Hawkesbury-Nepean River Flood Study

Technical Volume 12 – Probable Maximum Flood Modelling

Final Report

NSW Reconstruction Authority

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We advise this resource may contain images, or names of deceased persons in photographs or historical content.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

Executive Summary

The Hawkesbury-Nepean River catchment covers some 22,000 square kilometres, including the Warragamba and Nepean catchments, extending as far as Goulburn, Lithgow and Bowral, and downstream to Broken Bay. The focus of the Hawkesbury-Nepean River Flood Study is the part of the catchment within the Sydney Basin, including much of the urban growth areas of western and north western Sydney. 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 objective was achieved through:

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.

The various stages of the project are detailed in a number of technical volumes. This Technical Volume 12 provides a more detailed review of the PMF and the changes to the peak flood levels in the study area. It is intended to be read in conjunction with the main Flood Study Report and other associated Technical Volumes.

The probable maximum flood (PMF) is the largest flood that could reasonably be expected to occur for a catchment. The updates to the modelling approaches and methodology in this current study have resulted in changes to the PMF when compared against the 2019 Regional Flood Study.

Peak Flow Estimation

A modified approach to the 2019 Flood Study was adopted for the peak flow estimation, considering the estimation of the PMF flow at multiple locations within the study area. This resulted in the adoption of three different PMF events for inclusion in the TUFLOW model; a Wallacia focused 24-hour event, a Penrith focused 72-hour event, and a Sackville focused 96-hour event.

The adoption of these additional events, particularly the Sackville 96-hour event, has an influence on peak flood levels. The influence of this revised approach is estimated to contribute around an additional 0.6 metres at Windsor.

Floodplain Storage and Conveyance

The representation of the floodplain and its storage has been significantly improved compared to the 2019 Regional Flood Study through the use of the most up to date terrain data and the use of the TUFLOW 2D model (refer to **Technical Volume 3** for further details). In the PMF event, significantly greater floodplain storage is activated, both in terms of volume and spatial extent, and therefore the benefit of this improved representation becomes more pronounced.

In addition to the storage characteristics, the representation of conveyance in the Lower Hawkesbury has been improved following the significant data collection that occurred as a result of the March 2021, March 2022 and July 2022 events.

The influence of this improved understanding of storage and conveyance results in an increase in peak flood levels in the PMF at Windsor of around 1.9 metres relative to the 2019 Regional Flood Study.

Representation of River Bends

The flood study has provided the opportunity for an improved understanding of the river bends in the Lower Hawkesbury River. This area of the river is characterised by a number of tight and confined bends which can influence the hydraulic loss behaviour (for example, Singletons Mill Bend shown in Figure i). At higher flows (such as the PMF event), the hydraulic losses around these bends can become significant. This behaviour is better represented in the TUFLOW 2D model.

The inclusion of these bend losses within the modelling increases peak flood levels at Windsor by around 1.4 metres in the PMF.

Changes to Peak Flood Levels

The combination of these factors results in increases in peak PMF flood levels at a number of locations throughout the study area. While not a precise estimate, a rough order of magnitude estimate of the relative contribution of the changes in peak flood level is shown in Table 4-1, based on the previous sections.

Figure i Oblique view of Singletons Mill bend, looking downstream - March 2021 Flood (26 March 2021, source: Adam Hollingworth)

Table i. Approximate Contributions to Changes in Peak Water Level (m) - PMF

Location	River/Creek	Increase Relative to 2019 Regional Flood Study	Flow Estimation Methodology (Section 2)	Storage/ Conveyance (Section 3.2 & 3.3.1)	Bend Losses (Section 3.4)
Webbs Creek (Wisemans Ferry) (gauge)	Hawkesbury River	4.4	0.9	1.4	2.1
Sackville (gauge)	Hawkesbury River	5.8	0.7	2.5	2.7
Windsor Bridge (gauge)	Hawkesbury River	3.9	0.6	1.9	1.4
Victoria Bridge Penrith (gauge)	Nepean River	Negligible differences			
Wallacia Weir (gauge)	Nepean River	1.9	0.0	1.9	-

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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)
AVM	Average Variability Method
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
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
GWH	Great Western Highway
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
NRG	Near infrared/ Red/ Green
NSW	New South Wales
OSD	On-site Stormwater Detention
PMF	Probable Maximum Flood
PMP	Probable Maximum Precipitation
RFS	Rural Fire Service
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

The Hawkesbury-Nepean River Catchment covers some 22,000 square kilometres, including the Warragamba and Nepean catchments, extending as far as Goulburn, Lithgow and Bowral, and downstream to Broken Bay. 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.

1.1 Hawkesbury-Nepean Flood Strategy

The former NSW Government's *Resilient Valley, Resilient Communities: Hawkesbury–Nepean Valley Flood Risk Management Strategy* (2017) identified the risks and challenges in the Valley and recognised there is no simple solution to managing or reducing the valley's high flood 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.

1.2 PMF

The probable maximum flood (PMF) is the largest flood that could reasonably be expected to occur for a catchment. The updates to the modelling approaches and methodology in this current study have resulted in changes to the PMF when compared against the 2019 Regional Flood Study, as discussed in Technical Volume 11. This report has been prepared to provide further details on the changes to the methodology and modelling that have resulted in the changes to the PMF.

The model results from the 2019 Regional Flood Study are compared to results from the models developed for the current flood study in Table 1-1, for a number of representative locations. The largest differences in peak flood levels occur within the Windsor basin and downstream in the Lower Hawkesbury River.

There are several key changes to the approach in the current study that have resulted in changes to the peak flood level estimates for the PMF:

- Peak flow estimation – a modified approach to the peak flow estimation was adopted, considering the estimation of the PMF flow at multiple locations within the study area. This is discussed further in Section 2.
- The representation of the floodplain storage (refer Section 3.2)
- The hydraulic representation of the Lower Hawkesbury River, which is further discussed in Section 3.3.

Table 1-1. Comparison of PMF Peak Levels (m AHD)

Location	River/Creek	2019 Flood Study	Current Study	
			Rubicon	Tuflow
Webbs Creek (Wisemans Ferry) (gauge)	Hawkesbury River	14.4	16.3	19.1
Sackville (gauge)	Hawkesbury River	23.6	26.5	29.4
Windsor Bridge (gauge)	Hawkesbury River	26.7	28.9	30.6
Victoria Bridge Penrith (gauge)	Nepean River	32.8	32.9	32.7
Wallacia Weir (gauge)	Nepean River	66.3	66.4	68.2

2 PMF Flow Estimation

2.1 Approach

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).

A general overview of the process to estimate the PMF flows is shown in Figure 2-1.

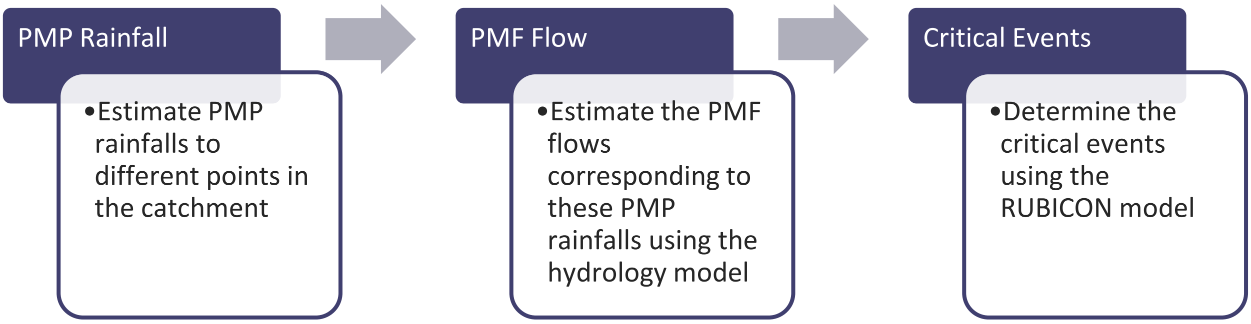

Figure 2-1. Overview of the PMF Flow Estimation

2.1.1 PMP Rainfall

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.

PMP estimates were obtained from the updated Generalised Southeast Australia Method (GSAM) (BoM, 2006). Table 2-1 lists the average depth of precipitation over the total catchment area to different focal points in the Hawkesbury-Nepean catchment.

Table 2-1. Probable maximum precipitation depths (mm)

Focal Catchment	24hr Duration	36hr Duration	48hr Duration	72hr Duration	96hr Duration
Wallacia	820	930	1000	1100	1190
Warragamba	530	620	680	790	870
Penrith	510	600	670	780	870
Sackville	490	580	650	760	850
Wisemans Ferry	440	520	580	690	770
Ocean	430	510	570	670	750

These PMP depths were applied to the catchment for which they are calculated (focal catchment). For example, the Penrith 72-hour PMP received a catchment average depth of 780mm, with the spatial pattern defined by ratios from the GSAM method.

Australian Rainfall and Runoff (ARR) provides no real guidance on what rainfall to assume downstream of the focal point and it is unrealistic to assume no rainfall. To inform emergency management, it is necessary to have realistic rainfalls downstream of the focal point. As an upper bound, the total rainfall downstream of a focal point should not exceed a PMP to that point. This same issue applies at Wallacia, which is not downstream of Warragamba Dam. At Wallacia, we need to consider a Nepean PMP, a Warragamba PMP and a combined PMP given the varied potential modes of flooding there.

Downstream of each focal point, depths were calculated to not exceed a PMP for each subsequent downstream focal point. This was done by calculating the total PMP rainfall volume to the downstream location of interest and subtracting the upstream PMP volume to the previous focal point. Dividing this volume by the residual catchment area between the two focal points gives the intermediate depth. This is best explained using a table for the case of a PMP to Penrith (Table 2-2). For example, 652mm is the depth applied on the residual catchment area of 2067km^2 between Penrith and Sackville such that the total rainfall to Sackville is 760mm, given 780mm has already been applied upstream of Penrith.

Table 2-2. Distribution of rainfall downstream of a 72hr PMP to Penrith

Focal point	72-hour PMP depth (mm)	Catchment area (km^2)	Location	Intermediate area (km^2)	Spatial distribution	Intermediate depth (mm)
Penrith	780	11166	Penrith focal point	11166	GSAM method	780
Sackville	760	13233	Penrith to Sackville	2067	GSAM method	652
Wisemans Ferry	690	20352	Sackville to Wisemans Ferry	7119	GSAM method	560
Ocean	670	21596	Wisemans Ferry to Ocean	1244	GSAM method	343

For each duration the AVM[1]-smoothed PMP temporal pattern was used in accordance with DCCEEW guidance for flood studies.

2.1.2 PMF Flows & Critical Events

For each of the 6 focal points and 5 durations, the PMP rainfalls were then applied to the hydrologic model to estimate PMF flows throughout the catchment. These were then applied to the RUBICON model to understand the resulting peak water levels in the floodplain. At key locations in the catchment (Wallacia, Penrith, Windsor, Sackville, Lower Portland, Wisemans Ferry), the results of the different scenarios were then ranked based on level.

By comparing the peak water levels from the different PMF events, three PMF events were selected for analysis in the TUFLOW model: the Wallacia 24-hour, the Penrith 72-hour and the Sackville 96-hour events. Reasons for selecting these events are as follows.

- The Wallacia centred 24-hour PMF was selected to assess the sensitivity of flood levels to a Nepean dominated PMF
- The rank for the Penrith-centred PMF events with 48-hour and 72-hour durations was similar. Based on insights from the TUFLOW modelling for events of a PMF scale, it is known that the Rubicon model is slightly underestimating storage between Wallacia and Bents Basin in extreme events. For this reason, the longer 72-hour event was selected.
- The Sackville centred 96-hour PMF has a larger volume than the 72-hour Penrith event. This results in higher flood levels in Windsor and further downstream.

An envelope of the three events modelled in TUFLOW is used to define the PMF for the 2023 Hawkesbury-Nepean River Flood Study.

2.2 Comparison to 2019 Regional Flood Study

The 2019 Regional Flood Study tested PMF levels for 5 durations and 3 locations, with multiple mechanisms for Wallacia. The Penrith-centred 72-hour PMF was adopted for the mapping and reporting, as it was only marginally different from the PMF at different locations.

Figure 2-2 compares PMF hydrographs at Victoria Bridge Penrith from (a) the 2019 Regional Flood Study, (b) the RUBICON model updated as part of the 2023 Flood Study, and (c) the new TUFLOW model.

The Penrith 72-hour event for both the 2019 Regional Flood Study and the current RUBICON model results are largely consistent, with only minor differences in the hydrographs.

The graph does show that while the Sackville 96-hour event has a lower peak at Victoria Bridge, the volume of the event is larger. As Windsor is more sensitive to the volume of the inflow, this results in a greater peak level there.

The differences between the TUFLOW model and the RUBICON model are further discussed in Section 3.

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[1] AVM = Average Variability Method. Technique of estimating design temporal pattern of average variability to ensure AEP neutrality in transition from PMF to PMP design flood.

