Hawkesbury-Nepean River March 2021 Flood Review

HAWKESBURY-NEPEAN VALLEY FLOOD RISK MANAGEMENT STRATEGY

Final Report
December 2021

NSW GOVERNMENT

Cover photo: Flooding of the Hawkesbury River and South Creek, 25 March 2021
Source: Infrastructure NSW. Image: Top Notch Video

Acknowledgments
This report was made possible through the contribution of many agencies, organisations and stakeholders, including: Commonwealth Bureau of Meteorology; Agriculture and Animal Services Functional Area; Energy and Utility Services Functional Area; Engineering Services Functional Area; Environmental Services Functional Area; NSW Department of Customer Service – Spatial Services; NSW Department of Education; NSW Department of Planning, Industry and Environment (DPIE) – Biodiversity Conservation Division; NSW DPIE – Place, Design and Public Spaces; NSW DPIE – Water (Manly Hydraulics Laboratory); NSW Police; NSW Rural Fire Service – Wallacia Rural Fire Brigade; NSW State Emergency Service; Resilience NSW; Soil Conservation Service; Telecommunications Services Functional Area; Transport for NSW; WaterNSW; Hawkesbury City Council; The Hills Shire Council; Hornsby Shire Council; Turf Australia; Hawkesbury River Oyster Shed; Peppercorn Services Inc; Hired Gun; Top Notch Video; WMAwater; Rhelm; Catchment Simulation Solutions.

Executive Summary

Severe flooding impacted many parts of NSW in March 2021, including the Hawkesbury-Nepean Valley (the valley) in Sydney's west and northwest. This report describes the causes, nature and impacts of the flood, and the response to and recovery from flooding in the valley. Our focus is on flooding of the main river between Bents Basin near Wallacia and Brooklyn, plus backwater flooding. The flood had significant impacts on communities in Penrith, Hawkesbury, Blacktown, The Hills, Hornsby and Central Coast local government areas.

As the largest flood in the Hawkesbury-Nepean Valley for 30 years, the March 2021 flood provides an opportunity for evaluation and improvement from lessons learnt. This review commenced in response to the Hawkesbury-Nepean Valley Flood Risk Management Strategy's monitoring / evaluation / reporting / improvement framework (outcome 9), which requires evaluation after a significant flood. This report includes an assessment of the difference various flood mitigation options would have made to this flood. We also consider briefly the 9 outcomes of the Flood Strategy in relation to the March 2021 flood.

Flood analysis

The March 2021 flood was an unusual event both in the historical record and in the context of nearly 20,000 modelled flood scenarios. A distinctive characteristic was its double peak in upstream areas. This was caused by the persistent presence of a coastal trough, generating rain for over a week. It resulted in a large volume of inflows to Warragamba Dam – the second highest in the dam's 60-year record, translating to a 1 in 40 chance per year inflow volume. However, the peak level in the dam was about a 1 in 10 to 20 chance per year event.

At Windsor and in the lower Hawkesbury River, the March 2021 flood was the highest and first major flood since 1990. At Penrith, it was the highest since 1925. The March 2021 flood has an average frequency of 1 in 10 to 20 chance per year at Windsor and Penrith. Considerably higher floods are possible – the 1867 flood of record at Windsor was about 7m higher.

Flood modelling shows that around 60% of the volume of floodwaters to Windsor came from the Warragamba subcatchment, with 40% from other tributaries including upper Nepean River, Erskine and Glenbrook creeks, Grose River and South Creek.

The double-peak flood in upstream areas translated to a long duration flood in downstream areas. This long duration is considered a likely causative factor in the extensive erosion of riverbanks. Rotational slips caused by saturation of soils were frequently observed along the Hawkesbury River.

Impacts

About 600 dwellings and 300 commercial/industrial buildings (most on rural land) are estimated to have been impacted by the Hawkesbury-Nepean flood. Communities/suburbs with more than 20 flood-impacted dwellings are Lower Macdonald, Lower Portland, Ebenezer, Windsor, Pitt Town Bottoms, Laughtondale, Londonderry, Wilberforce, Spencer and Pitt Town. No major urban areas were subject to widespread flooding. Some dwellings on urban fringes were affected.

The many caravan parks between Windsor and Gunderman in the lower Hawkesbury were severely impacted by the flood, with over 1400 manufactured homes flooded, and reports of some perilous evacuations and rescues.

Key roads and bridges across the Hawkesbury River were flooded for over 6 days, and the vehicular ferries were out of service for over 9 days. This, combined with flooding of the Colo River and a landslide on Bells Line of Road, isolated many communities for a prolonged period. Power outages disrupted communications, adding to the sense of isolation.

There was significant damage to some local roads, from both flooding and riverbank erosion. Councils' damage bills also included damage to many parks.

Only 1 school was directly impacted by floodwater. Many more were closed during the severe weather event.

Along with caravan park operators, turf farmers and vegetable farmers were among the most impacted businesses in the valley. Oyster farmers also sustained significant losses.

The flooding mobilised a large amount of debris, much of which was carried into the Hawkesbury River, its estuary, and beaches on the Central Coast and Northern Beaches of Sydney.

At least 45 recorded Aboriginal sites were within the footprint of flooding downstream of Warragamba Dam. A large number of non-indigenous heritage items were also impacted.

The total direct and indirect cost of the Hawkesbury-Nepean flood is expected to be in the order of several hundred million dollars.

Tragically, the flood claimed the life of a 25-year old driver at the flooded Cattai Ridge Road crossing of Cattai Creek in Glenorie.

Coming on the back of multiple disasters including drought, bushfire, the February 2020 flood and storm, and COVID-19, social service providers reported that the March 2021 flood has had serious psychosocial impacts on affected communities. This includes already socially vulnerable people such as social housing tenants, those living permanently in caravan parks, and people sleeping rough. It also includes people who suffered damage to their houses and farms. Some people have had challenges accessing support services, including due to damaged roads and limited communications infrastructure.

Response and recovery

The Bureau of Meteorology issued the first Flood Watch for the Hawkesbury-Nepean system on Thursday 18 March 2021. Flooding was expected from that date. The first Flood Warning for the Hawkesbury-Nepean was issued on Saturday 20 March. In all, 56 flood warnings were issued across 9 days.

Evacuation Warnings and Evacuation Orders were issued for various communities from the Saturday. The NSW State Emergency Service (NSW SES) responded to over 5636 requests for assistance in the Sydney Metropolitan Area including flood rescues, evacuations and resupplies.

A large clean-up operation began after the flood, on land and in the river, its estuary and the adjacent coastline. More than 1750 cubic metres of waste were removed from the Hawkesbury-Nepean area up to July.

Three recovery centres in the Hawkesbury-Nepean serviced nearly 1600 daily visitations up to June. Recovery is ongoing in response to both the acute and ongoing cumulative emotional, physical and financial impacts of the flood/storm (and previous bushfire, flood/storm and pandemic disasters).

‘What if’ scenarios

Various suggestions were made after the flood about how the flooding could have been reduced. A number of Warragamba Dam flood mitigation scenarios have been modelled to determine what difference these measures would have made to the height and timing of downstream flooding.

Pre-releasing water from Warragamba Dam storage in a realistic timeframe based on forecast rainfall would have provided minimal reduction of downstream flood peaks. It would also have brought forward closure of downstream bridges and the time at which designated ‘minor’ flood levels are reached – potentially impairing the flood response for some downstream communities.

Pre-releasing water any earlier would have presented a risk to water supply, and would still have provided relatively small benefits in terms of downstream flood peak reductions.

Permanently lowering the full supply level (FSL) at Warragamba Dam by 5m would have provided relatively small benefits to downstream flood peaks (0.6m reduction at Windsor) and consequently, relatively small reductions in the number of buildings impacted.

Permanently lowering FSL by 12m would have reduced the flood peak at Windsor by 1.9m, and delayed outflows from the dam by 2 to 3 days. The number of impacted dwellings and manufactured homes would have reduced by around 65% and 40%, respectively.

In a flood of this size (1 in 10 to 20 chance per year at Windsor), the volume of air space created by a 12m FSL-lowering can make a significant difference to downstream flooding. It is less effective at mitigating the larger and rarer floods – such as the 1 in 50 chance per year event or the 1867 flood of record – that pose the greatest risk to urban communities, which would require a larger air space for substantial mitigation.

The proposed raising of Warragamba Dam would have reduced the flood peak at Windsor by 3.4m, and delayed outflows from the dam by 3 to 4 days. The number of impacted dwellings and manufactured homes would have reduced by around 80% and 60%, respectively. These benefits would be achieved by temporarily capturing water in the approximately 1000-gigalitre flood mitigation zone made available by the dam raising.

Initial assessment of Flood Strategy outcomes in relation to the flood

An initial assessment of the 9 Flood Strategy outcomes shows that work prior to the flood realised benefits during the flood. Examples include improved flood awareness and coordinated response and recovery.

The assessment also identified areas where further work is needed. The NSW Government is committed to identifying and evaluating the range of issues, to increase resilience ahead of future, potentially larger floods.

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1. Introduction

Flood risk in the Hawkesbury-Nepean Valley (the valley) has been described as the highest single flood exposure in NSW, 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).

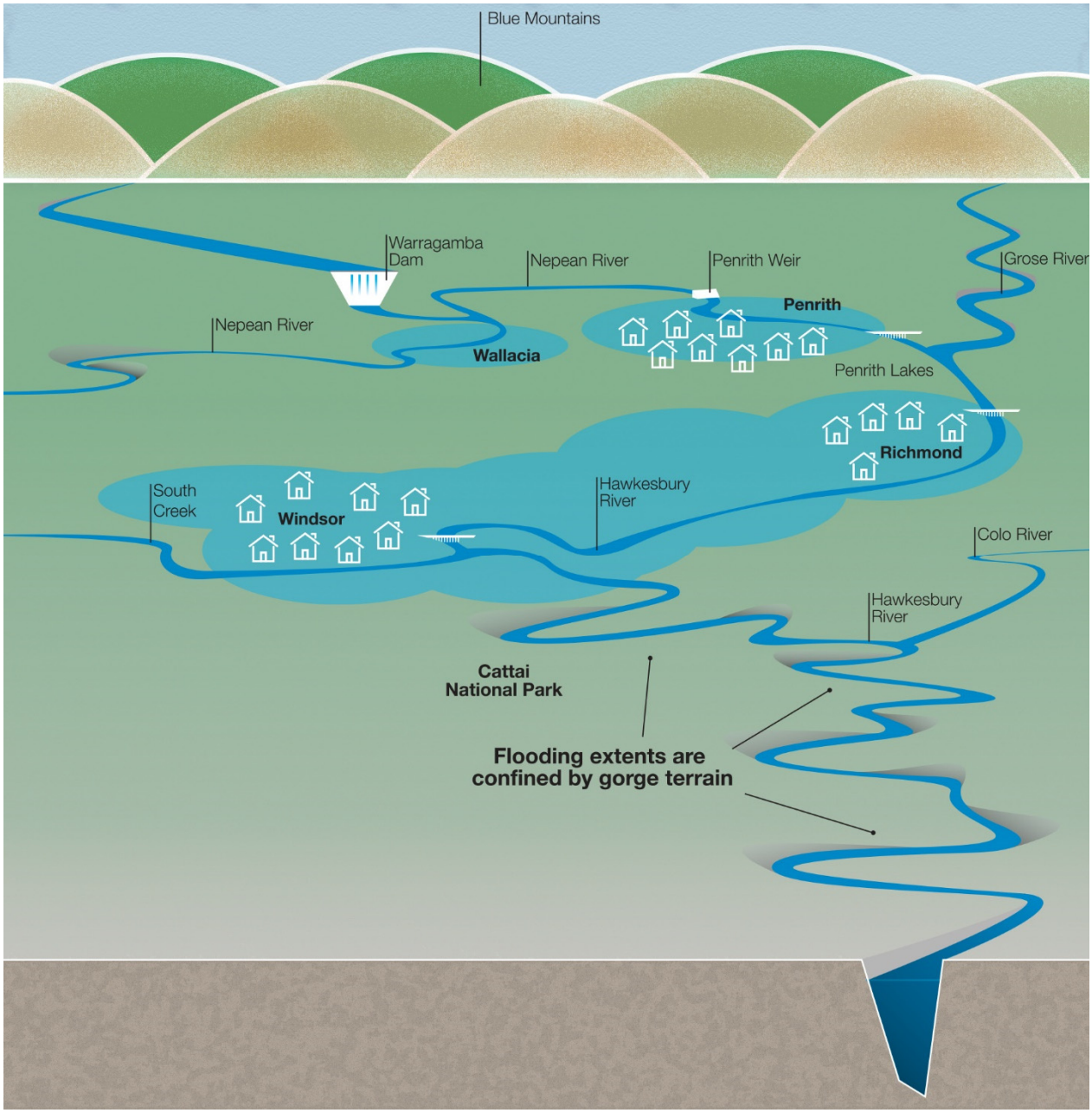


Figure 1: The 'bathtub' effect in the Hawkesbury-Nepean Valley

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).

Outcome 9 of the Flood Strategy states that ongoing monitoring and evaluation, reporting and improvement of the Flood Strategy will be undertaken to accommodate changes over time and to ensure that the strategy's actions continue to meet the objective and vision.

In March 2021, the Hawkesbury-Nepean River experienced the largest flood since 1990. The flood provides an opportunity for evaluation and improvement – to ensure flood information is accurate and contemporary, and to assess the effectiveness of ongoing initiatives to manage flood risks in the valley.

This report summarises the causes and nature of the flooding, and the impacts of, response to and recovery from flooding in the valley. 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.

The report also presents the results of modelling of various flood mitigation scenarios to ascertain what difference these would have made to downstream flooding.

2. Flood analysis

2.1 Weather

Moist easterly flow became established over coastal NSW on Wednesday 17 March 2021, associated with a strong, slow-moving high pressure system in the southern Tasman Sea between Tasmania and New Zealand (Figure 2). This onshore flow persisted for nearly a week, and was associated with high water vapour transport (Reid et al., 2021). During this period, troughs formed near the coast, and a small low pressure system moved slowly south along the NSW coast on 19 and 20 March, reinforcing the easterly flow on its southern side. The low did not reach the intensity required to be formally classified as an East Coast Low (BoM, 2021).

This weather generated heavy and persistent rain over coastal catchments, consistent with the high water vapour transport (Reid et al., 2021). Rainfall totals for NSW for the week ending Tuesday 23 March are presented in Figure 3, and approximate rainfall totals for the Hawkesbury-Nepean catchment in Figure 4. Some weather stations in the Hawkesbury-Nepean catchment recorded more than 500mm rain, including:

- 541mm at Hazelbrook STP
- 536mm at Blackheath (Wombat Street).

The heaviest rain fell in the 24-hour period to 9am Sunday 21 March (see Figure 5; Figure 6). Oakdale-Wollondilly recorded the highest rainfall over that 24-hour period with 181mm.

2.2 Climate drivers and soil moisture

The heavy rain fell against a backdrop of relatively wet antecedent conditions across most of the affected regions, associated with a La Niña which developed in the second half of 2020. Soils became more saturated during 2020, and water storage levels generally increased. This contributed to flooding being more widespread and severe than had been the case during a broadly comparable rain event in February 2020 (BoM, 2021).

From the Sydney region southwards, summer rainfall was close to average in most areas. Soil moisture as of February 2021 was generally average to above average, but not exceptionally high in coastal areas (BoM, 2021).

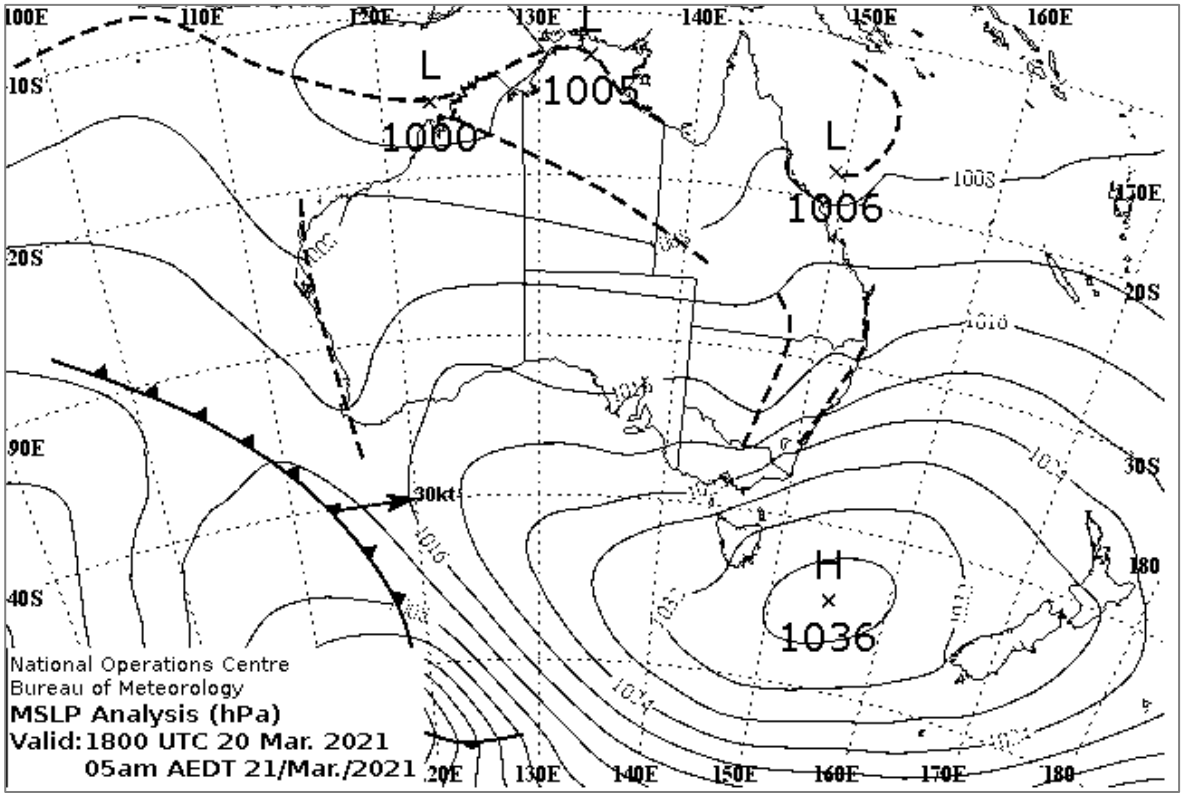


Figure 2: Weather chart, Sunday 21 March 2021

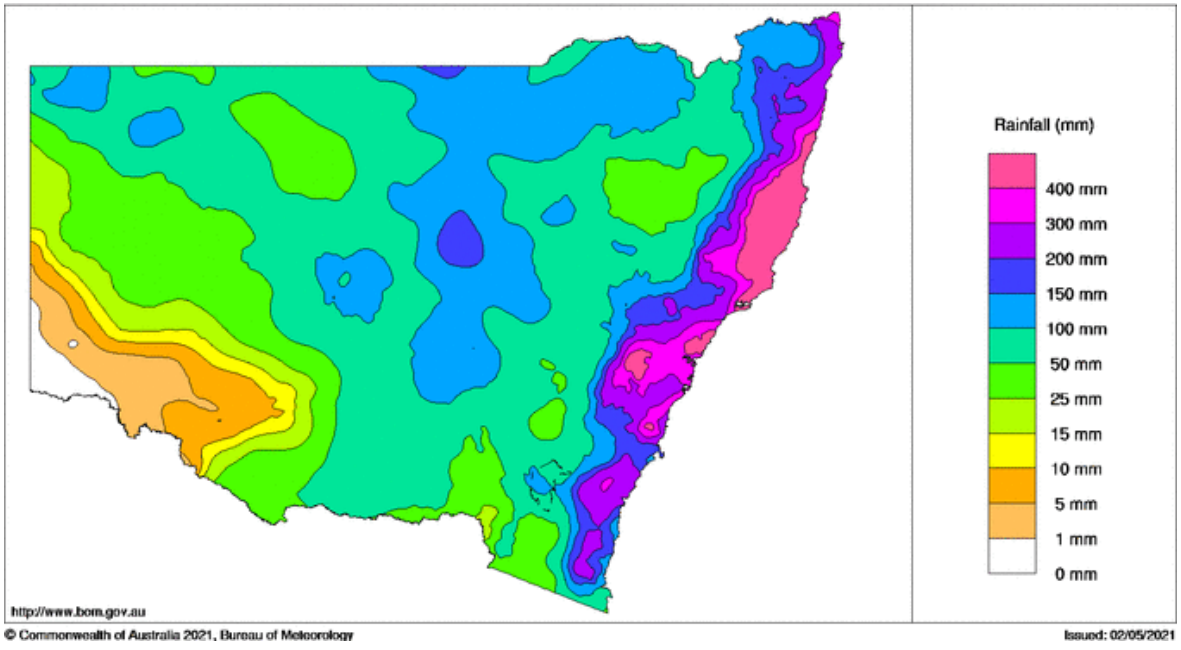


Figure 3: Rainfall totals for NSW in week ending 23 March 2021

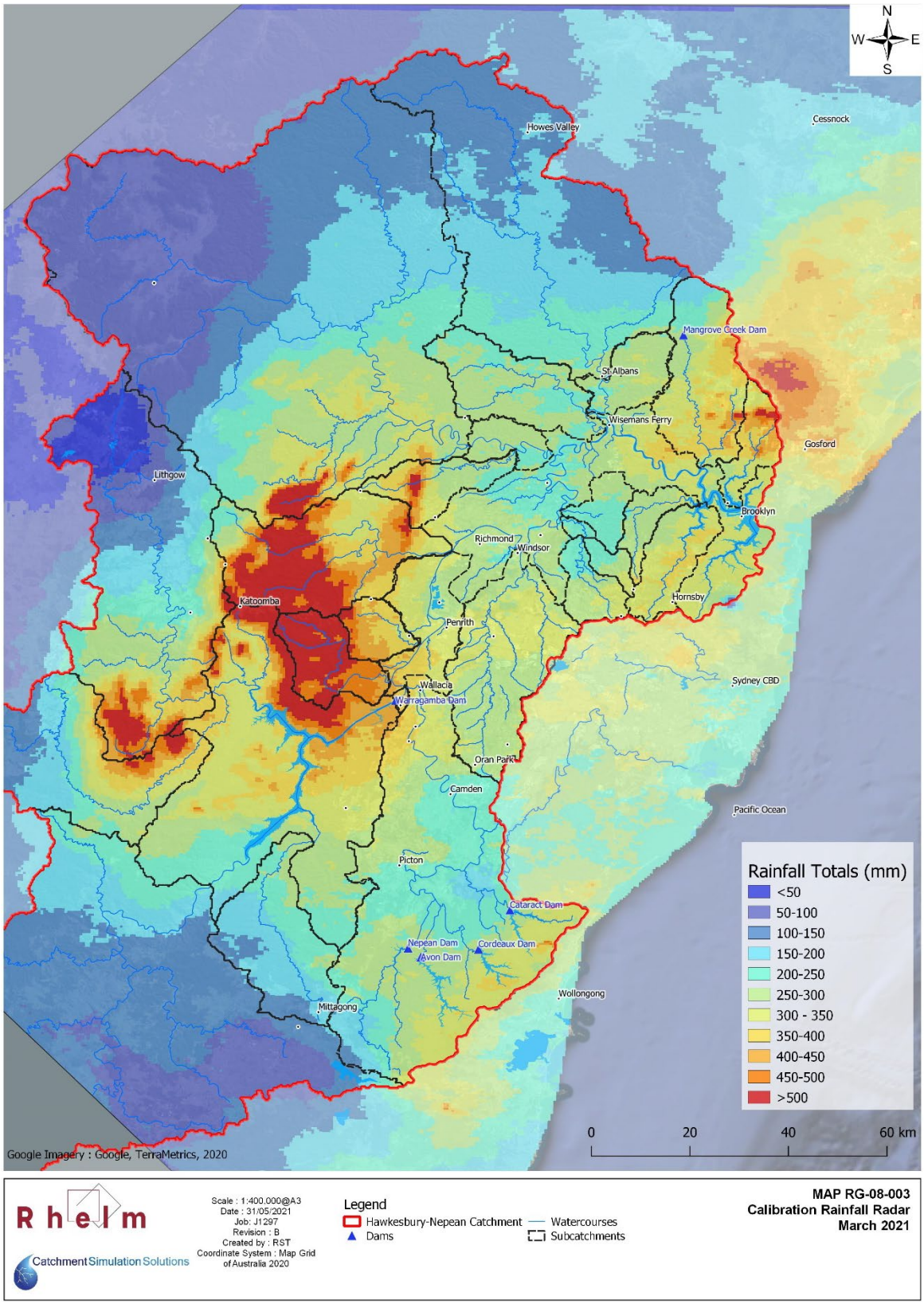


Figure 4: Radar rainfall totals for part of Hawkesbury-Nepean catchment, March 2021 event

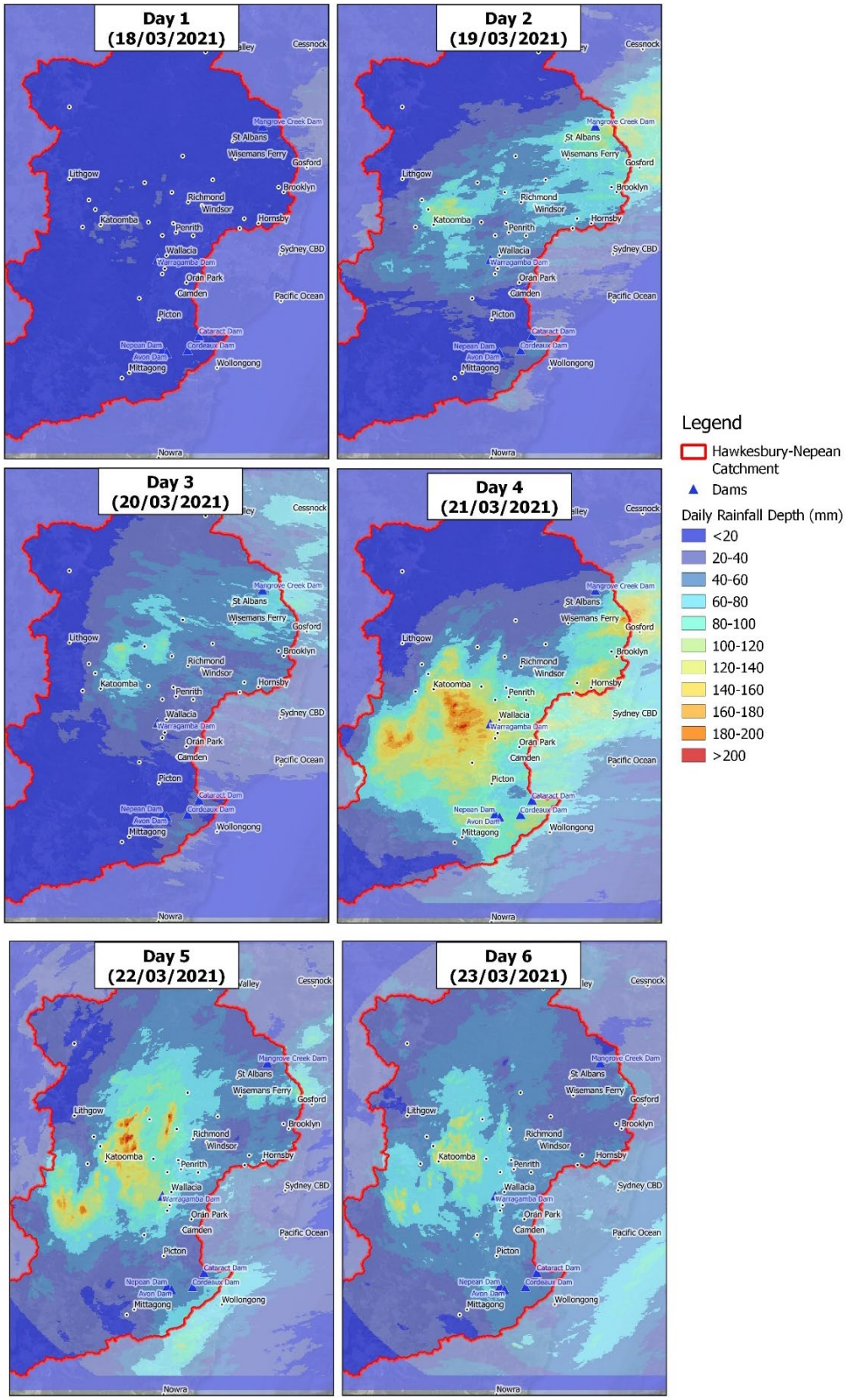


Figure 5: Daily (to 9am) radar rainfall totals for part of Hawkesbury-Nepean catchment, March 2021 event

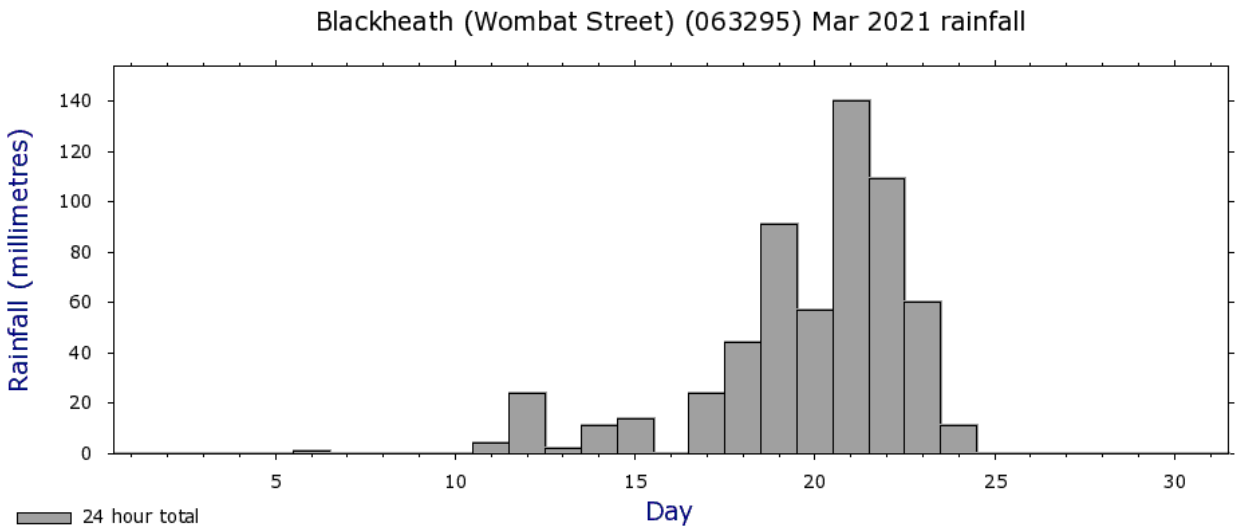


Figure 6: Daily (to 9am) rainfall, Blackheath, March 2021

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 Figure 7 and Figure 8. 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 9. Hydrographs for the 7 Hawkesbury-Nepean flood warning gauges within the study area are presented in Figure 10.

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. Figure 11 presents a timeline of flood classifications at the flood warning gauges.

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 B). 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 Sunday 21 March and the second on Tuesday 23 March (Figure 9). These 2 peaks reflect bursts of heavy rainfall. The first peaks were higher in the more western subcatchments (Coxs and Kowmung rivers), while the second peaks were higher in the more eastern subcatchments (upper Nepean and Wollondilly rivers) – indicating different intensities of rain over different parts of the catchment over the course of the event. The first peak resulted in the highest level in Warragamba Dam. The second peak contributed to a very large volume of inflows to the dam.

Prior to the flood, **Warragamba Dam** had been drawn down to 1m below full supply level (FSL) to minimise small fluctuations in water level near FSL, which can trigger gate openings. This draw down corresponded to a capacity of 96.3% of full supply at the start of the event. Inflows from the dam subcatchments resulted in FSL being reached at about 3pm Saturday 20 March. The flood inflows 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 12. An image of water spilling through the gates is presented in Figure 13. The storage reached its

[1] https://www.youtube.com/watch?v=1VFyKsrXKPk, accessed 10 November 2021

highest level of 1.53m above FSL at 4:45pm Sunday 21 March (Table 1). In all, the storage was higher than 1m above FSL for about 21 hours, and higher than FSL for about 12 days. It is calculated that the dam spilled approximately 1200 gigalitres (GL) in total (1 GL= 1 billion litres), with a peak discharge of 5069 m^3/s (Figure 12) or about 438 GL/day (note, a rate >430 GL/day was sustained for only about 5 hours).

Figure 9 and Figure 10 show that the 2 peaks observed in the Warragamba outflow and upper Nepean hydrographs continued downstream, with the 2 peaks clearly observed at Wallacia and Penrith. Interestingly, contra to the pattern at the upper Nepean gauges, the first peak at **Wallacia** was higher than the second peak, indicating a backwater influence from Warragamba Dam spills. At Wallacia Weir, the flood peaked at 8.57m in the minor range, though it was high enough to inundate Silverdale Road Bridge at Blaxlands Crossing.

