November 1961 flood, looking over Windsor towards the Blue Mountains
Photo courtesy NSW SES

Hawkesbury-Nepean Valley Flood Risk Management Strategy

# TASKFORCE OPTIONS ASSESSMENT REPORT

January 2019

ISBN 978-0-6480367-4-6



For enquiries, please contact mail@insw.com

# Preface

## Context

In response to the NSW Government's adoption of the *State Infrastructure Strategy 2012-2032* and ongoing community concerns about flood risk, the *Hawkesbury-Nepean Valley Flood Management Review* commenced in early 2013.

The 2013 Review assessed existing flood management and planning arrangements in the Hawkesbury-Nepean Valley (the valley) to identify ways in which flood risk could be more effectively managed. It concluded that no single mitigation option can address all the flood risk present in the valley, and that raising Warragamba Dam to temporarily capture floodwaters is the only infrastructure measure that significantly reduces and delays flood levels that have the greatest impact on risk to life and damage to homes and businesses (NSW Office of Water, 2014a; 2014b).

In May 2014, the NSW Government established the Hawkesbury-Nepean Valley Flood Management Taskforce (the Taskforce) to advance the work of the 2013 Review. This inter-agency group investigated feasible infrastructure and non-infrastructure options to reduce overall flood risk in the valley.

The Taskforce's work led to a set of recommendations that were reviewed by NSW Treasury in a 'Gateway' assurance process, which provides a level of confidence that the state's programs and projects are effectively developed and delivered, and are in line with Government's objectives. The recommendations were adopted by the NSW Government in June 2016 and incorporated into *Resilient Valley, Resilient Communities:* Hawkesbury-Nepean Valley Flood Risk Management Strategy (the Flood Strategy), released in May 2017 (INSW, 2017).

The Flood Strategy outlines the methods used to assess flood risks, the options evaluated, and nine key outcomes to be implemented to achieve the objective 'to reduce flood risk to life, property and social amenity from regional floods in the Hawkesbury-Nepean Valley now and in the future'.

Phase One of the Flood Strategy's implementation extends from 2016 to 2020.

## Purpose

This Taskforce Options Assessment Report details the investigations undertaken from 2014 to 2016, with some reference to work undertaken in the 2013 Review and to earlier regional investigations.

The primary purpose of this report is to inform the Warragamba Dam Raising proposal environmental impact assessment, which commenced in 2017. For this reason, considerable detail about alternative options for managing the flood risk is included. Results in this report will be updated for key options and included in the Warragamba Dam Raising Environmental Impact Statement (EIS), which is scheduled for completion in 2019.

The report also makes available considerably more detail than is described in the Flood Strategy. It is expected that information in this report will be of interest to valley communities and stakeholders.

## Evidence-based approach

An adaptive, evidence-based approach has been followed across the phased stages of investigation. This approach supports robust decision-making using the latest information and research, new data and technologies, contemporary policy guidance, and expert peer review.

In reading this Taskforce Options Assessment report, several points warrant consideration:

- A range of infrastructure options to manage the valley's flood risk was considered during the 2013 Review. Some were not carried through by the Taskforce because they did not meet the core objective of achieving a significant, regional reduction of flood risk. Similarly, as the Taskforce program progressed, it became apparent that some infrastructure options were more effective than others, focussing the evaluation on the preferred options. The detail with which the various options are described reflects this shortlisting process (**Figure 1**; see **Section 4.2**).
- Flood modelling advanced over the progress of the Taskforce investigations, in conjunction with advances in national practice and guidelines, so the preferred options were assessed with an updated flood model.
- Evacuation modelling became increasingly sophisticated through the innovations developed for the Taskforce investigations. The preferred options were assessed with updated evacuation simulations.
- For a risk management program of this complexity, refinement of proposals and advances in assessment methodologies are to be expected. This is consistent with application of the principle of continual improvement.
- The data presented are based on information collated by and for the Taskforce.
- Population, risk to life, flood damages and relevant cost estimates are being updated for the Warragamba Dam Raising EIS and preparation of a final business case to the NSW Government. Some material in this Taskforce Options Assessment Report will be superseded by this ongoing work.

# Table of Contents

## List of Figures

## List of Tables

## List of Boxes

# Flood likelihood terminology

The technical term used by hydrologists to describe the chance of a flood level being reached or exceeded is annual exceedance probability, or AEP (Ball et al., 2016). The AEP is normally expressed as a probability of a particular size flood, or larger, happening in any given year. The terms '1 in 100 AEP, or '100 year flood' refer to a flood that has a 1 in 100 (or 1%) chance of happening or being exceeded each year. It does not mean that the flood will happen once every hundred years. This report describes floods in terms of 1 in X chance per year.

Floods occur randomly, and the statistical probability of a flood occurring in each year is not affected by a flood that has occurred earlier that year. The 1 in 100 chance per year flood has a 1% chance of occurring or being exceeded in any given year. It is possible that such a flood could occur more than once in the same year.

For the purpose of floodplain management, the largest flood that could reasonably occur is referred to as the probable maximum flood (PMF). The PMF defines the extent of flood-prone land – the floodplain – from which people may need to evacuate prior to flooding. Flood risk management needs to consider all floods up to the PMF, although such an event is extremely rare.

For the purpose of this document, the PMF is defined as the extreme flood modelled using the probable maximum precipitation, consistent with the definition in the NSW Government's Floodplain Development Manual (2005).

# Executive summary

## Background

The Hawkesbury-Nepean Valley (the valley) in western Sydney has the highest flood risk in New South Wales, if not Australia. This high flood risk arises from the river being confined by narrow sandstone gorges, creating rapid deep backwater flooding over extensive floodplains. The floodplains are also home to a large existing population who would be impacted in a major flood.

In May 2017, the NSW Government released *Resilient Valley, Resilient Communities:* Hawkesbury-Nepean Valley Flood Risk Management Strategy (Flood Strategy) to address the flood risk to lives, homes, businesses and community assets in the valley.

The Flood Strategy was the product of four years of investigations – the Hawkesbury-Nepean Valley Flood Management Review (2013) and the Hawkesbury-Nepean Valley Flood Management Taskforce (2014-16) (**Figure 1**). This report details the assessments of alternative options that led to the adopted Flood Strategy.

The assessment of key options will be updated based on the latest population, risk to life, flood damages and relevant cost estimates, which will be provided in the Warragamba Dam Raising Environmental Impact Statement, scheduled for public exhibition in 2019.