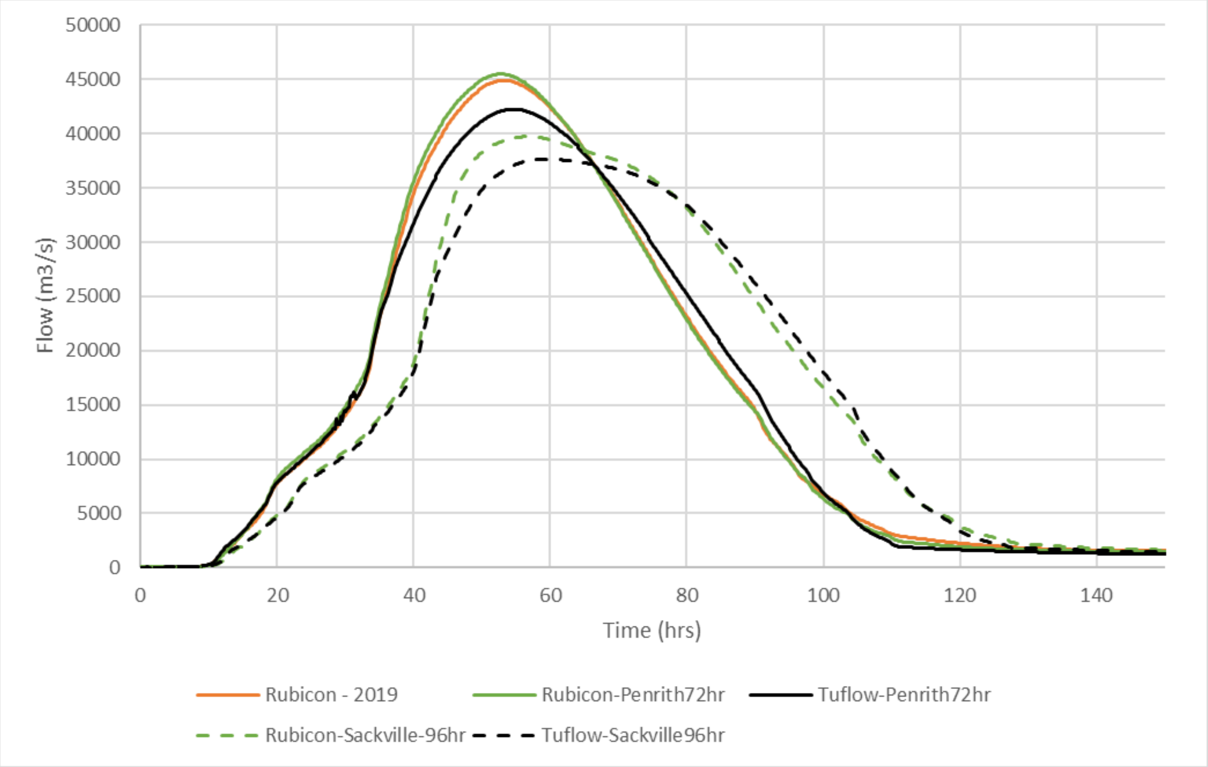

Figure 2-2. PMF Hydrograph Comparison – Victoria Bridge, Penrith [2]

2.3 Comparison of Levels

To understand the relative impact of adopting three different PMF events in the assessment, a comparison was undertaken using the TUFLOW model results. This allows for an estimation of the changes resulting from this specific input to the assessment.

Table 2-3 shows a comparison of the TUFLOW model results for the three PMF events that were analysed. For Victoria Bridge and Wallacia, the Penrith 72-hour PMF event is dominant, and means that there would be no change in these areas resulting from the updated PMF flow estimate methodology.

At Windsor, which is influenced by the volume of inflow, the Sackville 96-hour dominates, and results in flood levels that are approximately 0.6 metres higher than the Penrith 72-hour. Similarly, the Lower Hawkesbury, which is heavily influenced by the peak flood level at Windsor, is approximately 1.3 metres higher at Webbs Creek (Wisemans Ferry) in the Sackville 96-hour than the Penrith 72-hour.

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[2] The differences in the peak flows between the TUFLOW and RUBICON models are a result of the differences in the hydraulic representation of the floodplain - in particular, the storage characteristics, as discussed in Section 3.2.

Table 2-3. TUFLOW PMF Peak Flood Level (m AHD)

Location	River/Creek	Wallacia 24-hour	Penrith 72-hour	Sackville 96-hour
Webbs Creek (Wisemans Ferry) (gauge)	Hawkesbury River	14.4	17.8	19.1
Sackville (gauge)	Hawkesbury River	23.8	28.7	29.4
Windsor Bridge (gauge)	Hawkesbury River	25.7	30.0	30.6
Victoria Bridge, Penrith (gauge)	Nepean River	31.4	32.6	32.4
Wallacia Weir (gauge)	Nepean River	66.9	68.2	65.2

3 Hydraulic Characteristics

3.1 Hydraulic Behaviour

3.1.1 Inflows to Penrith

Figure 2-2 demonstrates the influences of different representations of hydraulic characteristics upstream of Penrith, showing a lower peak flow in the TUFLOW model compared with the RUBICON model. As shown in Figure 3-1, the cumulative volume is relatively similar between all three models.

The TUFLOW model has an improved representation of the Wallacia floodplain (Section 3.1.3), and also incorporates the floodplain storage upstream of Theresa Park Weir on the Nepean River near Camden, storages which are not included explicitly in the RUBICON model. The representation of these storages, together with an improved representation of the gorges in these areas, results in a different stage-storage-discharge relationship. As a result, slightly lower peak flows arrive at Penrith in the TUFLOW model.

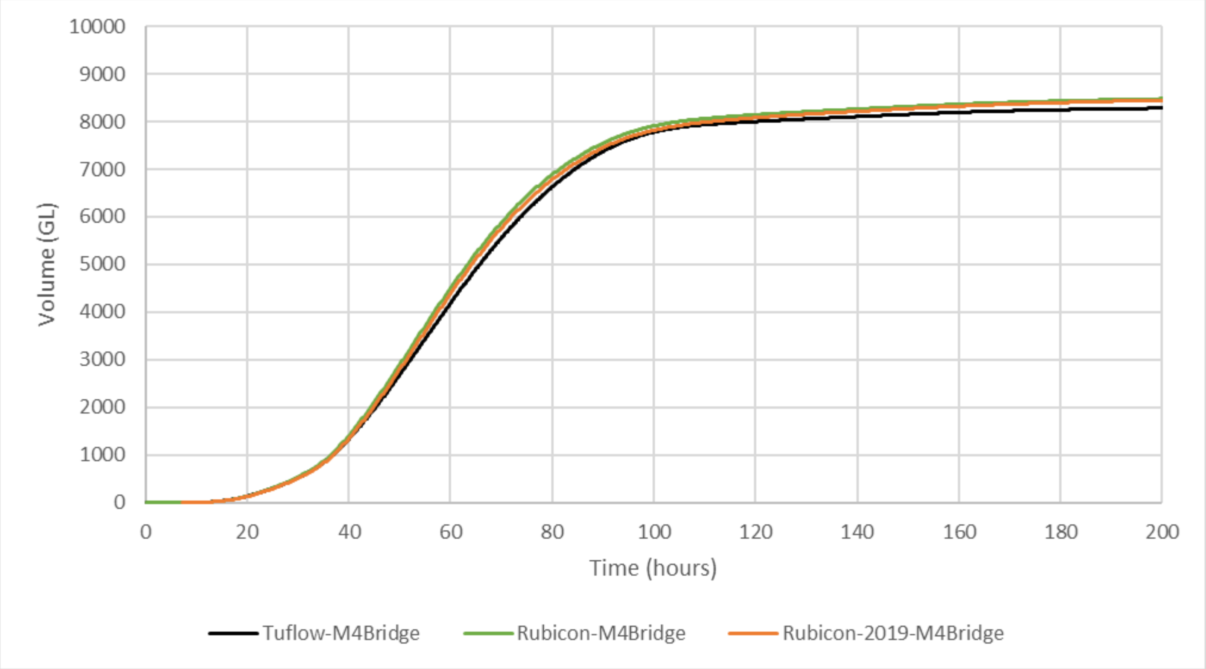

Figure 3-1. PMF Cumulative Inflow Volume - Nepean River at M4 Bridge

3.1.2 Windsor Basin

Further downstream, the storage characteristics of the Windsor basin are important. The Windsor Basin behaves in a similar way to a very large detention basin (the ‘bathtub’ effect), where the level at Windsor is a function of the capacity of the Lower Hawkesbury gorge downstream, together with the storage characteristics in the basin.

The representation of these two aspects in the model can influence the peak flood level estimate. A representation of this is provided in Figure 3-2, where the inflows at Penrith are compared with the outflows at Sackville. Penrith was adopted for this comparison as it represents the majority of the inflow volumes to the Windsor Basin. These hydrographs are shown for the Penrith 72-hour event, to allow a direct comparison with the 2019 Regional Flood Study model results.

Figure 3-3 provides a similar comparison, but using the cumulative inflow volumes. The differences shown in Figure 3-3 are the differences in the cumulative volumes, and provide an approximate representation of the active storage on the floodplain (recognising that inflows from Grose River, South Creek and other tributaries between Penrith and Sackville are not included).

The figures show that while the rate of inflow to the Windsor basin (represented by the M4 Bridge) is similar in all three models, the outflow rate at Sackville has greater differences between the models. This is largely the result of:

- Improved representation of the floodplain storage in the Windsor basin
- Improved hydraulic representation of the Lower Hawkesbury River, which represents the outflow from the Windsor 'bathtub'.

This is discussed further in Section 3.2 and 3.3.

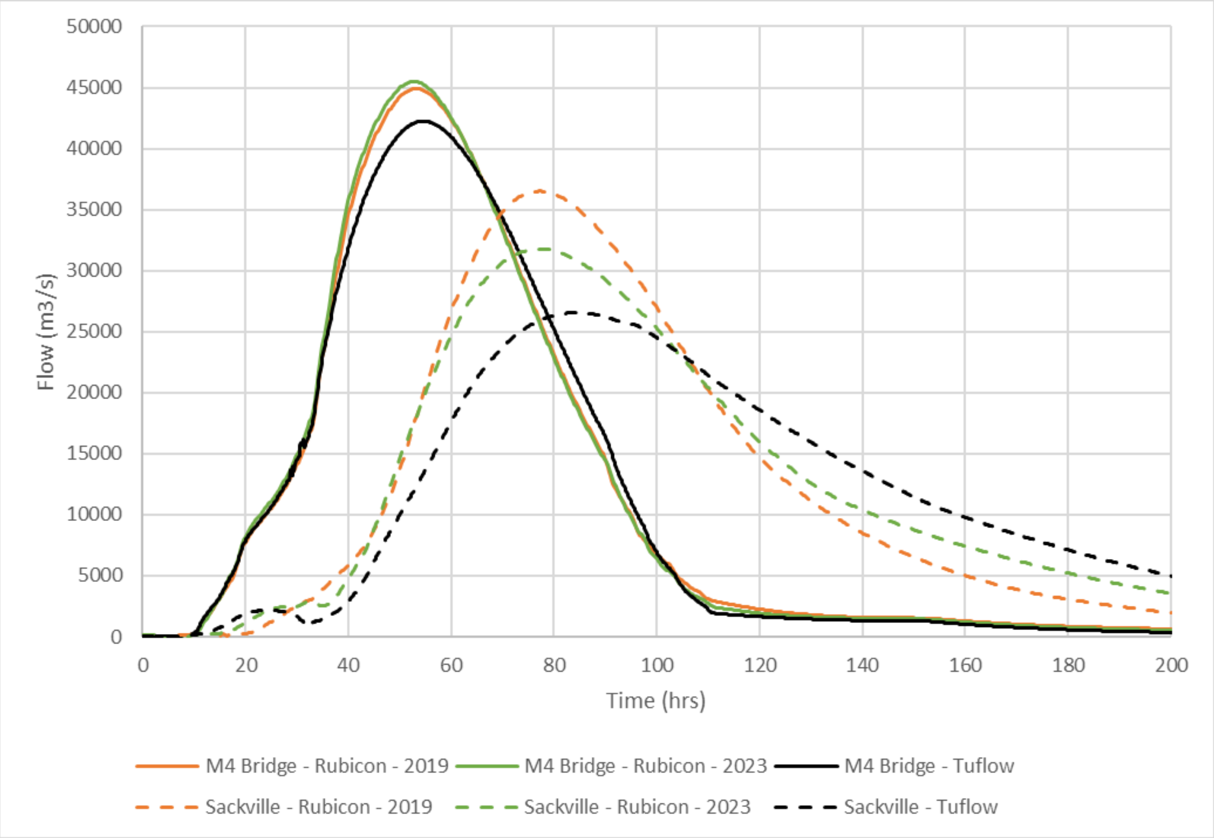

Figure 3-2. Windsor Basin - Inflows and Outflows – Penrith 72-hour PMF event

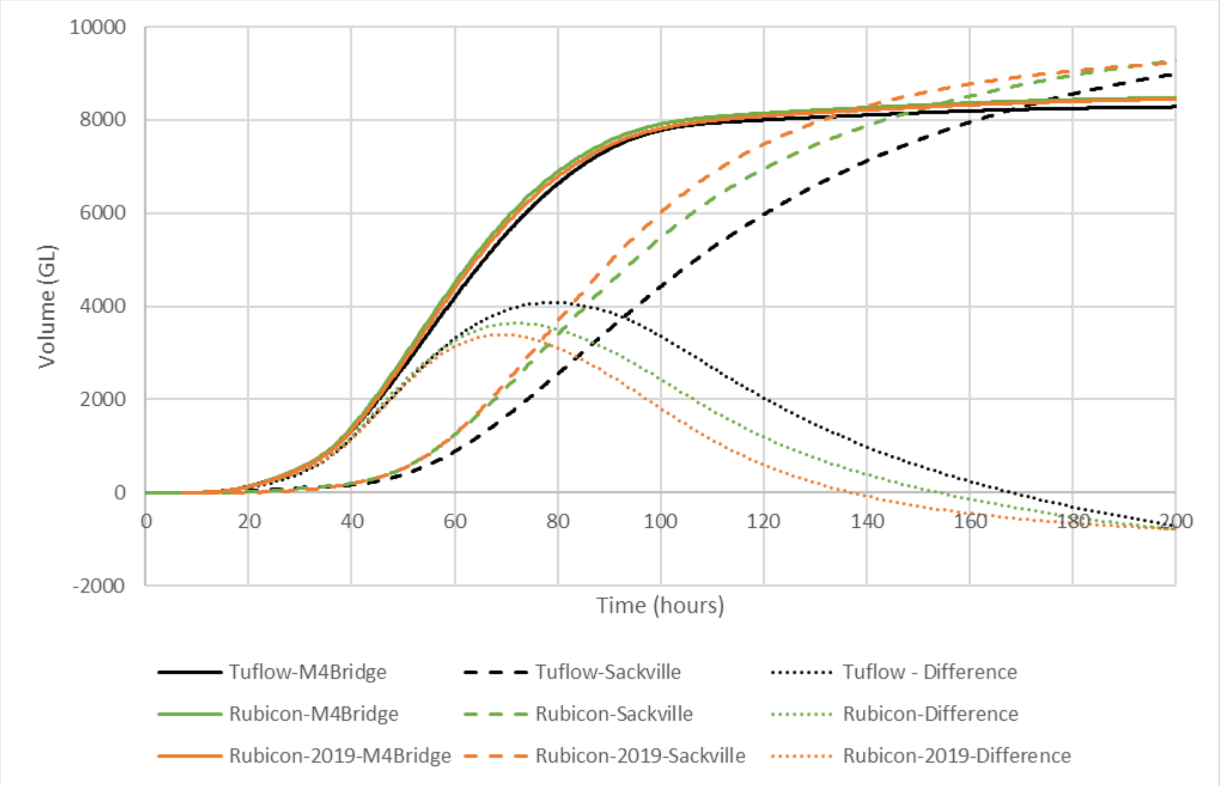

Figure 3-3. Windsor Basin - Cumulative Inflow and Outflow Volumes - Penrith 72-hour PMF event