Flooding at **Penrith** peaked in the moderate range at 9.99m at 5:45pm Sunday 21 March (Table 1) – aligned with the first peak from Warragamba Dam. While most floodwaters were confined to the river channel and adjoining areas, the flood was high enough to cut River Road in Emu Plains and approach riverside homes in Regentville, and backwater flooding affected streets near Peach Tree Creek in Penrith (see images at Appendix C).

At **North Richmond**, the arrival of the floodwaters from Warragamba, plus inflows from the Grose River, saw the Hawkesbury River rise steeply on Saturday 20 and Sunday 21 March, peaking with major flooding at 14.38m at 4:30pm Sunday (Figure 10; Table 1). While a lower, second peak was observed on Wednesday 24 March (13.41m), it was less pronounced compared to sites upstream (Figure 10).

At **Windsor**, while the 2 peaks can just be observed, the first peak of 12.66m at 6:30pm Monday 22 March was smaller than the second peak of 12.93m at about 9am Wednesday 24 March (Figure 10; Table 1). The switch in the relative height of the 2 peaks reflects an important driver of flood peaks in the Windsor floodplain. In contrast to Penrith, where the peak levels are driven by the *rate* of flow, at Windsor the *volume* of floodwaters – the quantity of floodwater entering and filling the 'bathtub' – is an important driver of peak levels. The major flood level of 12.2m was exceeded for nearly 3 days at Windsor (Figure 11).

Extensive flooding was observed in the Richmond/Windsor floodplain as the 'bathtub' filled. This may be observed in the aerial imagery captured by Spatial Services and Nearmap (see Appendix C).

Backwater flooding up South Creek is modelled to have extended beyond Mayo Road in Llandilo, and up Eastern Creek extended beyond Garfield Road in Riverstone. Similarly, backwater flooding is modelled to have extended a considerable distance up Killarney Chain of Ponds into Vineyard (not quite as far as Chapman Road).

Further downstream at **Sackville** the 2 peaks have fully merged producing a relatively flat long hydrograph with the peak timing being aligned with the second peak upstream (Figure 10). In this part of the river, tributary valleys including Little Cattai Creek, Currency Creek and Roberts Creek function as natural storages for floodwaters (see Appendix C). In general, the floodplain narrows, increasing the speed (velocity) of the water in the river. This was witnessed by NSW State Emergency Service (NSW SES) boat operators who struggled with the force of the current.

The flooding was also sustained at a high level for several days at **Colo Junction** (Figure 10). This gauge is located where the Colo River joins the Hawkesbury River at Lower Portland. For the March 2021 flood, the Colo River was at a high level for an unusually long time, meaning that the flows from the Colo and the Hawkesbury rivers were relatively synchronised (Figure 14). In most historic floods, the main Colo River flows passed Colo Junction before the main Hawkesbury River flows arrived. However, in this flood, levels in the lower Hawkesbury were increased by the closeness of the timing of inflows from the 2 catchments.

At the Webbs Creek gauge at **Wisemans Ferry**, the flood peaked at 4.36m at 9:45am Wednesday 24 March and exceeded the major flood height of 4.2m for about 18 hours (Table 1, Figure 10, Figure 11). The hydrograph shows that inflows from the catchment (including the Macdonald River valley which joins the Hawkesbury River at Wisemans Ferry) suppressed the normal tidal variation, though even near the peak, the influence of the tidal cycle can be detected (Figure 10). The earlier peak at Spencer downstream (Table 1) is attributed to the timing of the high tide there.

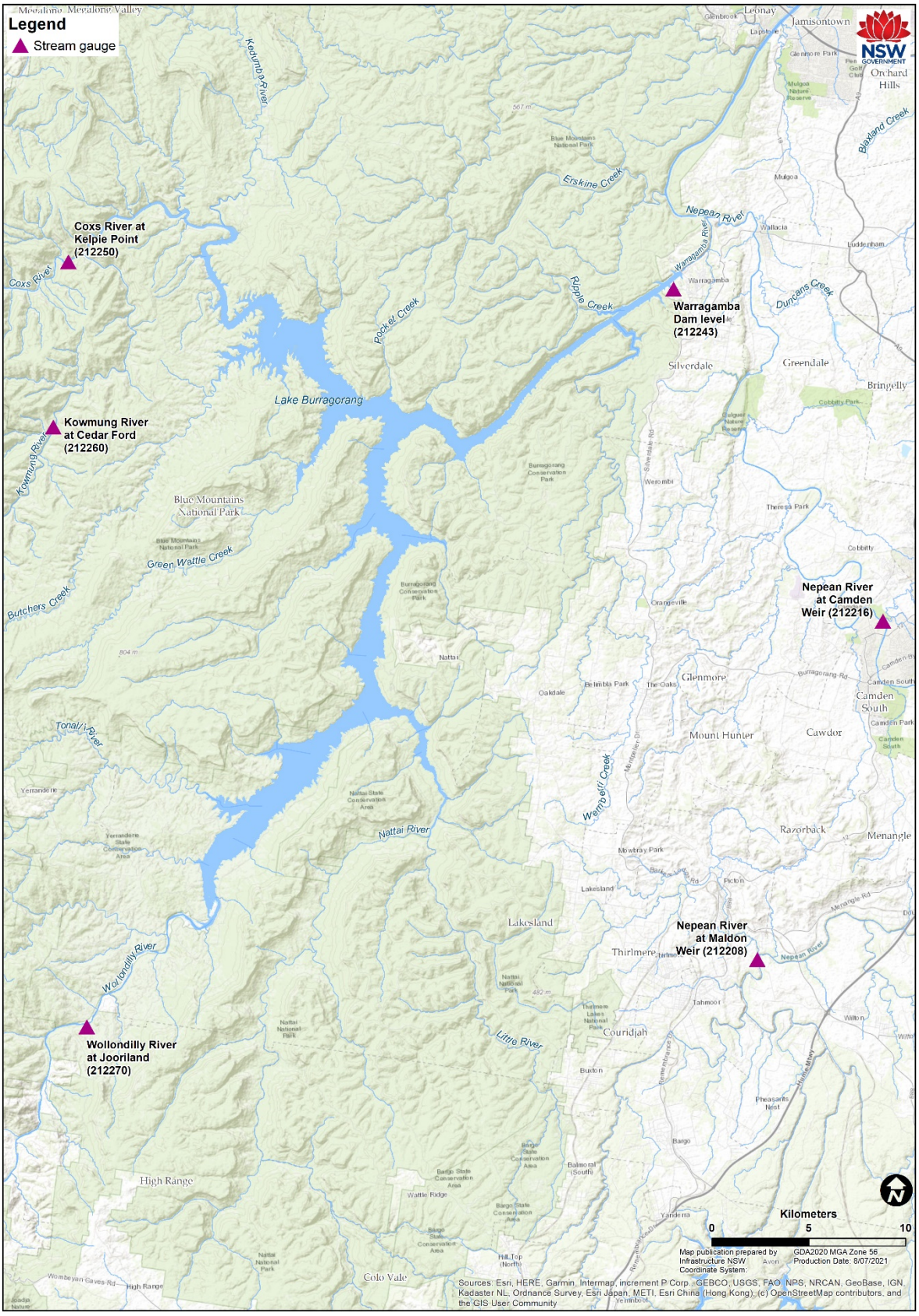


Figure 7: Water level recording stations, Warragamba and upper Nepean subcatchments

Source: Infrastructure NSW

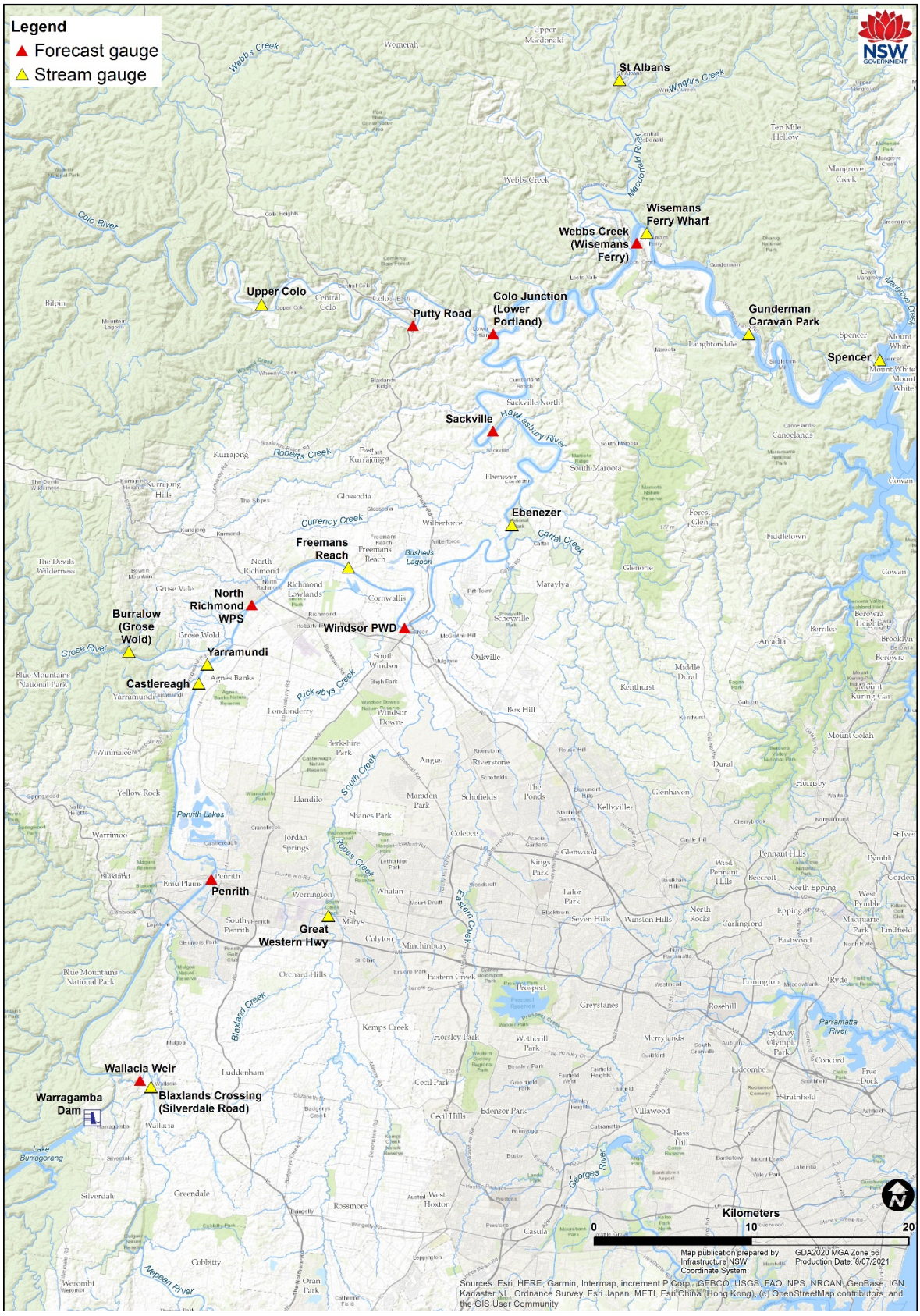


Figure 8: Water level recording stations, Hawkesbury-Nepean catchment below Warragamba Dam

Source: Infrastructure NSW

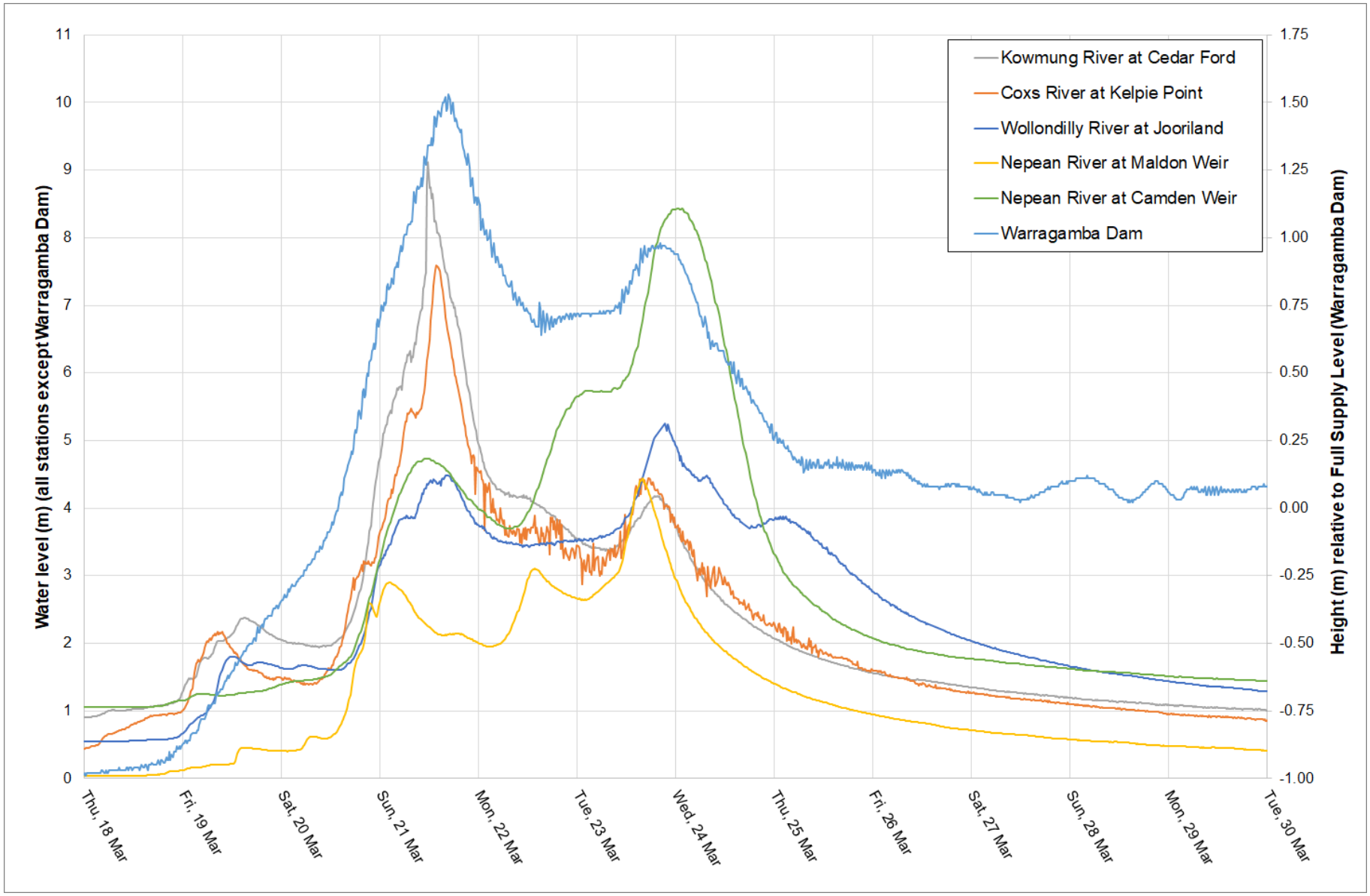


Figure 9: Flood hydrographs for selected river gauges in Warragamba and upper Nepean subcatchments, 18 to 29 March 2021

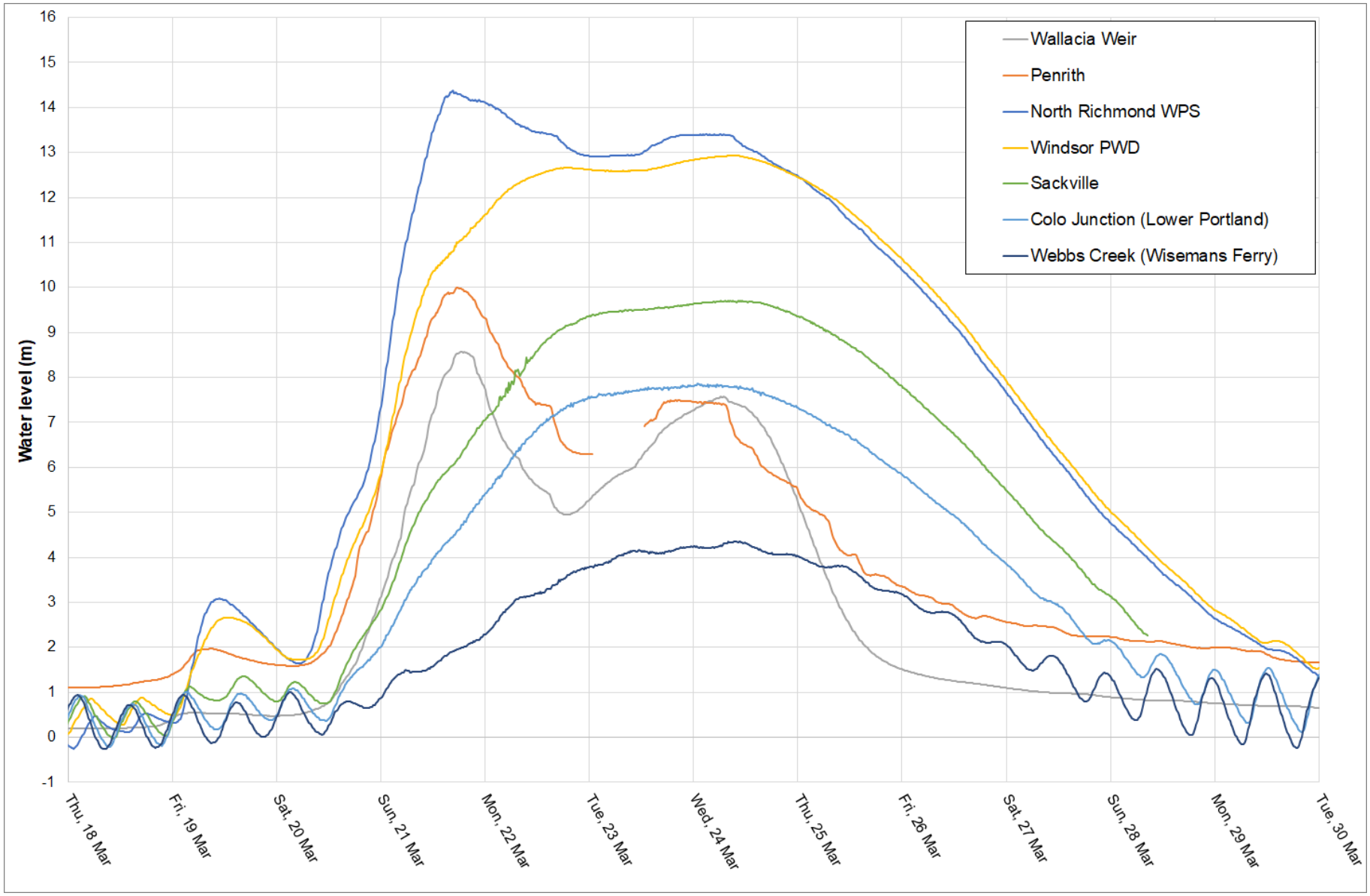


Figure 10: Flood hydrographs for selected Hawkesbury-Nepean flood warning gauges, 18 to 29 March 2021

Table 1: Flood peak level, time, classification and likelihood, March 2021 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	8.57m	35.16m	Sun 21/3 6:30pm	Minor	1 in 5 – 10
Penrith	212201	9.99m	24.13m	Sun 21/3 5:45pm	Moderate	1 in 10 – 20
Castlereagh	212404	16.82m[3]	16.82m[3]	Sun 21/3 4:00pm[3]	-	-
Yarramundi	2122001	15.55m	16.48m	Sun 21/3 4:15pm	-	-
North Richmond WPS	212200	14.38m	14.91m	Sun 21/3 4:30pm	Major	1 in 10 – 20
Freemans Reach	212410	13.42m	13.42m	Wed 24/3 4:00am	-	-
Windsor PWD	212426	12.93m	12.93m	Wed 24/3 9:00am	Major	1 in 10 – 20
Ebenezer	212427	11.79m	11.79m	Wed 24/3 11:45am	-	-
Sackville	212406	9.71m	9.71m	Wed 24/3 10:15am	Major	about 1 in 20
Colo Junction (Lower Portland)	212407	7.87m	7.87m	Wed 24/3 1:00am	Major	about 1 in 30
Webbs Creek (Wisemans Ferry)	212408	4.36m	4.36m	Wed 24/3 9:45am	Major	about 1 in 30
Wisemans Ferry Wharf	212460	3.91m	3.91m	Wed 24/3 9:30am	-	-
Gunderman Caravan Park	212429	2.54m	2.54m	Wed 24/3 9:15am	-	-
Spencer	212431	1.44m	1.44m	Wed 24/3 7:45am	-	-
Tributaries						
Warragamba Dam[4]	-	1.53m	118.25m	Sun 21/3 4:45pm	-	See Table F1
Grose River at Burralow	212291	8.83m[5]	-	Sun 21/3 3:30pm[5]	-	-
South Creek at Great Western Hwy	212048	6.21m	24.38m	Sun 21/3 6:30am	-	-
Colo River at Upper Colo	212290	14.97m	16.44m	Mon 22/3 4:15pm	Major	-
Macdonald River at St Albans	212228	7.68m[6]	10.44m[6]	Tue 23/3 10:00pm[6]	-	-

Notes:

[1] Flood peak data sourced from WaterNSW, Manly Hydraulics Laboratory and Bureau of Meteorology

[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.

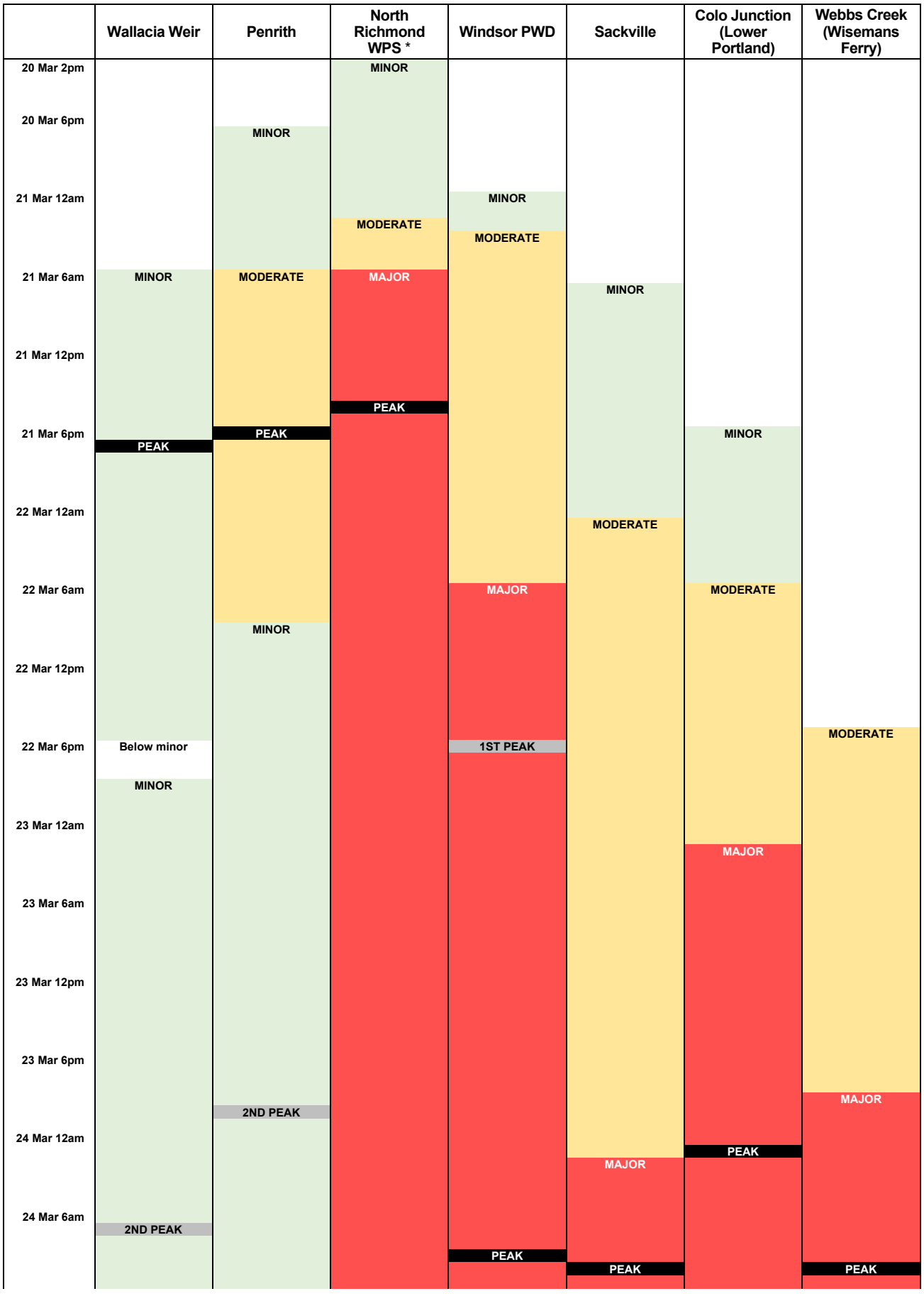
[3] Castlereagh gauge sustained orifice failure at about the peak. The recorded peak and time of peak may not be precise. Debris survey flood peak estimate is 16.74m AHD (MHL, 2021).

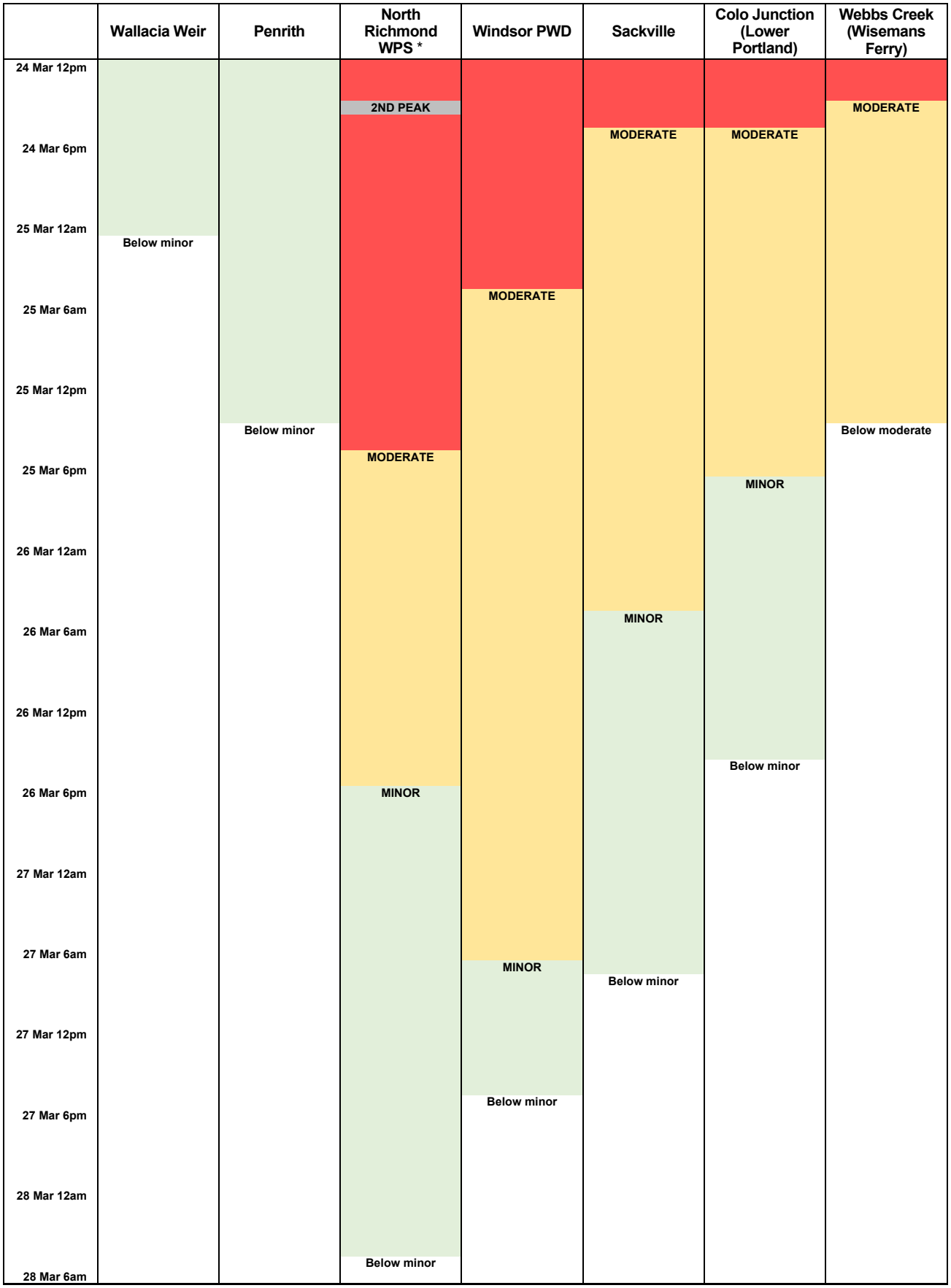
[4] Official data for Warragamba Dam was supplied by WaterNSW. The dam level peaked at 1.52m at station 212243. Warragamba Dam full water supply level is 116.72m AHD.

[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 11: Flood timeline at Hawkesbury-Nepean flood warning gauges, 20 to 28 March 2021





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

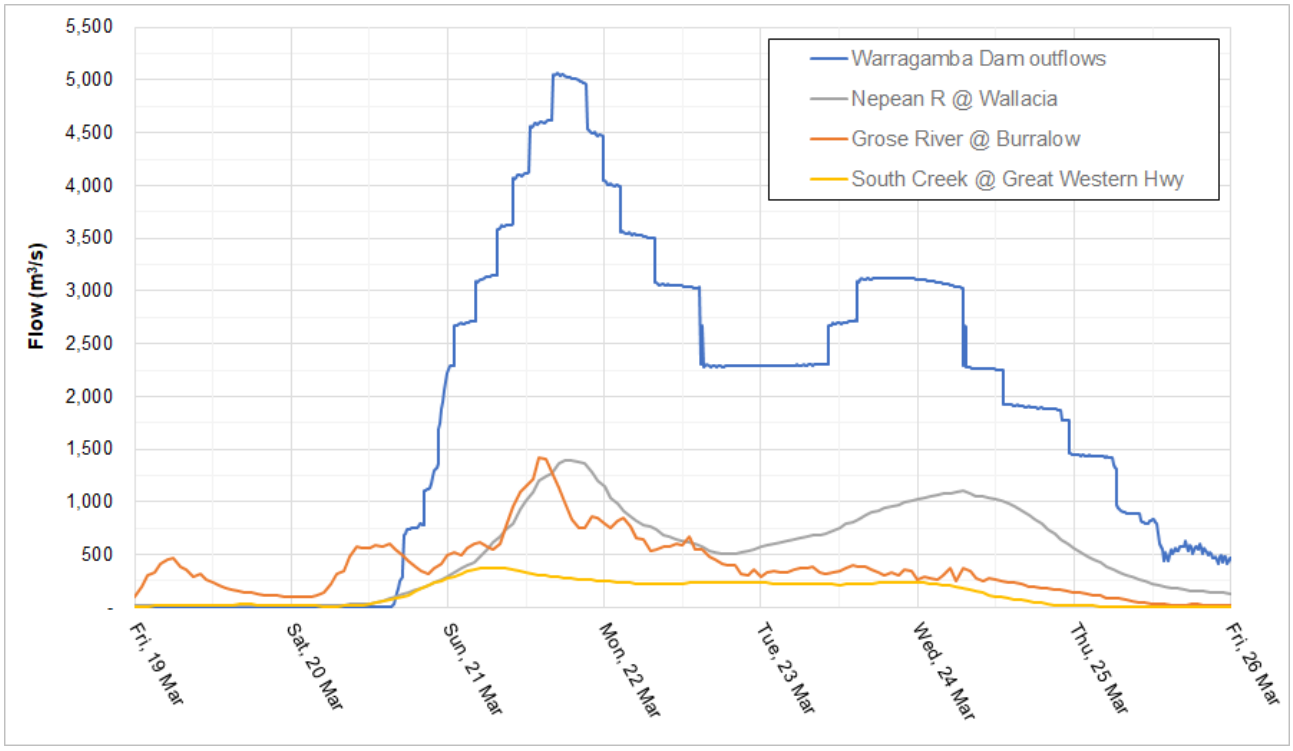


Figure 12: Flow hydrographs for key inflows to Windsor, March 2021 flood

Source: Rhelm for Infrastructure NSW

Figure 13: Warragamba Dam spilling, 26 March 2021

Source: Infrastructure NSW. Image: Adam Hollingworth

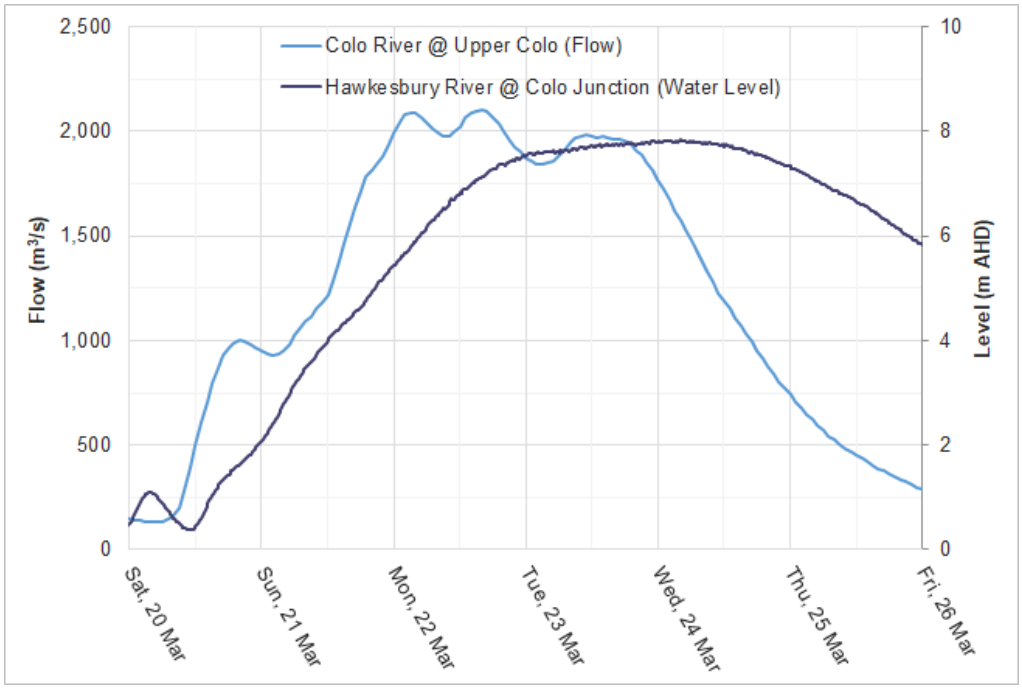


Figure 14: Timing of Colo and Hawkesbury rivers flows, March 2021 flood

Source: Rhelm for Infrastructure NSW

2.4 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
    - large 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 15). The period from 1993 to 2019 was remarkably free of moderate and major floods (at Windsor).
- 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 describes the approximate likelihood of the March 2021 flood for selected river gauges within the study area. Table 2 compares the March 2021 flood to the February 2020 flood and other historical events.

