	-	-	-
2017	34.54	-	-	-	-
2018	28.82	-	-	-	-
2019	27.12	-	-	-	-
2020	33.92	-	2970	125	2640
2021	35.16	-	6870	5070	4780
2022 (Jul)	40.44	-	7700	5120	5570

Notes

[1] From Appendix A of the Nepean River Flood Study (2015).

[2] Observed flow estimate using the Penrith Rating Curve from **Technical Volume 7**. Flows for the 2020-2022 events are extracted from the TUFLOW model, responding to changes in the rating relationship at Penrith as a result of variable vegetation densities (see **Technical Volume 11**).

[3] Observed flow estimates based on the revised Windsor – Sackville rating curve from **Technical Volume 7**.

Appendix C

APPENDIX C. RESOLVING DATA ANOMALIES

C.1. 1867 event

The 1867 event has been recorded as 47.17m AHD in the historical source. This is very similar to the level recorded for the 1873 event which was the highest on record at Camden, with levels highly driven by flows from the Upper Nepean River catchment. In contrast, the 1867 event was highly dominated from outflows from the Warragamba River catchment. Compared to other events, the 1867 event appears to be high at Wallacia. With near-identical values and no direct measurements between the two events at Wallacia, it is our opinion that the 1867 event record may have been confused with 1873 as the two levels are remarkably close. In reality, the level may have been lower at Wallacia and closer to the trendline for the Warragamba dominated events. While no adjustment has been made due to the lack of conclusive evidence, it was important to consider.

C.2. 1864 event

The 1864 event plots alongside the Nepean-dominated events (Diagram 7), however it was identified as likely to be a neutral event due to the results of the rank analysis (Diagram 8), without any heavy skew to either the Nepean or Warragamba rivers. This event is ranked 2nd at Camden, equal 2nd with the 1964 event at Windsor, and historical records at Penrith indicate it was the 2nd largest event after 1867, prior to 1961. Given the rank at Wallacia (9th) is low relative to Camden and Windsor, the level was adjusted from 41.1 to 45.0 m AHD using the pre-dam regression curve (purple dashed line) in Diagram 7.

C.3. 1969, 1976, 1978 corrections

Both the 1995 *Upper Nepean River Flood Study* (Lyall Macoun Consulting Engineers, 1995) and the WaterNSW gauge data provide extensive records where the duration of observations overlapped over several years. Unfortunately, large inconsistencies were identified between the two datasets (e.g. the 1995 Flood Study had a record of 42.24 m AHD for the year 1978, whereas WaterNSW recorded 33.49m AHD for the same year, it was later confirmed with a value close to 42.24 m AHD after datum adjustments were made). As a result, investigations were undertaken to determine which peak flood level to use for the annual maximum series where there was a discrepancy between two sources (with no third source to validate the data).

An assessment was undertaken by establishing correlation between the historical levels at Camden against Wallacia Weir. Data was divided into records that completely matched the event at both gauges and records that only indicated the year that it was recorded. For the latter, it is possible that the data could originate from different events, and no correlation is expected. Figure C 1 shows that the three events based on the WaterNSW records which plot a long way from the rest of the data Figure C 2 shows the records from the Upper Nepean Flood Study. On this basis the Upper Nepean Flood Study results were adopted. This approach was supported when WaterNSW confirmed the 1978 flood level.