3.1.3 Lower Hawkesbury

The flood behaviour in the Lower Hawkesbury is governed by the outflows of the Windsor basin, together with contributions from the Colo River and Macdonald River (**Technical Volume 5**). The differences in the model results can largely be attributed to similar factors to those of the Windsor Basin, and are discussed further below.

3.2 Floodplain Storage

The representation of the floodplain and its storage has been significantly improved compared to the 2019 Regional Flood Study through the use of the most up to date terrain data and the use of the TUFLOW 2D model (refer to **Technical Volume 3** for further details). In the PMF event, significantly greater floodplain storage is activated, both in terms of volume and spatial extent, and therefore the benefit of this improved representation becomes more pronounced.

Updates were undertaken to the RUBICON model, in parallel with the establishment of the TUFLOW model, to better represent this storage and conveyance. These changes were based on reproducing the TUFLOW model stage and flow for the calibration events. When comparing the RUBICON model in the current study with the 2019 Regional Flood Study, there is a change to the hydraulic representation throughout the Lower Floodplain.

While updates were made to the RUBICON model to better represent the storages using the most up to date information, there are some limitations particularly at the volumes of a PMF event. The RUBICON model represents storage through “nodes”, where a stage-storage relationship is adopted. While this provides a reasonable representation for smaller storage volumes, it likely provides a more efficient outflow characteristic compared to the TUFLOW 2D representation. For example, storage areas in the southern parts of the South Creek part of the floodplain would be more attenuated in the TUFLOW model due to the distance and the floodplain roughness.

Even when the same storage is introduced into a 1D model, the 1D model does not represent the processes controlling the drainage of the floodplain back to the river. This results in the 1D model responding too quickly in the drainage phase.

3.3 Lower Hawkesbury Hydraulic Behaviour

The other aspect influencing the levels on the Windsor floodplain are the outflow characteristics of the Lower Hawkesbury gorge downstream. Two key aspects have resulted in changes to the understanding of these outflows from the current study, when compared with the 2019 Regional Flood Study:

- An improved representation of the hydraulic conveyance in the Lower Hawkesbury River, which has been updated in both the RUBICON and TUFLOW models.
- A better understanding of the bend losses that occur in the Lower Hawkesbury, where confined meander bends in the gorge result in significant hydraulic losses, particularly at higher flow events.

3.3.1 Conveyance

Further information collated as a part of this study has allowed for an improved understanding of the hydraulic conveyance of the Lower Hawkesbury. This is particularly the case for the additional data that has been collated in recent events (March 2021, March 2022 and July 2022) where there was significantly greater gauged and observed data to inform this assessment. This has allowed for a greater collection of data on river gradients in this area, where available data in earlier events was generally scarce.

3.3.2 Bend Losses

The losses through the bends in the Lower Hawkesbury River are better understood and represented in the TUFLOW model. These confined bends throughout the gorge have a significant impact on the flow behaviour, particularly under rare and extreme events.

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 3-4). This complex flow behaviour is more pronounced at high flows and is difficult to represent, particularly in a 1D model such as RUBICON.

A review was undertaken to verify the hydraulic losses around river bends which were observed in the TUFLOW model, which is documented in **Appendix A**. The review includes:

- Historic Flood Validation – the March 2021, March 2022 and July 2022 events provided an invaluable opportunity to collect a significant amount of observed information on the flood behaviour, including within the Lower Hawkesbury where this resolution of information was not available for previous events. In addition to the broad validation discussion in **Technical Volumes 8, 9** and **10** this appendix reviews the head losses at several key areas in the Lower Hawkesbury. An example of some of the large eddies, associated with high bend losses, is shown in Figure 3-5. The model demonstrates a close correlation to the behaviour and characteristics for each historic event and, importantly, shows that the hydraulic model is not overestimating hydraulic losses around bends in the lower river for these events.

- TUFLOW Model Testing – tests were undertaken using a smaller scale 'test rig' model. The intent of this modelling was to test different model assumptions and configurations to ensure that these did not influence the hydraulic behaviour. This testing suggests that different configurations of the TUFLOW model would not significantly alter the hydraulic behaviour.
- Brisbane River Catchment Flood Study – comparisons were undertaken between the hydraulic losses predicted in the Brisbane River Catchment Flood Study and the Lower Hawkesbury. The Story Bridge bend in the Brisbane River has a number of very similar characteristics to the Singletons Mill bend in the Lower Hawkesbury. Comparisons were undertaken by comparing the head loss and discharge relationships between the two studies. The comparisons suggest that the Hawkesbury-Nepean River Flood Study model is producing bend losses of a similar, if not slightly lower magnitude to those predicted for the Brisbane River Catchment Flood Study.

Figure 3-4. Oblique view of Singletons Mill bend, looking downstream - March 2021 Flood (26 March 2021, source: Adam Hollingworth)

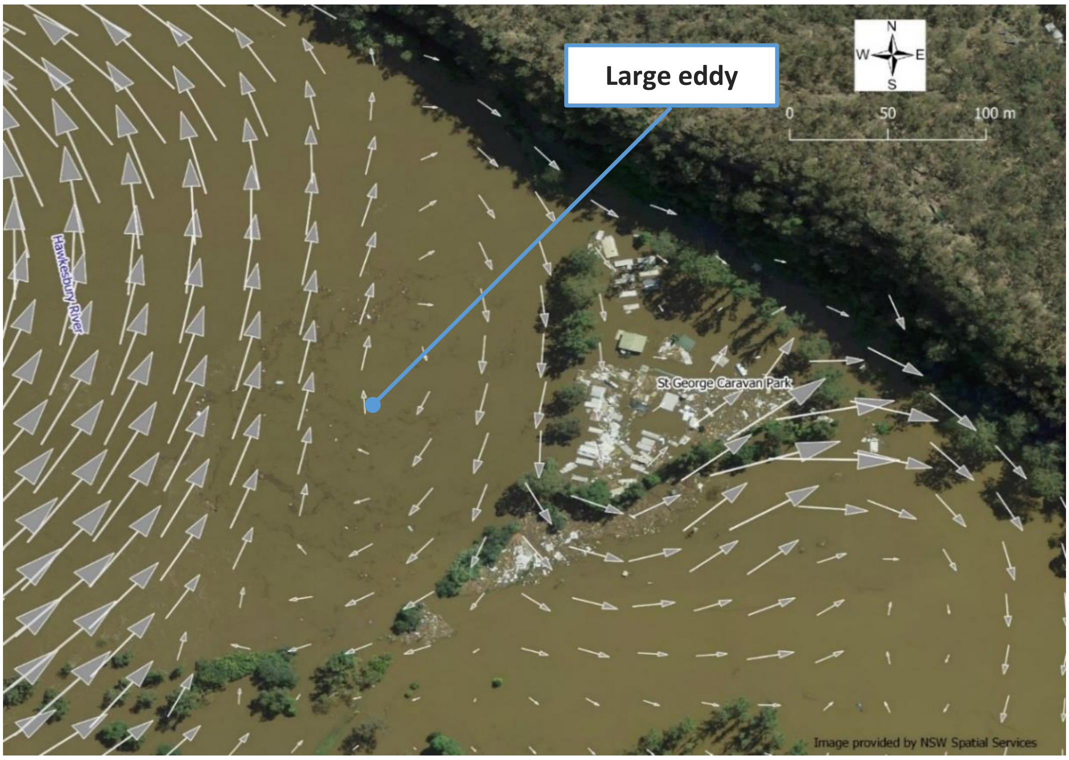

Figure 3-5. Simulated peak velocity vectors (where length represents magnitude of velocity) for March 2021 flood overlaid on March 2021 aerial imagery showing large eddy directly west of St George Caravan Park where substantial debris was deposited

3.4 Comparison of PMF Levels

To understand the differences from the improved representation of the hydraulic behaviour, a summary of the peak flood levels for the Penrith 72-hour event is provided in Table 3-1. This event was adopted to remove the influence of the different method of the PMF flow estimation discussed in Section 2, and to allow for a focus on the hydraulic influences on the PMF peak levels.

In summary:

- Wallacia – there are negligible differences in the peak levels between the updated RUBICON and 2019 RUBICON results. However, the TUFLOW shows differences of around 1.9 metres, which is likely attributable to the improved storage representation and the representation of the gorge downstream of Wallacia.
- Penrith – minor differences between the models.
- Windsor – the changes to the storages, as well as the improved understanding of the hydraulic characteristics of the Lower Hawkesbury, have resulted in the updated RUBICON model being approximately 1.9 metres higher than the 2019 RUBICON results. The TUFLOW model is a further 1.4 metres higher than the updated RUBICON, and this is likely attributable to the representation of the bend losses when compared with the RUBICON model.
- Lower Hawkesbury – the changes in the hydraulic representation result in increases in the RUBICON model of approximately 1.5 to 2.5 metres. The TUFLOW model suggest additional increases of approximately 2 to 2.5 metres in this area when compared with the updated RUBICON model.

Table 3-1. Peak PMF Flood Levels (m AHD) - Penrith 72-hour event

Location	River/Creek	2019 Flood Study	Current Study		Current Study – Difference to 2019 FS	
			Rubicon	Tuflow	Rubicon	Tuflow
Webbs Creek (Wisemans Ferry) (gauge)	Hawkesbury River	14.4	15.8	17.8	1.4	3.4
Sackville (gauge)	Hawkesbury River	23.6	26.1	28.7	2.5	5.1
Windsor Bridge (gauge)	Hawkesbury River	26.7	28.6	30.0	1.9	3.3
Victoria Bridge Penrith (gauge)	Nepean River	32.8	32.9	32.7	0.1	-0.1
Wallacia Weir (gauge)	Nepean River	66.3	66.4	68.2	0.1	1.9

Note: refer to Table 2-3 for results for the three PMF events, some of which are higher than for this event

4 Conclusion

The probable maximum flood (PMF) is the largest flood that could reasonably be expected to occur for a catchment. The updates to the modelling approaches and methodology in this current study have resulted in changes to the PMF when compared against the 2019 Regional Flood Study. This report has detailed changes to the methodology and modelling that have resulted in the changes to the peak levels in the PMF.

Several key changes to the approach in the current study have resulted in changes to the peak flood level estimates for the PMF when compared with the 2019 Regional Flood Study:

- Peak flow estimation – a modified approach to the peak flow estimation was adopted, considering the estimation of the PMF flow at multiple locations within the study area. This is discussed further in Section 2.
- The representation of the floodplain storage (refer Section 3.2), both in terms of the updated RUBICON model, as well as the improved representation within the TUFLOW 2D model.
- The hydraulic representation of the Lower Hawkesbury River, which is further discussed in Section 3.3.

The combination of these factors results in increases in peak PMF flood levels at a number of locations throughout the study area. While not a precise estimate, a rough order of magnitude estimate of the relative contribution of the changes in peak flood level is shown in Table 4-1, based on the previous sections.

Table 4-1. Approximate Contributions to Changes in Peak Water Level (m) - PMF

Location	River/Creek	Increase Relative to 2019 Regional Flood Study	Flow Estimation Methodology (Section 2)	Storage/ Conveyance (Section 3.2 & 3.3.1)	Bend Losses (Section 3.4)
Webbs Creek (Wisemans Ferry) (gauge)	Hawkesbury River	4.4	0.9	1.4	2.1
Sackville (gauge)	Hawkesbury River	5.8	0.7	2.5	2.7
Windsor Bridge (gauge)	Hawkesbury River	3.9	0.6	1.9	1.4
Victoria Bridge Penrith (gauge)	Nepean River	Negligible differences			
Wallacia Weir (gauge)	Nepean River	1.9	0.0	1.9	-

5 References

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

Infrastructure NSW [INSW] (2017). *Resilient Valley, Resilient Communities: Hawkesbury-Nepean Valley Flood Risk Management Strategy (Flood Strategy)*, January.

