Hawkesbury-Nepean River March and July 2022 Floods Review:

Hydrology, Riverbank Erosion, and Flood Mitigation Scenarios

HAWKESBURY-NEPEAN VALLEY FLOOD RISK MANAGEMENT STRATEGY

Final Report
February 2023

NSW GOVERNMENT

Cover photo: Nepean River, looking upstream from near Devlin Road towards Penrith Lakes, 3 March 2022
Source: Infrastructure NSW. Image: Adam Hollingworth

Acknowledgments
This report was made possible through the contribution of various agencies, organisations and stakeholders, including: Commonwealth Bureau of Meteorology; Engineering Services Functional Area; NSW DPE – Water (Manly Hydraulics Laboratory); NSW Public Works; NSW Rural Fire Service – Wallacia Rural Fire Brigade; Soil Conservation Service; WaterNSW; Hawkesbury City Council; Hired Gun; Top Notch Video; WMAwater; Rhelm; Catchment Simulation Solutions.

Executive Summary

In 2022, Sydney (Observatory Hill) received 2530 mm rain, its highest annual total since records began in 1859, breaking the previous record set in 1950 (2194 mm).

The Hawkesbury-Nepean River system experienced 4 floods in March, April, July and October. The 2 largest floods in March and July are the focus of this report.

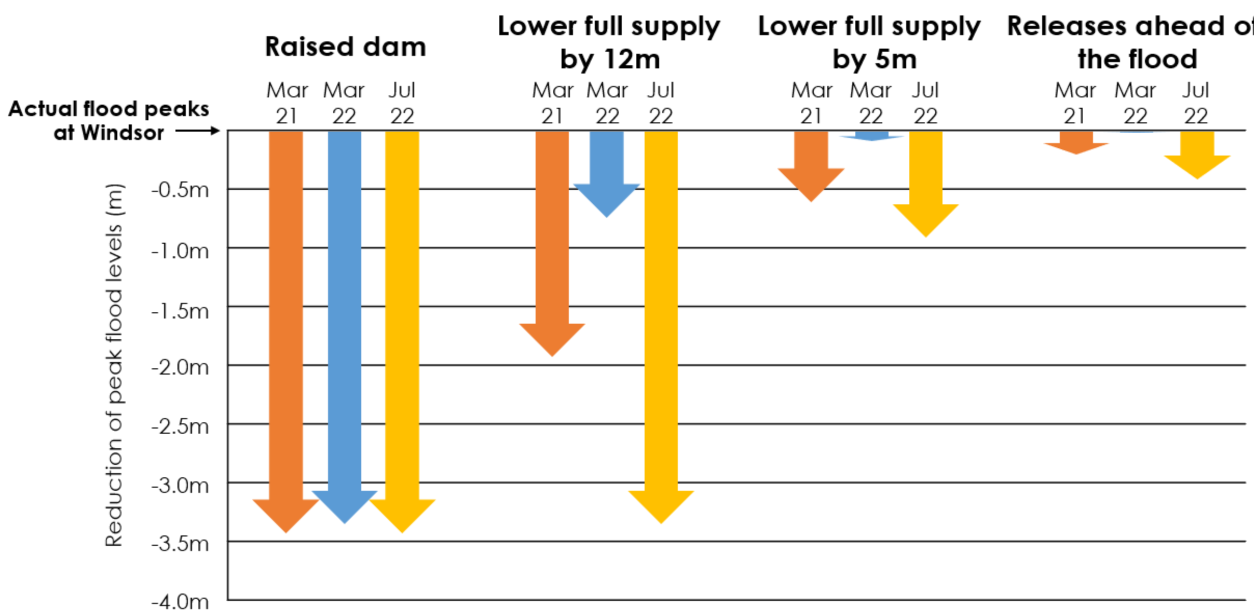
The March 2022 flood was a high-volume flood with 2 distinct peaks about 5 days apart. It was 1.7m lower than the March 2021 flood at Penrith but 0.9m higher at Windsor – the highest since 1978 there.

The July 2022 flood was a more typical single-peaked event. It was 0.5m lower than the March 2021 flood at Penrith but 1.0m higher at Windsor. It was also noticeably high in the lower Hawkesbury River – possibly the highest at Wisemans Ferry since 1889 – in part due to the movement of the storm and the timing of inflows from the Colo River.

The March and July 2022 floods were around 1 in 20 chance per year floods at Windsor.

Extensive riverbank erosion was experienced in both floods, predominantly through rotational slumping. Sandy soils, the absence of vegetation, the long duration of flooding, the rate of drawdown of the river, and the clustering of floods may all have contributed to the problem. Erosion is also associated with longer-term anthropogenic changes to the river including the construction of dams and weirs, and extensive sand and gravel extraction. The river channel is continuing to adjust as it re-establishes a more balanced dynamic equilibrium state.

Various Warragamba Dam flood mitigation scenarios were modelled to see what difference these would have made to downstream flooding for these events. Reductions to peak flood levels at Windsor with the different scenarios are shown in the figure below (along with results for the March 2021 flood). The proposed raised dam is the only mitigation measure that would have provided consistently high reductions in all 3 floods. Permanently lowering full supply level by 12 metres would have performed similarly to the raised dam in the July 2022 flood but would have provided only a small reduction in the March 2022 flood. Lowering full supply level by 5 metres, or making pre-releases ahead of the flood, would have provided less than 1m reduction in peaks, and in the March 2022 flood, negligible benefit.



Reductions of peak flood levels at Windsor with potential Warragamba Dam flood mitigation measures, March 2021, March 2022 and July 2022 floods

Contents

LIST OF TABLES

LIST OF FIGURES

1. Introduction

Flood risk in the Hawkesbury-Nepean Valley (the valley) has been described by the Insurance Council of Australia as the highest single flood exposure in New South Wales, if not Australia. This risk arises from a number of factors including the natural topography, climate change, the large and growing population, the challenges for evacuation, and low levels of flood awareness (Infrastructure NSW, 2017, 2019). Flooding in the valley arises from the contribution of 5 major tributaries flowing into 1 river system constrained by narrow downstream gorges. This causes floodwaters to back up across broad floodplains to considerable depths – known as the 'bathtub' effect (Figure 1).

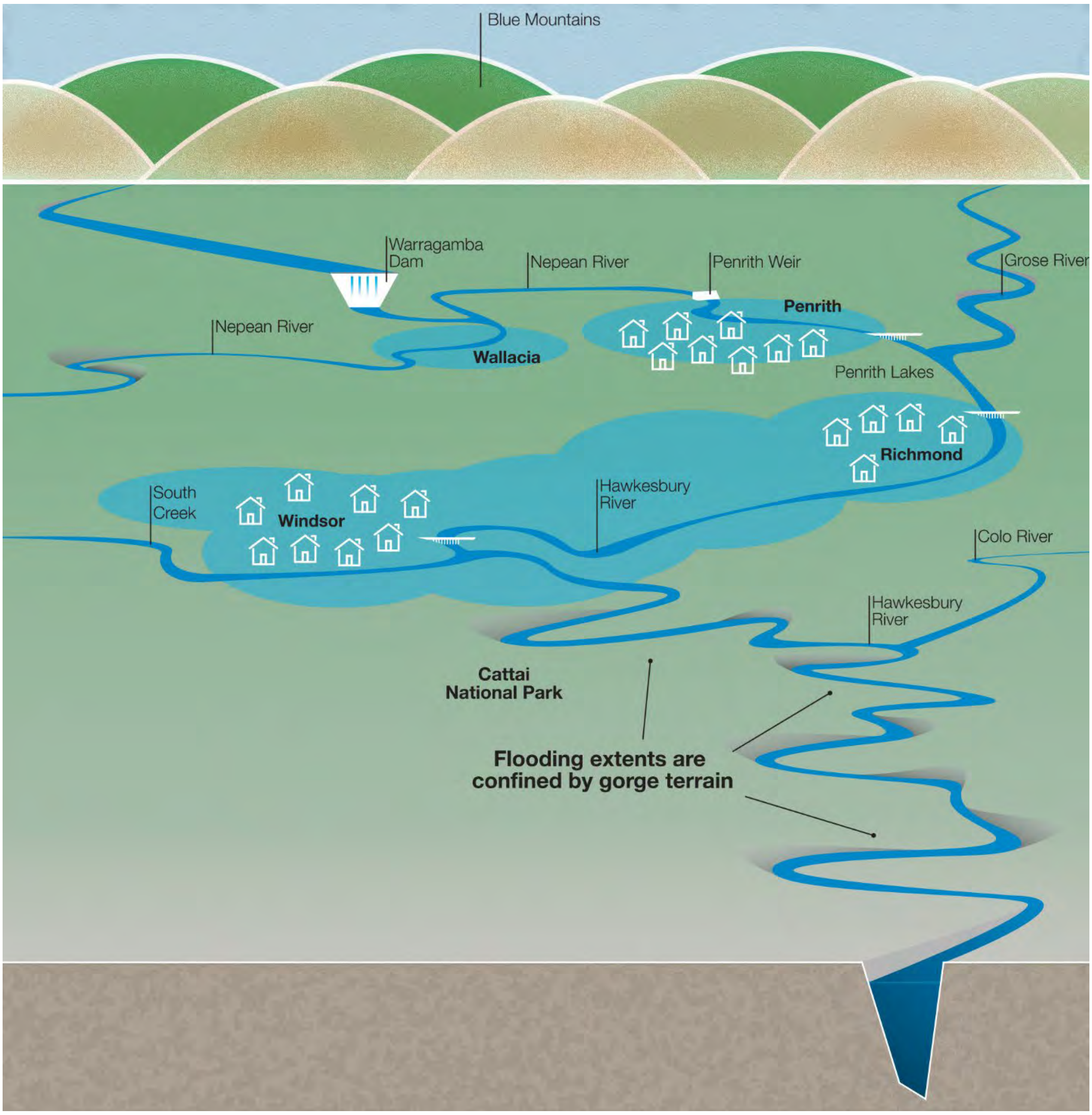


Figure 1: The 'bathtub' effect in the Hawkesbury-Nepean Valley

The Hawkesbury-Nepean Valley Flood Risk Management Strategy (the Flood Strategy) was launched in 2017. Its objective is to reduce the flood risk to life, property and social amenity from regional floods in the valley now and in the future. The vision is for valley communities and all levels of government to adapt to flooding by working together to:

- understand and be fully aware of flood risk
- act to reduce flood risk and manage growth
- be ready to respond and recover from flooding (Infrastructure NSW, 2017).

In March 2021, the Mid North Coast (particularly the Hastings, Camden Haven and Manning rivers) and the Hawkesbury-Nepean River were severely impacted by flooding. The Hawkesbury-Nepean floods were considered in the *March 2021 Flood Review* (Infrastructure NSW, 2021a).

In late February and early March 2022, record-breaking floods (based on the available history of river level records) occurred in the Northern Rivers inundating major towns, including Lismore (Wilsons River), Coraki and Woodburn (Richmond River), and Murwillumbah and Tumbulgum (Tweed River). The Wilsons River at Lismore peaked at a record high level of 14.4m, overtopping the riverbank levee with floodwaters inundating the city. This was over 2m above the previous record flood level (12.11m in 1954 and 1974), and was 2m above the 1 in 100 chance per year flood level (O'Kane & Fuller, 2022).

Major flooding (see glossary at Appendix A) was also experienced in the Hawkesbury-Nepean River in early March 2022. Unlike the Northern Regions region, these peaked well below the record flood level. For example, the peak flood level at Windsor was 13.8m, nearly 6m below the record of 19.7m set in June 1867, and 3.5m below the 1 in 100 chance per year flood level.

A renewed period of flooding around Greater Sydney happened in early April 2022, reaching the moderate category (see Appendix A) at Windsor.

Coastal areas of New South Wales from the Illawarra to the Mid North Coast were flooded in early July 2022. Major flooding was again experienced along the Hawkesbury-Nepean River, with higher flood peak levels than in March (13.9m at Windsor) – but still well below record levels.

Additional flooding happened in early October 2022, reaching the moderate category at Windsor. Severe flooding was experienced in inland New South Wales.

The town of Eugowra in the Central West was devastated by extreme flooding in November 2022.

This report focuses on the major March and July 2022 floods in the Hawkesbury-Nepean Valley. The causes and nature of the flooding and the riverbank erosion that resulted from the flooding are summarised. The results of modelling of various flood mitigation scenarios are presented, showing what difference these would have made to downstream flooding.

The study area is located between Bents Basin near Wallacia and Brooklyn, including communities around Penrith and Windsor. The focus in this review is on flooding of the Nepean and Hawkesbury rivers downstream of Warragamba Dam, and backwater flooding up tributaries associated with flooding of the main river, such as South and Eastern creeks.

2. March 2022 flood analysis

2.1 Climate drivers and soil moisture

In 2021, rainfall for much of New South Wales was above average (in the wettest 30% of years since 1900) (Figure 2).

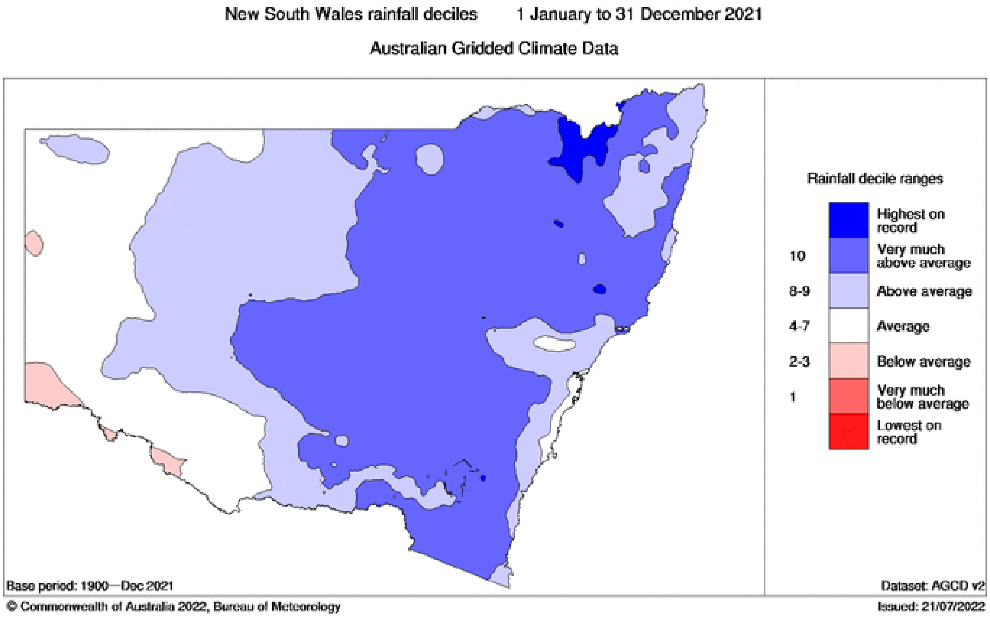


Figure 2: Annual rainfall deciles for New South Wales/ACT, 2021

Several climate drivers contributed to the development and maintenance of wetter conditions over 2021 and into summer 2021–2022. These included an active La Niña in the tropical Pacific Ocean, a persistent and strong positive phase of the Southern Annular Mode (SAM), warm oceans surrounding northern Australia, and several active phases of the Madden Julian Oscillation (MJO) (BoM, 2022).

On 21 February 2022, the daily root zone soil moisture in the Hawkesbury-Nepean catchment was assessed at about 50% (Figure 3). With consistent rain over the last week of February, this rose to 83% by 27 February. Thus, soils in the catchment were close to saturated when the flooding rains fell in early March, increasing runoff into creeks and rivers.

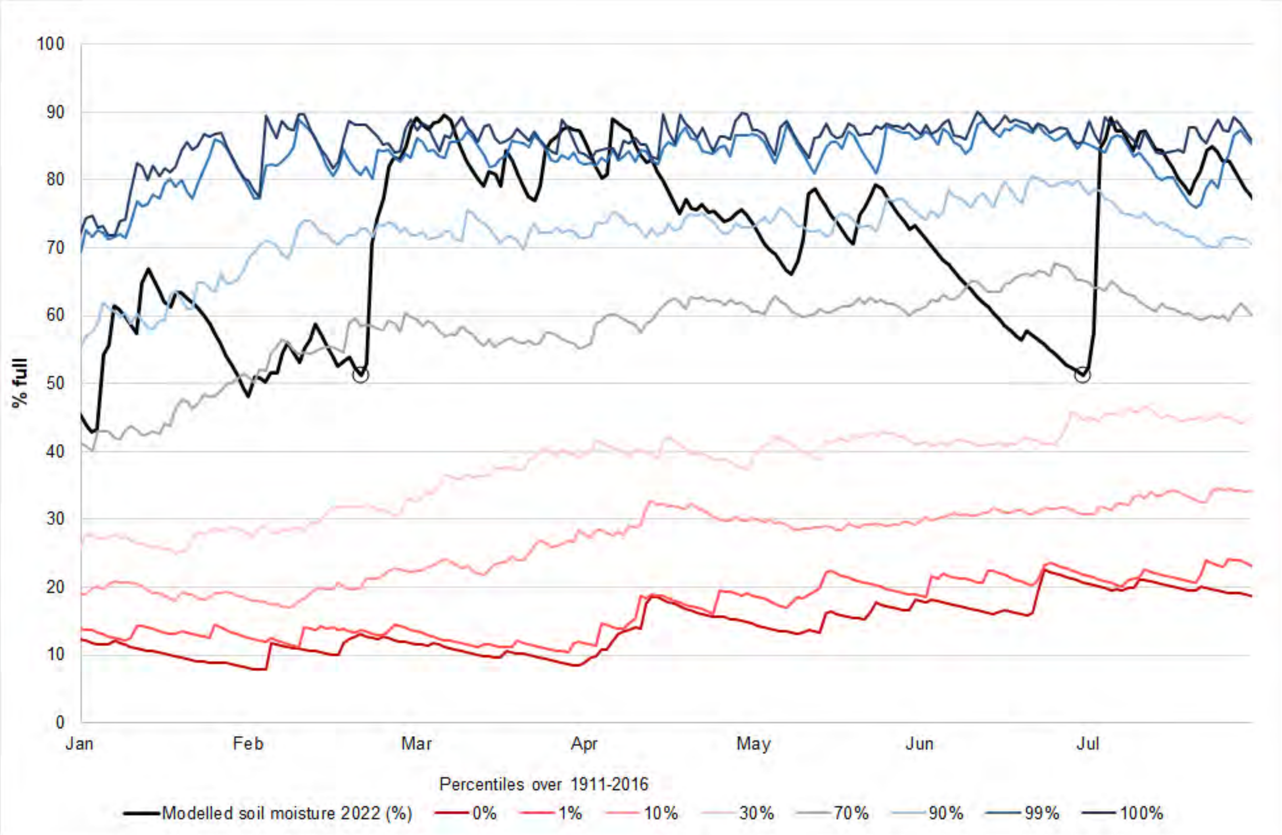


Figure 3: Daily root zone soil moisture, Hawkesbury-Nepean catchment, January-July 2022 compared to long-term percentiles

Data source: Bureau of Meteorology, Australian Landscape Water Balance

2.2 Weather

A low pressure system deepened from 2 March into an East Coast Low and moved towards the central New South Wales coast. This low dissipated on 5 March and rain temporarily eased, before a second low deepened from 6 March. This second low combined with a trough moving southward to deliver persistent southeasterly flow onto the New South Wales coast from the Mid North Coast to the South Coast, including the Hawkesbury-Nepean Valley (BoM, 2022). Weather charts depicting the two low pressure systems are provided in Figure 4.

This weather generated heavy and persistent rain over coastal catchments. Approximate rainfall totals for the Hawkesbury-Nepean catchment are presented in Figure 5, showing extensive areas receiving more than 500mm rain. The highest rainfall recorded for the event was at Robertson with 847mm (see Figure 6). The highest rainfall in a single day was recorded at Mittagong (Maguires Crossing) with 232mm.

Figure 7 shows that parts of New South Wales near the Hawkesbury-Nepean catchment received the highest rainfalls on record for the month of March, or more than 400% of the mean monthly rainfall.

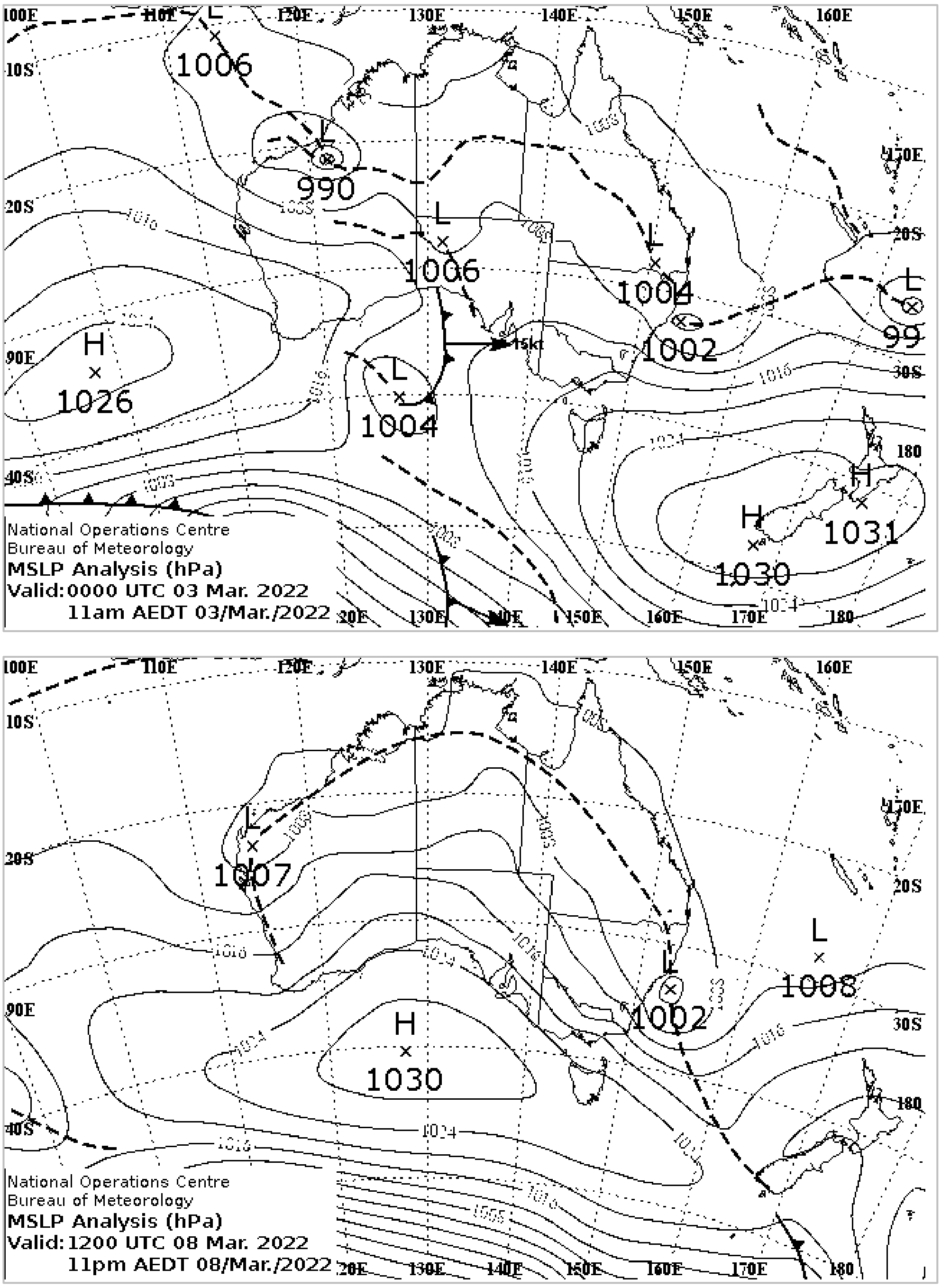


Figure 4: Weather charts, 3 and 8 March 2022

Source: Bureau of Meteorology

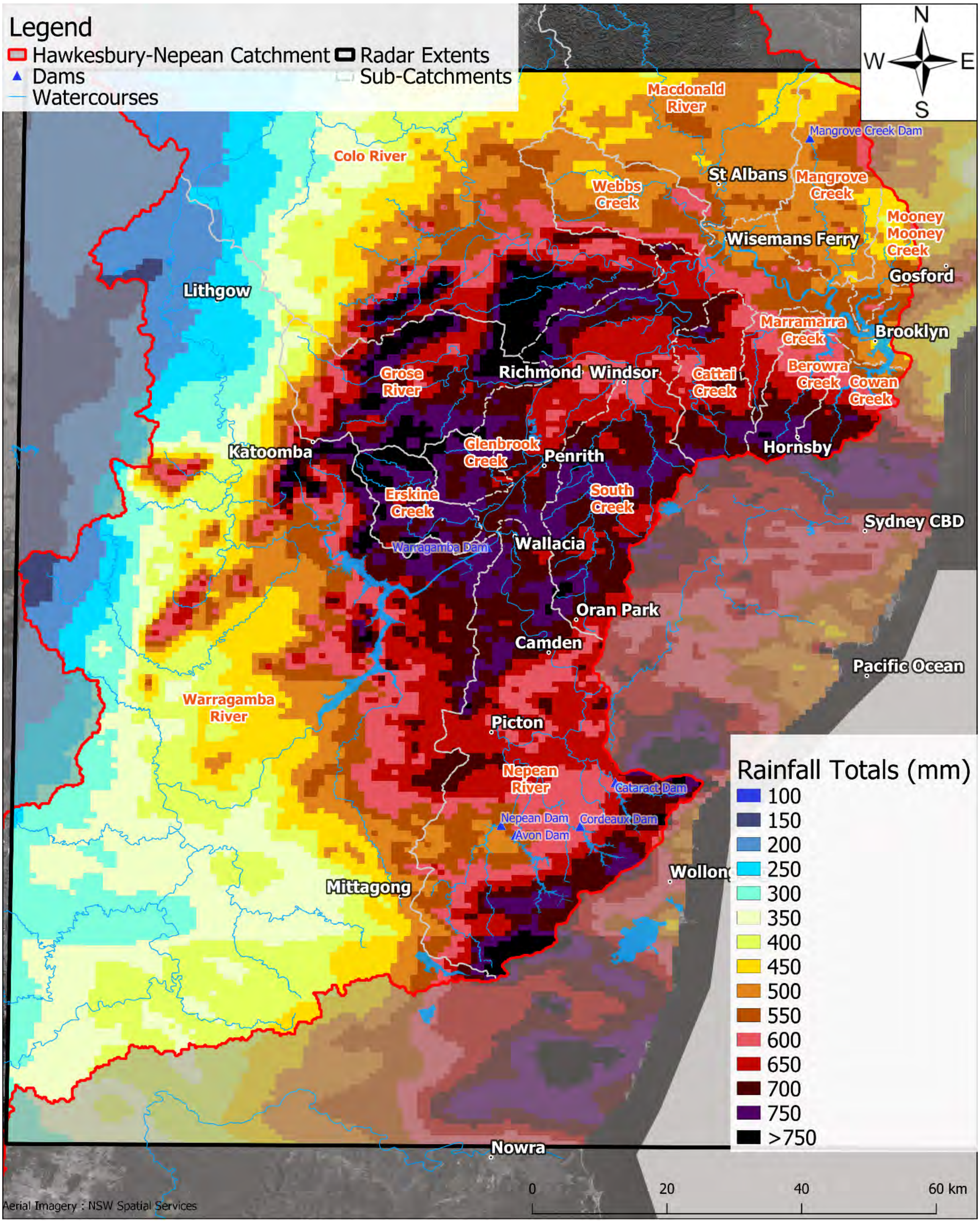


Figure 5: Radar rainfall totals for part of Hawkesbury-Nepean catchment, 25 February – 11 March 2022

Source: Rhelm for Infrastructure NSW, based on Bureau of Meteorology radar

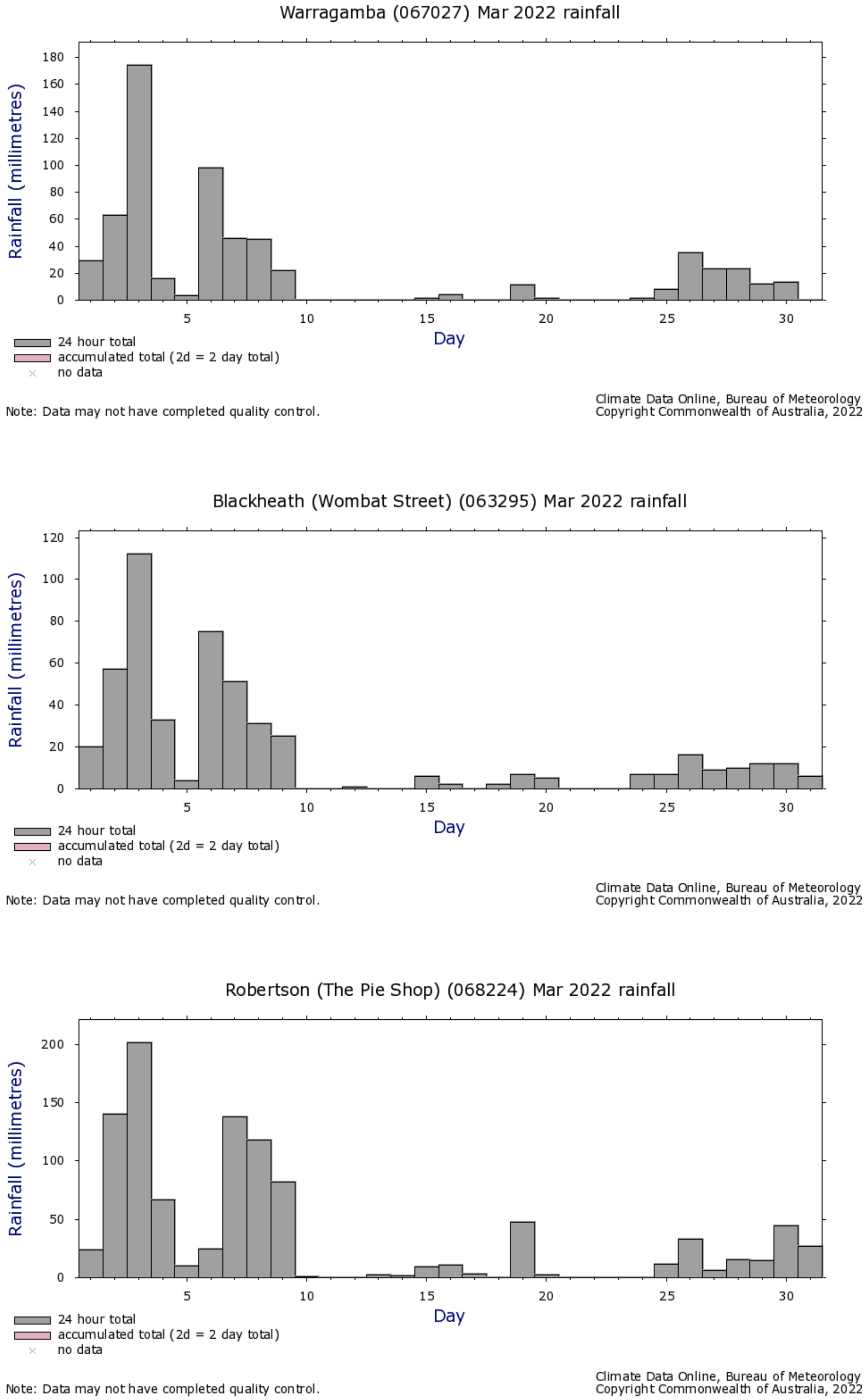
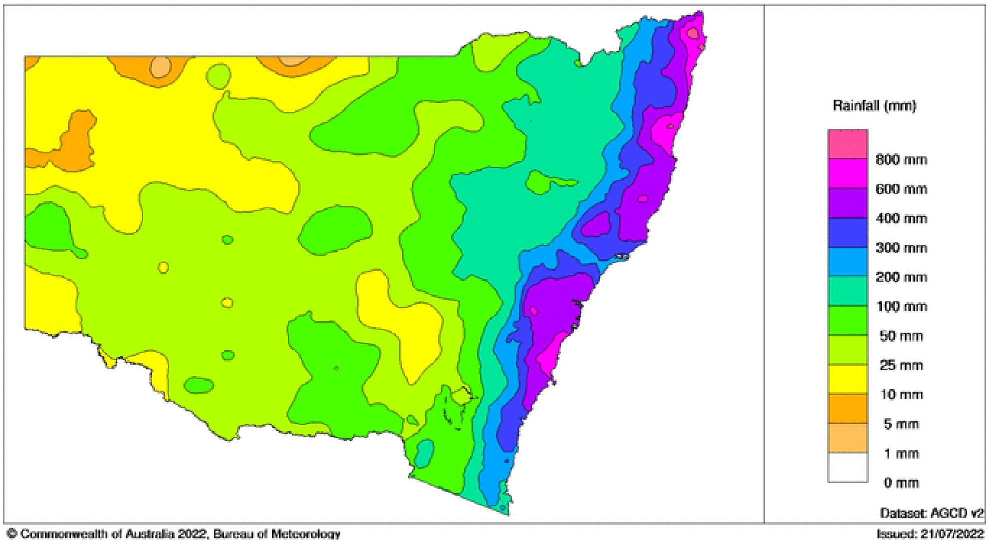


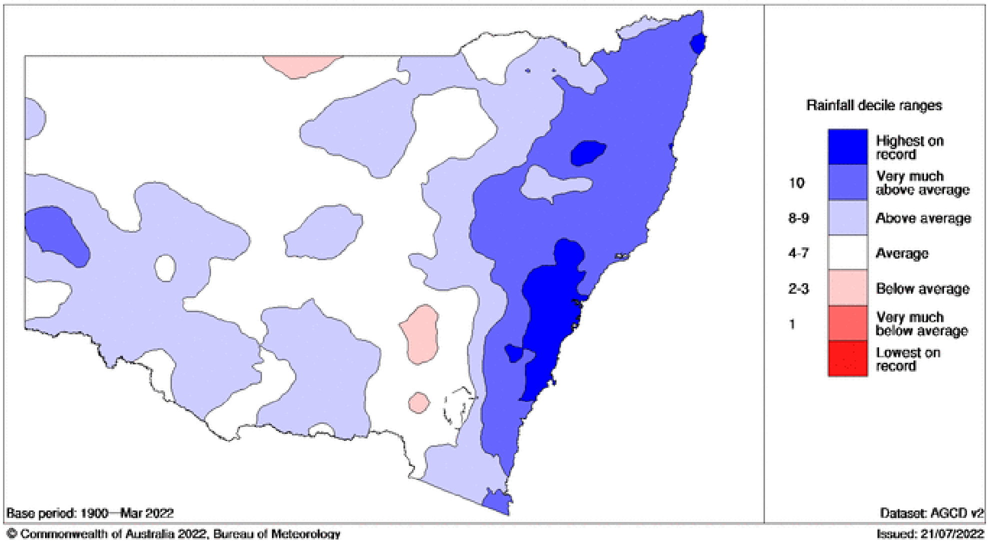
Figure 6: Daily (to 9am) rainfall at selected stations, March 2022

Source: Bureau of Meteorology

Monthly rainfall totals



Monthly rainfall deciles



Monthly rainfall percentages

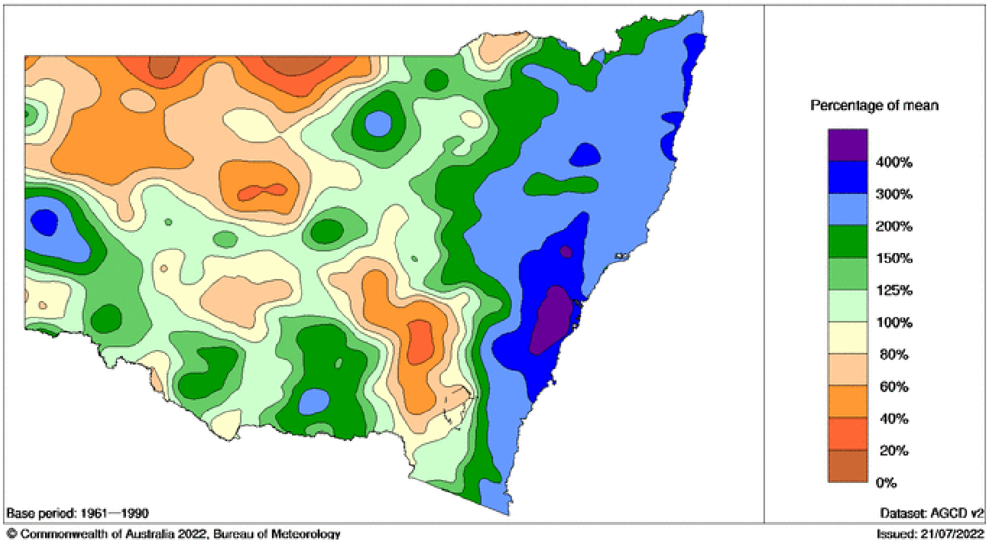


Figure 7: Monthly rainfall statistics for New South Wales/ACT, March 2022

Source: Bureau of Meteorology

2.3 Progress of the flood

Flood heights were recorded at automatic water level recording stations across the Hawkesbury-Nepean catchment. The locations of selected stations are shown in Appendix B. A flood hydrograph shows the rise and fall of a flood over time at a given station (gauge). Hydrographs for selected gauges in the Warragamba Dam and upper Nepean catchments are presented in Figure 8. Hydrographs for the 7 Hawkesbury-Nepean River flood warning gauges between Wallacia and Wisemans Ferry, plus a gauge downstream at Spencer, are presented in Figure 9.

Table 1 describes the height and time of the flood peak, as well as its flood classification, at all official gauges along the Hawkesbury-Nepean River between Wallacia and Spencer, as well as for key tributaries. The time taken for the flood peak to travel from one gauge to the next (travel time) is shown in Figure 10.

Flood classifications describe the *consequences* of flooding at locations around the flood warning gauges. The consequences are described in ‘minor’, ‘moderate’ and ‘major’ classes (see glossary at Appendix A) related to river heights (see Appendix C). It’s important to understand that because flood classifications are based on *impacts*, they are not aligned to the *likelihood* (chance) of floods. This is because a flood of the same chance may have different impacts at different locations. For example, it takes a rarer flood to reach a major level at Penrith than at Windsor, because the Nepean River at Penrith has a large channel that can convey high flows without causing the impacts that constitute a major flood.

The hydrographs in the upper Nepean and Warragamba Dam catchments show 2 distinct peaks, the first on 2/3 March and the second on 7/8 March (Figure 8). These 2 peaks reflect bursts of heavy rainfall. The first peaks were higher in the Coxs and Kowmung rivers, while the second peaks were higher in the Wollondilly and upper Nepean rivers – indicating different intensities of rain over different parts of the catchment over the course of the event. The second peak resulted in the higher level in Warragamba Dam and contributed to a very large volume of inflows to the dam.

Prior to the flood inflows, **Warragamba Dam** had been drawn down to about 0.7m below full supply level (FSL), corresponding to a capacity of 97.6% of full supply at the start of the event. The inflows resulted in FSL being reached at about 4am Wednesday 2 March. These were discharged through the dam’s gated spillway following the standard operating process during floods, known as the ‘H14 Protocol’.[1]

A hydrograph of the dam outflows was calculated from a log of the dam gate movements and is presented in Figure 11. The storage reached its highest level of 1.25m above FSL at 5-6am Tuesday 8 March (Table 1). In all, the storage was higher than 1m above FSL for about 1.2 days, and higher than FSL for over 21 days. It is calculated that the dam spilled 1500–1600 gigalitres (GL) (1 GL= 1 billion litres) (Figure 12), with a peak discharge of around 350 GL/day (Figure 11) (note, a rate >350 GL/day was sustained for only about 6 hours).

Figure 8 and Figure 9 show that the 2 peaks observed in the Warragamba outflow and upper Nepean hydrographs continued downstream, with the 2 peaks clearly observed along the Nepean and Hawkesbury rivers to at least Wisemans Ferry. The second peak was higher everywhere, though only marginally so at Penrith.

[1] https://www.youtube.com/watch?v=1VFyKsrXKPk, accessed 11 November 2022

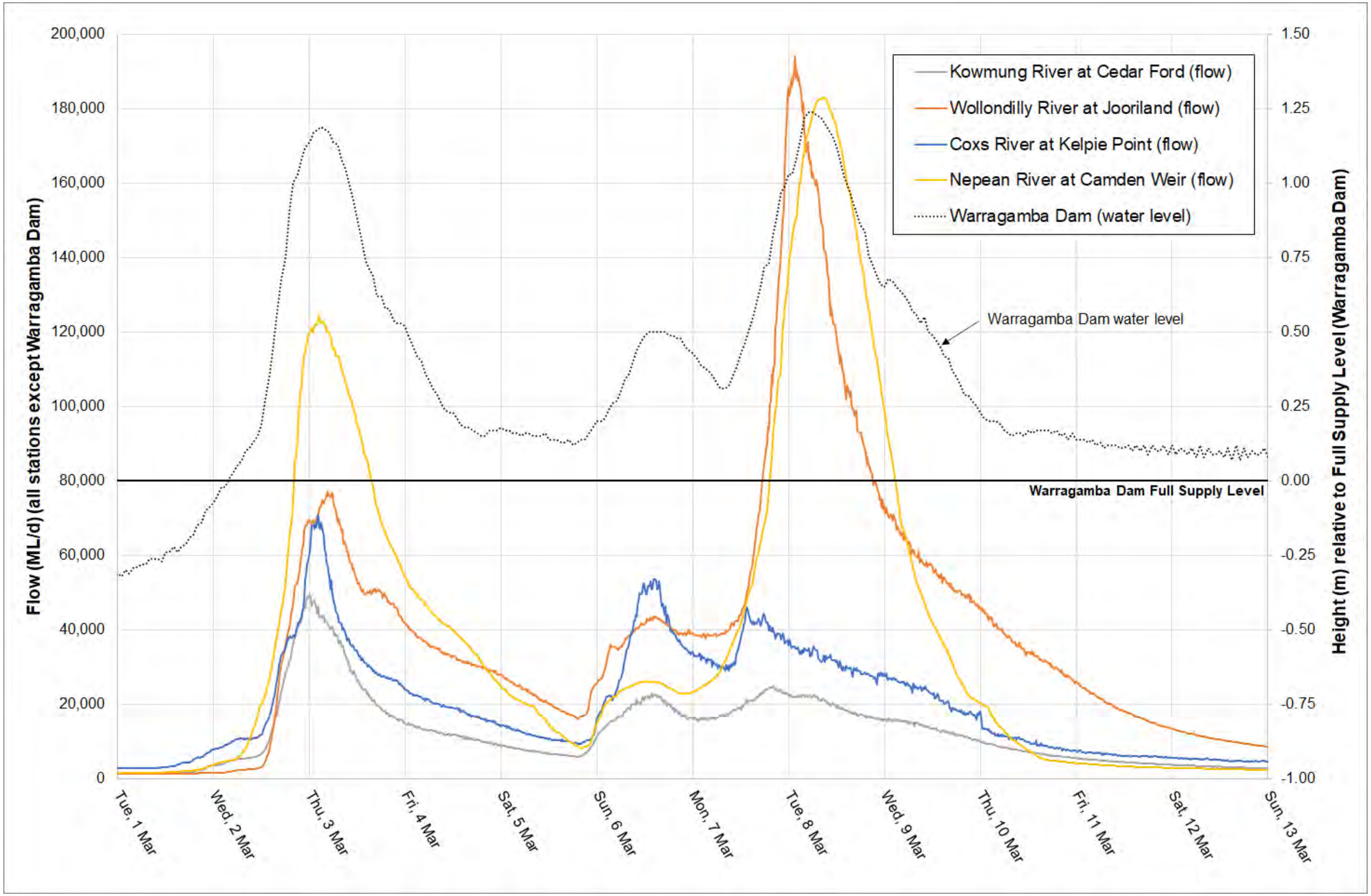


Figure 8: Flood hydrographs for selected river gauges in Warragamba and upper Nepean subcatchments, 1 to 12 March 2022

Data sources: WaterNSW, Rhelm (Camden Weir), WMAwater (dam level)

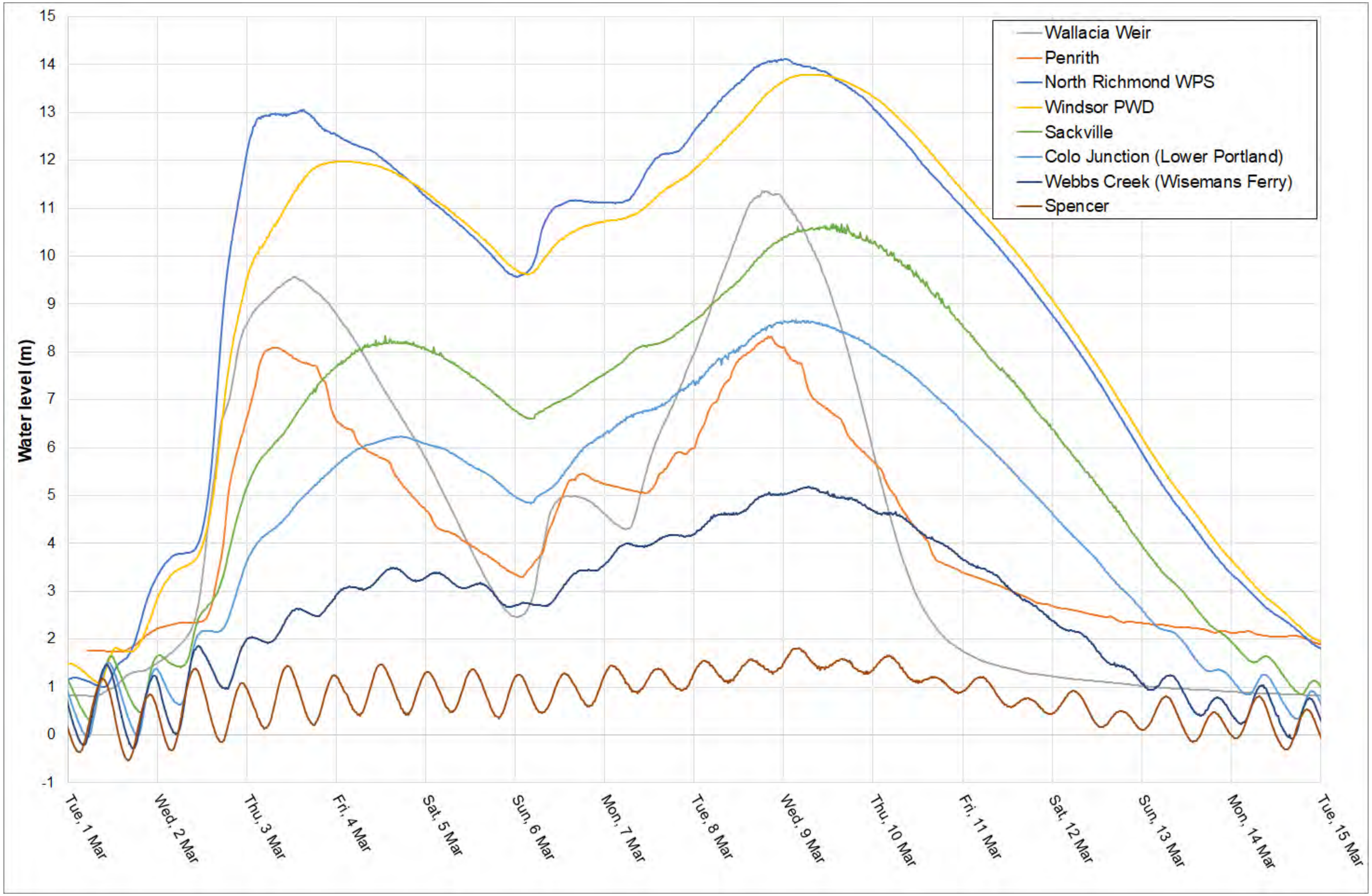


Figure 9: Flood hydrographs for selected Hawkesbury-Nepean gauges, March 2022

Data source: BoM

Table 1: Flood peak level, time, classification and likelihood, March 2022 Hawkesbury-Nepean flood

Gauge location	Gauge number	Flood peak level[1]		Flood peak date/time	Flood classification	Approximate likelihood (1 in X chance per year)[2]
		m local gauge	m AHD			
Hawkesbury-Nepean River						
Wallacia Weir	212202	11.35m	37.95m	Tue 8 Mar 7:30pm	Major	1 in 5-10
Penrith	212201	8.32m	22.46m	Tue 8 Mar 2:45pm	Moderate	1 in 5-10
Castlereagh	212404	15.90m	15.90m	Tue 8 Mar 6:30pm	-	
North Richmond WPS	212200	14.13m	14.66m	Wed 9 Mar 12:15am	Major	1 in 5-10
Freemans Reach	212410	-	13.91m [3]	-		
Windsor PWD	212426	13.80m	13.80m	Wed 9 Mar 6:30am-8:30am	Major	1 in 20
Ebenezer	212427	12.74m	12.74m	Wed 9 Mar 9:00am-12:00pm	-	
Sackville	212406	10.68m [4]	10.68m [4]	Wed 9 Mar 3:30pm	Major	TBC
Colo Junction (Lower Portland)	212407B	8.67m	8.67m	Wed 9 Mar 3:15am-5:15am	Major	TBC
Webbs Creek (Wisemans Ferry)	212408	5.18m	5.18m	Wed 9 Mar 6:30am	Major	TBC
Wisemans Ferry Wharf	212460	4.73m	4.73m	Wed 9 Mar 7:00am	-	
Gunderman Caravan Park	212429	3.13m	3.13m	Wed 9 Mar 4:45am	-	
Spencer	212431	1.81m	1.81m	Wed 9 Mar 4:00am	-	
Tributaries						
Warragamba Dam	212243	1.253m	117.973m	Tue 8 Mar 5:45am	-	
Grose River at Burralow [5]	212291	6.45m	-	Thu 3 Mar 2:30am	-	
South Creek at Great Western Hwy	212048	6.72m	24.89m	Thu 3 Mar 1:45am	-	
Colo River at Upper Colo	212290	16.65m	18.12m	Mon 7 Mar 11:45pm	Major	
Macdonald River at St Albans [6]	212228	8.33m	11.09m	Sun 6 Mar 5:30pm	-	

Notes:

[1] Flood peak data sourced from WaterNSW (Wallacia, Penrith, North Richmond, most tributaries), Manly Hydraulics Laboratory (DPE) (Castlereagh, Freemans Reach to Spencer), Bureau of Meteorology (Colo Junction, St Albans).