A record peak was set in the March 2021 flood at **Cedar Ford** on the Kowmung River (9.34m), exceeding the previous record set in 1978 (8.69m) for this subcatchment above Warragamba Dam. The Cedar Ford gauge began operating in 1968.

At **Warragamba Dam**, the peak outflow was the fourth highest since the dam was completed in 1960 (after 1961, 1964 and 1990), with an average frequency of 1 in 10 to 20 chance per year. Due to the persistence of the coastal trough with prolonged rainfall leading to 2 flood peaks, the total inflow volume to the dam was the second highest since the dam was completed. The average frequency of this inflow volume is calculated as 1 in 40 chance per year (see Table F1).

At **Wallacia**, the March 2021 flood was the highest since August 1990, but was still in the minor range, with an average frequency of 1 in 5 to 10 chance per year. There, the highest flood in living memory, in June 1964, was around 9m higher.

At **Penrith**, the March 2021 flood was slightly higher than the previous highest flood in living memory in November 1961, and was in fact the highest level since June 1925, when the river reached 24.5m AHD in the moderate range (WMAwater, 2019). Flood heights at Penrith are sensitive to the extent and density of vegetation in the channel and floodplain below Penrith Weir. A time series of aerial photography indicates this vegetation has increased significantly since the last large flood in August 1990 (see Figure 16). This pushes floodwaters higher for the same flow, when compared to earlier decades. Based on peak flow, the March 2021 flood was a 1 in 10 to 20 chance per year event at Penrith.

At **Windsor**, the March 2021 flood was the highest and first major flood since August 1990. It peaked slightly higher than the May 1988 flood. It was 3.6m higher than the moderate February 2020 flood, resulting in a larger flood extent and greater flood depths (Figure 17).

Based on peak height, the March 2021 flood was about a 1 in 10 to 20 chance per year flood. There have been 14 larger floods at Windsor since records began in the 1790s – the largest peaked around 7m higher (19.7m in 1867).

For its height, the March 2021 flood was a long duration event, driven by the prolonged presence of the coastal trough with associated rainfall leading to 2 upstream flood peaks. This can be seen by viewing historical hydrographs for floods of comparable peak height (Figure 18). The May 1988 flood (peak 12.8m) exceeded the major flood level at Windsor (12.2m) for just over 1 day, the August 1990 flood (peak 13.5m) for almost 2 days, while the March 2021 flood (peak 12.9m) exceeded the major level for almost 3 days.

At **Sackville**, the March 2021 flood was also the highest and first major flood since August 1990. The June 1964 flood was around 1m higher, while the record 1867 flood was around 6m higher. Here, the March 2021 flood was about a 1 in 20 chance per year flood.

At **Wisemans Ferry**, the March 2021 flood was:

- comparable to the August 1990 flood
- the highest since March 1978 (4.8m AHD)
- about 1m below the highest flood in living memory in June 1949, and
- 4 to 5m below the record flood in 1867.

Because of the somewhat unusual close timing of flows from the Colo and Hawkesbury rivers, the flooding at Colo Junction and Wisemans Ferry is calculated to be a little rarer than at upstream sites – being about a 1 in 30 chance per year event.

Table 2: Historical context of the March 2021 Hawkesbury-Nepean flood

Gauge location	Mar 2021 peak level (m AHD)	Feb 2020 peak level (m AHD)	Prior to Mar 2021 - most recent major flood (peak m AHD, year)		Prior to Mar 2021 - highest flood in living memory (peak m AHD, year)		Highest flood on record (peak m AHD, year)	
Wallacia Weir	35.2m	33.9m	39.3m	1990	43.9m	1964	47.1m	1867, 1873
Penrith	24.1m	20.3m	25.3m	1900	23.9m	1961	27.5m	1867
Windsor	12.9m	9.3m	13.5m	1990	15.0m	1961	19.7m	1867
Sackville	9.7m	5.8m	10.0m	1990	11.0m	1964	Approx. 15.5m	1867
Webbs Creek (Wisemans Ferry)	4.4m	2.4m	4.3m	1990	5.6m	1949	Approx. 9m	1867

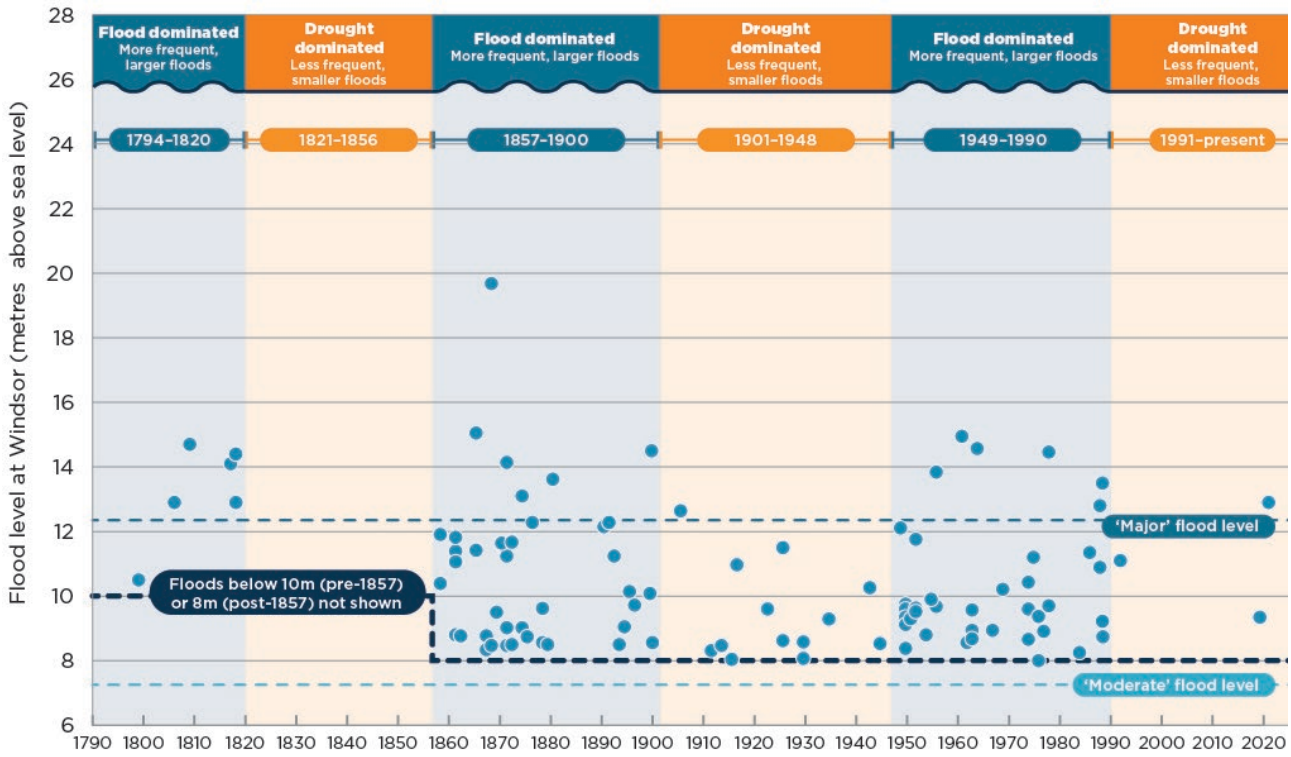


Figure 15: Flood history, Hawkesbury River at Windsor, 1794-2021

Source: Infrastructure NSW

Figure 16: View upstream towards Penrith, showing large amount of vegetation in channel and floodplain (5 days after March 2021 flood peak)

Source: Infrastructure NSW. Image: Rhys Thomson

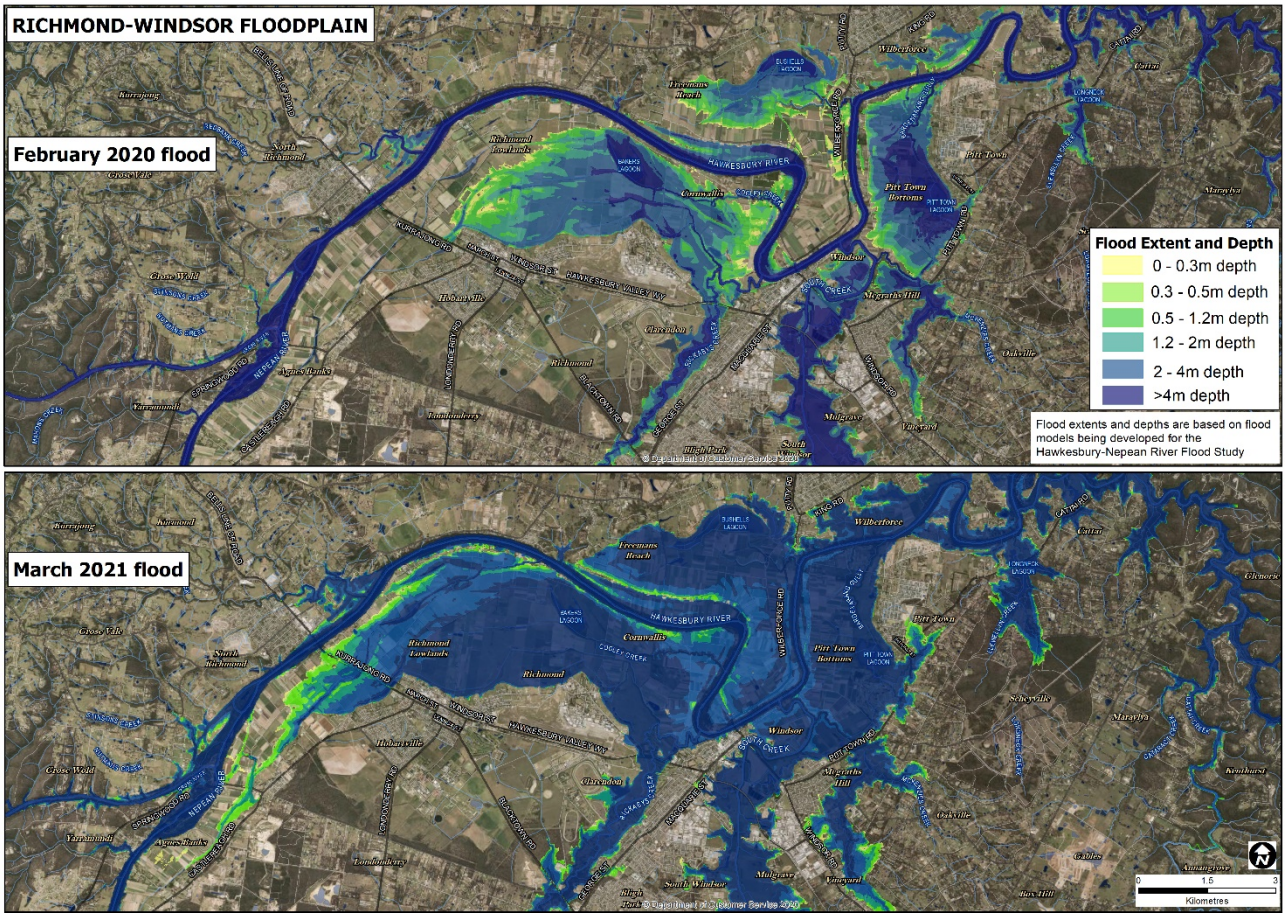


Figure 17: Flood extents/depths for February 2020 and March 2021 floods, Richmond/Windsor floodplain

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

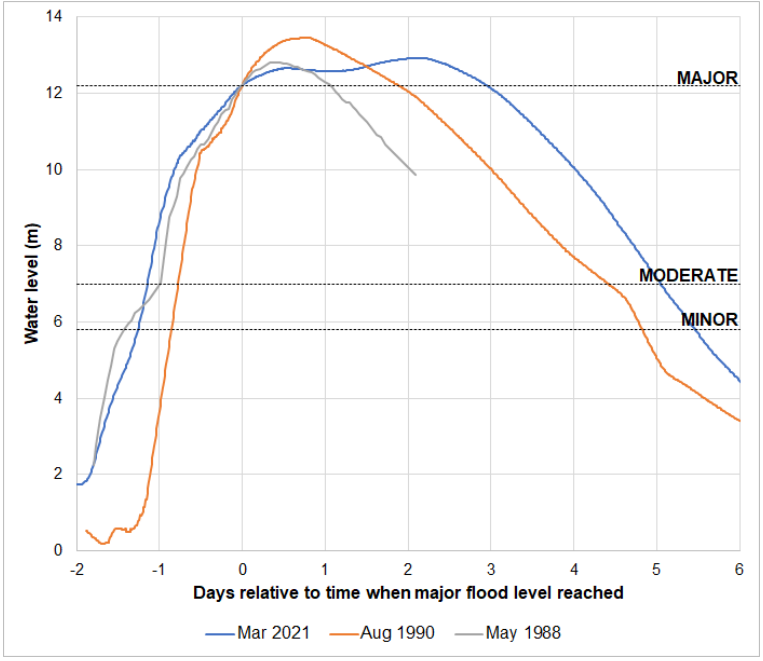


Figure 18: Historical flood hydrographs at Windsor, showing long duration of March 2021 event

Data sources: MHL for 2021 and 1990 floods, WMAwater for 1988 flood

2.5 Subcatchment contribution

The Hawkesbury-Nepean catchment is made up of several subcatchments. The largest of these is the Warragamba subcatchment, making up around 71% of the total catchment to Windsor. The second largest is the upper Nepean subcatchment (14%). While draining a high rainfall area, the Grose River subcatchment makes up only 5% of the total catchment to Windsor and so cannot alone drive significant flooding at Windsor.[2] 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.

A calibrated hydrological model was used to calculate the contribution by subcatchment of the volume of floodwaters to Windsor. The results for selected historic floods are presented in Figure 19.

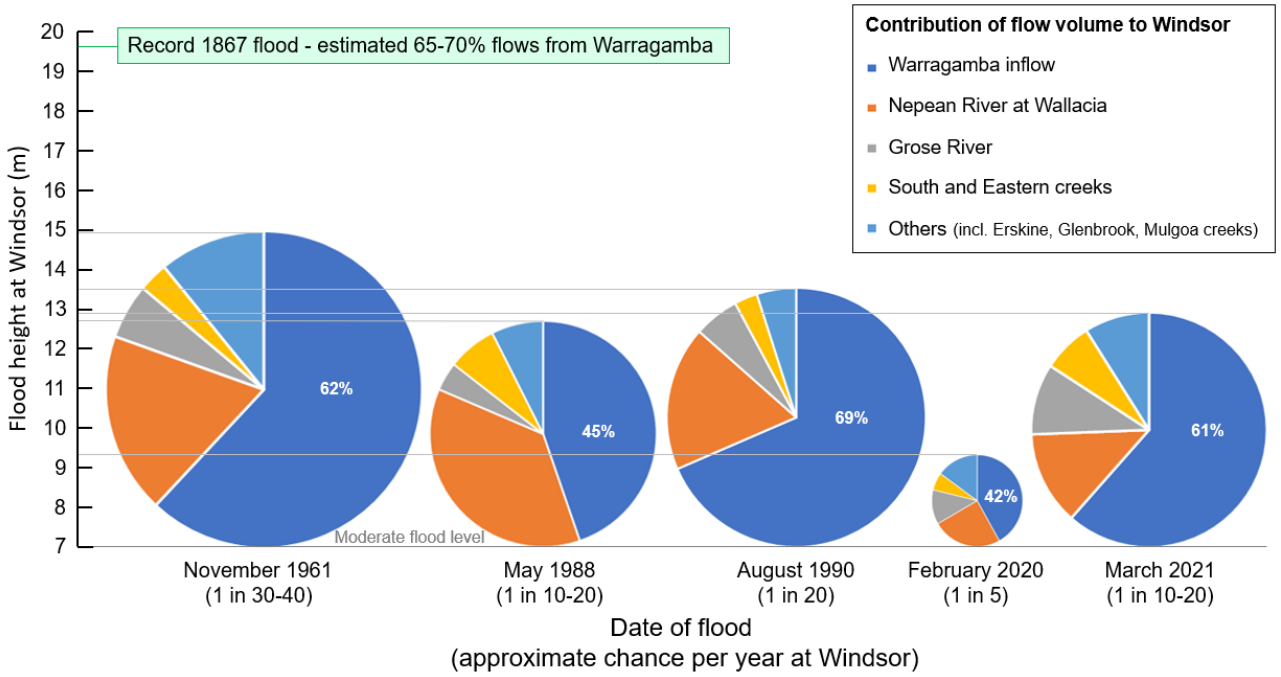


Figure 19: Contribution of flood volume to Windsor by subcatchment in historic floods

Data source: WMAwater for Infrastructure NSW

In the March 2021 flood, the Warragamba subcatchment contributed around 60% of floodwaters and other subcatchments contributed around 40% of floodwaters. Only a small proportion of floodwaters from the Warragamba subcatchment was retained in the dam, which was only 1m below FSL at the start of the event. The contribution from the Warragamba subcatchment in March 2021 is in the mid-range of Warragamba contributions across the range of floods shown in Figure 19. The highest contribution from the subcatchment occurred in the August 1990 flood (69%). Larger floods require significant contributions from the Warragamba subcatchment.

Figure 12 compares the peak flows from the main subcatchments contributing flow to Windsor in March 2021. This shows that the peak ouflows from Warragamba Dam were more than 3 times the peak flows from the Nepean and Grose rivers. The peak flow from the Colo subcatchment was about 2100 m^3/s (Figure 14). These flows join the Hawkesbury at Lower Portland and have minimal effect on flood levels at Windsor.

[2] 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).

2.6 Riverbank erosion

River channels are dynamic features of the landscape, responding to both natural changes (floods, droughts) and human-induced changes (for example, 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.

In the Hawkesbury-Nepean, multi-decadal cycles dominated by floods or droughts (Figure 15), 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).

The March 2021 flood triggered severe riverbank erosion along the Hawkesbury-Nepean River. A selection of images is provided in Figure 20, and additional images from a boat trip along the Hawkesbury River between Windsor Bridge and Cattai Creek are supplied in Appendix D. The images and inspection indicate that erosion was extensive, damaging bank protection works, farm pumps, and caravan parks. Rotational (or circular) slumps were observed to be a common mode of bank failure. This type of gravitational failure is conceptualised in Figure 21. One likely cause of this erosion was the long duration of this flood in the Richmond/Windsor floodplain and the lower Hawkesbury (Figure 18). This meant that soils were saturated for long periods and collapsed under the weight.

Interestingly, a previous survey of erosion after the August 1986 flood found that the same ‘slip circle’ type of bank failure was most common, in the same reaches of the Hawkesbury River (PWD, 1987). As the flood recedes, riverbanks are weaker and heavier due to saturation, and fail along slip planes by slumping.

Following the March 2021 flood, the Engineering Services Functional Area Coordinator engaged the Soil Conversation Service (SCS) to complete a rapid desktop assessment of erosion on the Hawkesbury River. 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 2021) was used for verification.

The assessment provided an overview of the type of erosion, the position of erosion along the river, and the distribution of erosion sites downstream of Windsor Bridge. Rotational slips were the most common type of erosion in the surveyed reach (Figure 22). The erosion was most common in straight sections of the river. Interestingly, the concave, outer meander bends where hydraulic forces are typically concentrated did not see an unusually high level of erosion. This is a further hint that slumping as a result of the long duration of flooding was the primary erosive mechanism in this flood.

The SCS assessed the risk of further erosion at the identified sites. The risk assessment scored the likelihood of erosion according to type of erosion, process of erosion, presence of protective vegetation, bank position, and proximity to assets. The risk assessment scored the consequence of erosion according to the type of asset exposed to erosion, considering threat to life, asset value and ability for the asset to be relocated (see SCS, 2021 for further information). Figure 23 indicates that most sites were rated a low or medium risk. The results are presented spatially in Figure 24, showing a concentration of very high risk sites around Sackville.

Collapsed rock gabions adjacent to The Terrace, Windsor

Source: Infrastructure NSW. Image: S. Yeo

Rotational slump, Sackville

Source: NSW SES

Rotational slump, Sackville North

Image: Simon Jones

Rotational slump, Sackville

Source: NSW SES

Figure 20: Riverbank erosion, March 2021 flood

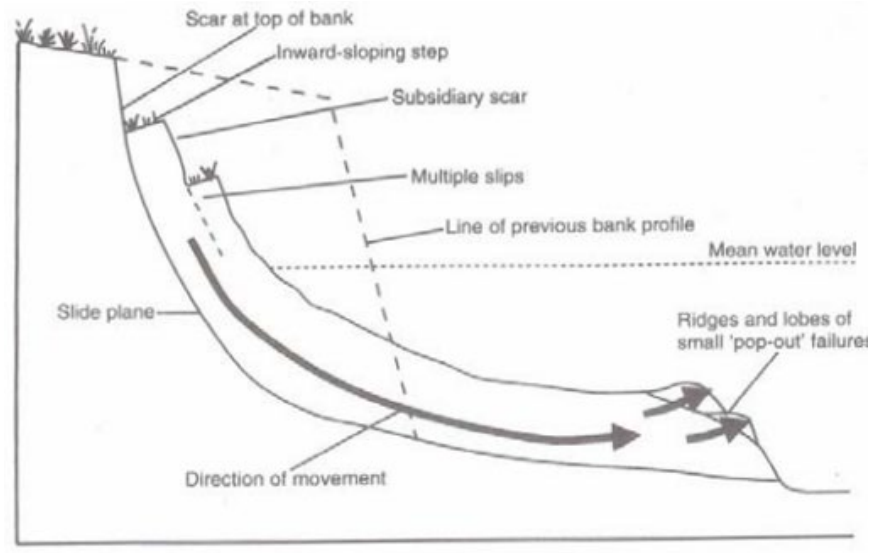


Figure 21: Riverbank erosion – cross section of rotational failure

Source: Environment Agency, 1999

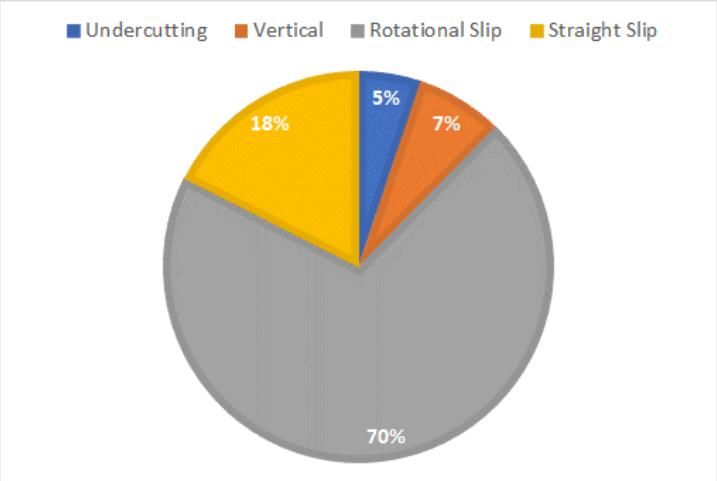


Figure 22: Type of erosion from SCS assessment, March 2021 flood

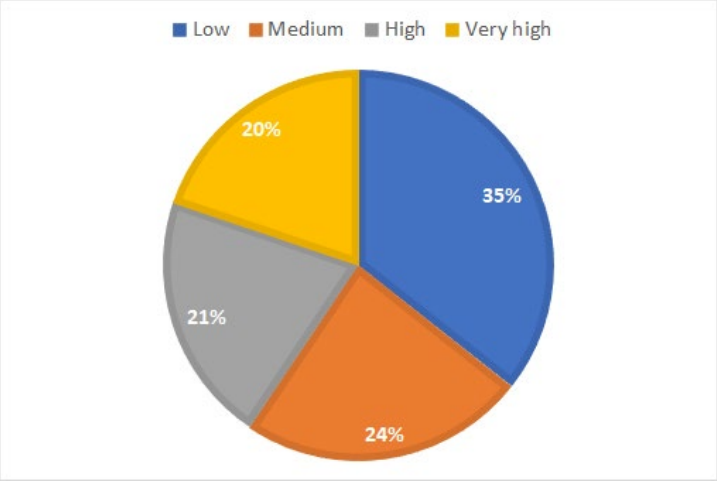


Figure 23: SCS riverbank erosion risk assessment summary, post March 2021 flood

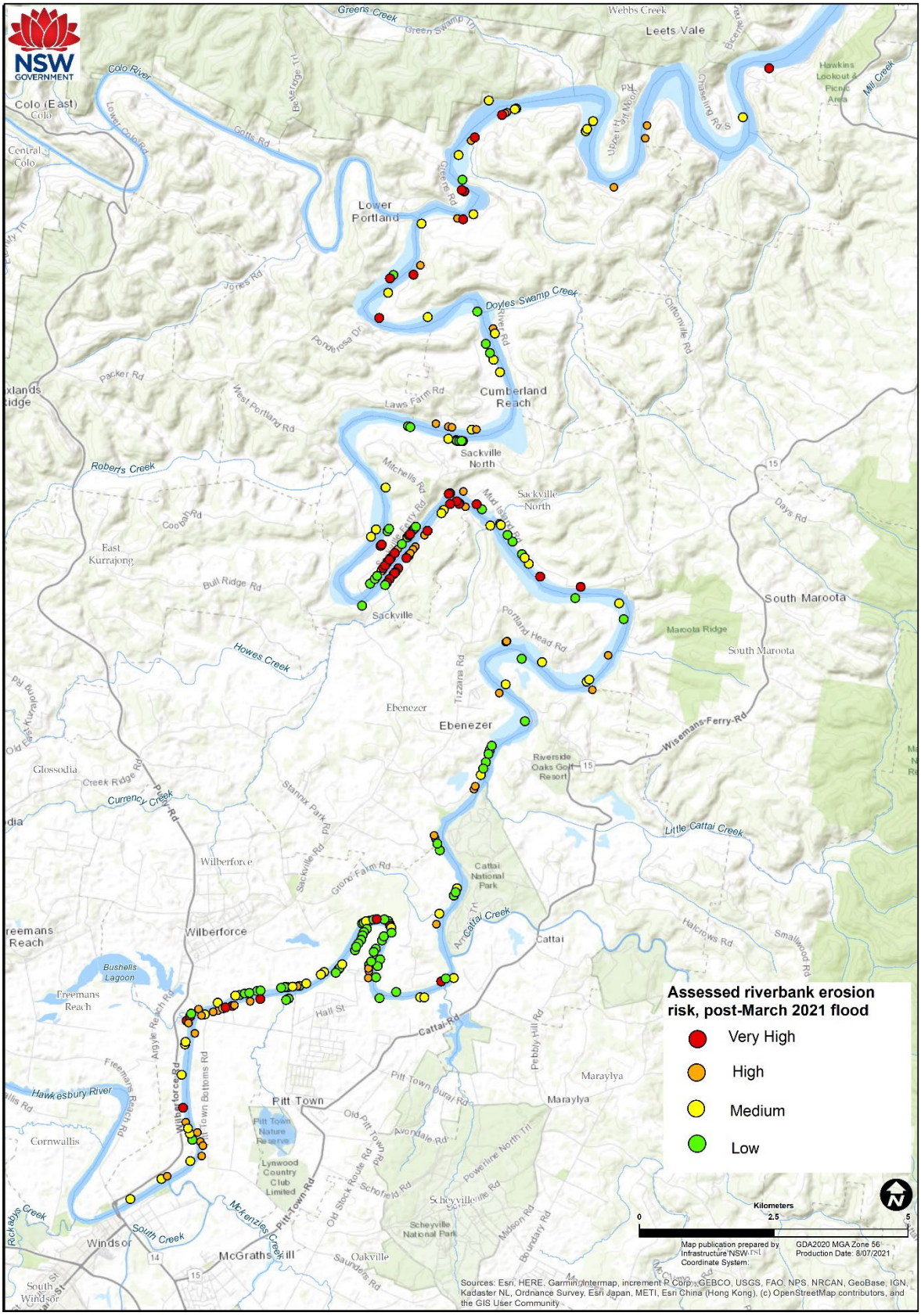


Figure 24: SCS riverbank erosion risk assessment spatial distribution, post March 2021 flood

3. Impacts

Flood impacts are a function of the scale of flooding, the exposure of people and property, and the vulnerability of people and property to flooding. Relative to the floods experienced in the past or that modelling indicates are possible, the March 2021 flood was not a particularly rare or large event. Nonetheless, there were some significant impacts, which are described below in the following categories:

- buildings
- caravan parks
- infrastructure (including transport and utilities)
- recreation
- schools
- agriculture and animals
- environment
- heritage
- insurance claims
- loss of life
- social.

Information was derived from several sources, including:

- aerial imagery taken during the flood by Spatial Services and Nearmap, as well as drone footage and images commissioned by Infrastructure NSW (see Appendix C)
- comparison of modelled flooding with distribution of buildings and manufactured homes in Infrastructure NSW's 2018 spatial assets database
- information from emergency management Functional Area coordinators including Agriculture and Animal Services, Energy and Utility Services, Engineering Services, Environmental Services and Telecommunications Services, as well as from NSW SES, Resilience NSW and TfNSW
- media reports.

3.1 Buildings

Inundation

A detailed new 2-dimensional flood model (see glossary at Appendix A) has been developed for the Flood Strategy's Hawkesbury-Nepean River Flood Study. This was used to model a March 2021 flood level surface. This was then compared to buildings in Infrastructure NSW's Hawkesbury-Nepean spatial assets database (2018).

Table 3 estimates the number of residential dwellings, commercial/industrial buildings and manufactured homes[3] impacted by the March 2021 flood according to local government area (LGA).

Based on this method, some 410 dwellings in Hawkesbury LGA are estimated to have been directly impacted by flooding (above ground level at the building) from the Hawkesbury-Nepean River. Fewer dwellings in the other LGAs were impacted, with about 40 each in Penrith, Blacktown, The Hills, Hornsby and Central Coast councils.

Some 280 commercial/industrial buildings in Hawkesbury LGA were impacted. The majority of these are sheds in agricultural/rural areas. Several buildings at sports grounds were also impacted.

[3] A manufactured home is a self-contained dwelling that is built off-site and then transported to the estate for installation. This includes any associated structures that form part of the dwelling.

Many manufactured homes in caravan parks downstream of Windsor were impacted. This is discussed in the next section.

Table 3: Estimated dwellings, commercial/industrial buildings and manufactured homes impacted by March 2021 Hawkesbury-Nepean flood

Local government area	No. of dwellings	No. of commercial/ industrial buildings	No. of manufactured homes in caravan parks
Penrith	40	20	0
Hawkesbury	410	280	480
Blacktown	40	<10	n/a
The Hills	40	<10	810
Hornsby	40	<10	n/a
Central Coast	40	<10	150
TOTAL:	**610**	**310**	**1450**

Communities/suburbs with more than 20 flood-impacted dwellings were, in descending order:

- Lower Macdonald
- Lower Portland
- Ebenezer
- Windsor
- Pitt Town Bottoms
- Laughtondale
- Londonderry
- Wilberforce
- Spencer
- Pitt Town.

No major urban areas were subject to widespread flooding. Some dwellings on urban fringes were impacted, including heritage houses built in the 1840s, as well as some 20th century houses.

The last flood of a similar magnitude to the March 2021 event was over 30 years ago in August 1990. Census data indicate that around one-third of the floodplain population turns over every 5 years. Reports give the impression that many of the impacted homeowners were new residents who were not prepared for flooding of this scale. A selection of images of flooded properties from the region is depicted in Figure 25.