NSW Government (2023). *Flood Risk Management Manual*, Department of Planning and Environment.

WMAwater (2019). *Hawkesbury-Nepean Valley Regional Flood Study*, Final Report, prepared for Infrastructure NSW, July.

6 Glossary[3]

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

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[3] 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	PMP is the primary input to PMF estimation
		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)	
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

Appendix A – Hydraulic Losses in Lower Hawkesbury River

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Tables

1 Introduction

1.1 Overview

The TUFLOW hydraulic model reports 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 headlosses 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 have a highly sinuous shape) which can influence the hydraulic loss behaviour.

A review was undertaken to verify the hydraulic losses around river bends which were observed in the TUFLOW model. This has been done in several different ways:

- Historic Flood Validation – the March 2021, March 2022 and July 2022 events provided a unique opportunity to collect a significant amount of observed information on the flood behaviour, including within the Lower Hawkesbury where this resolution of information was not available for previous events. In addition to the broad validation discussion in Technical Volume 8, 9 and 10, this appendix reviews the head losses at a number of key areas in the Lower Hawkesbury.
- TUFLOW Model Testing – tests were undertaken using a smaller scale Lower Hawkesbury River Test model. The intent of this modelling was to test different model assumptions and configurations to ensure that these did not influence the hydraulic behaviour.
- Brisbane River Flood Study – comparisons were undertaken between the hydraulic losses predicted in the Brisbane River Flood Study and the Lower Hawkesbury. The Story Bridge bend in the Brisbane River has a number of very similar characteristics to the Singletons Mill bend in the Lower Hawkesbury (see below).

1.2 Verification Area

For the TUFLOW model testing and to allow for comparative analysis of the Hawkesbury River behaviour with the Brisbane River, a representative and comparable area of the Lower Hawkesbury was selected. This area, the “Singletons Mill” bend, has high simulated headloss in flood events (i.e., headlosses of approximately 3 metres are predicted around this bend during the PMF). This bend is located downstream of Wisemans Ferry, as shown in Figure 1-1 and Figure 1-2. An oblique view of the bend is shown in Figure 1-3 and Figure 1-4.

Figure 1-5 shows the RUBICON model cross section locations, while Table 1-1 provides a summary of the TUFLOW and RUBICON model results for the 1 in 100 AEP, 1 in 2000 AEP, 1 in 5000 AEP and the PMF events. This comparison confirms that while the headloss is similar in the 1 in 100 AEP event, the difference in headloss between the TUFLOW and RUBICON models increases with the severity of the flood in this section of the river. This is most evident during the PMF.

The RUBICON model, as a 1D model, does not inherently incorporate headloss associated with bends. Adjustments are required to the 1D model parameters (e.g., higher loss coefficients), and it can be difficult to estimate these for bends like this, particularly when there is a lack of data to validate the adopted parameters (the lower Hawkesbury River suffers from a relative scarcity of historic flood information relative to other, more populated and better gauged areas of the river). A 2D model, such as TUFLOW, is more capable of reproducing some of the hydraulic losses associated with bends.

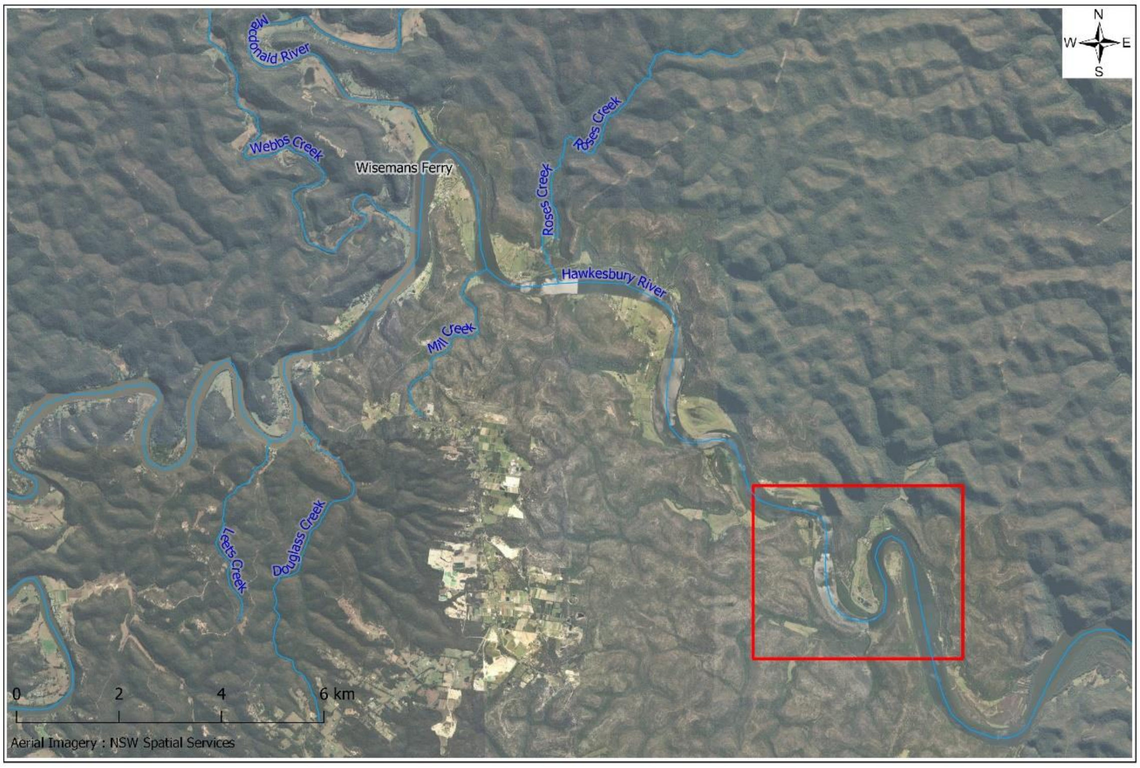

Figure 1-1. General Locality Plan (Source: Google Maps, Accessed January 2022)

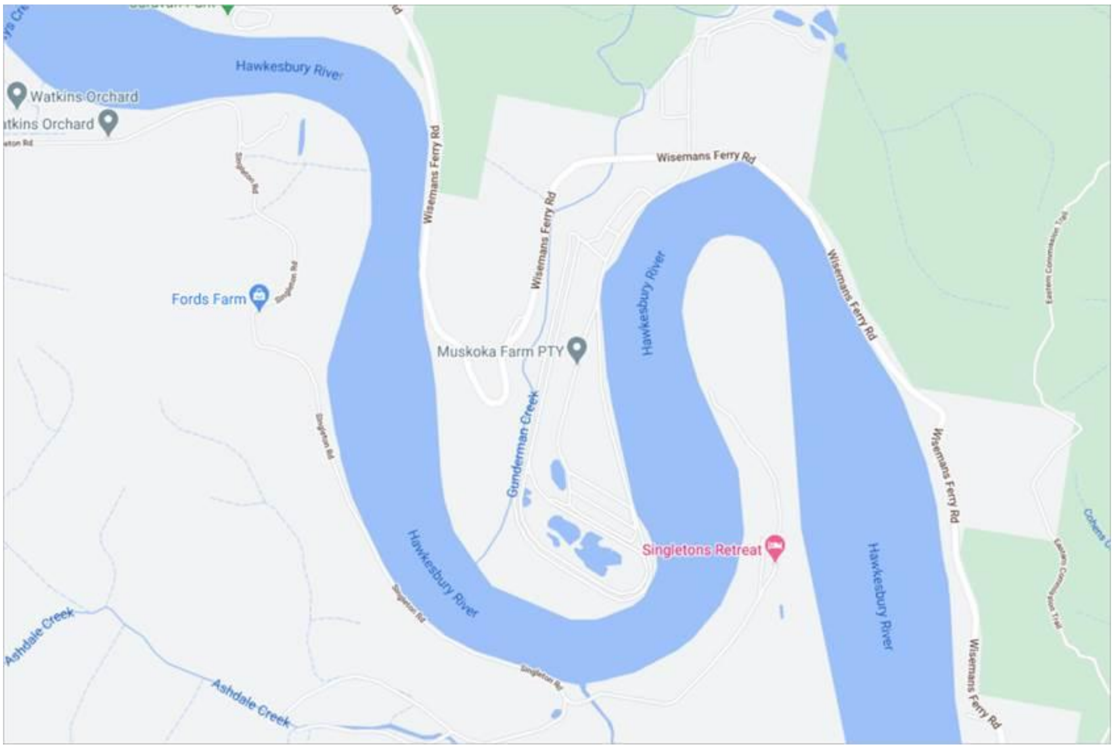

Figure 1-2. Singletons Mill Bend (Source: Google Maps, Accessed January 2022)

Figure 1-3. Oblique View of Singletons Mill Bend - March 2021 Flood (26 March 2021, source: Adam Hollingworth)

Figure 1-4. Oblique View of second bend in Singletons Mill Bend - March 2021 Flood (26 March 2021, source : Adam Hollingworth)

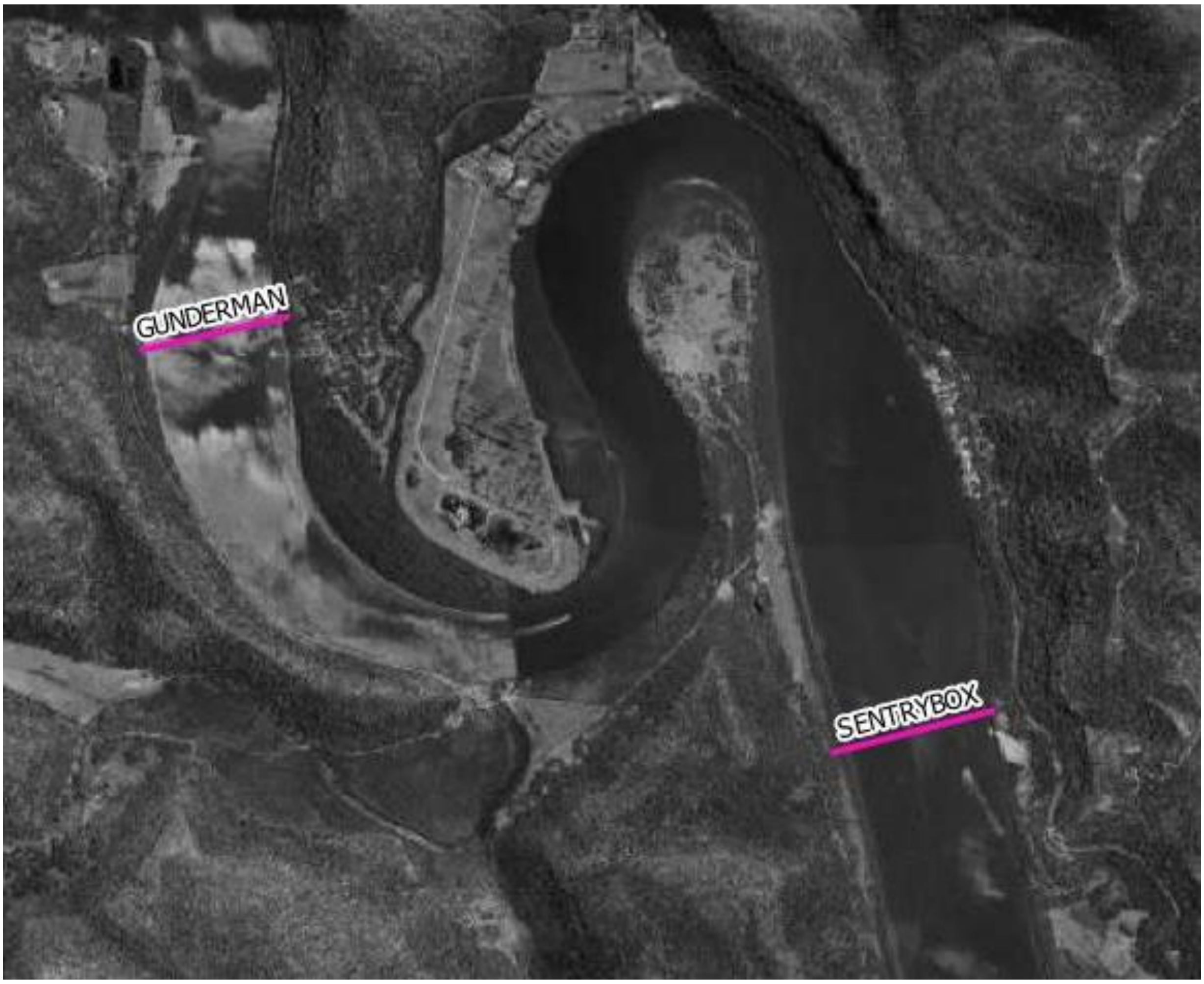

Figure 1-5. RUBICON Model Result Locations (Based Image: Google Earth Imagery)

Table 1-1. Comparison with RUBICON Model – Between GUNDERMAN and SENTRYBOX Cross Sections

	1 in 100 AEP		1 in 2000 AEP		1 in 5000 AEP		PMF	
	RUBICON	TUFLOW	RUBICON	TUFLOW	RUBICON	TUFLOW	RUBICON	TUFLOW
Water Level at Gunderman (m AHD)	4.7	4.3	9.1	9.5	10.1	10.5	13.5	15.4
Water Level Downstream of Bend – at Sentrybox (m AHD)	4.0	3.3	7.8	7.4	8.8	8.2	11.8	12.0
Total Head Loss (m)	0.7	0.8	1.3	2.1	1.3	2.3	1.7	3.5

The most significant headloss occurs in the TUFLOW model in the second part of the Singletons Mill bend. This second part of the bend has been used as the focus for verification. The specific alignment that was used for measuring headloss around this bend is shown in Figure 1-6. The TUFLOW model results at the upstream and downstream end of the alignment shown in Figure 1-6 are summarised in Table 1-2 for a range of large flood events.