[2] Approximate likelihood is based on preliminary results from a 2-dimensional flood model being developed for Infrastructure NSW, and may be subject to change. Modelled flood levels at Penrith have been updated to take account of revegetation in and near the river in recent years. Likelihoods for the lower Hawkesbury are being reassessed.

[3] Freemans Reach hydrograph incomplete due to bank instability. Peak flood level estimated from debris survey.

[4] Sackville data shows spikes around peak. The actual peak may be up to ~0.1m lower.

[5] Burralow gauge was likely impacted by high tailwater levels from the Nepean River.

[6] St Albans gauge was likely impacted by high tailwater levels from the Hawkesbury River.

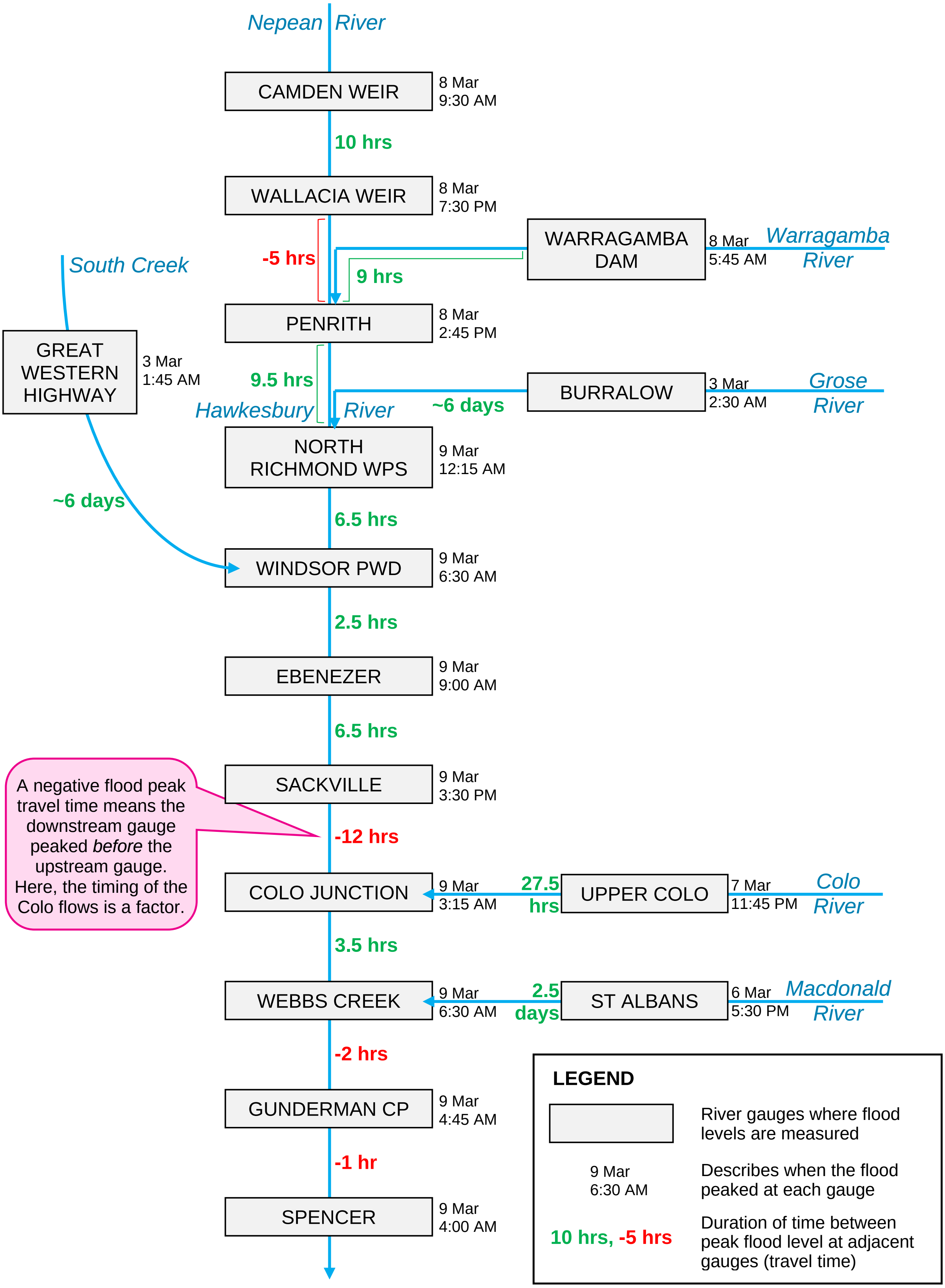


Figure 10: Flood peak travel times, March 2022 Hawkesbury-Nepean flood

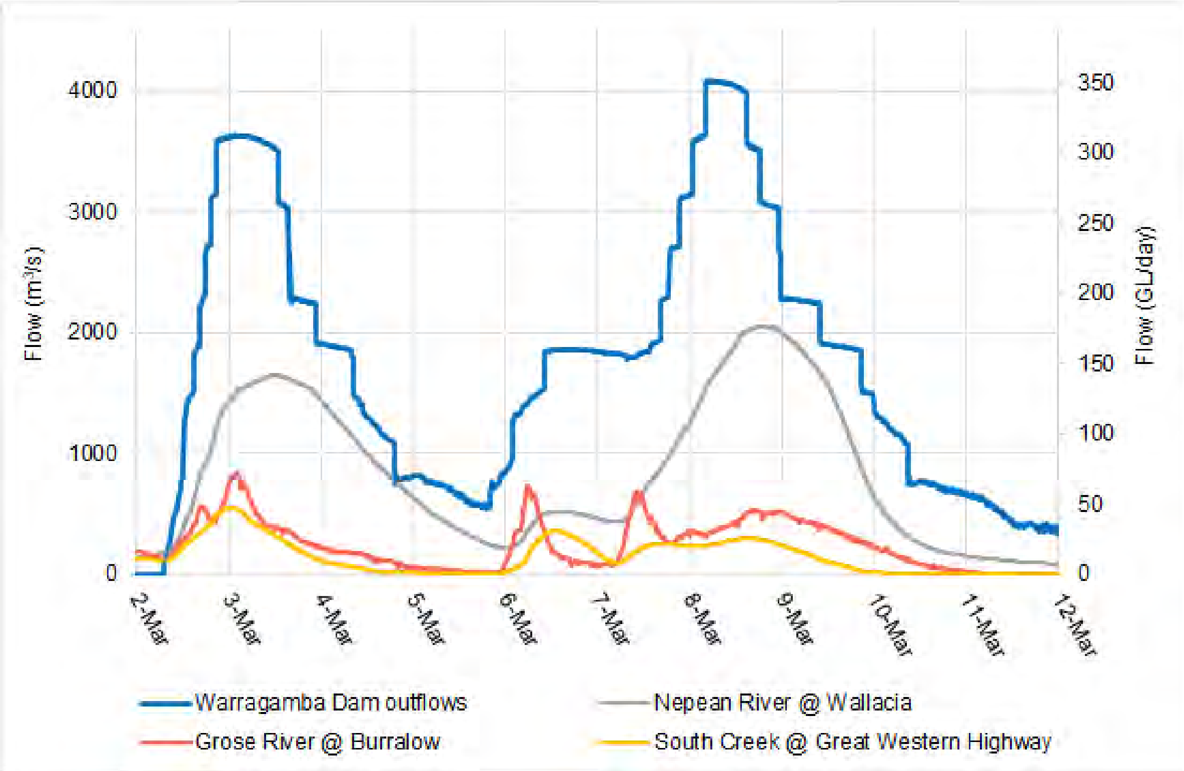


Figure 11: Flow hydrographs for key inflows to Windsor, March 2022 flood

Source: Rhelm for Infrastructure NSW

Note: Grose River flows are derived from the gauged heights, which on 8-9 March were likely impacted by high tailwater levels from the Nepean River. The actual flows generated from the Grose catchment were likely less than shown in this period.

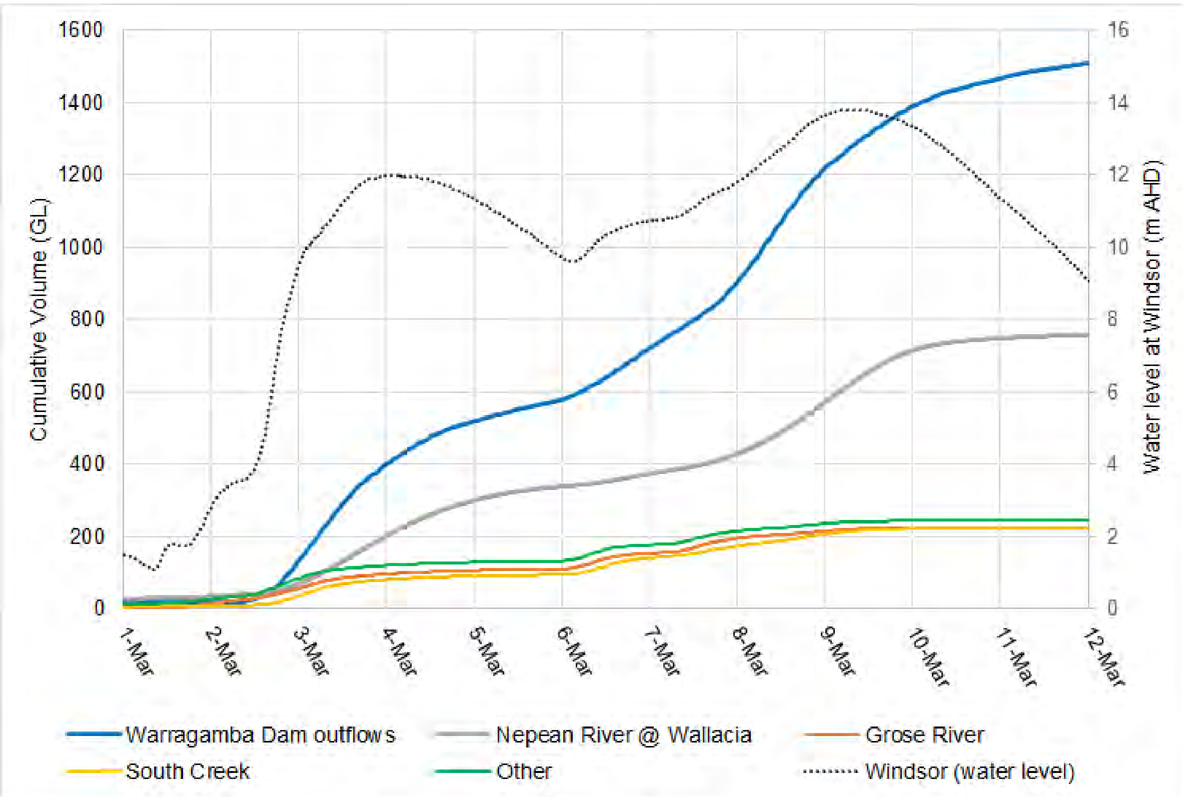


Figure 12: Cumulative volume by subcatchment to Windsor, March 2022 flood

Data source: Rhelm for Infrastructure NSW

At **Wallacia** Weir, the flood peaked first at 1pm 3 March at 9.56m in the moderate range, then again at 7:30pm 8 March at 11.35m in the major range (Figure 9, Table 1). Interestingly, these peaks occurred *after* the peak at Penrith – the main second peak by 5 hours (Figure 10). Silverdale Road Bridge at Blaxlands Crossing was flooded to a depth of over 4m at the peak (Figure 13).[2]

At **Penrith**, the flood peaked first at 2-3am 3 March at 8.09m in the moderate range. The second peak at 2:45pm 8 March reached 8.32m in the moderate range (Figure 9, Table 1). Floodwaters were generally confined to the river channel (Figure 13).

At **North Richmond**, the arrival of the floodwaters from Warragamba saw the Hawkesbury River rise steeply on 2 March, before initially peaking with major flooding at 13.06m at 3:15pm 3 March (Figure 9). The second peak reached 14.13m at 12:15am 9 March (Table 1). North Richmond Bridge was flooded to a depth approaching 6m at the peak.[3]

At **Windsor**, the first peak reached 11.99m in the moderate range at 1:30am 4 March, while the second peak reached 13.80m in the major range at 6:30-8:30am 9 March (Figure 9, Table 1). Windsor Bridge was flooded to a maximum depth of about 3.8m (Figure 13).

The high volume of this flood (Figure 12) translated to a long duration of flooding. The river at Windsor was above 10m AHD for 8 days, noting that 10m AHD approximately corresponds to the height of the riverbanks and the lowest deck level of (new) Windsor Bridge. Comparative durations are presented in Table 2, showing how distinctive the March 2022 flood was in its duration of overbank flooding.

Extensive flooding was observed in the Richmond/Windsor floodplain as the 'bathtub' filled.

Table 2: Duration of flooding above certain levels at Windsor, selected historical floods

Event	Peak height (m AHD)	Duration (days) above level (m AHD)		
		>8m	>10m	>12.2m (major)
1988 May	12.80	n/a	3.0	1.1
1990 Aug	13.5	4.6	3.6	1.9
2021 Mar	12.93	5.8	4.8	2.9
2022 Mar	13.80	9.6	8.0	2.4
2022 Jul	13.93	5.4	4.3	2.6

Legend:

Longest duration in category

[2] The bridge deck level is about 8.65m on the local bridge gauge. Wallacia RFS estimated that the flood reached a height of 12.8-12.9m on the gauge. Given a gauge zero of 26.44m AHD, this would translate to a peak level of 39.24-39.34m AHD at the bridge, which is located upstream of Wallacia Weir gauge. The March flood peak level at the bridge was subsequently surveyed at 39.33m AHD (Public Works Advisory for Infrastructure NSW).

[3] North Richmond Bridge deck level is 8.8m AHD (NSW SES, 2020). The flood was modelled to have peaked at 14.54m AHD at the bridge (Rhelm/CSS for Infrastructure NSW), which is located downstream of North Richmond WPS gauge.

Backwater flooding up Rickabys Creek is modelled to have extended beyond Kenmare Road in Londonderry, up South Creek to beyond Ninth Avenue in Llandilo, and up Eastern Creek to about Grange Avenue in Schofields (see Figure 13). Similarly, backwater flooding is modelled to have extended a considerable distance up Killarney Chain of Ponds into Vineyard (to about Chapman Road).

Downstream at **Sackville**, the first peak reached 8.33m in the moderate range at 1pm 4 March, while the second peak reached 10.68m in the major range at 3:30pm 9 March (Figure 9, Table 1). In this part of the river, tributary valleys including Little Cattai Creek, Currency Creek and Roberts Creek function as natural storages for floodwaters. A sense of this local storage is seen in Figure 13. Sackville Ferry ceased operating.

At **Colo Junction**, the first peak reached 6.23m in the moderate range at 4:15pm 4 March, while the second peak reached 8.67m in the major range at 3:15am 9 March (Figure 9, Table 1). This gauge is located where the Colo River joins the Hawkesbury River at Lower Portland. The timing of the main peak, 12 hours before Sackville, likely reflects the earlier peak on the Colo River (Figure 10; Figure 14).

At the Webbs Creek Ferry gauge at **Wisemans Ferry**, the first peak reached 3.49m (below moderate) at 2:30pm 4 March, while the second peak reached 5.18m in the major range at 6:30am 9 March (Figure 9, Table 1). Wisemans Ferry Bowling Club was flooded to a depth of about 0.1m above floor. Webbs Creek Ferry and Wisemans Ferry services ceased operating. A selection of images is shown in Figure 13.

The earlier peak at Spencer downstream (Table 1; Figure 10) is attributed to the timing of the high tide there.

Figure 13: Images of the March 2022 Hawkesbury-Nepean flood

Warragamba Dam spilling, 7/3/22

Photo by Adam Hollingworth courtesy of Infrastructure NSW

View south across Wallacia, with Nepean River on right, 11:55am, 8/3/22 (Wallacia Weir gauge 10.56m)

Photo by Adam Hollingworth courtesy of Infrastructure NSW

View west across Silverdale Road Bridge (Blaxlands Crossing), Wallacia, 4:55pm, 8/3/22 (Wallacia Weir gauge 11.20m - starting to peak)

Photo by Adam Hollingworth courtesy of Infrastructure NSW

View across Nepean River towards Regentville, 10:45am, 8/3/22 (Penrith gauge 8.14m)

Photo by Adam Hollingworth courtesy of Infrastructure NSW

View downstream Nepean River cross Yandhai and Victoria bridges, 3:15pm, 3/3/22 (Penrith gauge 7.43m)

Photo by Adam Hollingworth courtesy of Infrastructure NSW

View west along closed Springwood Road on approach to Yarramundi Bridge, 7/3/22

Photo by Adam Hollingworth courtesy of Infrastructure NSW

View northwest across Windsor Bridge, 10:30am, 9/3/22 (Windsor gauge 13.78m - near peak)

Photo by Adam Hollingworth courtesy of Infrastructure NSW

View northwest along Richmond Road at South Creek, 11:45am, 9/3/22 (Windsor gauge 13.77m - near peak)

Photo by Adam Hollingworth courtesy of Infrastructure NSW

View north across Garfield Road West, Riverstone, 12:30pm, 9/3/22 (Windsor gauge 13.76m - near peak)

Photo by Adam Hollingworth courtesy of Infrastructure NSW

View northwest across Hawkesbury River at Sackville towards Bradleys Swamp, 4:30pm, 9/3/22 (Sackville gauge 10.54m)

Photo by Top Notch courtesy of Infrastructure NSW

Webbs Creek Ferry on Wisemans Ferry side, 10:40am, 9/3/22 (Webbs Creek gauge 5.07m – near peak)

Photo by Rhys Thomson courtesy of Infrastructure NSW

View north across Wisemans Ferry, 2pm, 9/3/22 (Webbs Creek gauge 4.96m)

Photo by Top Notch courtesy of Infrastructure NSW

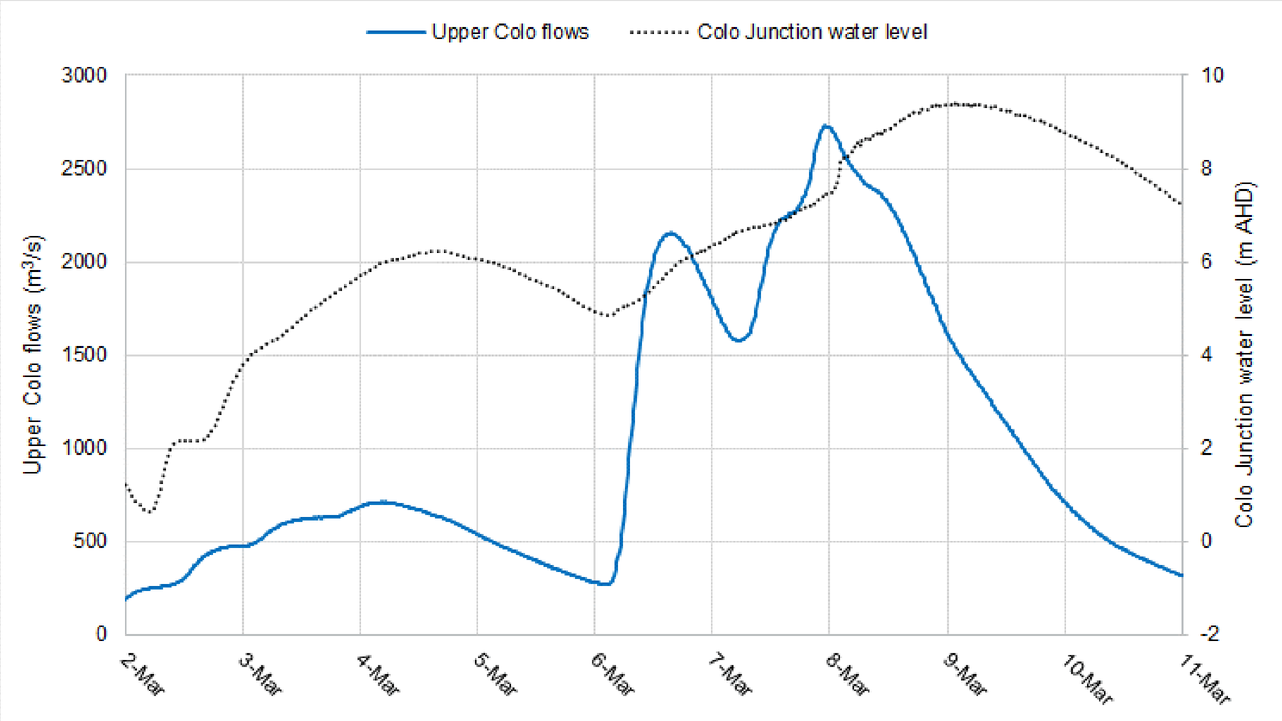


Figure 14: Timing of Colo and Hawkesbury rivers flows, March 2022 flood

Data source: Upper Colo flows modelled by Rhelm/CSS; Colo Junction data from Department of Planning and Environment

3. July 2022 flood analysis

3.1 Climate drivers and soil moisture

In early July, El Niño–Southern Oscillation (ENSO) indicators were mostly at neutral levels, though the Bureau of Meteorology's ENSO Outlook status was at La Niña Watch, indicating a higher-than-normal likelihood of La Niña forming later in 2022.[4] (The Bureau subsequently recognised an established La Niña in September 2022).

On 30 June 2022, the daily root zone soil moisture in the Hawkesbury-Nepean catchment was assessed at 51% (Figure 3). With heavy rain, this increased to 85% by 3 July.

3.2 Weather

An East Coast Low developed off the New South Wales coast on 2 July (see Figure 15). This directed moist winds across the Hawkesbury-Nepean catchment. Somewhat unusually when compared to historical Hawkesbury-Nepean storms, the centre of the rainfall shifted from the south to the north of the catchment, such that the Colo River peaked noticeably later than Nepean River at Penrith.

Approximate rainfall totals for the Hawkesbury-Nepean catchment are presented in Figure 16, showing a few areas such as the Upper Nepean dams receiving particularly heavy rain. The highest rainfall recorded for the event was at Darkes Forest with 755mm (see Figure 17). The highest rainfall in a single day was recorded at Cordeaux Quarters with 311mm.

[4] http://www.bom.gov.au/climate/enso/wrap-up/archive/20220705.archive.shtml Accessed 18 November 2022.

Figure 18 shows that parts of New South Wales near the Hawkesbury-Nepean catchment received the highest rainfalls on record for the month of July, or more than 400% of the mean monthly rainfall.

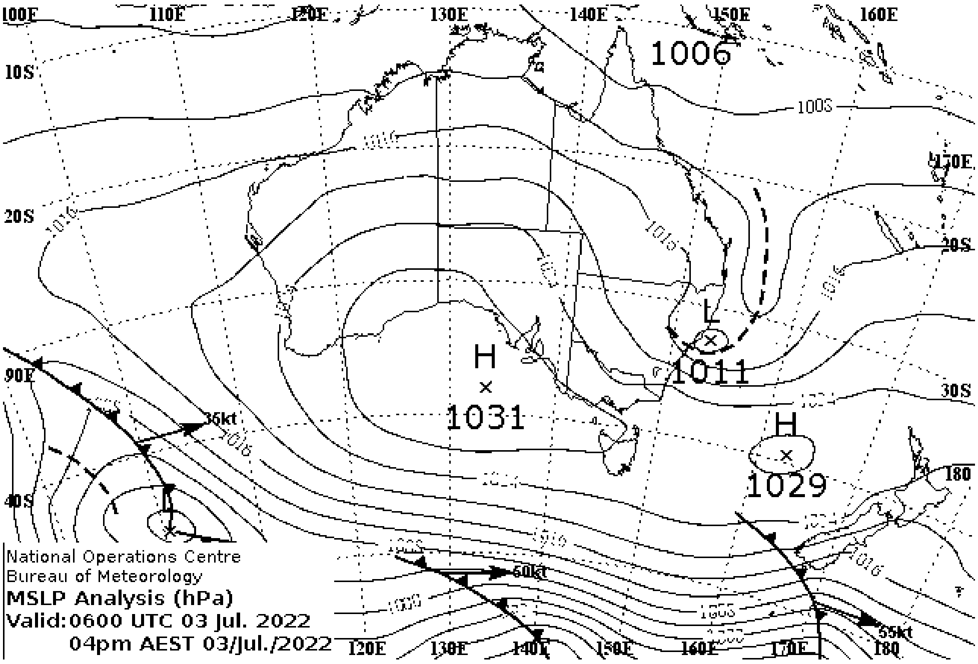


Figure 15: Weather chart, 3 July 2022

Source: Bureau of Meteorology

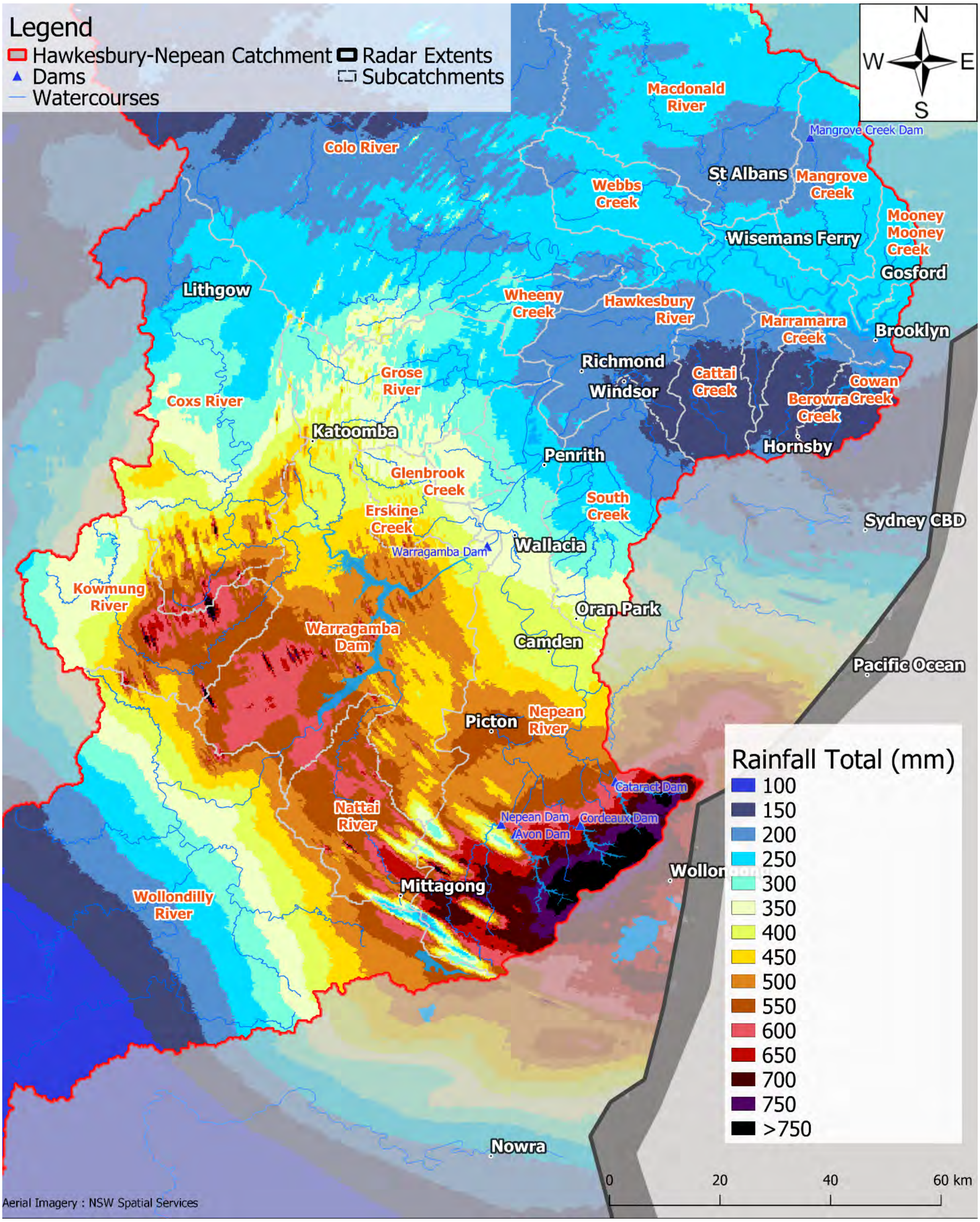


Figure 16: Radar rainfall totals for part of Hawkesbury-Nepean catchment, 1 – 7 July 2022

Source: Rhelm for Infrastructure NSW, based on Weather Chaser radar

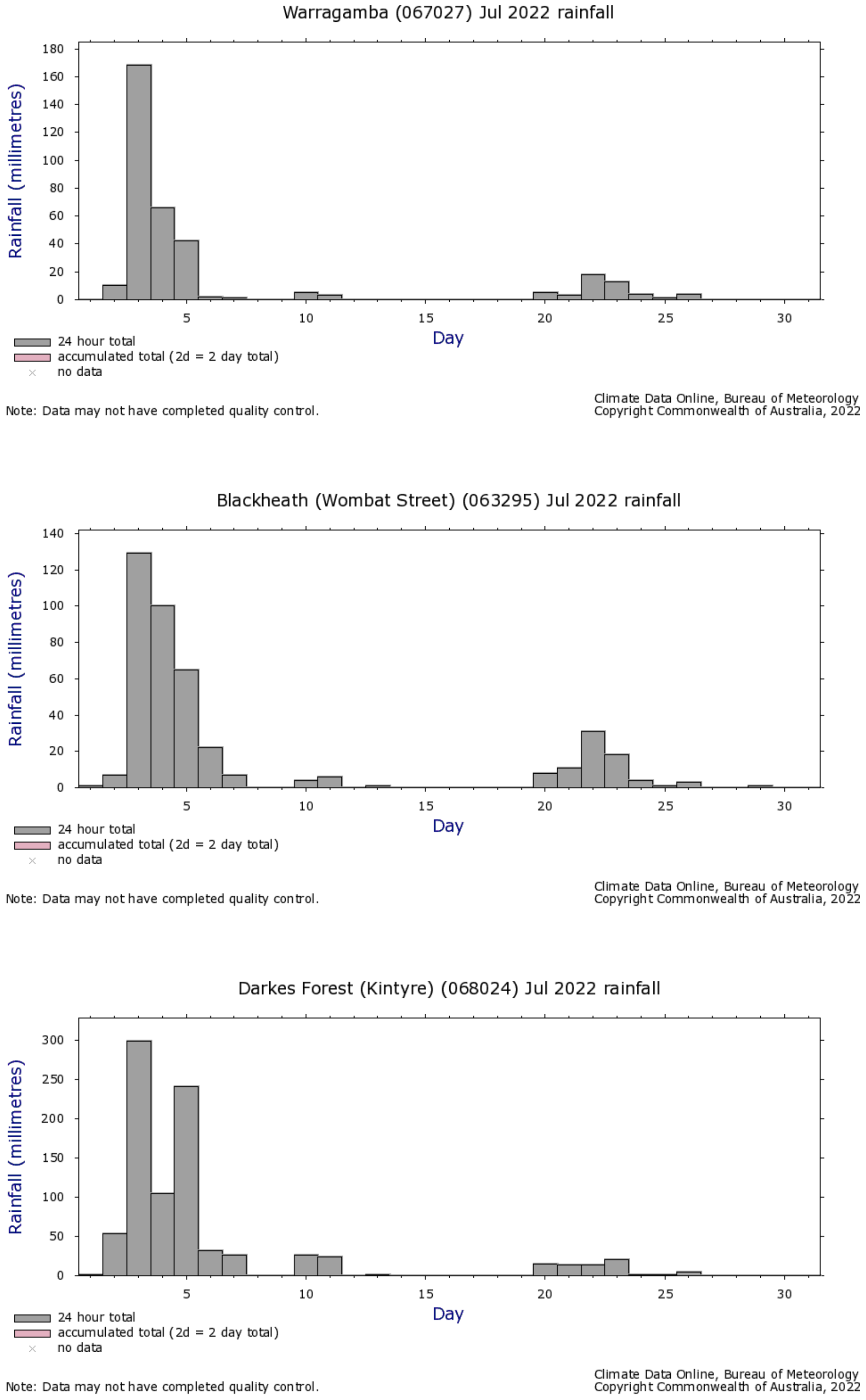
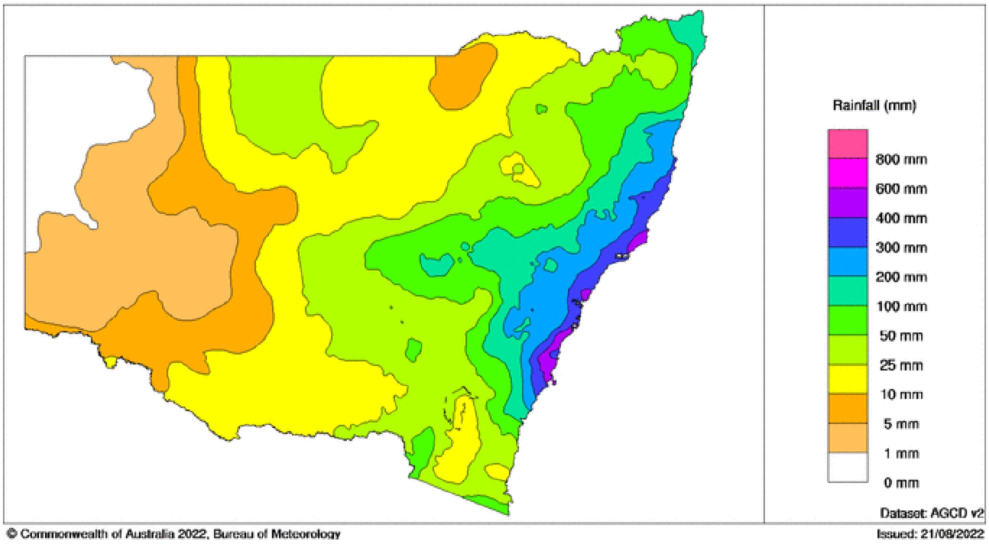
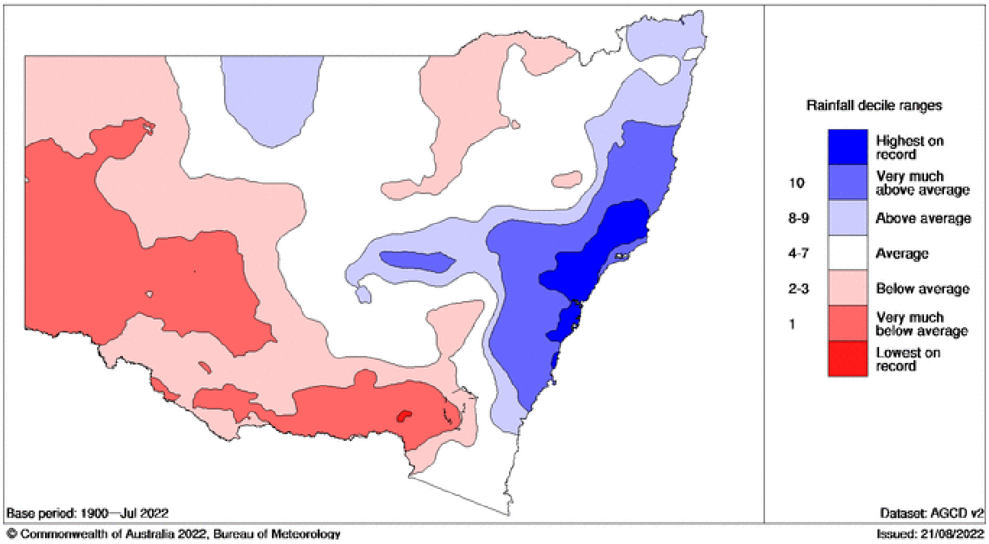


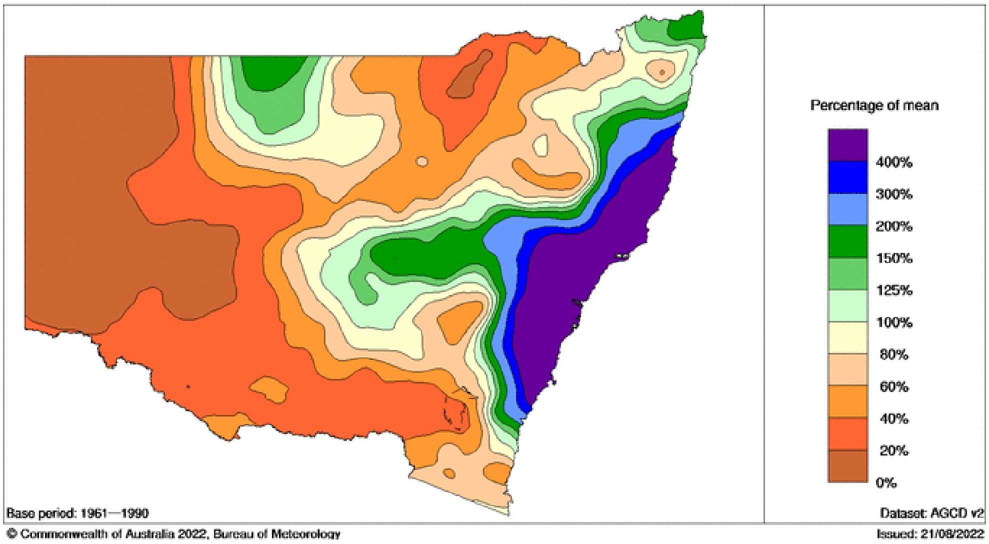
Figure 17: Daily (to 9am) rainfall at selected stations, July 2022



Monthly rainfall totals



Monthly rainfall deciles



Monthly rainfall percentages

Figure 18: Monthly rainfall statistics for New South Wales/ACT, July 2022

Source: Bureau of Meteorology

3.3 Progress of the flood

Flood heights were recorded at automatic water level recording stations across the Hawkesbury-Nepean catchment. Hydrographs for selected gauges in the Warragamba Dam and upper Nepean catchments are presented in Figure 19. Hydrographs for the 7 Hawkesbury-Nepean River flood warning gauges between Wallacia and Wisemans Ferry, plus a gauge downstream at Spencer, are presented in Figure 20.

Table 3 describes the height and time of the flood peak, as well as its flood classification, at all official gauges along the Hawkesbury-Nepean River between Wallacia and Spencer, as well as for key tributaries. The time taken for the flood peak to travel from one gauge to the next (travel time) is shown in Figure 21.

Prior to the flood inflows, **Warragamba Dam** had been drawn down to about 0.8-0.9m below full supply level (FSL), corresponding to a capacity of about 97% of full supply at the start of the event. The inflows resulted in FSL being reached at about 2am Sunday 3 July. These were discharged through the dam's gated spillway following the standard operating process during floods, known as the 'H14 Protocol'.

A hydrograph of the dam outflows was calculated from a log of the dam gate movements and is presented in Figure 22. The storage reached its highest level of 1.645m above FSL[5] at 4pm Sunday 3 July (Table 3). In all, the storage was higher than 1m above FSL for about 0.9 days, and higher than FSL for over about a month. It is calculated that the dam spilled about 950 gigalitres (GL) (1 GL= 1 billion litres) (Figure 23), with a peak discharge of 440-450 GL/day (Figure 22) (note, a rate >430 GL/day was sustained for about 13 hours).

At **Wallacia** Weir, the flood peaked at 13.85m in the major range, at 2:45am 4 July (Figure 20, Table 3). This peak happened around 13 hours after the peak at Camden and 11 hours after the peak at Warragamba Dam (Table 3, Figure 21). Silverdale Road Bridge at Blaxlands Crossing was flooded to a depth of nearly 6m at the peak.[6] The nearby caravan park was flooded (see Figure 24). Because Greendale Road at Duncans Creek, Mulgoa Road at Jerrys Creek, and the primary Park Road evacuation route at Jerrys Creek were all cut, Wallacia was for a time completely isolated by public road.

At **Penrith**, the flood peaked at 9.48m in the moderate range, at 1:30am 4 July, around 10 hours after the peak outflow from Warragamba Dam (Figure 20, Table 3, Figure 21). The floodwater was high enough to inundate River Road in Emu Plains (see Figure 24).

At **North Richmond**, the flood peaked at 14.32m in the major range, at 3am 4 July (Figure 20, Table 3). North Richmond Bridge was flooded to a depth of about 6.5m at the peak.[7]

At **Windsor**, the flood peaked at 13.93m in the major range, at 12pm 5 July (Figure 20, Table 3). The rate of rise is presented in Figure 25. The July flood rose at a particularly rapid rate while the flow was within the channel (maximum 1.16m/hr at Windsor), but once the riverbanks were exceeded, the rate of rise slowed to between about 0.2m/hr and 0m/hr for 44 hours as the river rose to peak. The 33-hour delay after the North Richmond peak (Figure 21) reflects the time taken to fill the Windsor 'bathtub'. Windsor Bridge was flooded to a maximum depth of about 3.9m (see Figure 24).

Extensive flooding was observed in the Richmond/Windsor floodplain as the 'bathtub' filled (Figure 26). Parts of the suburb of McGraths Hill were flooded, as well as some houses in Windsor and South Windsor.

Backwater flooding up Rickabys Creek is modelled to have extended towards Studley Street in Londonderry, up South Creek to beyond Ninth Avenue in Llandilo, and up Eastern Creek to about Grange Avenue in Schofields. Similarly, backwater flooding is modelled to have extended a considerable distance up Killarney Chain of Ponds into Vineyard (to about Chapman Road).

[5] A peak of 1.645m above FSL was recorded at Hideaway Bay, whereas the system logs (SCADA) returned a peak of 1.660m above FSL.

[6] The bridge deck level is about 8.65m on the local bridge gauge. Wallacia RFS estimated that the flood reached a height of around 14.5m on the gauge at about 3am Monday 4 July. Given a gauge zero of 26.44m AHD, this would translate to a peak level of 40.94m AHD at the bridge, which is located upstream of Wallacia Weir gauge. The July flood peak level at the southern end of the caravan park near the bridge was 40.81m AHD (Public Works Advisory for Infrastructure NSW).

[7] North Richmond Bridge deck level is 8.8m AHD (NSW SES, 2020). The flood was modelled to have peaked at 15.25m AHD at the bridge (Rhelm/CSS for Infrastructure NSW), which is located downstream of North Richmond WPS gauge.

Downstream at **Sackville**, the flood peaked at 10.87m in the major range, at 8pm 5 July, 8 hours after the peak at Windsor (Figure 20, Table 3, Figure 21). Sackville Ferry ceased operating.

At **Colo Junction**, the flood peaked at 8.99m in the major range, at 10:45pm 5 July (Figure 20, Table 3). This gauge is located where the Colo River joins the Hawkesbury River at Lower Portland. Flood heights here are sensitive to the size and timing of flows from the Colo as well as the typically dominant Hawkesbury. In this flood, the Colo at Upper Colo peaked close to the Hawkesbury peak at Colo Junction (Figure 21, Figure 27), adding to the flow at Lower Portland. Analysis of available historical flood data indicates that this is relatively unusual, with Colo flows typically peaking well before Hawkesbury flows.

At the Webbs Creek Ferry gauge at **Wisemans Ferry**, the flood peaked at 5.78m in the major range, at 6:15am 6 July (Figure 20, Table 3). Wisemans Ferry Bowling Club was flooded about 0.4m above floor (see Figure 24). Backwater flooding was observed a considerable distance up Webbs Creek (Figure 24). Lower Macdonald was heavily impacted (Figure 24). Webbs Creek Ferry and Wisemans Ferry services ceased operating.

The earlier peak at Spencer downstream (Table 3, Figure 21) is attributed to the timing of the high tide there.

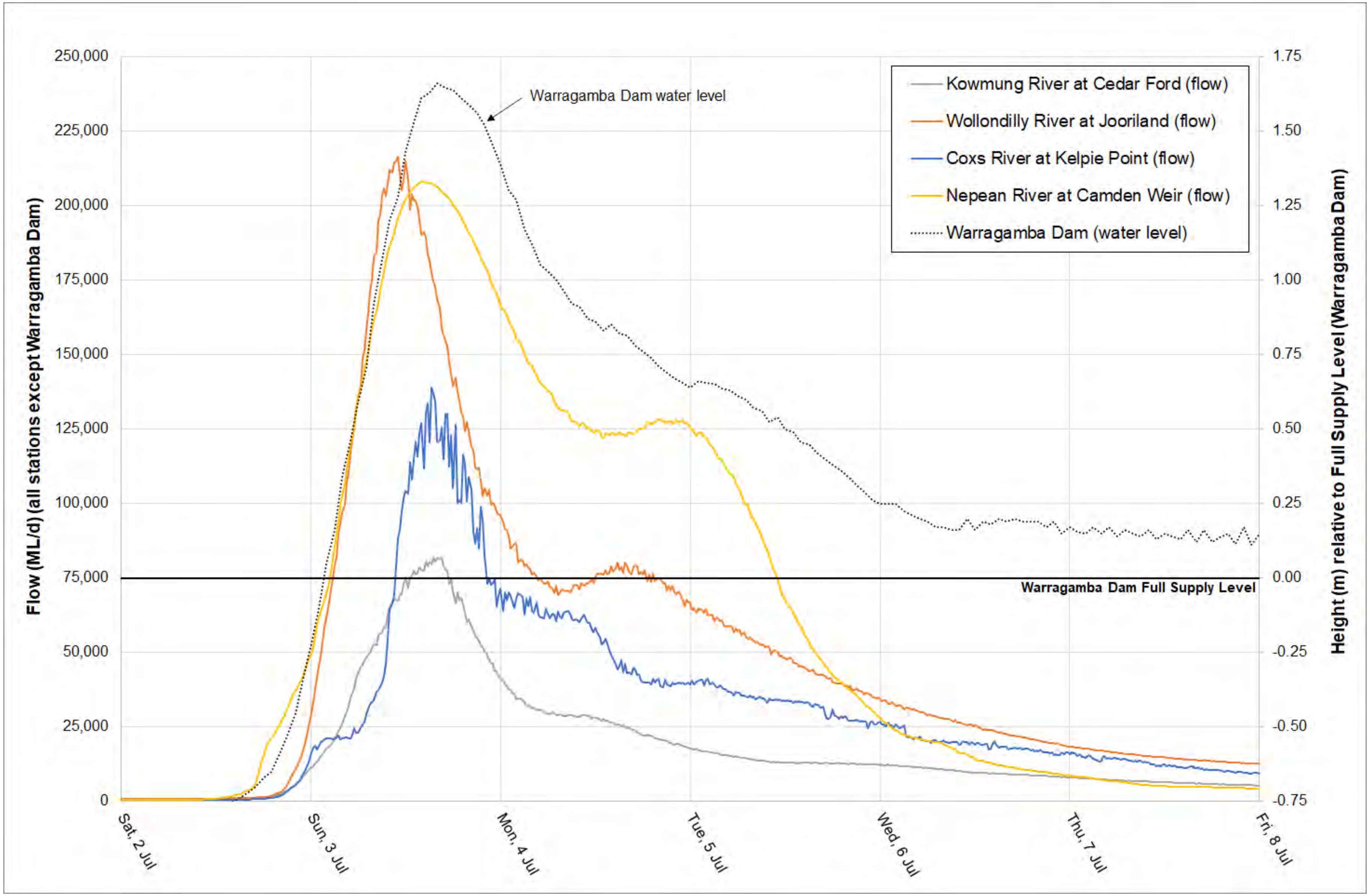


Figure 19: Flood hydrographs for selected river gauges in Warragamba and upper Nepean subcatchments, 2 to 7 July 2022

Data sources: WaterNSW, Rhelm (Camden Weir), WMAwater (dam level)

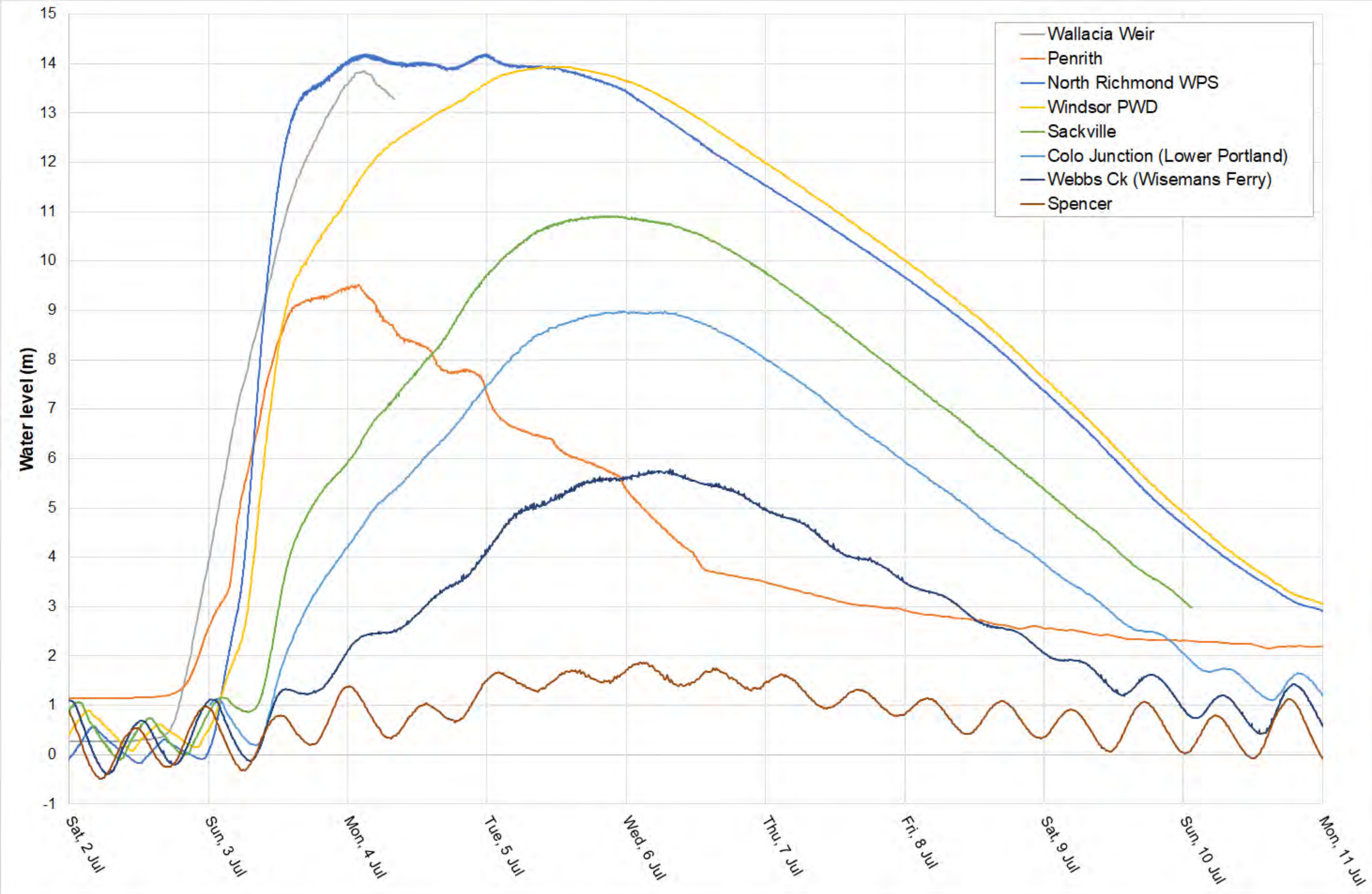


Figure 20: Flood hydrographs for selected Hawkesbury-Nepean gauges, July 2022

Data source: BoM

Table 3: Flood peak level, time, classification and likelihood, July 2022 Hawkesbury-Nepean flood

Gauge location	Gauge number	Flood peak level[1]		Flood peak date/time	Flood classification	Approximate likelihood (1 in X chance per year)[2]
		m local gauge	m AHD			
Hawkesbury-Nepean River						
Wallacia Weir	212202	13.85m	40.44m	Mon 4 Jul 2:45am	Major	1 in 10-20
Penrith	212201	9.48m	23.62m	Mon 4 Jul 1:30am	Moderate	1 in 10
Castlereagh	212404	Not operational				
North Richmond WPS	212200	14.32m	14.85m	Mon 4 Jul 3:00am	Major	1 in 10
Freemans Reach	212410	14.04m	14.04m	Tue 5 Jul 11:00am	-	-
Windsor PWD	212426	13.93m	13.93m	Tue 5 Jul 12:00pm	Major	1 in 20
Ebenezer	212427	13.04m [3]	13.04m [3]	Tue 5 Jul 3:30pm	-	-
Sackville	212406	10.87m	10.87m	Tue 5 Jul 8:00pm	Major	TBC
Colo Junction (Lower Portland)	212407	8.99m	8.99m	Tue 5 Jul 10:45pm	Major	TBC
Webbs Creek (Wisemans Ferry)	212408	5.78m [4]	5.78m [4]	Wed 6 Jul 6:15am	Major	TBC
Wisemans Ferry Wharf	212460	Partial hydrograph only excl. peak				
Gunderman Caravan Park	212429	3.40m	3.40m	Wed 6 Jul 4:30am	-	
Spencer	212431	1.87m	1.87m	Wed 6 Jul 2:30am	-	
Tributaries						
Warragamba Dam	212243	1.645m	118.365m	Mon 3 Jul 4:00pm	-	
Grose River at Burralow [5]	212291	8.38m	-	Mon 3 Jul 11:45am	-	
South Creek at Great Western Hwy	212048	6.40m	24.58m	Tue 5 Jul 1:45am	-	
Colo River at Upper Colo	212290	14.97m	16.44m	Wed 6 Jul 2:00am	Major	
Macdonald River at St Albans [6]	212228	9.97m	12.73m	Tue 5 Jul 6:30-7pm	-	

Notes:

[1] Flood peak data sourced from WaterNSW (Wallacia to North Richmond plus most tributaries), Manly Hydraulics Laboratory (Freemans Reach to Spencer) and Bureau of Meteorology (St Albans).