There are different ways to manage flood risk across the risk management cycle of preventing, preparing for, responding to and recovering from floods (**Figure 2**). The investigated options fall into two broad categories:

1. Infrastructure options, which can significantly reduce flood risk by lowering the chance of a flood event, reducing the exposure of homes and businesses to flooding, and with some options, increasing the certainty of time for evacuation. Infrastructure options considered include:
    - controlling flows into the floodplains (upstream dams)
    - reducing the constriction of the sandstone gorges (diversion channels, river dredging)
    - protecting areas within the floodplains (levees)
    - increasing evacuation capacity (road upgrades).
2. Non-infrastructure options, which address different elements of the flood risk management cycle, are essential to manage ongoing risk, and help ensure the benefits of any infrastructure options are maintained over time. They include:
    - helping to prevent exposure through integrated land use planning and appropriate flood planning controls
    - reducing existing flood risk exposure (voluntary house purchase and voluntary house raising)
    - increasing community awareness, preparedness and response
    - enhancing flood forecasting capability
    - improving emergency and recovery planning and response
    - strengthening the integration and coordination of organisations responsible for floodplain management.

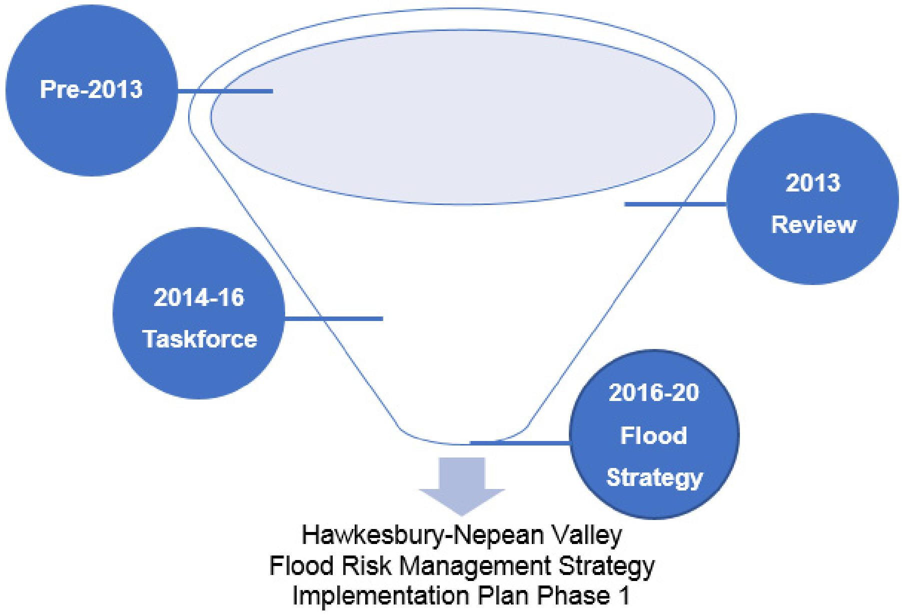



**Figure 1 Shortlisting of flood risk management options through the stages of investigation**

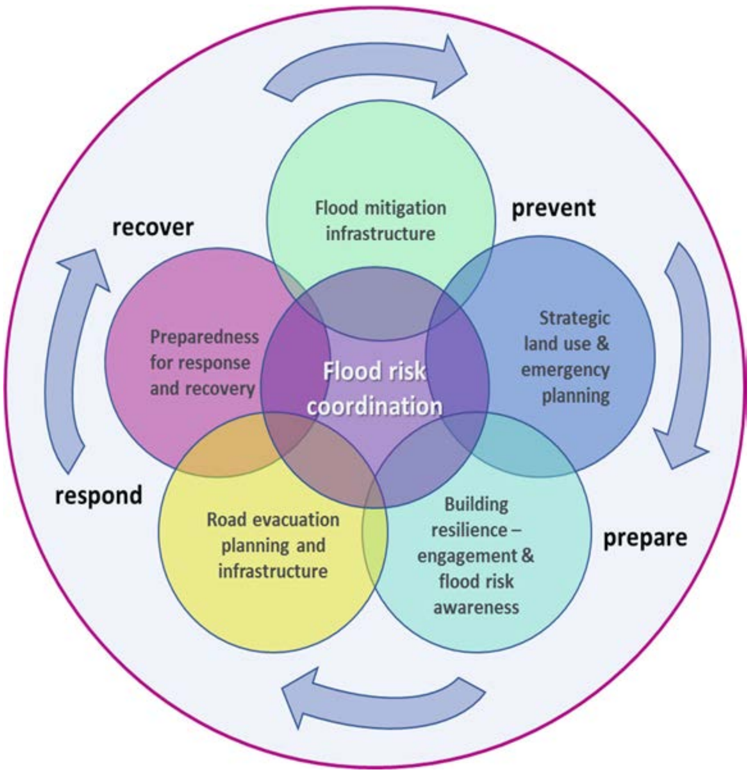



**Figure 2 Interaction of Flood Strategy components with emergency management framework**

## Assessment methods

Flood mitigation infrastructure options were progressively evaluated and shortlisted in a phased approach (**Figure 1**). Consistent with a project of this complexity, some options were investigated to a pre-feasibility stage, others to a feasibility stage, and others to a detailed feasibility stage.

Options that did not provide significant regional flood mitigation, or had extreme environmental or economic impacts were eliminated. An option was judged to *significantly* reduce flood risk if it provided sizeable reductions in regional peak flood levels in the range of 1 in 50 to 1 in 1,000 chance per year floods. This is because the 1 in 50 to 1 in 500 chance per year flood range contributes about two-thirds of the average annual flood damages, and the 1 in 1,000 chance per year flood cuts the last evacuation road isolating Richmond, the last major urban area isolated by floods.

Shortlisted options were subject to more detailed engineering, environmental and economic assessment. Decision-support tools developed for this detailed evaluation of options included flood modelling, an agent-based flood evacuation model to assess risk to life, and flood damages modelling.

Non-infrastructure options were assessed largely in relation to their contribution to the prevention, preparation, response and recovery aspects of the flood risk management cycle (**Figure 2**), as well as the extent to which they contributed to the maintenance of flood mitigation benefits over time.

**Table 1** summarises the options considered and the key reasons why they were taken forward or not progressed through the stages of investigation.

## Infrastructure options

Infrastructure options were assessed in two sub-categories: flood mitigation infrastructure options and evacuation road infrastructure options.