It is noted that the alignment can influence the overall headloss, as there is variance in right to left bank flows, so the head loss estimates should be treated as indicative. Figure 1-7 illustrates this right bank (inside of the bend) to left bank (outside of the bend) variance from the model results at a representative location on Singletons Mill Bend.

Figure 1-6. Key Focus of Bend Loss Assessment

Table 1-2. Head Loss Estimates on Singletons Mill Bend – TUFLOW

	1 in 100 AEP	1 in 2000 AEP	1 in 5000 AEP	PMF[1]
Discharge (m3/s)	9,100	15,700	18,100	33,800
Water level Upstream of Bend (m AHD)	3.3	6.8	7.9	14.8
Water Level downstream of Bend (m AHD)	3.0	5.7	6.6	11.7
Head Loss (m)	0.3	1.1	1.3	3.0

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[1] PMF water levels and headlosses are approximate, given that there is a reasonable left to right bank variance in water levels due to the bend.

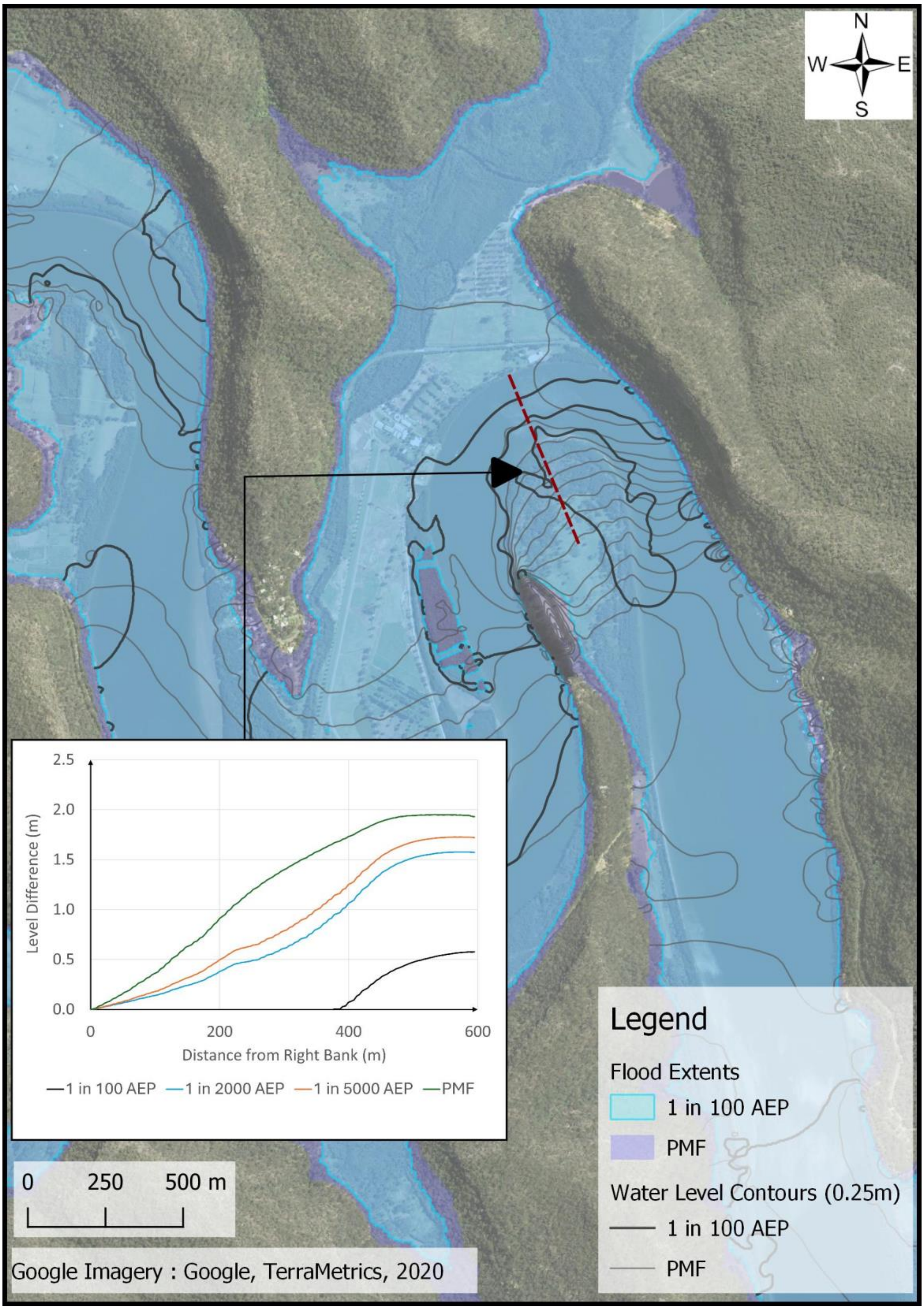

Figure 1-7. Modelled Right-Left Bank Level Variance at Singletons Mill Bend

1.3 Literature

There are a number of studies and literature that demonstrate the higher headloss along a channel as a result of the influence of bends. A common approach for 1D models, such as that adopted in Chow (1959), is to apply a multiplication factor on the Mannings 'n' roughness value along a length of river to represent the additional hydraulic losses associated with bends.

These approaches typically correlate the potential increase in Mannings 'n' based on the sinuosity of the river, which is a metric related to the actual channel length versus the straight-line distance along the valley. Rivers with high sinuosity (> 1.5) have significant bends and would be expected to have higher bend losses.

Table 1-3, based on Chow (1959), shows the sinuosity versus the increase in Mannings 'n' (often referred to as *m* or *n'/n*). A similar formulation is the Linearised SCS Method (LSCS), which itself derives from work undertaken in 1963, and has been shown by James and Wark (1992) to provide a reasonable representation of bend losses for in-bank flows. A comparison of this method and Chow (1959) is shown in Figure 1-8,where the LSCS provides similar results without the discontinuity of Chow (1959). Of note between both methods is that once the sinuosity exceeds 1.5 (noted as "severe" by Chow (1959)), Mannings 'n' is estimated to be 30% greater than a river with negligible sinuosity. This would suggest that a typical 1D model would require a roughness of 30% greater to account for the influence of the bends.

Table 1-3. Sinuosity categories (Source: Chow, 1959)

Sinuosity	Rating	Mannings 'n' Factor (n'/n)	Description
Degree of meandering (m)	Minor	1.00	Ratio of the channel length to straight line valley length is 1.0 to 1.2
	Appreciable	1.15	Ratio of the channel length to straight line valley length is 1.2 to 1.5
	Severe	1.30	Ratio of the channel length to straight line valley length is > 1.5

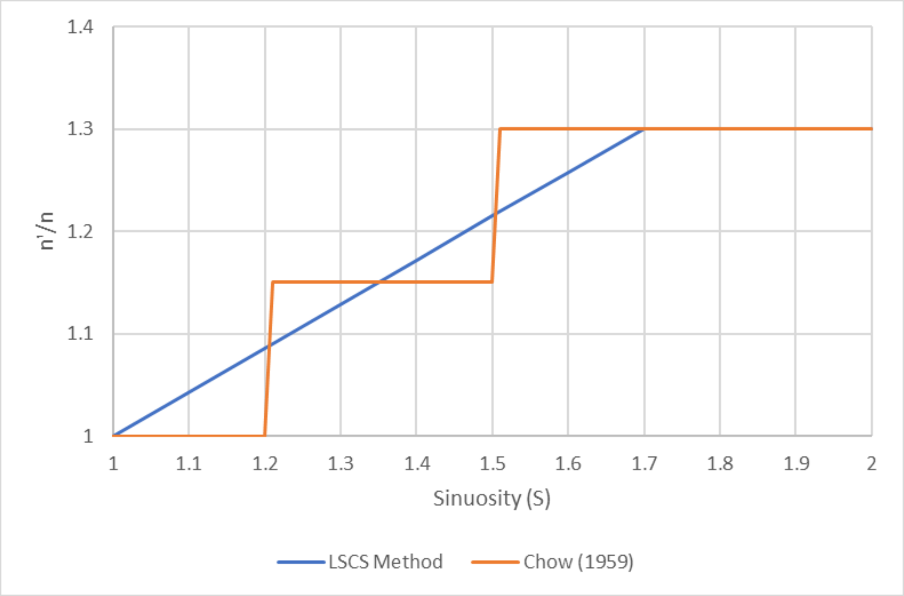

Figure 1-8. Mannings 'n' Factors Based on Sinuosity

The sinuosity through this small section of river is greater than 4. While it is not necessarily appropriate to apply an estimate of sinuosity over this small section, it does provide some indication of the overall severity of the sinuosity and how it may influence the hydraulic behaviour.

The key challenge with the majority of these methods in the literature is that they do not necessarily apply to high flows of the order of magnitude of the Lower Hawkesbury, or to the confined meander bends that are evident in the Lower Hawkesbury.

Colorado State University (2005) undertook laboratory experiments investigating the effects of losses associated with meander bends. This research correlated the bend loss with the friction loss, based on the ratio of bend radius to the top width of flow (R_c/T_w).

As the RUBICON 1D model does not explicitly incorporate the bend losses, a test was undertaken by applying the Colorado State University (2005) method to the RUBICON results, to derive an adjustment water level estimate. This was done by assuming the following:

- Derive the average friction loss per metre between the cross sections GUNDERMAN and SENTRYBOX. Estimate the friction loss associated with just the area measured around the Singletons Mill Bend (shown in Figure 1-6).
- Estimate the top width of the flow for each event. This was based on an estimate of where the majority of the flow was occurring.
- Apply the R_c/T_w ratio with the Colorado State University (2005) method to estimate the head loss associated through a combination of friction loss and bend loss.

Figure 1-9 provides a summary of these results, showing the original RUBICON results, the adjusted RUBICON results based on Colorado State University (2005), and the TUFLOW model results. In viewing these results, it is important to note that the R_c/T_w ratio was outside of the experimental range for the testing in Colorado State University (2005), and therefore some uncertainty remains in these estimates[2].

The results do show a reasonable degree of correlation up to the 1 in 5000 AEP event, although the TUFLOW model shows additional head loss in the PMF event. This is well outside of the Colorado (2005) experimental range, and the complexity of the hydraulic flow behaviour in these much larger flows are likely to introduce additional factors that would lead to higher losses.

Given some of the uncertainties, further verification of the representation of the bend losses was undertaken.

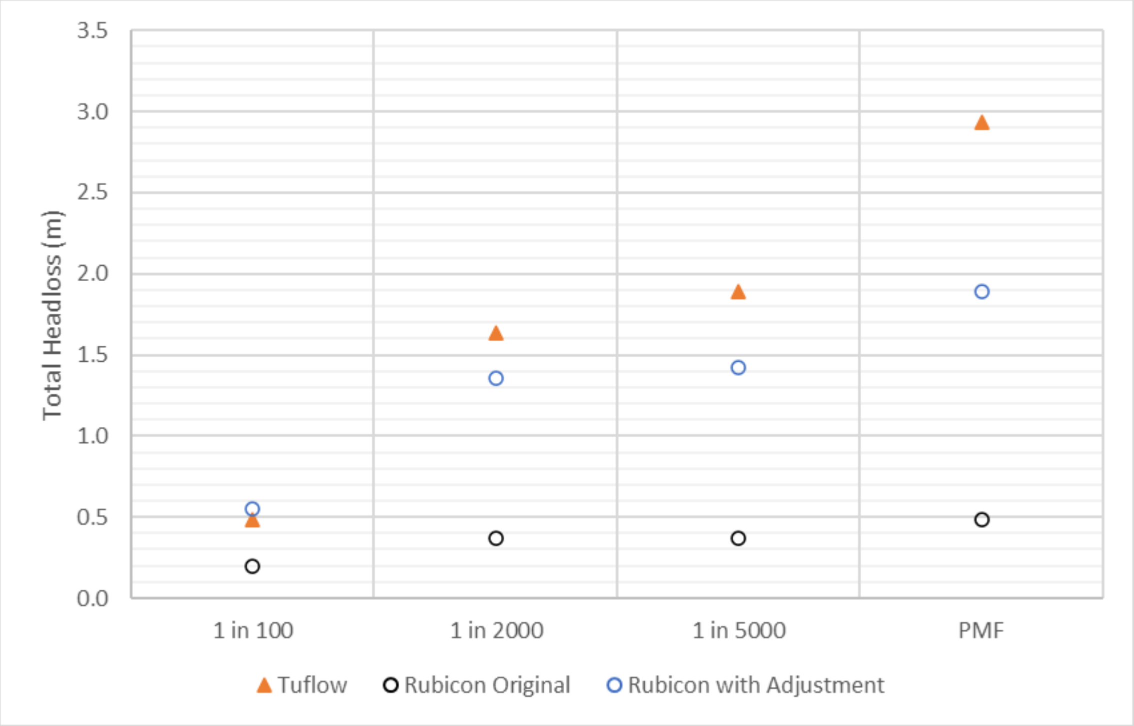

Figure 1-9. Singletons Mill Bend Head Loss Estimates

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[2] The minimum R_c/T_w ratio from Colorado State University (2005) was approximately 2.5, while the range for the Hawkesbury-Nepean River at Singletons Mill Bend for this testing was between 0.7 and 1.8 depending on the event.