While extensive and intensive efforts under the Flood Strategy's Community Resilience Program have increased awareness and preparedness for floods, there is no substitute for actual experience to help people understand the true impacts.

Isolation

Many more dwellings and households were isolated by the floods. Table 4 lists 30 communities that were isolated. Some isolations such as those near Penrith and Emu Plains were relatively short around the peak of the flood. However, many communities in the lower Hawkesbury, Colo and Macdonald valleys were isolated for more than a week.

Figure 26 illustrates the isolation of some properties in Emu Plains, McGraths Hill and Gronos Point (Ebenezer).

Arndell Street, Windsor, 9:13am, 25 March 2021

Source: Sydney Morning Herald. Image: Louise Kennerley

Blacktown Road, Londonderry, 9:39am, 23 March 2021

Source: Sydney Morning Herald. Image: Louise Kennerley

Lower Macdonald, 11:49am, 24 March 2021

Source: Sydney Morning Herald. Image: Janie Barrett

Figure 25: Flooded dwellings, Hawkesbury-Nepean, March 2021 flood

Not listed in Table 4 are the many communities on the north-western side of Hawkesbury River that were isolated by flooding of the North Richmond and Windsor bridges, flooding of Putty Road, and a landslide across Bells Line of Road near Mount Tomah. This combination of impacts isolated thousands of people in communities including Wilberforce, North Richmond, Grose Wold, Grose Vale, Kurrajong, and Kurmond.

Table 4: List of communities (>10 dwellings) isolated in Hawkesbury-Nepean area, March 2021 flood

LGA	Community
Penrith	Wallacia south
Penrith	Leonay north; Emu Plains; Emu Heights
Penrith	Peach Tree Creek, Penrith
Penrith	Penrith Lakes
Penrith	Agnes Banks lowlands
Hawkesbury	Agnes Banks; Londonderry
Hawkesbury	Richmond Lowlands
Hawkesbury	Freemans Reach; Wilberforce
Hawkesbury	Bligh Park
Hawkesbury	Windsor
Hawkesbury	Windsor east
Hawkesbury	McGraths Hill (part)
Hawkesbury	Mulgrave
Hawkesbury	Pitt Town north
Hawkesbury	Ebenezer; East Kurrajong
Hawkesbury	Cattai
Hawkesbury	Lower Portland north
Hawkesbury	Colo River
Hawkesbury	Leets Vale; Webbs Creek
Hawkesbury	Macdonald River
Hawkesbury	Oakville
Blacktown	Marsden Park (part)
Blacktown	Riverstone west
The Hills	Cattai; Sackville; South Maroota
The Hills	Lower Portland east
The Hills	Wisemans Ferry west
Hornsby	Bar Point to Brooklyn
Hornsby	Singletons Mill
Hornsby	Wisemans Ferry east
Central Coast	Gunderman; Spencer

Source: adapted from NSW SES, 2021a

River Road, Emu Plains, 2:25pm, 21 March 2021 (before peak)

Source: Infrastructure NSW. Image: Adam Hollingworth

McGraths Hill. 24 March 2021 (near peak)

Source: Infrastructure NSW. Image: Top Notch Video

Gronos Point, Ebenezer, 24 March 2021 (near peak)

Source: Infrastructure NSW. Image: Top Notch Video

Figure 26: Isolated dwellings, Hawkesbury-Nepean, March 2021 flood

3.2 Caravan parks

About 40 caravan or ski parks are situated in the Hawkesbury-Nepean floodplain. The 3 parks located in Penrith LGA were not flooded, though Nepean Shores on the eastern side of the Nepean River at Jamisontown was evacuated when floodwaters threatened. Many parks in Hawkesbury, The Hills and Central Coast LGAs are located on particularly low-lying land and were flooded to significant depths (>3m observed at some), resulting in severe impacts (Table 5). Riverbank erosion was also problematic at many parks, and severe at some.

A number of the impacted parks provide affordable accommodation for permanent residents. There were hurried evacuations at 2 parks, with a near fatality at 1.[4] Del Rio Riverside Resort at Webbs Creek has capacity for many tourists, and around 300 people were evacuated from this park by the end of Saturday 20 March. Most parks along the Hawkesbury River are ski parks with privately-owned cabins or vans on leased sites, used for holidays or weekends. It is reported that tenants of these sites tend to avoid visiting parks during bad weather, likely reducing the number of people exposed to the flood.

Many of the impacted caravan parks have a large number of manufactured homes (Table 3), which are not easily moved in the time available ahead of forecast flooding. Some of these were shifted off their foundations by the force of the floodwaters and some sustained structural damage to floors and walls. Several caravans floated downstream, some deposited at St George Caravan Park.

Across the flooded parks, cabins, vans and annexes sustained heavy damage to their contents, with piles of furniture, white goods and mattresses observed outside many parks after the flood.

Gas bottles and fuel drums were washed away, which – together with other flotsam – posed a risk to downstream river residents and users. This debris also presented a risk to the downstream riverine, estuarine and coastal environment.

Damage to park infrastructure was a significant expense for many parks, including replacement of flooded power boxes, wiring and electrical appliances.

Risk Frontiers conducted a post-flood survey of 9 caravan parks (George et al., 2021). The researchers found typical direct damages in the order of $100,000 to $200,000 per park, with 1 estimate exceeding $1 million.

Many parks were closed for an extended period after the flood due to the scale of damage and the clean-up, and the process and cost of site remediation.

Examples of flood damage are provided in Figure 27. Flood imagery for caravan parks is collated in Appendix E.

At the time of the flood, a draft flood emergency plan template developed under the Flood Strategy for Hawkesbury-Nepean caravan parks had been piloted on 4 parks. Early reports indicate that the process of developing plans, and the relationships fostered with the NSW SES units, increased the resilience and reduced the impacts at these and other floodplain parks. The template is in the process of being finalised and rolled out to all parks in this region.

[4] https://www.smh.com.au/national/nsw/it-was-harrowing-sam-s-great-escape-from-a-sinking-deathtrap-20210326-p57egn.html, accessed 10 November 2021

Table 5: Impacts on caravan and ski parks, March 2021 flood (arranged upstream to downstream)

Caravan park	Suburb	LGA	Description
Wallacia Caravan Park	Wallacia	Penrith	Not flooded.
Nepean Shores Lifestyle Community	Jamisontown	Penrith	Not flooded. Park evacuated residents when flood threatened.
Nepean River Holiday Village	Emu Plains	Penrith	Not flooded.
Windsor Riverside Van Park	Wilberforce	Hawkesbury	Mostly flooded. Permanent residents evacuated. Temporarily shut through service of emergency order. Remediation ongoing.
Hawkesbury Riverside Tourist Park	Pitt Town Bottoms	Hawkesbury	Flooded. Site structures and amenities inundated.
Percy's Place Caravan and Ski Park	Pitt Town	Hawkesbury	Lower sites flooded. Powered sites not flooded. Access to park cut. Some severe riverbank erosion.
Riverside Ski Park	Cattai	Hawkesbury	Most sites and amenities flooded. Riverbank erosion.
Kallawatta Ski Gardens	Ebenezer	Hawkesbury	Flooded. Most vans relocated before flood.
Hawkesbury Waters Leisure Park	Ebenezer	Hawkesbury	Flooded. Very extensive damage to infrastructure and site structures.
Pacific Park Water Ski Gardens and Motorcycle Park	South Maroota	The Hills	Mostly flooded.
Tizzana Downs	Ebenezer	Hawkesbury	Floodwater entered shed. Pontoon lost.
Sackville Ski Gardens	Sackville	Hawkesbury	Flooded. Very extensive damage to infrastructure and site structures. Severe riverbank erosion.
Ulinbawn Ski Park	Sackville North	The Hills	Flooded.
Caradon Leisure Park	Sackville North	The Hills	Part flooded.
Bundarra Ski Gardens	Cumberland Reach	Hawkesbury	Flooded. Damage to infrastructure and site structures.
Dargle Water Ski Resort	Lower Portland	The Hills	Flooded.
Ponderosa Ski Resort	Lower Portland	Hawkesbury	Mostly flooded. Vans relocated before flood. Minimal infrastructure damage. Some riverbank erosion.
Cornelia Water Ski Park	Lower Portland	The Hills	Flooded.
Hawkesbury Riverside Retreat	Lower Portland	Hawkesbury	Sites on northern end on river edge flooded. Others not flooded.
St George Caravan Park	Lower Portland	The Hills	Flooded. Severe damage. Affected by eddy.
DML Gardens	Lower Portland	The Hills	Mostly flooded.

Caravan park	Suburb	LGA	Description
Mt Andrew Caravan and Ski Park	Lower Portland	Hawkesbury	Lower area flooded. Slight inundation to some site structures only, none to infrastructure.
Child's Play Marine (Newall's Ski Park)	Lower Portland	The Hills	Flooded.
Riviera Ski Gardens	Lower Portland	The Hills	Flooded.
Private park, 1356 River Road	Lower Portland	The Hills	Flooded.
Private park, 1360 River Road	Lower Portland	The Hills	Flooded.
Leetsvale Caravan Park	Leets Vale	The Hills	Flooded.
Torrens Water Ski Gardens & Caravan Park	Wisemans Ferry	The Hills	Flooded.
Hawkesbury Riverside Village	Webbs Creek	Hawkesbury	Lower northern end of park flooded.
Del Rio Riverside Resort	Webbs Creek	Hawkesbury	Majority of park flooded. 300 people evacuated Saturday 20 March in anticipation of imminent ferry closure.
Carinya Ski Ranch	Wisemans Ferry	The Hills	Flooded.
Koveda Tourist Park and Water Ski Gardens	Wisemans Ferry	The Hills	Flooded. Few dozen permanent residents. Close rescue.
NSW Ski Gardens	Wisemans Ferry	The Hills	Flooded.
Rosevale Caravan Park	Gunderman	Central Coast	Flooded. Little damage to building structures. Extensive damage to contents.
Riverlands Caravan Park	Gunderman	Central Coast	Flooded.
Malaluka Caravan Park	Spencer	Central Coast	Some shallow flooding. Patrons self-evacuated as required.
Charlies Place Caravan Park	Lower Mangrove	Central Coast	Minimal impact.
Neverfail Holiday Park	Mount White	Central Coast	Minimal impact.
Greenmans on the Hawkesbury Caravan Park	Marlow	Central Coast	Minimal impact.

Sources: flood imagery captured by Spatial Services; flood mapping prepared by Rhelm/Catchment Simulation Solutions for Infrastructure NSW; Hawkesbury City Council; The Hills Shire Council; NSW SES; media reports

Shifted and toppled vans and annexes, Dargle Water Ski Resort, Lower Portland

Source: Sydney Morning Herald. Image: Nick Moir

Shifted van and damaged annexe at St George Caravan Park, Lower Portland

Source: The Hills Shire Council. Image: Daniel Giffney

Debris pile from Rosevale Caravan Park, Gunderman

Source: Infrastructure NSW. Image: S. Yeo

Figure 27: Damage at caravan parks, Hawkesbury-Nepean, March 2021 flood

3.3 Infrastructure

Roads and bridges

The March 2021 flood caused no significant damage to Transport for NSW (TfNSW) assets in the floodplain. However, some key road bridges were closed for many days, as shown in Table 6 and Figure 28. Silverdale Road Bridge was twice closed for about a day, Yarramundi Bridge was closed for more than 7 days, and North Richmond Bridge and the new Windsor Bridge were closed for more than 6 days. With Bells Line of Road cut due to a landslide at Mount Tomah, and Putty Road also closed for a time, the North Richmond area was completely isolated by road for several days.

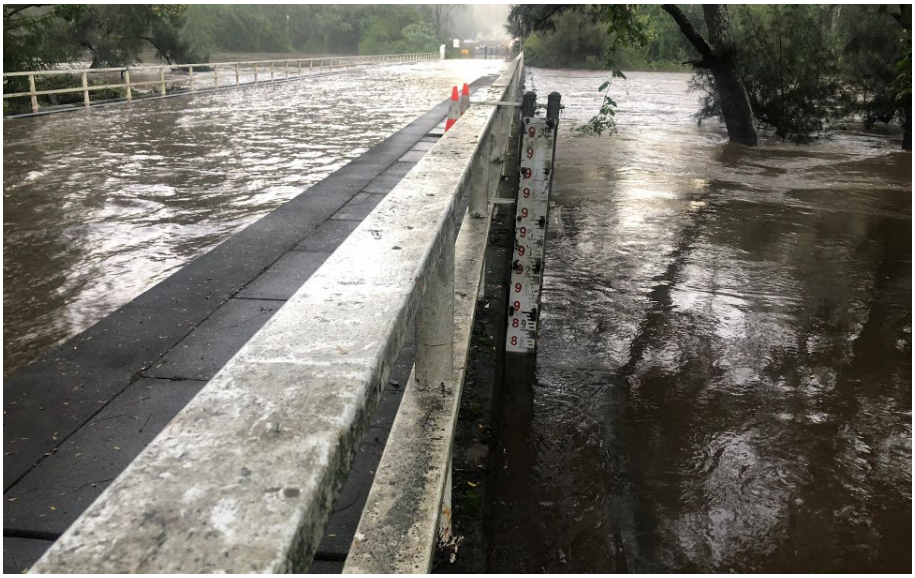
The old Windsor Bridge had a deck level of 7.2m AHD (NSW SES, 2020). The new Windsor Bridge has a sloping deck, with the lowest level at about 10.0m AHD at the north-western (Wilberforce) end of the bridge to align with the natural ground level there. Thus, the new bridge incorporates additional flood resilience. It was also designed and built to withstand the impacts of significant floods.

Jim Anderson Bridge was opened in 2007, connecting Windsor to Mulgrave, and providing a high-level flood evacuation route for Windsor. Its deck level is 17.3m AHD, which is the 1 in 100 chance per year flood level at Windsor. Since this flood was much lower (12.9m AHD), the bridge remained open and provided an important connection between Windsor and services beyond the valley (see Figure 28).

Table 6: Bridge closures, March 2021 flood

Road	Date/time road closed	Date/time road opened	Days closed	Asset owner
Silverdale Road Bridge, Wallacia	Sun 21 Mar, 3pm	Mon 22 Mar, 2:20pm	1.0 day	Council
	Wed 24 Mar, 1am	Thu 25 Mar, 9:36am	1.4 days	Council
Mulgoa Road Bridge	Sun 21 Mar, 1:17pm	Mon 22 Mar, 5:39am	0.7 days	TfNSW
Yarramundi Bridge (Springwood Road)	Sat 20 Mar, 4:35pm	Sun 28 Mar, 2pm	7.8 days	TfNSW
North Richmond Bridge (Bells Line of Road)	Sat 20 Mar, 10:18pm	Sat 27 Mar, 1:11am (restricted) Sat 27 Mar, 1:26pm (fully open)	6.1 days	TfNSW
New Windsor Bridge (Bridge Street)	Sun 21 Mar, 6:18am	Sat 27 Mar, 4:48pm	6.4 days	TfNSW
Colo River Bridge (Putty Road)	Mon 22 Mar, 10:40am	Tue 23 Mar, 9:18pm	1.4 days	TfNSW

Sources: TfNSW, Wallacia Rural Fire Brigade (Silverdale Road Bridge)



View west along flooded Silverdale Road Bridge, Wallacia, 7:04am, 24 March 2021 (at second peak, lower than first peak)

Source: Wallacia Rural Fire Brigade

View west along flooded Springwood Road approach to Yarramundi Bridge, 22 March 2021 (after peak at this site)

Source: Infrastructure NSW. Image: Top Notch Video

View south across flooded North Richmond Bridge, 23 March 2021 (after peak at this site)

Source: Hawkesbury Flood Statistics Unit Facebook page

View northwest across flooded Windsor Bridge, 10:35am, 22 March 2021 (before peak at this site, when flood level was ~12.5m at Windsor)

Source: Infrastructure NSW. Image: Adam Hollingworth

Jim Anderson Bridge, 26 March 2021 (2 days after peak at this site)

Source: Infrastructure NSW. Image: Adam Hollingworth

Figure 28: Hawkesbury-Nepean bridges, March 2021 flood

Other roads that were closed for multiple days, and in some cases weeks, due to flooding include:

- Castlereagh Road, Penrith, near the railway underpass
- Macquarie Street, Windsor, near the railway underpass
- Hawkesbury Valley Way near Rickabys Creek between Richmond and Windsor
- Windsor Road near South Creek between Windsor and McGraths Hill
- Garfield Road West near Eastern Creek, Riverstone
- Pitt Town Road near Mckenzies Creek
- Wisemans Ferry Road near Cattai Creek and Little Cattai Creek
- Cattai Ridge Road near Cattai Creek
- River Road between Lower Portland and Wisemans Ferry (see image in Appendix C).

Significant damage was caused to council-owned roads. As of early June, Hawkesbury Council estimated a preliminary damage bill of $18.5 million to repair council roads. The Hills Council reported damage to road pavements and embankments on Chapel Hill Road, Pages Wharf Road and Mitchells Road in Sackville, and potholes throughout the shire.

Examples of severe damage to roads from flooding and riverbank erosion are depicted in Figure 29.

Cornwallis Road, Cornwallis

Source: Hawkesbury City Council

Freemans Reach Road, Freemans Reach

Source: Hawkesbury City Council

Pages Wharf Road, Sackville North
Source: The Hills Shire Council

Upper Colo Bridge, Upper Colo
Source: Hawkesbury Post

Greens Road, Lower Portland
Source: Hawkesbury Post

Figure 29: Damaged local roads, March 2021 flood

Vehicular ferries

TfNSW operates vehicular ferries across the Hawkesbury River at Sackville, Webbs Creek and Wisemans Ferry. The Hills Shire Council operates a fourth ferry crossing at Lower Portland.

The TfNSW (2020) Flood Response Plan reportedly worked well, with all 3 ferries taken out of service safely and secured to mooring poles. There was no damage to any of TfNSW's vessels.

Sackville was the most at-risk site as the river very nearly rose above the mooring poles to which the ferry was secured. This could have resulted in an uncontrolled ferry travelling downstream. The southern bank at Sackville sustained severe bank collapse, leaving the whole area unstable.

The amenities building for TfNSW staff at Sackville Ferry was totally under water, and the amenities building at Wisemans Ferry was just under water – both needed repairs. These buildings also house surveillance servers for the cameras.

The ferries were closed for more than 9 days, prolonging isolation for many communities that rely on the services. The Sackville and Wisemans Ferry services ceased operating before the nominated trigger level due to the amount and size of debris in the floodwater.

The Berowra Creek ferry service was not impacted.

Table 7: Vehicular ferry closures, March 2021 flood

Source: TfNSW

Ferry	Date/time service ceased	Date/time service recommenced	Days out	Local gauge level when service ceased	Comment
Sackville	Sat 20 Mar, 2pm	Wed 31 Mar, 3:02pm	11 days	1.13m AHD (Sackville gauge)	Closed before trigger of 1.6m AHD due to debris
Lower Portland	Sat 20 Mar, 6:54pm	Sun 4 Apr, 10:50am	14.7 days	1.54m AHD (Colo Junction gauge)	
Webbs Creek	Sun 21 Mar, 5:48am	Tue 30 Mar, 7:05pm	9.6 days	1.48m AHD (Webbs Creek gauge)	Heavy debris
Wisemans Ferry	Sat 20 Mar, 10pm	Tue 30 Mar, 11:29am	9.6 days	0.68m AHD (Webbs Creek gauge)	Closed before trigger of 1.5m AHD with tree caught on cable

Rail

Stations and services on Sydney's Richmond line from Vineyard to Richmond were closed due to flooding from the early hours of Monday 22 March to the afternoon of Saturday 27 March – about 5 ½ days.

Electricity

Severe weather often impacts electricity services. This may occur when trees fall on powerlines, or when severe flooding affects the network.

In the March 2021 event, power was proactively cut to about 1100 low-lying properties along the Hawkesbury and Colo rivers and adjoining creek catchments, to reduce the risk where homes were flooded. Restoration was achieved as quickly as possible once the floodwaters had receded, roads and bridges had reopened, and repairs and safety checks were completed.

A larger number of properties were impacted by power outages during the event as a whole.

Communications

Carrier-provided public communications networks were affected by loss of power in some localities which resulted in communities being isolated from Triple Zero (000) and community warning services.

The primary cause of network failures related to power outages and subsequent battery failures. Communities were affected in several locations by mobile phone network outages (including mobile broadband internet) and/or NBN fixed and wireless services outages which affected land lines. This was exacerbated by delays accessing sites to install generators due to flooding, downed trees on roads, and landslides.

Flooding of telecommunications infrastructure was mostly limited to NBN services and primarily affected localised land line and internet services.

The Public Safety Network (PSN, formerly Government Radio Network or GRN) was not impacted by any outages or degraded service in the Greater Metropolitan Area over the reporting period.

Key impacts across the Greater Metropolitan Area were as follows:

- Megalong Valley: Fixed and mobile telephone services were offline due to an equipment failure in transmission equipment. Restoration was delayed by a landslide that prevented access to the area for 3 days. The community was unable to access Triple Zero (000), Emergency Alerts and other warning products distributed electronically in most of the valley for about 4 days; however, small pockets of reception from adjoining sites were identified by and relayed through the community for emergency use as required. Access was restored by the council.
- St Albans: Fixed and mobile telephone services were offline due to a power failure and exhaustion of batteries. Flooding prevented access to restore services. The community was potentially unable to access Triple Zero (000), Emergency Alerts and other warning products distributed electronically for approximately 2 days.
- Wisemans Ferry: Mobile telephone services were offline due to a power failure and exhaustion of batteries. Flooding and storm damage prevented access to restore services for 3 days. Poor quality mobile telephony and broadband data limited community access to warning products and posed challenges for emergency response coordination.

Water supply

Heavy rain in Sydney's water supply catchments caused large inflows of poorer quality water to Greater Sydney's dams. This compounded the effects of the 2019-2020 bushfires and February 2020 flood inflows. An increased level of sediments and organic material entered storages.

WaterNSW actively manages the water supply network to minimise issues and implications. Monitoring and modelling, and expertise enabled WaterNSW to effectively predict, anticipate and respond to the event. There was no impact on Sydney's raw water supply.

Sanitation

At wastewater treatment plants, some infrastructure and settlement ponds were impacted by floodwaters (for example, McGraths Hill). Repairs to electricals, fencing and plumbing infrastructure were required.

Elsewhere, flooding of aerated wastewater treatment systems (AWTS) caused problems, especially to electricals. Flooded systems required servicing before they could be operated again. Some popped tanks were observed, and 1 floated away. Some septic tanks needed to be desludged. While these impacts may entail considerable cost to the owners, the discharge of effluent is diluted by the volume of floodwater.

3.4 Recreation

Parks and sportsgrounds are often located in floodplains and were significantly impacted by the March 2021 flood.

Impacted national parks, conservation areas and reserves included:

- Bents Basin State Conservation Area and Gulguer Nature Reserve (still closed due to flood damage as of July 2021)
- Longneck Lagoon walking track, Scheyville National Park (open as of July 2021)
- Cattai campground and picnic area, Cattai National Park (still closed for flood damage repairs as of July 2021).

Impacted council-operated reserves included:

- in Penrith City Council:
    - Tench Reserve, Penrith
    - River Road Reserve, Emu Plains
- in Hawkesbury City Council:
    - Yarramundi Reserve
    - Navua Reserve, Grose Wold
    - Smith Park and Pughs Lagoon Reserve, Richmond
    - Deerubbin Park, Cornwallis
    - Macquarie Park, Windsor
    - Howe Park, Windsor
    - Governor Philip Park, Windsor
    - Colbee Park, McGraths Hill
- in The Hills Shire Council:
    - Wisemans Ferry Park, where the playground soft fall, fencing and barbeques were damaged; embankment and foreshore stabilisation works were also required.

A variety of private recreation facilities were also impacted. The Upper Hawkesbury Power Boat Club building located in Governor Philip Park suffered significant structural damage following ground subsidence as a result of the flood. Bowling greens at Wisemans Ferry Bowling Club, and the nearby Wisemans Ferry Men's Shed were flooded (Figure 30).

3.5 Schools

A list of the 55 schools that closed during the severe weather event, in or proximate to the Hawkesbury-Nepean study area, is provided in Table 8. Only 1 of these was flooded – the Longneck Lagoon Environmental Education Centre at Maraylya (Figure 31). Flooding there was 350mm deep in the classroom and kitchen, causing substantial damage to learning resources, infrastructure and appliances. The elevated boardwalk over the lagoon was destroyed and the creek area where many learning activities take place was damaged. The floodwater was 6.5m deep at the edge of the lagoon and at the creek.

Wisemans Ferry Bowling Club greens, 10:18am, 24 March 2021 (near peak)

Source: Infrastructure NSW. Image: S. Yeo

Wisemans Ferry Men's Shed, 24 March 2021 (near peak)

Source: Julian Leeser Member of Parliament. Image: Jack Abadee

Figure 30: Impacts on recreational facilities, March 2021 flood

Table 8: School closures in or proximate to Hawkesbury-Nepean Valley study area, March 2021 flood

School	School
Arndell Anglican College, Oakville	Longneck Lagoon Environmental Education Centre, Maraylya
Bede Polding College, South Windsor	Macdonald Valley Public School, Central Macdonald
Bilpin Public School, Bilpin	Maraylya Public School, Maraylya
Bligh Park Public School, Bligh Park	Maroota Public School, Maroota
Castlereagh Public School, Castlereagh	Marsden Park Public School, Marsden Park
Casuarina School, Riverstone	Oakville Public School, Oakville
CathWest Innovation College (McCarthy Campus), Emu Plains	Penola Catholic College Emu Plains
Cattai Public School, Cattai	Pitt Town Public School, Pitt Town
Chisholm Primary, Bligh Park	Quakers Hill Public School, Quakers Hill
Colo Heights Public School, Colo Heights	Richmond High School, Richmond
Colo High School, North Richmond	Richmond North Public School, North Richmond
Comleroy Road Public School, Kurrajong	Richmond Public School, Richmond
Ebenezer Public School, Ebenezer	Riverstone High School, Riverstone
Freemans Reach Public School, Freemans Reach	Riverstone Public School, Riverstone
Galungara Public School, Schofields	Schofields Public School, Schofields
Glenorie Public School, Glenorie	South Creek School, Riverstone
Glossodia Public School, Glossodia	St Matthew's Primary, Windsor
Grose View Public School, Grose Wold	St Monica's Primary, Richmond
Hambledon Public School, Quakers Hill	Vineyard Public School
Hawkesbury High School, Freemans Reach	Wallacia Public School, Wallacia
Hillside Public School, Glenorie	Wilberforce Public School
Hobartville Public School, Hobartville	Windsor High School
Kurmond Public School, Kurmond	Windsor Park Public School
Kurrajong East Public School, East Kurrajong	Windsor Public School
Kurrajong North Public School, Kurrajong Hills	Windsor South Public School
Kurrajong Public School, Kurrajong	Wisemans Ferry Public School
Leonay Public school, Leonay	Wyndham College, Quakers Hill
Londonderry Public School, Londonderry	

Figure 31: Longneck Lagoon Environmental Education Centre at Maraylya, 24 March 2021

Source: Longneck Lagoon EEC. Images: Vicky Whitehead

3.6 Agriculture and animals

The Agriculture and Animal Services Functional Area developed an online survey, which 17 landholders in Hawkesbury LGA completed up to 8 June 2021. While this is known to be a low representation for the valley, it does provide an insight into the type and scale of flood damages sustained by the rural sector. These include loss or damage to:

- horticulture, principally turf farms and vegetable product
- infrastructure, including fencing, pipes, farm roads, sheds, animal housing and machinery
- fodder and animal products
- pasture
- grain crops
- animals including beef cattle.[5]

From the sample of 17 responses, the total damage was $7.7 million. The greatest damages were sustained to horticulture ($7.1 million) and infrastructure ($0.5 million). Damage to turf farms and vegetables were the largest contributors to the horticultural damage. The average damage per respondent was about $460,000. The assessment did not include ongoing business costs such as freight.

A separate assessment of damage to turf farms up to 15 June 2021 estimated the loss of 86 hectares of turf, at a farm gate value of over $86 million. This assumes a conservative value of $9 – 10/$m^2$ of turf. A complete picture of damage to turf may not be available until spring 2021, when growers attempt to harvest their crop. This cost estimate does not count the damage to farm infrastructure including sheds and roads, the cost of cleaning up and re-establishing paddocks.[6]

While turf can tolerate some inundation, the damaging effect of this flood's prolonged inundation on root structure, and the heavy silt deposits, prevented the turf from being rolled up during harvest.

The Hawkesbury Valley has a significant vegetable growing industry which includes brassicas, lettuce, Asian vegetables, sweet corn and pumpkin production. Growers in South Creek and Kemps Creek were also impacted, with crops destroyed from sustained heavy rain and water logging. The estimated cost to the vegetable industry in the Greater Sydney region is $19 million in crop loss and infrastructure damage. Clubroot is endemic in the Hawkesbury Valley and growers have learnt to manage the disease; however, spores of the pathogen are carried in floodwaters and have potential spread to new growing areas.[7]

Oyster farms in the Hawkesbury estuary were impacted by the prolonged inflows of fresh water. Oysters need saline water to feed. In attempt to save its oysters, the Hawkesbury River Oyster Shed relocated leases closer to the ocean. Despite these efforts, some 80 – 90% of Pacific oysters were lost.[8]

A selection of images is provided at Figure 32.

[5] A Cornwallis resident also described the loss of alpaca, sheep and goats (https://www.skynews.com.au/australia-news/flood-victim-tells-story-of-daring-rescue-of-seven-horses-at-300am/video/b25d82304f0c83d57a0839f7be25e8bb, accessed 10 November 2021)

[6] Jenny Zadro, Turf Australia, pers. comm., 15 June 2021, 16 July 2021. This total includes 1 turf farm from Taree, with most from the Hawkesbury.

[7] https://ausveg.com.au/articles/flood-recovery-journey-continues-for-new-south-wales-veg-growers/, accessed 10 November 2021

[8] Deb O'Sullivan, Hawkesbury River Oyster Shed, pers. comm., 19 July 2021

Flooded sheds

Source: Infrastructure NSW. Image: Adam Hollingworth

Damaged turf, Freemans Reach

Source: Turf Australia

Relocating oysters from Marramarra to Porto Bay

Source: Sydney Morning Herald. Image: James Brickwood (Oysters under threat (smh.com.au))

Figure 32: Impacts on agriculture, March 2021 flood

3.7 Environment

Floods are naturally occurring events that can both benefit and impact upon ecological communities.

Flooding is important for wetland ecosystems. In March 2021, flooding reached recognised nationally important wetlands including Pitt Town Lagoon and Longneck Lagoon.

On the other hand, vegetation in the riparian zone along the Nepean River downstream of Warragamba junction was impacted by high energy flows.

Flooding of houses, caravan parks, and rural industries mobilised significant amounts of debris, which was deposited in the Hawkesbury River, its estuary, and adjacent coastlines. The waste included building parts, caravans, chemical drums and containers, gas bottles, cars, shipping containers, agricultural waste, large hay bales, and branches and trees.

The Environmental Services Functional Area coordinated a clean-up program with assistance from supporting agencies including NSW Maritime, NSW National Parks and Wildlife Service (NPWS), Department of Planning, Industry and Environment (DPIE) Science, Economics and Insights, Engineering Services Functional Area and local government.

Aerial surveillance was used to identify debris, and subsequently to confirm the effectiveness of the shoreline clean-up program. The Environmental Services Functional Area Coordinator engaged specialist marine contractor Avcon Projects Australasia to clean up debris from the river, estuary and coasts within the Hawkesbury-Nepean, Central Coast and Northern Beaches areas.

Approximately 1750 cubic metres of waste were removed from the Hawkesbury River area from early April to July. Completion of the work was delayed by Sydney's COVID-19 lockdown.

Hornsby Council reported asbestos contamination at a flooded site in Wisemans Ferry, which is estimated to cost $3 – 4 million to remediate.

A selection of images is provided at Figure 33.

3.8 Heritage

Aboriginal cultural heritage

The Engineering Services Functional Area Coordinator engaged the Soil Conservation Service (SCS) to undertake a rapid desktop assessment to identify items of Aboriginal heritage potentially impacted by riverbank erosion or flooding. The assessment drew upon Aboriginal Heritage Information Management System (AHIMS) data, which has a variable level of spatial accuracy. The AHIMS data was supplied for an area of interest extending 500m either side of the river centreline, from the Nepean River near Glenbrook Creek to the Hawkesbury estuary. SCS intersected this dataset with a March 2021 flood extent and post-flood Nearmap imagery from April 2021.[9]

The assessment identified:

- 1 Aboriginal Place within the area of interest and Hawkesbury-Nepean flood extent
- 45 recorded Aboriginal sites within the area of interest and Hawkesbury-Nepean flood extent
- 5 recorded Aboriginal sites within 500m of an identified erosion point
- 2 recorded Aboriginal sites in the Sackville area near (< 10m) an erosion point classed as high to very high priority for works.

The rapid desktop assessment did not include any assessment of the actual flood/erosion impact on the identified sites.