[2] Approximate likelihood is based on preliminary results from a 2-dimensional flood model being developed for Infrastructure NSW, and may be subject to change. Modelled flood levels at Penrith have been updated to take account of revegetation in and near the river in recent years. Likelihoods for the lower Hawkesbury are being reassessed.

[3] A gap is present in the hydrograph – peak could be slightly higher.

[4] High compared to adjacent timesteps – peak could be slightly lower (5.72m).

[5] Burralow gauge was likely impacted by high tailwater levels from the Nepean River.

[6] St Albans gauge was likely impacted by high tailwater levels from the Hawkesbury River.

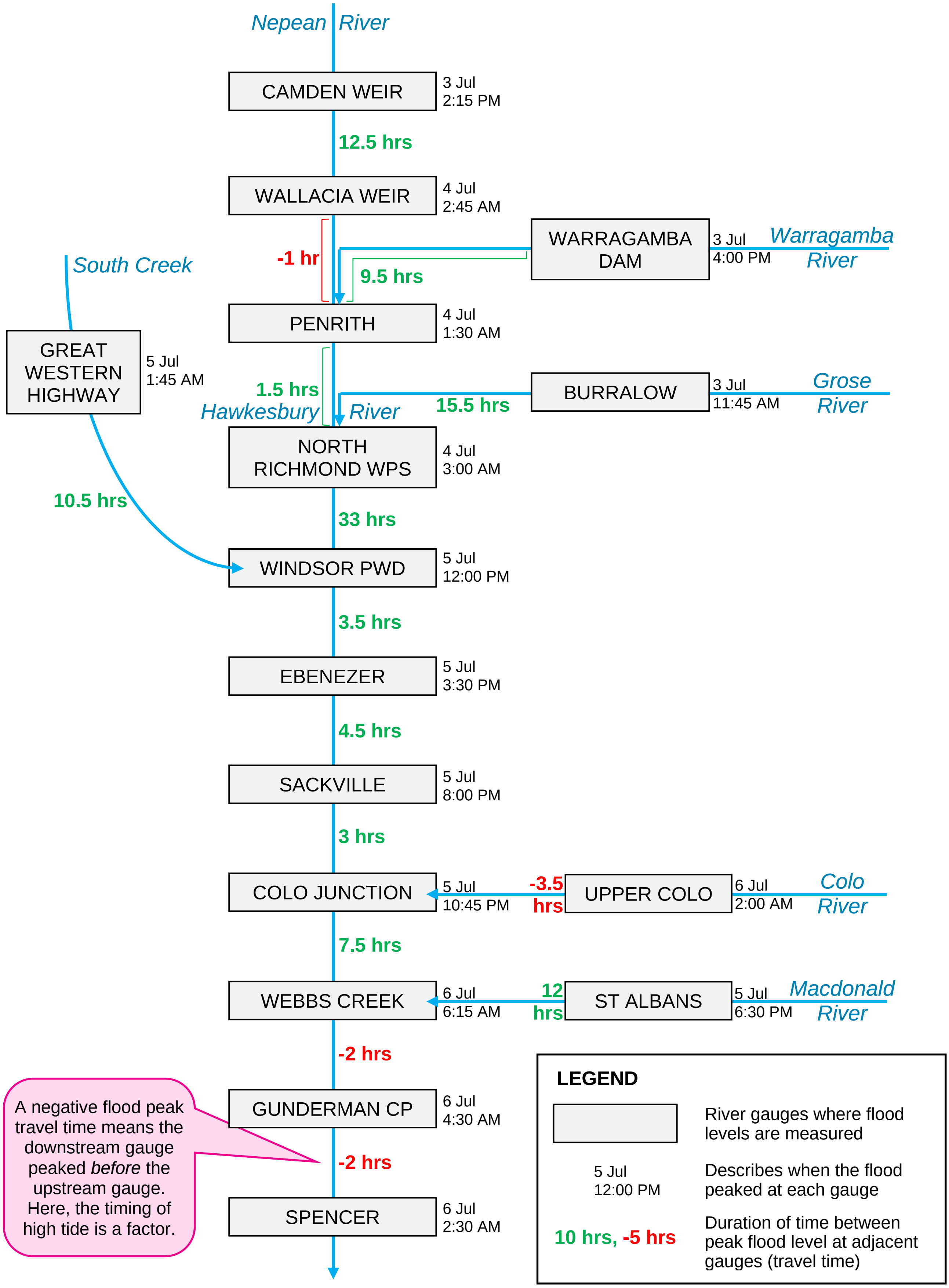


Figure 21: Flood peak travel times, July 2022 Hawkesbury-Nepean flood

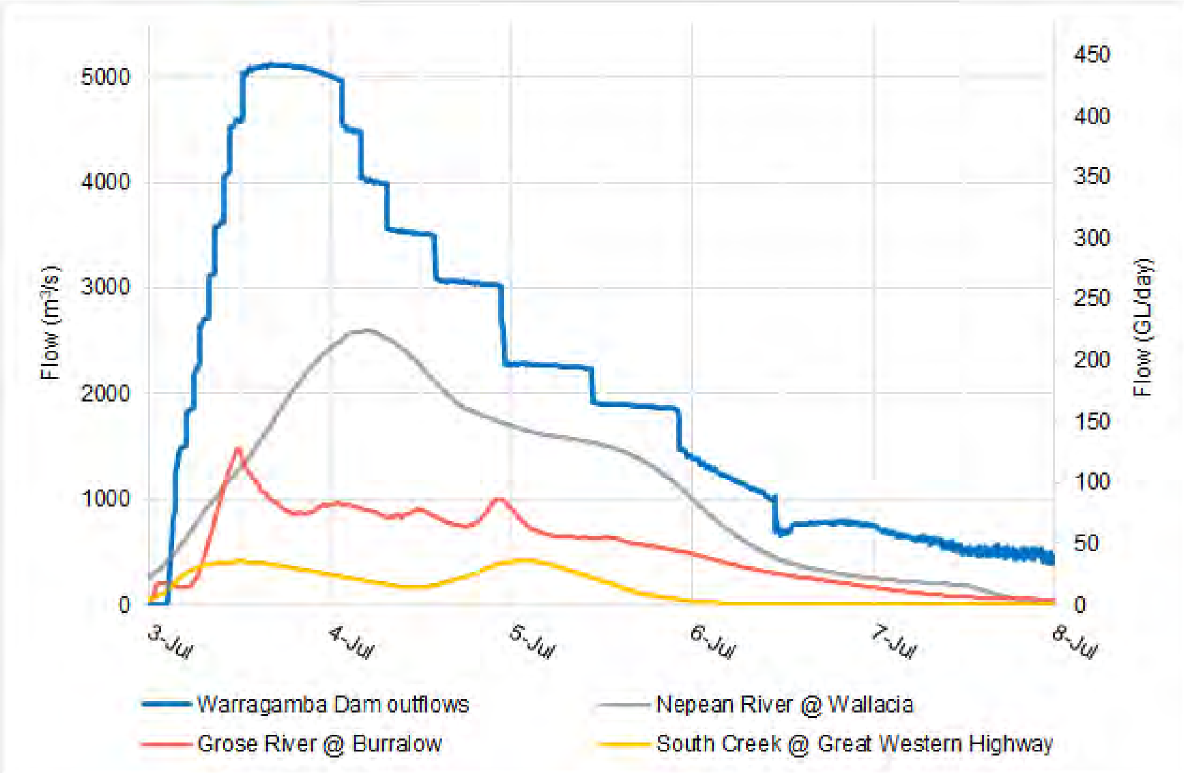


Figure 22: Flow hydrographs for key inflows to Windsor, July 2022 flood

Source: Rhelm for Infrastructure NSW

Note: Grose River flows are derived from the gauged heights, which were likely impacted by high tailwater levels from the Nepean River. The actual flows generated from the Grose catchment were likely less than shown.

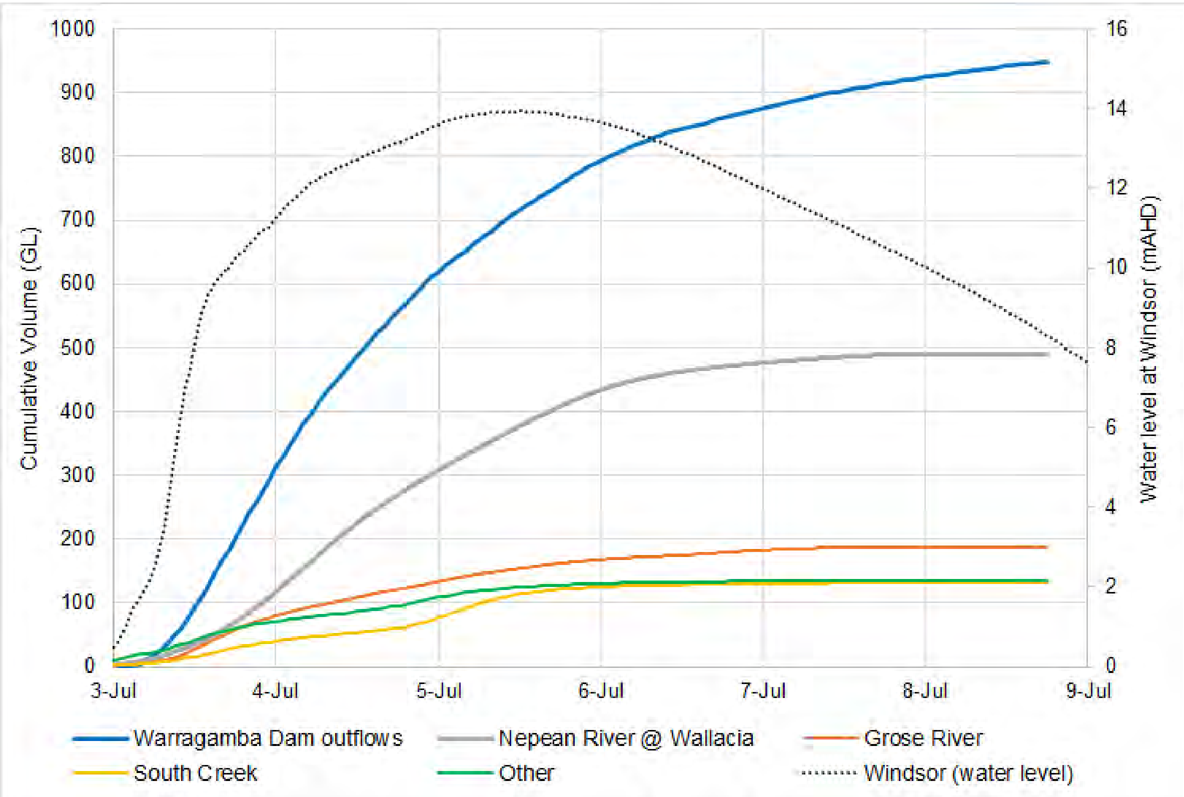


Figure 23: Cumulative volume by subcatchment to Windsor, July 2022 flood

Data source: Rhelm for Infrastructure NSW

Figure 24: Images of the July 2022 Hawkesbury-Nepean flood

Road closure

Photo courtesy of Wallacia RFS

Road closure

Photo courtesy of Wallacia RFS

Road closure

Photo courtesy of Wallacia RFS

Road closure

Photo courtesy of Wallacia RFS

Wallacia Caravan Park, ~3am 4/7/22, near peak

Photo courtesy of Wallacia RFS

River Road, Emu Plains, 9am, 4/7/22 (Penrith gauge 8.46m, about 1.0m below peak level)

Photo by David Tetley courtesy of Infrastructure NSW

View upstream towards Victoria Bridge, Penrith, 10:25am, 4/7/22 (Penrith gauge 8.37m, more than 1.0m below peak level)

Photo by David Tetley courtesy of Infrastructure NSW

Springwood Road near Mahons Creek crossing, Yarramundi, 4/7/22

Photo by Natalie James

Terrace Road near Redbank Creek crossing, North Richmond, mid-morning 5/7/22

Photo by Jeanette Hayden

Flooded Windsor Bridge, 12:46pm, 6/7/22 (Windsor PWD gauge 12.88m, around 1.0m below peak)

Photo by S. Yeo courtesy of Infrastructure NSW

Doyles Creek Road, Webbs Creek, 11:15am, 5/7/22 (Webbs Creek Ferry gauge 5.11m, around 0.7m below peak); modelling indicates this location near Webbs Creek around 9km upstream from its junction with the Hawkesbury River was impacted by Hawkesbury backwater

Photo by Chris Ward courtesy of NSW SES The Hills Unit

Wisemans Ferry Bowling Club, morning of 6/7/22

Photo courtesy of Transport for NSW

Lower Macdonald, 7/7/22

Photo by Andy Williams courtesy of NSW SES The Hills Unit

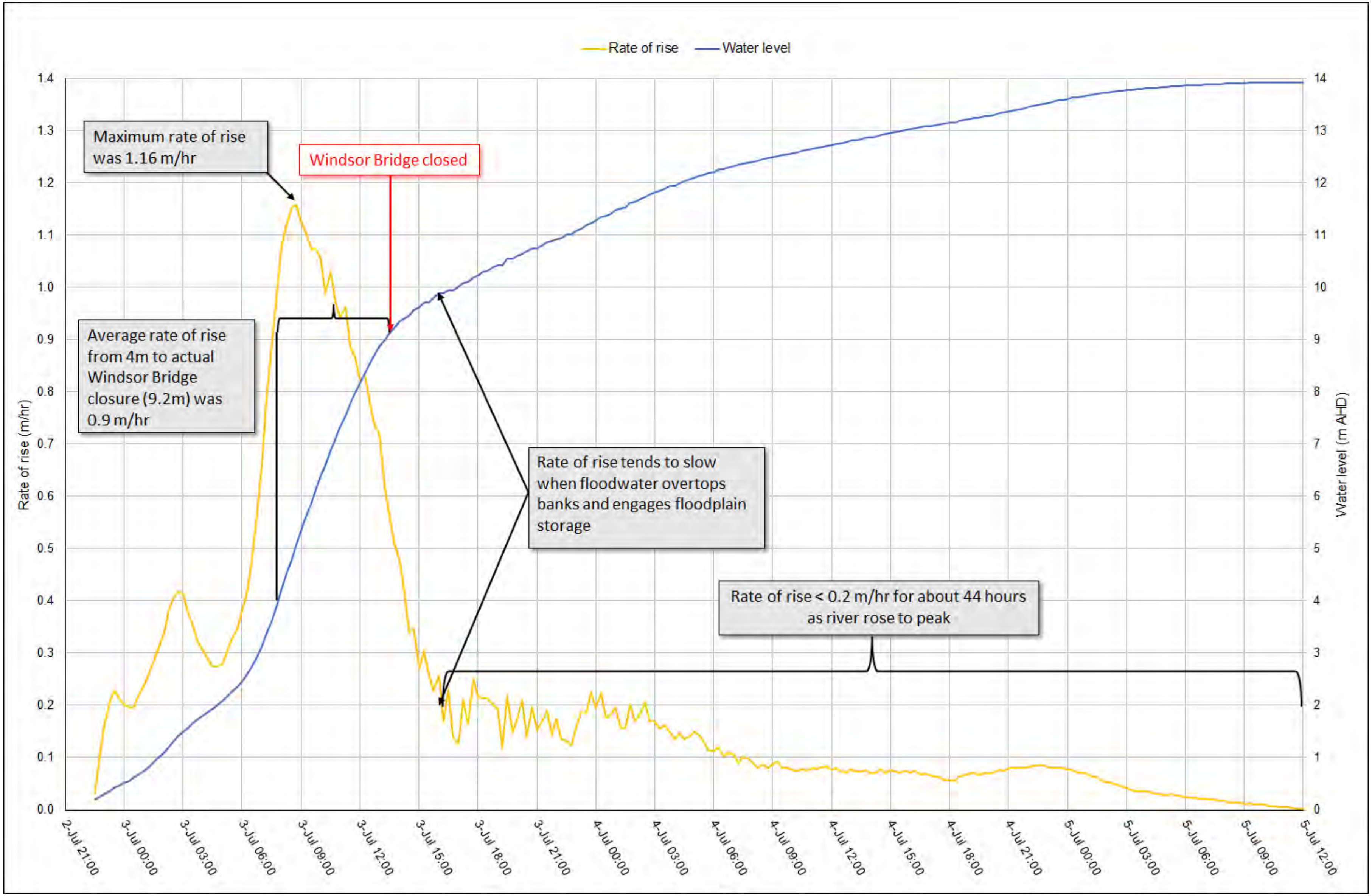


Figure 25: Rate of rise to peak, Windsor PWD gauge, July 2022 flood

Data source: Windsor water level data courtesy of Department of Planning and Environment

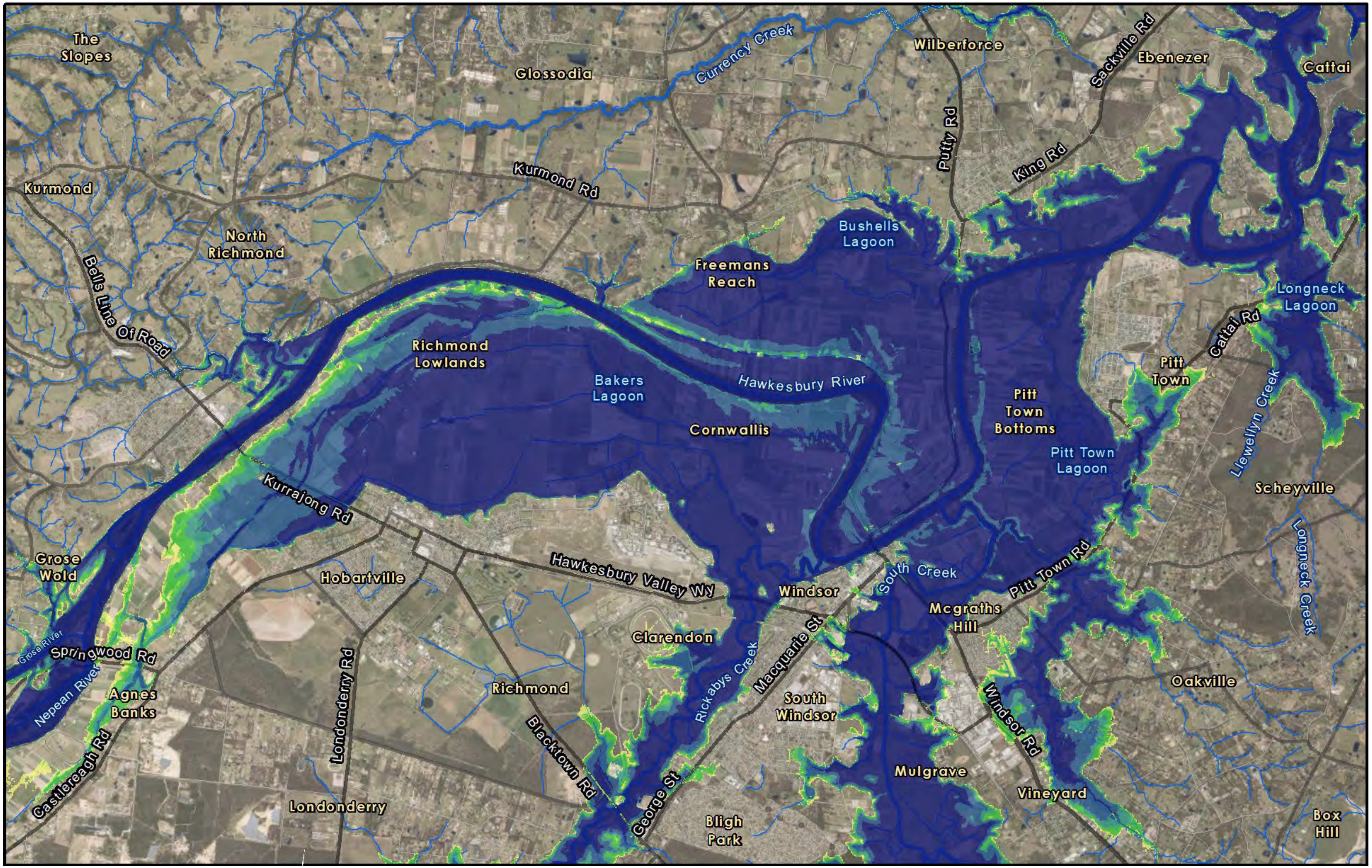


Figure 26: Flood extents/depths in Richmond/Windsor floodplain, July 2022 flood

Source: Infrastructure NSW using calibrated model output supplied by Rhelm/Catchment Simulation Solutions

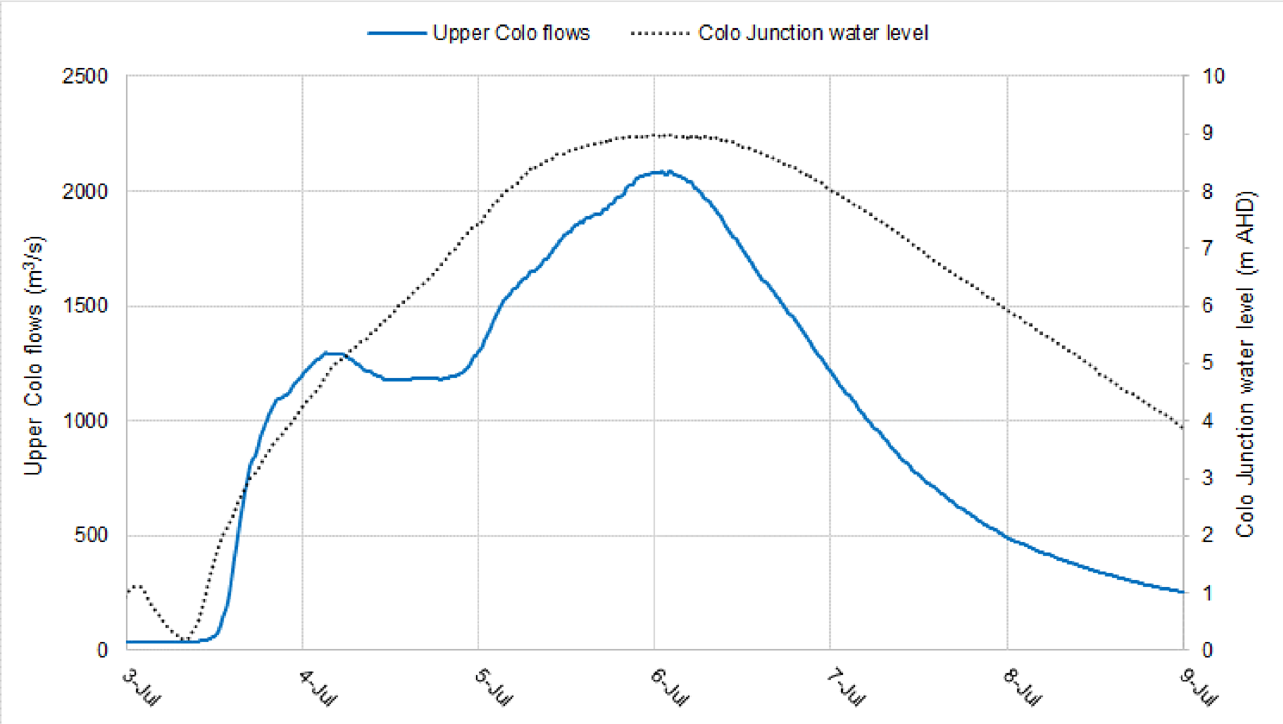


Figure 27: Timing of Colo and Hawkesbury rivers flows, July 2022 flood

Data sources: Upper Colo flows modelled by Rhelm/CSS; Colo Junction data from Department of Planning and Environment

4. Historical context

4.1 Flood size/chance and historical context

In considering the likelihood or chance of flooding, there are a few important points:

- Flood chance is related to flood size:
    - small floods like a 1 in 5 chance per year flood happen more frequently
    - larger floods like a 1 in 20 chance per year flood happen less frequently
    - very large floods like a 1 in 100 chance per year flood happen infrequently.
- The occurrence of floods in the Hawkesbury-Nepean Valley has a high degree of year-to-year variability. There also have been periods lasting several decades with frequent and high floods, followed by periods of similar length with infrequent and small floods (see Figure 28). The 28-year period from February 1992 to February 2020 was remarkably free of moderate and major floods at Windsor. The period from February 2020 to October 2022 saw 6 moderate or major floods at Windsor, possibly signalling the start of a new flood-rich period.
- The calculation of average flood chance accounts for the decades-long periods of both high and low flood activity.
- The chance of a particular flood may vary throughout the valley, depending on the spatial pattern of rainfall and the timing of tributary inflows.

Table 1 and Table 3 describe the approximate likelihood of the March and July 2022 floods for selected river gauges within the study area. Table 4 documents flood heights from the recent flood cluster and compares them to selected historical events. Table 5 documents the maximum observed rates of rise for 4 of the recent floods.

At **Warragamba Dam**, the March 2022 flood had a small peak inflow but the 2 flood peaks that characterised this flood combined to have the largest inflow volume since the dam was completed in 1960, with an average frequency of about 1 in 70 chance per year (Table E1). The July 2022 flood had an inflow volume equivalent to about 1 in 20 chance per year (Table E1).

At **Wallacia**, the highest of the recent floods was in July 2022 – the highest since April/May 1988, with an average frequency of 1 in 10 to 20 chance per year. There, the highest flood in living memory, in 1964, was 3.5m higher. The highest floods in the historical record – in 1867 and 1873 – were nearly 7m higher.

At **Penrith**, the July 2022 flood was about 0.5m below the March 2021 flood, which was the highest since 1925 (not shown in Table 4). The July 2022 flood was about a 1 in 10 chance per year event at Penrith.

At **North Richmond**, the ranking of the recent floods was the same as Penrith, though the July 2022 flood was only slightly below the March 2021 flood peak.

At **Windsor**, the March 2022 flood was about 0.9m higher than the March 2021 flood, and the July 2022 flood was slightly higher again. The most recent higher flood was in 1978.

The March and July 2022 floods were around 1 in 20 chance per year events at Windsor. The highest recorded flood in 1867 peaked nearly 6m higher.

At **Sackville**, the July 2022 flood was the highest since 1964, while the record 1867 flood was nearly 5m higher.

At **Colo Junction**, the July 2022 flood appears to have been the highest measured, though the 1867 flood would have been higher (considering the records at Sackville and Wisemans Ferry).

At **Wisemans Ferry**, the July 2022 flood was:

- a little higher than the June 1949 flood (5.6m)
- possibly the highest flood since May 1889 (7.3m)
- 3-4m below the record 1867 flood (9.1m).

Table 4: Peak heights of recent Hawkesbury-Nepean floods compared to selected historical floods

Gauge location	Flood level (m AHD)													
	Jun 1867	May 1889	Jun 1949	Nov 1961	Jun 1964	Mar 1978	Apr 1988	Aug 1990	Feb 2020	Mar 2021	Mar 2022	Apr 2022	Jul 2022	Oct 2022
Hawkesbury-Nepean River														
Wallacia Weir	47.11	n/a	38.25	41.46	44.15	42.35	40.92	39.32	33.92	35.17	37.95	37.51	40.44	30.91
Penrith [a]	27.47	n/a	21.38	23.89	23.74	23.35	22.62	23.44	20.25	24.13	22.46	20.06	23.62	18.66
North Richmond WPS [b]	n/a	n/a	n/a	n/a	n/a	n/a	14.89	15.39	12.08	14.91	14.66	10.70	14.85	8.64
Windsor PWD	19.68	12.15	12.11	14.95	14.57	14.46	12.80	13.50	9.28	12.93	13.80	9.07	13.93	7.38
Sackville	15.47	n/a	8.4	10.4	10.97	10.71	8.55	9.98	5.78	9.71	10.68	5.18	10.87	4.60
Colo Junction (Lower Portland) [b]	n/a	n/a	6.8	7.21	7.72	7.80	5.30	7.40	4.73	7.87	8.67	3.48	8.99	3.75
Wisemans Ferry (Webbs Creek)	9.1	7.3	5.6	3.95	4.20	4.80	2.84	4.30	2.39	4.36	5.18	1.64	5.78	2.08
Tributaries														
Warragamba Dam (lake level) [c]	before dam	before dam	before dam	119.51	118.89	118.01	118.06	118.72	below FSL	118.25	117.97	117.00	118.37	117.02
Grose River at Burralow (m) [d]	n/a	n/a	n/a	n/a	n/a	n/a	6.27	8.86	10.95	8.83	6.45	4.65	8.38	3.79
South Creek at Great Western Hwy	n/a	n/a	n/a	n/a	n/a	n/a	24.73	23.76	25.10	24.38	24.89	23.25	24.58	23.67
Colo River at Upper Colo	n/a	n/a	17.4	9.3	14.61	20.65	8.32	15.21	17.21	16.44	18.12	9.20	16.44	13.86
Macdonald River at St Albans	13.8	15.1	14.6	3.8	10.4	11.25	n/a	8.75	8.06	10.44	11.09	5.03	12.73	8.57

Legend:

- Highest flood in 2020-22 flood cluster
- Most recent higher flood prior to 2020-22 flood cluster
- Highest flood in historic record

Notes:

a. Penrith's most recent higher flood was in 1925 (not shown)
b. The highest flood in the historical record was likely in 1867
c. Full supply level at Warragamba Dam is 116.72m AHD
d. Grose River at Burralow heights to gauge datum (m)

Data sources:

Wallacia: 1867 - WMAwater (2019); 1949-2022 - WaterNSW
Penrith: 1867-1964 - WMAwater (2019); 1978-2022 - WaterNSW
North Richmond WPS: 1988-2022 - WaterNSW
Windsor: 1867-1990 - WMAwater (2019); 2020-22 - MHL
Sackville: 1867 - draft HNR Flood Study; 1949-64 - AWACS (1997); 1978 - PWD (1978); 1988-90 - BoM; 2020-22 - MHL
Colo Junction: 1949, 1978 - AWACS (1997); 1961-64, 1988-90 - BoM; 2020-22 - MHL
Wisemans Ferry: 1867-1964 - draft HNR Flood Study; 1978 - PWD (1978); 1988-90 - BoM; 2020-22 - MHL
Warragamba Dam: WMAwater (see Table E1); WaterNSW (other events)
Grose R @ Burralow: 1988-2022 - WaterNSW
South Ck @ GWH: 1988-2022 - WaterNSW
Colo R @ Upper Colo: 1949-1964 - AWACS (1997); 1978-2022 - WaterNSW
Macdonald R @ St Albans: 1867, 1889 - Erskine (1986); 1949, 1978, 1990 - WMA (2004); 1961, 1964 - AWACS (1997); 2020-22 – BoM

Table 5: Maximum rates of rise of recent Hawkesbury-Nepean floods

Location	Height range (m on gauge)	Maximum hourly rate of rise (m/hr)			
		Feb 2020 flood	Mar 2021 flood	Mar 2022 flood	Jul 2022 flood
Wallacia	>2.5m	0.6	0.6	0.8	0.7
Penrith	>2.0m	0.6	0.6	0.8	1.1
Yarramundi	>2.0m	1.3	0.8	n/a	n/a
North Richmond	>2.0m	1.2	0.8	1.2	1.6
Windsor	>2.0m	0.9	0.6	0.7	1.2
Ebenezer	>2.0m	0.6	0.4	0.6	0.9
Sackville	>2.0m	n/a	0.4	0.4	0.7
Lower Portland	>1.0m	0.6	0.3	0.5	0.5
Leets Vale	>1.0m	0.5	n/a	0.5	n/a
Wisemans Ferry	>1.0m	0.4	0.2	0.5	0.3
Gunderman	>1.0m	0.4	0.2	0.4	0.3
Spencer	>0.5m	0.4	0.2	0.4	0.3

Legend:

Fastest rate-of-rise in 2020-22 flood cluster

Data source: observed hydrographs from WaterNSW, MHL

Notes:

a. Rate of rise rounded up to nearest 0.1m interval
b. Higher rates of rise than shown here are possible (e.g. see Appendix F in the Hawkesbury-Nepean Valley Regional Flood Study (WMAwater, 2019))

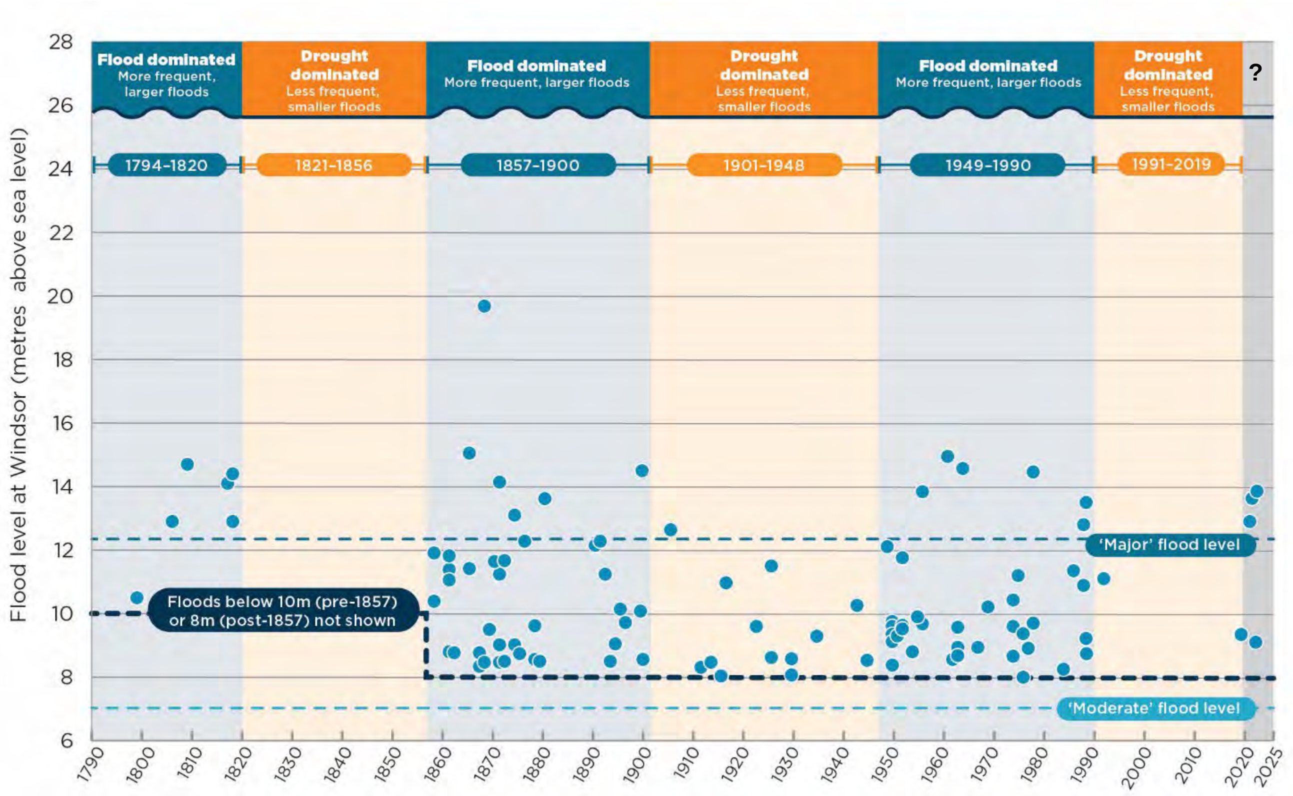


Figure 28: Flood history, Hawkesbury River at Windsor, 1794-2022

Source: Infrastructure NSW

Gauge readings confirm what was described by several council and NSW SES contacts – the July 2022 flood was notable for the speed with which it rose, especially in the Nepean at Penrith and Upper Hawkesbury (Table 5). At one point, the river rose 1.6m in 1 hour at the North Richmond WPS gauge. This is important intelligence for flood emergency planning.

4.2 Potential role of climate change

There is a good deal of interest in the potential role of climate change in exacerbating the 2022 floods. This issue was explicitly considered by the Australian Research Council Centre of Excellence for Climate Extremes (CLEX) at the University of NSW as part of the *2022 NSW Flood Inquiry* (O'Kane and Fuller, 2022; Pitman et al., 2022), with a focus on the February-March floods in New South Wales.

Other recent summaries of the current evidence relevant to Australia include:

- BoM and CSIRO (2022) *State of the Climate 2022* (see extract in Figure 29)
- CSIRO (2022) *Understanding the causes and impacts of flooding*
- IPCC (2021) *Weather and Climate Extreme Events in a Changing Climate* (Seneviratne et al., 2021).

Climate change, extreme rainfall and flood risk

Flooding is one of the major natural hazards facing Australia. Multiple factors contribute to the risk of flooding. The most important weather-related factors include how extreme a rainfall event is and how wet catchments are prior to the rain event. In estuarine and coastal environments, tides and sea levels can also be important. Flood risk can also change over time as a result of changes in land use and land cover, and through changes in the extent to which streams in the catchment area are regulated.

Sustained heavy rainfall and associated flooding in much of Australia, particularly the east, is most common during La Niña, as illustrated by the multiple floods that occurred in eastern Australia in 2022. The 11 wettest years on record in eastern Australia were all influenced by La Niña. Many of eastern Australia's most significant flood years, such as 1974, 2010–11 and 2021–22, have occurred during strong La Niña events, although significant flooding can sometimes occur in non-La Niña years. The impact of multiple flood events is particularly pronounced when La Niña events occur in multiple successive years, as occurred in 2020–22, and previously in periods such as 1954–56 and 1973–76.

Flood risk is influenced by rainfall at a range of timescales, depending on the catchment. Flash flooding is driven by intense rainfall in localised regions on timescales of minutes to hours, while river flooding in larger catchments responds to rainfall on timescales of days to weeks. While the observed trend in daily rainfall extremes is mixed across Australia, with some areas showing increases and others decreases, an increase in sub-daily extremes is now very clear over recent decades.

It is expected that extreme rainfall will increase in Australia with climate change. At particular locations, extreme rainfall changes in particular locations are also influenced by changes in weather systems, such as east coast lows and tropical cyclones (both of which are expected to become less frequent). This may lead to some regions experiencing trends in extreme rainfall that differ from typical values at national or global scale. Climate change may also affect the drivers of multi-day rainfall extremes, such as atmospheric rivers for moisture transport, the behaviour of El Niño and La Niña, and persistent blocking highs (strong high-pressure systems that remain almost stationary for an extended period of time, blocking the eastward progression of weather systems across southern Australia) in the Tasman Sea, but the details of these effects are subject to ongoing research. Changes in extreme rainfall will not necessarily follow those in mean rainfall: regions in southern Australia, which are expected to see continued long-term drying, may still experience increases in extreme rainfall.

Figure 29: Extract from State of the Climate 2022

Source: BoM and CSIRO, 2022

In short, the specific contribution of climate change to individual events such as the 2022 Hawkesbury-Nepean floods is difficult to assess. This is because climate change is superimposed upon large natural climate variability including El Niño-Southern Oscillation (ENSO) and the 30–50-year periods observed in Windsor's flood history dominated by either droughts or floods (Figure 28). Assessing the extent to which climate change and natural climate variability play a role in extreme events can be attempted using attribution studies. This research can take 1-2 years and is not yet available for the 2022 floods. The CLEX expressed doubt about current technical capabilities to accurately constrain the human-induced climate signal for such complex events.

Climate change is expected to increase rainfall intensities – on a global scale, for each 1-degree Celsius rise in temperature, the atmosphere can hold approximately 7% more water (Seneviratne et al., 2021). However, the CLEX notes that this thermodynamic process is insufficient to explain the extreme rainfall observed in February-March 2022. Rather, the extreme rainfall was the result of a series of complex and persistent weather patterns including an atmospheric river, trough, blocking high pressure system and an east coast low. These weather systems were in turn influenced by multiple Rossby wave breaking events. (Rossby waves are planetary-scale waves in high-altitude winds that are largely responsible for a variety of weather experienced at the surface. When these waves deform, amplify and break, they can result in a mixing of high potential vorticity air from the stratosphere and irreversibly alter the mean atmospheric flow (Pitman et al., 2022)).

It's important to note that while there is evidence for increasing *sub-daily* rainfalls in parts of Australia, there is limited evidence for increasing *multi-day* rainfall intensities of more relevance to the flooding of large catchments like the Hawkesbury-Nepean – typically, 3 consecutive days of heavy rain is required to generate serious Hawkesbury-Nepean floods.

As for the actual flood record, there is no discernible trend in the magnitude/frequency of floods in the Hawkesbury-Nepean since 1857 (Figure 30). It's important to understand that changes in rainfall intensity/frequency may not necessarily translate to changes in flood intensity/frequency because rainfall is only one of many factors impacting floods (Seneviratne et al., 2021). Antecedent soil moisture could decrease due to increased evaporation – though Figure 3 shows how soil moisture can rapidly increase during the initial stages of a rain event. Changing land use cover, water storage, river channel shape and riparian vegetation can all influence flooding.

In summary, climate change is potentially a contributing factor to the 2022 floods but is not the cause of the floods (O'Kane and Fuller, 2022). This is consistent with the finding in the latest IPCC Assessment Report of overall '*low confidence* in general statements to attribute changes in flood events to anthropogenic climate change' (Seneviratne et al., 2021, p.1569).

As the *State of the Climate 2022* indicates, there is much ongoing research to unpack how in the future climate change could impact dynamic drivers of multi-day rainfall extremes including atmospheric rivers, La Niña, and blocking highs in the Tasman Sea (Figure 29). For example, Reid et al. (2021) found that by the end of the century, the frequency of events that are a similar scale to the March 2021 New South Wales floods (in terms of the magnitude of water vapour transport over Sydney) are likely to increase by 80% under both moderate and high emissions scenarios.

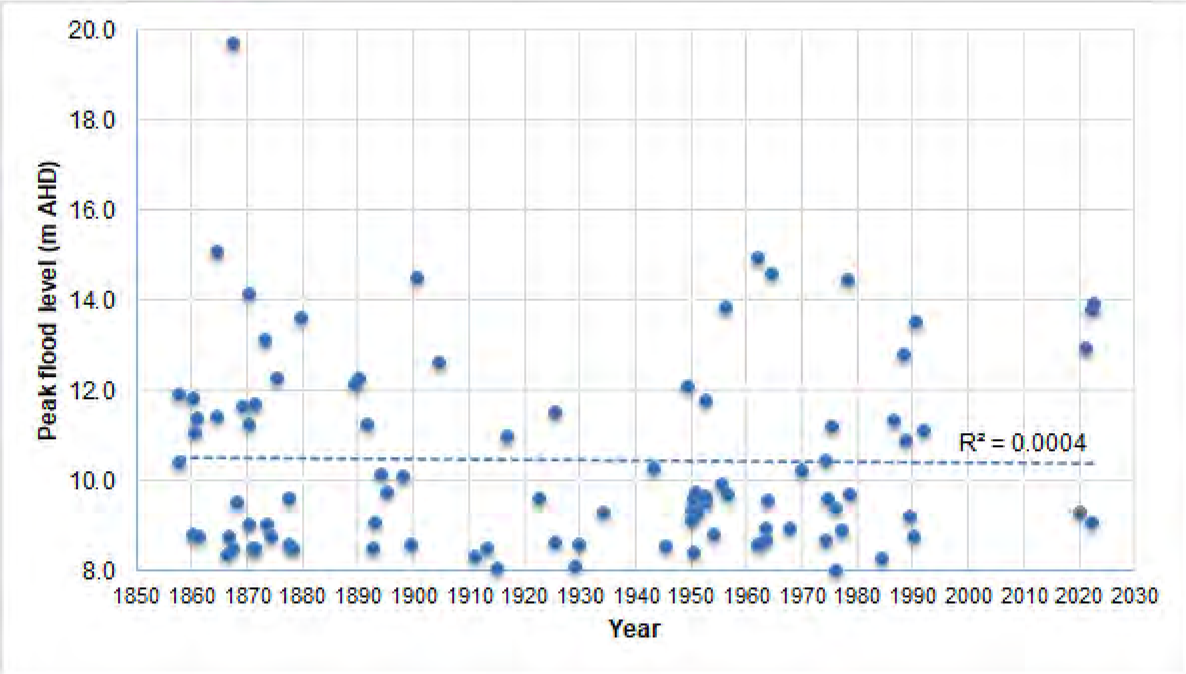


Figure 30: Flood history (events ≥ 8m), Hawkesbury River at Windsor, 1857-2022, with trend line

Source: Infrastructure NSW

4.3 Subcatchment contribution

The Hawkesbury-Nepean catchment is made up of several subcatchments. The largest of these is the Warragamba subcatchment (9000 km^2), making up around 80% of the catchment to Penrith and 70% to Windsor. The upper Nepean subcatchment (1760 km^2 to Wallacia) makes up 16% of the catchment to Penrith and 14% to Windsor. While draining a high rainfall area, the Grose River subcatchment (650 km^2) makes up only 5% of the total catchment to Windsor and so cannot alone drive significant flooding at Windsor.[8] The South and Eastern creeks subcatchment and the combined creek subcatchments between the junction of the Nepean and Warragamba rivers and Windsor (including Erskine, Glenbrook and Mulgoa creeks) each make up about 5% of the total catchment to Windsor.

To Penrith

Flood heights in the Nepean River at Penrith are driven principally by peak flows. Figure 11 and Figure 22 compare the peak flows from the main subcatchments contributing flow to Windsor in the March and July 2022 floods. This shows that the peak ouflows from Warragamba Dam were about 2 times the peak flows in the Nepean River at Wallacia, for these 2 floods.

To Windsor

Historical

Flood heights in the Windsor floodplain are driven more by the volume of floodwaters filling the ‘bathtub’. The volume of floodwaters coming from the main subcatchments in the March and July 2022 floods was derived from calculated outflows at Warragamba Dam and calibrated hydrological and hydraulic models for the other tributaries. The results are compared to selected historic floods in Figure 31.

[8] Modelling shows that even the highest possible flood (the probable maximum flood, or PMF) in the Grose River subcatchment would not reach the flood planning level at Windsor. Best estimates of tributary inflows during the record 1867 flood suggest 65 – 70% of floodwaters came from the Warragamba subcatchment and 10 – 12% of floodwaters came from the Grose River subcatchment (Babister, 2021).