2 Historical Flood Behaviour – 2021 and 2022 Events

The March 2021, March 2022 and July 2022 events provided the opportunity to observe the hydraulic behaviour of the river bends and the losses associated with these bends through an extensive post-flood data collection program. The events also provided an opportunity to verify the hydraulic model bend losses.

2.1 Bend Locations with Observed Water Level Data

Figure 2-1, Figure 2-2 and Figure 2-3 provide a localised view of two areas in the Lower Hawkesbury River for March 2021, March 2022 and July 2022 respectively. These locations, for the purposes of this discussion, have been characterised into three sets of bends: Colo Junction, Cliftonville and Wisemans Ferry (Figure 2-1). A summary of the approximate observed headloss, together with the modelled headloss, is shown in Table 2-1.

The measurement of observed levels is approximate and is a compilation of levels that were measured by the project team during the flood, together with post-flood survey (which is based on water and debris marks). This leads to a degree of uncertainty in the observed levels. Further, access during and after the flood event, together with the location of the flood marks, means that in larger events there is a lower density of observations around the bends.

In consideration of the above uncertainties in the observed levels, the hydraulic model provides a reasonable representation of the hydraulic model losses in the vicinity of the river bends in this area.

Table 2-1. Comparison of Observed and Model Headloss

Area	Event	Description	Observation	Model
Colo Junction	March 2021	Headloss measured over an approximate 6.6km distance, from near Dargyle to around 1.3km downstream of Colo Junction.	0.7	0.7
	March 2022	Headloss measured over an approximate 6.6km distance, from near Dargyle to around 1.3km downstream of Colo Junction.	0.9	0.8
Cliftonville	March 2021	Relatively short distance from near Cliftonville Road to approximately 1.2km downstream	0.3	0.3
Colo Junction to Cliftonville	March 2022	Headloss over an approximate 13.1km distance from near Dargyle to Cliftonville Road	2.0	2.1
	July 2022	Headloss over an approximate 13.7km distance from near Dargyle (upstream of the March 2022 observation) to Cliftonville Road	1.7	2.0
Wisemans Ferry	March 2021	Webbs Creek gauge through to downstream of the bend, near Mill Creek	0.6 – 1.0	0.4
	March 2022	Webbs Creek gauge through to downstream of the bend, around 500m downstream of Wisemans Ferry Bowling Club	0.7	0.5
	July 2022	Webbs Creek gauge through to downstream of the bend, near Mill Creek	0.8	0.6

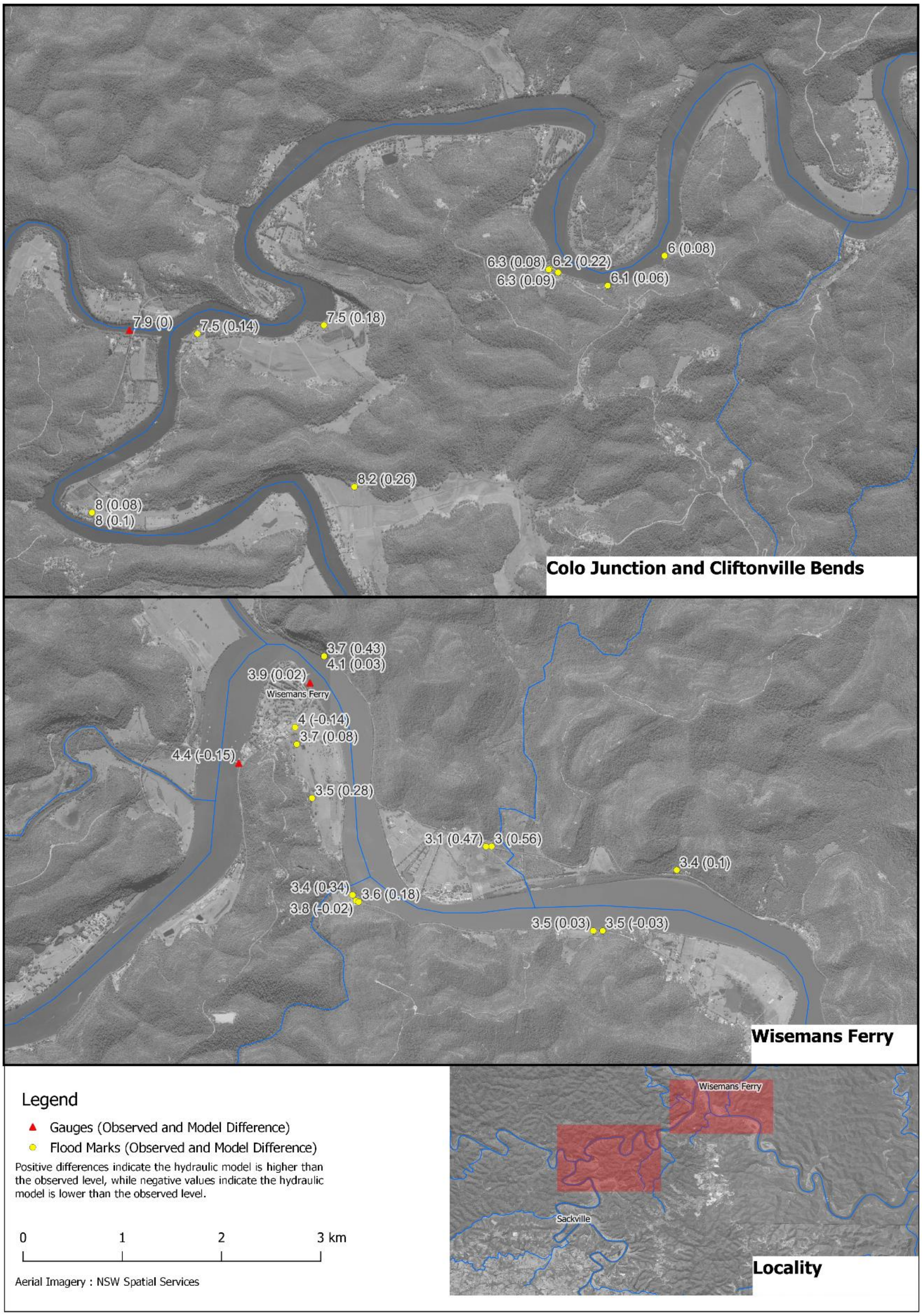
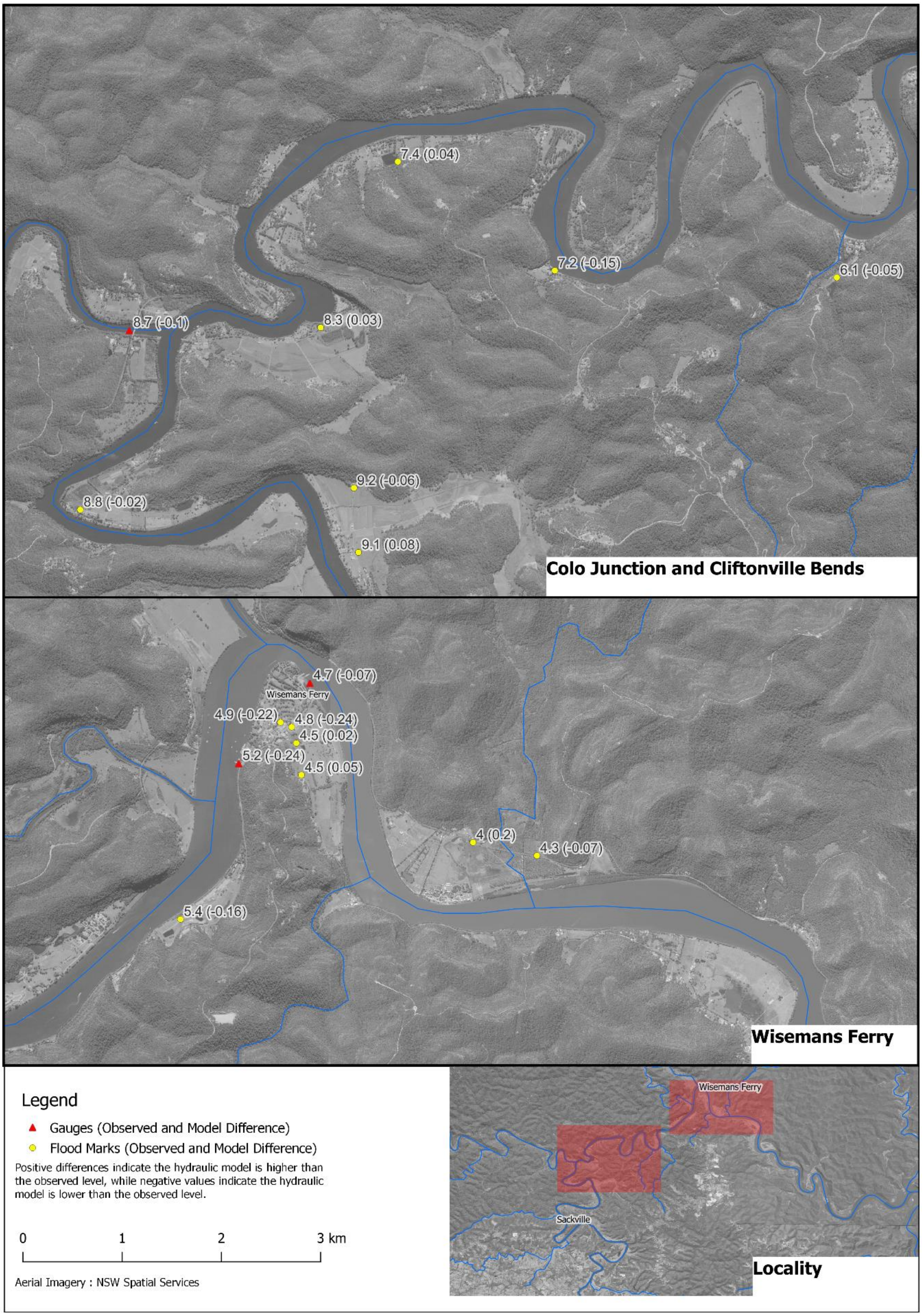


Figure 2-1. March 2021 Observed Levels compared with Hydraulic Model



Positive differences indicate the hydraulic model is higher than the observed level, while negative values indicate the hydraulic model is lower than the observed level.

Aerial Imagery : NSW Spatial Services

Figure 2-2. March 2022 Observed Levels compared with Hydraulic Model

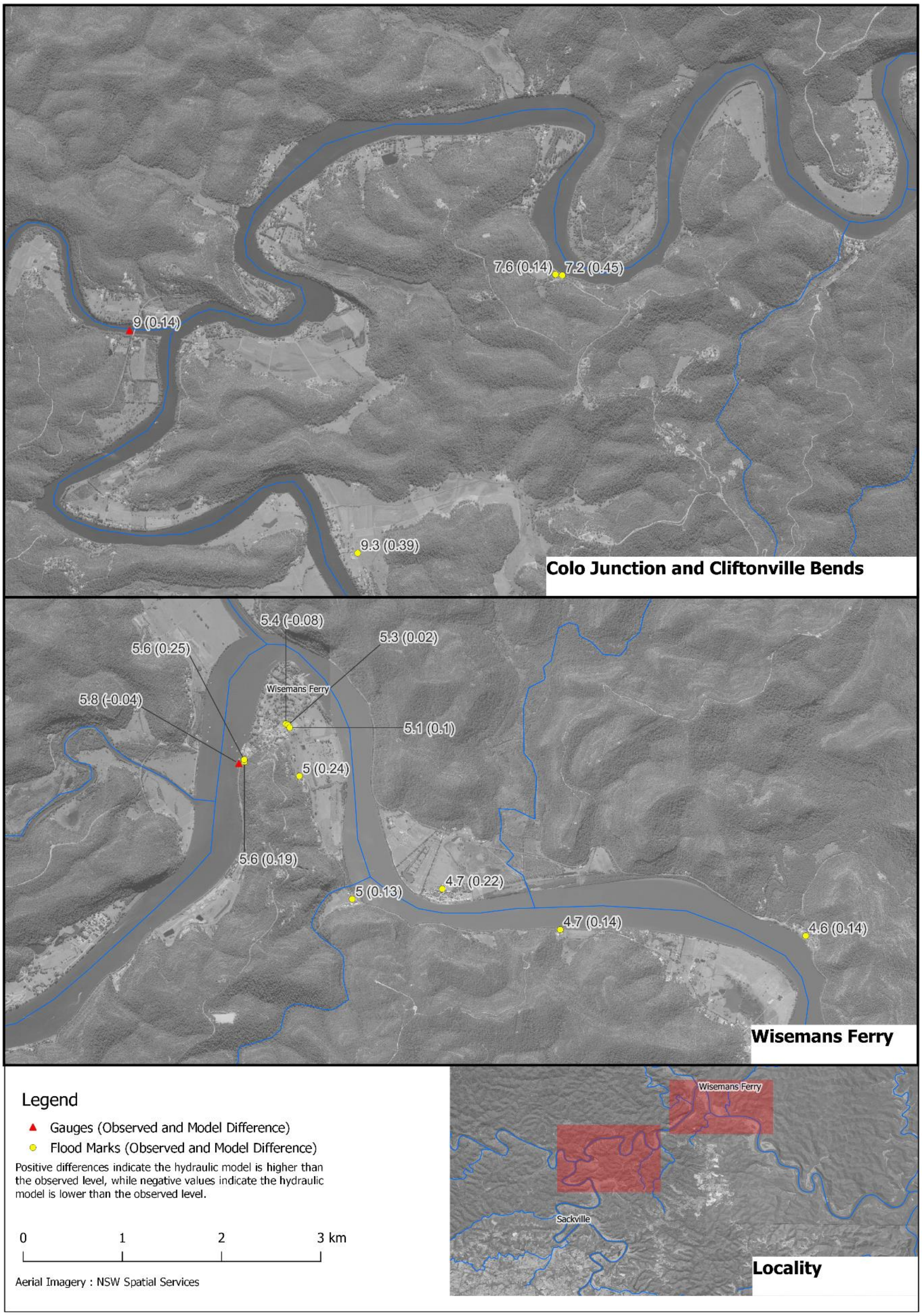


Figure 2-3. July 2022 Observed Levels compared with Hydraulic Model

2.2 Turbulent Flow Locations with Visual Observations

The March 2021 event also provided an additional opportunity to observe the hydraulic behaviour of the Lower Hawkesbury River bends under flood flows. As identified in **Technical Volume 8**, in addition to observed flood levels, significant data was collated in terms of aerial imagery, drone imagery, helicopter imagery and on the ground footage which provides an opportunity to review the flood behaviour.