[9] This methodology means that only places and sites within both the nominal area of interest (500m either side of the river centreline) and flood extent were counted. This will not necessarily capture all places and sites within the flood extent.

Vegetation inundated by high velocity flows along the edge of the Nepean River, Fairlight Gorge

Source: Infrastructure NSW. Image: Rhys Thomson

Debris in lower Hawkesbury

Source: Infrastructure NSW. Image: Adam Hollingworth

Tank being salvaged from river

Source: NSW EPA

Figure 33: Impacts on environment, March 2021 flood

Non-Aboriginal heritage

The Engineering Services Functional Area Coordinator also engaged the SCS to undertake a rapid desktop assessment to identify items of non-Aboriginal heritage within the Hawkesbury-Nepean March 2021 flood extent. The assessment identified the following items within the mapped extent:

- 198 items of local significance under relevant Local Environmental Plan (LEP) under the Environmental Planning and Assessment Act 1979
- 32 items of state significance under relevant LEP under the Environmental Planning and Assessment Act 1979
- 6 items of local significance under relevant SEPP under the Environmental Planning and Assessment Act 1979
- 4 items of state significance under relevant SEPP under the Environmental Planning and Assessment Act 1979
- no items where the Minister has made an Interim Heritage Order.

The rapid desktop assessment did not include any assessment of the actual flood/erosion impact on the identified items.

Impacted items included the State-heritage listed 'Doctor's House' and North Street cottage in Windsor, and the former Methodist Chapel cemetery at Sackville North.

3.9 Insurance claims

Following the storms and flooding in large parts of NSW and parts of South East Queensland, the Insurance Council of Australia (ICA) declared an Insurance Catastrophe (No. 212). The cost of claims to mid-November 2021 was about $645 million, of which 10 – 15% (between $65 million and $97 million) were incurred in the Hawkesbury-Nepean region.[10]

Insurance claims do not represent the total damage because much damage was incurred to sectors that were not insured (for example, transport infrastructure, turf), and even for sectors with greater insurance penetration such as home insurance, social service providers report a widespread lack of insurance (or underinsurance) for flood. Insurance premiums would be high for buildings that are impacted as frequently as once every 10 to 20 years on average. Anecdotal reports of premiums as high as $30,000 a year would be prohibitive for homeowners in these areas.

The total direct and indirect cost of the Hawkesbury-Nepean flood would be expected to be in the order of several hundred million dollars.

3.10 Loss of life

Sadly, flooding of the Hawkesbury-Nepean River (including backwater) in March 2021 claimed the life of a 25-year old male driver at the flooded Cattai Creek crossing on Cattai Ridge Road in Glenorie.

3.11 Social impacts

Research conducted by Deloitte Access Economics (2016) indicated that flooding could have social costs as great as the direct costs to houses, businesses, infrastructure and agriculture. A study of the 2019 North Queensland floods found that 'intangible' social impacts on people's health and well-being contributed about 40% of total costs (Deloitte Access Economics, 2019).

While formal social impact reports are yet to be finalised, social services providers have identified a range of impacts from the March 2021 Hawkesbury-Nepean flood.

[10] https://insurancecouncil.com.au/news-hub/current-catastrophes/catastrophe-212-march-floods-nsw-and-se-queensland/, accessed 10 November 2021; Mark Campbell, ICA, pers. comm. 26/8/2021, 17/9/2021.

First, it is known that socially vulnerable members of the community were impacted. This includes social housing tenants and those living permanently in caravan parks due to the unavailability of affordable housing in the region. Several people impacted are identified as rough sleepers who resided in encampments along the river edge.

Second, multiple disasters within a short period have a cumulative physical, financial and social/emotional impact. The March 2021 flood followed drought in 2019, severe bushfires in 2019-2020, a flood and storm in February 2020, and the COVID-19 pandemic and restrictions over 2020-2021. The March 2021 flood exacerbated a raft of pre-existing recovery-related issues across and within communities.

Repeated disaster trauma has increased demand for support services but has also increased levels of fatigue among the service providers. Workers and volunteers are working long hours and facing an extensive work program for the recovery period. Many have been working in bushfire recovery since early 2020 and are now dealing with compounding recovery issues.

A range of psychosocial issues and support needs have emerged across and within communities including anxiety, fear, sadness, stress and/or trauma due to:

- loss of all personal belongings
- loss of community among caravan park residents
- uncertain housing futures
- separation from pets
- seeing stock trapped and removing carcasses
- seeing impacted wildlife
- returning to live on flood-impacted properties; this event has given residents a consequential understanding of flood risk – there will continue to be significant floods in the region, increasing the risk of repeated trauma
- the presence of mould in flood-impacted houses
- the presence of debris on impacted properties
- damaged roads and bridges increasing social isolation
- cumulative landscape impacts of bushfire and flood:
    - soil erosion (from storm run-off) affecting paddocks, farm dams and the stability of fire damaged trees
    - riverbank erosion
    - weed proliferation.

Psychosocial issues have also been exacerbated through the financial impacts of the flood:

- There is a reported widespread lack of insurance (or underinsurance) for flood. Many people have also experienced a loss of income during and after the event due to an inability to attend their jobs and/or their workplace being flood-affected (for example, caravan and ski parks, primary producers, turf farmers).
- This lack of insurance and loss of income caused financial stress, impacting the ability to repair and rebuild. Costs relate to clean-up of buildings (increased electricity/gas use for heaters drying out buildings), and re-establishment of fencing, crops, hives and infrastructure for larger primary producer and hobby farmer properties. The loss of fencing, crops and feed is particularly significant for those landholders working to re-establish these assets following the bushfires.
- Perceived inequity between bushfire and flood recovery funding (fewer funds available for flood).

Social service providers have described the following evidence of increased psychosocial issues:

- clients' disclosed high levels of concern about their capacity (physical, financial, mental) to 'start again' after the bushfire recovery
- increased disclosure of suicidal thoughts
- emergence of community fracturing and conflict.

Accessing support services has been difficult due to:

- confusion around grants, assistance and services available
- a long wait list for mental health/counselling services
- residents who have been required to relocate out of area; many are now disconnected by distance from family, friends, employment, and health services, with no transport of their own
- damage to access routes for some remote communities. (This also means that families have been unable to receive care services for people with disability or who are aging).
- poor internet and phone connectivity in some areas impacting recovery communications and the ability to engage with support (note, these are largely pre-existing communications infrastructure issues exacerbated by multiple disaster events)
- some culturally and linguistically diverse (CALD) communities requiring translation services (for example, primary producer and market garden cohort). Low levels of literacy need to be considered in some remote areas.

The Flood Strategy's Community Resilience Program focuses on communities that are most vulnerable to floods. The experience of major natural disasters shows that these communities are more likely to face challenges in preparing for, responding to, and recovering from floods. Examples of existing social vulnerabilities and complex needs are:

- older people with low mobility
- people living with a disability
- single parents with dependents
- people without access to a vehicle.

The program has focused on 8 priority communities which include: CALD communities; people living with a disability in their own homes; residential aged care providers and residents; at risk families; people with pets and large animals; childcare providers; caravan park managers and residents; and social housing tenants and providers.

4. Response and recovery

Emergency management is often considered as a continuum in 4 phases: prevent (or mitigate), prepare, respond and recover (or 'PPRR'). This section documents aspects of the official response and recovery.

4.1 Flood Watches/Warnings

The Bureau of Meteorology (the Bureau) is responsible for delivering flood warning services to the NSW community in accordance with the Bureau's Service Level Specifications for NSW (SEMC, 2018; BoM, 2020). The Bureau issues a Flood Watch to provide early advice of a developing situation that may lead to flooding. A Flood Warning is issued when the Bureau is more certain that flooding is expected, often when rain has started to fall.

A list of Flood Watches and Flood Warnings issued for the March 2021 Hawkesbury-Nepean event is provided in Table 9.

It's important to note that until Thursday 18 March 2021, weather models did not forecast a major rain event for the Hawkesbury-Nepean Valley.

The first Flood Watch indicating 'possible' flooding of the Hawkesbury-Nepean Valley was issued at 10:14am on Thursday 18 March 2021. Catchments listed as likely to be affected included:

- upper Nepean River (minor flooding)
- Hawkesbury and lower Nepean Rivers (minor flooding)
- upper Coxs River
- Colo River (minor flooding)
- Macdonald River.

The next Flood Watch issued at 4:19pm on Thursday 18 March indicated that flooding was 'expected', and increased predicted flood classifications for some rivers:

- upper Nepean River (minor flooding)
- Hawkesbury and lower Nepean Rivers (minor to moderate flooding)
- upper Coxs River
- Colo River (minor to moderate flooding)
- Macdonald River.

Forecast rainfall increased significantly as the event unfolded. On Tuesday, 30 – 60mm rainfall was forecast, with no spill from Warragamba Dam predicted. On Friday, 110 – 230mm rainfall was forecast, identifying the possibility of a large spill from Warragamba Dam. The actual Warragamba catchment average rainfall of around 274mm resulted in a major flood in the Hawkesbury-Nepean Valley.

The first Flood Warning for the Hawkesbury-Nepean was issued at 5:28am Saturday 20 March, indicating possible moderate flooding at North Richmond, Windsor and Putty Road (Colo River) on Saturday. A Flood Warning issued at 9:04am (No. 3) described possible rises to major flood levels at North Richmond, Windsor, Sackville and in the Colo River. The warning indicated that flooding may be similar to February 2020.

With heavy rain observed across the Hawkesbury-Nepean catchment on the Saturday, Warragamba Dam starting to spill around 3pm, and river levels rising, the remaining warnings issued on Saturday conveyed the sense of a growing flood threat.

Table 9: Flood Watches and Warnings, Hawkesbury-Nepean, March 2021 flood

Source: Bureau of Meteorology

Flood Watch		Headline
2	18/3/2021 @ 10:14am	Flooding possible – minor
4	18/3/2021 @ 4:19pm	Flooding expected – minor to moderate
5	19/3/2021 @ 10:38am	as above
Flood Warning		**Headline**
1	20/3/2021 @ 5:28am	Moderate flooding possible at North Richmond, Windsor and Putty Road on Saturday
3	20/3/2021 @ 9:04am	Major flooding possible at North Richmond, Windsor and Sackville from late Saturday
4	20/3/2021 @ 11:48am	as above
5	20/3/2021 @ 3:00pm	as above
6	20/3/2021 @ 5:38pm	as above
7	20/3/2021 @ 8:59pm	Major flooding possible at North Richmond, Windsor and Sackville from early Sunday morning
8	20/3/2021 @ 11:56pm	as above
9	21/3/2021 @ 2:48am	Major flooding expected at North Richmond early Sunday morning. Major flooding possible at Windsor and Sackville
10	21/3/2021 @ 5:58am	Major flooding occurring at North Richmond
11	21/3/2021 @ 9:14am	as above
12	21/3/2021 @ 10am	as above
13	21/3/2021 @ 11:23am	as above
14	21/3/2021 @ 12:49pm	Major flooding similar to 1961 event expected along Hawkesbury River
15	21/3/2021 @ 3:21pm	Major flooding higher than 1961 event expected along Hawkesbury River
16	21/3/2021 @ 5:36pm	as above
18	21/3/2021 @ 9:38pm	Major flooding similar to 1961 event expected along Hawkesbury River
19	21/3/2021 @ 11:58pm	Major flooding similar to 1961 event possible along Hawkesbury River
20	22/3/2021 @ 2:56am	as above
21	22/3/2021 @ 7:46am	Major flooding similar to 1988 and 1990 events occurring along Hawkesbury River
22	22/3/2021 @ 10:51am	as above
23	22/3/2021 @ 1:58pm	as above
24	22/3/2021 @ 4:54pm	as above
25	22/3/2021 @ 7:49pm	Major flooding similar to 1990 event occurring along Hawkesbury River
26	22/3/2021 @ 11:59pm	as above
27	23/3/2021 @ 2:56am	Major flooding similar to 1978 flood possible along Colo River on Tuesday afternoon. Major flooding occurring along Hawkesbury River at North Richmond and downstream
28	23/3/2021 @ 5:56am	as above
29	23/3/2021 @ 9:02am	Major flooding occurring along Hawkesbury River at North Richmond, Windsor and downstream, and on Colo River
30	23/3/2021 @ 11:56am	as above
31	23/3/2021 @ 3:01pm	as above
32	23/3/2021 @ 3:56pm	Major flooding occurring along Hawkesbury River at North Richmond, Windsor and downstream, and on Colo River. Major flooding possible on upper Nepean River at Menangle Tuesday evening
33	23/3/2021 @ 5:54pm	Major flooding occurring along Hawkesbury River at North Richmond, Windsor and downstream, on Colo River, and on Nepean River at Menangle

Flood Warning		Headline
34	23/3/2021 @ 9:22pm	as above
35	24/3/2021 @ 12:33am	as above
36	24/3/2021 @ 2:46am	Major flooding occurring along Hawkesbury River at North Richmond, Windsor and downstream
37	24/3/2021 @ 5:51am	as above
38	24/3/2021 @ 8:51am	as above
39	24/3/2021 @ 11:51am	as above
40	24/3/2021 @ 2:55pm	as above
41	24/3/2021 @ 5:41pm	as above
43	24/3/2021 @ 10:52pm	as above
44	25/3/2021 @ 12:17am	Major flooding occurring along Hawkesbury River at North Richmond and Windsor
45	25/3/2021 @ 3:00am	as above
46	25/3/2021 @ 5:59am	as above
47	25/3/2021 @ 8:44am	Moderate to major flooding continuing along Hawkesbury River at North Richmond and downstream
48	25/3/2021 @ 3:06pm	as above
49	25/3/2021 @ 8:59pm	Moderate flooding continuing along Hawkesbury River at North Richmond and downstream
50	26/3/2021 @ 7:59am	Moderate flooding continuing along Hawkesbury River at North Richmond and Windsor
51	26/3/2021 @ 1:52pm	as above
52	26/3/2021 @ 4:55pm	as above
53	27/3/2021 @ 8:00am	Minor flooding continuing along Hawkesbury River at North Richmond and Windsor
54	27/3/2021 @ 8:52am	as above
55	27/3/2021 @ 1:49pm	as above
56	28/3/2021 @ 8:53am	Hawkesbury River at North Richmond and Windsor has fallen below minor flood levels

Note: Some Flood Watches and Flood Warnings were reissued. In such circumstances, only 1 Flood Watch or Flood Warning is listed here. This accounts for occasional gaps in the numbering.

The Flood Warning issued at 2:48am Sunday 21 March (No. 9) indicated that major flooding was now expected at North Richmond. By the 5:58am warning (No. 10), the river at North Richmond had exceeded the major level. The 9:14am warning (No. 11) for the first time indicated that the Hawkesbury could reach similar levels to the April 1988 flood (12.8m at Windsor) – higher than the February 2020 flood. It also indicated possible major flooding at Penrith.

The Flood Warning issued at 12:49pm Sunday 21 March (No. 14) conveyed an increased threat, marking the warning as ‘top priority’ for broadcast, and now indicating the Hawkesbury flooding would likely be higher than the February 2020, April 1988 and July 1990 floods, and that it may reach similar levels to the November 1961 flood, which had peaked at 15.0m at Windsor. The driver for this increase appears to have been the faster than expected rises at Penrith, and a forecast there of 9.8m, similar to the 1961 flood.

The Flood Warning issued at 3:21pm Sunday 21 March (No. 15) increased the predictions, indicating that major flooding higher than the 1961 event was expected along the Hawkesbury River, including a possible rise to 15.6m at Windsor.

With the Nepean River at Penrith peaking lower than predicted at about 10.0m, the Flood Warning issued at 9:01pm Sunday 21 March (No. 17) eased the predicted flood level for Windsor to 15.0m, similar to the 1961 flood. The Flood Warning issued at 11:58pm (No. 19) further eased the predicted level to 14.0m. The headline banner also shifted from ‘Major flooding higher than the 1961 event expected along the Hawkesbury River’ to ‘Major flooding similar to the 1961 event possible along the Hawkesbury River’.

The Flood Warning issued at 2:56am Monday 22 March (No. 20) downscaled the flood of comparison at Windsor to the May 1988 event[11], but maintained the comparison to the 1961 flood at Lower Portland and Wisemans Ferry given the major flooding observed on the Colo River. The next Flood Warning issued at 7:46am (No. 21) adjusted the flood of comparison for the lower Hawkesbury gauges (Sackville, Lower Portland and Wisemans Ferry) to the July 1990 flood.

Flood warnings continued to be issued until 8:53am Sunday 28 March, by which time the river level at North Richmond had fallen below the minor flood level. In all, 56 flood warnings for the Hawkesbury-Nepean River were issued across 9 days.

4.2 Flood Bulletins

NSW SES is the lead agency for flood preparedness and response within NSW. One of its roles is to issue Flood Bulletins. These translate predicted flood heights at gauges to consequences and include actions for communities such as raising pumps. For the March 2021 flood, the NSW SES issued a similar number of Flood Bulletins as Flood Warnings for the Hawkesbury-Nepean River issued by the Bureau.

4.3 Evacuation Warnings and Orders

Evacuating areas that could be impacted by flooding, before flooding cuts evacuation routes, is the primary means of reducing the risk to life during a flood emergency in the Hawkesbury-Nepean Valley. Evacuation Warnings indicate the affected communities should prepare to evacuate. Evacuation Orders indicate the affected communities should evacuate immediately.

In the March 2021 flood, the forecast flood heights caused the NSW SES to issue a number of Evacuation Warnings and Evacuation Orders for communities in the Hawkesbury-Nepean (Table 10). The Evacuation Warnings and Orders were issued using Emergency Alert and via door knocking, social media, radio broadcasting and television broadcasting.

About 14,300 dwellings were impacted by Evacuation Warnings and about 1300 dwellings were impacted by Evacuation Orders within the Hawkesbury-Nepean study area.

As a flood is rising, typically there are higher levels of uncertainty about the precise extent of flooding that will be realised, resulting in a larger area covered by Evacuation Warnings. Fortunately, the flood at Windsor peaked well below levels that were at one stage predicted, allaying the need to issue Evacuation Orders for large urban communities.

[11] Floods described as April 1988 or May 1988 refer to the same event.

Table 10: Evacuation Warnings and Orders, Hawkesbury-Nepean, March 2021 flood

Source: NSW SES, 2021a

Locality	LGA	Evacuation Warning	Evacuation Order	All Clear
Pitt Town Bottoms	Hawkesbury	20/3/2021 @ 8:30am	21/3/2021 @ 1:50am	31/3/2021 @ 1:27pm
Gronos Point	Hawkesbury	20/3/2021 @ 8:30pm	21/3/2021 @ 1:50am	29/3/2021 @ 5:00pm
North Richmond (low lying parts)	Hawkesbury	20/3/2021 @ 8:30pm	21/3/2021 @ 1:50am	29/3/2021 @ 5:00pm
Cornwallis/Richmond Lowlands	Hawkesbury		21/3/2021 @ 1:50am	31/3/2021 @ 1:32pm
Pitt Town north	Hawkesbury		21/3/2021 @ 1:50am	31/3/2021 @ 1:20pm
Freemans Reach	Hawkesbury	21/3/2021 @ 2:45am	21/3/2021 @ 3:30am	1/4/2021 @ 3:00pm
Agnes Banks north	Hawkesbury	21/3/2021 @ 5:00am	21/3/2021 @ 6:00am	29/3/2021 @ 5:00pm
Western parts of Jamisontown	Penrith		21/3/2021 @ 3:35pm	22/3/2021 @ 10:00pm
Northern end of Mulgoa	Penrith		21/3/2021 @ 3:35pm	22/3/2021 @ 10:00am
Western parts of Penrith	Penrith		21/3/2021 @ 3:35pm	22/3/2021 @ 10:00am
Windsor CBD	Hawkesbury	21/3/2021 @ 7:00pm		25/3/2021 @ 8:30pm
McGraths Hill	Hawkesbury	21/3/2021 @ 7:00pm		25/3/2021 @ 8:30pm
South Windsor (eastern part)	Hawkesbury	21/3/2021 @ 7:00pm		28/3/2021 @ 3:00pm
Caravan parks along Hawkesbury River	Hawkesbury	21/3/2021 @ 7:00pm		29/3/2021 @ 6:30pm
Wilberforce (southern part)	Hawkesbury	21/3/2021 @ 7:00pm		28/3/2021 @ 3:00pm
Areas of Marsden Park at western end of Eastern Creek	Blacktown	21/3/2021 @ 7:30pm		25/3/2021 @ 7:00pm
Eastern part of Eastern Creek	Blacktown	21/3/2021 @ 7:30pm		25/3/2021 @ 7:00pm
Eastern Creek at Colebee and Stonecutters Ridge	Blacktown	21/3/2021 @ 7:30pm		26/3/2021 @ 7:00pm
Mulgrave	Hawkesbury	21/3/2021 @ 8:30pm		25/3/2021 @ 8:00pm
Vineyard	Hawkesbury	21/3/2021 @ 8:30pm		25/3/2021 @ 8:00pm
Clarendon (Rickabys Creek)	Hawkesbury	22/3/2021 @ 2:30pm		25/3/2021 @ 8:00pm
Londonderry (Rickabys Creek)	Penrith	22/3/2021 @ 2:30pm		27/3/2021
Colo River (Upper Colo, Lower Colo, Colo Central and Wheeny Creek)	Hawkesbury	22/3/2021 @ 10:30pm		29/3/2021 @ 6:30pm
Wisemans Ferry to Brooklyn (Hawkesbury River Lower Reaches)	Hawkesbury	23/3/2021 @ 11:30am		25/3/2021 @ 8:00pm

4.4 Requests for assistance including flood rescue and resupply

During the March 2021 severe weather event, the NSW SES responded to over 5636 requests for assistance (RFAs) in the Sydney Metropolitan Area. The distribution and nature of flood-related RFAs in the NSW SES units servicing the Hawkesbury-Nepean floodplain are shown in Table 11. A large majority of these were serviced by the Hawkesbury SES unit, with the Penrith SES unit also responding to more than 100 RFAs.

Table 11: Distribution and nature of flood-related requests for assistance, March 2021 weather event

Source: NSW SES, 2021b

Note: excludes RFAs categorised as storm; not all RFAs for flood will relate to mainstream Hawkesbury-Nepean floods

SES unit	Flood misc.	Flood rescue	Evacuation	Resupply	Medical resupply	Fodder drop	Total
Blacktown	22	3	0	0	0	0	**25**
Gosford	7	1	0	6	1	0	**15**
Hawkesbury	297	109	125	103	35	8	**677**
Hornsby	23	1	0	3	0	0	**27**
Liverpool	22	3	0	0	0	0	**25**
Penrith	139	5	5	0	0	0	**149**
The Hills	29	2	3	29	2	2	**67**
Wollondilly	24	1	0	0	1	0	**26**

Flood rescues

Across the Hawkesbury-Nepean and Sydney Metropolitan area of operation, 194 flood rescues were activated. The nature of these rescues is listed in Table 12. Animal rescues, vehicles in floodwater and people trapped by floodwater were the most common rescue types (see Figure 34). NSW SES, Fire and Rescue NSW, NSW Police and interstate in-water flood rescue teams were utilised throughout the emergency response.

Table 12: Nature of flood rescues across Hawkesbury-Nepean and Sydney Metro, March 2021 flood

Source: NSW SES, 2021a

Rescue type	Number of rescues
Animal	56
Concern for welfare	8
Evacuation assistance	19
Medical assistance	8
Persons in floodwater	9
Trapped by floodwater (house/property)	45
Vehicle in floodwater	49

Hawkesbury SES unit analysed the actual numbers of large animals that were the subject of RFAs in the Londonderry, Hawkesbury, Colo and Lower Macdonald areas:

- 92 horses
- 152+ cattle and calves
- 8 goats
- 100+ sheep
- 8 llama/alpacas.

Evacuation centres

Evacuation centres were established at 5 locations in Sydney for community members (Table 13). Some 300 people attended these centres. Many evacuees sourced their own accommodation.

Table 13: Evacuation locations across Hawkesbury-Nepean and Sydney Metro, March 2021 flood

Source: NSW SES, 2021a

Evacuation location	Registrations
Richmond Club	103
North Richmond Community Centre	102
Castle Hill RSL	93
Bringelly Community Centre	Unknown
Cecil Hills	Unknown

Resupplying isolated communities

A total of 152 requests for resupply were received for isolated communities within the Hawkesbury-Nepean and Metropolitan area of operation. Flooding of roads and bridges, and the cessation of the ferry services, isolated many communities (Table 4) – some for more than 1 week. A noteworthy example was the need to service stranded communities around North Richmond.[12] [13] [14]

Figure 34 depicts a resupply operation.

4.5 Clean up

The Engineering Services Functional Area undertook bulk waste removal from flood-inundated properties in Hawkesbury and The Hills councils, including from residential, commercial/industrial and council-owned properties. There was also a large effort to remove waste from flood-damaged caravan and ski parks. Some 1600 bins and 260 skip bins were deployed.

Members of the NSW Rural Fire Service, NSW SES and Australian Defence Force helped residents with the clean-up, together with other volunteers.

As described earlier, the Environmental Services Functional Area coordinated clean-up of debris from the Hawkesbury River, the estuary and adjacent coasts. Some 1750 cubic metres of waste were removed from early April to July.

[12] https://www.hawkesburygazette.com.au/story/7182909/coles-runs-convoy-via-hunter-valley-to-flood-bound-hawkesbury-store/, accessed 10 November 2021

[13] https://www.hawkesburygazette.com.au/story/7184262/raaf-base-richmond-supports-flood-evacuees-coordinates-support/, accessed 10 November 2021

[14] https://www.hawkesburygazette.com.au/story/7192834/medications-sent-by-helicopter-to-nursing-home-during-the-flood/, accessed 10 November 2021

Rescuing a horse, Windsor Downs

Source: NSW SES

Rescuing people trapped by floodwater, Windsor

Source: Sydney Morning Herald. Image: Nick Moir

Resupplying isolated communities

Source: Infrastructure NSW. Image: Top Notch Video

Figure 34: Examples of NSW SES activities, Hawkesbury-Nepean River, March 2021 flood

4.6 Recovery

The establishment of Recovery Support Services to assist flood-affected people was a vital part of the recovery approach in the region. Peppercorn Services Recovery Support Service was activated in the initial recovery phase to provide immediate support to the residents of flood-affected caravan parks.

Peppercorn's relatively early deployment represented an innovative recovery response to a unique regional recovery issue. Dedicated support workers continue to provide personalised, long-term support to flood-affected caravan park residents. Peppercorn's role has subsequently expanded, linking flood-affected people across the region with personalised recovery support workers to help them navigate and access services and disaster assistance packages.

Peppercorn is now working alongside the Department of Primary Industries Rural Recovery Support Service, which is connecting with flood-affected primary producers and rural landholders to provide recovery support specific to their needs.

Resilience NSW partnered with Hawkesbury and The Hills councils to operate 3 recovery centres in the Hawkesbury-Nepean Valley (North Richmond, South Windsor and Wisemans Ferry) in response to the March 2021 flood. These serviced many impacted people, with over 1500 daily visitations recorded over the period of operation (Table 14). Recovery centres are an effective recovery tool in the early intense weeks following an event offering a safe location where clients can receive emotional, practical and financial assistance from a range of government and community services.

Table 14: Daily visitations to Hawkesbury-Nepean recovery centres

Source: Resilience NSW

Recovery Centre	April 2021	May 2021	June 2021	Opening Date	Closing Date	Total
North Richmond	51	0	0	7 April	21 April	51
South Windsor	609	347	47	1 April	4 June	1003
Wisemans Ferry	363	177	0	9 April	21 May	540
Total						**1594**

In addition, mobile recovery visits and community recovery meetings were offered by councils and Service NSW, including at:

- Wallacia
- Wilberforce
- Colo Heights
- St Albans
- Wisemans Ferry.

Recovery is a long-term process in response to both the acute and ongoing cumulative emotional, physical and financial impacts of the flood/storm (and previous bushfire, flood/storm and pandemic disasters).

5. ‘What if’ scenarios

The March 2021 flood was the largest flood in the Hawkesbury-Nepean River for more than 30 years (Table 2) and caused substantial damage. Various suggestions were made after the flood about how the flooding could have been reduced.

A number of Warragamba Dam flood mitigation scenarios have been modelled to determine what difference these measures would have made to the height and timing of the March 2021 flood downstream. These scenarios all involve creating air space for the temporary capture of floodwaters, but by different means. The methodology and results of this assessment are detailed in Appendix F.

The modelled scenarios include:

- pre-releasing water from the Warragamba Dam storage before the flood
- permanently lowering Warragamba Dam full supply level (FSL) by either 5m or 12m
- raising Warragamba Dam spillways to create a 14m flood mitigation zone while retaining current FSL.

Figure 35 compares the reduction in downstream peak flood levels at Penrith and Windsor for the different scenarios. Figure 36 compares the time at which Warragamba Dam would have spilled. Figure 37 compares the time at which several representative downstream consequences would have occurred. Figure 38 considers the duration of flooding at the new Windsor Bridge. The results are discussed below.