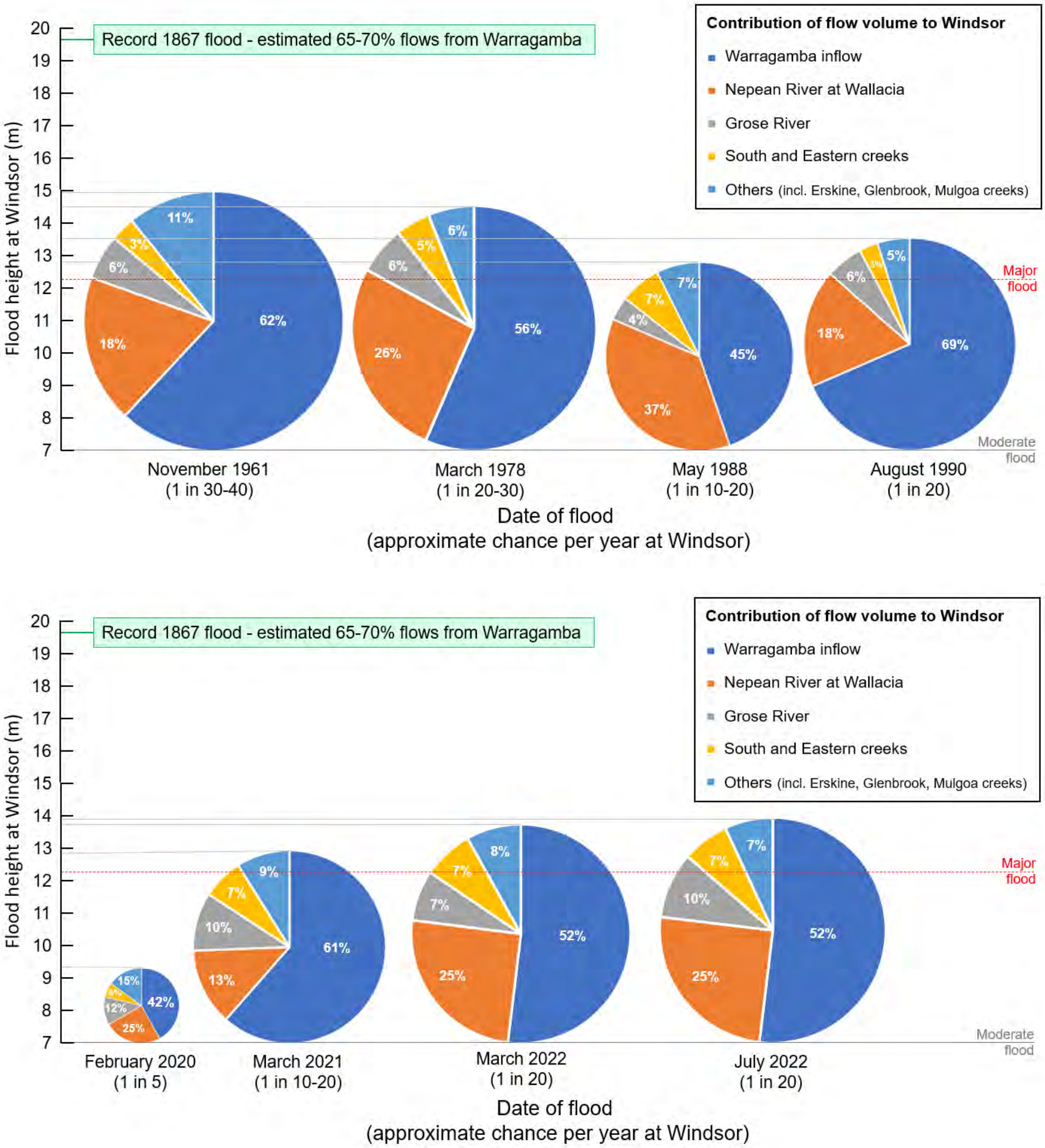


Figure 31: Contribution of flood volume to Windsor by subcatchment in historical floods

Data sources: WMAwater and Rhelm for Infrastructure NSW

Note: rounding may mean percentages do not tally exactly 100%

In both the March and July 2022 floods, the Warragamba subcatchment contributed 52% of floodwaters and other subcatchments contributed 48% of floodwaters, although March produced substantially larger volumes in total. Only a small proportion of floodwaters from the Warragamba subcatchment was retained in the dam, which was about 0.7m below FSL at the start of the February/March event and about 0.8-0.9m below FSL at the start of the July event. Of the historic floods in Figure 31, the highest contribution from the Warragamba subcatchment occurred in August 1990 (69%). The figure also shows that the Warragamba subcatchment generated an estimated 65-70% of flows in the record 1867 flood – very large floods require a high percentage from the Warragamba subcatchment.

One question concerns the proportion of volume contributed by each subcatchment *when the flood peaks at Windsor*. This may be interpreted from Figure 12 and Figure 23, which plot the cumulative volumes from the subcatchments contributing flow to Windsor for the March and July 2022 floods. These show how at the peaks of the floods, the Warragamba catchment was by far the largest single contributor:

- In March, at the peak, over the course of about 7 days, Warragamba had spilled nearly 1300 GL, the Nepean River to Wallacia had contributed about half that volume, and Grose River, South and Eastern creeks, and combined other subcatchments had each contributed a little over 200 GL
- In July, at the peak, over the course of just over 2 days, Warragamba had spilled 720 GL, the Nepean River to Wallacia had contributed 380 GL, and the Grose River, South and Eastern creeks, and combined other subcatchments had each contributed 100-150 GL.

Potential

Flood modelling has considered the variability of subcatchment contributions to Windsor across thousands of flood scenarios. This is shown in Figure 32, which also includes selected historical floods for comparison. Again, unsurprisingly, the Warragamba subcatchment is the largest contributor, of between 51% (10th percentile) and 71% (90th percentile) of the volume of floodwaters to Windsor. For all modelled 1 in 100 chance per year events, the Warragamba subcatchment contributes at least half the volume of floodwaters to Windsor (Infrastructure NSW, 2019).

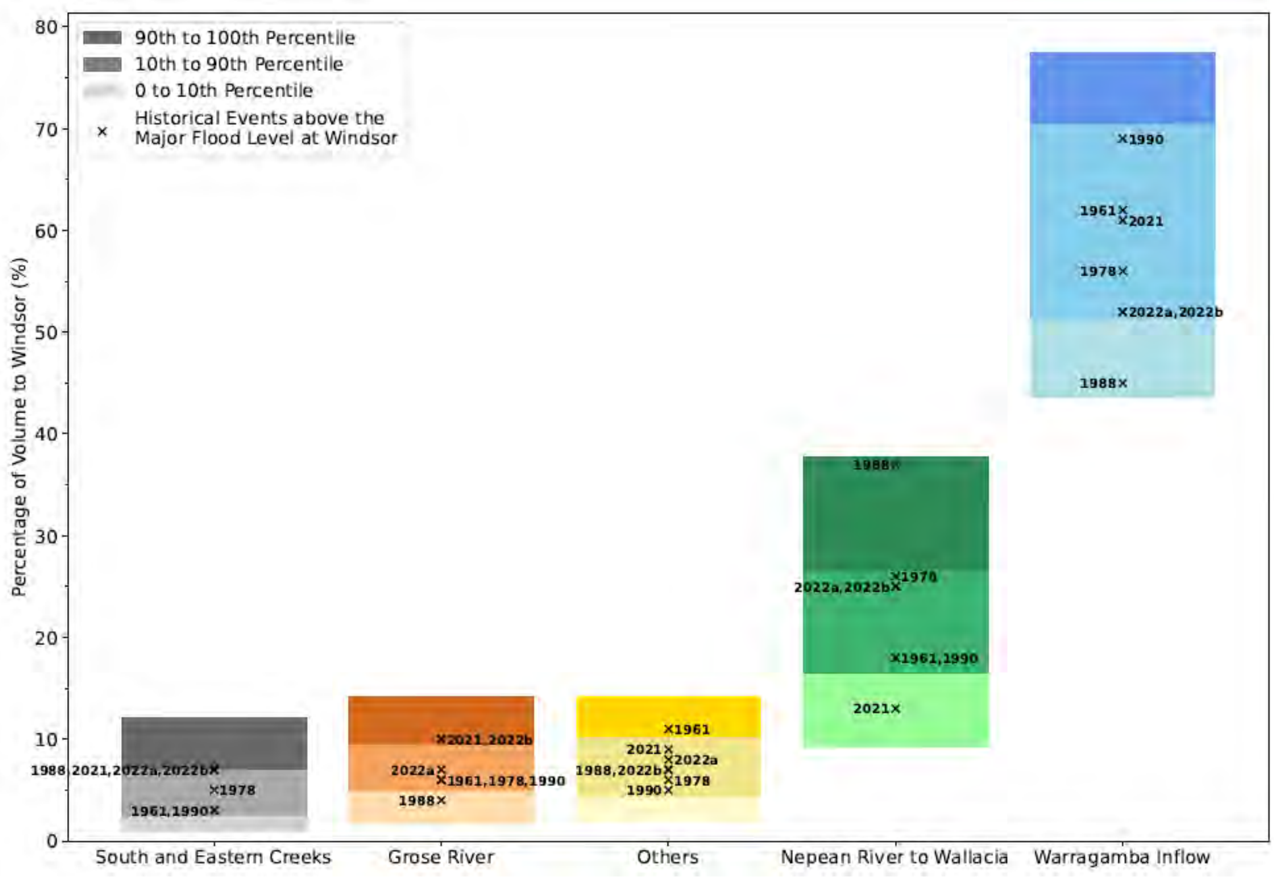


Figure 32: Contribution of flood volume to Windsor by subcatchment in all modelled floods reaching at least 10m AHD at Windsor, with comparison to recent major floods

Sources: WMAwater for Infrastructure NSW
Note: 2022a = March 2022, 2022b = July 2022

To Lower Portland

The Colo River drains a large 4630 km^2 catchment, joining the Hawkesbury River at Lower Portland, over 40 kilometres downstream of Windsor. The size, relative timing and duration of inflows from the Colo River can make a significant difference to flooding in the lower Hawkesbury River at Lower Portland and downstream.

In March 2022, similar to March 2021, the Colo River had sustained high flows. Figure 14 shows that the Colo peak occurred over 1 day before the Hawkesbury peak at Colo Junction (Lower Portland), but the Colo still contributed flows in the order of 1500 m^3/s (130 GL/day) when the Hawkesbury was peaking.

In July 2022, the Colo River peak was relatively synchronised with the Hawkesbury peak – an unusual pattern when compared to historical floods. Figure 27 shows that the Colo contributed flows of over 2000 m^3/s (~170 GL/day) when the Hawkesbury was peaking at Colo Junction.

Colo River inflows have a lesser and decreasing impact in the Hawkesbury River with increasing distance upstream from Colo Junction. This is conveyed in Figure 33, which shows a profile of flood peaks for the recent events at the Hawkesbury River gauges. In the 3 largest floods among the recent cluster, the flood slope meant that flood heights at Colo Junction were about 5m lower than at Windsor, even with historically significant flood peaks at Upper Colo (Table 4). In the minor to moderate 2020 flood, smaller inflows into the upper Hawkesbury (noting Warragamba did not spill), combined with significant, synchronised inflows from the Colo, appeared to have raised flood levels at Sackville, upstream of Colo Junction.

Modelling of the March and July 2022 floods shows that if all Colo inflows were removed, the flood levels at Windsor would have been reduced by 0.27m and 0.08m, respectively. This confirms that Colo flows generally have minimal impact on flood levels at Windsor.

To Wisemans Ferry

The Macdonald River drains a 1910 km^2 catchment, joining the Hawkesbury River at Wisemans Ferry, over 60 kilometres downstream of Windsor. The size, relative timing and duration of inflows from the Macdonald River can make a difference to flooding in the lower Hawkesbury River at Wisemans Ferry and downstream.

The July 2022 flood was the highest at St Albans on the Macdonald River since 1949 (Table 4), and, together with Colo River inflows, contributed significant flow to the lower Hawkesbury River. The 1889 and 1949 events were also high floods at St Albans (Table 4), and higher at Wisemans Ferry than expected from the flow rates at Windsor. This suggests that inflows from the Colo and Macdonald rivers can add metres in height to floods at Wisemans Ferry.

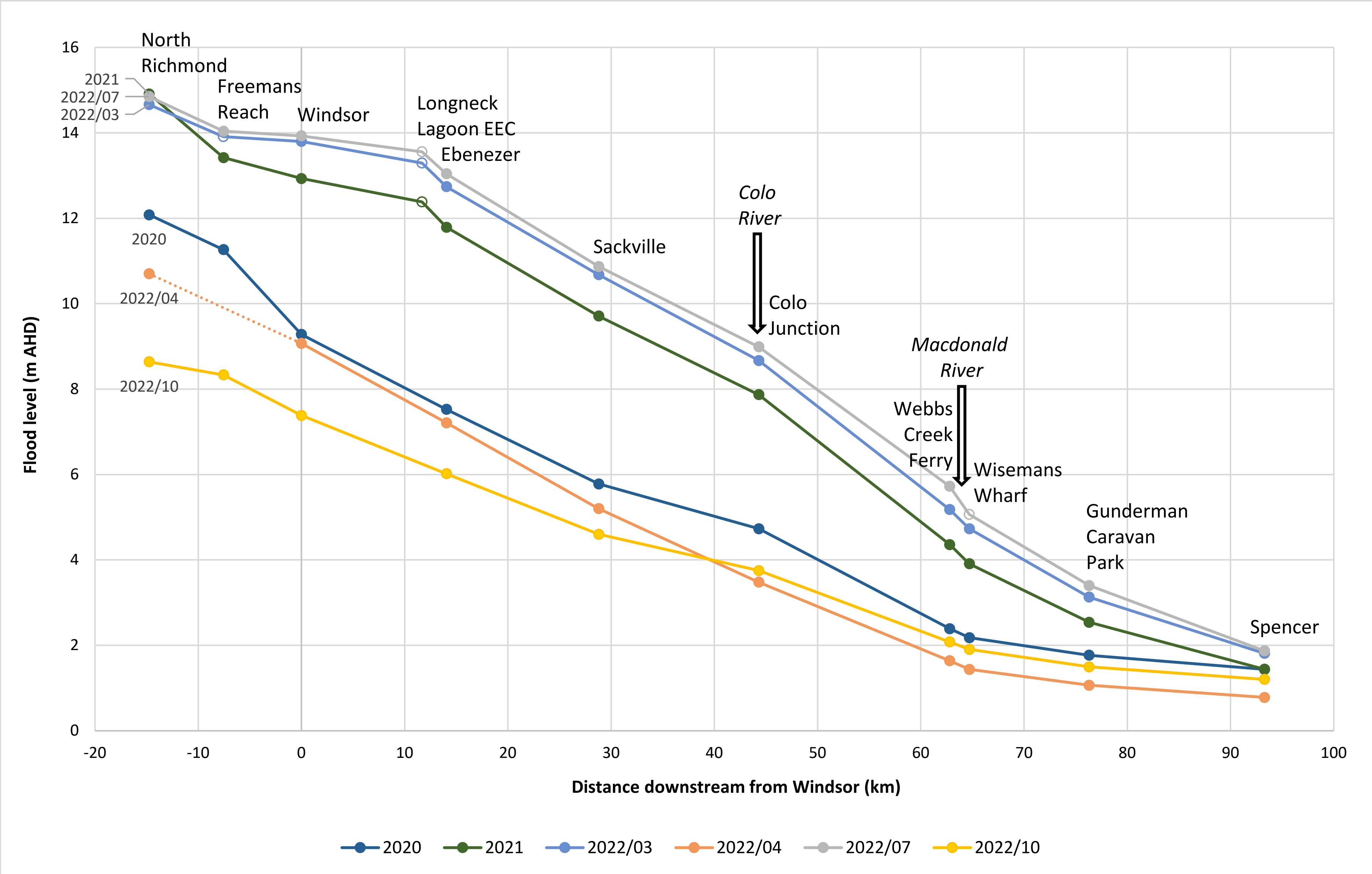


Figure 33: Hawkesbury River flood gradient for recent floods

Notes: Based on gauged data except where points have hollow circles representing post-flood survey using debris marks. Longneck Lagoon EEC survey available only for higher floods. Freemans Reach not available for April 2022.

5. Riverbank erosion

A bit like sandy coasts, alluvial river channels are dynamic features of the landscape, responding to both natural changes (floods, droughts) and human-induced changes (for example, farming, urbanisation, dams, sand and gravel extraction, dredging). Large floods typically promote erosion of river channels, while long periods without floods often promote deposition of materials in river channels including the formation of in-channel benches (Warner, 1994). The presence of riparian vegetation typically increases bank stability; its absence leaves riverbanks exposed to erosive forces.

A selection of historical images and descriptions of riverbank erosion in the Hawkesbury is provided in Appendix D. This illustrates that riverbank erosion has been a frequent occurrence. In the Hawkesbury-Nepean, multi-decadal cycles dominated by floods or droughts (Figure 28), as well as multiple human activities, have led to a changing, unstable river channel. The channel is still adjusting to a range of human actions including the construction of weirs and dams, and the long-term extraction of sand and gravel. These have caused a deficit of river sediment, resulting in erosion of the channel bed and banks, especially below Windsor (Warner, 1991).

Following the March and April 2022 floods, the Engineering Services Functional Area Coordinator engaged the Soil Conversation Service (SCS) to complete a rapid desktop assessment of erosion on the Hawkesbury-Nepean River – similar to the assessment completed after the March 2021 flood summarised in Infrastructure NSW (2021a). The assessment used erosion points identified by Environmental Protection Authority (EPA) and National Parks and Wildlife Service (NPWS) post-flood aerial surveillance. Nearmap high-resolution vertical aerial imagery (dated April 2022) was also used.

As for the post-2021 flood assessment, rotational (or circular) slumps were the dominant form of erosion identified for the Hawkesbury-Nepean (Figure 34), with a high concentration of these observed between Richmond Lowlands and Gronos Point, and also at Sackville (Figure 35).

Examples of the observed erosion including rotational slumps are provided in Figure 36.

A team of geomorphologists from Beca inspected the river after the July 2022 flood (Beca, 2022). Consistent with the SCS assessment, the Beca team judged that gravitational slumping caused by elevated pore water pressures in the riverbank was the likely cause of the majority of failures. Beca (2022) described this type of failure as follows:

> ‘As the floodwater recedes, the pore water pressure in the riverbank remains high as groundwater takes longer to drain/recede than the river. The increase in pore pressure in the bank, combined with the floodwater no longer providing a supporting buttress, can result in gravitational slumping of the bank. Non-cohesive soils will drain faster than cohesive soils but will also become saturated faster when flooding does occur.’ (p.6)

Beca (2022) also found that evidence of piping was common upstream of Cattai Creek (e.g. Figure 36b). Engineering geologists from NSW Public Works Advisory interpreted a prominent erosion site along the Richmond Lowlands as a piping/tunnelling failure (Figure 36d) (Neville, 2022). Beca (2022) described this type of failure as follows:

> ‘Piping type failure is the result of internal erosion by groundwater, within a non-cohesive soil mass. It is common in interbedded non-cohesive soils where groundwater flows preferentially along permeable layers within the soil mass. Silt and fine sand particles can become entrained as the groundwater drains out of the riverbank after a drop in water levels, leading to linear voids or ‘pipes’. These voids can collapse causing mass failure of the soil mass at the riverbank. The ability for the silt and sand particles to become entrained is determined by the ‘exit velocity’ of groundwater as it drains out of the soil. Higher exit velocities will entrain more particles when compared with lower exit velocities. The exit velocity is dependent on the permeability of the soil, and the hydraulic gradient (the difference between the groundwater level in the bank, and the level of the river).’ (p.6)

Several factors may have contributed to the erosion:

- *Soil type*. According to the River Styles framework, the Upper Hawkesbury is mapped as laterally unconfined, low sinuosity, fine grained, with a moderate fragility (GHD, 2013). If boundary sediments had been assessed as sandy rather than fine grained, a high fragility rating would have resulted. Beca's July 2022 site visits found that the riverbanks between North Richmond and Cattai Creek are fairly consistently interbedded fine sand and fine sandy silt deposits with very low clay content. These are considered highly erodible alluvial sediments, including through piping processes.
- *Presence/absence of vegetation*. Rotational slumps can occur with or without vegetation, but 77% of the rotational slumps identified by SCS had no observed vegetation. Similarly, a previous assessment of the Hawkesbury River found frequent coincidence between bank erosion and riverbanks cleared of vegetation (BMT WBM, 2013). Research has shown that the presence of riparian forest on riverbanks significantly reduces the likelihood of mass failure due to reinforcement of riverbank soils by tree roots (Hubble et al., 2010).
- *Duration of overbank flooding*. The March 2022 flood had a very long duration of overbank flooding – 8 days above 10m AHD at Windsor (Table 2). This meant that soils were saturated for long periods.
- *Rate of drawdown*. The rate of drawdown of the river after the March and July 2022 flood peaks was similar, with March being marginally faster, with a maximum rate of 0.133 m/hr at Windsor. The water level in the river dropped by 1m approximately every 8 to 12 hours. As described above, this rate of drawdown may have led to gravitational slumping of saturated riverbanks.
- *Sequencing of floods.* The clustering of floods and the very wet weather experienced in 2022 could also be a factor, allowing the riverbanks little time to dry out and recover.
- *Local factors*. A number of other site-specific factors could also have exacerbated riverbank erosion, including:
    - points where pipes discharge local stormwater into the river
    - a bedrock outcrop and a river bend causing a large eddy that undermined the opposite silty sand riverbank (Douglas Partners, 2022)
    - 'hard' bank protection works or other foreshore structures that can redirect and accelerate flows that may then exacerbate bank erosion and/or cause adjacent 'soft' banks to be damaged (BMT WBM, 2013).

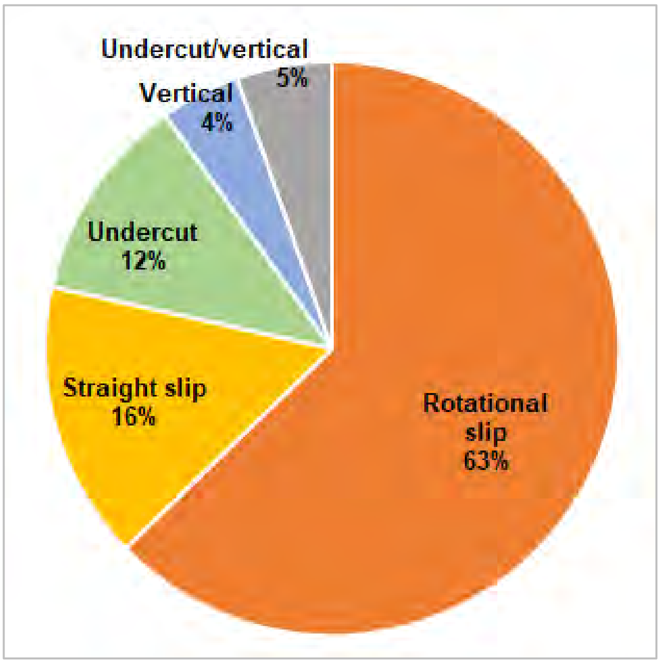


Figure 34: Type of erosion, Hawkesbury-Nepean River, post March/April 2022 floods

Data source: SCS, 2022 (N = 223)

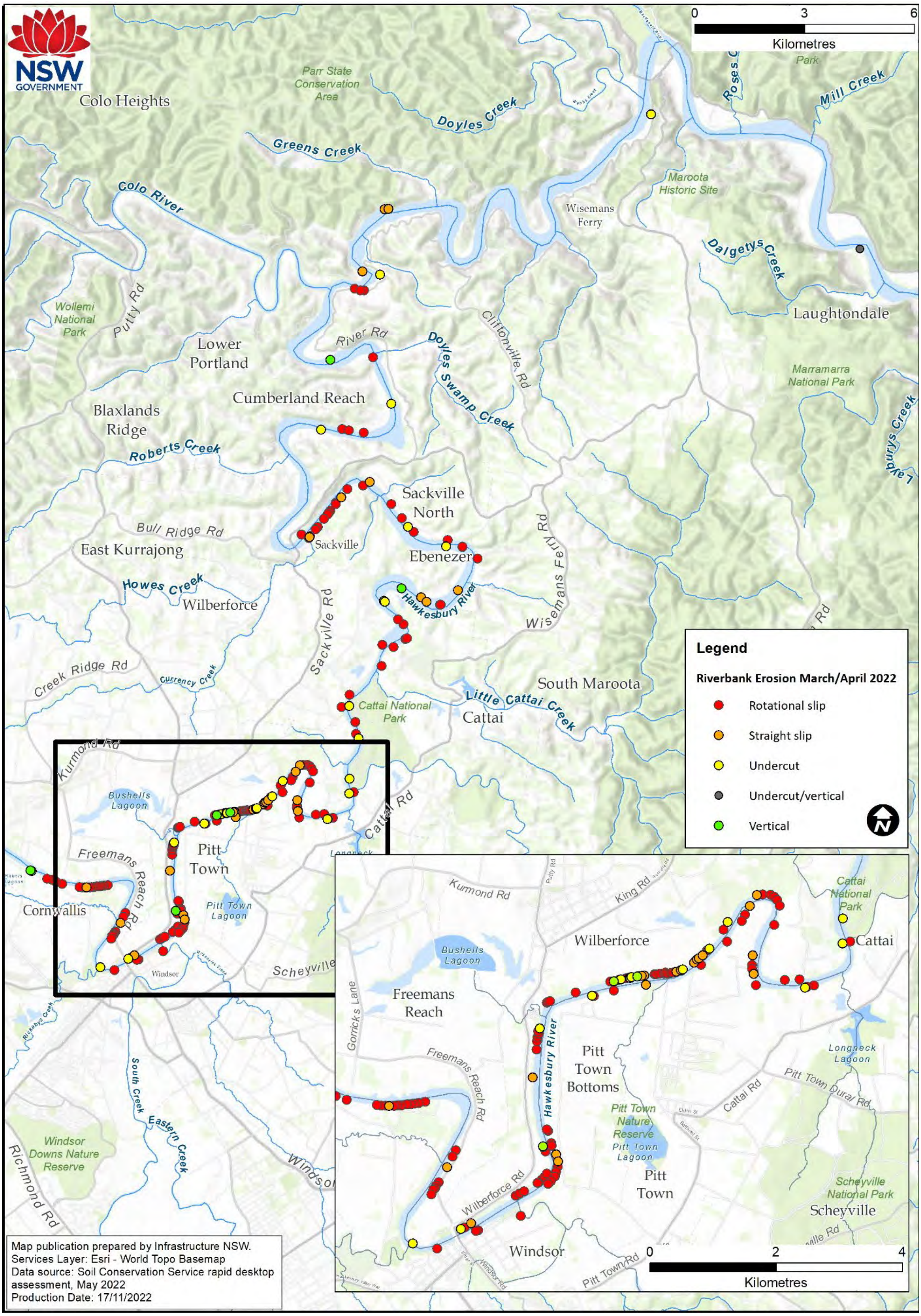


Figure 35: Type of erosion by spatial distribution, Hawkesbury River, post March/April 2022 floods

Figure 36: Riverbank erosion, 2022 floods

a. Riverbank Drive, Emu Heights, 4 August 2022

Photo by S. Yeo courtesy of Infrastructure NSW

b. Piping in riverbank downstream of North Richmond, July 2022

Photo courtesy of Beca (2022)

c. Edwards Road, Richmond Lowlands, 19 July 2022

Photo by Top Notch courtesy of Infrastructure NSW

d. Edwards Road, Richmond Lowlands, 4 August 2022 – interpreted as a piping failure (Neville, 2022)

Photo by S. Yeo courtesy of Infrastructure NSW

e. Cornwallis Road, Cornwallis, 4 August 2022

Photo by S. Yeo courtesy of Infrastructure NSW

f. Cornwallis Road, Cornwallis, 4 August 2022

Photo by S. Yeo courtesy of Infrastructure NSW

g. The Terrace, Windsor, 6 August 2022

Photo by S. Yeo courtesy of Infrastructure NSW

h. Governor Phillip Park, Windsor, 6 August 2022

Photo by S. Yeo courtesy of Infrastructure NSW

i. View from Punt Road Pitt Town across river to Wilberforce, 14 March 2022

Photo by Greg Miles, courtesy of Hawkesbury City Council

j. Wilberforce, 22 March 2022

Photo courtesy of NSW EPA

k. Portland Head Road, Ebenezer, after March 2022 flood

Photo by Greg Miles courtesy of Hawkesbury City Council

l. River Road, Lower Portland, 22 March 2022

Photo courtesy of NSW EPA

6. 'What if' scenarios

The March and July 2022 floods were the largest events at Windsor since 1978, and caused substantial damage. Various suggestions were made after the flood about how the flooding could have been reduced.

Given the Warragamba subcatchment provides the greatest contribution of high flows causing significant flooding along the Hawkesbury-Nepean River (see Section 4.3, Figure 31, Figure 32), the flood mitigation options most likely to offer regional flood mitigation benefits are those controlling floodwater from Warragamba.

Accordingly, several Warragamba Dam flood mitigation scenarios have been assessed using detailed models being developed for the Hawkesbury-Nepean River Flood Study. These show what difference these scenarios would have made to the height, timing and duration of the floods downstream. These scenarios all involve creating air space for the temporary capture of floodwaters, but by different means:

- pre-releasing water supply from Warragamba Dam on the basis of forecast rainfall rather than observed rainfall. This creates a risk that the inflows will not be sufficient to replenish the released supply by the conclusion of the event. Two hypothetical scenarios were modelled:
    - a 'realistic' scenario, where dam operators would have reasonable confidence that released supply would be replaced by inflows
    - an 'unrealistic' scenario, where dam operators would have less confidence that the forecast inflows would fill the dam, but would provide larger pre-releases
- permanently lowering Warragamba Dam full supply level (FSL)
    - by 5 metres
    - by 12 metres
- raising Warragamba Dam spillways and retaining current FSL to create a 14m flood mitigation zone.

A series of figures present the results of the assessments:

Metric	March 2022 flood	July 2022 flood
Reduced downstream peak levels at Penrith and Windsor for different scenarios	Figure 37 (Penrith), Figure 38 (Windsor)	
Reduced number of impacted buildings in the valley for different scenarios	Figure 39	Figure 40
Comparative timing of Warragamba Dam outflows for different scenarios	Figure 41	Figure 42
Comparative timing of representative downstream transport closures for different scenarios	Figure 43	Figure 44
Reduced duration of flooding at Windsor Bridge for different scenarios	Figure 45	Figure 46

The number of impacted buildings was assessed with reference to the distribution of residential dwellings, commercial/industrial buildings and manufactured homes in Infrastructure NSW's 2018 assets database.

The methodology and results of the assessment are detailed in Appendix E.

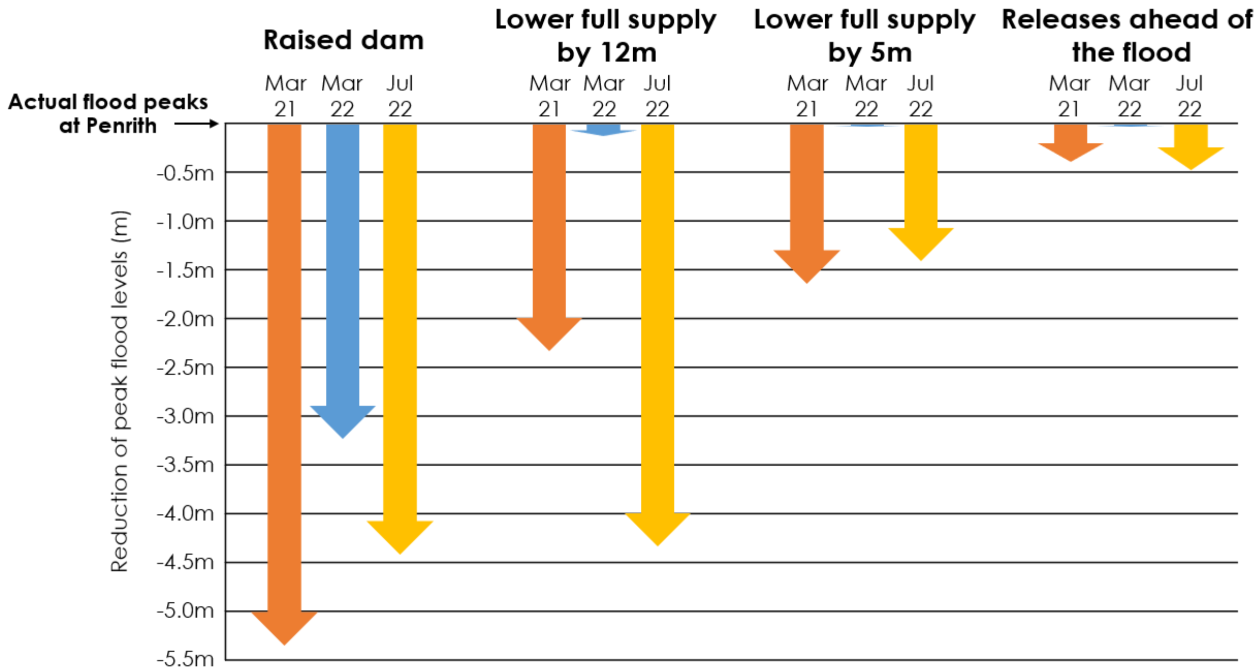


Figure 37: Reductions of peak flood levels at Penrith with potential Warragamba Dam flood mitigation measures, March 2021, March 2022 and July 2022 floods

Note: 'Releases ahead of the flood' presents the 'realistic' pre-release scenario

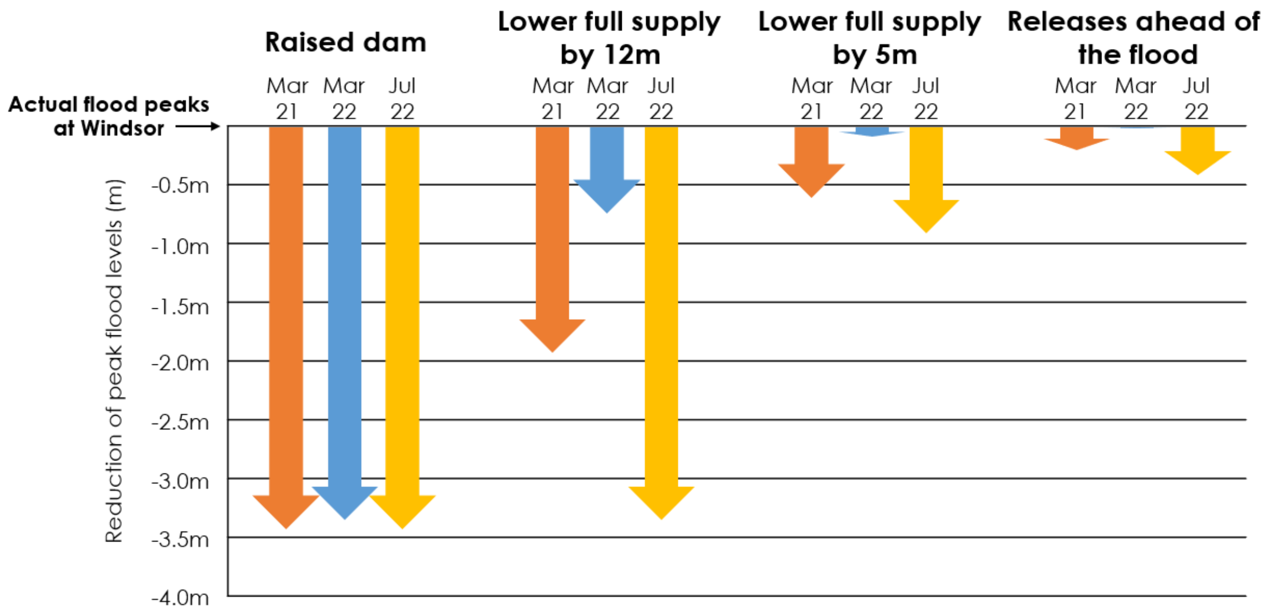


Figure 38: Reductions of peak flood levels at Windsor with potential Warragamba Dam flood mitigation measures, March 2021, March 2022 and July 2022 floods

Note: 'Releases ahead of the flood' presents the 'realistic' pre-release scenario

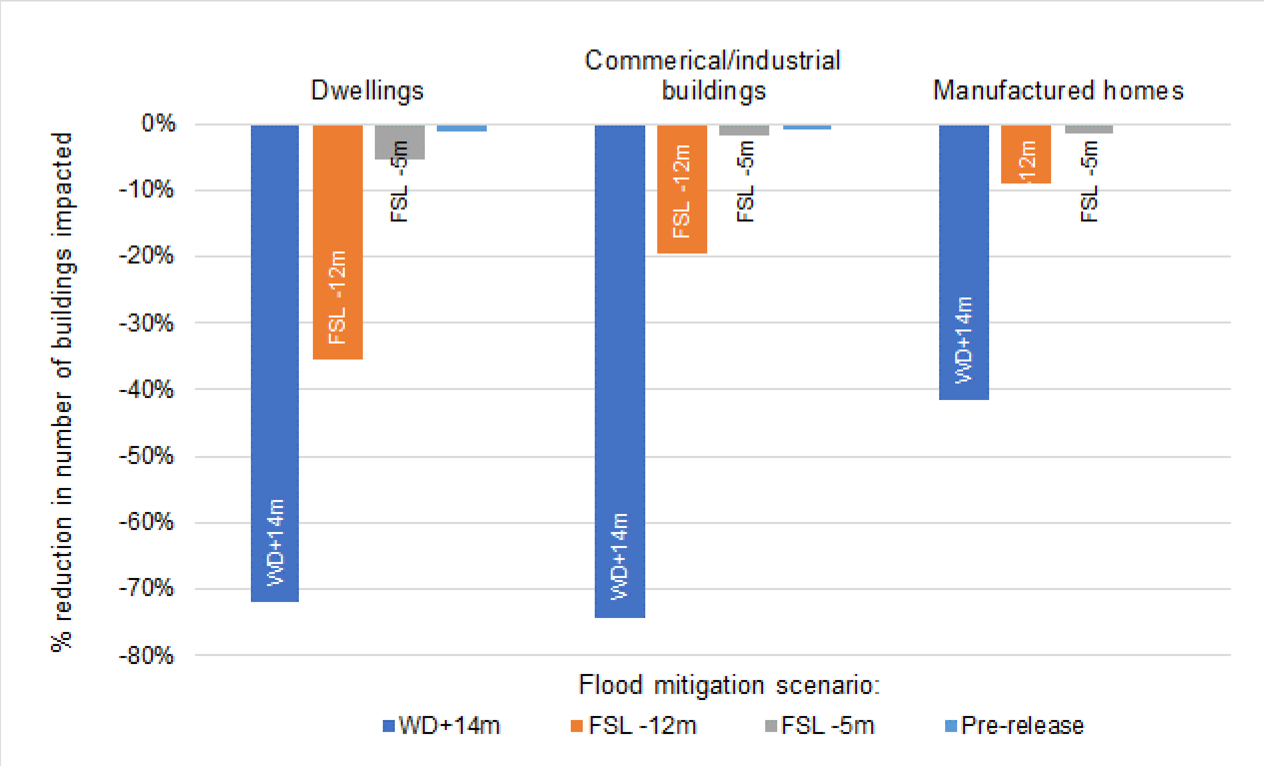


Figure 39: Change in number of buildings in the valley impacted with different flood mitigation scenarios, March 2022 flood

Note: 'Pre-release' presents the 'realistic' pre-release scenario

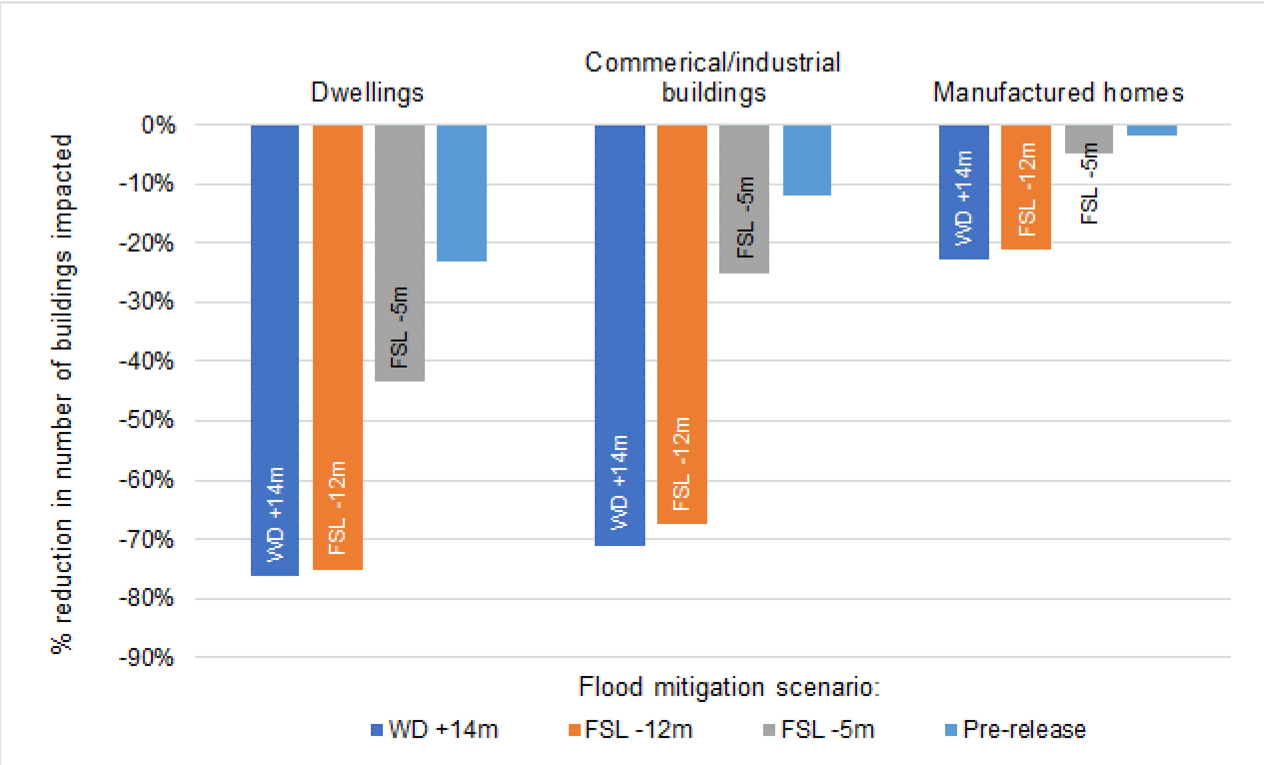


Figure 40: Change in number of buildings in the valley impacted with different flood mitigation scenarios, July 2022 flood

Note: 'Pre-release' presents the 'realistic' pre-release scenario

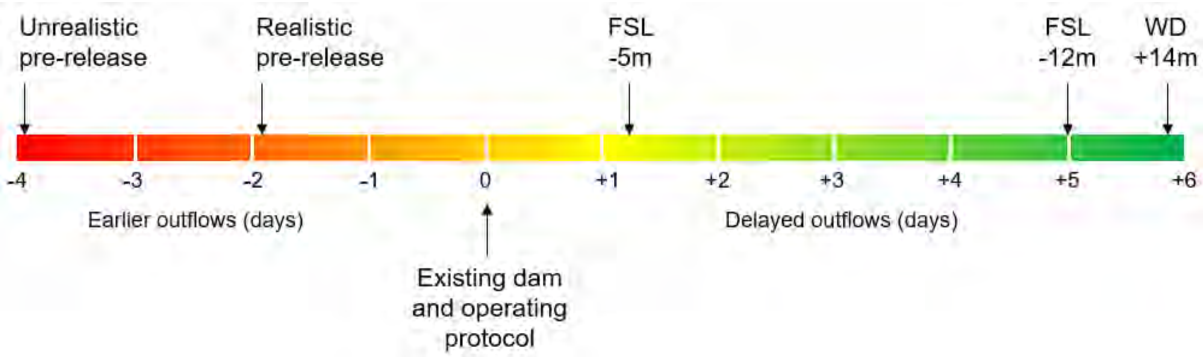


Figure 41: Effect of potential Warragamba Dam flood mitigation measures on timing of outflows from Warragamba Dam, March 2022 flood

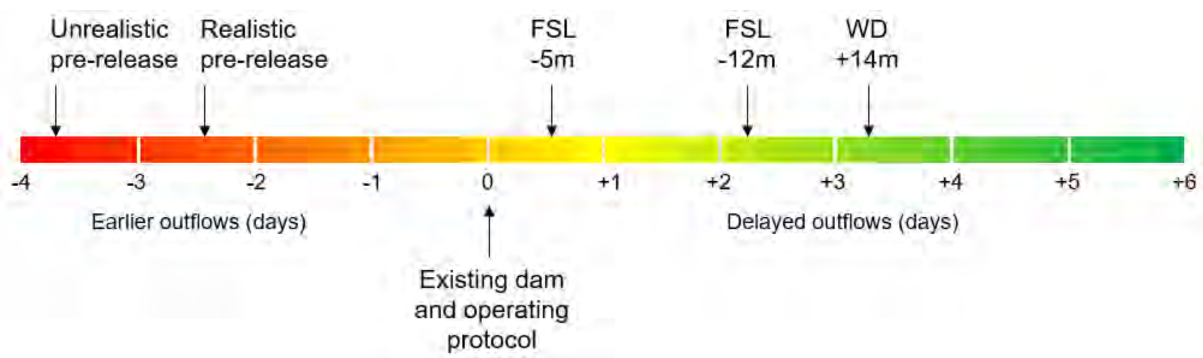


Figure 42: Effect of potential Warragamba Dam flood mitigation measures on timing of outflows from Warragamba Dam, July 2022 flood

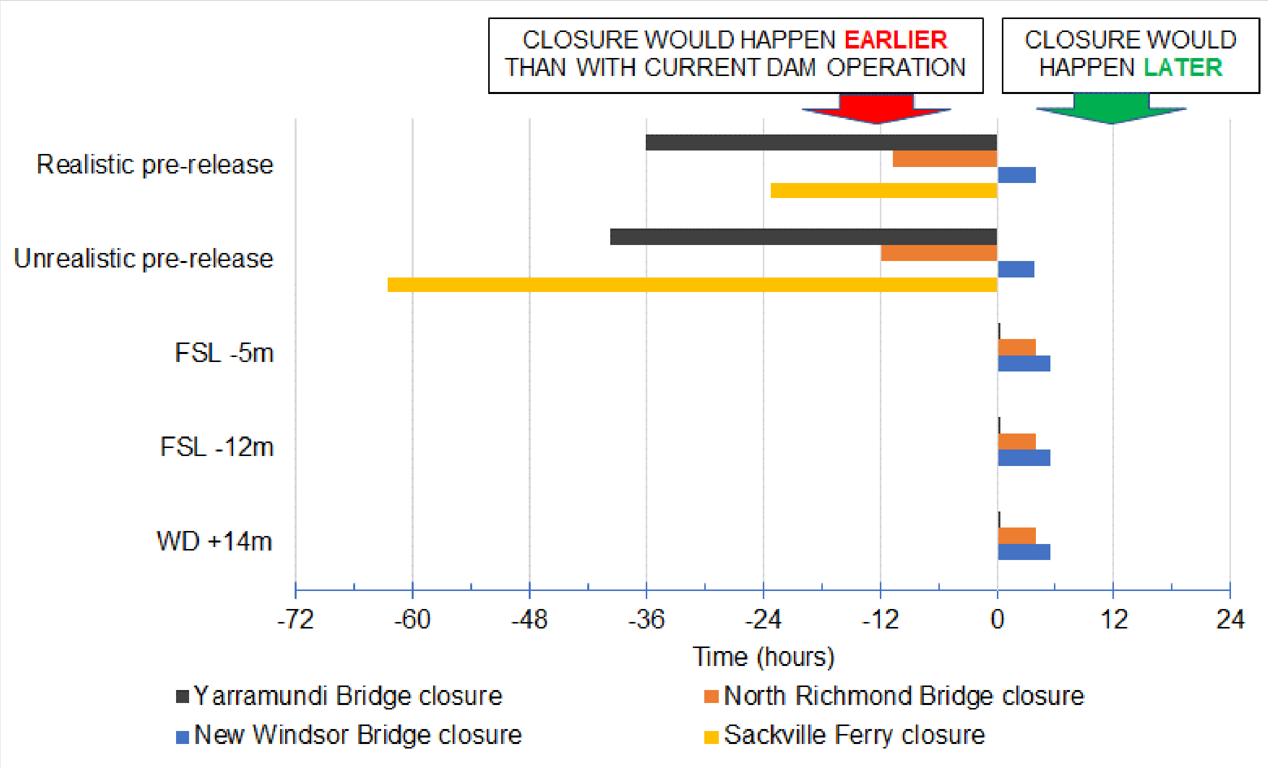


Figure 43: Effect of potential Warragamba Dam flood mitigation measures on timing of downstream consequences, March 2022 flood

Note: Only first March 2022 flood peak considered

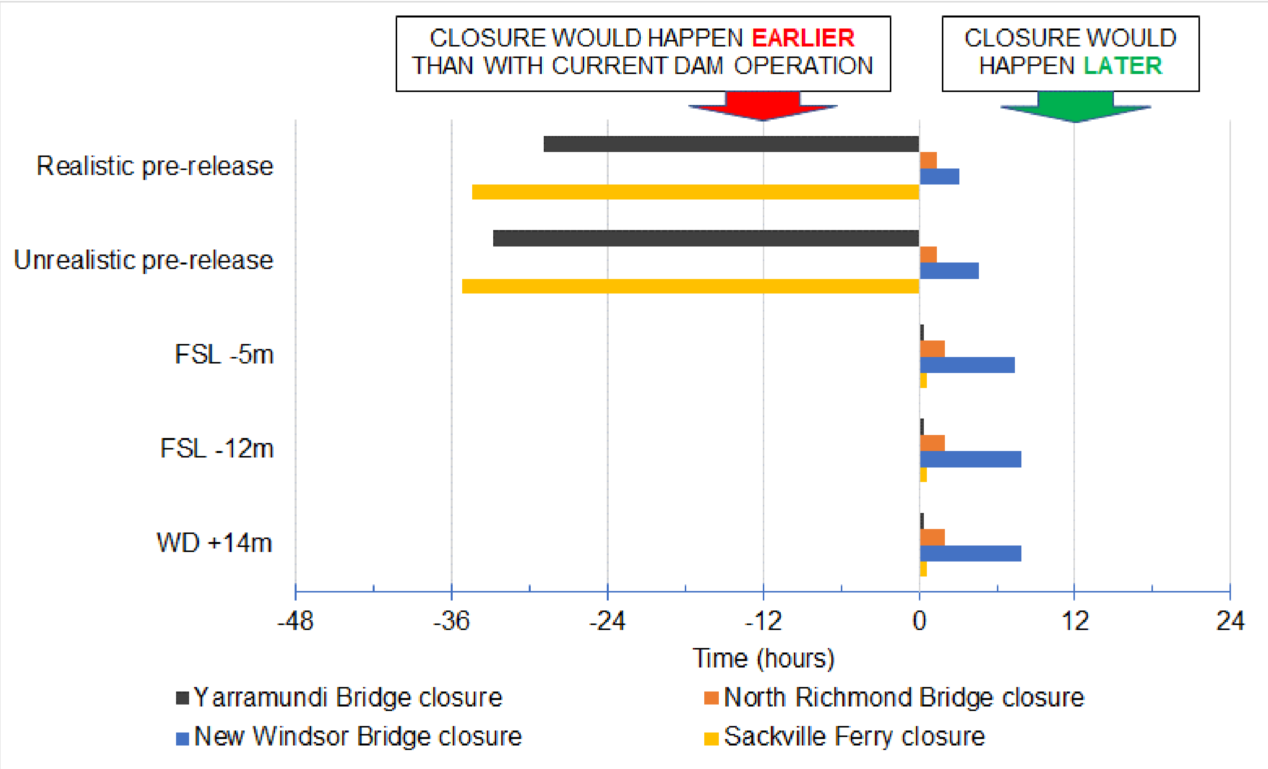


Figure 44: Effect of potential Warragamba Dam flood mitigation measures on timing of downstream consequences, July 2022 flood

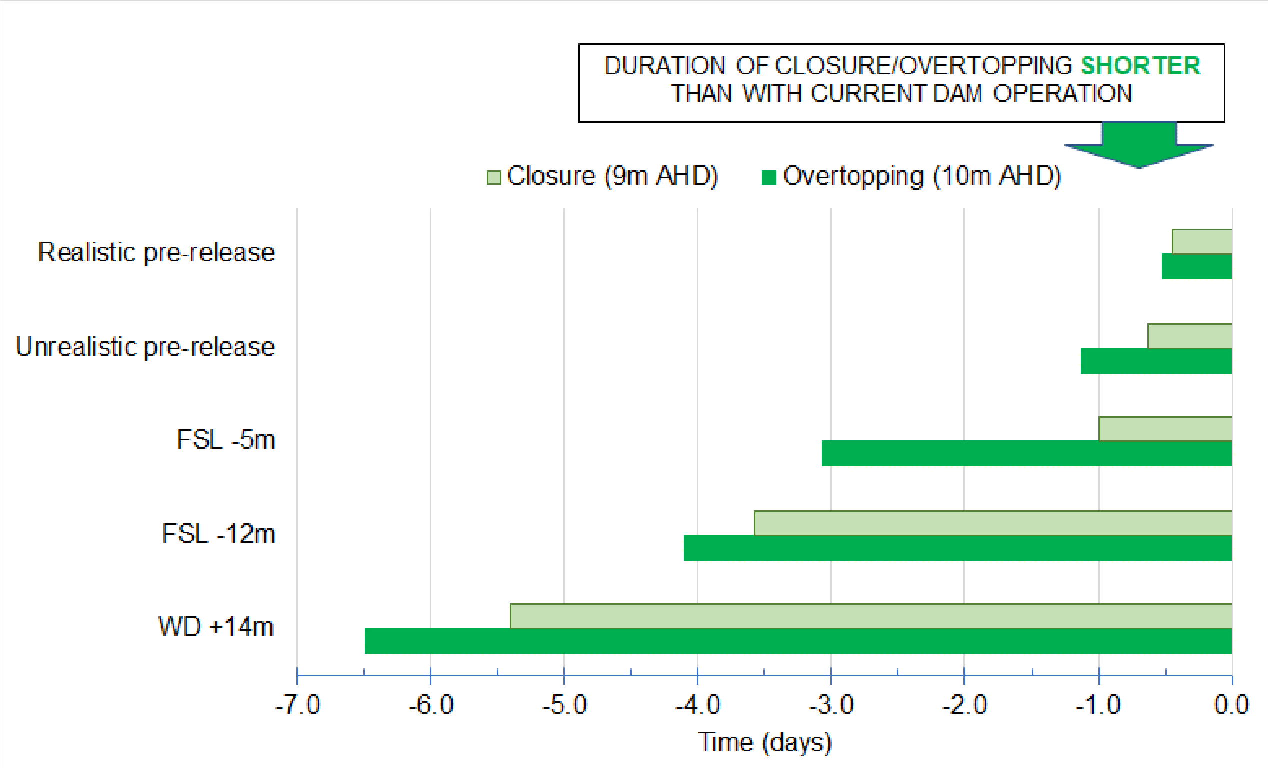


Figure 45: Effect of potential Warragamba Dam flood mitigation measures on duration of new Windsor Bridge closure, March 2022 flood

Note: Overtopping of the bridge is likely to increase the time of closure. When the bridge deck is flooded it can take 1 or 2 days to clear the debris and mud to make the bridge safe to reopen. Hence, reduced overtopping durations are also shown above.