### *Flood mitigation infrastructure options*

*Warragamba Dam wall raising*

Raising Warragamba Dam by about 14 metres to provide dedicated airspace to temporarily capture floodwaters was found to be the infrastructure measure that provided the highest net benefit (**Figure 3**). It significantly reduces the risk to life downstream, reduces flood damages by around 75% on average per annum, and increases the certainty of time for people to evacuate while balancing the impacts on the upstream environment.

Raising Warragamba Dam by 20 metres would provide greater mitigation of downstream flood peaks than a 14-metre dam raising. However, it has a lower net benefit (**Figure 3**). While the 20-metre option captures more water, it potentially would have greater incremental, temporary upstream impacts compared to what happens now. It could also prolong low level inundation downstream associated with post flood releases.

**Table 1 Summary of options assessment**

| Option | Prevent* | Prepare | Respond | Recover | Finding | Key reason(s) |
|---|---|---|---|---|---|---|
| **Infrastructure measures** | | | | | | |
| Surcharge existing Warragamba Dam gates during floods | ✓ | | | | Not supported | Does not provide significant, regional reduction of flood risk |
| Pre-release water from Warragamba Dam before forecast flood events | ✓ | | | | Not supported | Does not provide significant, regional reduction of flood risk; risk of loss of water supply |
| Permanently lower Warragamba Dam full water supply level by 5m | ✓ | | | | Not supported | Does not provide significant, regional reduction of flood risk |
| Permanently lower Warragamba Dam full water supply level by 12m | ✓ | | | | Not supported | Provides moderate regional benefits in critical flood range but has high net cost due to high costs of addressing water supply security and water quality |
| New flood mitigation dams upstream of Warragamba | ✓ | | | | Not supported | High social, environmental and cultural heritage impacts; no sites as well suited as Warragamba |
| New flood mitigation dams downstream of Warragamba | ✓ | | | | Not supported | Does not mitigate predominant Warragamba Catchment floods |
| Raise Warragamba Dam wall by about 14m | ✓ | | | | **Supported** | Provides significant, regional reduction of flood risk; highest net benefit of all options considered |
| Raise Warragamba Dam wall by 20m | ✓ | | | | Not supported | Provides greatest flood mitigation but has lower net benefit than WD +14m; potentially higher impacts from temporary upstream inundation and downstream releases |
| Currency Creek diversion channel | ✓ | | | | Not supported | Does not provide significant, regional reduction of flood risk; high net cost; high to extreme environmental impact |
| Sackville cut-off (short diversion) | ✓ | | | | Not supported | Does not provide significant, regional reduction of flood risk |
| Sackville large diversion | ✓ | | | | Not supported | Does not provide significant, regional reduction of flood risk; extreme cost; likely extreme environmental impact |
| Dredging between Windsor and Wisemans Ferry | ✓ | | | | Not supported | High net cost; high to extreme environmental impact; must be maintained for ongoing flood mitigation |
| Levees (Peachtree Creek, McGraths Hill, Pitt Town) | ✓ | | | | Not supported | Provides local benefit only and not for severe or catastrophic floods; may discourage evacuation and increase risk of catastrophe if overtopped |
| Regional evacuation road upgrades | | | ✓ | | Not supported | Even with multiple major road upgrades, less effective at reducing risk to life than dam raising; high net cost due to large scale of upgrades; provides capacity for evacuation only – does not reduce property damages |
| Local evacuation road upgrades | | | ✓ | | **Supported** | Improves local evacuation, complementing existing regional evacuation routes |

| Option | Prevent* | Prepare | Respond | Recover | Finding | Key reason(s) |
|---|---|---|---|---|---|---|
| **Non-infrastructure measures** | | | | | | |
| Flood risk-based regional land use planning and development control | ✓ | ✓ | | | **Supported** | Essential and complementary to infrastructure measures; limits increase in future exposure; manages impact of growth on evacuation capacity |
| Flood risk-based regional road planning | | | ✓ | | **Supported** | Road evacuation master planning necessary to take account of flood evacuation risk when regional roads are upgraded for growth |
| Voluntary house purchase (VP) | ✓ | | | | Not supported | Extreme cost (billions) to significantly reduce flood risk; extreme social disruption requiring mass relocation |
| Voluntary house raising (VHR) | ✓ | | | | Not supported | Impractical due to house construction types and extreme flood depths |
| Improved flood forecasting and warning system | | | ✓ | | **Supported** | Complementary to infrastructure measures; provides increased certainty of time for evacuation |
| Community flood awareness, preparedness, responsiveness | | ✓ | ✓ | | **Supported** | Complementary to infrastructure measures; critical component for successful evacuation and resilient communities |
| Best practice emergency response and recovery | | ✓ | ✓ | ✓ | **Supported** | Complementary to infrastructure measures; critical for optimum decision-making, rescue capacity, efficient recovery |
| Improved governance of flood risk management (FRM) | ✓ | ✓ | ✓ | ✓ | **Supported** | Essential for coordination and integration of FRM and maintenance of risk reduction in valley over time |
| Collection of post-event flood data/intelligence | ✓ | ✓ | ✓ | ✓ | **Supported** | Underpins continuous improvement of flood models, emergency response and recovery plans |

* In the strict sense, flood mitigation measures and measures that target exposure such as land use planning can reduce or manage the risk but not prevent it.

*Operating existing Warragamba Dam for flood mitigation*

Options to operate the existing Warragamba Dam differently for flood mitigation were considered but do not provide the same quantum of benefits as the proposed dam raising. Changing the operation of the gates to temporarily hold back floodwaters (known as surcharging) does not significantly reduce downstream flood risk and can increase the risk of gate failure.

The flood mitigating benefit of pre-releasing water supply from Warragamba Dam to create temporary airspace for the capture of flood inflows was tested. Three days would be required to create a flood mitigation zone (FMZ) large enough to provide a minimum level of flood mitigation. It was found that benefits would not meet the key objective of providing a significant, regional reduction of flood risk.

There is also a significant risk that pre-releases based on forecast rainfall would not be replaced by flood inflows. At the current time, the ability of weather models to predict the spatial and temporal pattern of rainfall with the confidence required for implementing a pre-release strategy from a water supply dam is limited. In the case of a pre-release of 130 GL/day over three days (390 GL), about 19% of the dam's storage capacity could be released and not replaced.