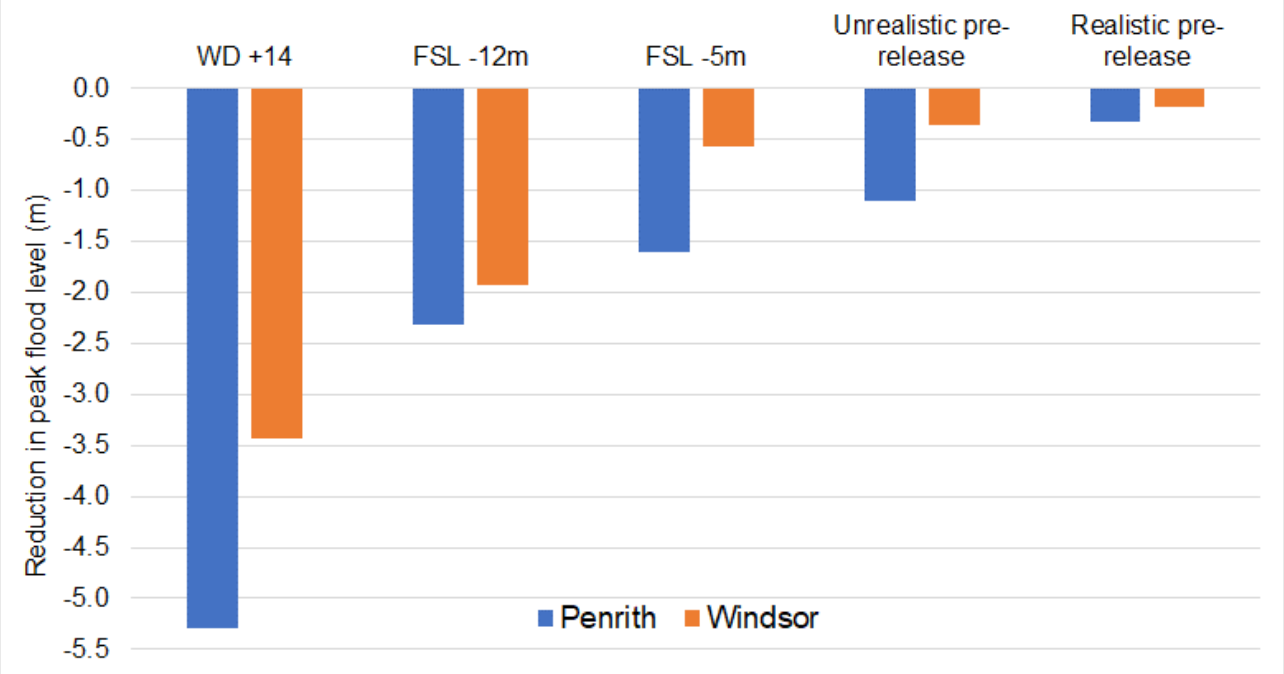


Figure 35: Effect of potential Warragamba Dam flood mitigation measures on downstream peak flood levels, March 2021 flood

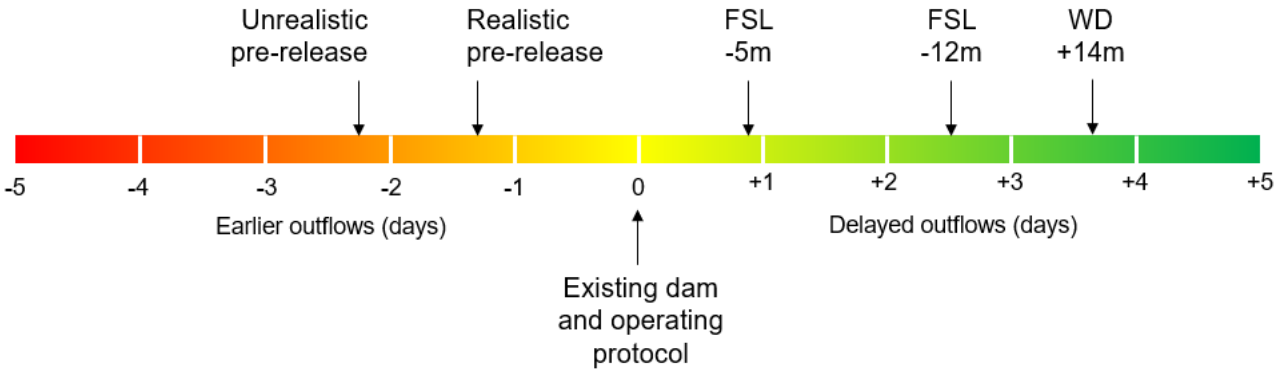


Figure 36: Effect of potential Warragamba Dam flood mitigation measures on timing of outflows from Warragamba Dam, March 2021 flood

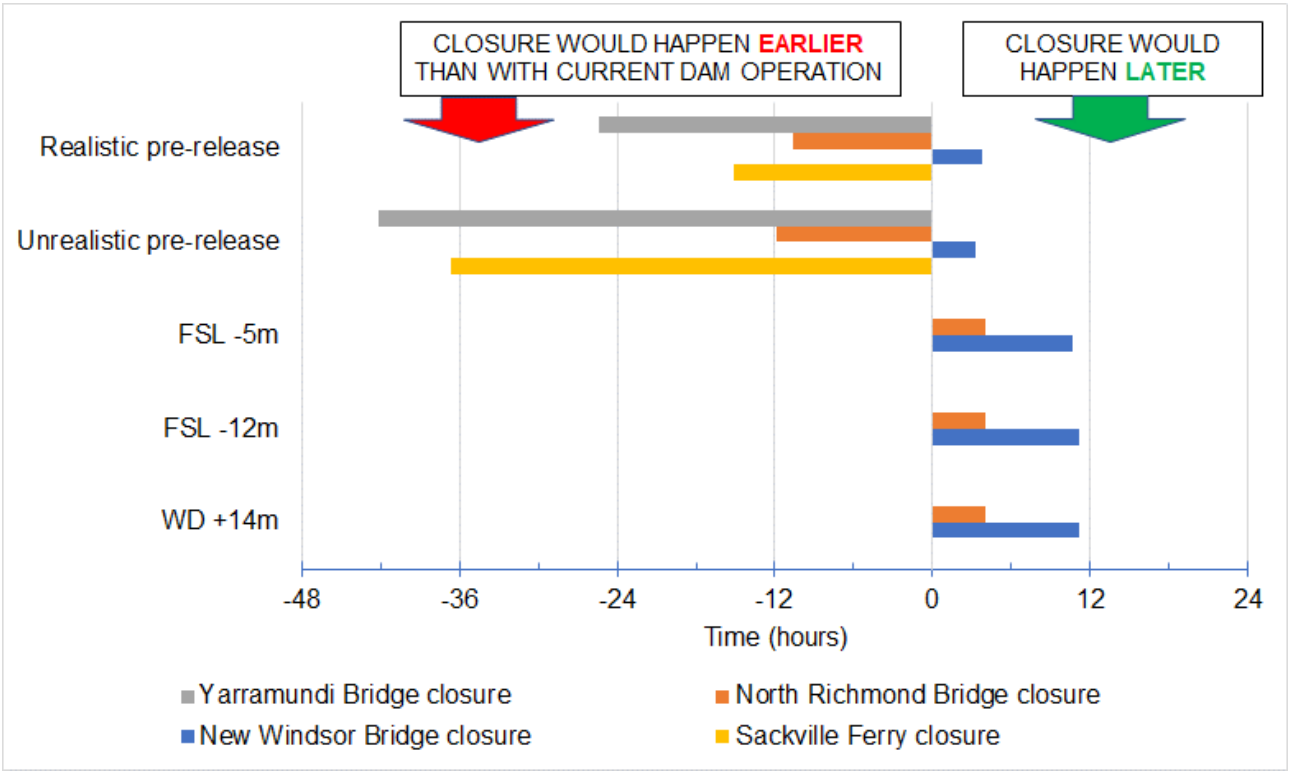


Figure 37: Effect of potential Warragamba Dam flood mitigation measures on timing of downstream consequences, March 2021 flood

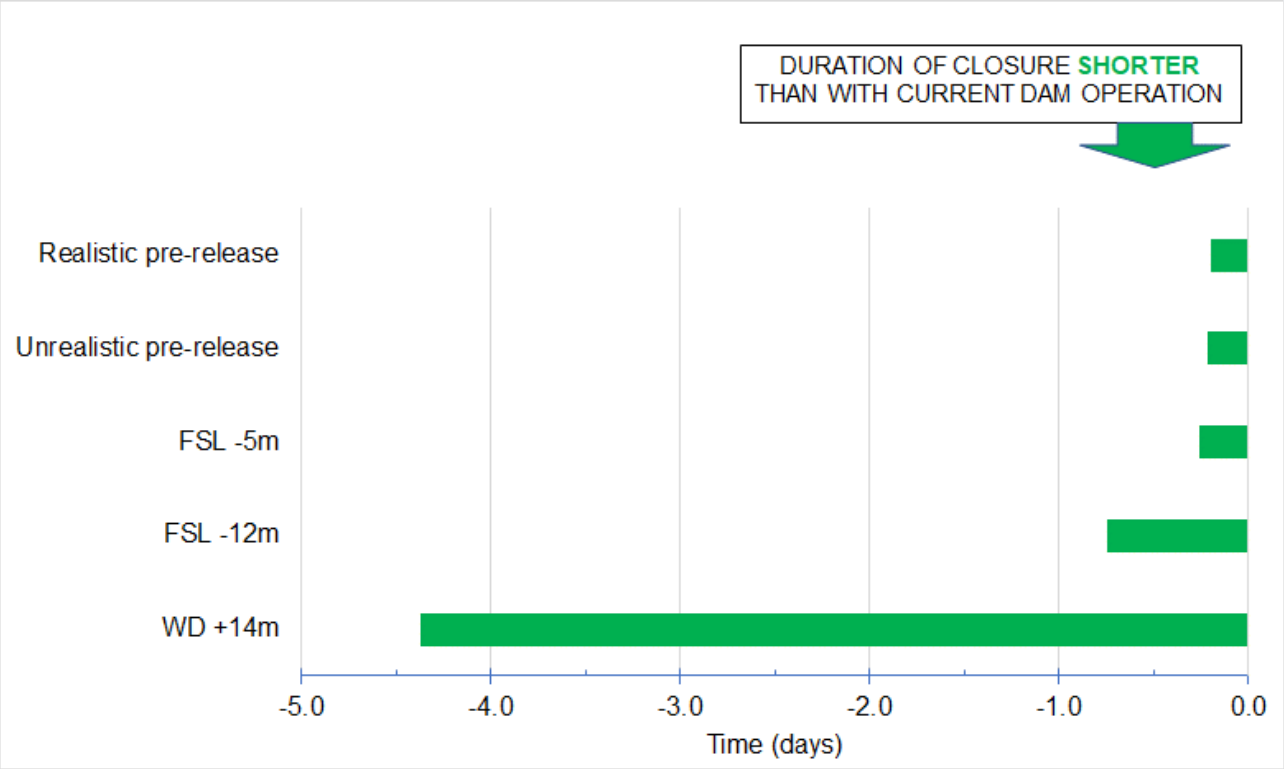


Figure 38: Effect of potential Warragamba Dam flood mitigation measures on duration of new Windsor Bridge closure, March 2021 flood

5.1 Pre-releases

After the flood, 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 were described in the *Taskforce Options Assessment Report* (Infrastructure NSW, 2019).

One constraint is legal: the dam owner and operator, WaterNSW, cannot legally undertake pre-releases in the way suggested by some stakeholders. Warragamba Dam is the primary water supply for the Greater Sydney region, 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 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.[15]

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 the severe drought of 2017-2019.

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. Here, the rate of release was modelled at 100 GL/day to limit unacceptable downstream impacts. Such a pre-release does fill the river and some of the floodplain and would constrain the evacuation window for some residences. In some events it would make some evacuation routes susceptible to earlier closure if there is intense rainfall downstream of the dam during the evacuation phase.

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

Realistic pre-release – commencing 19 March

In the case of the March 2021 flood, due to the evolving nature of the event and the forecasts, the dam operators would not have had enough certainty that rainfall was going to fill and spill the dam until the morning of Friday 19 March. This was the first time during the event that median (50% chance) rain forecasts for the dam catchment exceeded 100mm. Based on this time, pre-releases commencing at 9am on Friday 19 March are described in the preceding figures as a 'realistic' pre-release.

Figure 35 shows that this realistic pre-release scenario would reduce peak flood levels at Penrith and Windsor by only 0.3m and 0.2m respectively. Outflows from the dam would commence over 1 day earlier than under normal operating protocols (Figure 36). Figure 37 shows that Yarramundi Bridge would close over 1 day earlier, and North Richmond Bridge and the Sackville ferry service would close around half a day earlier, bringing forward the isolation of communities.

Table F11 in Appendix F shows that with pre-releases commencing on 19 March the minor flood level at Windsor would have been reached around half a day earlier. This scale of flooding can have serious consequences for communities downstream of Windsor. Far from reducing the risk, pre-releases could inhibit evacuation and property-saving efforts.

Unrealistic pre-release – commencing 18 March

A forecast for a 25% chance of more than 140mm rain in the Warragamba catchment had been issued on Thursday 18 March, indicating that the dam might spill. However, dam operators would not have enough confidence in a 25% chance forecast to commence releasing water from the storage, since there was a significant chance that the discharged supply would not be replenished by inflows. Accordingly, the above figures describe this scenario as an 'unrealistic' pre-release.

Even if pre-releases had commenced at 10am on Thursday 18 March, Figure 35 shows that this scenario would provide only about 0.3m reduction in peak flood levels at Windsor. Figure 37 shows that it would bring forward the closure of Yarramundi Bridge and the Sackville ferry service by over 1½ days. Minor flooding at Windsor would have commenced about 1½ days earlier (Table F11).

La Niña season pre-release

Another suggestion was that because La Niña was forecast for the 2020-2021 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 and fuller storages.

There have been La Niña years with Hawkesbury-Nepean floods, and sometimes multiple floods, such as in 1950, 1956, and 1988. However, there have also been La Niña years without Hawkesbury-Nepean floods, such as in the dry La Niña of 1938-1939.[16] It's also noteworthy that 3 of the 4 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 also unpredictable. For example, rain associated with the 2020-2021 La Niña largely missed the Wivenhoe Dam catchment in south-east Queensland, which fell to 36% capacity.

In short, the occurrence of La Niña does not guarantee heavy rainfall, or heavy rainfall within a specific catchment. This means that releasing storage water ahead of a La Niña represents a significant risk to water security.

5.2 Lower FSL by 5 metres

An assessment of the flood mitigation benefits of a strategy to permanently lower Warragamba Dam FSL by 5m, against the full range of floods, was 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.

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

Modelling of the March 2021 flood with FSL lowered by 5m shows the following results:

- peak flood levels at Penrith and Windsor reduced by 1.6m and 0.6m, respectively (Figure 35)
- outflows from Warragamba Dam delayed by 0.9 days (Figure 36)
- initial time of closure of new Windsor Bridge delayed by around 11 hours (Figure 37)
- duration of closure of new Windsor Bridge shortened by 0.3 days (Figure 38).

The limited benefit of lowering FSL by 5m reflects the limited air space created (Figure 39). This option also comes at significant cost because it would permanently reduce Warragamba Dam's water supply by 360 gigalitres or around 18% (Figure 39) which would need to be replaced with other new sources of supply.

5.3 Lower FSL by 12 metres

An assessment of the flood mitigation benefits of a strategy to permanently lower Warragamba Dam FSL by 12m, against the full range of floods, was 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 March 2021 flood with FSL lowered by 12m shows the following results:

- peak flood levels at Penrith and Windsor reduced by 2.3m and 1.9m, respectively (Figure 35)
- outflows from Warragamba Dam delayed by 2.5 days (Figure 36)
- initial time of closure of new Windsor Bridge delayed by around 11 hours (Figure 37)
- duration of closure of new Windsor Bridge shortened by 0.7 days (Figure 38).

The benefits of lowering FSL by 12m reflects the quantum of air space created (Figure 39). This option also comes at very significant cost because it would permanently reduce Warragamba Dam's water supply by 795 gigalitres or around 39% (Figure 39) which would need to be replaced.

5.4 Raise Warragamba Dam for flood mitigation

An assessment of the flood mitigation benefits of raising Warragamba Dam wall to create a 14m flood mitigation zone, against the full range of floods, was 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 (EIS).

Modelling of the March 2021 flood with the raised dam shows the following results:

- peak flood levels at Penrith and Windsor reduced by 5.3m and 3.4m, respectively (Figure 35). The March 2021 flood at Windsor – with a raised dam – would have peaked at a level very similar to what was observed in the moderate February 2020 flood (see Figure 17).
- outflows from Warragamba Dam delayed by 3.7 days (Figure 36)
- initial time of closure of new Windsor Bridge delayed by around 11 hours (Figure 37)
- duration of closure of new Windsor Bridge shortened by (at least) 4.4 days (Figure 38).

The significant downstream benefits of raising Warragamba Dam as proposed reflects the quantum of air space created (Figure 39).

Heights behind a raised dam with a dedicated flood storage zone are largely a function of inflow volume. The unusual double-peaked nature of this flood, with large inflow volumes to Warragamba Dam, would have resulted in a peak height upstream of the proposed raised dam of 130.20m AHD.

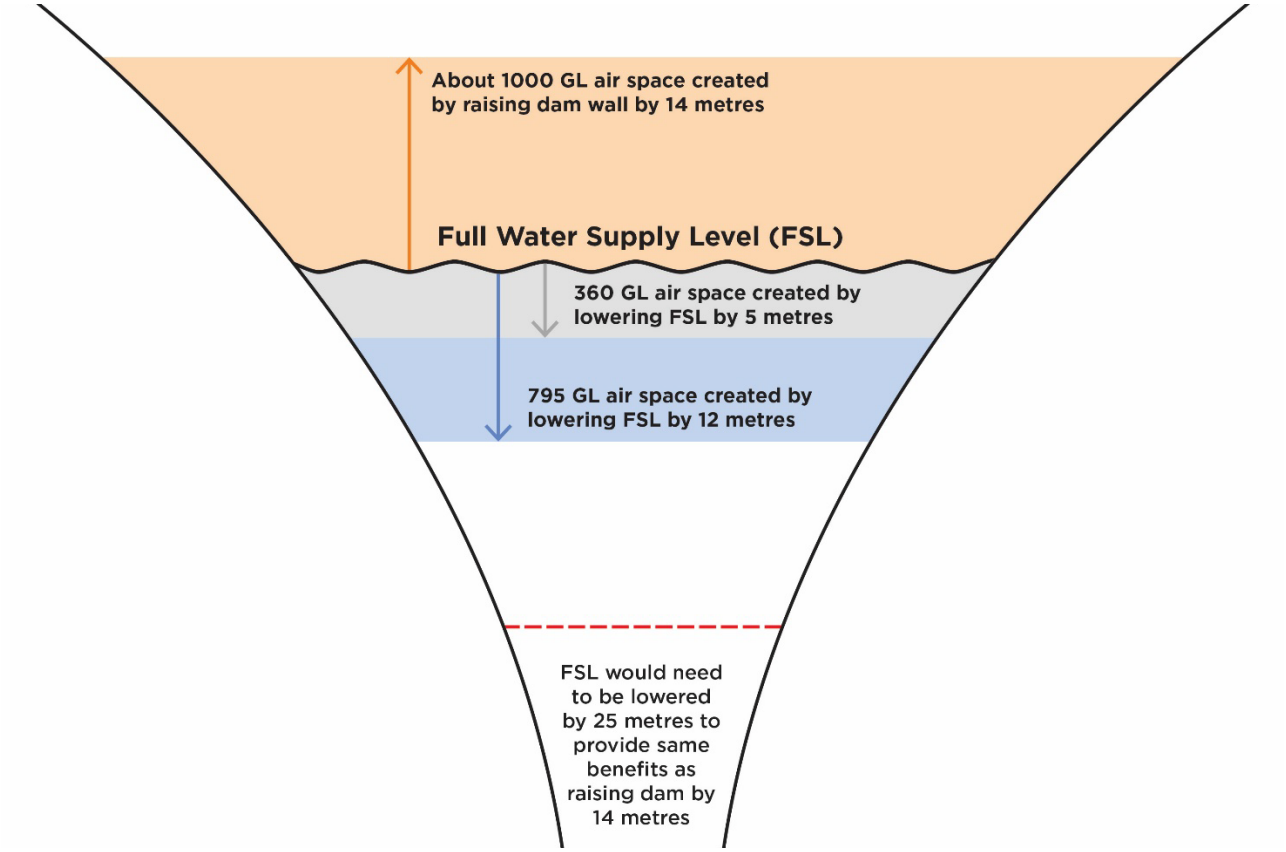


Figure 39: Schematic of Warragamba Dam flood mitigation scenarios

5.5 Number of buildings impacted

Detailed modelling of the March 2021 flood with the dam raising, FSL-lowering scenarios and pre-release scenarios was compared to the distribution of residential dwellings, commercial/industrial buildings and manufactured homes in Infrastructure NSW's 2018 assets database. The results in terms of percentage reduction from the existing dam base case are presented in Figure 40.

As expected, given the greater reduction in flood peaks and extents made possible by the proposed raised dam, this option would provide the greatest reduction in the number of dwellings impacted by the March 2021 flood, by almost 80%.

Permanently lowering the FSL by 12m would provide a significant reduction (65%) in the number of dwellings impacted by the March 2021 flood. Two caveats should be considered:

- Analysis has shown that with the current dam gate infrastructure, it is unlikely that a storage level 12m below current FSL could be achieved before large floods, as required to achieve the full quantum of benefit shown here (see Appendix F).
- For a flood of this size, the distinction between the proposed raised dam and lowering FSL by 12m is less pronounced than for larger, rarer floods like the 1 in 50 chance per year event or the 1867 flood of record, when the larger flood mitigation zone afforded by dam raising would be vital.

Figure 40 shows the limited ability of the 5m-FSL lowering and pre-release scenarios (both realistic and unrealistic) to reduce the number of dwellings impacted.

Many manufactured homes are located in low-lying caravan parks, with some 1450 manufactured homes in more than 30 caravan parks impacted in the March 2021 flood (Table 3). The proposed dam raising would reduce the number impacted by over 60%, the 12m-FSL lowering would reduce the number impacted by around 40%, while the 5m-FSL lowering and pre-release scenarios would reduce the number impacted by less than 10%.

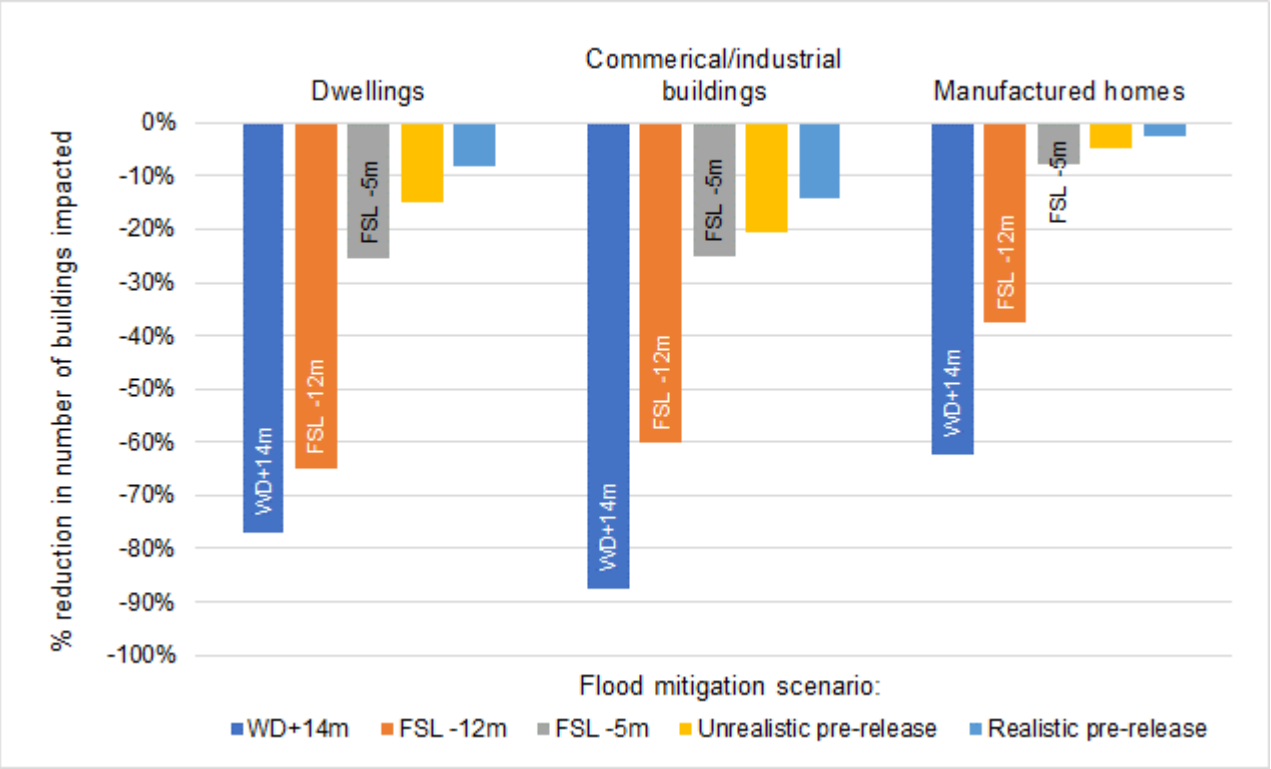


Figure 40: Change in number of buildings impacted with different flood mitigation scenarios, March 2021 flood

6. Initial assessment of Flood Strategy outcomes

Outcome 9 of the Flood Strategy (Infrastructure NSW, 2017) states that ongoing monitoring and evaluation, reporting and improvement of the Flood Strategy will be undertaken to accommodate changes over time and to ensure that the strategy's actions continue to meet the vision and objective.

As the largest flood in over 30 years, the March 2021 flood provides an opportunity for learning – to assess the effectiveness of initiatives to manage flood risks in the valley, and to consider future needs.

Table 15 presents an initial assessment of the 9 outcomes of the Flood Strategy in relation to the March 2021 flood. It is noted that many agencies with a role in flood risk management have undertaken or are undertaking their own after-action reviews.

The initial assessment shows that Flood Strategy work prior to the flood realised benefits during and following the flood including:

- Expertise and networks across agencies contributed to coordinated response and recovery.
- Flood information and maps prepared as part of the *Hawkesbury-Nepean Valley Regional Flood Study* informed the community and the response.
- Broad flood awareness campaigns and local deep engagement reduced damages.
- The Bureau of Meteorology's flood warning service during the flood benefitted from an updated hydrological model, a deeper understanding of stakeholder needs, and training.
- The response to the flood benefitted from updates to the Hawkesbury Nepean Flood Plan and training exercises.

Extensive data collected after the flood (for example, survey of flood levels – Figure 41) has been used to update and validate the flood models that are used to understand potential floods such as the 1 in 100 chance per year flood.

Figure 41: Surveying March 2021 flood levels to update flood models

Source: Infrastructure NSW. Images: Akhil Sud, Isabelle Testoni

The initial assessment shows that further work is needed including:

- to quantify the social impacts of disasters
- to reduce the flood risk through flood mitigation infrastructure, which would also likely increase insurance affordability
- to reduce and manage the flood risk associated with caravan parks and other low-lying developments
- continuing to help communities to prepare, and maintain preparedness, for flooding
- continuing to enhance the flood warning system through:
    - drawing on the results of the latest hydraulic modelling to update the rating tables (the relationship at a gauge between flows and the height of water corresponding to those flows) used for flood forecasting
    - making available locally understandable flood information during a rising flood
    - adopting best practice communications and messaging
- continuing to improve systems for the timelier issuance of Evacuation Warnings and Orders
- continuing to improve systems for streamlined recovery.

The NSW Government will identify and evaluate the range of issues that have emerged from the March 2021 flood, to increase resilience ahead of future floods.

Table 15: Consideration of Flood Strategy outcomes in relation to March 2021 flood

Flood Strategy Outcome	Comment
1. Coordinated flood risk management	The multi-agency framework established to deliver the Flood Strategy supported coordinated response to and recovery from the March 2021 flood, drawing on networks, relationships, expertise and skillsets across agencies. The flood highlighted the associated hazard of riverbank erosion, and the need for coordinated management. A multi-agency Hawkesbury-Nepean Regional Riverbank Task Group led by Resilience NSW was established to develop and implement appropriate recovery strategies to assist landowners, businesses and communities recover from the disaster. There is also a need for research to deepen understanding of the distribution, types, mechanisms and mitigation of riverbank erosion for a river heavily modified by legacy issues. In line with the Australian Business Roundtable for Disaster Resilience and Safer Communities (Deloitte Access Economics, 2016) and priorities of the National Disaster Risk Reduction Framework (Commonwealth of Australia, 2018), there is a need to capture 'intangible' as well as tangible impacts of disasters, to inform investment decision making. While formal social impact reports are yet to be finalised, social services providers identified significant psychosocial impacts from the flood. Further research is needed into how to quantify the medium and long-term costs of social impacts of disasters.
2. Reduced flood risk in the valley by raising Warragamba Dam wall	Analysis of the March 2021 flood confirms that dam raising would have provided greater peak level reductions than FSL-lowering or pre-releases. Pre-releases would have brought forward closure of downstream river crossings and the onset of minor flooding, making emergency responses before the flood more difficult (see Section 5). Anecdotal reports after the flood suggest relatively high levels of non-insurance and under-insurance for floods due to the prohibitively high costs quoted. This emphasises the need for measures to reduce the risk.
3. Strategic and integrated land use and road planning	The March 2021 flood highlighted the high flood risk to life, property and the environment associated with caravan parks and other developments located below today's flood planning levels, and the need to manage growth in risk including through land use planning and development control. The NSW Government's Flood Prone Land Policy recognises that the primary responsibility for floodplain risk management rests with local councils. In view of the March 2021 flood impacts, councils could consider (1) the appropriateness of settings under their development control plans, and (2) the appropriateness of conditions by which (a) relocatable homes, rigid annexes and associated structures are installed on flood prone land and (b) caravan parks are approved to operate under the *Local Government Act 1993*. The NSW Department of Planning, Industry and Environment is developing a Regional Land Use Planning Framework for land impacted by Hawkesbury-Nepean regional floods. The framework will encompass a strategic approach that better considers flood risk and carefully manages population growth and development in the valley.
4. Accessible contemporary flood risk information	Flood information and maps prepared as part of the *Hawkesbury-Nepean Valley Regional Flood Study* (WMAwater, 2019) helped to inform the Hawkesbury Nepean Flood Plan (SEMC, 2020) and the response to the March 2021 flood. The web mapping portal[17] that displays a selection of maps was also used by the community. The next stage of flood investigations, the Hawkesbury-Nepean River Flood Study being developed by Rhelm and Catchment Simulation Solutions for Infrastructure NSW, is well advanced, and uses a detailed new 2-dimensional model to describe flood extents, depths, velocities and hazard. A significant effort was put into collecting data from the March 2021 flood, which has been used to update and validate the flood models that are used to understand potential floods. The flood confirmed the need for a Colo River Flood Study, which Hawkesbury City Council is developing.

[17] https://www.ses.nsw.gov.au/hawkesbury-nepean-floods/, accessed 10 November 2021

Flood Strategy Outcome	Comment
5. An aware, prepared and responsive community	Anecdotal reports point to the benefit of the Flood Strategy's flood awareness campaigns and messaging over 2019, 2020 and the La Niña summer preceding the March 2021 flood. NSW SES personnel reported hearing a lot less 'I didn't expect this' comments than had previously been heard. The Flood Strategy's focus on helping caravan park managers to understand their flood risk and plan for floods, and the relationships the project fostered between NSW SES units and the parks, helped to empower and connect managers and reduced damages at participating parks. Nonetheless, the flood showed that segments of the impacted population were not prepared for the flood, pointing to the need for further work.
6. Improved weather and flood predictions	The Bureau of Meteorology's flood warning service during the March 2021 flood benefitted from improvements done as part of Pilot Extended Lead Time Flood Forecasting Service for the valley developed under the Flood Strategy. The benefits included an updated hydrological model, a greater understanding of stakeholder requirements, and training. The flood showed that rating tables used for flood forecasting need to be updated to take account of recent changes in the river. Work has commenced to operationalise a Probabilistic Flood Forecast for the valley. The flood highlighted issues with electricity and communications infrastructure in remote parts of the valley, inhibiting the transmission of warnings. The flood also showed the need for an improved end-to-end flood warning service, in which members of the community can more readily translate height predictions and historical flood comparisons at water level recording stations to their homes and workplaces. A multi-agency project is underway to adopt best practice communications and messaging in flood warnings in the Hawkesbury-Nepean Valley.
7. Best practice emergency response and recovery	The response during the March 2021 flood benefitted from work developed under the Flood Strategy, including revision of the Hawkesbury Nepean Flood Plan (SEMC, 2020) and the emergency management test exercise in June 2019 known as Exercise Deerubbin. The flood showed the need for further improvement to systems for the timelier issuance of Evacuation Warnings and Orders. This particular flood highlighted the risk of isolation for thousands of people in communities around North Richmond, given the loss of all road access for a time. Further work is needed to minimise and manage the risk (likelihood and consequences) of such isolations. The ongoing recovery has benefitted from the networks and relationships developed under the Flood Strategy. Nonetheless, the flood revealed a range of lessons for enhanced recovery (Appendix G).
8. Adequate local roads for evacuation	In the March 2021 flood, mass evacuations weren't required. Nonetheless, some local roads were damaged, and remediation is still underway. This could potentially impact evacuation and/or isolation in future floods.
9. Ongoing monitoring and evaluation, reporting and improvement of the Flood Strategy	This report is a product of the monitoring/evaluation/reporting/improvement framework required under Outcome 9.

7. Conclusion

The March 2021 flood was an unusual event. A persistent coastal trough generated rain for over a week and led to two flood peaks in upstream areas. This resulted in a large volume of inflows to Warragamba Dam – the second highest in the dam's 60-year record, translating to a 1 in 40 chance per year inflow volume.

At Windsor and in the lower Hawkesbury River, the March 2021 flood was the highest and first major flood since 1990. At Penrith, it was the highest since 1925. At Windsor and Penrith, the March 2021 flood has an average frequency of 1 in 10 to 20 chance per year.

About 600 dwellings and 300 commercial/industrial buildings (most on rural land) are estimated to have been impacted by the flood. The many caravan parks between Windsor and Gunderman were severely impacted, with over 1400 manufactured homes flooded.

Flooding and riverbank erosion also caused severe damage to local roads, turf farms and vegetable crops.

Coming on the heels of drought, bushfire, the February 2020 flood and storm, and COVID-19, the March 2021 flood is known to have compounded psychosocial impacts on affected communities. This includes already socially vulnerable people.

Various suggestions were made after the flood about how the flooding could have been reduced. A number of Warragamba Dam flood mitigation scenarios were modelled to determine what difference these measures would have made to the height and timing of downstream flooding. Raising Warragamba Dam spillways to create a 14m flood mitigation zone would have provided a significantly larger reduction of downstream flood peaks when compared to the other dam scenarios that were modelled, including pre-releasing water or permanently lowering full supply level.

As the largest flood in over 30 years, the March 2021 flood provides an opportunity for learning – to assess the effectiveness of initiatives to manage flood risks in the valley, and to implement improvements. The flood is being examined with a view to increasing resilience ahead of future, potentially larger events.