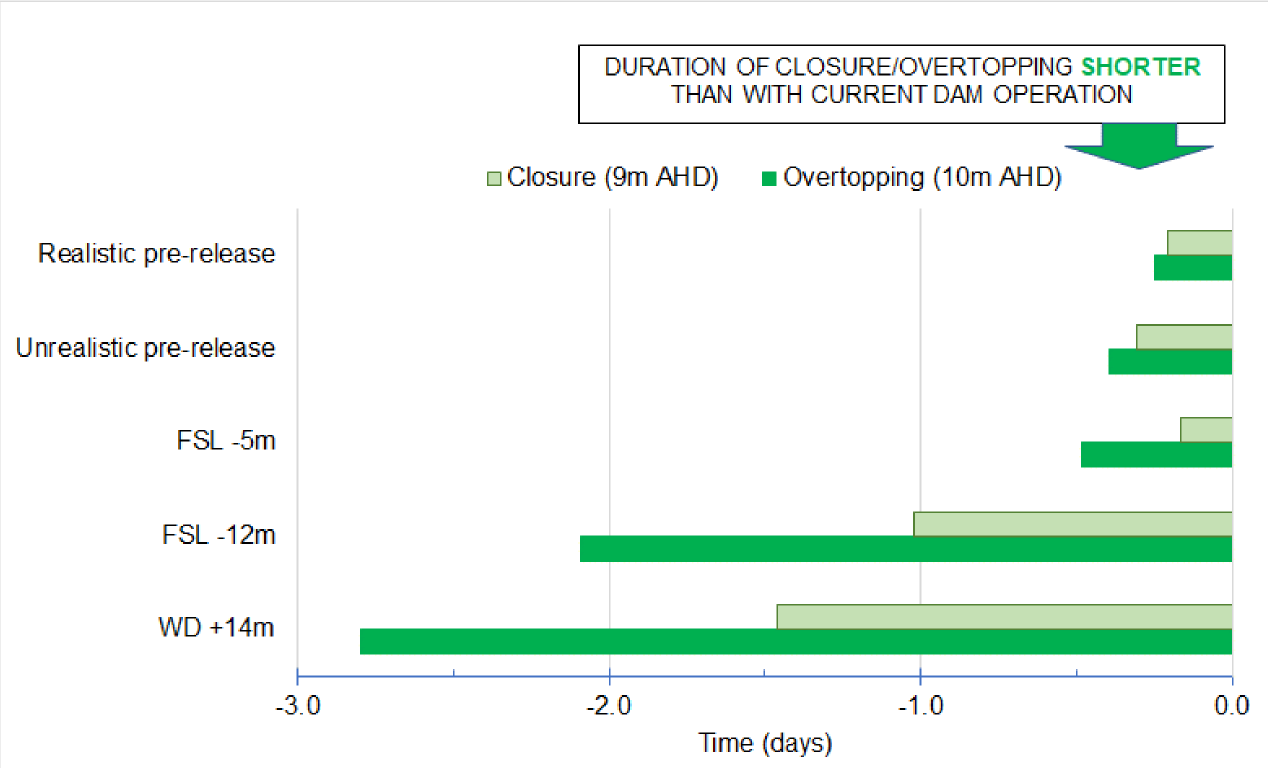


Figure 46: Effect of potential Warragamba Dam flood mitigation measures on duration of new Windsor Bridge closure, July 2022 flood

Note: Overtopping of the bridge is likely to increase the time of closure. When the bridge deck is flooded it can take 1 or 2 days to clear the debris and mud to make the bridge safe to reopen. Hence, reduced overtopping durations are also shown above.

6.1 Pre-releases

After the floods, there were suggestions that Warragamba Dam's water supply level should have been drawn down before the flood to make space for anticipated flood inflows to the dam, to reduce downstream flooding. The constraints upon and limited effectiveness of such a pre-release dam operational strategy have been described in the *Taskforce Options Assessment Report* (Infrastructure NSW, 2019), the *Hawkesbury-Nepean River March 2021 Flood Review* (Infrastructure NSW, 2021a), and a 'Hawkesbury-Nepean flooding and Warragamba Dam' fact sheet (Infrastructure NSW, 2021b).

One constraint is regulatory: the dam owner and operator, WaterNSW, is not authorised to undertake pre-releases in the way suggested by some stakeholders. Warragamba Dam is the primary water supply for Greater Sydney, and is operated to capture and store water. Small releases are made when the dam is at FSL to maintain a level 0.3m to 1.0m below FSL, to avoid the main radial gates repeatedly opening and closing due to small fluctuations around FSL. To release any more water prior to a forecast rain event – noting that water supply would be lost if the rain didn't come – would be a breach of the dam's key operation objective to provide water security for Greater Sydney.[9]

Gelling (2022) identified that to operate Warragamba Dam for flood mitigation would likely require changes to the WaterNSW operating licence, Greater Metropolitan Water Sharing Plan, the dam's water supply works and water use approvals and the associated operating protocol.

A second constraint is the greater uncertainty of rainfall forecasts in the timeframe required to release enough stored water to make a difference to peak levels downstream. The example of the June 2016 flood was provided in the *Taskforce Options Assessment Report*. Contrary to early rainfall forecasts, most rain fell over the Georges River catchment rather than the Warragamba catchment. Had pre-releases from Warragamba Dam been made on the basis of the early forecasts, water supply would have been lost unnecessarily, which would have had significant implications for Greater Sydney in the severe drought of 2017-2020.

A third constraint is the need to minimise the adverse downstream impacts of pre-releases. If the releases are too high, critical transport routes will be cut earlier, and flood preparations will be disrupted. A maximum rate of release of 100 gigalitres per day (GL/day) – accounting for inflows from the upper Nepean River as well as Warragamba releases – was adopted for these scenarios as a trade-off between the objectives of:

- limiting unacceptable downstream impacts, though at least Yarramundi Bridge would be flooded at this rate, and
- making enough space in the dam to capture sufficient inflows to potentially provide benefits downstream.

In some events this rate of release would make some evacuation routes susceptible to earlier closure if there is intense rainfall downstream of the dam during the evacuation phase.

Despite these constraints, 2 hypothetical pre-release scenarios were modelled for both the March and July 2022 floods, to assess what difference these could have made to downstream flooding. These scenarios were provided by WaterNSW. A 'realistic' pre-release scenario is one in which the 50% chance rainfall forecast would give the dam operators reasonable confidence that the released water would be replaced by inflows. An 'unrealistic' pre-release scenario is one based more on the 25% chance rainfall forecast (judged to have too much uncertainty to release water supply).

[9] https://www.waternsw.com.au/about/newsroom/2020/operating-warragamba-when-at-100-capacity, accessed 10 November 2021

Realistic pre-release

In the case of the March 2022 flood, a realistic pre-release could have commenced on 28 February, and in the case of the July 2022 flood, it could have commenced on 30 June.

Figure 37 and Figure 38 show that such a pre-release in the March event would have provided zero mitigation of peak flood heights at Penrith and Windsor. This is an important finding – in some floods such as the double-peaked, high volume March flood, pre-releases will provide no 'gain' despite some 'pain' (described below). Even in the more typical, single peaked July flood, peak flood levels would have been reduced by less than 0.5m. In general, pre-releases fail to provide a significant regional reduction of flood risk, which was one of the key criteria informing the Flood Strategy.

The 'pain' from pre-releases is that early releases from the dam (Figure 41, Figure 42) elevate the river levels earlier and bring forward the closure of important transport routes including Yarramundi Bridge, Sackville Ferry, and, in some circumstances, North Richmond Bridge (Figure 43, Figure 44).

Table E12 in Appendix E shows that in March a realistic pre-release would also have brought forward the time at which the 'minor' flood level at Windsor would have been reached by nearly 2 days. This scale of flooding can have serious consequences for communities downstream of Windsor.

Far from reducing the risk, pre-releases could affect evacuation timing and property-saving efforts.

Unrealistic pre-release

In the case of the March 2022 flood, an unrealistic pre-release might have commenced on 26 February, and in the case of the July 2022 flood, it might have commenced on 29 June.

Like the realistic pre-release, the unrealistic pre-release would have provided negligible reductions of flood peaks in March, and small (<1m) reductions of flood peaks in July (see Tables E7 and E10).

Its downside in bringing forward closure of downstream transport routes is even more pronounced than for the realistic scenario (Figure 43, Figure 44).

La Niña season pre-release

Another suggestion was that because La Niña was forecast for the 2021-2022 summer, Warragamba Dam should have been drawn down earlier in the season. This is because La Niña events are typically accompanied with an increased chance of wetter catchments conducive to water runoff.

There have been La Niña years with Hawkesbury-Nepean floods, and sometimes multiple floods, such as in 1950, 1956, 1988, and, as it's turned out, 2022. However, there have also been La Niña years without Hawkesbury-Nepean floods, such as in the dry La Niña of 1938-1939.[10] It's also noteworthy that 3 of the 6 largest Hawkesbury floods since Warragamba Dam was completed in 1960 did not correlate with La Niña – in 1961, 1978 and 1990.

The actual pattern of rainfall in La Niña years is unpredictable. For example, rain associated with the 2020-2021 La Niña largely missed the Wivenhoe Dam catchment in south-east Queensland, with the dam falling to 36% capacity.

The challenges of forecasting East Coast floods at a seasonal scale, or at precise locations, are underscored by a paper commissioned by the *2022 NSW Flood Inquiry* (Pitman et al., 2022). Pertinent extracts are provided below:

> 'Climate phases do not in themselves cause extreme rainfall, which makes prediction of extreme rainfall on seasonal timescales very challenging' (p.8)
>
> 'None of the climate drivers reliably signal that a … *flooding* summer is likely to occur… The climate drivers do not provide this kind of predictive skill' (p.9)
>
> 'The forecasting of extreme rainfall that typically causes the most extreme floods is not skilful beyond about a week at any time of year' (p.9)

[10] Australian rainfall during El Niño and La Niña events (bom.gov.au), accessed 10 November 2021

> 'On timescales of a few days, the forecasting of an event in the *proximity* to a specific catchment is feasible, within limits associated with the predictability of any extreme event' (p.9).

On the question of future prospects, the paper made this salient point:

> *'It is unlikely that forecasts of localised extreme rainfall at a specific location on timescales of weeks will ever be possible…'* (p.9, emphasis added).

A key reason why La Niña is of limited value for flood forecasting on the Eastern Seaboard is the weak to non-existent relationship between the frequency and intensity of East Coast Lows and climate drivers (Pepler et al, 2014; Pepler, 2022).

In short, the occurrence of La Niña does not guarantee flooding rainfall, or flooding rainfall within a specific catchment. This means that releasing storage water ahead of a La Niña would represent a significant risk to Greater Sydney's water security.

6.2 Lower FSL by 5 metres

Permanently lowering Warragamba Dam's FSL by 5 metres would provide about 360 GL of air space in the dam to temporarily capture flood inflows. This corresponds to about 18% of Warragamba's storage volume. An assessment of the flood mitigation benefits of permanently lowering FSL by 5 metres, against the full range of floods, is described in the *Taskforce Options Assessment Report* (Infrastructure NSW, 2019). It shows that the benefits of this option rapidly diminish for floods rarer than the 1 in 20 chance per year event, where the bulk of the flood risk is concentrated.

Modelling of the recent floods with FSL lowered by 5 metres shows the following results:

- Figure 37 and Figure 38 show that in the March 2022 event, lowering FSL by 5 metres would have provided minimal mitigation of peak flood heights at Penrith and Windsor; the number of dwellings impacted by the flood across the valley would have been reduced by 5% (Figure 39)
- Greater mitigation of flood peaks would have been possible in the smaller volume July 2022 flood – 1.4m at Penrith (Figure 37) and 0.9m at Windsor (Figure 38); the number of dwellings impacted by the flood across the valley would have been reduced by 43% (Figure 40)
- Lowering FSL by 5 metres would have done very little in either flood to save manufactured homes in caravan parks (Figure 39, Figure 40)
- Outflows from Warragamba Dam would have been delayed by 1.2 days in March (Figure 41) and 0.6 days in July (Figure 42)
- The initial time of closure of Windsor Bridge would have been delayed by around 6 hours in March (Figure 43) and 8 hours in July (Figure 44)
- The duration of closure of Windsor Bridge would have been shortened by 1 day in March (Figure 45) and 0.2 days in July (Figure 46).

Relative to the proposed dam raising or lowering FSL by 12 metres, the benefits of lowering FSL by 5 metres would have been minimal (March) to small/moderate (July). This reflects the limited air space created (Figure 47). It doesn't provide the *significant*, regional reduction of flood risk that was a key criterion in developing the Flood Strategy.

This option also has significant implications for Greater Sydney's water supply. Had FSL been lowered by 5 metres in 2016, the subsequent 2017-2020 drought would have seen dam storage volumes dropping to a critical 26% in February 2020 (Figure 48) – lower even than the 34% recorded during the Millennium drought. Lowering FSL by 5 metres would result in a yield reduction of 35 GL/year or 8 months' worth of Sydney's water supply. Changing the Sydney Desalination Plant to run full time is modelled to result in an increased supply of 20 GL/year (source: WaterNSW). Thus, the shortfall could not be made up by existing water sources – new sources of supply would be required to be built, such as additional desalination plants or water recycling plants.

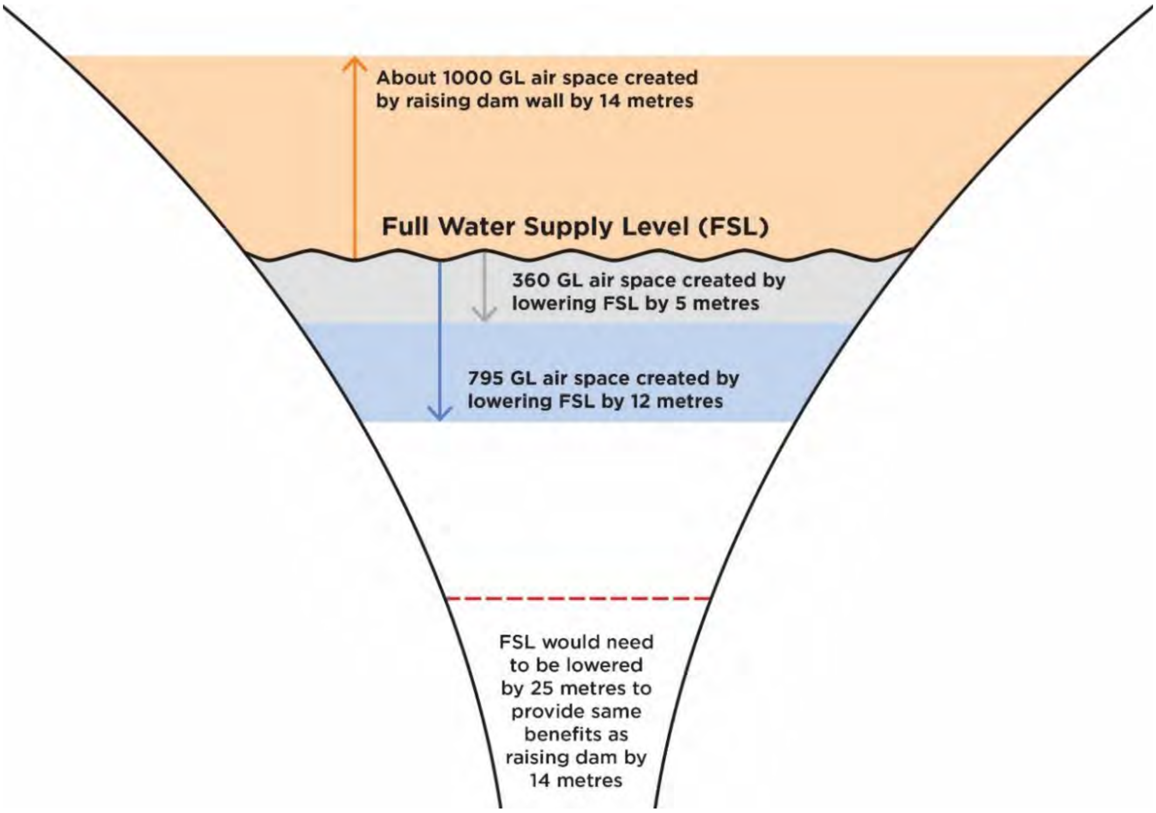


Figure 47: Schematic of Warragamba Dam flood mitigation scenarios

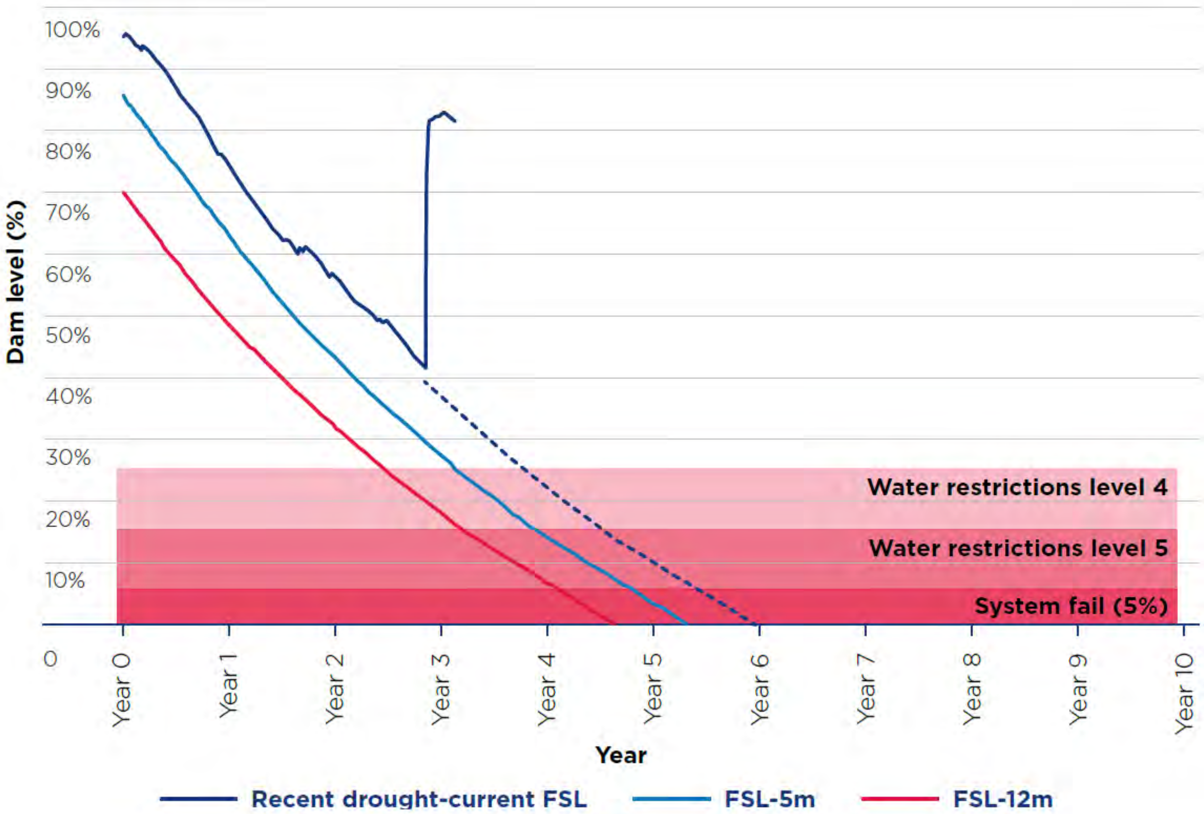


Figure 48: Impact of reducing the full supply level (FSL) of Warragamba Dam on time to reach total system storage critical levels

Source: Greater Sydney Water Strategy (DPE, 2022)

The limited benefits of lowering FSL by 5 metres, and the costs associated with alternative water supply, means the option has a benefit-cost ratio of 0.52 (Infrastructure NSW, 2021c).

6.3 Lower FSL by 12 metres

Permanently lowering Warragamba Dam's FSL by 12 metres would provide about 795 GL of air space in the dam to temporarily capture flood inflows. This corresponds to about 39% of Warragamba's storage volume. An assessment of the flood mitigation benefits of permanently lowering FSL by 12 metres, against the full range of floods, is described in the *Taskforce Options Assessment Report* (Infrastructure NSW, 2019). It shows that this option would provide moderate benefits (1 – 2m reduction in flood peaks) for most of the critical flood range at Windsor.

Modelling of the recent floods with FSL lowered by 12 metres shows the following results:

- Figure 37 and Figure 38 show that in the March 2022 event, lowering FSL by 12 metres would have provided small mitigation of peak flood heights at Penrith (0.1m) and Windsor (0.7m); the number of dwellings impacted by the flood across the valley would have been reduced by 35% but the number of impacted manufactured homes by only 9% (Figure 39)
- Greater mitigation of flood peaks would have been possible in the smaller volume July 2022 flood – 4.4m at Penrith (Figure 37) and 3.3m at Windsor (Figure 38); the number of dwellings impacted by the flood across the valley would have been reduced by 75% and the number of manufactured homes by 21% (Figure 40)
- Outflows from Warragamba Dam would have been delayed by 5 days in March (Figure 41) and 2.3 days in July (Figure 42)
- The initial time of closure of Windsor Bridge would have been delayed by around 6 hours in March (Figure 43) and 8 hours in July (Figure 44)
- The duration of closure of Windsor Bridge would have been shortened by 3.6 days in March (Figure 45) and 1 day in July (Figure 46).

For events of the scale of the March and July 2022 floods – assessed as around 1 in 20 chance per year events based on peak heights at Windsor – the option to lower Warragamba Dam FSL by 12 metres is generally expected to provide about 3m reduction to peak heights at Windsor (Figure 49). However, the results for the recent floods are somewhat mixed:

- Because the March flood had 2 peaks and was of relatively high volume, the 795 GL air space in the dam created by lowering FSL would have been filled, and the second peak from the dam would have been unmitigated. Hence, peak levels at Penrith would have been reduced by a small amount, though Windsor would have seen somewhat greater reductions, and the valley-wide reduction in dwellings impacted would still have been reasonable – albeit substantially less than for the raised dam scenario.
- In the smaller volume July flood, lowering FSL by 12 metres would have performed better than in March, and similar to the raised dam.

The distinction between the proposed raised dam and lowering FSL by 12 metres is generally more pronounced in larger, rarer floods like the 1 in 50 chance per year event or the 1867 flood of record, similar to a 1 in 500 chance per year flood (Figure 49). This reflects 2 aspects:

- The volume of water stored before the dam spills. Figure 47 shows the relative sizes of the air spaces provided by each option.
- The way floodwaters are released when it is spilling. With the 12m-lowering, once the dam storage levels reach the current FSL, to maintain dam safety the 12m-high gates have to open in rapid succession to minimise further rises in dam level, which minimises any further mitigation capacity. The proposed raised dam has fixed spillways at 12m and 14m above FSL, which means that the

dam level will continue to rise and provide flood mitigation until the discharges over the spillway match the dam inflows.

It is noted that the results for this option are conservative (that is, likely to slightly overstate the benefits of the -12m option). This is because the very low discharge capacity when the storage level approaches 12 metres below FSL would mean that most large floods would start in the range of -10m to -12m. The option would require modifications to the dam to enable controlled releases of flood inflows at lower levels.

This option also has significant implications for Greater Sydney's water supply because it would reduce Warragamba Dam's storage by around 39% and the total system storage by around 30%. Had FSL been lowered by 12 metres in 2016, the subsequent 2017-2020 drought would have seen total system storage volumes dropping to a critical 20% in February 2020 (Figure 48). This option would reduce the long-term sustainable supply by 80 GL/year (DPE, 2022). The shortfall of supply would need to be replaced with other new sources of supply, such as additional desalination plants or water recycling plants.

Lowering FSL by 12 metres might also have adverse impacts on water quality in the storage when it floods. Especially for the March 2022 flood, it would have reduced the dilution of the dirty intrusion and limited the flexibility to select optimum water for supply.

The high costs associated with the alternative water supply and required dam modification means the option has a benefit-cost ratio of 0.38 (Infrastructure NSW, 2021c).

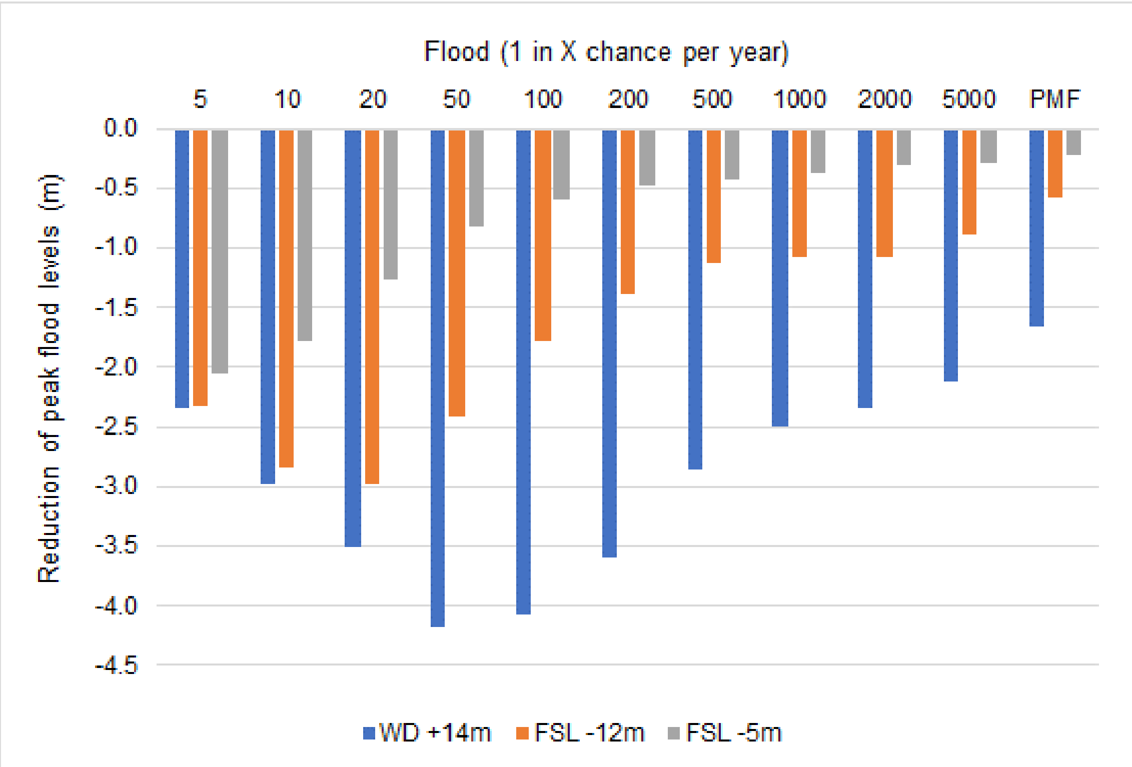


Figure 49: Modelled reduction in peak flood levels at Windsor, by flood size

Source: Adapted from *Warragamba Dam Raising Environmental Impact Statement* (SMEC, 2021) Figure 4-13

6.4 Proposed raised dam

An assessment of the flood mitigation benefits of raising Warragamba Dam wall to create a 14-metre flood mitigation zone against the full range of floods is described in the *Taskforce Options Assessment Report* (Infrastructure NSW, 2019). This was the preferred option carried forward to the *Warragamba Dam Raising Environmental Impact Statement* (SMEC, 2021).

Modelling of the recent floods with the proposed raised dam shows the following results:

- The raised dam is the only scenario that would have significantly reduced peak heights at Penrith and Windsor in the double-peaked, high volume March 2022 flood (Figure 37, Figure 38)
- The reductions in the extent and depth of the March 2022 flood in the Richmond/Windsor floodplain are presented in Figure 50 – the areas flooded to depths >4m are much reduced
- The number of impacted dwellings, commercial/industrial buildings, and manufactured homes across the valley in March 2022 would have been reduced by 72%, 74% and 42%, respectively (Figure 39)
- The raised dam would have provided similar or greater peak height reductions in the July 2022 flood, as well as in the March 2021 flood (Figure 37, Figure 38); the raised dam is the only Warragamba Dam flood mitigation option that would have provided consistently large reductions in flood peaks across all 3 of these different floods
- The reductions in the extent and depth of the July 2022 flood in the Richmond/Windsor floodplain are presented in Figure 51 – similar to the result for the March 2022 event
- The number of impacted dwellings, commercial/industrial buildings, and manufactured homes across the valley in July 2022 would have been reduced by 76%, 71% and 23%, respectively (Figure 40). The relatively small reduction in the number of impacted manufactured homes may reflect the high exposure (low elevations) of caravan parks, as well as the height of the July flood especially in the lower Hawkesbury, so that even with significant reductions in peak heights from a raised dam, many manufactured homes would remain exposed.
- Outflows from Warragamba Dam would have been delayed by nearly 6 days in March (Figure 41) and over 3 days in July (Figure 42)
- The initial time of closure of Windsor Bridge would have been delayed by around 6 hours in March (Figure 43) and 8 hours in July (Figure 44)
- The duration of closure of Windsor Bridge would have been shortened by 5.4 days in March (Figure 45) and 1.5 days in July (Figure 46) – a greater benefit than the other scenarios.

The significant downstream benefits of raising Warragamba Dam as proposed reflects the quantum of air space created (Figure 47), as well as design features to optimise flood mitigation.

The distinction between the proposed raised dam and other options is typically more pronounced in larger, rarer floods like the 1 in 50 chance per year event or the 1867 flood of record, similar to a 1 in 500 chance per year flood (Figure 49). This is where more exposure is located, with around 60% of average annual damages in the valley occurring within this critical flood range (SMEC, 2021, Figure 4-9).

Raising Warragamba Dam, while retaining current FSL, would have no lasting impacts on the volume of water available for supply, unlike the 2 options lowering FSL.

Raising Warragamba Dam would raise and prolong temporary inundation upstream of the dam wall. The heights behind a raised dam with a dedicated flood storage zone are largely a function of inflow volume. The unusual double-peaked nature of the March 2022 flood, with large inflow volumes to Warragamba Dam, is modelled to have resulted in a peak height upstream of the proposed raised dam of about 131.62m AHD. The more typical single-peaked July 2022 flood is modelled to have reached 126.89m AHD upstream of the proposed raised dam.

There has been considerable interest in how the proposed raised dam could impact the duration of flooding downstream, given the prolonged controlled releases to draw down the flood mitigation zone to FSL. This has been assessed for the recent floods, with changes in duration presented for the Richmond/Windsor floodplain in Figure 52 and Figure 53. There are a few notable features:

- As also displayed in Figure 50 and Figure 51, there are substantial areas that would no longer have flooded (see 'was wet now dry')
- The durations of flooding would have been reduced in many areas including much of Richmond Lowlands, especially in the lower volume July flood
- Some low-lying areas would have had longer duration flooding including areas adjacent to South and Eastern creeks.

It's noteworthy that the floodplain is characterised by some lagoons/wetlands (see Appendix F), which are already flooded. That these survived the 28-year period between 1992 and 2020 without moderate floods suggests that they may be adequately fed by local catchments, and that they exhibit a degree of resilience to the variable climate.

Recent work has also considered how controlled releases from a raised dam could influence riverbank erosion (Beca, 2022). The dominant form of erosion seen in the March and July 2022 floods – gravitational/rotational slumping as the flood recedes – would likely reduce because of lower peak flood levels and slower drawdown of the river level thus reducing the hydraulic gradient between pore water in the riverbank and water in the river. However, sustained bank full flows in the river could promote gravitational failures induced by undercutting and cleanout at the base of the predominately sandy banks.

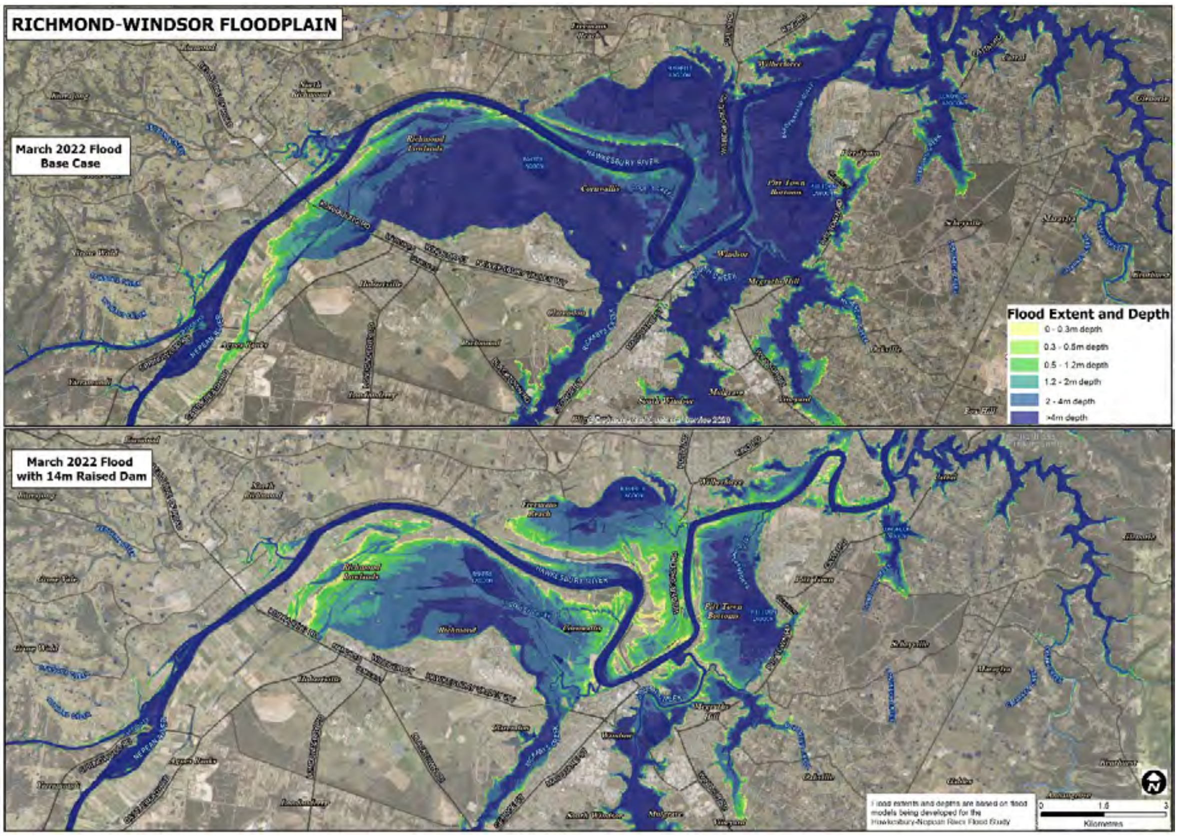


Figure 50: Flood extents/depths, March 2022 flood, existing dam operations versus raised dam, Richmond/Windsor floodplain

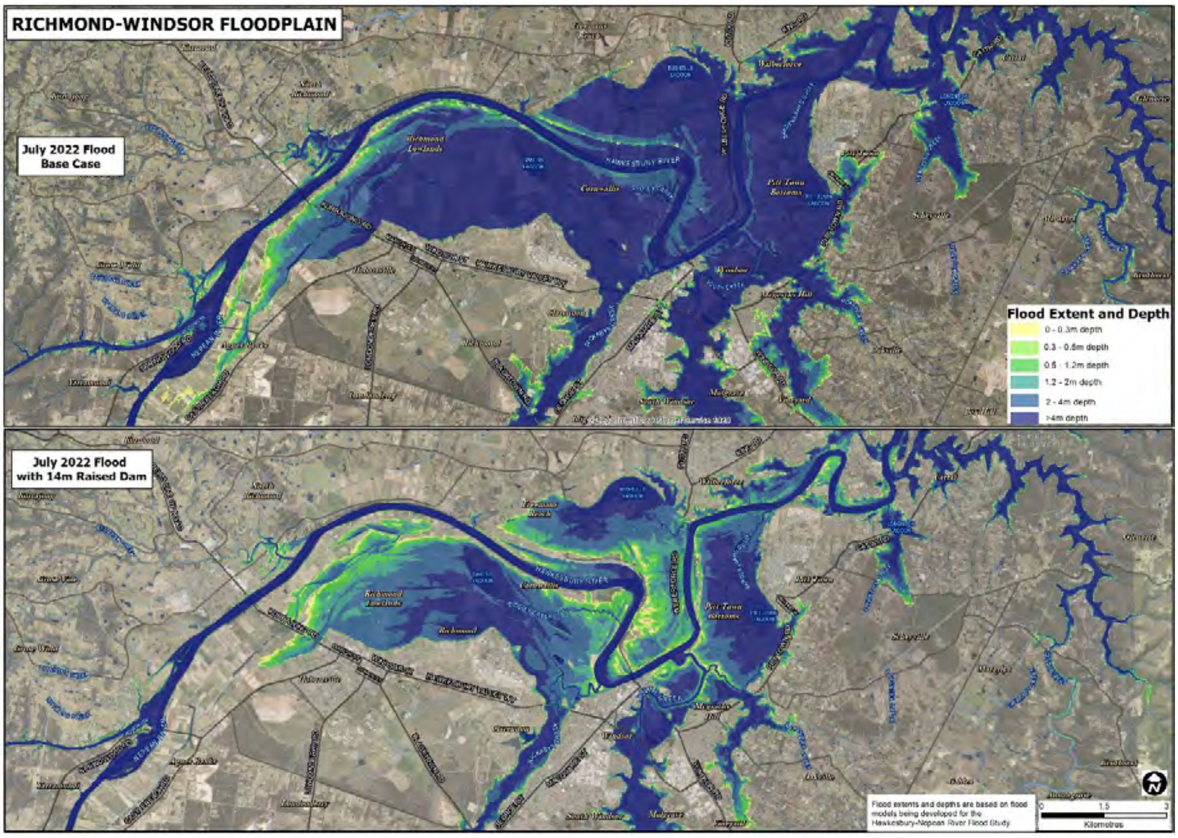


Figure 51: Flood extents/depths, July 2022 flood, existing dam operations and with raised dam, Richmond/Windsor floodplain

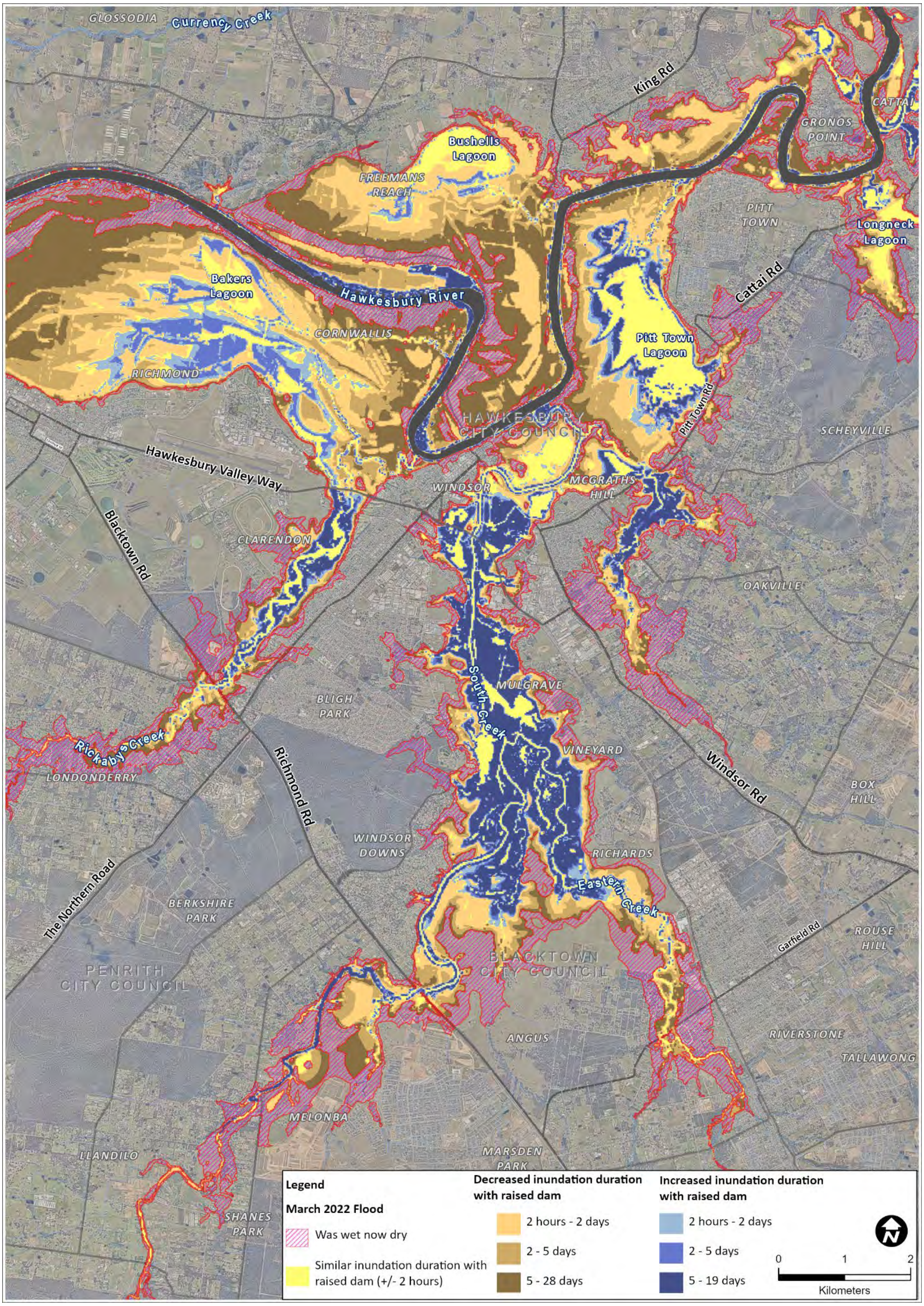


Figure 52: Change in flood duration, March 2022 flood, existing H14 dam operations versus raised dam, Richmond/Windsor floodplain

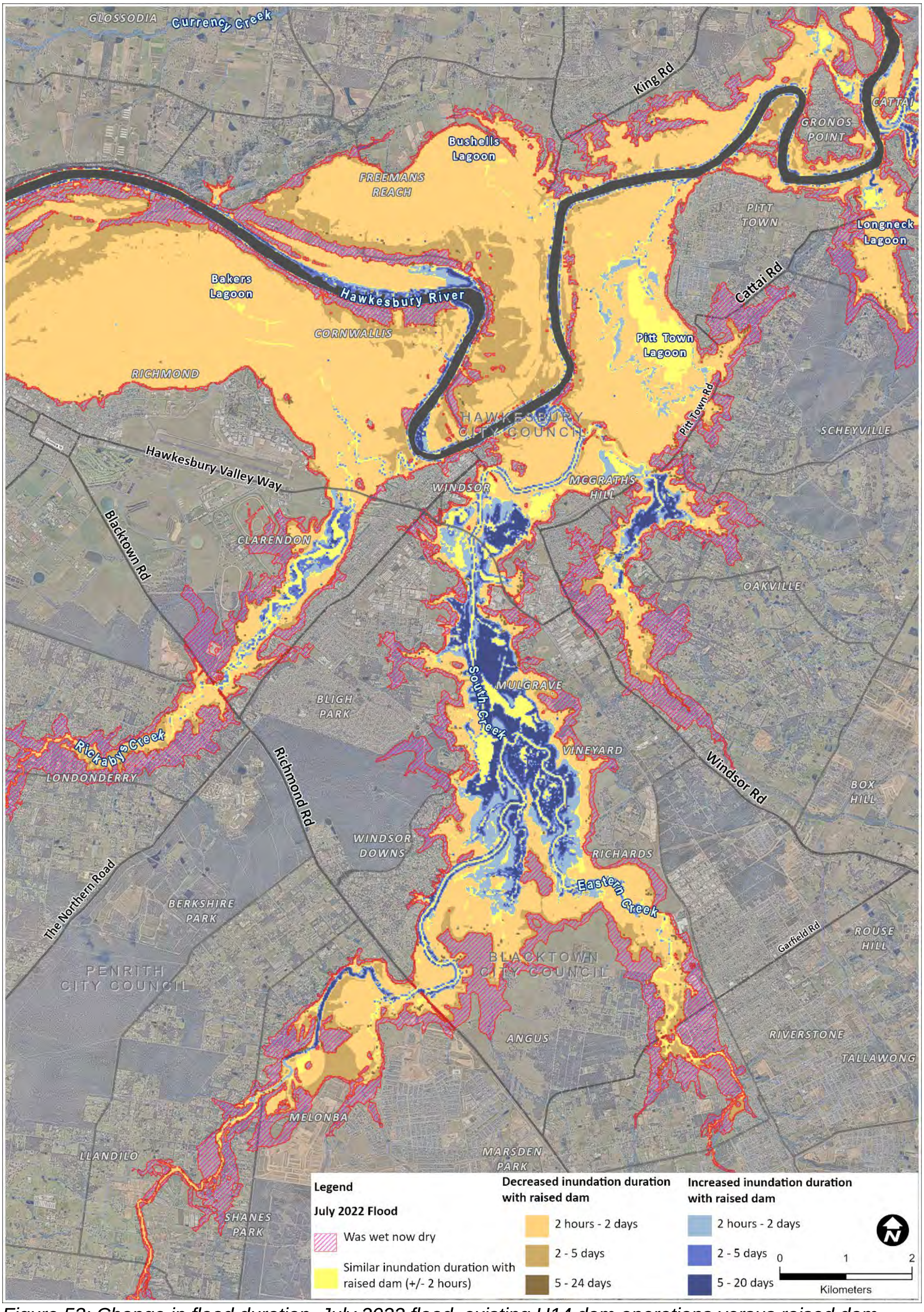


Figure 53: Change in flood duration, July 2022 flood, existing H14 dam operations versus raised dam, Richmond/Windsor floodplain

7. Conclusion

In 2022, Sydney (Observatory Hill) received 2530 mm rain, its highest annual total since records began in 1859, breaking the previous record set in 1950 (2194 mm).

The Hawkesbury-Nepean River system experienced 4 floods in March, April, July and October 2022. The 2 largest floods in March and July are the focus of this report. In most parts of the valley, these were higher than the March 2021 flood, and therefore afford the opportunity for additional learning about flood behaviour, flood impacts and flood mitigation in the valley.

The March 2022 flood was a high-volume flood with 2 distinct peaks about 5 days apart. It was 1.7m lower than the March 2021 flood at Penrith but 0.9m higher at Windsor – the highest since 1978 there.

The July 2022 flood was a more typical single-peaked event. It was 0.5m lower than the March 2021 flood at Penrith but 1.0m higher at Windsor. It was also noticeably high in the lower Hawkesbury River – possibly the highest at Wisemans Ferry since 1889 – in part due to the movement of the storm and the timing of inflows from the Colo River.

The March and July 2022 floods were around 1 in 20 chance per year floods at Windsor.

Extensive riverbank erosion was experienced in both floods, predominantly through rotational slumping. Sandy soils, the absence of vegetation, the long duration of flooding, the rate of drawdown of the river, and the clustering of floods may all have contributed to the problem. Erosion will continue to happen regardless of whether the dam is raised for flood mitigation, albeit the type of erosion may vary.