Two options to lower the dam's full water supply to create permanent flood mitigation airspace were examined: five metres and 12 metres (the maximum possible to the depth of the spillway gates). The five-metre lowering was found to have limited benefits for the larger floods that pose the most risk to lives and property.

While 12-metre lowering provides moderate flood mitigation capacity, it reduces the dam's water supply capacity by nearly 40% and Sydney's total water supply by around one third. This would have a very significant impact on water security for greater Sydney. Before this option could be implemented, major new sources of water would need to be built and the current desalination plant would need to be continuously operated at maximum effective capacity, with high capital and ongoing costs.

A lower FSL would also increase the risk of poor water quality in Lake Burragorang, as the reduced level of water in the dam would have a significant impact on the ability of the storage to act as a buffer to muddy and polluted flood inflows.

Due to its impacts on water security and water quality, lowering FSL by 12 metres has a high net cost (**Figure 3**). This cost does not include modifications to the existing dam wall that would be required to effectively manage releases from a FMZ formed by lowering FSL.

*New flood mitigation dams*

Alternative dam sites for flood mitigation dams were considered and rejected in reviews in the 1980s and 1990s. These and other alternative dam sites were considered by the Taskforce, but no new information was found that would justify further investigation of new dam sites for flood mitigation.

*Reducing the constriction of the sandstone gorges (diversion channels, river dredging)*

Options to speed the conveyance of floodwaters through the constricting gorges of the lower Hawkesbury River were modelled. River diversion channels would only make a minor difference to more frequent, smaller floods at Windsor, and would offer no benefit to Penrith.

Deep dredging of the Hawkesbury River channel by up to 10 metres from Windsor to Wisemans Ferry would be necessary to achieve moderate flood mitigation benefits at Windsor. This option offers no benefit to Penrith. River dredging would have a high net cost (**Figure 3**), high to extreme environmental impact, and would need to be maintained for ongoing flood mitigation.

*Protecting areas within the floodplains (levees)*

Seventeen levee options were investigated across the valley by the 2013 Review. Shortlisted levees at Penrith and McGraths Hill were considered by the Taskforce to have some merit as local measures.

As demonstrated in other floodplains, levees can be overtopped by floods that exceed their design height. Levees can also create a false sense of security that can impact on emergency response. The Peachtree Creek levee at Penrith could be further considered by council as a local measure to mitigate the backwater effects of Nepean River flooding.

### *Evacuation road infrastructure options*

The NSW SES's *Hawkesbury Nepean Flood Plan* recognises that effective evacuation of the valley relies on the majority of people using their private vehicles to leave before roads at the many low points are cut by floodwaters. The depth and extent of flooding mean that sheltering in place during flood events is not safe or feasible.

In a flood similar to the flood of record (1867), around 90,000 people would need to evacuate. The time required to evacuate people ahead of such large events exceeds the forecast time provided by the Bureau of Meteorology. This can force the emergency services to call evacuations based on predicted rainfall and less certain flood forecasts.

The regional road network is vital for timely evacuation during actual flood events. Nine packages of major road upgrades were assessed for their ability to increase evacuation efficiency and thus reduce risk to life. To be effective, major roads would require upgrading at multiple locations across the evacuation network.

Even with multiple major road upgrades, they are still less effective at reducing regional risk to life than dam raising. By controlling the major contributor to valley flooding, the proposed dam raising significantly reduces the scale of required evacuation and delays the flood peak. These road upgrade packages would also come at a high net cost (**Figure 3**). Road upgrades have low benefits partly because they do not reduce the impact of flooding on homes, businesses and other critical assets.

While dam raising was more effective than major road upgrades for reducing the existing risk, a Regional Evacuation Road Master Plan was identified as a key action to ensure that evacuation requirements are considered when the regional road network is upgraded over time.

The Flood Strategy does require more detailed investigation of around 40 local road upgrade packages. These upgrades would address drainage and other minor constrictions in the existing evacuation road network enabling more reliable access to the existing regional evacuation routes.