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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).
Evacuation Order	When flooding is about to happen and people in the affected area are required to evacuate, the NSW State Emergency Service may issue an Evacuation Order advising people of what to do and where to go.
Evacuation Warning	When flooding is likely to cut evacuation routes or inundate property, the NSW State Emergency Service may issue an Evacuation Warning to indicate people in the affected area should get prepared to evacuate.
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 Bulletin	Communication issued to radio stations by NSW SES to inform people about what is expected to happen during flooding. NSW SES Flood Bulletins contain information on likely flood consequences and what actions are required to protect persons and property.
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 bulletins and 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.
Flood Watch	A Flood Watch is an early advice of increased flood risk over a catchment up to 4 days in advance of large-scale weather systems that have the potential to cause flooding. Flood Watches 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.
Manning's 'n'	Manning's 'n' is an estimate of channel roughness, used in the calculation of flow velocity and discharge. The value of n varies with channel slope, bed material composition, in-stream vegetation and channel sinuosity.
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: 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 C: Images of March 2021 flood

Warragamba Dam spilling, 26 March 2021 (after peak)

Source: Infrastructure NSW. Image: Adam Hollingworth

Floodwaters meet at the confluence of the Warragamba River (bottom left) and Nepean River (right) around 3km downstream of the dam, 22 March 2021 (after peak)

Source: Infrastructure NSW. Image: Top Notch Video

Looking southeast across the Nepean River to homes in Bellevue Road Regentville, 2:39pm 21 March 2021

Source: Infrastructure NSW. Image: Adam Hollingworth

Backwater flooding in Peach Tree Creek and Ladbury Avenue Penrith, 6:37pm 21 March 2021

Source: Infrastructure NSW. Image: Adam Hollingworth

View west across Nepean River and backwater flooding in Peach Tree Creek Penrith, 6:38pm 21 March 2021

Source: Infrastructure NSW. Image: Adam Hollingworth

View downstream to Victoria Bridge Penrith, 6:12pm 21 March 2021 (near peak)

Source: Infrastructure NSW. Image: Adam Hollingworth

View downstream to Victoria Bridge Penrith, 6:15pm 21 March 2021 (near peak)

Source: Infrastructure NSW. Image: Adam Hollingworth

Looking south along the Nepean River which stayed largely within banks at Penrith, 11:30am 21 March 2021

Source: Infrastructure NSW. Image: Adam Hollingworth

Nepean River floodwaters flowed in and out of the Wildlife Lake at Penrith Lakes, 23 March 2021 (after peak)

Source: Infrastructure NSW. Image: Top Notch Video

Inundated recreation area, Springwood Road near Lynches Creek, Yarramundi, 4:42pm 21 March 2021 (near peak)

Source: Infrastructure NSW. Image: Top Notch Video

Floodwaters meet at the confluence of the Nepean River (left) and Grose River (right), Yarramundi, 5:07pm 21 March 2021 (near peak)

Source: Infrastructure NSW. Image: Adam Hollingworth

View west along flooded Springwood Road approach to Yarramundi Bridge, 4:38pm 21 March 2021 (near peak)

Source: Infrastructure NSW. Image: Adam Hollingworth

View west across flooded Cornwallis (left foreground), Richmond Lowlands (left distance), Freemans Reach (right), 24 March 2021 (near peak)

Source: Australian Defence Force. Image: Robert Plath. © Commonwealth of Australia 2021

View west across flooded Rickabys Creek towards RAAF Base Richmond and flooded Richmond Lowlands, 24 March 2021 (near peak)

Source: Australian Defence Force. Image: Robert Plath. © Commonwealth of Australia 2021

View north across flooded Butterfly Farm, Windsor Riverside Van Park and Australiana Pioneer Village, Wilberforce, 24 March 2021 (near peak)

Source: Australian Defence Force. Image: Robert Plath. © Commonwealth of Australia 2021

Looking southeast across flooded Windsor Bridge towards South Creek, 7:20am, 25 March 2021 (after peak, when flood level was ~12.0m at Windsor)

Source: Infrastructure NSW. Image: Top Notch Video

Debris against new Windsor Bridge, 26 March 2021 (2 days after peak)

Source: Infrastructure NSW. Image: Adam Hollingworth

Flooded caravan park and house, Pitt Town Bottoms, 9:20am, 25 March 2021 (after peak)

Source: Infrastructure NSW. Image: Top Notch Video

River Road east of Cliftonville Lodge, Lower Portland, 11:58am, 24 March 2021 (just after peak)

Source: Infrastructure NSW. Image: S. Yeo

View across Hawkesbury River towards Webbs Creek, 22 March 2021 (before peak)

Source: Infrastructure NSW. Image: Top Notch Video

Lower Macdonald, 11:30am, 24 March 2021 (just after peak)

Source: NSW Police. Image: William Andrews

Wisemans Ferry, 11:28am, 24 March 2021 (just after peak)

Source: NSW Police. Image: William Andrews

Wisemans Ferry, 11:28am, 24 March 2021 (just after peak)

Source: NSW Police. Image: William Andrews

Serpentine bends at Gunderman and Singletons Mill, 26 March 2021 (2 days after peak)

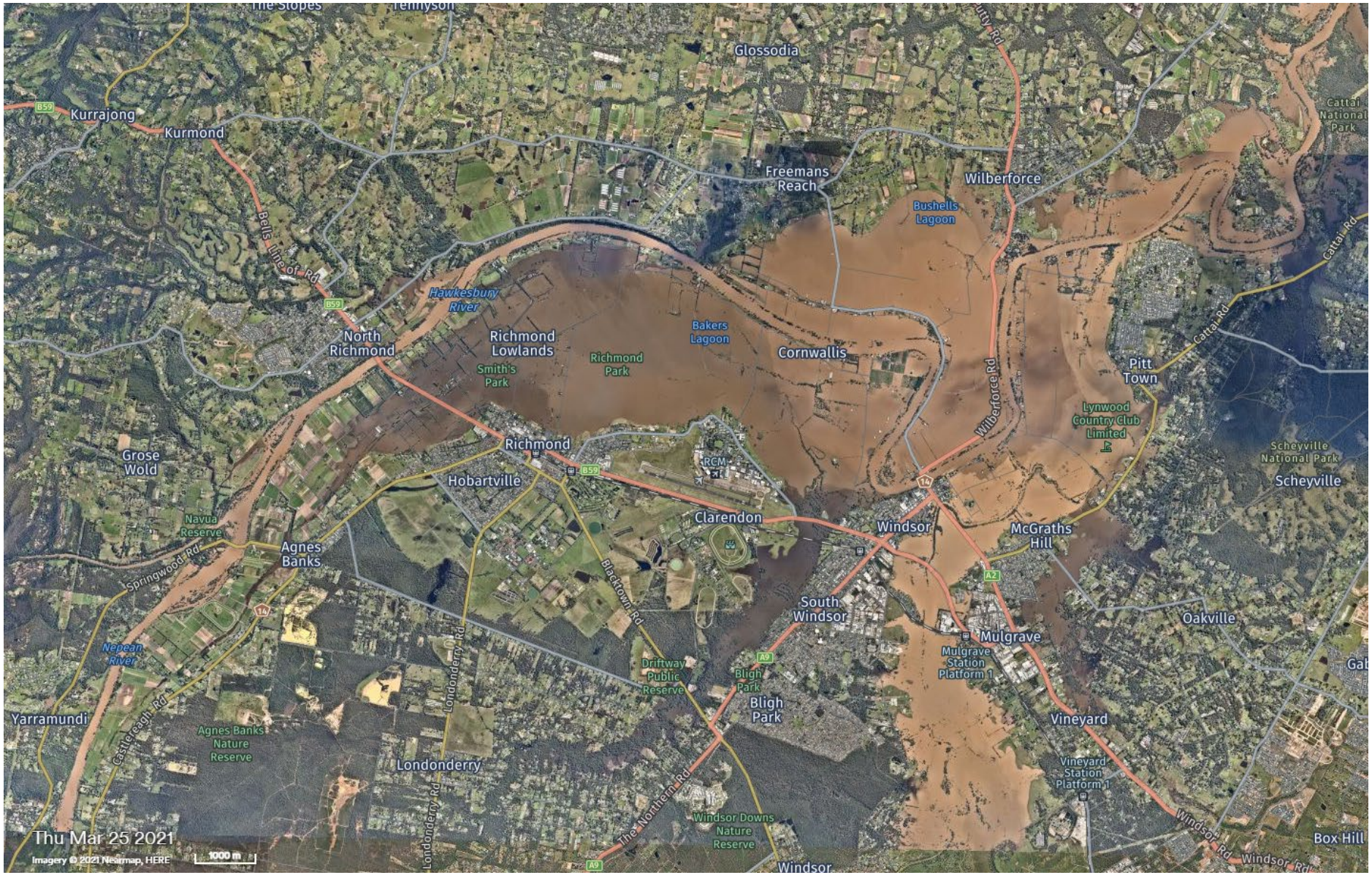
Source: Infrastructure NSW. Image: Adam Hollingworth

Windsor, east of Bridge Street, 24 March 2021 (near peak)

Source: Spatial Services

Southern side of McGraths Hill, 24 March 2021 (near peak)

Source: Spatial Services



Yarramundi to Cattai, 25 March 2021 (after peak)

Source: Nearmap

Freemans Reach to Cumberland Reach, 25 March 2021 (after peak)

Source: Nearmap

Windsor area, 25 March 2021 (after peak)

Source: Nearmap

Appendix D: Images of riverbank erosion after March 2021 flood

Rotational slip, straight reach, Pitt Town Bottoms, 3 April 2021

Source: Infrastructure NSW. Image: S. Yeo

Rotational slip, straight reach, Pitt Town Bottoms, 3 April 2021

Source: Infrastructure NSW. Image: S. Yeo

Rotational slip, straight reach, Pitt Town Bottoms, 3 April 2021

Source: Infrastructure NSW. Image: S. Yeo

Rotational slip, outside of meander bend, Wilberforce (opposite Halls Point), 3 April 2021

Source: Infrastructure NSW. Image: S. Yeo

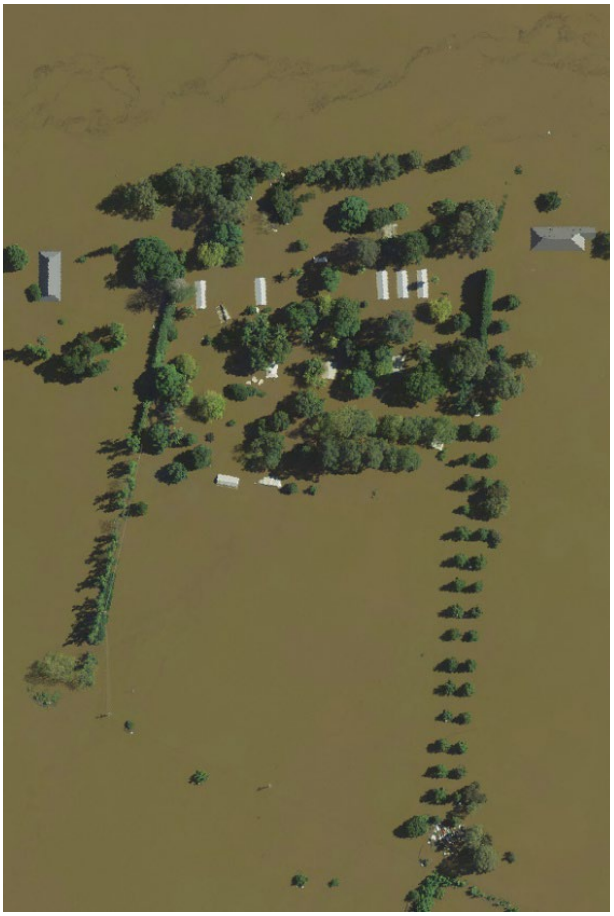
Rotational slip, outside of meander bend, Wilberforce (opposite Halls Point), 3 April 2021

Source: Infrastructure NSW. Image: S. Yeo

Appendix E: Images of flooded Hawkesbury caravan parks, March 2021 flood

Windsor Riverside Van Park, Wilberforce, 24 March 2021 (near peak)

Source: Spatial Services, extracted 14 July 2021



Hawkesbury Riverside Tourist Park, Pitt Town Bottoms, 24 March 2021 (near peak)

Source: Spatial Services, extracted 14 July 2021

Percy's Place Caravan Park, Pitt Town, 24 March 2021 (near peak)

Source: Infrastructure NSW. Image: Top Notch Video

Riverside Ski Park, Cattai, 24 March 2021 (near peak)

Source: Spatial Services, extracted 14 July 2021

Kallawatta Ski Gardens, Ebenezer, 24 March 2021 (near peak)

Source: Spatial Services, extracted 14 July 2021

Hawkesbury Waters Leisure Park, Ebenezer, 24 March 2021 (near peak)

Source: Spatial Services, extracted 14 July 2021

Pacific Park Water Ski Gardens and Motorbike Park, South Maroota, 23 March 2021 (before peak)

Source: Pacific Park Motorcycle Park Facebook page

Sackville Ski Gardens, Sackville, 24 March 2021 (near peak)

Source: Spatial Services, extracted 14 July 2021

Ulinbawn Ski Park, Sackville North, about 11:30am 24 March 2021 (near peak)

Source: Ulinbawn Facebook page

Caradon Leisure Park, Sackville North, 24 March 2021 (near peak)

Source: Spatial Services, extracted 14 July 2021

Bundarra Ski Gardens, Cumberland Reach, 24 March 2021 (near peak)

Source: Spatial Services, extracted 14 July 2021

Dargle Water Ski Resort, Lower Portland, 24 March 2021 (near peak)

Source: Spatial Services, extracted 14 July 2021

View north across Ponderosa Ski Resort (foreground) and Cornelia Water Ski Park (midground), Lower Portland, morning of 23 March 2021 (before peak)

Source: Cornelia Water Ski Park Facebook page. Image: Benjamin Whitehurst

Hawkesbury Riverside Retreat, Lower Portland, 24 March 2021 (near peak)

Source: Spatial Services, extracted 14 July 2021

St George Caravan Park, Lower Portland, 26 March 2021 (2 days after peak)

Source: Infrastructure NSW. Image: Adam Hollingworth

DML Gardens (bottom left) and Childs Play Marine (Newall's) (top right), Lower Portland, 24 March 2021 (near peak)

Source: Spatial Services, extracted 14 July 2021

Mt Andrew Caravan Park, Lower Portland, 24 March 2021 (near peak)

Source: Spatial Services, extracted 14 July 2021

Riviera Ski Gardens, Lower Portland, 24 March 2021 (near peak)

Source: Spatial Services, extracted 14 July 2021

Leetsvale Caravan Park, Leets Vale, 26 March 2021 (2 days after peak)

Source: Infrastructure NSW. Image: Adam Hollingworth

Torrens Water Ski Gardens, Wisemans Ferry, 24 March 2021 (near peak)

Source: Spatial Services, extracted 14 July 2021

Carinya Ski Ranch, Wisemans Ferry, 12:18pm, 24 March 2021 (just after peak)

Source: NSW Police
Image: William Andrews

Del Rio Riverside Resort, Webbs Creek, 12:17pm, 24 March 2021 (just after peak)

Source: NSW Police
Image: William Andrews

Looking northeast across Koveda Holiday Park (centre) and NSW Ski Gardens (top right), Wisemans Ferry, 26 March 2021 (2 days after peak)

Source: Infrastructure NSW. Image: Adam Hollingworth

Rosevale Caravan Park, Gunderman, 26 March 2021 (2 days after peak)

Source: Infrastructure NSW. Image: Adam Hollingworth

Riverlands Caravan Park, Gunderman, 24 March 2021 (near peak)

Source: Spatial Services, extracted 14 July 2021

Appendix F: Flood modelling of Warragamba Dam flood mitigation options

Memorandum

TO:	Infrastructure NSW
FROM:	WMAwater, Rhelm, Catchment Simulation Solutions
DATE:	10 November 2021
SUBJECT:	March 2021 Hawkesbury-Nepean Flood Scenario Modelling

1. INTRODUCTION

In February 2020, Rhelm and Catchment Simulation Solutions (CSS) were engaged by Infrastructure NSW to develop the Hawkesbury-Nepean River Flood Study, which was well advanced at the time of the March 2021 flood. The flood study has involved development and calibration of detailed hydrologic and hydraulic flood models to understand flooding downstream of Warragamba Dam.

These tools have been used 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 2021 event.

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 level upstream of the proposed raised dam.

2. METHODOLOGY

The following steps were taken:

- calculate Warragamba Dam outflows and inflows for the existing dam (WMAwater)
- validate hydrologic model developed for flood study (Rhelm/CSS)
- validate hydraulic model developed for flood study (Rhelm/CSS)
- calculate Warragamba Dam outflows for various flood mitigation scenarios (WMAwater)
- model flood behaviour of various flood mitigation scenarios (Rhelm/CSS)
- assess downstream impacts of the various flood mitigation scenarios (WMAwater, INSW)
- model peak flood level upstream of proposed raised dam (WMAwater).

These steps are described below.

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 F1).

Figure F1. 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.

Analysis of the flood suggested that the accepted calculation of discharges at relatively shallow heights over the central drum gate could under-report actual flows. The discharge of the drum gate was historically calculated using a rating curve set at 1m intervals. To improve the outflow calculation, the drum gate discharge was calculated using a weir flow equation which, once checked against the stage discharge relationship, was able to provide more accurate flows between full supply level (116.72m AHD) and 118m AHD.

The outflow hydrograph was 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 are shown on Figure F2. The peak outflow of 5069 m^3/s was reached at 4:45pm on 21 March 2021.

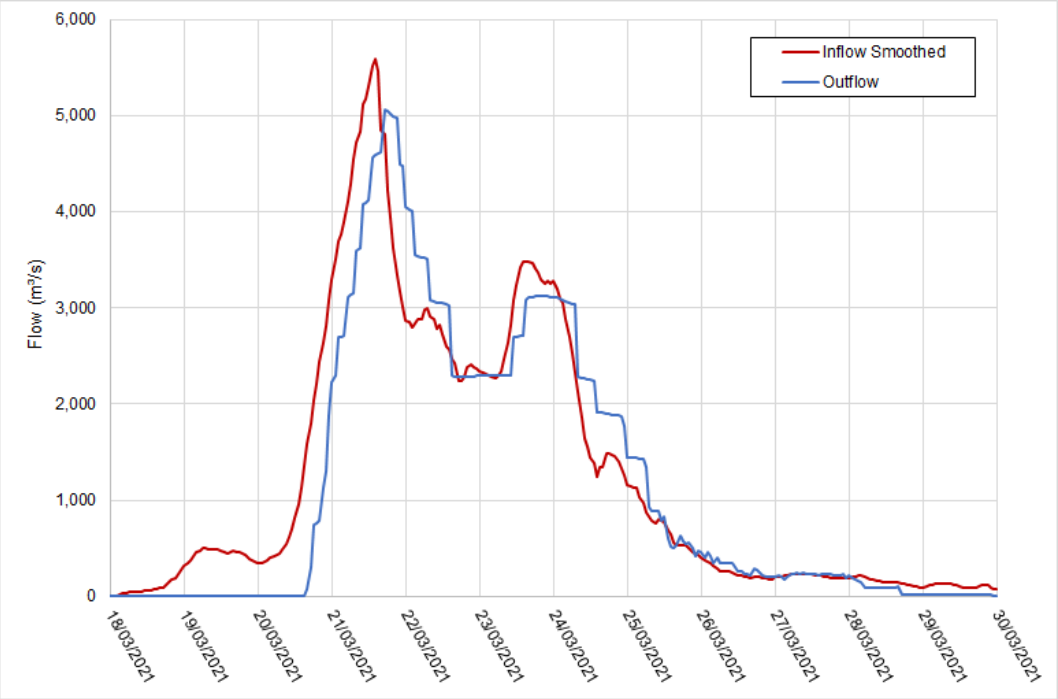


Figure F2: Warragamba Dam inflow and outflow hydrographs, March 2021 flood

2.1.1 Historical context at Warragamba Dam

Compared to historical floods since Warragamba Dam was completed in 1960, the March 2021 flood was an unusual event. The most unusual aspect of this event was that it had 2 distinct peaks (Figure F2).

Table F1 lists key characteristics.

Table F1: Historic 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 (m³/s)	AEP (1 in X)	Rank since 1960	Total Inflow Volume (GL)	AEP (1 in X)*	Rank since 1960
1867#				19593	330		2629	560	
Nov-61	119.51	37	1	11033	40	1	1418	49	1
Jun-64	118.89	26	2	9322	27	3	1012	24	5
Jun-75	118.15	12	5	7293	16	5	710	14	6
Mar-78	118.01	10	7	9644	29	2	1212^	34^	3
Apr-88	118.06	10	6	7143	15	6	602	11	7
Aug-90	118.72	23	3	8817	23	4	1086	28	4
Mar-21	118.25	13	4	5591	9	7	1299	40	2

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 historic 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 March 2021 event is the fourth highest on record (Table F1 peak dam level rank). The peak level drives the rate of outflow through the gated spillway.

The March 2021 peak inflow ranks fairly low (seventh since 1960) (Table F1 peak dam inflow rank).

However, due to its double-peaked nature, the March 2021 event is much higher in terms of total inflow volume (ranked second since 1960 – see Table F1 total dam inflow rank, Figure F3).

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 flood having a peak inflow to the dam of approximately 1 in 9 AEP (Annual Exceedance Probability – see glossary at Appendix A), but a total inflow volume to the dam of 1 in 40 AEP (Table F1).

The peculiarity of this combination in the historical record since 1960 is illustrated in Figure F4. The unusual combination of very high volume for the relatively low peak flow also stands out in the context of the full range of 19,500 simulated model events.

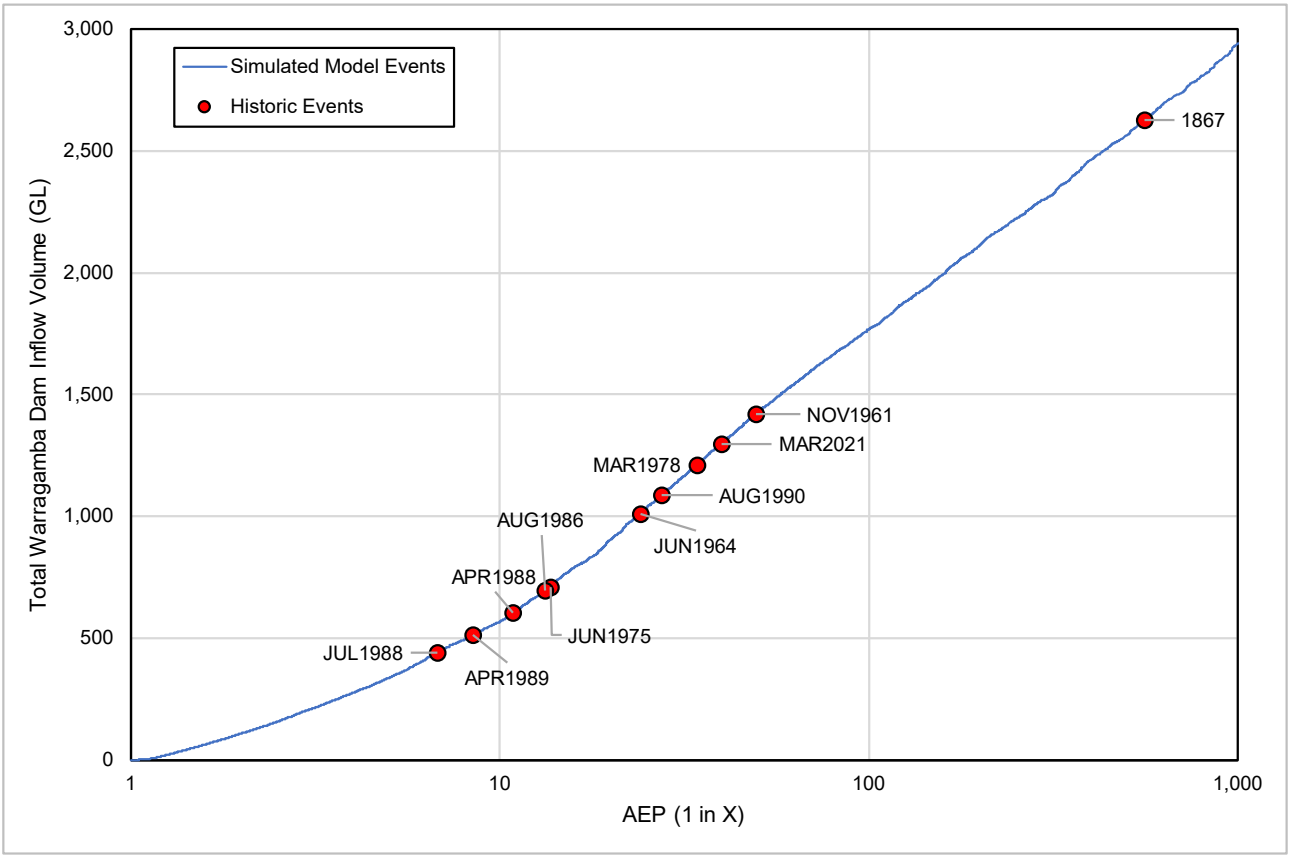


Figure F3: Warragamba Dam total inflow volume, historic and modelled

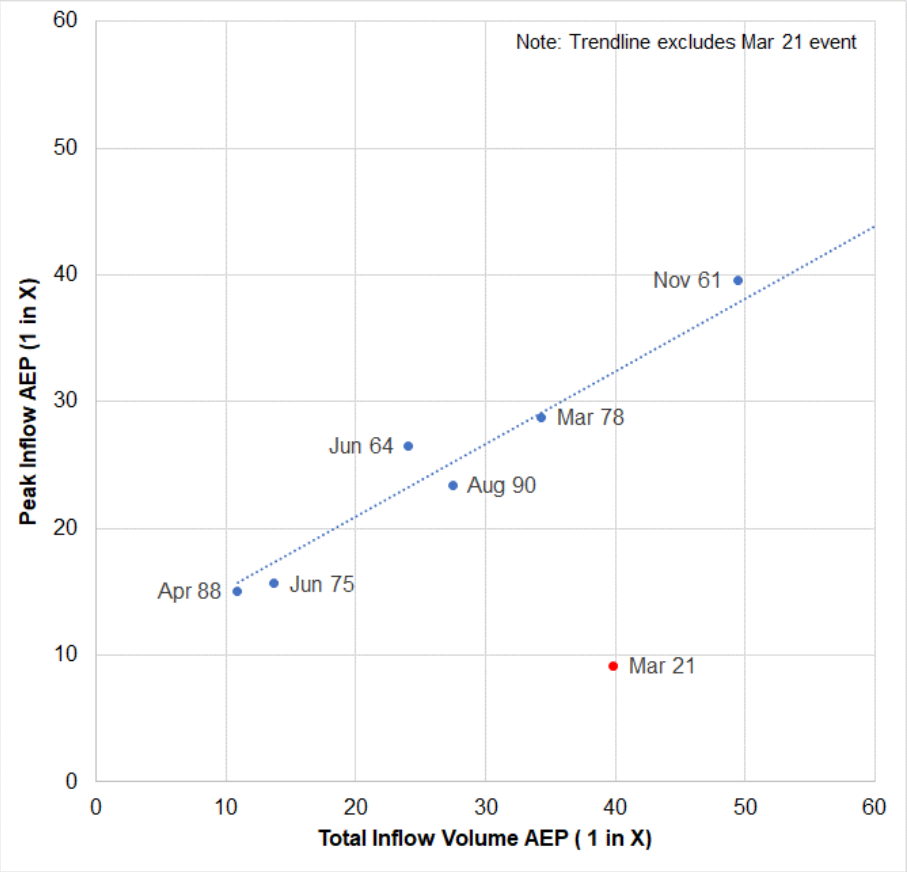


Figure F4: Warragamba Dam peak inflow vs total inflow volume frequency, historic events

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 was calibrated to 8 historic floods (2020, 1998, 1990, 1988, 1986, 1978, 1975 and 1964). The March 2021 flood has been used to validate the hydrologic model, as follows:

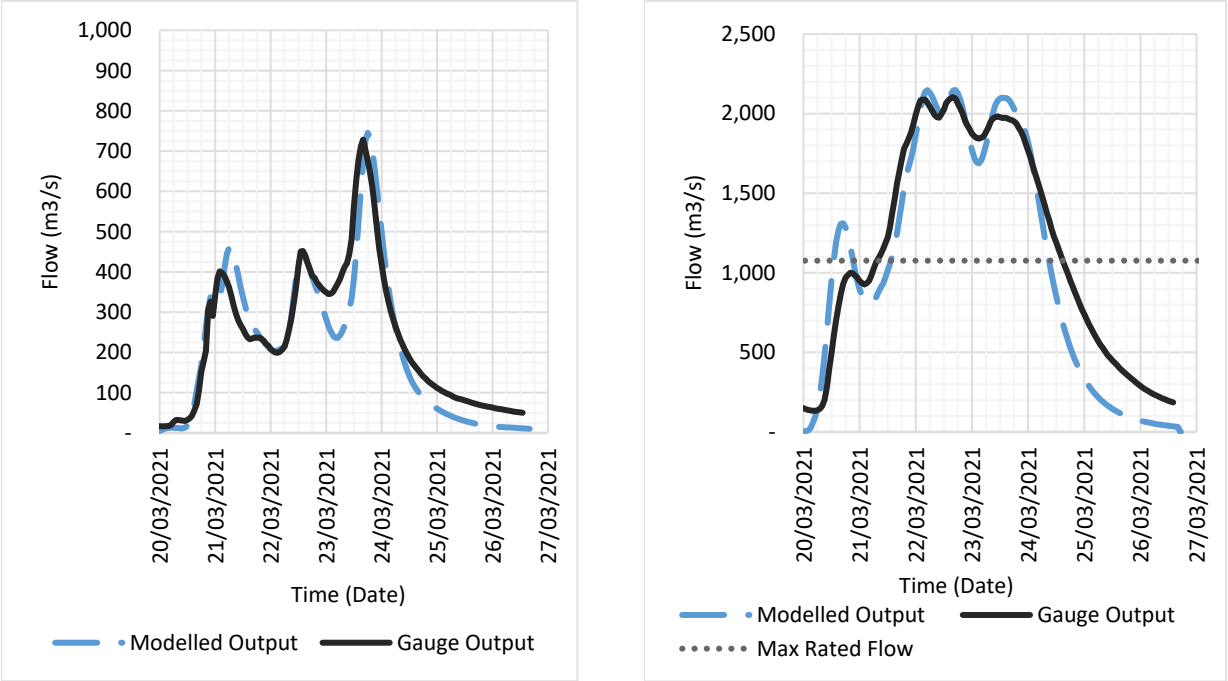
- model setup – update the model to reflect March 2021 rainfall and the starting water levels in the upper Nepean Dams
- model losses – iteratively modify the initial and continuing rainfall losses within acceptable ranges to achieve a reasonable comparison with the gauged flow data
- review – review 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 intensity 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 2021 flood. Two examples of hydrographs are provided in Figure F5.



a. Nepean River at Maldon Weir

b. Colo River at Upper Colo

Figure F5. Example observed and modelled flow hydrographs, March 2021 flood

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).

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 was calibrated to 8 historic floods (2020, 1990, 1988, 1986, 1978, 1975, 1964 and 1961). The March 2021 flood has been used to validate the hydraulic model, as follows:

- capture a large amount of flood information including surveyed flood peak levels
- remove the old Windsor Bridge from the model
- modify the ‘roughness’ representation of trees in the model
- review the results by comparing modelled flood hydrographs to observed flood hydrographs.

Figure F6 and Figure F7 show the observed and modelled river height hydrographs at Penrith and Windsor. Table F2 shows the observed and modelled peak levels at Penrith and Windsor.

The hydraulic model provides a good representation of the observed flood hydrographs and is therefore suitable for the subsequent assessment of flood mitigation options.

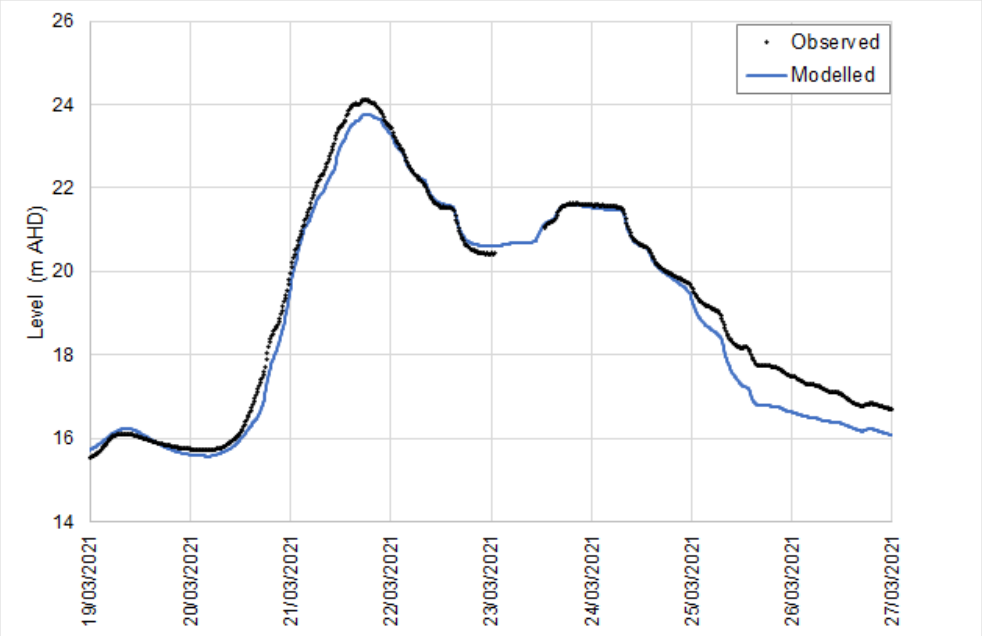


Figure F6: Observed and modelled stage hydrographs, Penrith, March 2021 flood

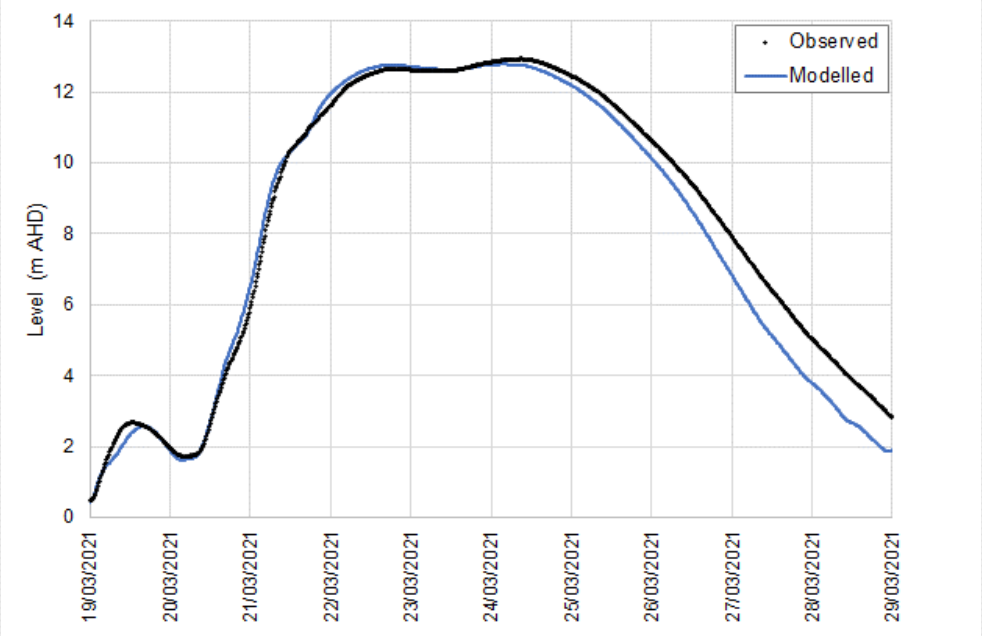


Figure F7: Observed and modelled stage hydrographs, Windsor, March 2021 flood

Table F2: Peak level comparison

	Penrith		Windsor	
	1st peak	2nd peak	1st peak	2nd peak
Observed level	24.13m AHD	21.63m AHD	12.66m AHD	12.93m AHD
Modelled level	23.78m AHD	21.61m AHD	12.77m AHD	12.78m AHD
Difference	-0.35m	-0.02m	+0.11m	-0.15m

2.4 Warragamba Dam outflows for mitigation options

Several Warragamba Dam flood mitigation options were assessed. These were compared with the operation of the existing dam as the base case.