Various Warragamba Dam flood mitigation scenarios were modelled to see what difference these would have made to downstream flooding for the March and July 2022 events, building on the previous assessment for the March 2021 flood (Infrastructure NSW, 2021a). The proposed raised dam is the only mitigation measure that would have provided consistently high reductions to flood depths in all 3 floods. Permanently lowering full supply level by 12 metres would have performed similarly to the raised dam in the July 2022 flood but would have provided only a small reduction in the March 2022 flood. Lowering full supply level by 5 metres, or making pre-releases ahead of the flood, would have provided less than 1m reduction in peaks, and in the March 2022 flood, negligible benefit.

Pre-releases would also have brought forward closure of some key downstream roads, potentially impacting preparation and evacuation. Lowering full supply level would require new sources of supply and could impact water quality in the reservoir. The proposed raised dam would raise and prolong temporary inundation upstream of the dam wall. The duration of floodplain inundation downstream would have decreased in many areas.

8. References

AWACS (Australian Water and Coastal Studies) (1997) *Lower Hawkesbury River Flood Study*, final draft report, April 1997.

Babister M, Ward M and Retallick M (2021) 'Drivers of flooding in the Hawkesbury', paper presented to *2021 Digital Floodplain Management Australia National Conference*, 26-28 May 2021.

Beca (2022) 'Warragamba Dam Raising – Geomorphology Technical Notes' in: WaterNSW, *Warragamba Dam Raising Submissions Report*, Appendix G.

BMT WBM (2013) *Upper Hawkesbury River Bank Erosion, Foreshore Structure and Weed Mapping*, prepared for Hawkesbury City Council, November 2013.

BoM (Bureau of Meteorology) (2020) *Service Level Specification for Flood Forecasting and Warning Services for New South Wales and the Australian Capital Territory*, Version 3.13, March 2020, accessed 10 November 2021.

BoM (Bureau of Meteorology) (2022) *Special Climate Statement 76 – Extreme rainfall and flooding in southeastern Queensland and eastern New South Wales*, Version 1, 25 May 2022, accessed 15 September 2022.

BoM (Bureau of Meteorology) and CSIRO (Commonwealth Industrial and Scientific Research Organisation) (2022) *State of the Climate 2022*.

CSIRO (Commonwealth Industrial and Scientific Research Organisation) (2022) 'Understanding the causes and impacts of flooding', accessed 12 January 2023.

Douglas Partners (2022) 'Assessment of landsliding: Portland Head Road Ebenezer', prepared for Public Works Advisory, 22 March 2022.

DPE (Department of Planning and Environment) (2022) *Greater Sydney Water Strategy*, August 2022.

Erskine WD (1986) 'River metamorphosis and environmental change in the Macdonald Valley, New South Wales, since 1949', *Australian Geographical Studies*, 24, 88-107.

Gelling C (2022) *Operating Warragamba Dam for flood mitigation: current legal and regulatory barriers*, NSW Parliamentary Research Service, e-brief Issue 3/2022, September 2022.

GHD (2013) *River Styles Assessment Report*, prepared for Hawkesbury Nepean CMA, May 2013.

Hubble TCT, Docker BB, Rutherfurd ID (2010) 'The role of riparian trees in maintaining riverbank stability: A review of Australia experience and practice', *Ecological Engineering*, 36, 292-304.

Infrastructure NSW (2017) *Resilient Valley, Resilient Communities: Hawkesbury-Nepean Valley Flood Risk Management Strategy*, accessed 10 November 2021.

Infrastructure NSW (2019) *Hawkesbury-Nepean Valley Flood Risk Management Strategy: Taskforce Options Assessment Report*, accessed 10 November 2021.

Infrastructure NSW (2021a) *Hawkesbury-Nepean River March 2021 Flood Review*, accessed 23 September 2022.

Infrastructure NSW (2021b) *Hawkesbury-Nepean flooding and Warragamba Dam*, accessed 9 November 2022.

Infrastructure NSW (2021c) *Hawkesbury-Nepean Valley Flood Risk Management Strategy: Interim Evaluation to June 2021*, accessed 9 November 2022.

Neville, M. (2022) 'Memorandum: 105 Edwards Road Richmond Lowlands: Site Assessment Report', NSW Public Works Advisory.

NSW SES (2020) *Hazard and Risk in the Hawkesbury-Nepean Valley Annex A Supporting document to the Hawkesbury-Nepean Flood Plan*, June 2020, accessed 10 November 2021.

O'Kane M and Fuller M (2022) *2022 Flood Inquiry – Volume Two: Full report*, 29 July 2022.

Pepler A, Coutts-Smith A and Timbal B (2014) 'The role of East Coast Lows on rainfall patterns and inter-annual variability across the East Coast of Australia', *International Journal of Climatology* 34, 1011-1021.

Pepler A (2022) 'Australian climate influences and their impact on natural hazard activity', presented at Risk Frontiers Seminar Series, 27 October 2022.

Pitman AJ, Barnes M, King A, Reid K and Taschetto A (2022) 'The background and causes of the extreme rainfall and flooding in NSW in 2022', ARC Centre of Excellence for Climate Extremes, 7 June 2022. In: *2022 Flood Inquiry - Volume Three: Appendices*, 29 July 2022.

PWD (Public Works Department) (1978) *Hawkesbury River March 1978 Flood Report*.

Reid KJ, O'Brien TA, King AD and Lane TP (2021) 'Extreme Water Vapor Transport during the March 2021 Sydney Floods in the Context of Climate Projections', *Geophysical Research Letters* doi: 10.1029/2021GL095335

Seneviratne SI, Zhang X, Adnan M, Badi W, Dereczynski C, Di Luca A, Ghosh S, Iskandar I, Kossin J, Lewis S, Otto F, Pinto I, Satoh M, Vicente-Serrano SM, Wehner M and Zhou B (2021) 'Weather and Climate Extreme Events in a Changing Climate'. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte V, Zhai P, Pirani A, Connors SL, Péan C, Berger S, Caud N, Chen Y, Goldfarb L, Gomis MI, Huang M, Leitzell K, Lonnoy E, Matthews JBR, Maycock TK, Waterfield T, Yelekçi O, Yu R and Zhou B (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp.1513-1766, doi:10.1017/9781009157896.013.

SMEC (2021) *Warragamba Dam Raising Environmental Impact Statement,* prepared for WaterNSW, September 2021.

TfNSW (Transport for NSW) (2021) *Sydney Basin Vehicular Ferry Flood Response Plan 2020*, Version 1.0, January 2021.

WMA (Webb McKeown & Associates) (2004) *Lower Macdonald River Flood Study*, prepared for Hawkesbury City Council, August 2004.

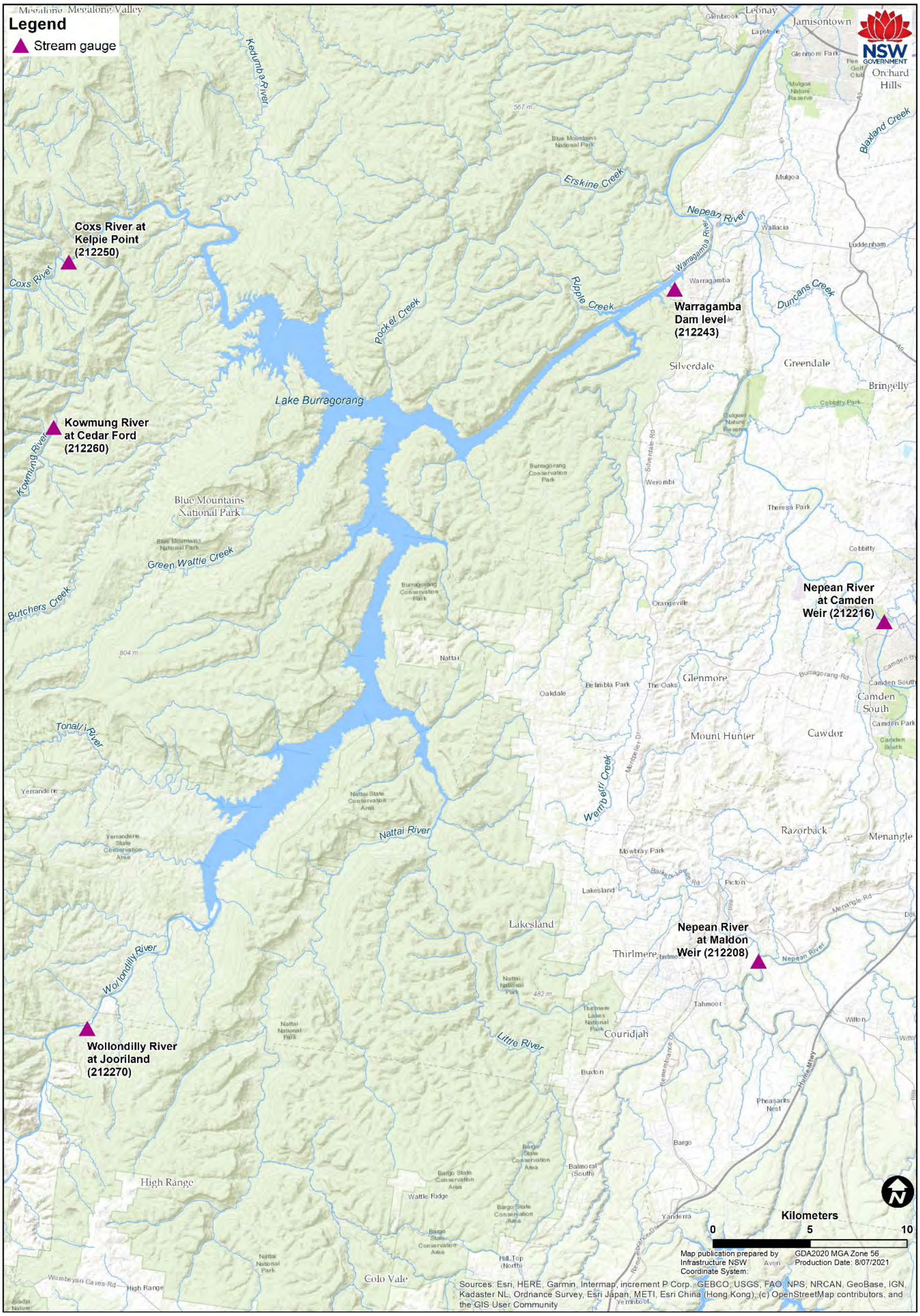
WMAwater (2019) *Hawkesbury-Nepean Valley Regional Flood Study*, prepared for Infrastructure NSW, July 2019.

Appendix A: Glossary

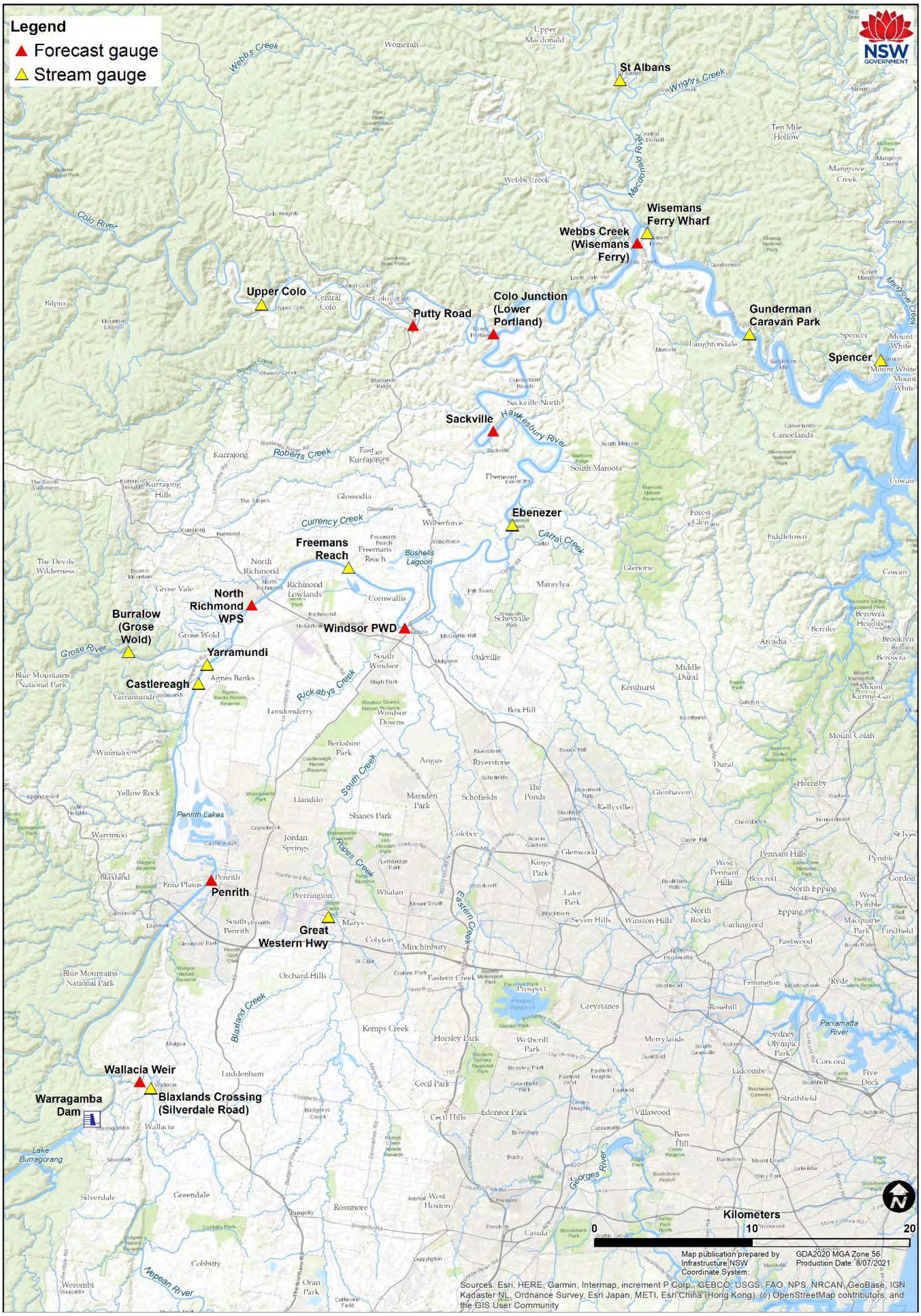
1-dimensional hydraulic flood model	A computer model that simulates the movement of floodwaters in 1 dimension (in the primary direction of water movement) using depth-averaged hydraulic equations to derive information on floodwater depths, velocities and levels. The geometry in 1-dimensional models is defined by cross-sections. As a result, 1-dimensional models only provide outputs at discrete locations.
2-dimensional hydraulic flood model	A computer model that simulates the movement of floodwaters across an area of interest in 2 dimensions (in the horizontal plane) using depth-averaged hydraulic equations to derive information on floodwater depths, velocities and levels. It is informed by a continuous terrain model and provides a continuous surface of results.
Annual exceedance probability (AEP)	The chance of a flood of a given or larger size occurring in any 1 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 (a 1-in-20 chance) of a 500 m^3/s or larger event occurring in any 1 year.
Australian Height Datum (AHD)	A common national surface level datum approximately corresponding to mean sea level.
Catchment	The land area draining through the mainstream, as well as tributary streams, to a particular site. It always relates to an area above a specific location.
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).
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 Classifications	Locally-defined flood levels used in flood warnings to give an indication of the severity of flooding (minor, moderate or major) expected. These levels are defined and then used by the NSW SES and the Bureau in flood warnings.
Flood liable land	Is synonymous with flood prone land (that is, land susceptible to flooding by the probable maximum flood (PMF) event).
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.
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 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 Warning	Advance notice that a flood may occur in the near future at a certain location. In the Hawkesbury-Nepean Valley, warnings normally include predicted flood heights at the forecast location. Flood Warnings are renewed at regular intervals until the relevant river level gauge drops to below the minor flood level. Flood Warnings are distributed to the media by the Bureau of Meteorology and are published on the Bureau website.
Hydraulics	Hydraulics is the study of the physical movement of water flow along rivers and creeks and over floodplains. Hydraulic modelling is used to determine flood levels, extents, depths, velocities (speed and direction) and hazard.

Hydrograph	A graph which shows how the discharge or flood level ('stage') at any particular location varies with time during a flood.
Hydrology	Hydrology is the study of how rainfall is converted into runoff from a catchment over time. It takes into account the rainfall (amount, timing and location) and ground conditions in the catchment.
Mainstream flooding	Inundation of normally dry land occurring when water overflows the natural or artificial banks of a stream, river, estuary, lake or dam.
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.
Median forecast	The daily median (50% chance of more than) rainfall forecast shown on MetEye (bom.gov.au) is the rainfall amount with 50% chance being exceeded in the 24 hours from 1:00am to 1:00am EST.
Major flooding	Flooding which causes inundation of extensive rural areas, with properties, villages and towns isolated and/or appreciable urban areas flooded. Evacuation of flood affected areas may be required. Utility services may be impacted.
Minor flooding	Flooding which causes inconvenience. Low-lying areas next to watercourses are inundated. Minor roads may be closed and low-level bridges submerged. In urban areas inundation may affect some backyards and buildings below the floor level as well as bicycle and pedestrian paths. In rural areas removal of stock and equipment may be required.
Moderate flooding	Flooding which inundates low-lying areas, requiring removal of stock and/or evacuation of some houses. Main traffic routes may be flooded. In addition to the effects of minor flooding, the area of inundation is more substantial. Main traffic routes may be affected. Some buildings may be affected above the floor level. Evacuation of flood affected areas may be required. In rural areas removal of stock is required.
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.
Probability	A statistical measure of the expected chance of flooding (see AEP).
Rating curve/table	A graph/table of discharge (flow) versus stage (water level) for a given location in a stream.
Riparian	A riparian zone or riparian area is the interface between land and a river or stream. Plant habitats and communities along the river margins and banks are called riparian vegetation.
Risk	Chance of something happening that will have an impact. It is measured in terms of consequences and likelihood. In the context of this report, 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 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.
TUFLOW	A 1-dimensional and 2-dimensional hydraulic simulation software. It simulates the complex movement of floodwaters across a particular area of interest using mathematical equations to derive information on floodwater depths, velocities and levels.

Appendix B: Locations of selected stream gauges



Selected water level recording stations, Warragamba and upper Nepean subcatchments



Selected water level recording stations, Hawkesbury-Nepean catchment below Warragamba Dam

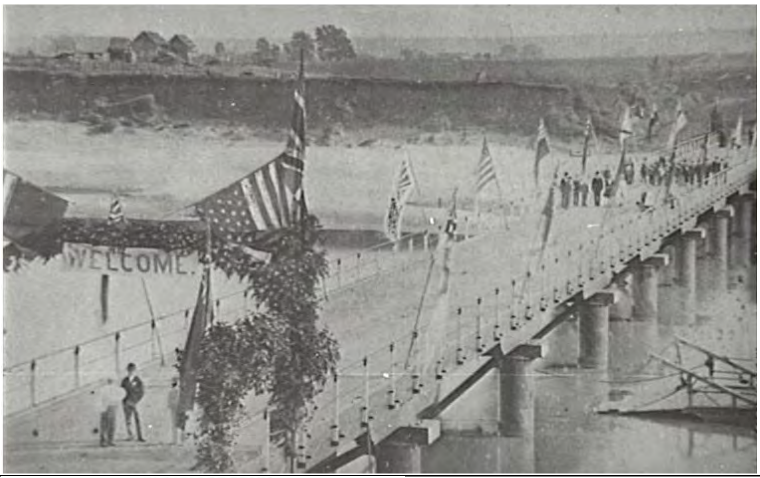
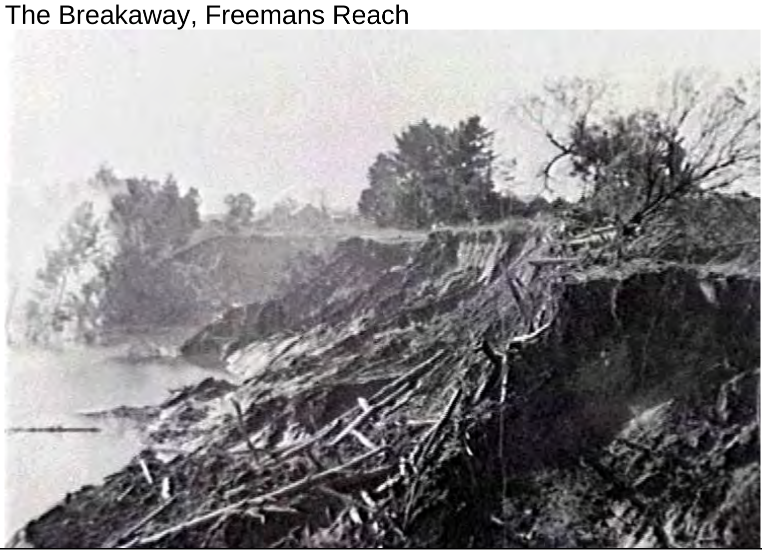
Appendix C: Hawkesbury-Nepean forecast gauge flood classifications

Forecast location	Flood classification			Gauge zero (m AHD)
	Minor	Moderate	Major	
Menangle Bridge	5.2	9.2	12.2	58.47
Camden Weir	6.8	8.3	13.8	55.284
Wallacia Weir	5.0	8.7	11.0	26.596
Penrith	3.9	7.9	10.4	14.139
North Richmond WPS	3.8	7.9	10.5*	0.529
Windsor PWD	5.8	7.0	12.2	0
Sackville	4.6	7.3	9.7	0
Putty Road (Colo River)	2.7	5.7	10.7	not known
Colo Junction (Lower Portland)	4.6	6.1	7.6	0
Webbs Creek (Wisemans Ferry)	n/a	3.5	4.2	0

Sources: BoM (2020), NSW SES, WaterNSW, Manly Hydraulics Laboratory

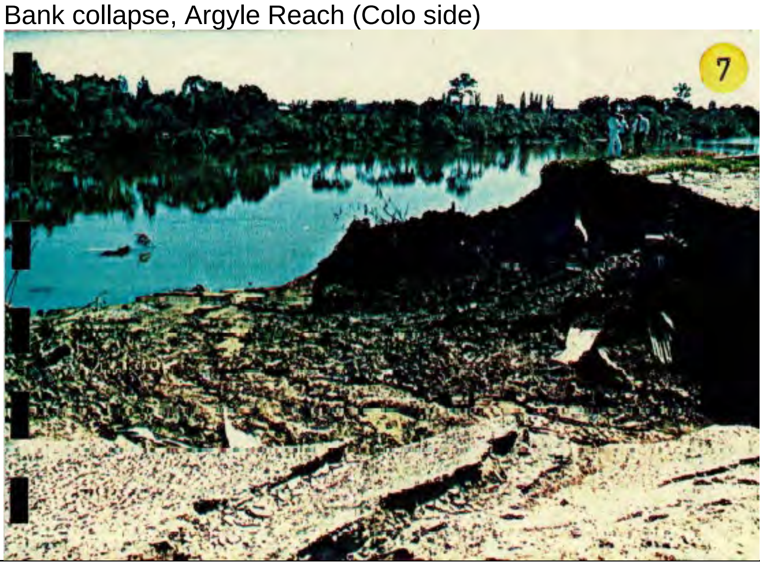
* The height threshold for major floods at North Richmond is subject to review to reassess the consequences at this river height

Appendix D: Historical images/descriptions of riverbank erosion

Year or flood	Description / Image	Source
1874	Opening of Windsor Bridge, showing riverbank erosion on northwest bank  	Hawkesbury Library Service. Image No. 6328, possibly Thomas Boston
1925	 **REVEALING HAVOC** Hawkesbury Flood Receding **ROAD SLIPS AWAY** WINDSOR, Thursday. As the waters of the Hawkesbury recede the havoc wrought by the flood is revealed. Great damage has been done to the main road to Freeman's Reach. Opposite Mr. James Vaughan's residence there has been a big landslide. There is a yawning chasm in the road, and the land is still breaking away. Two telegraph poles are down.	The Sun (Sydney, NSW : 1910 - 1954) Thu 25 Jun 1925 Page 13 REVEALING HAVOC
No year	The Breakaway, Freemans Reach 	Hawkesbury Library Service. Image No. 728

Year or flood	Description / Image	Source
1949	**MAJOR DAMAGE** He said that included in the most severe damage to council property was the loss of the new Books' Ferry Bridge, and the complete disappearance of part of the Freeman's Reach Road as the result of erosion of the river bank after the flood had subsided.	Windsor and Richmond Gazette (NSW : 1888 - 1961) Wed 27 Jul 1949 Page 1 SHIRE COUNCIL IN DIRE STRAITS
1952	The Breakaway, Freemans Reach 	Hawkesbury Library Service. Image No. 2236
1952	The Breakaway, Freemans Reach 	Hawkesbury Library Service. Image: 2230
1956	**P.W.D. To Prepare Plan For Erosion Control** A large public meeting at Wilberforce on the afternoon of March 26 was assured that the Department of Public Works would have an outline plan and rough estimate of cost for coping with the Freeman's Reach river bank breakaway prepared within three or four weeks.	Windsor and Richmond Gazette (NSW : 1888 - 1961), Wednesday 4 April 1956, page 2

Year or flood	Description / Image	Source
1961 Nov	The Terrace, Windsor 	Hawkesbury Library Service. Image No. 3083, Sid Klein
1961 Nov	Possibly Freemans Reach or Wilberforce 	Hawkesbury Library Service. Image No. 3073, Sid Klein

Year or flood	Description / Image	Source
1964 Jun	Wilberforce 	Hawkesbury Library Service. Image No. 60887, Keith Cobcroft
1978 Mar	Bank collapse, Argyle Reach (Colo side) 	PWD, 1978

<table>
<tr><th>Year or flood</th><th>Description / Image</th><th>Source</th></tr>
<tr><td>1978 Mar</td><td>Typical bank collapse, opposite Gronos Point
</td><td>PWD, 1978</td></tr>
<tr><td>1986 Jul (before flood)</td><td>Toe erosion on regraded bank at Governor Phillip Park, Windsor
</td><td>PWD, 1986</td></tr>
<tr><td>1986 Jul (before flood)</td><td>Slip circle failures, Wilberforce Reach
</td><td>PWD, 1986</td></tr>
</table>

Year or flood	Description / Image	Source
1990 Aug	Hawkesbury district 	Hawkesbury Library Service. Image No. 13263, Chris Daley
1990 Aug	Windsor 	Hawkesbury Library Service. Image No. 13275, Chris Daley
2021 Mar	Sackville 	Infrastructure NSW, 2021a

Memorandum

March 2022 and July 2022 Hawkesbury-Nepean Flood Mitigation Scenario Modelling

16 December 2022

Infrastructure NSW

1. INTRODUCTION

In February 2020, Infrastructure NSW commissioned Rhelm and Catchment Simulation Solutions (CSS) to develop the Hawkesbury-Nepean River Flood Study, with additional input from WMAwater and Baird. The flood study has involved development of detailed hydrologic and hydraulic flood models to understand flooding downstream of Warragamba Dam (between Bents Basin and West Head). The models have been calibrated and validated to multiple floods including the March 2021 flood, which provided a good understanding of contemporary flooding. While the flood study is expected to be finalised in 2023, the models are appropriate to use to assess the impacts various Warragamba Dam flood mitigation scenarios would have had on downstream flooding if they had been implemented prior to the March 2022 and July 2022 events.

WMAwater was engaged to calculate Warragamba Dam outflows for the existing dam and different flood mitigation scenarios. This assessment was supported with input from the dam owner and operator, WaterNSW. While not the focus of the assessment, WMAwater also calculated the peak flood levels upstream of the proposed raised dam.

2. METHODOLOGY

The following steps were taken:

a. calculate Warragamba Dam outflows and inflows for the existing dam for the March and July 2022 floods (WMAwater)

b. validate the hydrologic and hydraulic models developed for the flood study against recorded water levels for the March and July 2022 floods (Rhelm/CSS)

c. calculate Warragamba Dam outflows for various flood mitigation scenarios (WMAwater)

d. taking the calculated dam outflows and the modelled inflows for all other tributaries, use the validated flood models to assess the flood behaviour of various flood mitigation scenarios (Rhelm/CSS)

e. assess the downstream impacts of the various flood mitigation scenarios (Infrastructure NSW)

f. model the peak flood level upstream of the proposed raised dam (WMAwater).

The steps are set out below. The validation of the hydrologic and hydraulic models will be described in greater detail in forthcoming technical volumes of the Hawkesbury-Nepean River Flood Study.

2.1 Warragamba Dam outflows and inflows for existing dam

Flood inflows to Warragamba Dam storage are discharged from the gated spillway using an automatic system known as the H14 protocol for the drum and radial gates (see Figure E1).

Figure E1. Warragamba Dam central spillway drum and radial gates

Source: WaterNSW website at https://vimeo.com/91375437

The amount of flow spilling through the gates is calculated by these steps:

- adopt the official dam water level record that WaterNSW uses for its automatic gate opening system. This water level is based on an average of water levels at 3 gauges near the dam wall and in Hideaway Bay upstream of the dam wall.
- extract the observed gate opening and closing times from the system logs (SCADA). The H14 protocol opens the radial gates in a set of predetermined steps based on the dam levels and uses a lower set of water level triggers on the closing sequence.
- develop gate opening and closing rating curves (relationship between gate opening heights and outflows) based on the observed dam levels, gate changes and accepted gate equations (US Bureau of Reclamation, 1987)
- use the rating curves to calculate the outflows.

As also found for the March 2021 flood (see Appendix F of Infrastructure NSW, 2021), analysis of the March 2022 and July 2022 floods suggested that the accepted calculation of discharges when the central drum gate is partially open could under-report actual flows. As for the March 2021 flood assessment, the drum gate discharge was calculated using a weir flow equation which, once checked against the stage discharge relationship, was able to provide a better representation of flows when the gate is partially open, between full supply level (116.72m AHD) and 118m AHD. For the current assessment, an additional adjustment was made to better align the estimated drum gate discharge with flows estimated at Warragamba Weir gauge downstream of the dam, within the range 116.78m AHD to 116.94m AHD at the dam.

The outflow hydrographs were reverse routed using the methodology outlined by Boyd et al. (1989) to generate a dam inflow hydrograph that was adopted for the modelling of mitigation options.

The adopted outflow and inflow hydrographs for the March 2022 and July 2022 floods are presented in Figures E2 and E3, respectively.

In the March flood, the peak outflow of 4080 m^3/s was reached at about 5am to 6am on 8 March.

In the July flood, the peak outflow of 5125 m^3/s was reached at 4pm on 3 July.

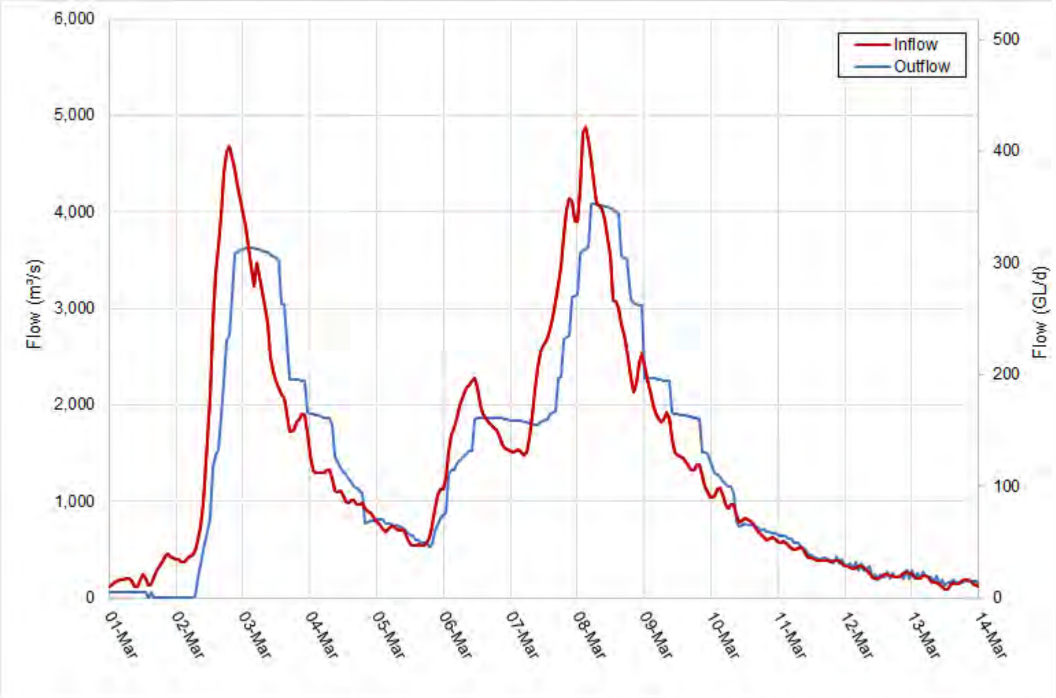


Figure E2: Warragamba Dam inflow and outflow hydrographs, March 2022 flood

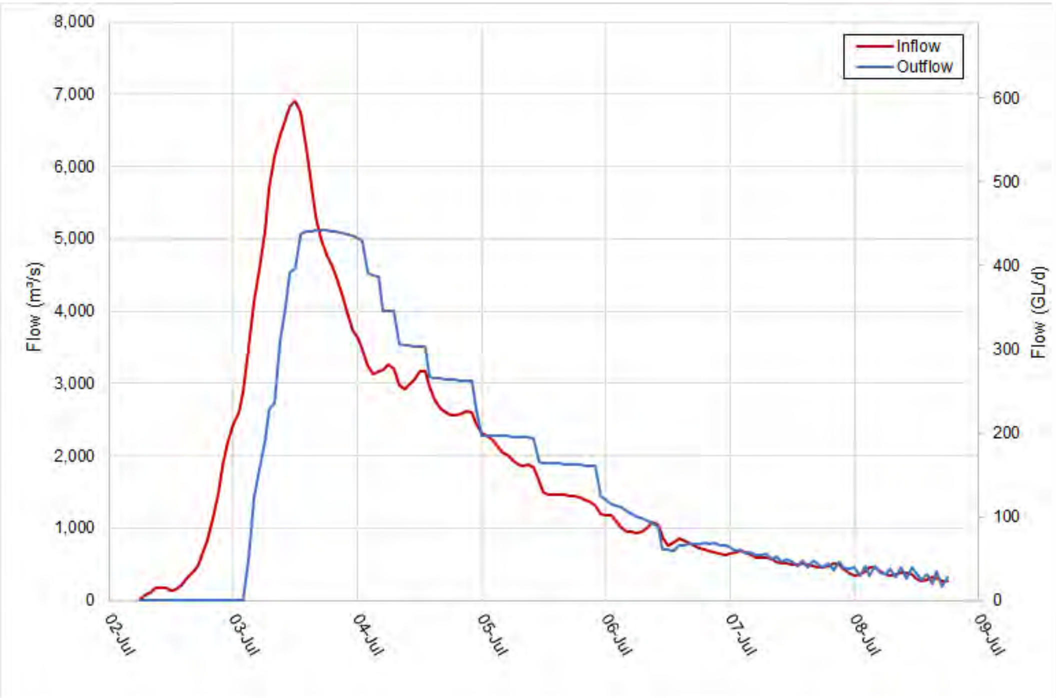


Figure E3: Warragamba Dam inflow and outflow hydrographs, July 2022 flood

2.1.1 Historical context at Warragamba Dam

Compared to historical floods since Warragamba Dam was completed in 1960, the March 2022 flood was an unusual event, with 2 distinct peaks (Figure E2). The July 2022 flood had 1 peak (Figure E3).

Table E1 lists key characteristics of the floods.

Table E1: Historical event inflow comparison

Event	Peak Dam Level			Peak Dam Inflow			Total Dam Inflow Volume		
	Peak Level (m AHD)	AEP (1 in X)	Rank since 1960	Peak Inflow (m^3/s)	AEP (1 in X)	Rank since 1960	Total Inflow Volume (GL)	AEP (1 in X)*	Rank since 1960
1867[#]	n/a	n/a	n/a	19593	330	-	2629	560	-
Nov-61	119.51	37	1	11033	40	1	1418	49	2
Jun-64	118.89	26	2	9322	27	3	1012	24	7
Jun-75	118.15	12	6	7293	16	5	710	14	8
Mar-78	118.01	10	8	9644	29	2	1212[^]	34[^]	4
Apr-88	118.06	10	7	7143	15	6	602	11	9
Aug-90	118.72	23	3	8817	23	4	1086	28	5
Mar-21	118.25	13	5	5591	9	8	1299	40	3
Mar-22	117.97	10	9	4880	7	9	1612	72	1
Jul-22	118.37	15	4	6909	14	7	1016	24	6

Notes

* The peak inflow and total inflow volume AEPs have been calculated following Australian Rainfall and Runoff (Ball et al., 2019) which uses critical duration assumptions for design events. As these assumptions use a single duration, they may slightly underestimate inflow hydrograph volumes. Alternative duration assumptions would result in more frequent AEPs for the historical volumes.

[#] The 1867 inflow is only approximate and occurred before Warragamba was built. It is the largest historically recorded flood in the valley below the dam and has been included for context.

[^] As the inflow hydrograph is based on the reverse routed outflow, and the March 1978 outflow hydrograph had limited data points, this is an estimate.

Based on peak level in the dam, the July 2022 event is the fourth highest on record and the March 2022 event is the ninth highest on record (Table E1 peak dam level rank). The peak level drives the rate of outflow through the gated spillway following the H14 protocol.

The peak inflows rank fairly low – seventh for the July event and ninth for the March event (Table E1 peak dam inflow rank).

However, due to its double-peaked nature, the March event is much higher in terms of total inflow volume (ranked first since 1960 – see Table E1 total dam inflow rank and Figure E4). The July event is ranked sixth by inflow volume.

There is usually a high correlation between the peak inflow and total inflow volume, but double-peaked events are by their very nature much higher in volume compared to peak flow. This results in the March 2022 flood having a peak inflow to the dam of 1 in 7 AEP (Annual Exceedance Probability – see glossary at Appendix A), but a total inflow volume to the dam of about 1 in 70 AEP (Table E1).

The peculiarity of this combination in the historical record since 1960 is illustrated in Figure E5, with both the double-peaked March 2021 and March 2022 floods plotting away from the general trend.

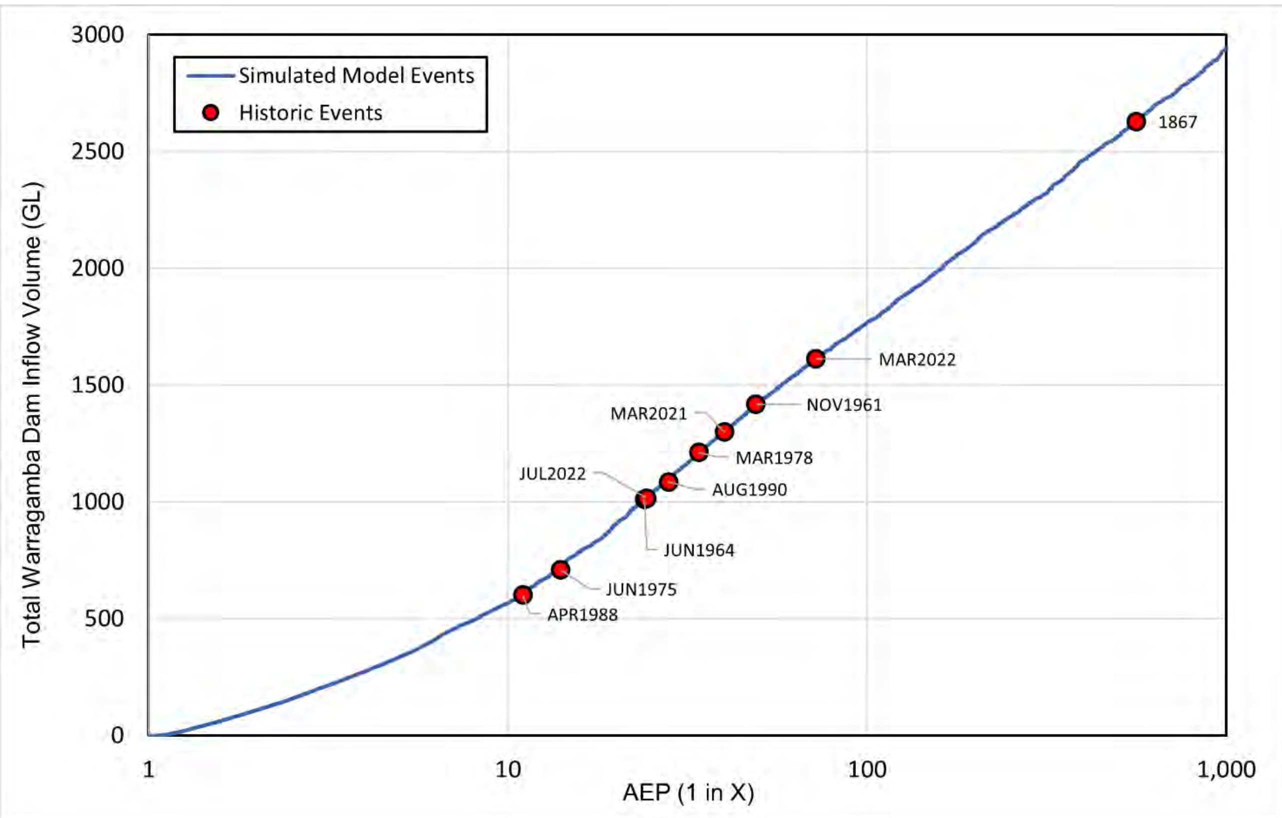


Figure E4: Warragamba Dam total inflow volume, historical and modelled

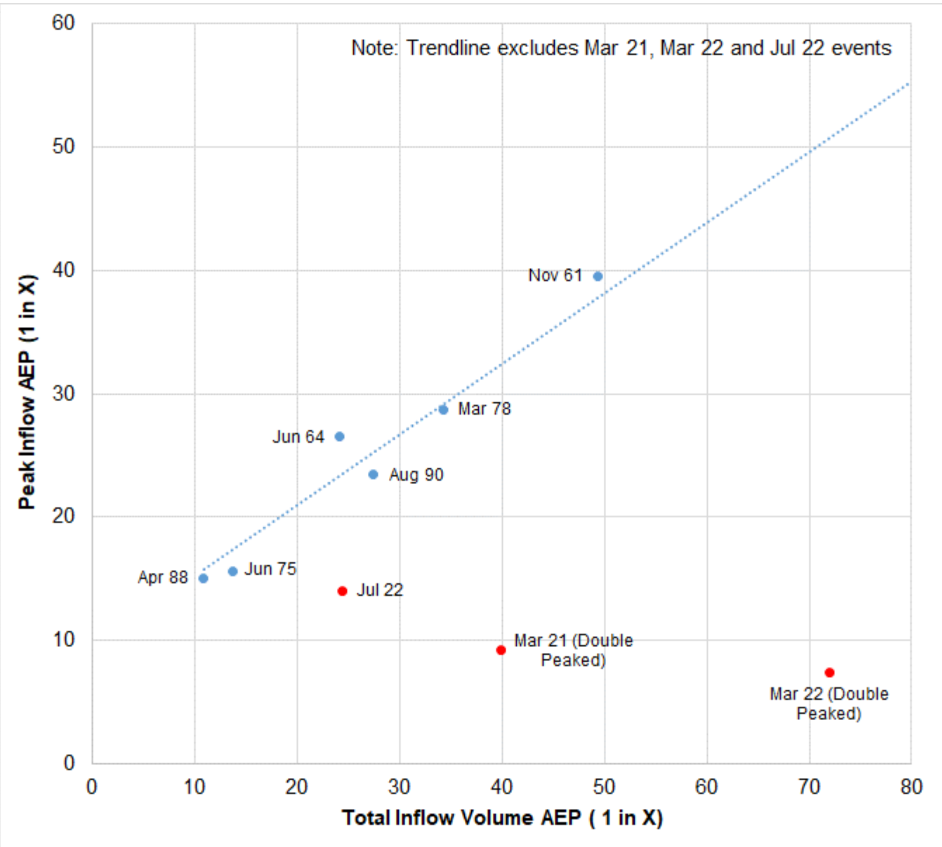


Figure E5: Warragamba Dam peak inflow vs total inflow volume frequency, historical events

2.2 Hydrologic model validation

Hydrology is the study of how rainfall is converted into runoff from a catchment over time. It takes into account the rainfall (amount, timing and location) and ground conditions in the catchment. A hydrologic model is used to calculate the river flows resulting from rainfall events, with the model outputs shown as a time series of flows (flood hydrographs).

A hydrologic model (WBNM) has been developed for the Hawkesbury-Nepean River catchment as part of the Hawkesbury-Nepean River Flood Study, which Rhelm and CSS are preparing for Infrastructure NSW. This model has been calibrated and validated to 9 historical floods (2021, 2020, 1998, 1990, 1988, 1986, 1978, 1975 and 1964). The March and July 2022 floods have been used to validate the hydrologic model, as follows:

- model setup – update the model to reflect March and July 2022 rainfalls and the starting water levels in the upper Nepean dams
- model losses – iteratively modify the initial and continuing rainfall losses within acceptable ranges to achieve a reasonable comparison with the gauged flow data
- review – review the results to ensure that the model schematisation represents the catchment response appropriately.

The review compares observed flow hydrographs at water level recording stations (stream gauges) throughout the catchment with modelled flow hydrographs at the same locations. With some important caveats, the closeness of the match between observed and modelled hydrograph shapes is used as an indicator of the performance of the model. These caveats include:

- the reliability of observed or measured flows depends on the quality of the 'rating' curve (the relationship between the observed height of water at the gauge and the flow corresponding to that height). Typically, there is greater uncertainty in measured flow estimates at higher levels.
- the density of rain gauges in the catchment. Where rain gauges are sparse, there is uncertainty about the distribution of rain between the gauges (though radar rainfall may fill in the gaps). This uncertainty may be reflected in the modelled flows.
- complexities caused by the influence of backwater effects at gauges.

Overall, given the caveats, the hydrologic model provides a good match to observed flows in the March and July 2022 floods. Example hydrographs are provided in Figures E6 and E7.

The hydrologic model provides the inflows for nearly all tributaries, including the upper Nepean River, Erskine and Glenbrook creeks, Grose River, South and Eastern creeks, Colo River and Macdonald River. The exception is Warragamba Dam, where the calculated outflow and inflow hydrographs were used for this assessment (Section 2.1).