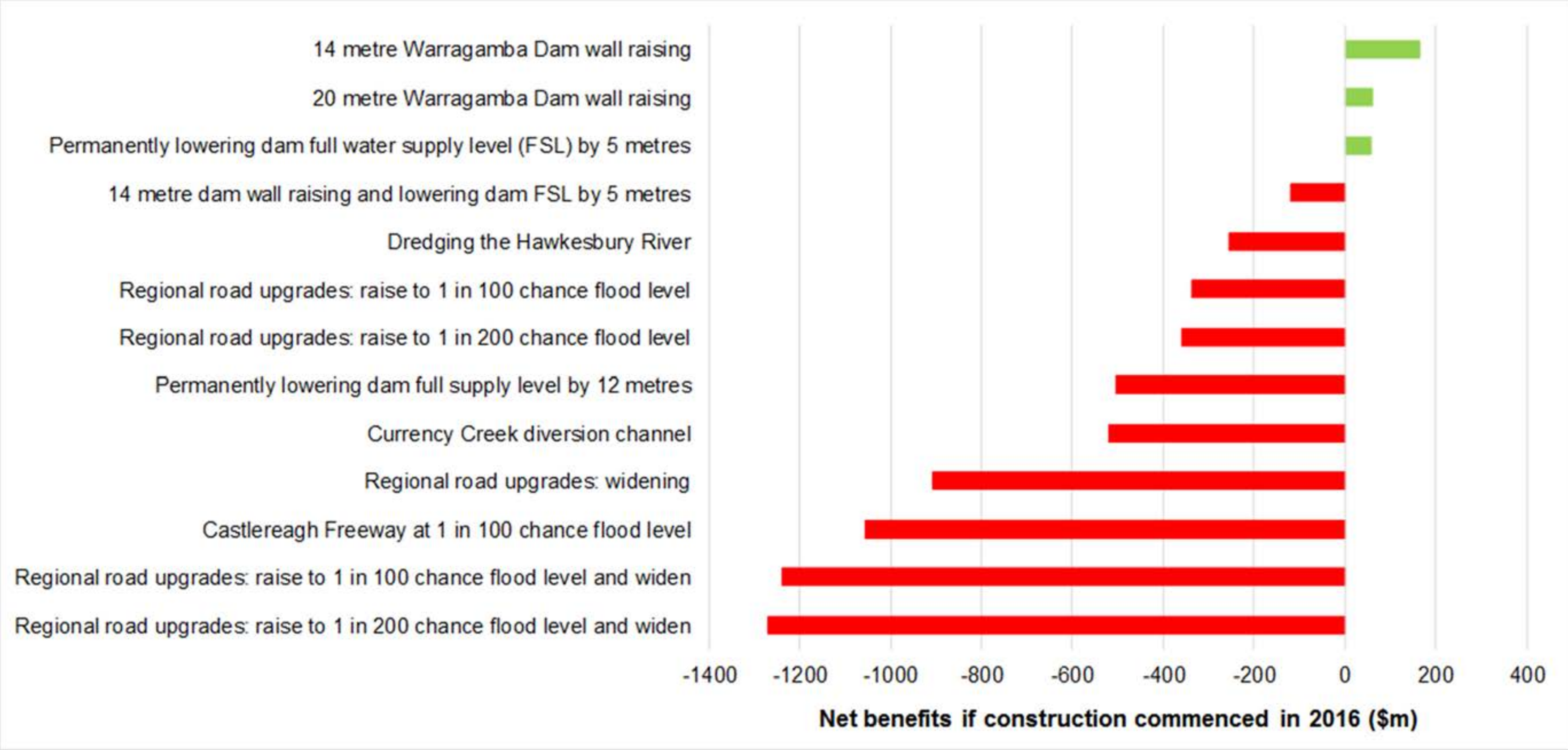



**Figure 3 Net benefits of flood mitigation and evacuation road infrastructure options**

*Source:* CIE

*Note:* 'Central' case assumed; loss of life was not measured for dredging, or the Currency Creek diversion, or -12m FSL or the combination of a raising of the dam wall by 14 metres and a -5m FSL, as these options performed less well than other options in early analysis. Additional Castlereagh Freeway options are not shown, and have greater net costs than the options shown. The analysis assumed construction of each option commenced in 2016.

## Non-infrastructure options

The Flood Strategy includes a mix of non-infrastructure measures critical to an integrated and sustainable approach to managing flood risk in the valley. They include measures that are vital so the community is better prepared, more responsive and resilient to flood events that occur infrequently but have high social and economic consequences.

### *Flood risk-based regional land use planning and development control*

The Taskforce highlighted the need to integrate land use and road planning to adapt to and manage flood risk in the valley. Much of the flood risk relates to homes and businesses above the 1 in 100 chance per year flood level, the current flood planning level. While this level may be appropriate for other regions, it does not adequately take account of flood risk in the Hawkesbury-Nepean Valley – where flood levels can be up to nine metres above the flood planning level at Windsor.

An action under the Flood Strategy is to review the current planning policy arrangements to account for the high flood risk above the 1 in 100 chance per year flood level. This review will be consistent with the principles of the Western Sydney District Plan, which includes consideration of the full range of flood risk. The results will be a new Regional Land Use Planning Framework, that will take account of the cumulative impacts of growth on evacuation capacity across the relevant local government areas, and a Regional Evacuation Roads Master Plan.

These new regional land use, road and emergency planning frameworks will be critical to managing ongoing flood risk and to ensuring benefits of any infrastructure investment, such as the proposed Warragamba Dam raising, are maintained in the longer term.

### *Measures to increase community flood awareness, preparedness, responsiveness*

The Hawkesbury-Nepean Valley communities are diverse, with a combination of urban communities, regional centres and rural properties. Since the last major flood in 1990, there has been significant development and population growth in some areas within the floodplain.

Many people in the valley have not directly experienced flooding – including the thousands of residents who have moved in since the 1990s and a generation of young people who have grown up during those years.

Community research undertaken for the Taskforce has shown very low levels of flood risk awareness, preparedness and responsiveness. If only a small percentage of residents don't comply with evacuation orders during a major flood, many hundreds of lives will be at risk.

One of the Flood Strategy's key outcomes is to deliver 'an aware, prepared and responsive community' through a coordinated and comprehensive community engagement and education program. To build resilience to natural hazards, activities target communities of concern who are at greater flood risk, as well as the broader floodplain communities.

The Taskforce also identified the need to provide 'accessible contemporary flood risk information'. This includes the development and release of a new regional flood study for the Hawkesbury-Nepean Valley to help local communities understand their flood risk; inform land use, road and emergency planning; and allow for more accurate pricing of flood risk.

### *Improved flood forecasting and warning system*

To effectively evacuate people in a flood emergency, the NSW State Emergency Service relies on forecasting and flood predictions from the Bureau of Meteorology.

The Taskforce identified an action for the Bureau to enhance its flood forecasting capability for the Hawkesbury-Nepean Valley. As part of the Flood Strategy, improved rainfall and flood forecasts, new modelling, and new decision-support tools will be developed to provide greater clarity about the timing, behaviour and heights of floods. This will support improved emergency response and recovery.

#### *Best practice emergency response and recovery*

Given the scale of the potential emergency response and recovery from a major flood in the valley, it is vital to continuously improve emergency response and recovery preparedness. The Taskforce recognised this and included in its recommendations the need to review and update, test and improve local and regional emergency plans and assets. Ensuring the necessary plans and capabilities are maintained over time is critical for flood events that occur infrequently but can be catastrophic.

#### *Improved governance to support integrated flood risk management*

The Taskforce identified the need for improved governance arrangements that support an integrated, coordinated and efficient approach to flood risk management in all stages of disaster management (prevention, preparedness, response and recovery).

The Flood Strategy includes actions to coordinate implementation of key outcomes and share responsibility for flood risk management, while clarifying accountability for key actions across the government and other stakeholders.

To lead the implementation of the first phase of the Flood Strategy (2016-2020), the Hawkesbury-Nepean Valley Flood Risk Management Directorate has been established within Infrastructure NSW.

#### *Voluntary purchase and house raising*

Voluntary purchase (VP) of flood prone dwellings was considered as an option to reduce people's exposure to flooding. This option was not taken forward as it would come at an extreme financial and social cost. VP would be cheaper than a 14-metre dam raising only if its scope was confined to dwellings impacted by the 1 in 20 chance per year or smaller floods. This would not provide a significant, regional reduction of flood risk.

Voluntary house raising was considered impractical given housing construction types and the extreme depths of inundation in the valley. Many newer dwellings are brick/slab-on-ground which are costly or impractical to raise.

## Conclusion: Flood Strategy

The Taskforce progressed and refined work of the 2013 Review to identify a suite of complementary flood risk management options for the Hawkesbury-Nepean Valley. In doing this, the Taskforce developed new and innovative modelling tools and assessment processes, and drew on the latest international, national and state approaches and guidelines.