There were several locations along the Lower Hawkesbury River where large eddies and turbulent flow were observed on the river bends, indicative of the additional hydraulic losses that would be experienced in these areas.

There were three specific areas of turbulent flow/eddies that were observed during the flood event, although it is likely that there were others. These include:

- the bend upstream of Sackville Ferry,
- the bend near St George Caravan Park and
- the bend near Cliftonville.

Upstream of the Sackville Ferry a local resident observed a large eddy that formed on the outside of the bend (see Figure 2-4 where the disturbance in the flow behaviour is observed in the model). The resident noted that large floating debris (like furniture such as lounges/couches) was “sucked” under the water by the eddy, only to re-emerge a few hundred metres downstream.

Figure 2-5 and Figure 2-6 show the large eddy that formed near the St George Caravan Park, downstream of Colo Junction. This large eddy can be seen circulating in the various imagery available for this area and takes up a large portion of the river width. The model also suggests a large circulation in this area, as shown by the velocity vectors in Figure 2-5.

Smaller eddies and turbulence were observed by the project team in site inspections that were undertaken near Cliftonville, as shown in Figure 2-7 and Figure 2-8, on 24 March 2021. Large surging, turbulent flow and eddies were observed by the project team, representative of the hydraulic losses that would be experienced on these tight bends. The replication of the observed levels in this area, as shown in Figure 2-1, suggests that the model is reproducing the losses associated with these bends.

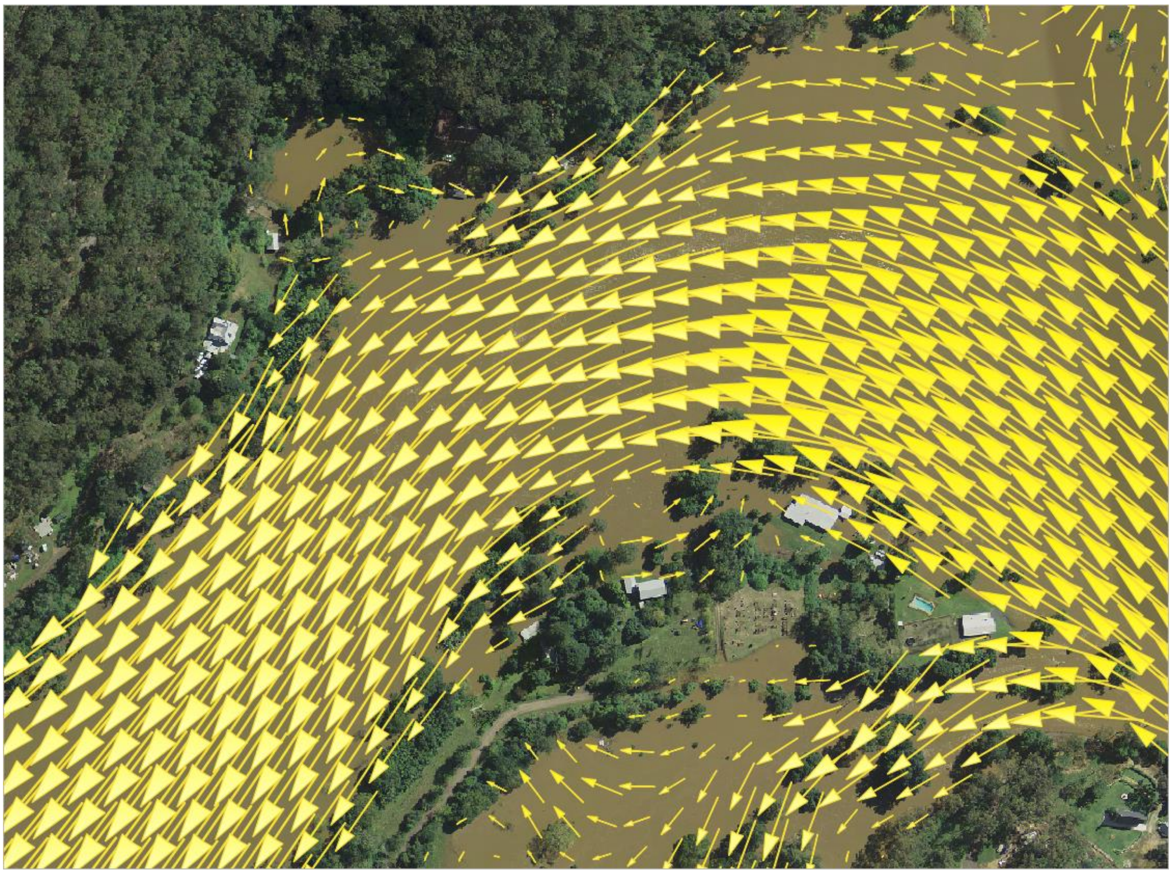


Figure 2-4. Aerial Imagery Upstream of Sackville Ferry from 25 March 2021 with simulated velocity vectors superimposed (Image source : NSW Spatial Services)

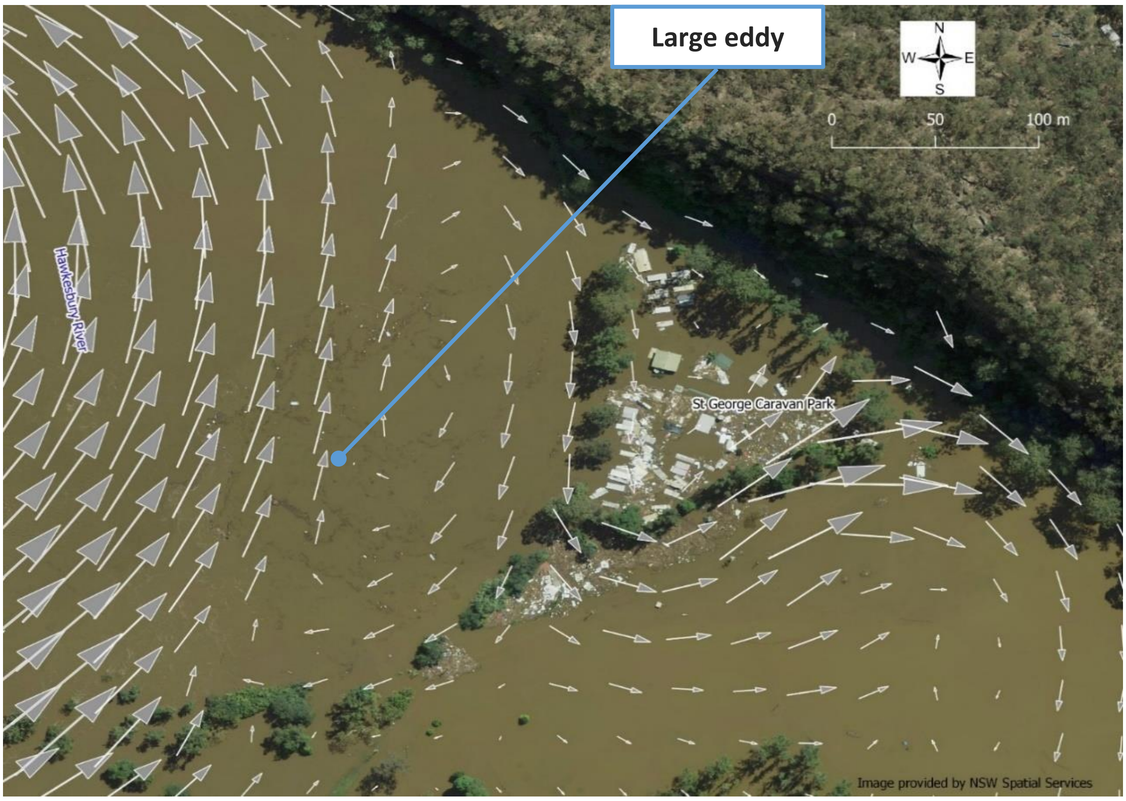


Figure 2-5. Simulated peak velocity vectors (where length represents magnitude of velocity) for March 2021 flood overlaid on March 2021 aerial imagery showing large eddy directly west of St George Caravan Park.

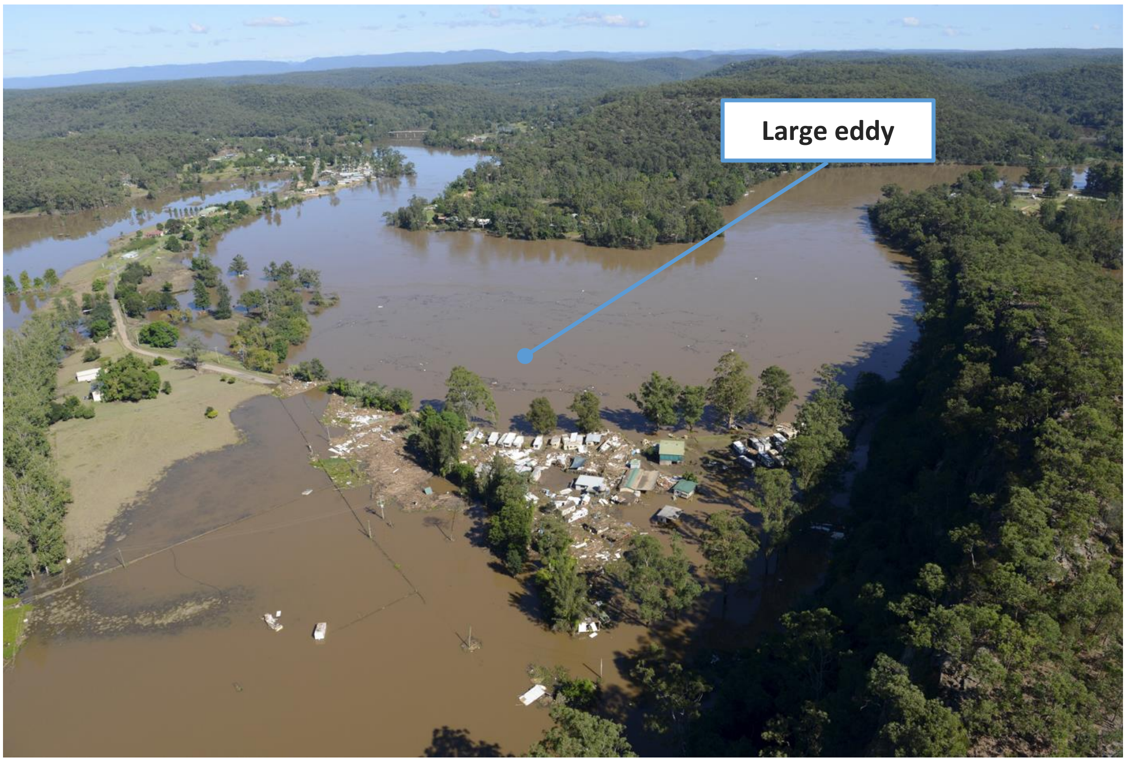


Figure 2-6. Oblique View of St George Caravan Park and Large Eddy (26 March 2021, Source : Adam Hollingworth)

Figure 2-7. River Bends near Cliftonville showing approximate location of photo shown in Figure 2-8 (Source : Google Maps)

Figure 2-8. Lower Hawkesbury near Cliftonville - Turbulent Flow and Eddies Observed (24 March 2021)

3 TUFLOW Model Testing

The first part of the testing involved the use of a Lower Hawkesbury River Test model covering the Hawkesbury River between Sackville and the Pacific Motorway (M1) bridge. This mini-model was used to test a number of alternate model arrangements to determine if the existing model arrangement was suitable and/or could be improved upon. The model adopted a representative PMF flow from an earlier version of the full model, and therefore there were some minor differences to the peak flows relative to the final model runs.

The scenarios tested include:

- 15m and 20m grid sizes with sub-grid sampling (SGS) activated
- 20m grid size without SGS
- "Streamlined" 20m grid size version with backwater areas removed from model (this was attempting to more closely mimic the Brisbane River which is discussed in Section 4)
- 20m grid size with grid orientation changed by 45 degrees, to determine whether the grid orientation was influencing the bend losses.

Stage hydrographs were extracted immediately upstream and downstream of the Singletons Mill bend for each of the above simulations for the PMF event. The results showed all model variants produced similar stage hydrographs and were generally similar to the full model.

Peak water levels were also extracted upstream and downstream of the bend and are provided in Table 3-1. This confirms that each of the model variants produced water levels that typically agree to within 0.1m upstream and downstream of the bend. It also shows that the overall headloss around the bend is very similar across each version of the model (i.e., about 3m). Therefore, it appears that regardless of the model arrangement that is adopted, the headloss around the bend is similar.