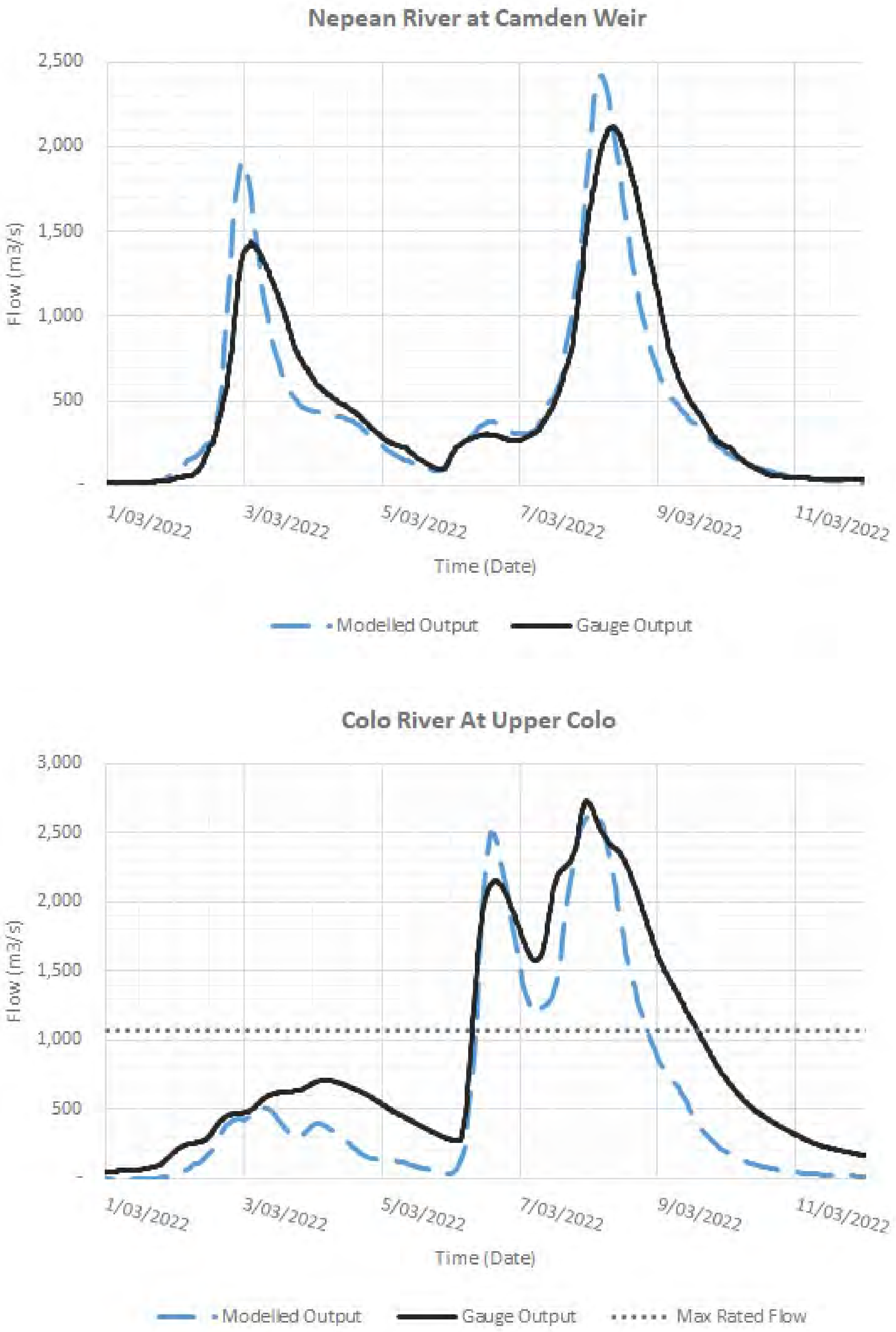
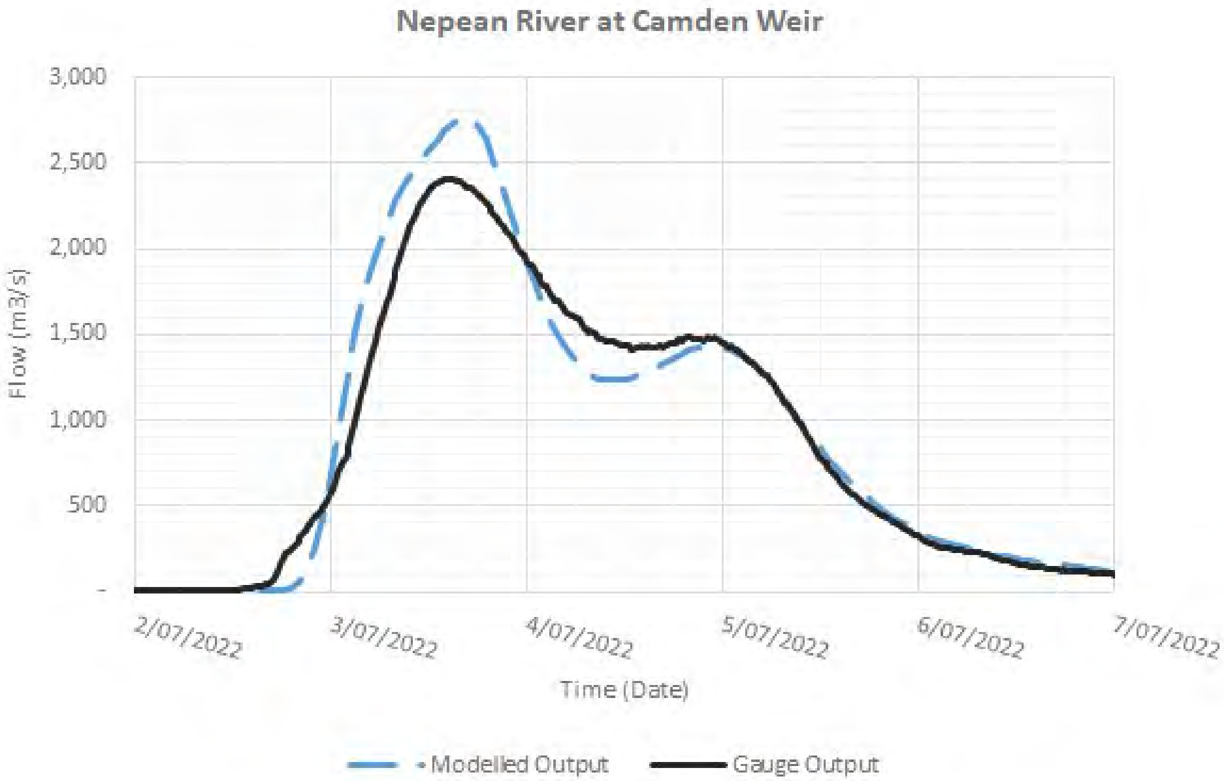


Figure E6. Example observed and modelled flow hydrographs, March 2022 flood



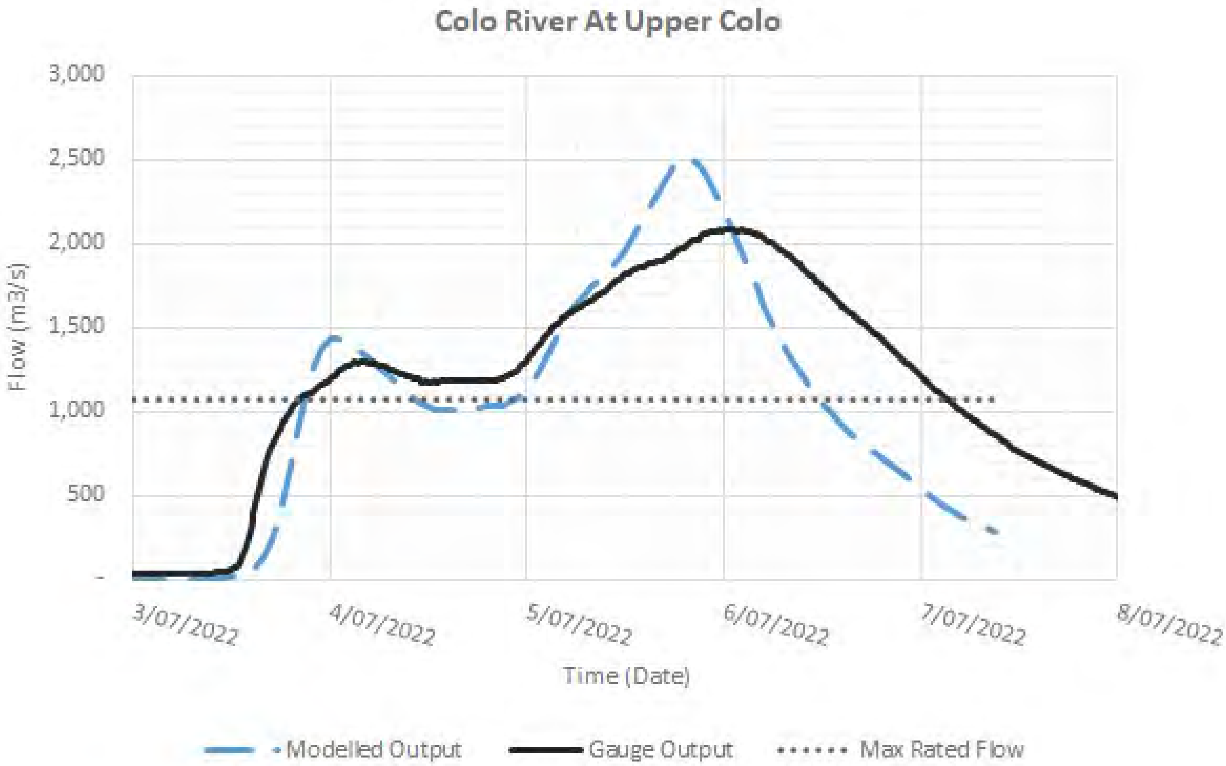


Figure E7. Example observed and modelled flow hydrographs, July 2022 flood

2.3 Hydraulic model validation

Hydraulic studies assess the physical movement of water flowing along rivers and creeks and over floodplains. Hydraulic modelling is used to determine flood levels, extents, depths, velocities (speed and direction) and hazard.

The flows from Warragamba Dam and the WBNM hydrologic model were input to a TUFLOW hydraulic model, which Rhelm and CSS have developed for the Hawkesbury-Nepean River as part of the Hawkesbury-Nepean River Flood Study. This model has been calibrated and validated to 9 historical floods (2021, 2020, 1990, 1988, 1986, 1978, 1975, 1964 and 1961). The March and July 2022 floods have been used to validate the hydraulic model, as follows:

- capture a large amount of flood information including surveyed peak flood levels (e.g., Figure E8)
- update the model's representation of vegetation to reflect changes that occurred along sections of the Nepean River during the March 2021 flood
- review the results by comparing modelled flood hydrographs to observed flood hydrographs, and modelled flood peaks to surveyed flood peaks away from gauge locations.

At this stage the eroded riverbank at Cornwallis (Figure E9) has not been incorporated into the hydraulic model's digital elevation model. It is planned to model how the changed landform would have impacted the flooding. But given the size of the floods (1 in 20 AEP at Windsor) and likely works to manage local flood dynamics, for this assessment it is considered appropriate to model the March and July 2022 floods with the terrain present in 2019/2020.

Figure E8. March and July 2022 flood marks at Longneck Lagoon Environmental Education Centre were surveyed by Public Works Advisory surveyors

Source: Longneck Lagoon EEC. Images: Vicky Whitehead

Figure E9. Riverbank erosion, Cornwallis, after July 2022 flood

Source: Nearmap, 24 Aug 2022

Figures E10 to E13 show the observed and modelled river height hydrographs at Penrith and Windsor, for the March and July 2022 floods. Tables E2 and E3 show the observed and modelled peak levels at Penrith and Windsor, for the 2 floods.

Overall, the hydraulic model provides a good representation of the observed flood hydrographs. The modelled July 2022 flood peaks at Penrith and Windsor match the observed peaks particularly well. The modelled March 2022 flood peaks match the observed peaks reasonably well.

It is apparent that there is a relatively consistent discrepancy between the modelled and recorded levels of the receding limbs of the hydrographs at Penrith and Windsor for both events. The consultant team considered potential reasons for this pattern including adopted base flows and inflows from ungauged creeks between Wallacia (where the hydrographs show good fits) and Penrith. The most likely reason is insufficient flow volume potentially related to the uncertainty in flow rates at relatively low flows over Warragamba Dam's drum gate (see Section 2.1).

Given the overall good match, the TUFLOW model is suitable for the subsequent assessment.

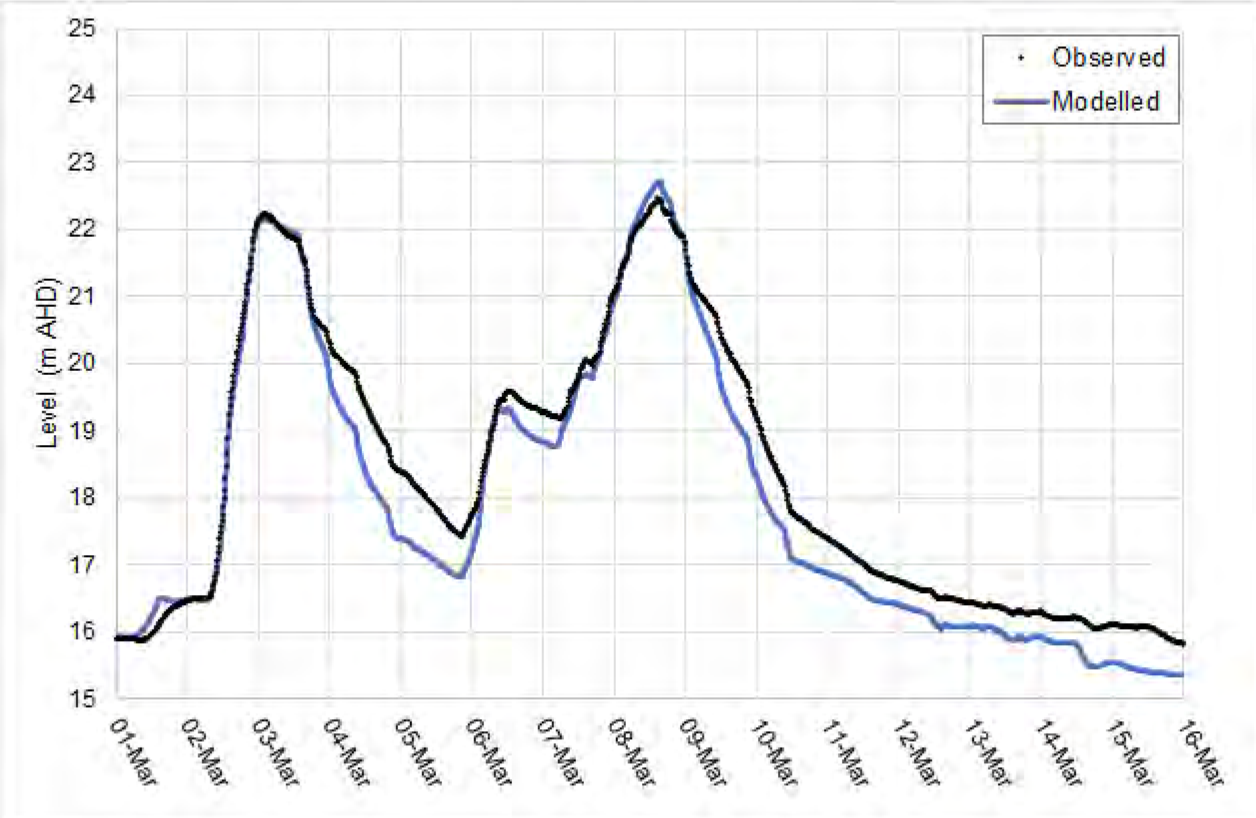


Figure E10: Observed and modelled stage hydrographs, Penrith, March 2022 flood

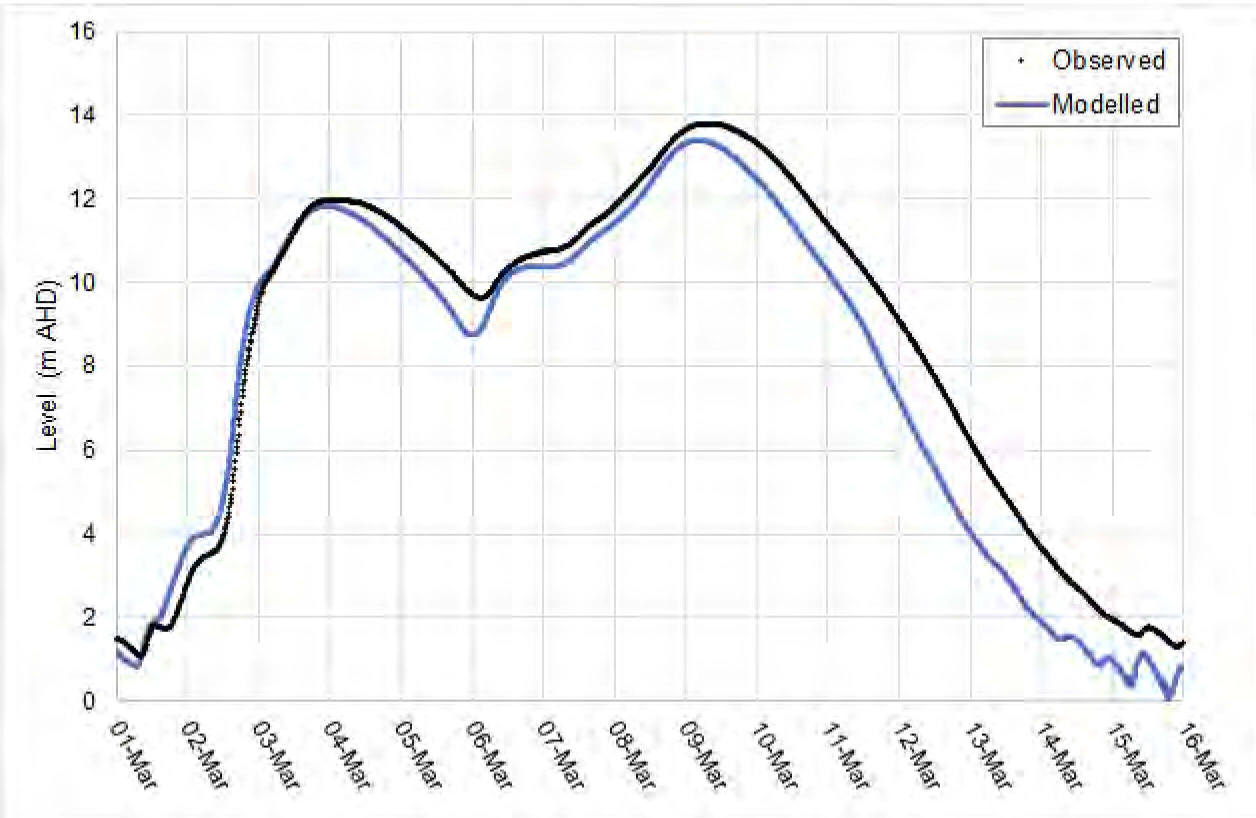


Figure E11: Observed and modelled stage hydrographs, Windsor PWD, March 2022 flood

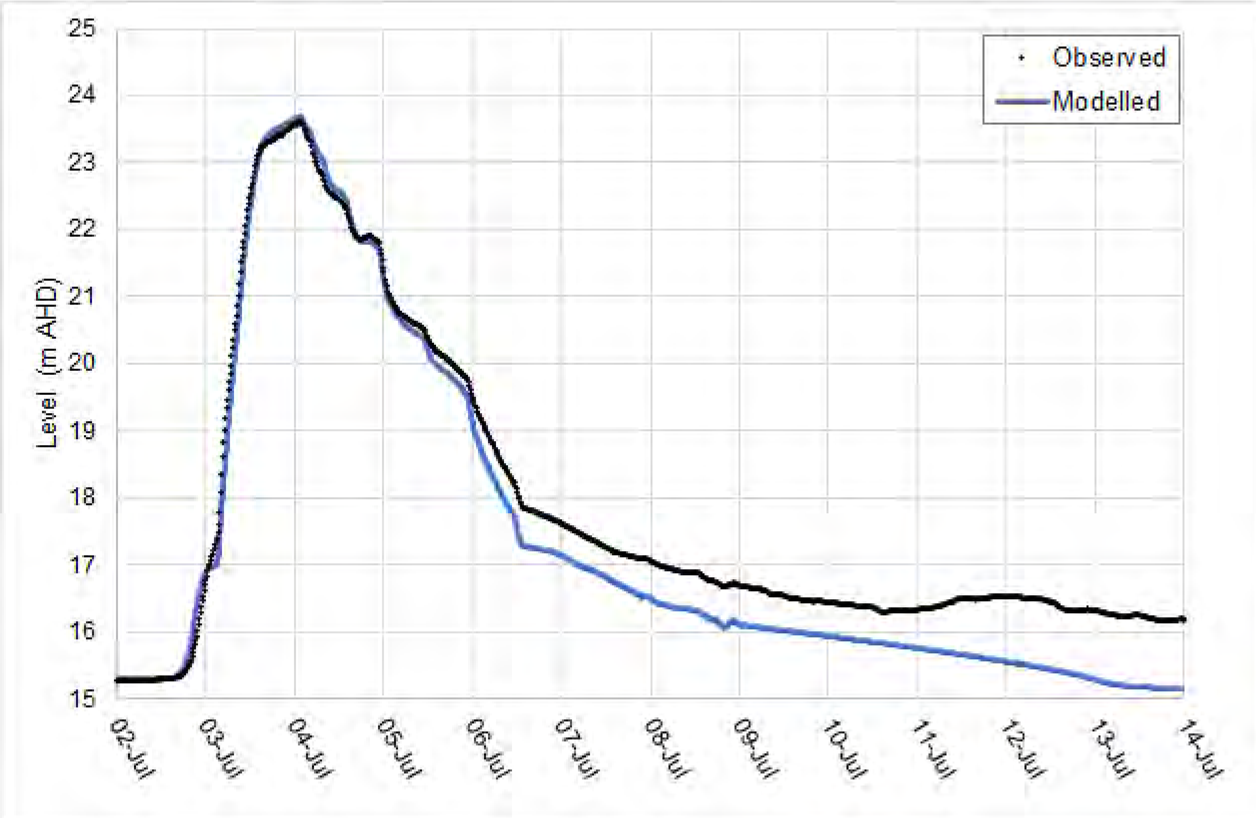


Figure E12: Observed and modelled stage hydrographs, Penrith, July 2022 flood

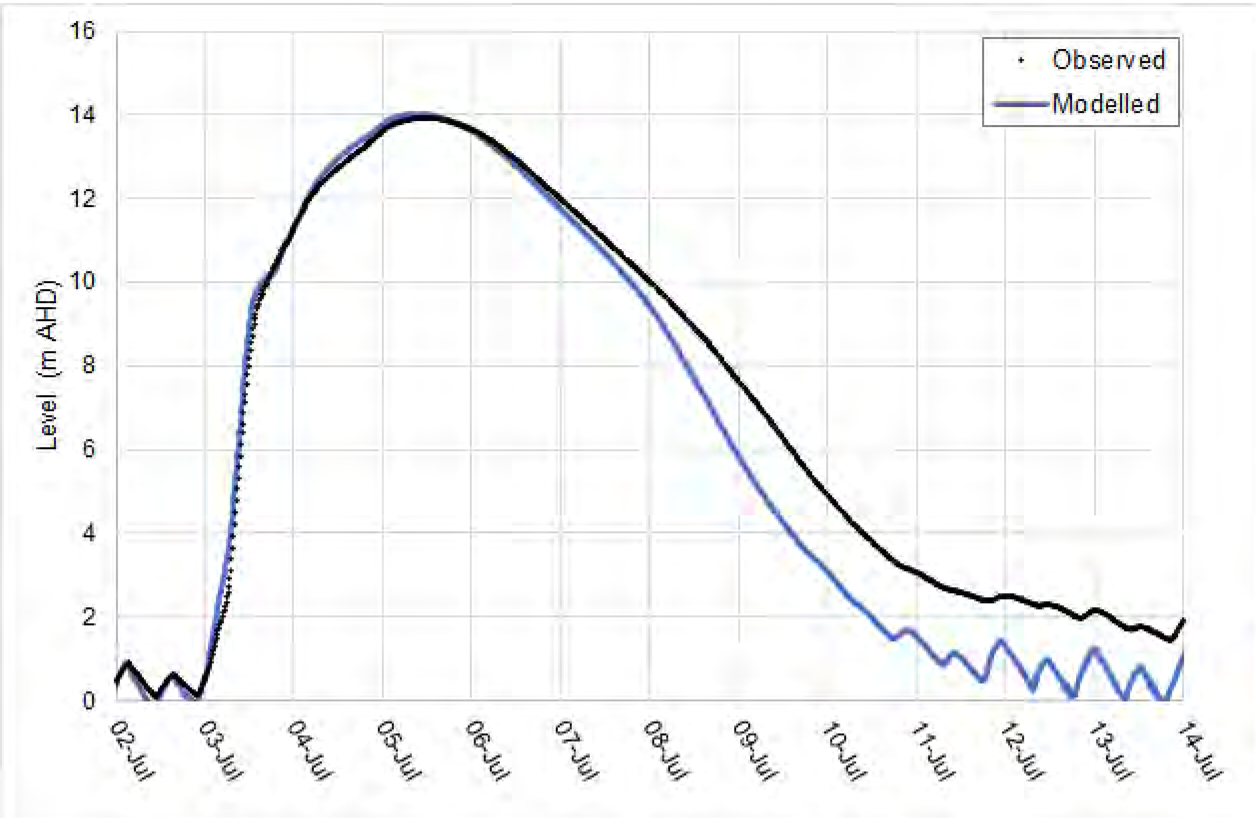


Figure E13: Observed and modelled stage hydrographs, Windsor PWD, July 2022 flood

Table E2: Peak level comparison, March 2022 flood

	Penrith		Windsor PWD	
	1st peak	2nd peak	1st peak	2nd peak
Observed level	22.23m AHD	22.46m AHD	11.99m AHD	13.80m AHD
Modelled level	22.20m AHD	22.76m AHD	11.84m AHD	13.42m AHD
Difference	-0.03m	+0.30m	-0.15m	-0.38m

Table E3: Peak level comparison, July 2022 flood

	Penrith	Windsor PWD
Observed level	23.62m AHD	13.93m AHD*
Modelled level	23.68m AHD	14.02m AHD
Difference	+0.06m	+0.09m*

Note: * Surveyed levels from 2 clear debris lines near the Windsor PWD gauge were 14.00m AHD and 14.03m AHD.

2.4 Warragamba Dam outflows for mitigation options

Several Warragamba Dam flood mitigation options were assessed. This involved comparing the results from the simulations of each dam mitigation option against the results of the H14 gate operation for the existing dam.

The mitigation options assessed were:

- raising Warragamba Dam spillways to create a 14m flood mitigation zone while retaining current full supply level (FSL)
- creating a flood mitigation zone by permanently reducing FSL by:
  - 5 metres
  - 12 metres
- pre-releasing water supply from Warragamba Dam
  - a ‘realistic’ scenario, where dam operators would have reasonable confidence that released supply would be replaced by inflows
  - an ‘unrealistic’ scenario, where dam operators would have less confidence that the forecast inflows would fill the dam, but would provide larger pre-releases

The calculated inflow hydrographs for Warragamba Dam (Figures E2 and E3) were adopted for the modelling of the scenarios.

Each scenario produced a different outflow hydrograph from Warragamba Dam, as presented in Figures E14 and E15. The different times of the start of outflows are listed in Tables E4 and E5.

A description of how the various scenarios were modelled to derive different outflow hydrographs is provided below.

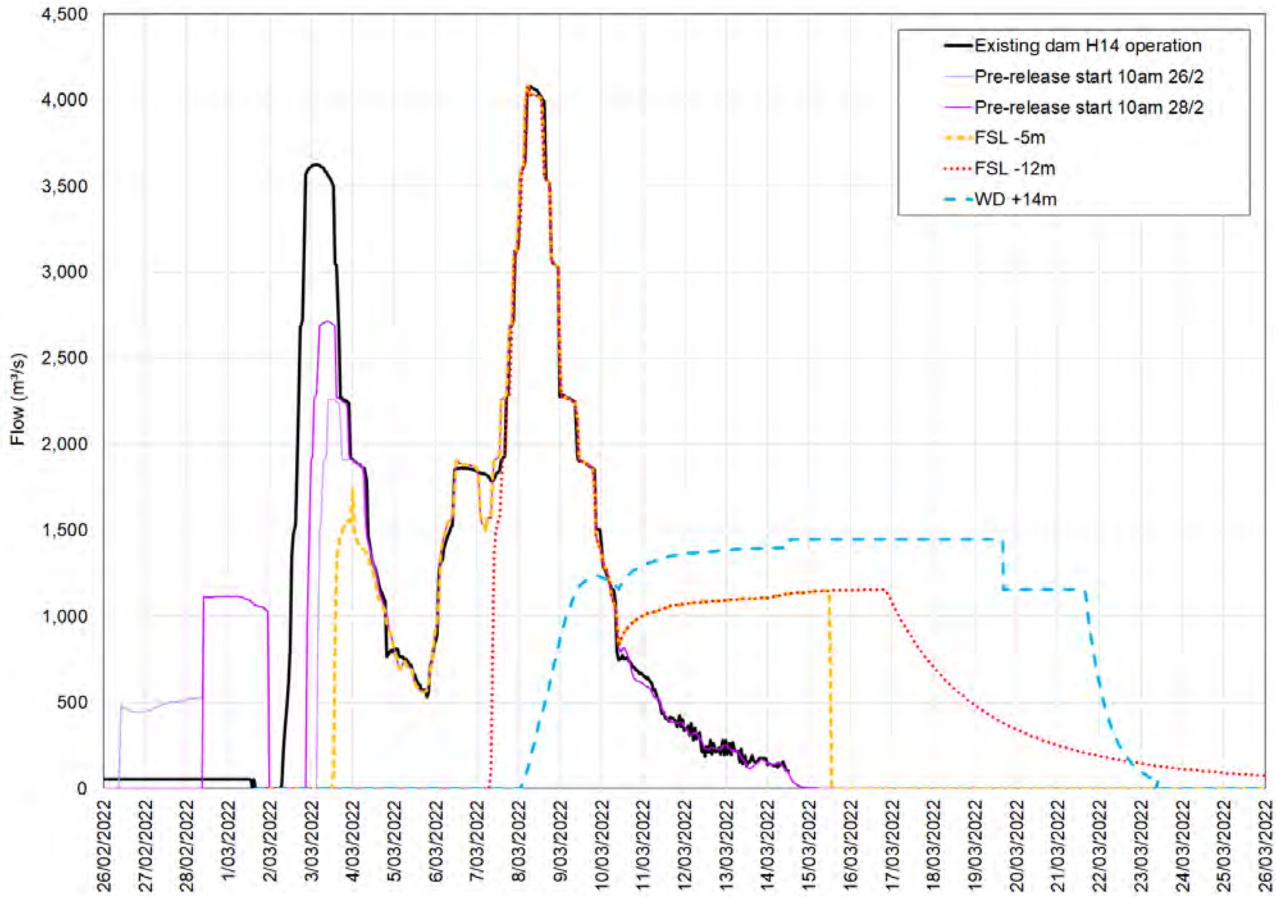


Figure E14: Warragamba Dam outflow for various scenarios, March 2022 flood

Table E4: Time of start of outflows from Warragamba Dam with various flood mitigation scenarios, March 2022 flood

Scenario	Start of outflow*
Unrealistic pre-release	26 February 10am
Realistic pre-release	28 February 10am
Existing Dam	2 March 8am
FSL -5m	3 March 1pm
FSL -12m	7 March 8am
WD +14m	8 March 4am

* Outflows exceeding 50 m^3/s

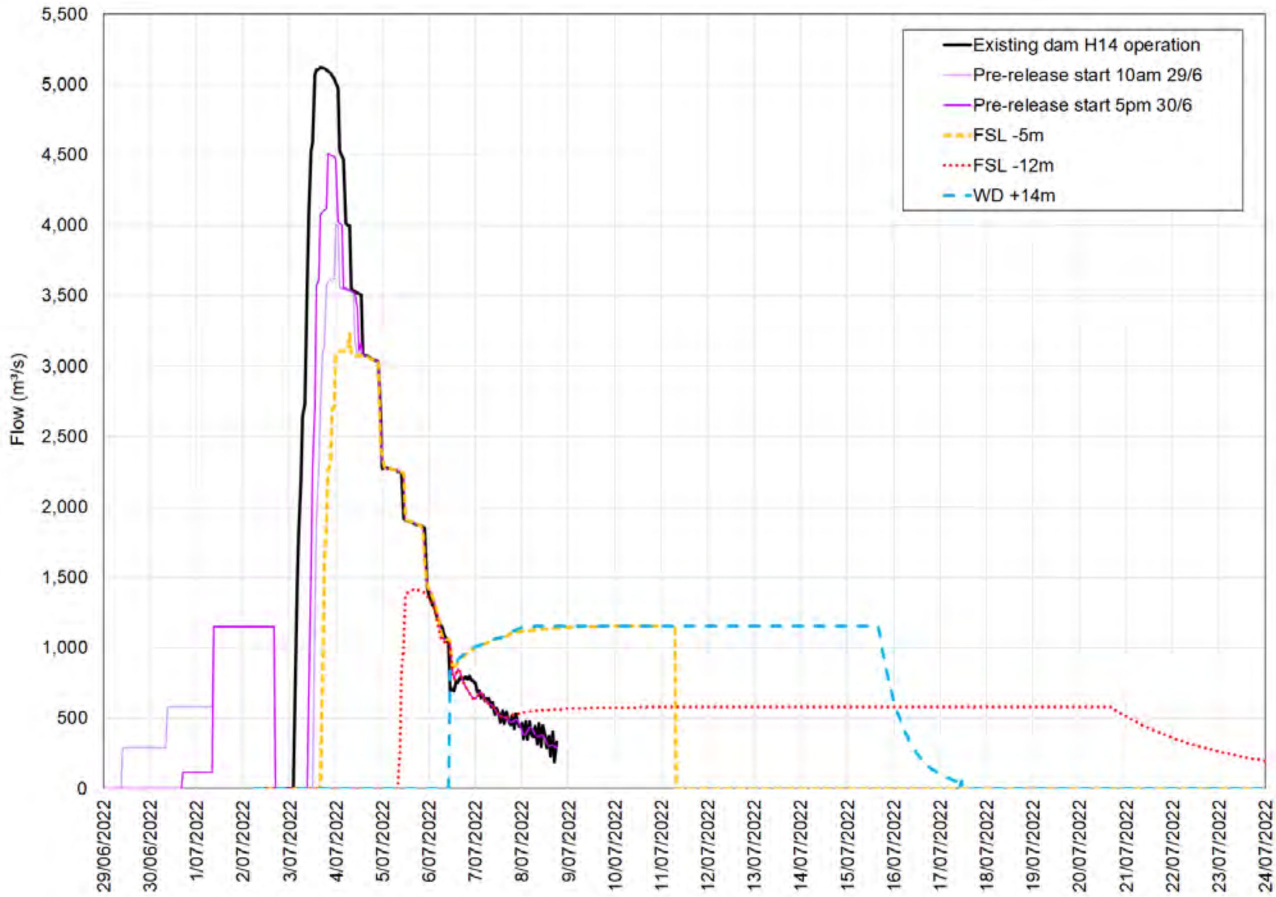


Figure E15: Warragamba Dam outflow for various scenarios, July 2022 flood

Table E5: Time of start of outflows from Warragamba Dam with various flood mitigation scenarios, July 2022 flood

Scenario	Start of outflow*
Unrealistic pre-release	29 June 10am
Realistic pre-release	30 June 5pm
Existing Dam	3 July 3am
FSL -5m	3 July 5pm
FSL -12m	5 July 9am
WD +14m	6 July 11am

* Outflows exceeding 50 m^3/s

2.4.1 Pre-releases

Pre-releases are intended to increase the available air space in the dam by actively making releases ahead of the event. Their effectiveness relies on the rate of release and the length of time before the flood that pre-releases commence.

The rate of release is constrained by the need to limit downstream impacts. This modelling exercise adopted pre-release rates to avoid exceeding a total flow rate of 100 GL/day in the Nepean River below the dam, recognising that this would still close some transport routes like Yarramundi Bridge.

The length of time before the flood that pre-releases commence is constrained by increasing uncertainty in rainfall forecasts with increasing time before an event, recalling the current primary objective that Greater Sydney's main drinking water supply be maintained. WaterNSW provided 2 hypothetical scenarios based on rainfall forecasts:

- Realistic pre-release, based on median (50% chance) rainfall forecasts
- Unrealistic pre-release, based more on the 25% chance rainfall forecasts.

For the March 2022 flood:

- A realistic operation might have involved pre-releasing stored water at a rate of 100 GL/day on Monday 28 February after the Bureau of Meteorology upgraded its 50% chance 7-day rain forecast from 31mm to 66mm, when the storage was 0.32m below FSL
- An unrealistic operation might have involved commencing releases at 50 GL/day from Saturday 26 February, when the storage was 0.59m below FSL, based on receiving 32mm catchment average rainfall over the previous 2 days and the consistency of both the 25% and 50% 7-day rainfall forecasts. On Monday 28 February, the release would have been ramped up to 100 GL/day based on the updated forecast.
- With the aim of keeping flow below 100 GL/day at Penrith, pre-releases would have ceased around 11pm Tuesday 1 March.

For the July 2022 flood:

- A realistic operation might have involved pre-releasing stored water on Thursday 30 June, after the Bureau of Meteorology upgraded its forecast at 4pm, with the 50% chance 7-day rain forecast increasing from 63 to 103 mm. WaterNSW considered that a release at a rate of 10 GL/day could happen that afternoon transitioning to 100GL/day until the Nepean River began to rise.
- An unrealistic operation might have involved commencing releases at 25 GL/day after 9am Wednesday 29 June, based on the 25% chance 7-day rain forecast of 66 mm. This could have risen to 50 GL/day on Thursday 30 June, and 100 GL/day until the Nepean River began to rise.
- With the aim of keeping flow below 100 GL/day at Penrith, pre-releases would have ceased around 4pm Saturday 2 July.

For the purpose of this modelling exercise, only 1 hour is allowed between the Bureau forecast and the commencement of releases. This may be optimistic considering the advance notice of releases that would be required to inform farmers, recreational river users, Transport for NSW contractors responsible for monitoring and closing bridges, and others.

It is noted that these are hypothetical scenarios made with the benefit of hindsight, after the flood. The reality is there remains considerable uncertainty in forecasting rainfall intensity and distribution.[11]

[11] At the current time, the Bureau of Meteorology's target warning lead time is to provide a minimum 8 hours at Penrith and 15 hours at Windsor before the trigger heights of 11.3m at Penrith and 13.7m at Windsor are exceeded. The target peak accuracy is for 70% of peak forecasts to be within +/- 0.3m (BoM, 2020). This reflects the limited accuracy of forecasting rainfall intensity and extent, the challenges with rainfall forecasts days in advance of a potential event, and the uncertainty of upstream floodplain behaviour.

2.4.2 Lowering full supply level

Permanently lowering FSL within the current dam would create flood mitigation zones of different sizes for the temporary capture of flood inflows. Lowering FSL by 5 metres to 111.72m AHD would create about 360 GL of air space, while lowering FSL by 12 metres to 104.72m AHD would create about 795 GL of air space.

While the dam can theoretically be lowered to 12m below the current FSL using the existing gates, the very low discharge capacity at -12m would mean that most large floods would start in the range of 10m to 12m below current FSL.

The daily inflows to Warragamba Dam since November 2021 were analysed to ascertain what starting levels could have been achieved at the commencement of the March, April and July 2022 floods. The results are presented in Table E6. Given the relatively constant inflows over this La Niña period, and the constrained outflows when approaching -12m, the dam could not have been lowered to 12m below current FSL, even with a large 100 GL/day drawdown between floods. The starting level for the April flood, coming so soon after the March flood, would have been about -11m. If a lower drawdown rate (37 GL/day) was used, enabling Yarramundi Bridge to remain open, the dam could have been lowered to only 7.7m below current FSL ahead of the April flood. This indicates that the 12m-lowering option would require the construction of flood mitigation zone outlets in order to maintain the entire flood mitigation zone.

Nonetheless, for this scenario testing against the March and July 2022 floods, the entire 12m air space was assumed to be available. Therefore, the results are conservative (i.e. likely to slightly overstate the benefits of the -12m option).

The -5m and -12m scenarios were modelled using the same H14 protocol as the existing dam, then as floodwaters downstream fall, the flood mitigation zones were emptied according to the following drawdown rules:

- If the peak outflow from the dam exceeded 250 GL/day (~2900 m^3/s), then a drawdown of 100 GL/day was applied. Where the peak outflow from the dam was less than this, a drawdown of 50 GL/day was applied. As a result, the following was applied:
    - For the March flood, 100 GL/day drawdown was applied for both the -5m and -12m options. No drawdown was applied between the 2 peaks.
    - For the July flood, 100 GL/day drawdown was applied for the -5m option and 50 GL/d drawdown was applied for the -12m option.
- The flow at Penrith (assumed to be the Wallacia flow + Warragamba Dam outflow) was to be a maximum of the release threshold (50GL/day or 100GL/day). This dictates the maximum dam outflow.

Table E6: Calculated dam starting levels ahead of March, April and July 2022 floods, with different rates of drawdown

Event	Drawdown rate:	Dam starting level (metres below FSL)			
		7 GL/day	37 GL/day	50 GL/day	100 GL/day
March 2022		-1.10m	-11.30m	-11.30m	-11.30m
April 2022		0.06m	-7.68m	-10.75m	-10.97m
July 2022		-2.17m	-11.78m	-11.78m	-11.78m

Note: 7 GL/day is the current drawdown approach and does not consider Nepean flows while the higher rates do. 37 GL/day is guaranteed to get under Yarramundi Bridge.

2.4.3 Raised dam

The proposed raised dam design spillway levels are 128.45m AHD for the central spillway (11.73m above FSL) and 130.6m AHD for the side spillway (13.88m above FSL). Raising the dam spillways while retaining the current FSL would create a flood mitigation zone of about 1000 GL for the temporary capture of flood inflows.

This proposed design and the draft operating protocols were run through the model to calculate the outflow from the raised dam.

2.5 Model downstream flood behaviour with mitigation options

The dam outflow hydrographs for the various flood mitigation scenarios were run through the downstream TUFLOW hydraulic model. The inflows for all tributaries apart from Warragamba Dam were taken from the WBNM hydrologic model and were not changed for the different scenarios. The TUFLOW model determines the difference that the various Warragamba Dam flood mitigation scenarios would have made.

2.6 Assess downstream impacts of mitigation options

Several representative downstream impacts have been considered for the comparison of options. The effect the various scenarios would have on the peak flood level, the flood classification[12], and flood timings are described for the Penrith (Section 3.1) and Windsor floodplains (Section 3.2), where flood risk exposure in the valley is concentrated. Peak flood level drives the extent and depth of inundation, which is the main determinant of flood damages. The flood classification provides an indication of impact. Flood timings are important for managing evacuations.

The impact on buildings in the valley is described in Section 3.3.

The impact on flooding of key river crossings is described in Section 3.4.

2.7 Model upstream flood behaviour with proposed raised dam

Separate flood models have been used to understand flood behaviour upstream of Warragamba Dam, both for existing dam operations and with various flood mitigation scenarios.

A RORB hydrologic model developed by the former Sydney Catchment Authority (now WaterNSW) was used to model inflows from the tributaries. The calibration and validation of this model using 7 historical floods are described in the *Hawkesbury-Nepean Valley Regional Flood Study* (WMAwater, 2019).

A Mike-11 1-dimensional hydraulic model (see glossary at Appendix A) of Lake Burragorang was initially developed by the Sydney Catchment Authority. As part of the Warragamba Dam Raising EIS project, the model was extended upstream of the tributary gauging stations and the Kedumba River was added. The Mike-11 hydraulic model was used to generate rating curves (height-discharge relationships) based on different dam levels at each cross section upstream of the dam.

These tools have been used to calculate the peak flood level upstream of the proposed raised dam if it had been implemented prior to the March and July 2022 events. The results are described in Section 3.5.

[12] The Bureau of Meteorology, in consultation with the NSW State Emergency Service, classifies flood levels at selected gauges as minor, moderate, or major flooding (see glossary at Appendix A). These levels are based on flood impacts near each gauge and are not related to the frequency of the flood event.

3. RESULTS

This section presents the assessment of the impacts the various Warragamba Dam flood mitigation measures would have had on flooding in March and July 2022.

3.1 Penrith

3.1.1 Flood peak

The reduction in peak flood levels at Penrith for the different dam flood mitigation scenarios is described in Table E7. The flood hydrographs for the different scenarios are presented in Figures E16 and E17.

Flood peaks at Penrith in the March and July 2022 floods were less than in March 2021, with the bulk of floodwater confined to the channel and low-level floodplain.

Nonetheless, it is informative to consider the relative benefits of the options. The proposed raised dam would have reduced the March 2022 flood peak at Penrith by 3.2m, and the July 2022 flood peak by 4.4m.

Lowering FSL by 12 metres would have produced a similar reduction in the July 2022 flood, but negligible reduction in the March 2022 flood because the second peak would not have been captured in the dam.

Lowering FSL by 5 metres would have provided moderate reduction in the July 2022 flood, but negligible reduction in the March 2022 flood.

The realistic pre-release would have provided a small reduction in the July 2022 flood, and negligible reduction in the March 2022 flood.

3.1.2 Flood classification

The March and July 2022 floods peaked at Penrith in the moderate range. The proposed raised dam would have reduced the peak for both events to the minor range. Lowering FSL by 12 metres would have achieved this result for the July event. None of the other options would have made sufficient difference to peak levels to lessen the flood category, for either flood (Table E8).

3.1.3 Timing

Table E9 reports the delay in timing in hours. This represents the difference in time at which certain levels are reached between the different scenarios. A positive value indicates the level for the scenario was reached after it was reached for the modelled existing dam base case. A negative value indicates the level for the scenario was reached before it was reached for the modelled existing dam base case.

In the March 2022 flood, the proposed raised dam is the only scenario that delays the peak at Penrith. The effect of the 12m-lowering option in the July 2022 flood is to create 2 peaks – the first driven by Nepean flows, the second when Warragamba Dam spills. Since the second peak is slightly the higher, a significant delay in the peak is recorded.

Table E7: Penrith flood peak reduction for various flood mitigation scenarios, March and July 2022 floods

Modelled Scenario	Reduction in peak (m)	
	March 2022	July 2022
Existing Dam	-	-
WD +14m	3.2	4.4
FSL -12m	0.1	4.4
FSL -5m	<0.1	1.4
Unrealistic pre-release	<0.1	0.9
Realistic pre-release	<0.1	0.5

Table E8: Penrith flood categorisation for various flood mitigation scenarios, March and July 2022 floods

Modelled Scenario	Flood category	
	March 2022	July 2022
Existing Dam	Moderate	Moderate
WD +14m	Minor	Minor
FSL -12m	Moderate	Minor
FSL -5m	Moderate	Moderate
Unrealistic pre-release	Moderate	Moderate
Realistic pre-release	Moderate	Moderate

Minor flood level at Penrith is 18.04m AHD
Moderate flood level at Penrith is 22.04m AHD

Table E9: Penrith time delay for various flood mitigation scenarios, March and July 2022 floods

Modelled Scenario	Time delay (hrs)					
	March 2022			July 2022		
	MIN	MOD	PEAK	MIN	MOD	PEAK
Existing Dam	-	-	-	-	-	-
WD +14m	8	Level not reached	5.5	5	Level not reached	2
FSL -12m	8	127	-2	5	Level not reached	38
FSL -5m	8	127	-1	5	14	6
Unrealistic pre-release	8	127	-1	5	9	0
Realistic pre-release	8	127	-1	5	5	-1

Minor flood level at Penrith is 18.04m AHD
Moderate flood level at Penrith is 22.04m AHD

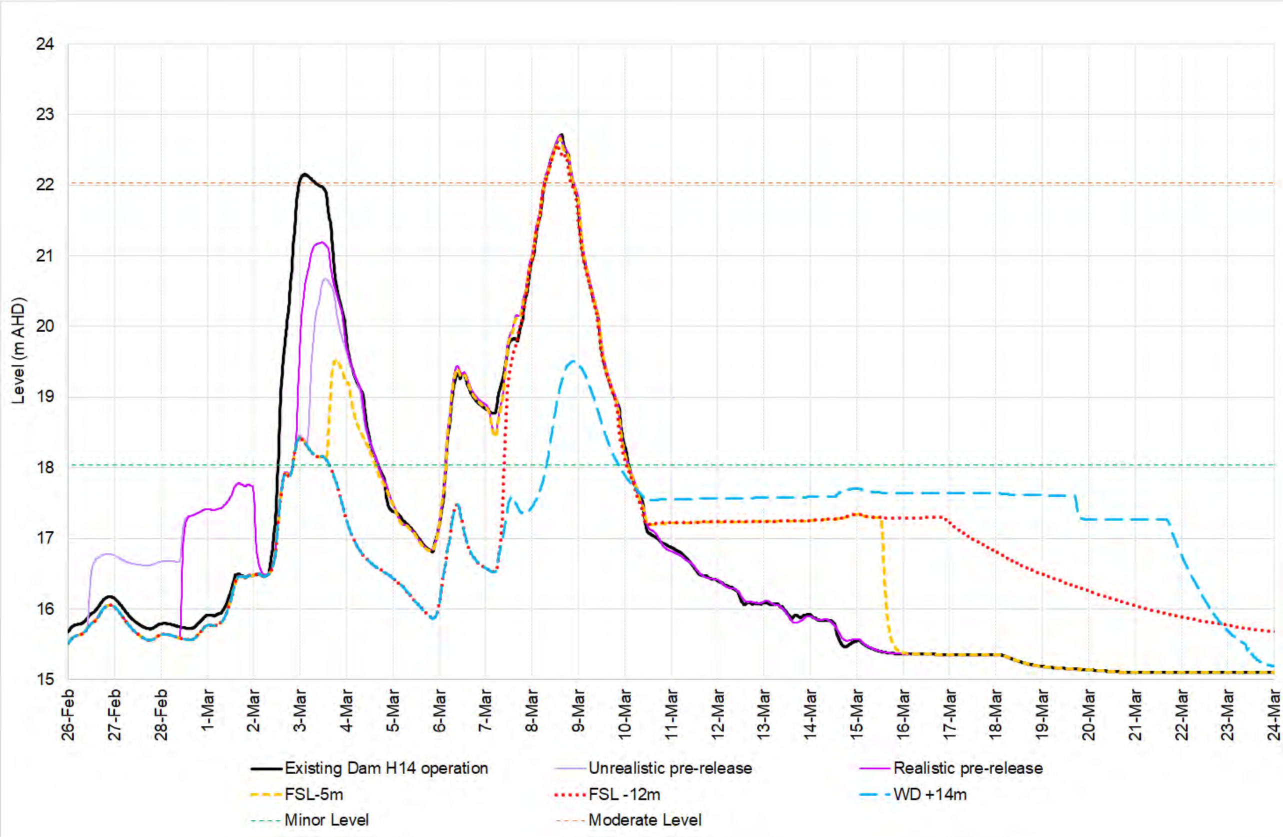


Figure E16: Penrith level hydrograph for various flood mitigation scenarios, March 2022 flood

Note: at the start of the flood there was a small manual release of about 50 m^3/s. This was not included in the modelled scenarios.

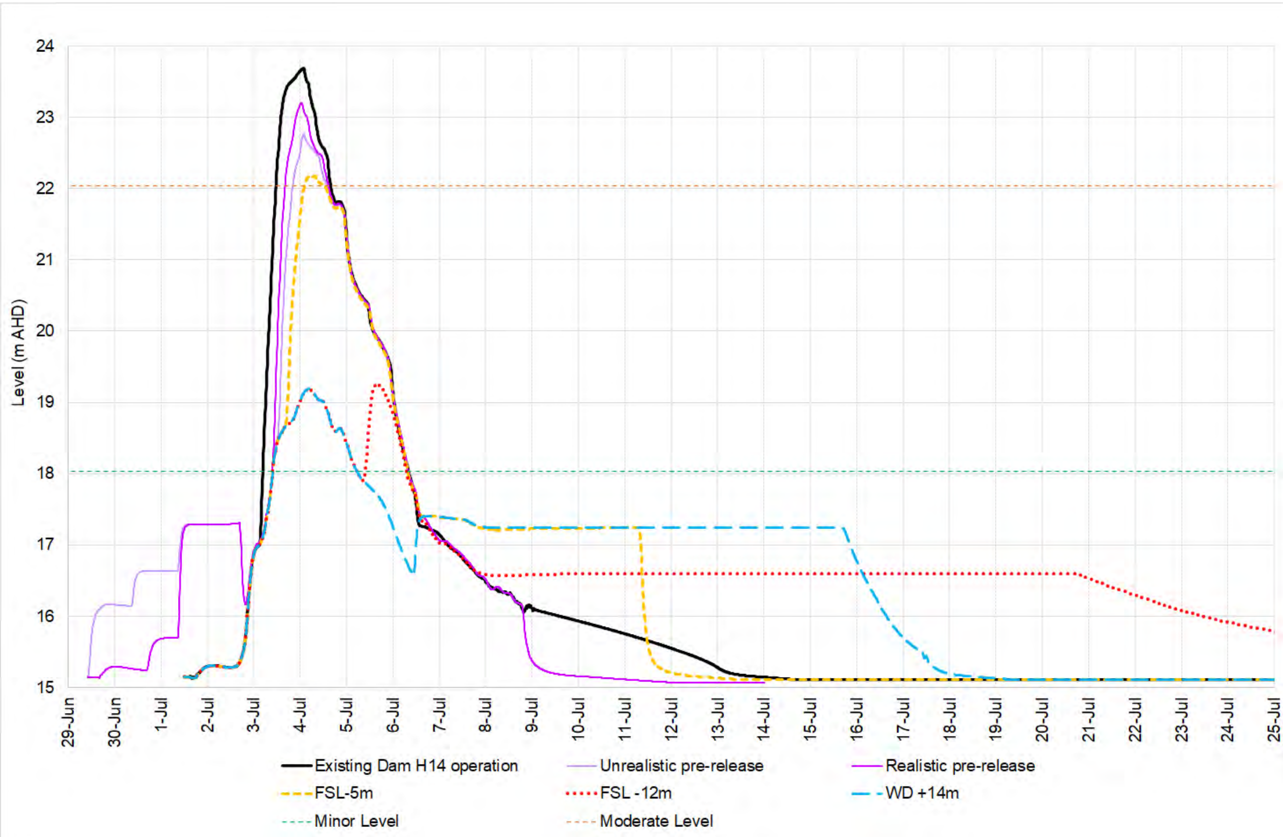


Figure E17: Penrith level hydrograph for various flood mitigation scenarios, July 2022 flood

3.2 Windsor

3.2.1 Flood peak

The reduction in peak flood levels at Windsor for the different dam flood mitigation scenarios is described in Table E10. The flood hydrographs for the different scenarios are presented in Figures E18 and E19.