The resulting *Resilient Valley, Resilient Communities:* Hawkesbury-Nepean Valley Flood Risk Management Strategy (INSW, 2017) confirms that there is no single or simple solution to reduce flood risk.

Following more than four years of research and analysis, the nine key outcomes of the Flood Strategy identify the mix of actions necessary to address the current and emerging risks in this important region of New South Wales.

Flood mitigation infrastructure options that provide the greatest, regional benefit are those controlling floodwater from the Warragamba Catchment. This is because the Warragamba Catchment provides the greatest contribution of high flows causing significant flooding in the Hawkesbury-Nepean River system.

Raising Warragamba Dam by around 14 metres would prevent 83% of flood events that currently reach or exceed the 1 in 100 chance per year flood level at Windsor (17.3 metres) from reaching this level. In addition, the 17% of flood events that would exceed this level would be delayed (70% by more than 10 hours). This means the number of people requiring evacuation for any given event would be significantly reduced, and the evacuation order would be based on a more certain flood forecast.

The 14-metre dam raising would also reduce damages to homes, business and critical assets by 75% on average per annum. This would reduce recovery time after flood events and is expected to reduce flood insurance premiums.

The Flood Strategy also includes infrastructure measures that can be implemented in the shorter term, such as improving local evacuation roads to support the evacuation of potentially tens of thousands of people during floods.

Non-infrastructure actions form an important part of best-practice flood risk management and are cost-effective ways of increasing community resilience and compliance with flood evacuation orders, which is a key factor in reducing loss of life. They include regional and integrated land use, roads and emergency planning, community awareness through better flood risk mapping and information, improved flood forecasting, and continuously improved response and recovery planning.

While the Flood Strategy will significantly reduce the flood risk, it will not eliminate it. The unique nature of this valley means the residual flood risk is higher than in most other river valleys. However, if implemented as a whole – and with the NSW Government, councils, business and community working together – the Flood Strategy is designed to manage this risk both now and into the future.

# 1 Introduction

## 1.1 Flood problem

### *1.1.1 A long history of flooding*

Floods have played a major role in shaping the landscape of the Hawkesbury-Nepean Valley. The extensive floodplains of the Hawkesbury-Nepean River – notably around Richmond/Windsor – were formed over thousands of years by the deposition of sediment during floods.

The Aboriginal people of the Hawkesbury-Nepean Valley experienced loss from flooding, but also learned to adapt to floods. Governor King learned from the traditional owners of the land that high floods occurred in about 1780 and in March 1788. In 1780, people took refuge in the tallest trees but were still swept away (King, 1806). In 1799, it was reported that the Aboriginal population perceived the threat and warned the new settlers of the coming flood (Hunter, 1799).

Early European explorers detected signs of significant floods. On their first trip up the Hawkesbury River in 1789, at about Yarramundi, Governor Phillip and his party saw in the branches of trees 'vast quantities of large logs which had been hurried down by the force of the waters, and lodged thirty to forty feet above the common level of the river' (Hunter, 1793).

The fertile floodplain around Windsor was settled by Europeans in 1794, and a good record of flooding is available since about that time. This makes the Windsor flood record the longest in Australia. Floods were a frequent occurrence in the early years of the colony. Damage from the major flood of 1809 prompted Governor Macquarie to establish five townships on higher ground: Castlereagh, Richmond, Windsor (already settled as Green Hills), Pitt Town and Wilberforce – collectively known as the Macquarie towns. After further damaging floods in 1816 and 1817, Macquarie issued General Orders calling for settlers to relocate from their low-lying farms to the townships, which few settlers obeyed (Karskens, 2016).

The period from 1820 to 1856 had fewer and smaller floods, the largest of these was in 1830.

The period from 1857 to 1900 had many floods, including the highest and second-highest floods on record, in 1867 and 1864, respectively. The 1867 flood reached 27.5 metres Australian Height Datum (m AHD) at Penrith and 19.7 m AHD at Windsor (Bracewell & McDermott, 1985; WMA, 1996), causing massive damage, and the loss of 12 members of the Eather family at Cornwallis. Although many floods have occurred since then, none have come near the heights reached in 1867.

Records and research reveal that even higher floods occurred prior to the arrival of Europeans. After the 1867 flood, one observer from the Hawkesbury described that 'There are certainly in this district several indications of much higher inundations, but evidently works of very ancient floods, probably centuries ago' (Pitt, 1867). Palaeoflood investigations examine and study this ancient evidence. One such investigation examined deposits from floods in Fairlight Gorge near the junction of the Nepean and Warragamba rivers (Saynor & Erskine, 1993). Analysis of minerals and radiocarbon dating found that, at that location, a flood at least eight metres higher than the 1867 flood had occurred in the Holocene (that is, the last approximately 10,000 years).

The period from 1901 to 1948 had fewer and smaller floods compared to the 1857-1900 period.

But the period from 1949 to 1992 had more frequent and larger floods, despite the completion of Warragamba Dam for water supply in 1960.

No major or moderate floods (using NSW SES categories – see glossary) have been observed at Windsor in the 26 years since 1992.

Since European observations began, the decades-long periods of either frequent and higher floods or infrequent and smaller floods has led scientists to describe the hydrological regimes that characterises the Hawkesbury-Nepean as either flood-dominated or drought-dominated. On top of these underlying regimes are large annual variations in rainfall and runoff, such that floods can still occur in drought-dominated regimes, and droughts in flood-dominated regimes (Warner, 2009).

The history of floods at Windsor is summarised in **Table 1.1**. Since European settlement, about 130 moderate to major floods have been recorded (not all shown in **Table 1.1**), around 20 of which occurred since Warragamba Dam was completed.

### *1.1.2 Highest flood risk in New South Wales*

Floods in the Hawkesbury-Nepean Valley are considered by the Insurance Council of Australia to be the highest single flood exposure in New South Wales, if not Australia. The floodplain is located in the Western Sydney region, one of Australia's largest and most diverse economies, with an annual gross regional product of about $104 billion (2013/14). Large flood events could impact the entire New South Wales economy by affecting transportation routes and utilities outside the valley. Many of the urban centres on the floodplain are subject to infrequent but severe to catastrophic flooding. This risk arises from a number of factors outlined below.