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 reducing FSL by:
    - 5m
    - 12m
- pre-releasing stored water ahead of a flood at a rate of 100GL/d at different starting times:
    - 10am on 18 March 2021
    - 9am on 19 March 2021.

The calculated inflow hydrograph for Warragamba Dam in March 2021 (Figure F2) was adopted for the modelling of the scenarios.

Each scenario produced a different outflow hydrograph from Warragamba Dam, as presented in Figure F8. The different times of the start of outflows are listed in Table F3.

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

Table F3: Time of start of outflows from Warragamba Dam with various flood mitigation scenarios

Scenario	Start of outflow*
100GL/d pre-release starting 10am on 18 March	18 March 10am
100GL/d pre-release starting 9am on 19 March	19 March 9am
Existing Dam	20 March 4pm
FSL -5m	21 March 1pm
FSL -12m	23 March 5am
WD +14m	24 March 8am

* Outflows exceeding 50 m^3/s

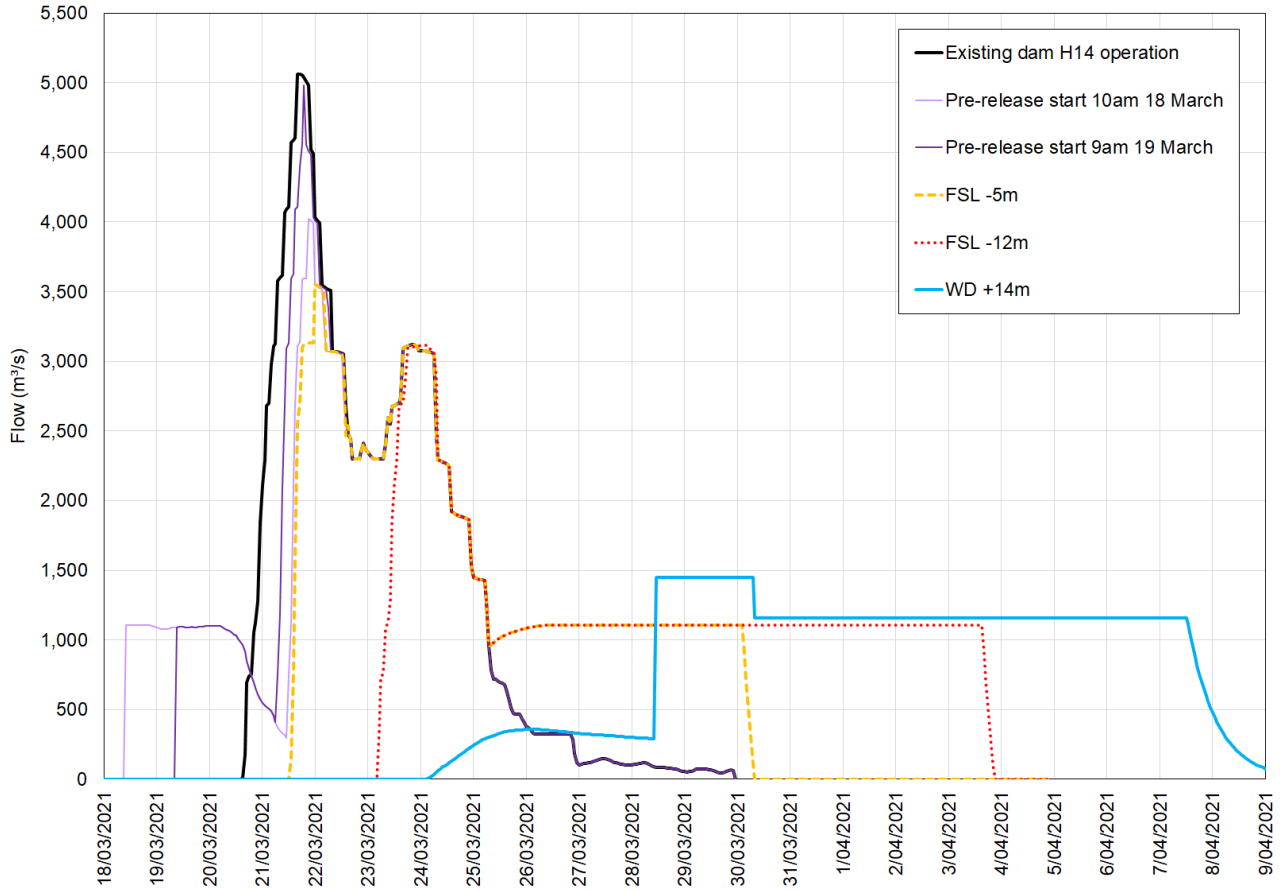


Figure F8: Warragamba Dam outflow for various scenarios, March 2021 flood

2.4.1 Pre-releases

Pre-releases are intended to increase the available volume of storage 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, such as inundation of key downstream bridges and low-lying lands. This modelling exercise adopted pre-release rates to avoid exceeding a total flow rate of 100 GL/d in the Nepean River below the dam.

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. Prior to 19 March, there was insufficient certainty of forecast information to know that major flooding was going to occur, so dam operators would not have had confidence that water supply lost through pre-releases would have been replaced.[18]

Nonetheless, a pre-release commencing on 18 March has been modelled as a purely hypothetical scenario. This pre-release was assumed to commence at 10am based on the Bureau of Meteorology update being released at 9am. The Bureau released flood predictions at 8am on 19 March so the pre-release scenario is modelled to commence at 9am on that day.

[18] 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 5m to 111.72m AHD would create about 360 GL of air space, while lowering FSL by 12m 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. The 12m-lowering option would require the construction of flood mitigation zone outlets in order to maintain the proposed flood mitigation zone.

Both scenarios were modelled using the same H14 protocol that is used for the existing dam, then as floodwaters downstream fall, the flood mitigation zones were emptied to avoid exceeding a total flow rate of 100 GL/d in the Nepean River. This approach to emptying the flood mitigation zones created by lowering FSL is simplified because it overestimates the rate at which floodwaters could be discharged through the current gates for the -12m scenario.

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. As Figure F8 shows, the largest outflow from the raised dam would occur on 28 – 30 March, when the flood mitigation zone is being drawn down and other tributaries have nearly returned to normal flow conditions.

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 flood mitigation scenarios would have made.

2.6 Assess downstream impacts of mitigation options

A number of representative downstream impacts have been considered for the comparison of options.

The results are described in terms of the impact the various scenarios would have on the level and timing of the flood peak at Penrith (Section 3.1) and Windsor (Section 3.2). The peak flood level drives the depth of inundation, which is the main determinant of flood damages. The timing of the flood peak is important for managing evacuations.

The impacts of the various scenarios on flood classifications at Penrith and Windsor are also described. 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.

The impact on the timing of inundation of key river crossings is described in Section 3.3.

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) has been used to model inflows from the tributaries. The calibration and validation of this model using 7 historic 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 has been 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 2021 event. The results are described in Section 3.4.

3. RESULTS

This section presents the assessment of the impacts the various Warragamba Dam flood mitigation measures would have had on flooding in March 2021.

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 F4. The flood hydrographs for the different scenarios are presented in Figure F9.

The proposed raised dam would reduce flood peaks at Penrith by more than 5.0m, compared to reductions of 2.3m and 1.6m for the options to lower FSL by 12m or 5m, respectively.

The assessed pre-releases provide less reduction of downstream peaks, due to the difficulty of creating significant volume in the dam storage through pre-releases. The drawdown below the current Warragamba Dam FSL that would be made through pre-releases is set out in Table F5. This shows that even the early pre-release on 18 March – not feasible given the dam's function as a water supply dam – would result in an additional drawdown below the starting level of around 2m (totalling 3m below FSL).

Table F4 also reports the delay to the peak in hours. This represents the difference in time at which the maximum level is reached between the different scenarios. A positive value indicates the peak level arrived after the peak for the modelled existing dam base case. A negative value indicates the peak arrived before the peak for the modelled existing dam base case.

Almost all mitigation options delay the peak. One exception is for the raised dam. Because there is no outflow from Warragamba Dam until much later (24 March – see Table F3), the much-reduced peak at Penrith for the raised dam scenario is wholly driven by the upper Nepean flows, which arrive earlier in the event.

In the other scenarios, the upper Nepean flows are surpassed by the Warragamba outflows, so the peak for those scenarios is still Warragamba-driven, albeit delayed.

Table F4: Penrith reduction in flood peak for various flood mitigation scenarios

Modelled Scenario	Reduction in peak (m)	Delay in peak (hrs)
Existing Dam	-	-
WD +14m	-5.3	-1
FSL -12m	-2.3	53
FSL -5m	-1.6	10
100GL/d pre-release starting 10am on 18 March	-1.1	6
100GL/d pre-release starting 9am on 19 March	-0.3	2

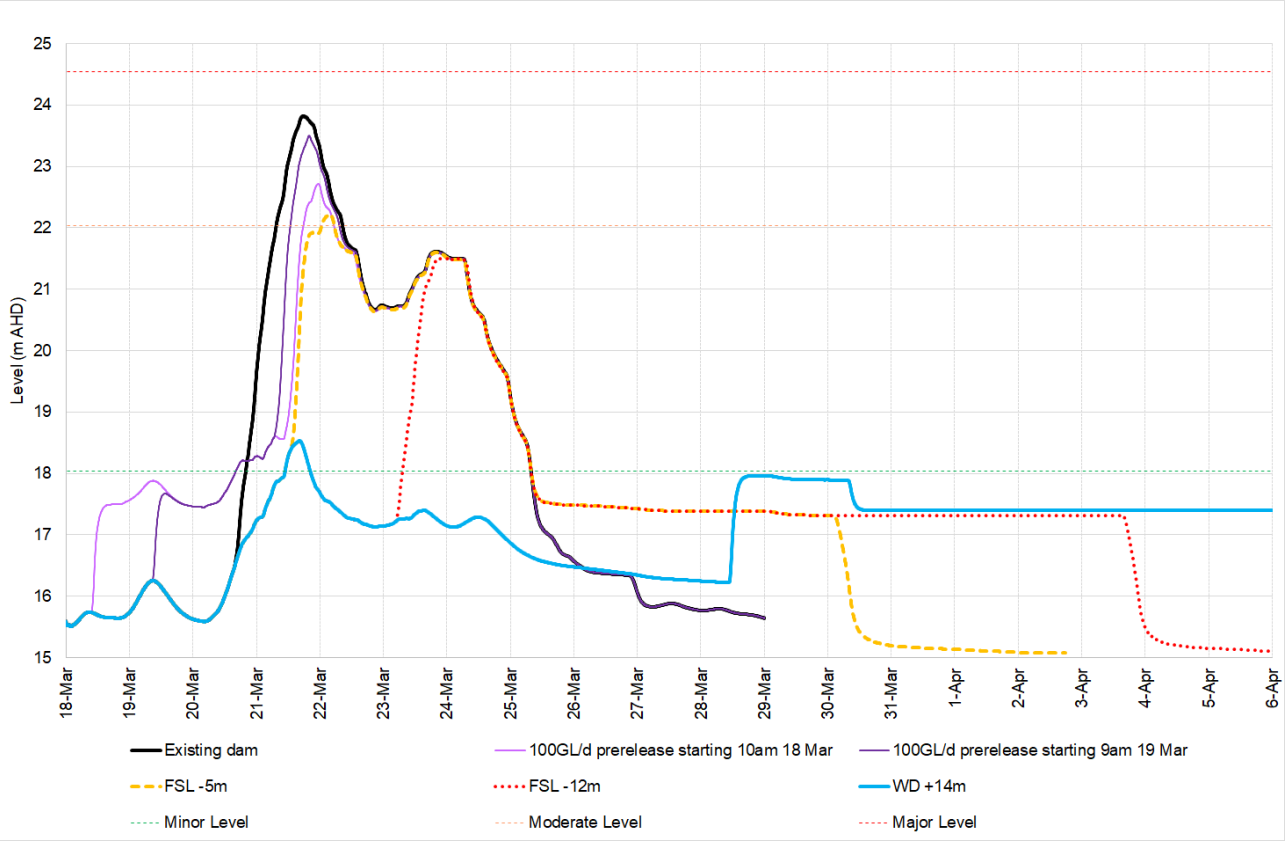


Figure F9: Penrith level hydrograph for various flood mitigation scenarios, March 2021 flood

Table F5: Drawdown in Warragamba Dam resulting from various pre-release scenarios

Starting drawdown	Minimum dam water level (m AHD)	Difference to existing (additional drawdown)	Difference to FSL (total drawdown)
Existing Dam - actual	115.73	-	-0.99
100GL/d pre-release starting 10am on 18 March	113.89	-1.84	-2.83
100GL/d pre-release starting 9am on 19 March	115.15	-0.58	-1.57

3.1.2 Flood classifications

The March 2021 flood peaked at Penrith in the moderate range. Two scenarios – the proposed raised dam and lowering FSL by 12m – would have reduced the flood peak to the minor range and delayed the minor level being reached by about 15 hours (Table F6, Table F7). Pre-releases would have slightly brought forward the times at which the minor flood level was reached.

Table F6: Flood categorisation for various flood mitigation scenarios at Penrith

Modelled Scenario	Flood category
Existing Dam	Moderate
WD +14m	Minor
FSL -12m	Minor
FSL -5m	Moderate
100GL/d pre-release starting 10am on 18 March	Moderate
100GL/d pre-release starting 9am on 19 March	Moderate

*Table F7: Penrith **minor** flood level statistics for various flood mitigation scenarios*

Modelled Scenario	Time reached	Delay to reach (hrs)
Existing Dam	20/3/2021 20:00	-
WD +14m	21/3/2021 10:50	15
FSL -12m	21/3/2021 10:50	15
FSL -5m	21/3/2021 10:50	15
100GL/d pre-release starting 10am on 18 March	20/3/2021 16:10	-4
100GL/d pre-release starting 9am on 19 March	20/3/2021 16:10	-4

* Minor flood level at Penrith is 18.039m AHD

*Table F8: Penrith **moderate** flood level statistics for various flood mitigation scenarios*

Modelled Scenario	Time reached	Delay to reach (hrs)
Existing Dam	21/3/2021 07:20	-
WD +14m	Level not reached	Level not reached
FSL -12m	Level not reached	Level not reached
FSL -5m	22/3/2021 00:40	17
100GL/d pre-release starting 10am on 18 March	21/3/2021 17:40	10
100GL/d pre-release starting 9am on 19 March	21/3/2021 12:40	5

* Moderate flood level at Penrith is 22.039m AHD

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 F9. The flood hydrographs for the different scenarios are presented in Figure F10.

The proposed raised dam would have reduced flood peaks at Windsor by around 3.4m, compared to reductions of 1.9m and 0.6m for the options to lower FSL by 12m or 5m, respectively. The relative ineffectiveness of pre-releases reflects the small volume of storage that pre-releases are able to provide (Table F5).

Table F9: Windsor reduction in flood peak for various flood mitigation scenarios

Modelled Scenario	Reduction in peak (m)	Delay in peak (hrs)
Existing Dam	-	-
WD +14m	-3.4	-53*
FSL -12m	-1.9	13
FSL -5m	-0.6	6
100GL/d pre-release starting 10am on 18 March	-0.4	6
100GL/d pre-release starting 9am on 19 March	-0.2	3

* The raised dam mitigates flows from the Warragamba catchment so the peak downstream is largely generated by Nepean and local tributary flows, which brings it forward, although it is 3.4m lower.

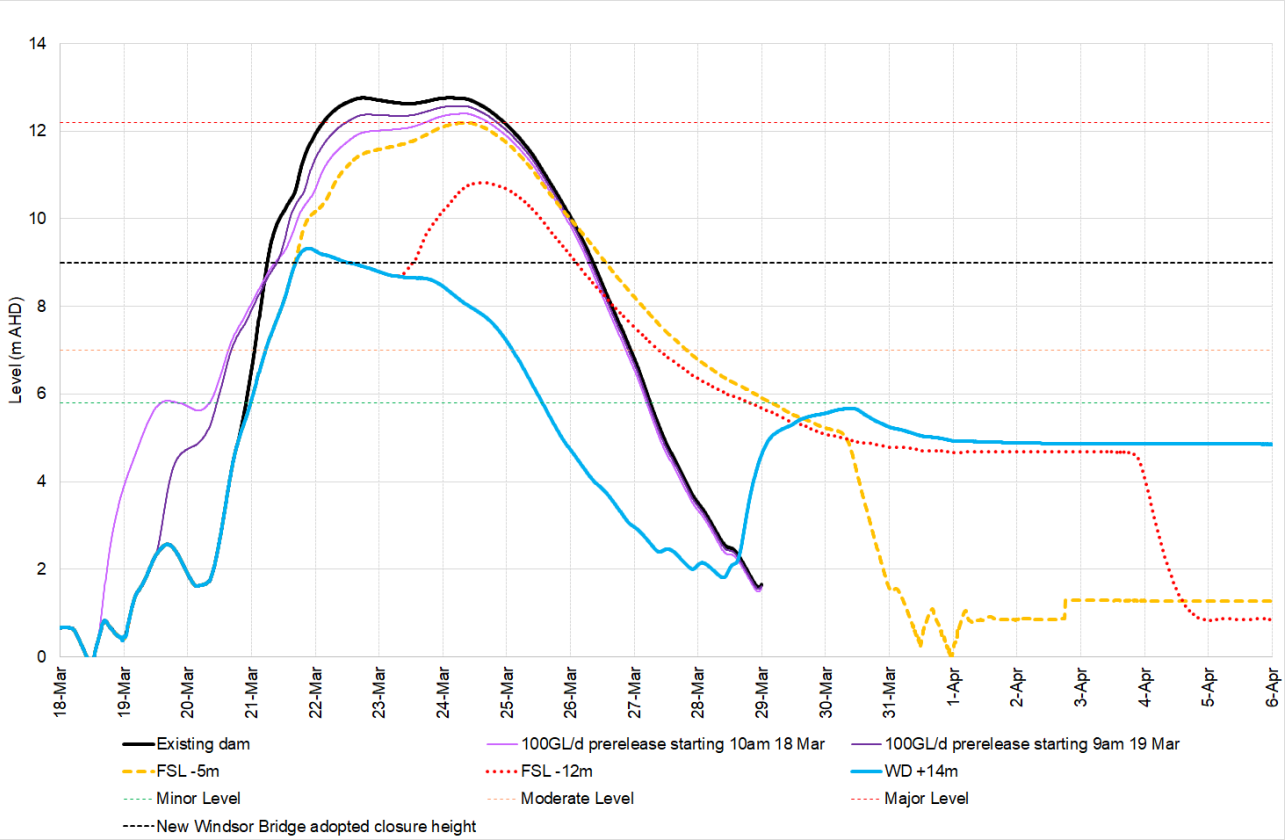


Figure F10: Windsor level hydrograph for various flood mitigation scenarios, March 2021 flood

3.2.2 Flood classifications

The March 2021 flood peaked at Windsor as a major flood. The dam raising and 12m FSL-lowering options would have reduced the flood to the moderate range (Table F10).

The salient feature of Table F11 and Table F12 is how pre-releases would have brought forward minor and moderate flooding at Windsor. The threshold for minor flooding would have been reached about half a day earlier with the most feasible pre-release scenario (starting 19 March), or about 1½ days earlier with pre-releases starting on 18 March. 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.

Table F13 shows that the most feasible pre-releases would have slightly delayed the timing at which the major flood level at Windsor was reached.

Table F10: Flood categorisation for various flood mitigation scenarios at Windsor

Modelled Scenario	Flood category
Existing Dam	Major
WD +14m	Moderate
FSL -12m	Moderate
FSL -5m	Major
100GL/d pre-release starting 10am on 18 March	Major
100GL/d pre-release starting 9am on 19 March	Major

*Table F11: Windsor **minor** flood level statistics for various flood mitigation scenarios*

Modelled Scenario	Time reached	Delay to reach (hrs)
Existing Dam	20/3/2021 21:50	-
WD +14m	20/3/2021 23:40	1.8
FSL -12m	20/3/2021 23:40	1.8
FSL -5m	20/3/2021 23:40	1.8
100GL/d pre-release starting 10am on 18 March	19/3/2021 13:50	-32
100GL/d pre-release starting 9am on 19 March	20/3/2021 10:50	-11

* Minor flood level at Windsor is 5.8m AHD

*Table F12: Windsor **moderate** flood level statistics for various flood mitigation scenarios*

Modelled Scenario	Time reached	Delay to reach (hrs)
Existing Dam	21/03/2021 01:10	-
WD +14m	21/03/2021 05:10	4
FSL -12m	21/03/2021 05:10	4
FSL -5m	21/03/2021 05:10	4
100GL/d pre-release starting 10am on 18 March	20/03/2021 15:10	-10
100GL/d pre-release starting 9am on 19 March	20/03/2021 16:20	-9

* Moderate flood level at Windsor is 7.0m AHD

*Table F13: Windsor **major** flood level statistics for various scenarios*

Modelled Scenario	Time reached	Delay to reach (hrs)
Existing Dam	22/03/2021 02:50	-
WD +14m	Level not reached	Level not reached
FSL -12m	Level not reached	Level not reached
FSL -5m	24/03/2021 08:50	54
100GL/d pre-release starting 10am on 18 March	23/03/2021 17:20	39
100GL/d pre-release starting 9am on 19 March	22/03/2021 11:40	9

* Major flood level at Windsor is 12.2m AHD

3.3 Downstream river crossings

Tables F14, F15 and F16 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 March 2021 flood assessment, there is little to no delay to closure times with a raised dam or FSL-lowering.

On the other hand, pre-releases would bring forward all these closures and the potential isolation of communities on the western and northern sides of the river.

Table F14: Yarramundi Bridge closure statistics for various scenarios

Modelled Scenario	Time reached*	Delay to reach (hrs)
Existing Dam	20/3/2021 15:30	-
WD +14m	20/3/2021 15:30	0
FSL -12m	20/3/2021 15:30	0
FSL -5m	20/3/2021 15:30	0
100GL/d pre-release starting 10am on 18 March	18/3/2021 21:20	-42
100GL/d pre-release starting 9am on 19 March	19/3/2021 14:10	-25

* Closure level set at 5.61m AHD

Table F15: North Richmond Bridge closure statistics for various scenarios

Modelled Scenario	Time reached*	Delay to reach (hrs)
Existing Dam	20/3/2021 23:00	-
WD +14m	21/3/2021 03:00	4
FSL -12m	21/3/2021 03:00	4
FSL -5m	21/3/2021 03:00	4
100GL/d pre-release starting 10am on 18 March	20/3/2021 11:10	-12
100GL/d pre-release starting 9am on 19 March	20/3/2021 12:20	-11

* Closure level set at 7.82m AHD

Table F16: Sackville Ferry closure statistics for various scenarios

Modelled Scenario	Time reached*	Delay to reach (hrs)
Existing Dam	20/3/2021 14:10	-
WD +14m	20/3/2021 14:10	0
FSL -12m	20/3/2021 14:10	0
FSL -5m	20/3/2021 14:10	0
100GL/d pre-release starting 10am on 18 March	19/3/2021 01:30	-37
100GL/d pre-release starting 9am on 19 March	19/3/2021 23:00	-15

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

Table F17 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 9.99m AHD. At that point the underside of the bridge deck is 7.99m AHD. The analysis assumes that the bridge would close 1m below the lowest bridge deck level.

Raising the dam would have delayed closing the bridge by 11 hours and shortened the duration of closure by more than 4 days. Lowering FSL would have delayed closing the bridge by a similar time, but the duration of closure would have been reduced from the existing case by less than 1 day. Pre-releases would have made little difference to the initial closing time or the length of closure (Table F17).

The difference in duration of closure between the raised dam and the other scenarios for this flood is likely to be more pronounced than the numbers suggest. Had the raised dam been built, the deck would not have flooded, in contrast to all other scenarios. While an engineering inspection would be required because the underside of the bridge (soffit) would have been flooded, when the surface of 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. Figure F11 illustrates some of the debris on the bridge as the actual flood receded.

Table F17: Windsor Bridge closure statistics for various scenarios

Modelled Scenario	Time reached*	Delay to reach (hrs)	Duration closed (days)#	Delay to be overtopped (hrs)	Duration overtopped (days)
Existing Dam	21/3/2021 06:20	-	5.1^	-	4.5
WD +14m	21/3/2021 17:30	11	0.7	Not overtopped	Not overtopped
FSL -12m	21/3/2021 17:30	11	4.3**	59	1.5
FSL -5m	21/3/2021 17:00	11	4.8	12	4.0
100GL/d pre-release starting 10am on 18 March	21/3/2021 09:40	3	4.9	6	4.2
100GL/d pre-release starting 9am on 19 March	21/3/2021 10:10	4	4.9	3	4.3

* Closure level set at 8.99m AHD

This is a simple representation of duration closed for comparative purposes. Where the structure is 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.

^ This duration compares to an actual duration of closure in the March 2021 flood of 6.4 days.

** Figure F10 shows that the hydrograph for FSL -12m falls ~0.3m below the adopted closure level before rising above it again. It is doubtful that the bridge would have been reopened during this time given upstream gauges would show a rise. The calculated duration of closure does not include this period.

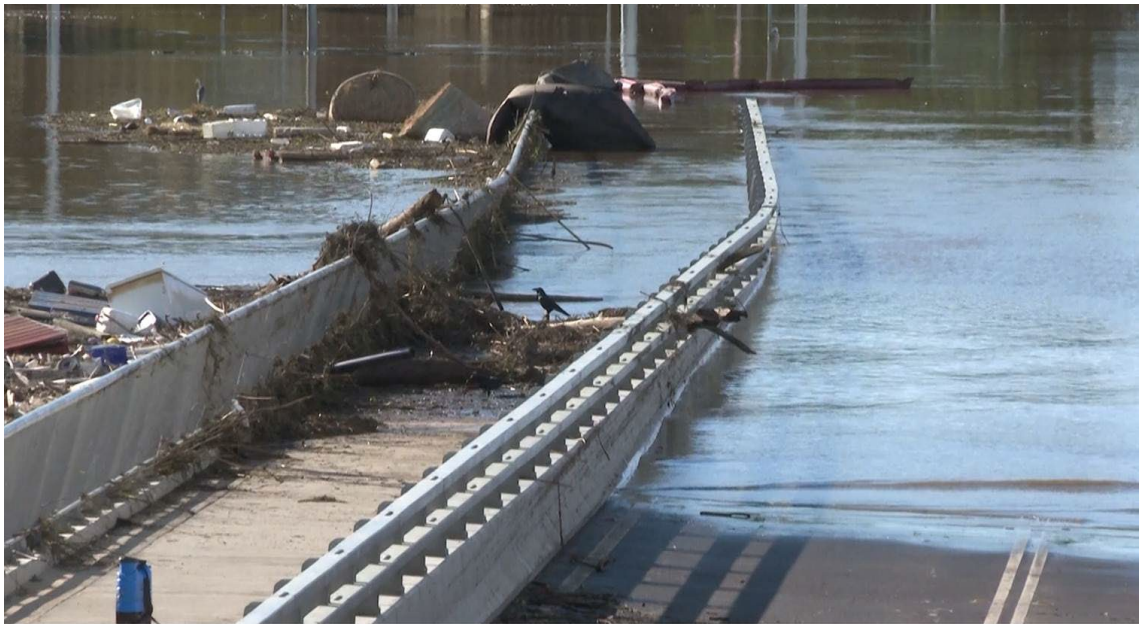


Figure F11: Debris on new Windsor Bridge as floodwater recedes, March 2021 flood

Source: Infrastructure NSW. Image: Top Notch Video

3.4 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 2021 event was characterised by a particularly high total inflow volume to Warragamba Dam – corresponding to about a 1 in 40 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 2021 flood, water levels upstream would have peaked at a height of 130.20m AHD.

Due to its double-peaked nature, the March 2021 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 informed by ongoing modelling and analysis of historic events including the March 2021 flood.

4. CONCLUSION

Infrastructure NSW engaged WMAwater, Rhelm and CSS to assess the impacts various Warragamba Dam flood mitigation measures would have had on downstream flooding if implemented prior to the March 2021 event. The assessment drew upon detailed, calibrated hydrologic and hydraulic models that were validated and adjusted to the March 2021 flood.

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.

While the pre-release scenarios would have reduced flood levels at both Penrith and Windsor, the impact is small when compared to the other scenarios. All pre-release scenarios perform the worst at Windsor, which is the centre of the exposed population. This is due to the volume of water required to be mitigated to have a benefit in the vast Windsor floodplain.

The pre-release scenarios would also have brought forward the time when the minor flood level is reached at Penrith and Windsor, as well as the time the moderate flood level is reached at Windsor. Minor and moderate flooding has serious consequences for low-lying properties including many caravan parks, and requires time for emergency preparation and evacuation – so shortening that time could be problematic. Pre-releases would also have brought forward closure of key downstream river crossings – again potentially disrupting flood preparations and extending isolation.

The proposed dam raising would have reduced peak flood levels by 5.3m at Penrith and 3.4m at Windsor. Compared to the option of permanently lowering FSL by 12m, the dam raising would have provided additional peak level reductions of 3.0m and 1.5m for Penrith and Windsor, respectively. The raised dam would also have spared the new Windsor Bridge from being overtopped, much reducing closure time.

5. REFERENCES

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Appendix G: Learnings for response (NSW SES) and recovery (Resilience NSW)

Resilience NSW identified the following needs:

- Review evacuation procedures to ensure they reflect the needs of specific known cohorts, for example, communities of concern (residents of temporary accommodation or people with limited mobility), CALD communities. This should include consideration of accessibility, accommodation, physical and mental health, and translation needs (and adequate staff resourcing) in evacuation centre planning.
- Establish recovery registration and data sharing protocols across services, organisations and agencies providing recovery support to disaster impacted people to ensure they tell their story once (or as little as possible)
- Ensure recovery resources are embedded in Emergency Operation Centres from their inception to enable community recovery needs to be scoped and responded to in a timely manner
- Support the development of Community Resilience Networks with formal links into Local Emergency Management Committees and Local Recovery Plans
- Improve accessibility to Recovery Centres and Hubs by increasing availability of translation services and support for low literacy levels
- Consider the potential cumulative impact of previous / consecutive disaster events on communities when planning recovery activities
    - Several communities impacted by the March 2021 severe weather event experienced bushfire impacts in 2019/20, storm and flood damage in February 2020, followed by COVID-related financial and social disruption. The March 2021 flood and storm event exacerbated a raft of pre-existing recovery-related issues across these communities (many of which are geographically remote and have limited service coverage). This complexity highlights the need to more actively consider high levels of fatigue and triggering recall of previous traumatic experiences among communities when planning recovery activities.
- Reflect specific needs of community cohorts in the design of Recovery Support Services and establish a capability to rapidly deploy post-event to:
    - provide place-based support and case management to address the immediate relief and recovery needs of pre-identified communities of concern with complex needs (for example, residents of some caravan parks, people with limited mobility)
    - assist residents experiencing cumulative emotional, physical and financial impacts following successive disaster events (fire, flood and pandemic) to navigate and access services and assistance
- Recognise the extent and severity of indirect impacts of disasters on communities (for example, the relative social isolation and business disruption resulting from damaged roads and bridges) and consider how to address the needs of these communities in a timely manner
- Build the capability and capacity of recovery workers and volunteers faced with long hours in challenging conditions over a potentially prolonged recovery period (especially following a catastrophic event). Consideration should also be given to supporting workers involved in pre-existing recovery efforts with communities exposed to successive disaster events (fire-flood-COVID-flood), and to the needs of ‘accidental counsellors’ in frontline roles exposed to vicarious trauma (for example, hairdressers, hospitality workers).

View upstream across Del Rio Riverside Resort, Webbs Creek, 24 March 2021

Source: NSW Police. Image: William Andrews