The proposed raised dam would have reduced the peaks of the March and July 2022 floods at Windsor by around 3.4m – the same result as for the March 2021 flood (Infrastructure NSW, 2021).

Lowering FSL by 12 metres would have produced a similar reduction to the raised dam in the July 2022 flood, but a much smaller 0.7m reduction in the double-peaked, high volume March 2022 flood.

Lowering FSL by 5 metres, or pre-releases, would have provided less than 1.0m reduction in the July 2022 flood, and negligible benefit in the March 2022 flood. The relative ineffectiveness of these options reflects the relatively small volume of air space in the dam that either a permanent lowering of FSL by 5 metres or pre-releases can provide.

3.2.2 Flood classification

The March and July 2022 floods peaked at Windsor in the major range. The proposed raised dam would have reduced the peak for both events to the moderate range. Lowering FSL by 12 metres would have achieved this result for the July event. None of the other options would have made sufficient difference to have lessened the flood category (Table E11).

3.2.3 Timing

The salient feature of Table E12 is how pre-releases would have brought forward minor flooding at Windsor in the March 2022 flood by nearly 1 day (see Figure E18). For the Windsor floodplain and communities in the lower Hawkesbury, including many low-lying caravan parks, minor flooding can have serious consequences. Reaching minor level flooding earlier than normal would limit the time for emergency preparations.

There has been considerable interest in how the proposed raised dam could impact the duration of flooding, given the prolonged controlled releases to draw down the flood mitigation zone to FSL (see Figures E14 and E15). The prolonged minor flooding at Windsor, associated with these releases in the March 2022 scenario, may be seen in Figure E18.

The durations of flooding in the existing case, and with the proposed raised dam's releases, may also be compared in Figures E20 to E24. The March 2022 flood was a relatively high-volume event, with large parts of the Richmond Lowlands, areas around the natural lagoons, and South Creek, flooded for more than 10 days (Figure E20). By taking 3.3m off the peak, the proposed raised dam would have reduced the extent of flooding (see 'was wet now dry' in Figure E21). It would also have reduced the duration of flooding in many areas including much of Richmond Lowlands. However, some low-lying areas would have had longer duration flooding including areas adjacent to South and Eastern creeks.

The July 2022 flood had a smaller volume in the dam, and shorter durations of overbank inundation downstream (Figure E22). The releases from the proposed raised dam would have been at a lower rate than in March (compare Figures E14 and E15). Again, by taking 3.4m off the peak, the proposed raised dam would have reduced the extent of flooding (see 'was wet now dry' in Figure E23). It would also have reduced the duration of flooding in many areas.

A similar figure showing changed durations of flooding around Windsor with the proposed raised dam for the March 2021 flood (not previously reported) is provided in Figure E24.

Table E10: Windsor flood peak reduction for various flood mitigation scenarios, March and July 2022 floods

Modelled Scenario	Reduction in peak (m)	
	March 2022	July 2022
Existing Dam	-	-
WD +14m	3.3	3.4
FSL -12m	0.7	3.3
FSL -5m	<0.1	0.9
Unrealistic pre-release	<0.1	0.6
Realistic pre-release	<0.1	0.4

Table E11: Windsor flood categorisation for various flood mitigation scenarios, March and July 2022 floods

Modelled Scenario	Flood category	
	March 2022	July 2022
Existing Dam	Major	Major
WD +14m	Moderate	Moderate
FSL -12m	Major	Moderate
FSL -5m	Major	Major
Unrealistic pre-release	Major	Major
Realistic pre-release	Major	Major

Moderate flood level at Windsor is 7.0m-12.2m AHD
Major flood level at Windsor is ≥12.2m AHD

Table E12: Windsor time delay for various flood mitigation scenarios, March and July 2022 floods

Modelled Scenario	Time delay (hrs)							
	March 2022				July 2022			
	MIN	MOD	MAJ	PEAK	MIN	MOD	MAJ	PEAK
Existing Dam	-	-	-	-	-	-	-	-
WD +14m	1	2	Level not reached	7	2	2	Level not reached	0
FSL -12m	1	2	10	3	2	2	Level not reached	14
FSL -5m	1	2	2	1	2	2	18	5
Unrealistic pre-release	-21	-1	1	0	1	1	10	4
Realistic pre-release	-20	-1	0	1	1	1	7	2

Minor flood level at Windsor is 5.8m-7.0m AHD
Moderate flood level at Windsor is 7.0m-12.2m AHD
Major flood level at Windsor is ≥12.2m AHD

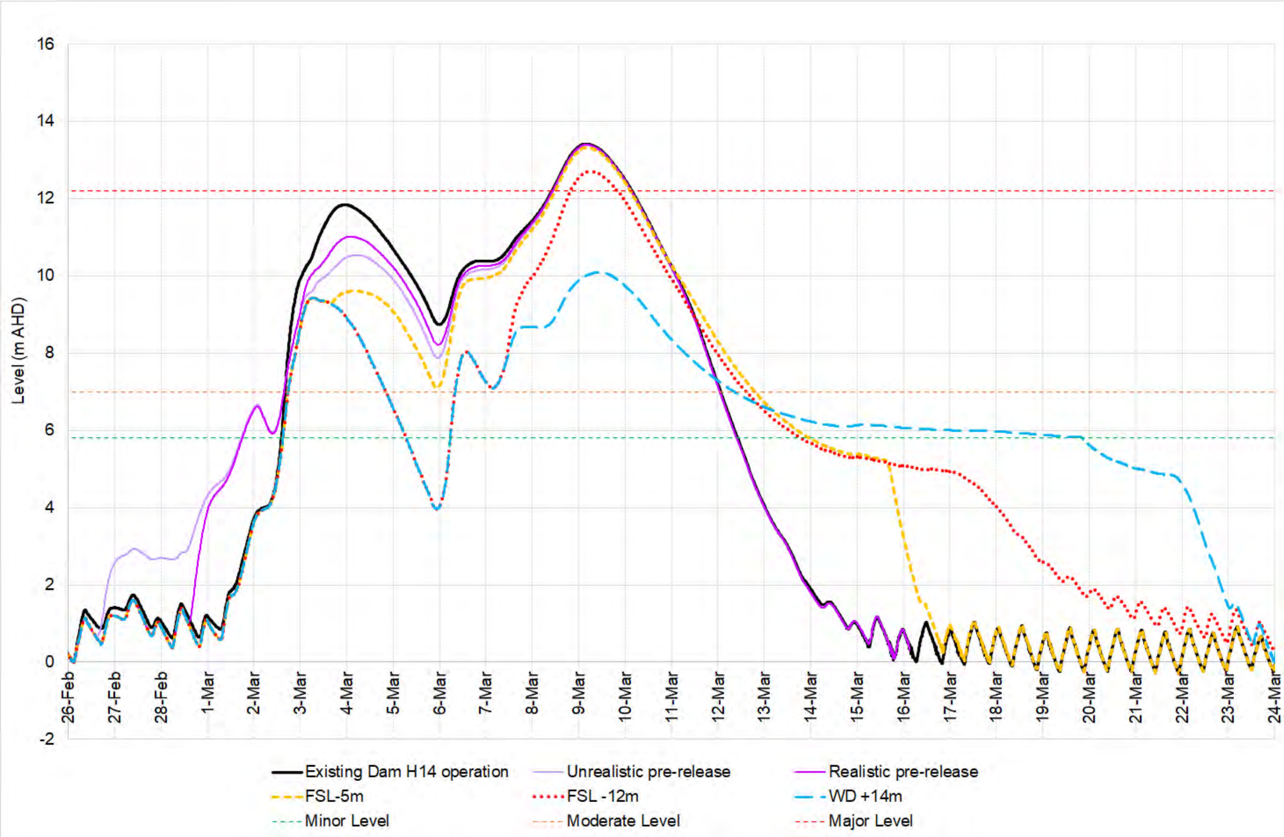


Figure E18: Windsor level hydrograph for various flood mitigation scenarios, March 2022 flood

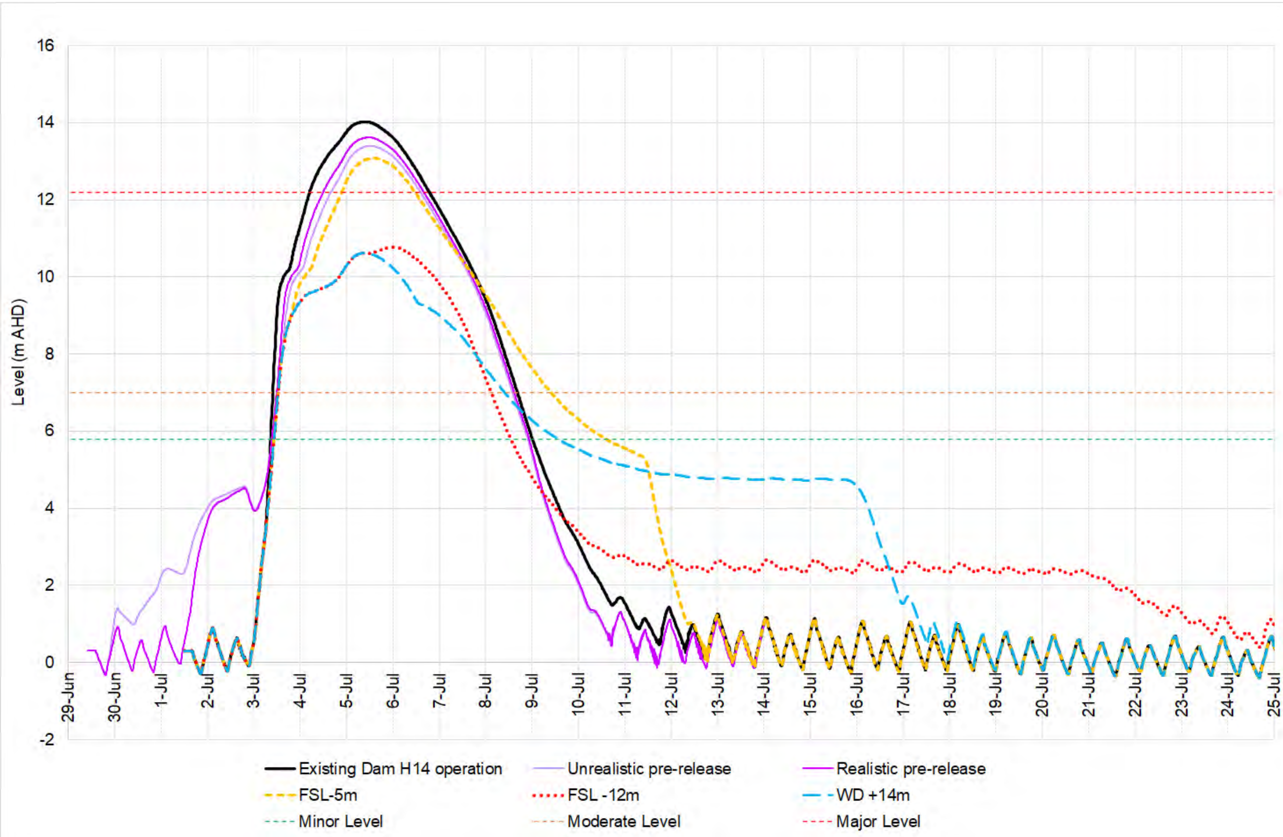


Figure E19: Windsor level hydrograph for various flood mitigation scenarios, July 2022 flood

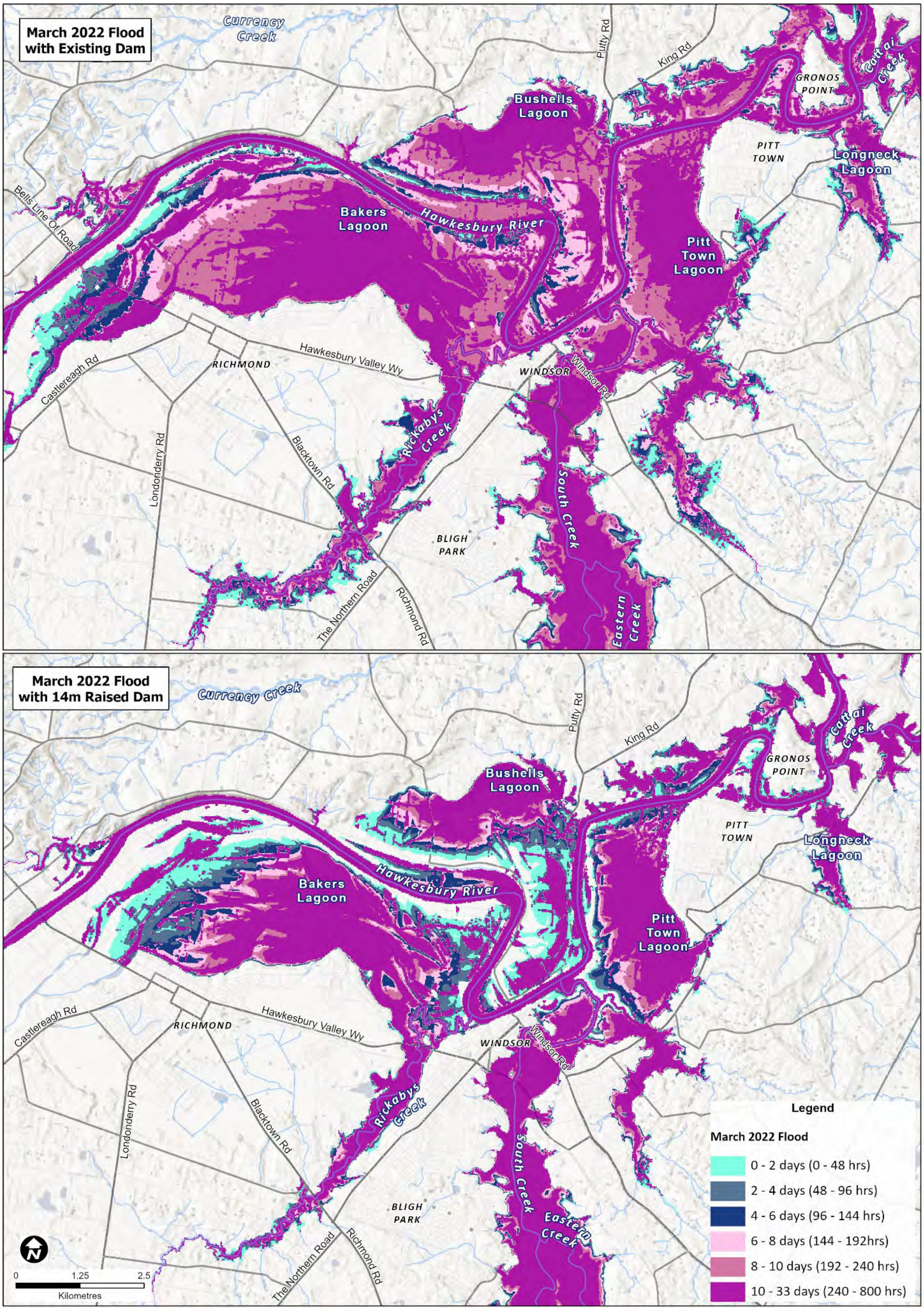


Figure E20: Flood duration, March 2022 flood, existing dam operations and with raised dam, Richmond/Windsor floodplain

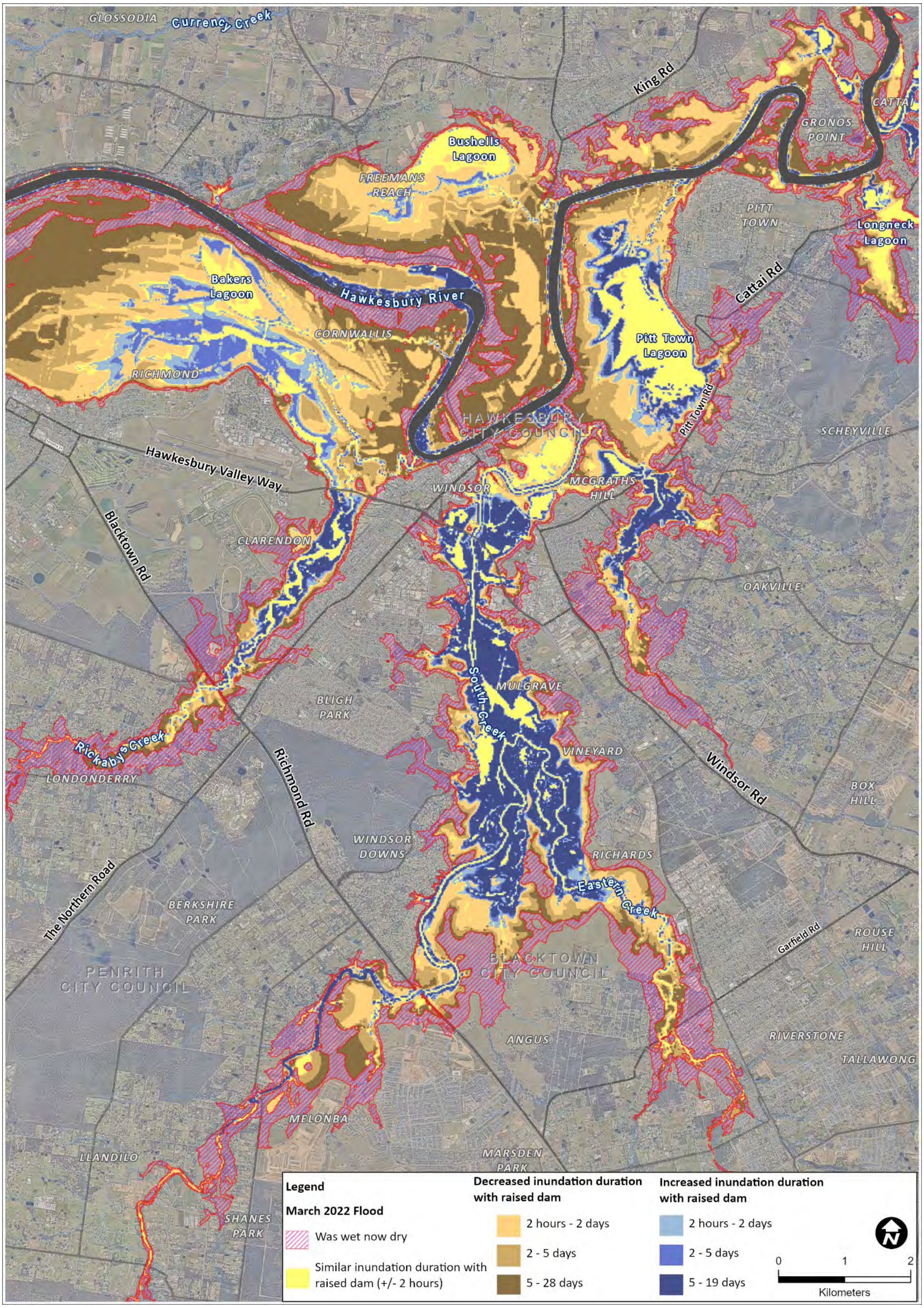


Figure E21: Change in flood duration, March 2022 flood, existing dam operations versus raised dam, Richmond/Windsor floodplain

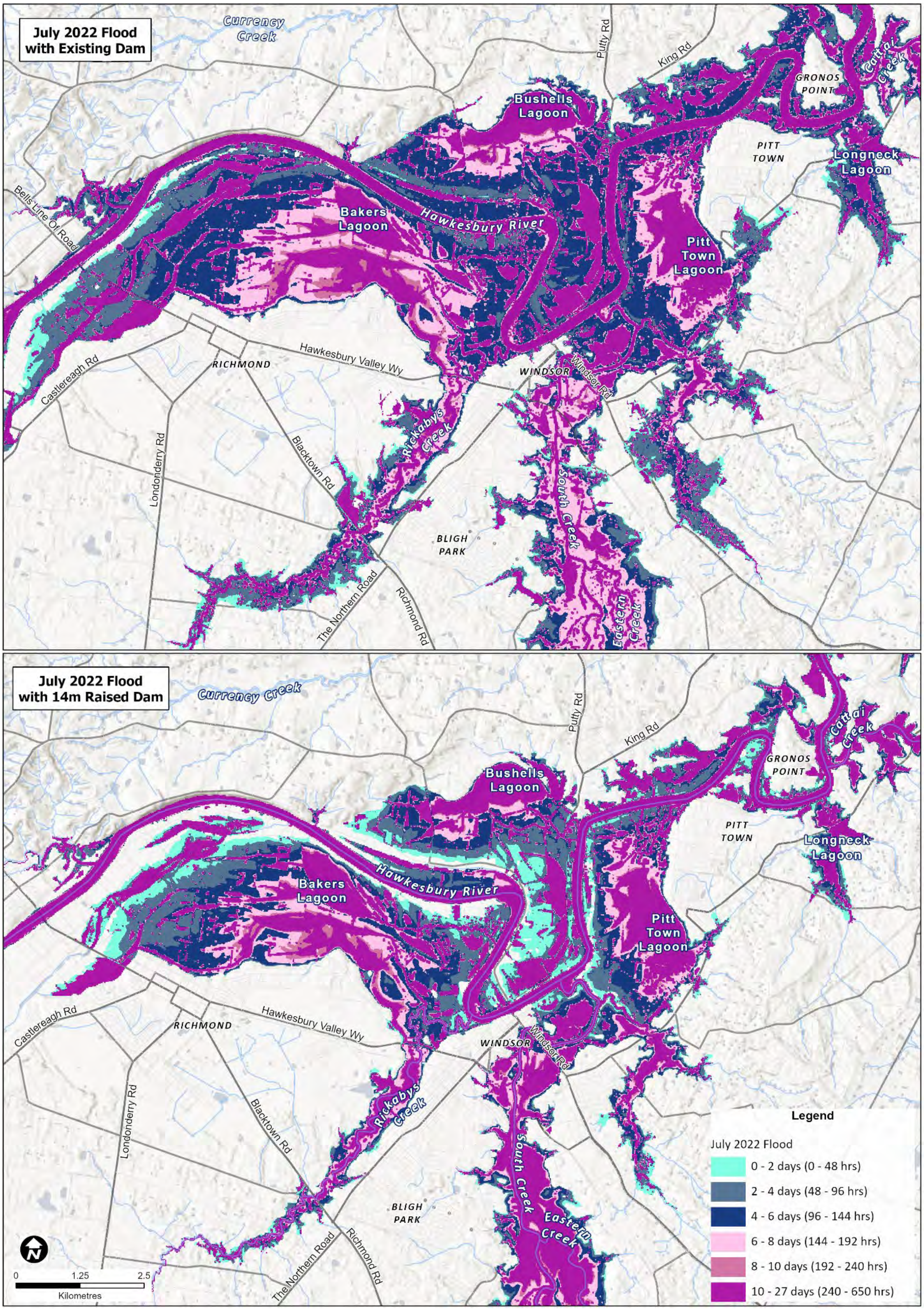


Figure E22: Flood duration, July 2022 flood, existing dam operations and with raised dam, Richmond/Windsor floodplain

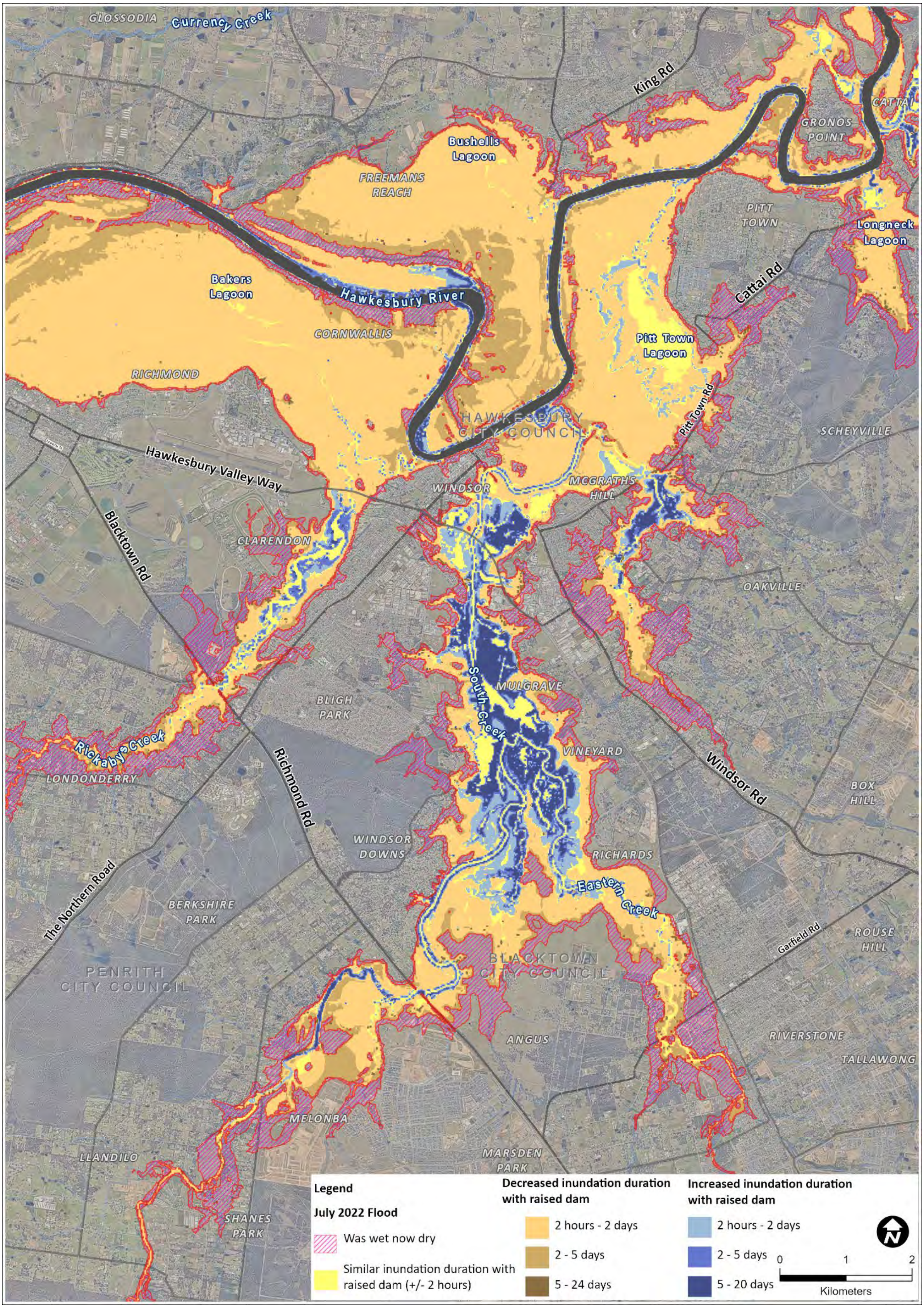


Figure E23: Change in flood duration, July 2022 flood, existing dam operations versus raised dam, Richmond/Windsor floodplain

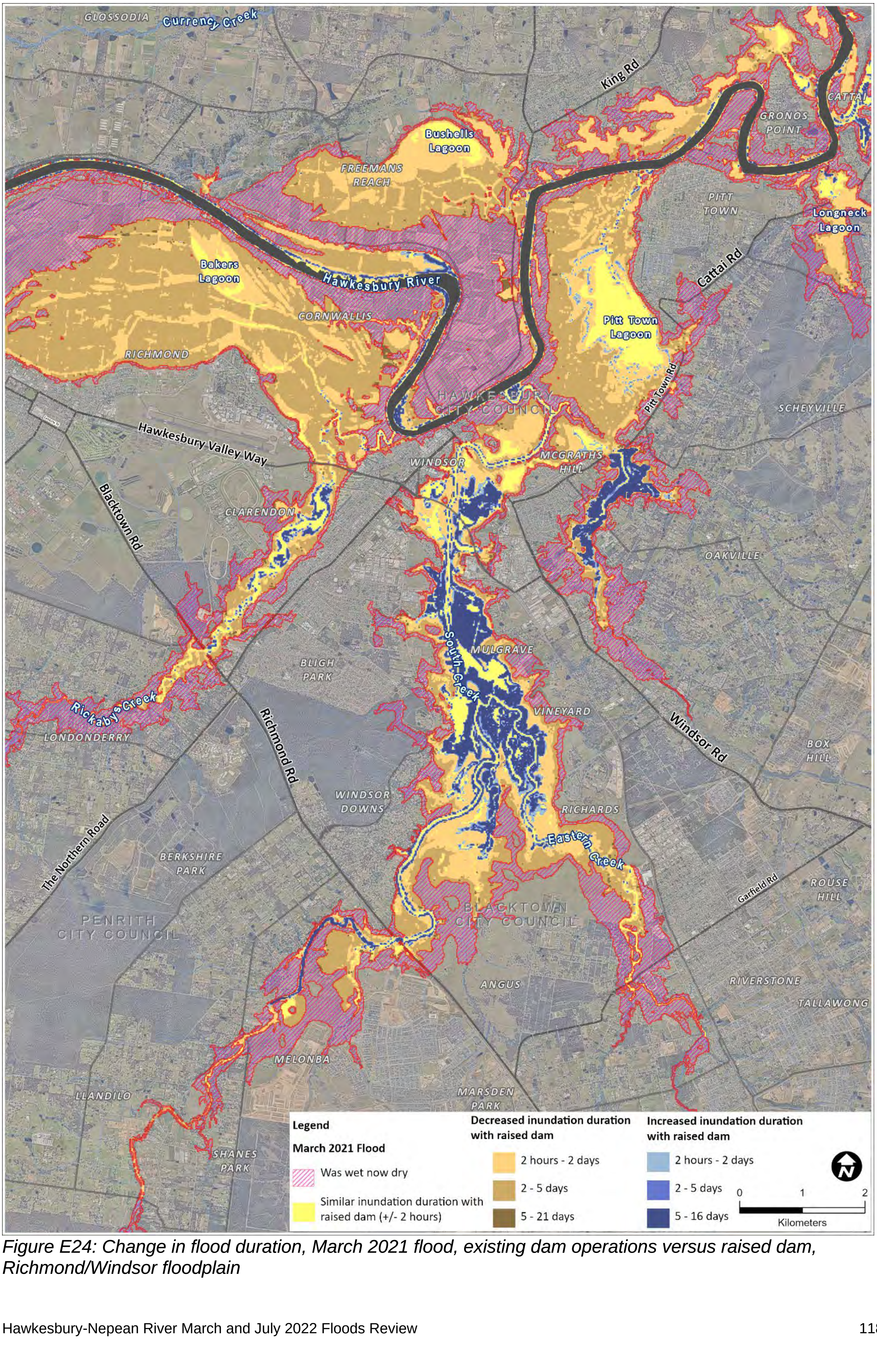


Figure E24: Change in flood duration, March 2021 flood, existing dam operations versus raised dam, Richmond/Windsor floodplain

3.3 Buildings impacted

The effect of the various scenarios in reducing the number of residential dwellings, commercial/industrial buildings and manufactured homes impacted by the floods is set out in Table E13. The numbers of assets on the floodplain are taken from Infrastructure NSW's 2018 assets database.

As expected, given the greater reduction in flood peaks and extents made possible by the proposed raised dam, this option would have provided the greatest reduction in the number of dwellings impacted by the March and July 2022 floods, by 70-80%. Lowering FSL by 12 metres would have provided a similar reduction in the July flood, but noticeably lower benefit in the March flood. Lowering FSL by 5 metres and pre-releases would have provided some reduction in the numbers of dwellings impacted in the July flood, but very small benefit in the March flood.

Many manufactured homes are located in low-lying caravan parks, with nearly 1500 impacted in the March 2022 flood and over 1600 impacted in the July 2022 flood. The proposed dam raising would have reduced the number impacted in March by over 40%, and the number in July by over 20%. This reduction is less than assessed for the March 2021 flood (Infrastructure NSW, 2021), probably because the March and July 2022 floods were noticeably higher than the earlier flood in most of the valley, so that even with the benefit of the raised dam, large numbers of manufactured homes would still have been impacted.

Table E13: Number of buildings impacted, and percentage reduction, Hawkesbury-Nepean Valley study area, March and July 2022 floods, under different Warragamba Dam mitigation scenarios

	March 2022			July 2022		
Modelled Scenario	**Dwellings**	**Comm/Ind**	**Manufactured Homes**	**Dwellings**	**Comm/Ind**	**Manufactured Homes**
Existing Dam	840	360	1490	1320	430	1650
WD +14m	240 (-72%)	90 (-74%)	870 (-42%)	310 (-76%)	130 (-71%)	1280 (-23%)
FSL -12m	540 (-35%)	290 (-19%)	1350 (-9%)	330 (-75%)	140 (-68%)	1310 (-21%)
FSL -5m	800 (-5%)	350 (-2%)	1460 (-2%)	750 (-43%)	320 (-25%)	1580 (-5%)
Unrealistic pre-release	820 (-3%)	350 (-1%)	1470 (-1%)	900 (-32%)	360 (-17%)	1610 (-3%)
Realistic pre-release	830 (-1%)	350 (-1%)	1480 (0%)	1010 (-23%)	380 (-12%)	1620 (-2%)

Notes:

[1] Buildings impacted are counted as those within the flood footprint for each scenario. No account is taken of floor heights in this analysis.

[2] The Hawkesbury-Nepean Valley study area extends from Bents Basin near Wallacia to Brooklyn, and includes areas impacted by backwater flooding. Thus, buildings impacted near Camden are not counted.

[3] Numbers are rounded; percentages relate to unrounded numbers

3.4 Downstream river crossings

Tables E14, E15 and E16 describe the change in timing of closure of Yarramundi Bridge, North Richmond Bridge and Sackville Ferry.

These closures all happen at relatively low levels of flooding because the bridges are set below bank height, and the ferry services in the lower Hawkesbury are sensitive to even small river rises. These low levels can be reached by inflows from tributaries other than Warragamba, which is why for the first peak in the March 2022 flood, and for the July 2022 flood, there is little to no delay to closure times with a raised dam or FSL-lowering. It is possible that with the proposed raised dam or the 12m-lowering option, North Richmond Bridge could have reopened between the 2 peaks in March.

Pre-releases would bring forward closures and the potential isolation of communities, especially on the western and northern sides of the river.

Table E14: Yarramundi Bridge closure statistics for various scenarios

	March 2022^		July 2022	
Modelled Scenario	**Time reached***	**Delay to reach (hrs)**	**Time reached***	**Delay to reach (hrs)**
Existing Dam	2/3/2022 9:50	-	3/7/2022 05:40	-
WD +14m	2/3/2022 10:10 6/3/2022 3:10	0 89	3/7/2022 06:00	0
FSL -12m	2/3/2022 10:10 6/3/2022 3:10	0 89	3/7/2022 06:00	0
FSL -5m	2/3/2022 10:10	0	3/7/2022 06:00	0
Unrealistic pre-release	28/2/2022 18:10	-40	1/7/2022 20:50	-33
Realistic pre-release	28/2/2022 21:50	-36	2/7/2022 00:40	-29

Notes
* Closure level set at 5.61m AHD
^ The March 2022 flood had 2 peaks, with the water level for 2 scenarios (+14m, -12m) rising above the adopted closure level, falling below this closure level (to 4.33m), then (after 0.7 days) rising above the closure level again. Hence, 2 closure times and 2 changes in closure time comparing scenarios to the existing dam operations (rounded to the nearest whole hour) are reported. It is unlikely that, under these 2 scenarios, the bridge would have reopened between the 2 peaks.

Table E15: North Richmond Bridge closure statistics for various scenarios

	March 2022^		July 2022	
Modelled Scenario	**Time reached***	**Delay to reach (hrs)**	**Time reached***	**Delay to reach (hrs)**
Existing Dam	2/03/2022 14:20	-	3/07/2022 7:50	-
WD +14m	2/03/2022 15:40 6/03/2022 6:50	1 89	3/07/2022 9:50	2
FSL -12m	2/03/2022 15:40 6/03/2022 6:50	1 89	3/07/2022 9:50	2
FSL -5m	2/03/2022 15:40	1	3/07/2022 9:50	2
Unrealistic pre-release	1/03/2022 17:50	-21	3/07/2022 9:10	1
Realistic pre-release	1/03/2022 18:00	-20	3/07/2022 9:10	1

Notes
* Closure level set at 7.82m AHD
^ The March 2022 flood had 2 peaks, with the water level for 2 scenarios (+14m, -12m) rising above the adopted closure level, falling below this closure level (to 4.25m), then (after 1.6 days) rising above the closure level again. Hence, 2 closure times and 2 changes in closure time comparing scenarios to the existing dam operations (rounded to the nearest whole hour) are reported. It is possible that, under these 2 scenarios, the bridge would have reopened between the 2 peaks.

Table E16: Sackville Ferry closure statistics for various scenarios

	March 2022		July 2022	
Modelled Scenario	**Time reached***	**Delay to reach (hrs)**	**Time reached***	**Delay to reach (hrs)**
Existing Dam	1/03/2022 21:50	-	3/07/2022 9:20	-
WD +14m	1/03/2022 22:00	0	3/07/2022 10:00	1
FSL -12m	1/03/2022 22:00	0	3/07/2022 10:00	1
FSL -5m	1/03/2022 22:00	0	3/07/2022 10:00	1
Unrealistic pre-release	27/02/2022 7:10	-63	1/07/2022 22:10	-35
Realistic pre-release	28/02/2022 22:40	-23	1/07/2022 22:50	-35

* Closure level set at 1.6m AHD (as per TfNSW, 2020)

Table E17 describes changes to the timing and duration of closure of the new Windsor Bridge. The new bridge is on a grade with the lowest bridge deck level at about 10m AHD. At that point the underside of the bridge deck is about 8m AHD. The analysis assumes that the bridge would close 1m below the lowest bridge deck level. Table E18 describes similar metrics with respect to the actual overtopping of the bridge deck.

In the March 2022 flood, raising the dam would have delayed closing the bridge by 6 hours on the first peak and nearly 2½ days on the second peak, and shortened the duration of closure by more than 5 days. With a raised dam, the bridge deck would have been just overtopped for about ½ a day, shortening the duration of overtopping by more than 6 days.

In the July 2022 flood, raising the dam would have delayed closing the bridge by 8 hours, and reduced the duration of closure by over 1 day.

Lowering FSL by 12 metres would have delayed closing the bridge in the March flood by 6 hours on the first peak and about 1½ days on the second peak, and reduced the duration of closure by about 3½ days. The bridge would still have been overtopped for 3 days. The benefits of this scenario in the July flood would have been similar to the dam raising proposal.

Lowering FSL by 5 metres, or pre-releases, would have provided relatively small benefits in terms of delays and duration of closure of Windsor Bridge.

Table E17: Windsor Bridge closure statistics for various scenarios

	March 2022^			July 2022		
Modelled Scenario	Time reached*	Delay to reach (hrs)	Duration closed (days)#	Time reached*	Delay to reach (hrs)	Duration closed (days)#
Existing Dam	2/3/2022 20:00 6/3/2022 3:50	-	3.0+5.3 = 8.3 total	3/07/2022 12:00	-	4.6
WD +14m	3/3/2022 1:30 8/3/2022 12:30	6, 57	0.9+2.0 = 2.9 total	3/07/2022 19:50	8	3.2
FSL -12m	3/3/2022 1:30 7/3/2022 14:30	6, 35	0.9+3.9 = 4.7 total	3/07/2022 19:50	8	3.6
FSL -5m	3/3/2022 1:30 6/3/2022 7:40	6, 4	2.0+5.3 = 7.3 total	3/07/2022 19:20	7	4.5
Unrealistic pre-release	2/3/2022 23:50 6/3/2022 6:20	4, 3	2.5+5.2 = 7.7 total	3/07/2022 16:40	5	4.3
Realistic pre-release	3/3/2022 0:00 6/3/2022 5:50	4, 2	2.6+5.2 = 7.9 total	3/07/2022 15:10	3	4.4

Notes

* Closure level set at 9.0m AHD. In March 2022, the bridge closed at 10:01pm on 2 March when the river height was 8.74m; in July 2022, the bridge closed at 1:39pm on 3 July when the river height was 9.18m.

^ Figure E18 shows that the March 2022 flood had 2 peaks, with the water level between the 2 peaks falling below the adopted closure level, then rising above the closure level again, for all scenarios. Hence, 2 closure times, 2 changes in closure time comparing scenarios to the existing dam operations (rounded to the nearest whole hour), and 2 durations (rounded to 1 decimal point in days) are reported.

This is a simple representation of duration closed for comparative purposes, based on the adopted closure level of 9.0m AHD. Where the bridge structure and deck are flooded, the time of closure is likely to be longer because the bridge will need to be inspected and cleared of debris and mud before opening. Also, the March 2022 flood hydrographs for all scenarios fall below the adopted closure level before rising above it again (Figure E18). With the exception of the +14m and -12m scenarios, it is doubtful that the bridge would have been reopened during this time. The calculated durations of closure do not include this period.

Table E18: Windsor Bridge overtopping statistics for various scenarios

	March 2022^			July 2022		
Modelled Scenario	Time reached*	Delay to reach (hrs)	Duration overtopped (days)	Time reached*	Delay to reach (hrs)	Duration overtopped (days)
Existing Dam	3/3/2022 0:40 6/3/2022 10:10	-	2.4+4.7= 7.0 total	3/07/2022 15:20	-	4.2
WD +14m	- 9/3/2022 3:30	- 65	0+0.6= 0.6 total	4/07/2022 19:50	29	1.4
FSL -12m	- 8/3/2022 0:10	- 38	0+3.0= 3.0 total	4/07/2022 19:50	29	2.1
FSL -5m	- 7/0/2022 4:00	- 18	0+4.0= 4.0 total	4/07/2022 2:00	11	3.7
Unrealistic pre-release	3/3/2022 13:10 6/3/2022 13:30	13, 3	1.4+4.5= 5.9 total	3/07/2022 21:50	7	3.8
Realistic pre-release	3/3/2022 5:30 6/3/2022 12:00	5, 2	1.9+4.6= 6.5 total	3/07/2022 19:20	4	3.9

Notes

* Lowest bridge deck level 10.0m AHD

^ Figure E18 shows that the March 2022 flood had 2 peaks, with the water level between the 2 peaks falling below the deck level, then rising above the deck level again, for 3 scenarios (existing dam, 2 x pre-releases). Hence, for these 3 scenarios, 2 closure times, 2 changes in closure time comparing scenarios to the existing dam operations, and 2 durations are reported.

3.5 Upstream of Warragamba Dam

A raised Warragamba Dam for flood mitigation would operate by temporarily detaining flood inflows within the flood mitigation zone, to delay outflows and reduce the peak levels downstream. This would increase inundation levels behind the raised dam wall until the flood mitigation zone was emptied once the downstream flood peak had passed.

As noted in Section 2.1.1 of this memo, because of its unusual double-peaked nature, the March 2022 event was characterised by a particularly high total inflow volume to Warragamba Dam – corresponding to about a 1 in 70 AEP event. This is significant because when a dam has a large, dedicated flood storage zone like the proposed raised Warragamba Dam, the levels in the dam change from being driven by a combination of peak flow and volume to being largely a function of volume.

Due to its large total inflow volume, modelling shows that had the proposed raised dam been in place at the time of the March 2022 flood, water levels upstream would have peaked at a height of 131.62m AHD.

Comparatively, the single-peaked July 2022 flood event had a total inflow volume corresponding to about a 1 in 20 AEP event. As a result, modelling suggests that with the raised dam the upstream water level would have peaked at 126.89m AHD.

Due to its double-peaked nature, the March 2022 event would present unusual challenges for efficiently emptying the flood mitigation zone. It is noted that the precise operating rules for the proposed raised dam are yet to be finalised. Subject to approval of the proposed dam raising, the operating rules will be refined by ongoing modelling and analysis of historical events including the March 2022 flood.

4. CONCLUSION

Infrastructure NSW engaged Rhelm/CSS and WMAwater to assess the impacts various Warragamba Dam flood mitigation measures would have had on downstream flooding if implemented prior to the March and July 2022 events. The assessment drew upon detailed, calibrated hydrologic and hydraulic models that were validated and adjusted to the floods.

Different Warragamba outflow hydrographs were derived for various flood mitigation options. These were run through the hydraulic model to assess changes in downstream flood behaviour and impacts.

The pre-release scenarios would have provided small to negligible reductions of downstream flood peaks, and yet would have brought forward closure of some downstream transport routes and the time at which the minor flood level was reached at Windsor in March.

Lowering FSL by 5 metres would have provided modest reductions of downstream flood peaks in July 2022, translating to around a 40% reduction in the number of impacted dwellings. It would have provided very small benefits in the large volume March 2022 flood.

Lowering FSL by 12 metres would have provided a good reduction of downstream flood peaks in July 2022, translating to a 75% reduction in the number of impacted dwellings. It would have provided a small reduction in peak levels in the March 2022 flood, though still translating to a 35% fall in impacted dwellings.

The proposed dam raising would have reduced peak flood levels substantially for both the March and July 2022 floods, translating to a 70-80% reduction in the number of dwellings impacted in both floods. It would also have reduced the duration of closure of Windsor Bridge more than any other option. For these 2 floods, the duration of flooding around the Windsor floodplain would have been reduced in most areas, with some increases adjacent to creek lines as a result of drawing down the flood mitigation zone.

5. REFERENCES

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

BoM (Bureau of Meteorology) (2020) *Service Level Specification for Flood Forecasting and Warning Services for New South Wales and the Australian Capital Territory*, Version 3.13, March 2020.

Boyd MJ, Pilgrim DH, Knee RM and Budiawan D (1989) 'Reverse routing to obtain upstream hydrographs', *Hydrology and Water Resources Symposium, Christchurch, NZ, 23-30 November*, Preprints of Papers (p: 372). Institution of Engineers, Australia.

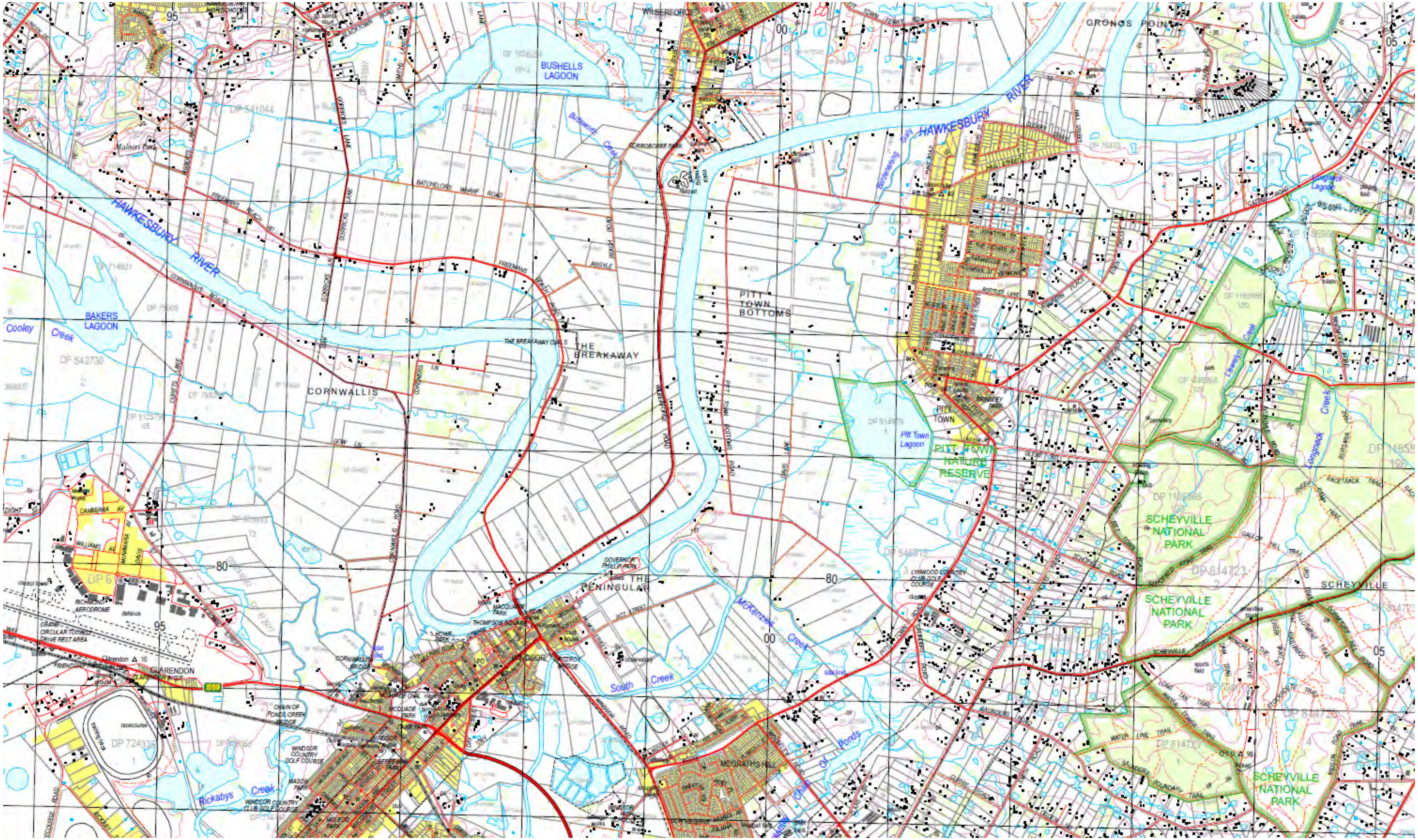
Infrastructure NSW (2021) *Hawkesbury-Nepean River March 2021 Flood Review*, accessed 23 September 2022.

TfNSW (Transport for NSW) (2021) *Sydney Basin Vehicular Ferry Flood Response Plan 2020*, Version 1.0, January 2021.

US Bureau of Reclamation (1987) *Design of Small Dams*, Ch.9 Spillways, 9.16 Discharge Over Gate-Controlled Ogee Crests, A Water Resources Technical Publication, Third edition, Bureau of Reclamation, US Department of the Interior.

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

Appendix F: Extract from Wilberforce 9030-1N 1:25000 topographic map (2017 edition)



The Terrace, Windsor, 6 July 2022 (Photo by S. Yeo courtesy of Infrastructure NSW)