#### *Natural characteristics of the valley*

The Hawkesbury-Nepean Valley consists of large upstream catchments and a series of narrow downstream sandstone gorges. This combination results in floodwaters backing up behind these natural 'choke points' as water enters the system faster than it can escape. Floodwaters rise rapidly, causing significant flooding both in terms of area and depth. The spread of floodwaters in this natural 'bathtub' can be seen in **Figure 1.1**. The 'bathtub effect' is unusual, since most river valleys tend to widen as they approach the sea.

Floodwaters in the valley are much deeper than most other floodplains in New South Wales and Australia. At Lismore (north coast) and Nyngan (inland), the difference between a 1 in 100 chance per year flood level and the probable maximum flood (PMF) level is about two to three metres. At Windsor, this difference is about nine metres (**Figure 1.2**).

The narrow exit for floodwaters also means that flooding may be prolonged. In the 1867 flood – the highest since European settlement – a reconstruction of a flood hydrograph showed that water levels at Windsor exceeded 14.0 m AHD, or around 13.5 metres above normal river level, for nearly four days (Yeo et al., 2017).

## Table 1.1 Windsor flood history

| Date | Level |
|---|---|
| 1799 Mar | 10.5 |
| 1806 Mar | 12.9 |
| 1809 May | 14.7 |
| 1816 Jun | 14.1 |
| 1817 Feb | 14.4 |
| 1819 Mar | 12.9 |
| 1857 Jul | 10.39 |
| 1857 Aug | 11.91 |
| 1860 Feb | 8.8 |
| 1860 Apr | 11.82 |
| 1860 Jul | 11.06 |
| 1860 Nov | 11.39 |
| 1861 Apr | 8.77 |
| 1864 Jun | 15.05 |
| 1864 Jul | 11.42 |
| 1866 Jun | 8.34 |
| 1866 Jul | 8.77 |
| 1867 Apr | 8.47 |
| 1867 Jun | 19.68 |
| 1868 Feb | 9.5 |
| 1869 May | 11.64 |
| 1870 Mar | 9.02 |
| 1870 Apr | 14.14 |
| 1870 May | 11.24 |
| 1870 Nov | 8.47 |
| 1871 May | 11.67 |
| 1871 May | 8.5 |
| 1873 Feb | 13.1 |
| 1873 Jun | 9.02 |
| 1874 Feb | 8.74 |
| 1875 Jun | 12.28 |
| 1877 May | 9.62 |
| 1877 Jul | 8.56 |
| 1878 Feb | 8.5 |
| 1879 Sep | 13.62 |
| 1889 May | 12.15 |
| 1890 Mar | 12.28 |
| 1891 Jun | 11.24 |
| 1892 Sep | 8.5 |
| 1893 Mar | 9.05 |
| 1894 Mar | 10.14 |
| 1895 Jan | 9.72 |
| 1898 Feb | 10.08 |
| 1899 Aug | 8.56 |
| 1900 Jul | 14.5 |
| 1904 Jul | 12.64 |
| 1911 Jan | 8.31 |
| 1913 May | 8.47 |
| 1915 Jan | 8.04 |
| 1916 Oct | 10.97 |
| 1922 Jul | 9.6 |
| 1925 May | 8.62 |
| 1925 Jun | 11.5 |
| 1929 Feb | 8.07 |
| 1929 Oct | 8.58 |
| 1934 Feb | 9.29 |
| 1943 May | 10.26 |
| 1945 Jun | 8.53 |
| 1949 Jun | 12.11 |
| 1950 Jan | 9.12 |
| 1950 Mar | 9.35 |
| 1950 Jun | 9.6 |
| 1950 Jul | 8.38 |
| 1950 Oct | 9.75 |
| 1951 Jan | 9.3 |
| 1952 Jun | 9.52 |
| 1952 Jul | 11.76 |
| 1952 Aug | 9.63 |
| 1954 Feb | 8.8 |
| 1955 May | 9.9 |
| 1956 Feb | 13.84 |
| 1956 Jun | 9.68 |
| 1960 – Warragamba Dam completed | |
| 1961 Nov | 14.95 |
| 1962 Jan | 8.56 |
| 1963 Apr | 8.68 |
| 1963 Jun | 8.94 |
| 1963 Aug | 9.57 |
| 1964 Jun | 14.57 |
| 1967 Aug | 8.94 |
| 1969 Nov | 10.21 |
| 1974 Apr | 8.66 |
| 1974 May | 10.43 |
| 1974 Aug | 9.6 |
| 1975 Jun | 11.2 |
| 1976 Jan | 9.37 |
| 1976 Mar | 8.0 |
| 1977 Mar | 8.91 |
| 1978 Mar | 14.46 |
| 1978 Jun | 9.7 |
| 1984 Jul | 8.25 |
| 1986 Aug | 11.35 |
| 1988 May | 12.8 |
| 1988 Jul | 10.89 |
| 1989 Apr | 9.22 |
| 1990 Apr | 8.74 |
| 1990 Aug | 13.5 |
| 1992 Feb | 11.1 |

*Source*: WMA (1996); 1992 level from OEH

*Notes:*

(1) Peak flood levels shown in metres AHD (Australian Height Datum), which is approximately equal to mean sea level
(2) Only floods > 8.0 m AHD (7.5 metres above normal river height) are recorded (moderate to major range)
(3) Only floods > 10.0 m AHD (9.5 metres above normal river height) are recorded prior to 1857
(4) Pre-1857 floods are being reassessed from historical records