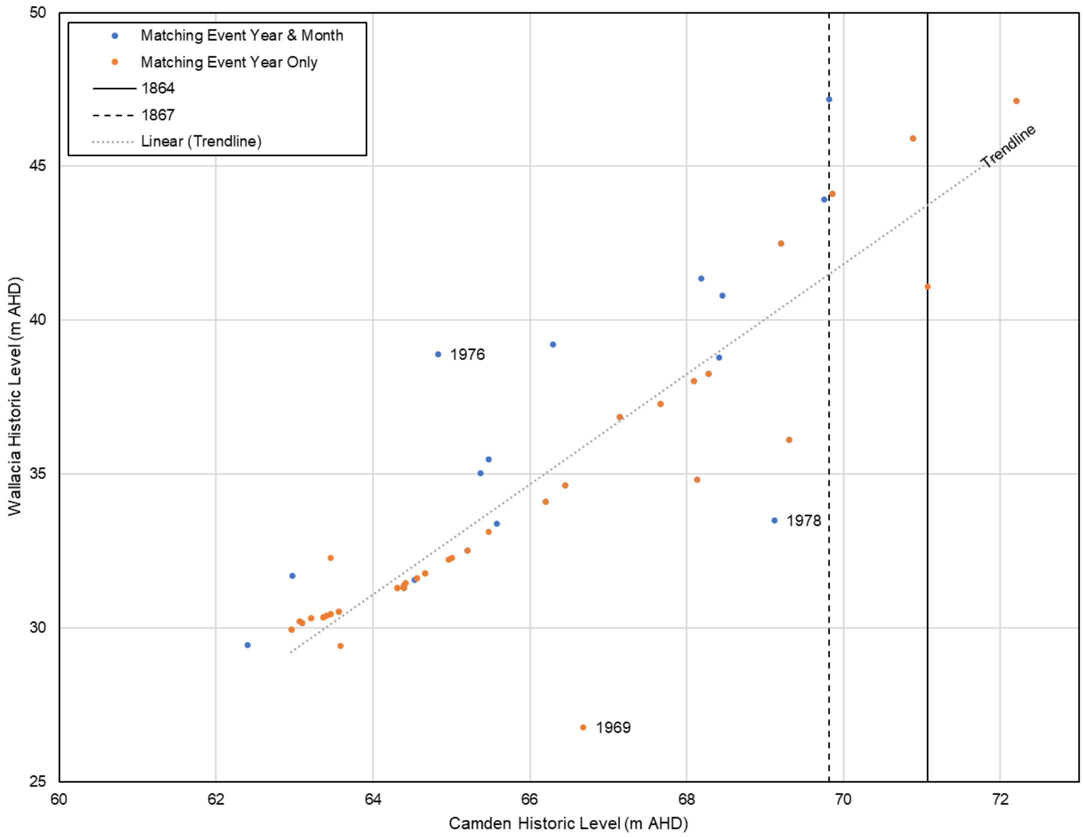


Figure C1: Camden vs Wallacia Weir Historical Level Plot – WaterNSW

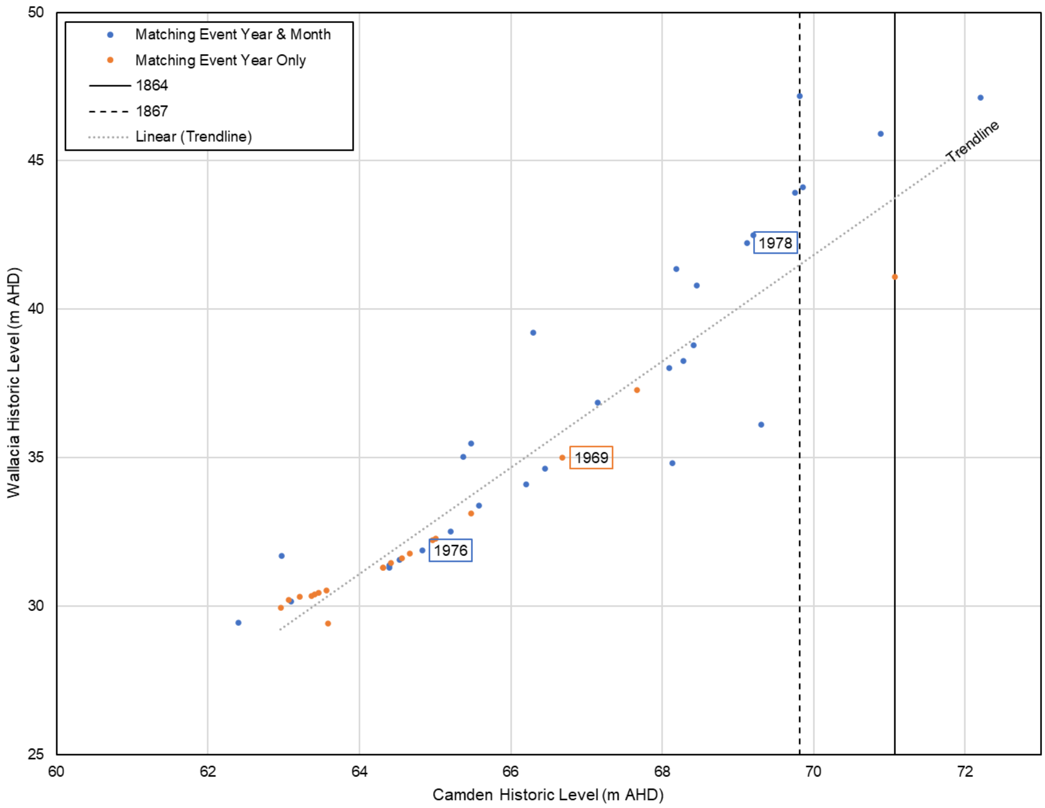


Figure C2: Camden vs Wallacia Weir Historical Level Plot - 1995 Upper Nepean River Flood Study