Table 3-1. Lower Hawkesbury Test Model Results

	Head Loss (m)				
	20m SGS	**15m SGS**	**20m(Non SGS)**	**20m Streamlined**	**20m SGS 45° angle**
Head Loss (m)	3.10	3.05	3.07	3.05	3.20

4 Brisbane River Flood Study

The Story Bridge/ Kangaroo Point bend on the Brisbane River has a number of similar characteristics to the Singletons Mill Bend. A comparison of the key dimensions is provided in Table 4-1, while the bend itself is shown in Figure 4-1. In addition to having similar dimensions, the Story Bridge/ Kangaroo Point bend is also confined by elevated terrain, similar to the Singletons Mill Bend in the Lower Hawkesbury, and therefore provides a good basis for comparison of the bend losses between the two studies.

Table 4-1. Bend Dimension Comparisons

Parameter	Brisbane River	Hawkesbury River
Top Width of Channel (T_w) (m)[3]	270	250
Bend Radius (R_c) (m)	470	460
R_c/T_w	1.74	1.84

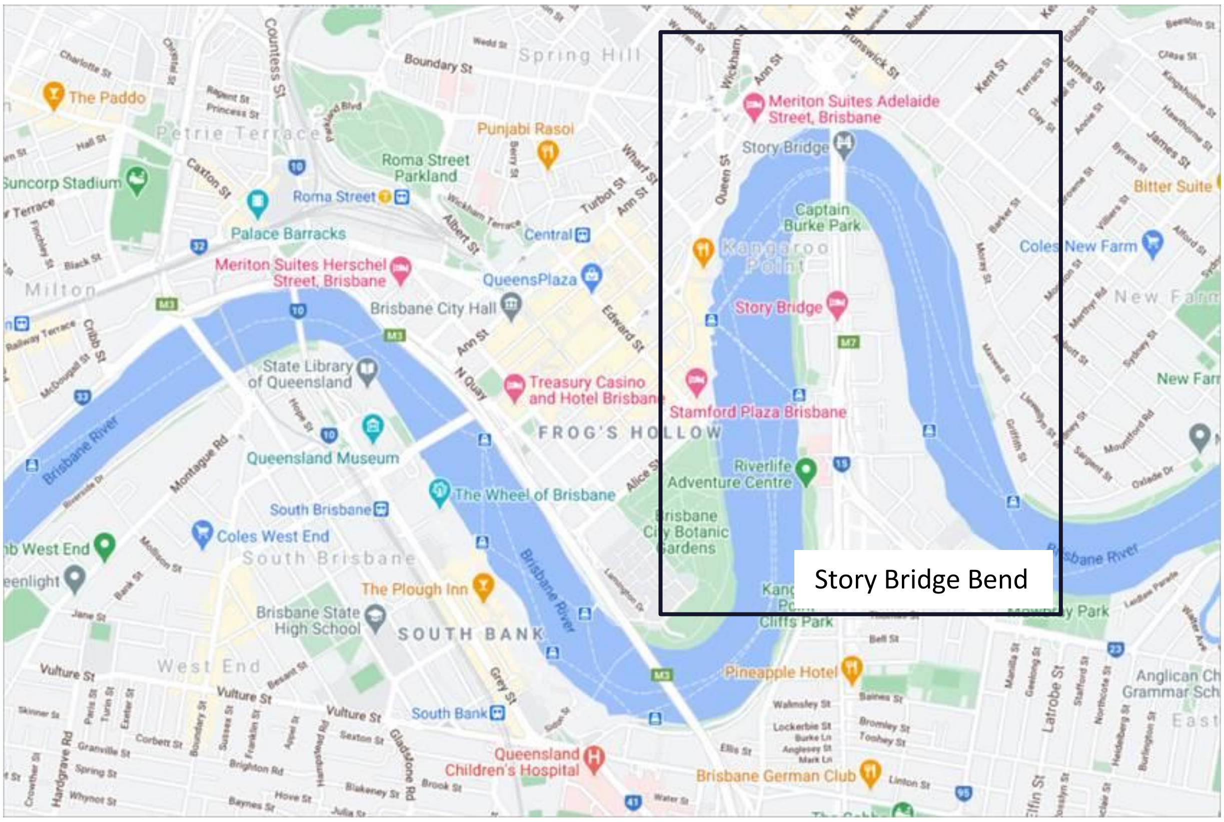


Figure 4-1. Brisbane River - Story Bridge/ Kangaroo Point Bend (source : Google Maps)

The Brisbane River Catchment Flood Study (BMT WBM, 2018) undertook calibration and verification of the model to historical flood events, including the 2011 flood event. The Kangaroo Point area benefits from a good range of historic flood information. Therefore, this bend has been subject to a robust calibration and provides a valuable dataset to assist with bend loss validation.

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[3] Tw is typically the cross sectional average top width of the channel. In this case, the approximate waterway was estimated in the Brisbane River Catchment Flood Study based on normal flow conditions. The Tw was estimated based on the 1 in 100 AEP, and where the majority of the flow was based.

Figure 4-2 shows surveyed flood levels (red labels) for the 2011 flood in the Brisbane River along with simulated depths, velocity and levels generated by a 2D TUFLOW model (i.e., the same software used to develop the hydraulic model for the Hawkesbury-Nepean River Flood Study). It indicates that around the Kangaroo Point/Story Bridge bend, a headloss of about 0.5 metres was observed/ simulated. However, it was noted that the 2011 flood produced a peak flow of 8,900m^3/s near the Brisbane CBD which is similar in magnitude to a 1 in 100 AEP flood in the Lower Hawkesbury. Therefore, it provides a useful comparison for a larger flood event than has been observed in recent history for the Lower Hawkesbury.

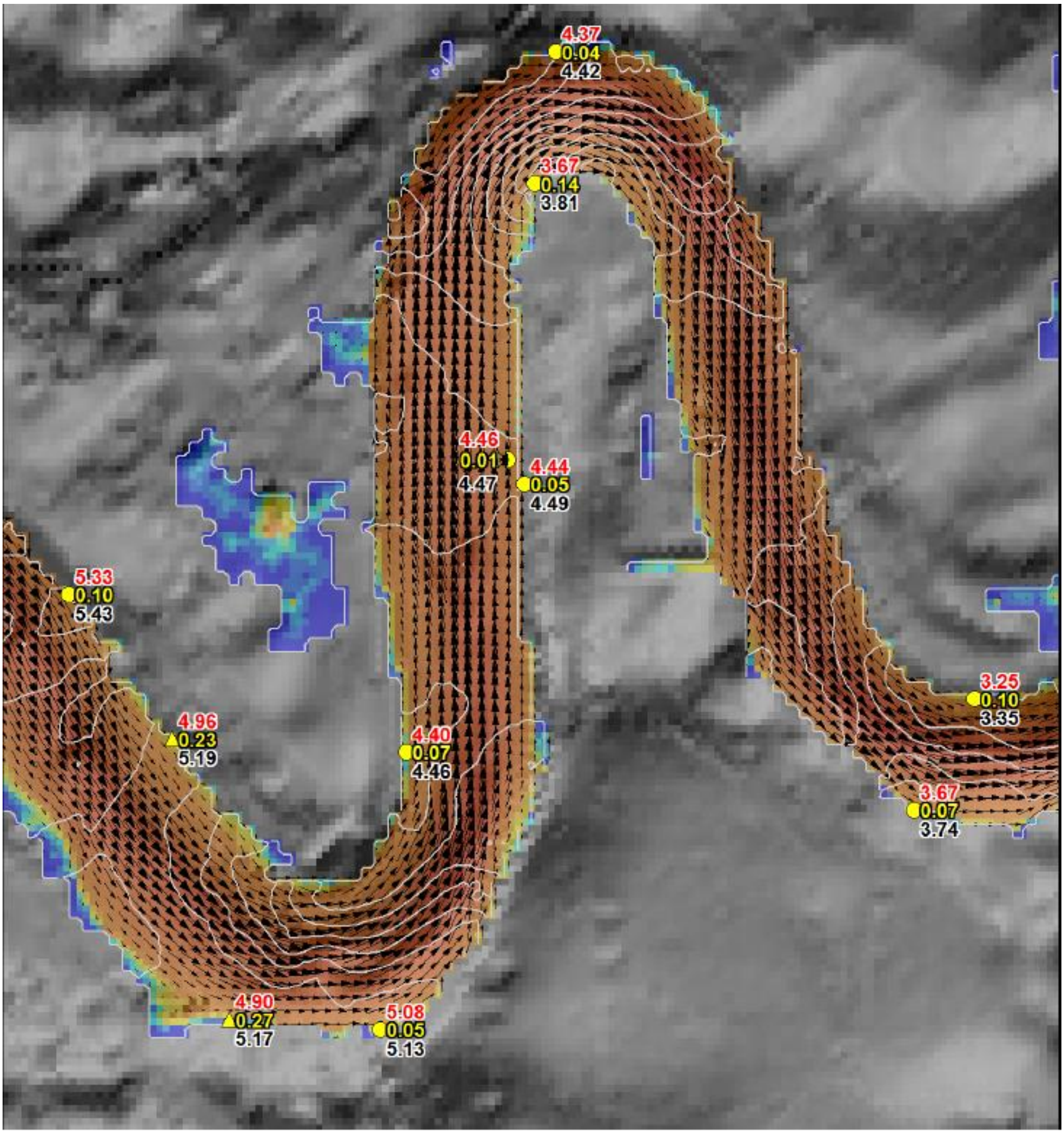

Figure 4-2. 2011 Model Calibration at the Story Bridge Bend on the Brisbane River (Source : BMT WBM, 2018) – red font shows observed level, black font modelled level, and yellow shows the difference

A comparison was made between the Brisbane River Catchment Flood Study results at the Story Bridge bend relative to the Lower Hawkesbury TUFLOW model results at the Singletons Mill Bend. Like the Hawkesbury River, there is a reasonable left to right bank variance in levels around the bend (for example, Figure 4-2), and therefore the placement of the long section can influence the estimate of the headloss. Therefore, the headloss should be treated as indicative.

The comparison of headloss is shown in Figure 4-3, and shows a reasonable correlation between peak flow and the associated bend losses in both sets of models. Both models show the much larger headloss observed on the bend under larger flows. Given the similarities in the bend characteristics, this outcome provides confidence in the Hawkesbury-Nepean flood model representation of these bend losses.

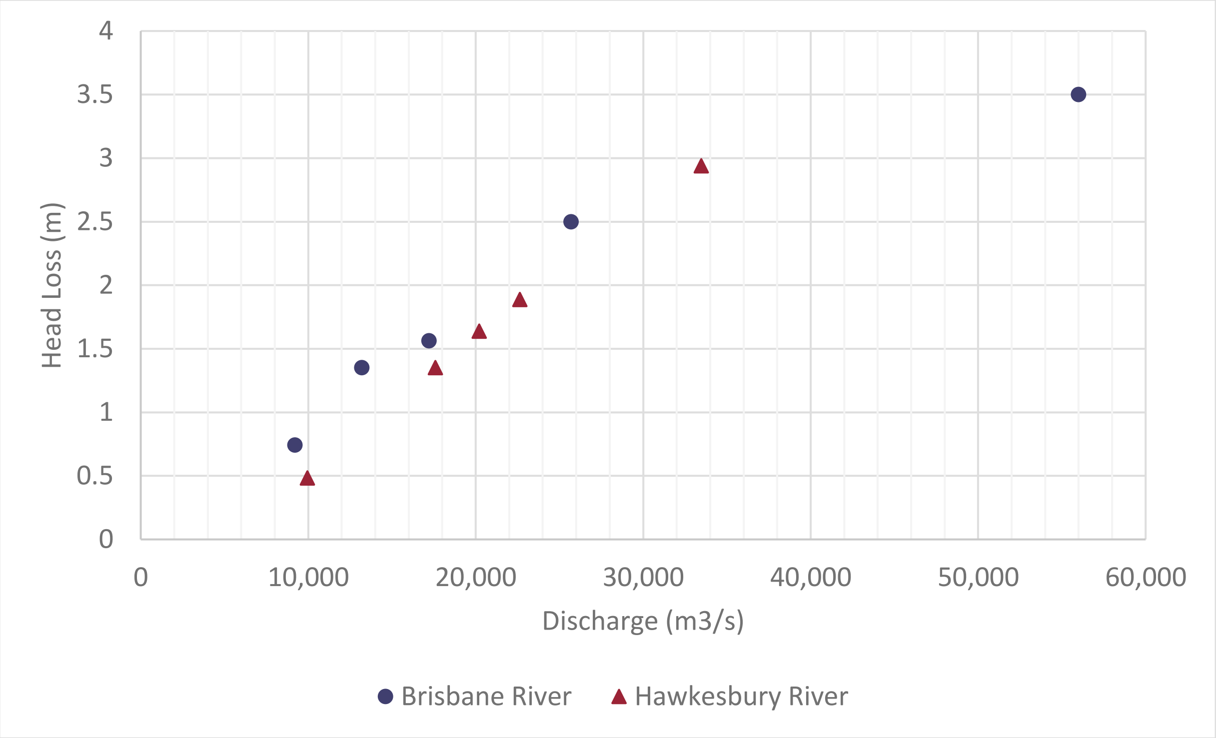

Figure 4-3. Head Loss Comparison – Brisbane River Kangaroo Point/ Story Bridge Bend vs Hawkesbury Singleton Mill Bend

5 Conclusions

Overall, the outcomes of the model validation indicate that the TUFLOW model setup appears to provide a reliable representation of flood behaviour in large Hawkesbury River floods. Although the lack of data for a very large Hawkesbury River flood makes it difficult to fully confirm the performance of the model during large floods, the simulated headlosses around the Lower Hawkesbury River bends appear reasonable and in agreement with available literature, observed flood information as well as other flood studies.

6 References

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James C & Wark J (1992). *Conveyance Estimation for Meandering Channels*, HR Wallingford Report SR 329, UK.

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