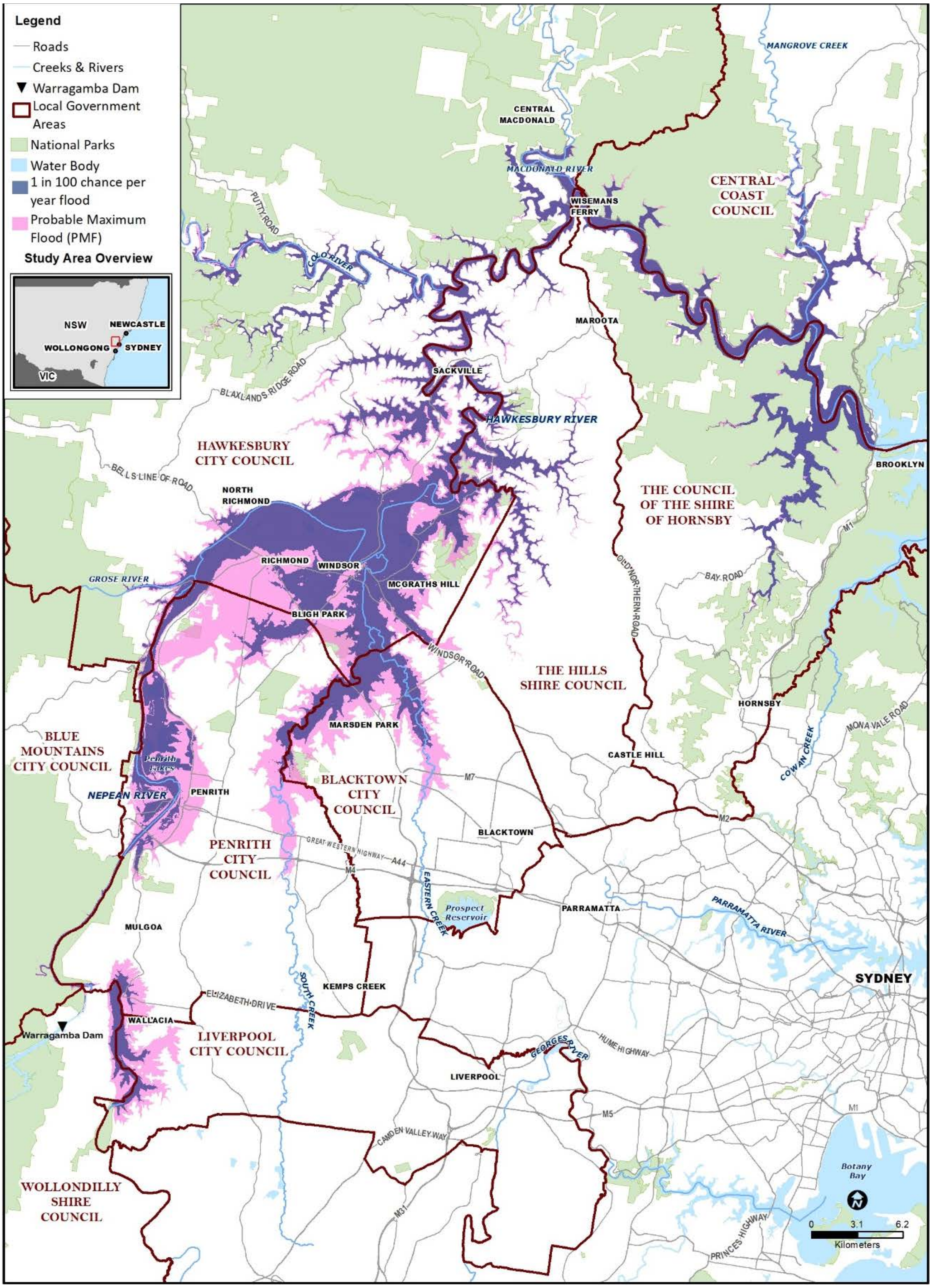



**Figure 1.1 Hawkesbury-Nepean Valley floodplain**

*Source*: INSW, NSW SES

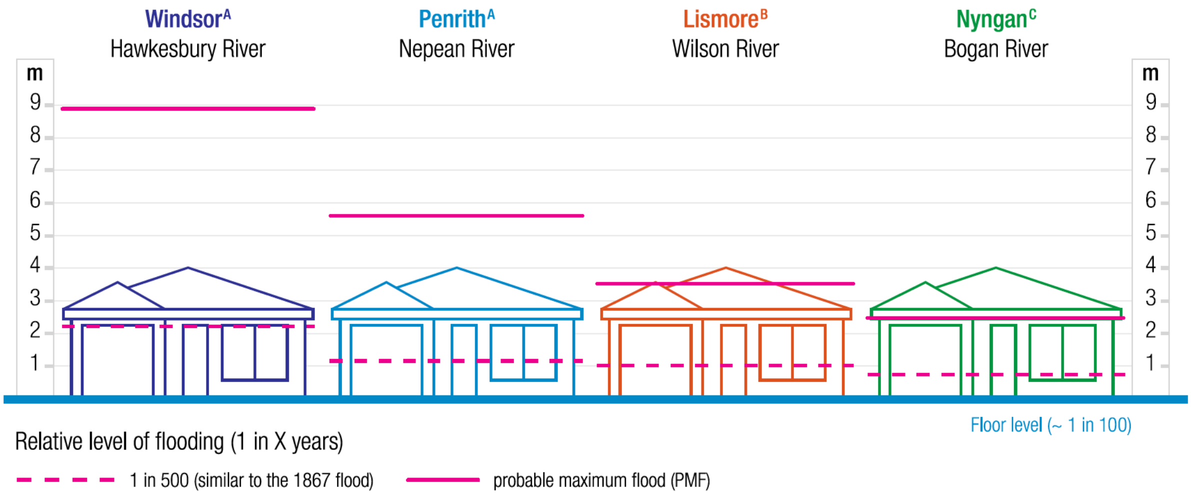



**Figure 1.2 Comparison of the differences in flood levels and flood risk between the Hawkesbury-Nepean River and other floodplains**

*Source*: Adapted from ERM Mitchell McCotter (1995)

A. WMAwater for the Taskforce
B. Lismore Floodplain Risk Management Plan – Glossary and Appendices (Lismore City Council, 2014)
C. Nyngan April 1990 Flood Investigation (NSW Department of Water Resources, 1990)

### *Climate change*

The valley's high flood hazard may increase in the future as a result of climate change. Climate change has the potential to alter the frequency and severity of rainfall extremes, change rainfall patterns and increase the likelihood of flooding in the valley. Possible impacts on flood levels in the valley are described in **Section 3.2.4**.

### *Large and growing population*

An assessment for the Taskforce found that up to 134,000 people currently live and work on the floodplain and could require evacuation in advance of an extreme flood. Thirty-year population forecasts were prepared to understand the future exposure of communities to floods and to test the efficacy of risk treatments under various growth assumptions.

Over 25,000 residential properties and two million square metres of commercial space are currently subject to flood risk (INSW, 2017).

Although large flood events are infrequent, they have high economic and social consequences. A 1 in 100 chance per year flood – similar to the 2011 Brisbane flood – would impact about 5,000 residential properties, require the evacuation of 64,000 people, and cause over $2 billion in damages (INSW, 2017). It would significantly impact the New South Wales and Australian economies. Communities within and outside the valley would be without some essential services and transport links for extended periods of time.

If a flood similar to the 1867 flood – a 1 in 500 chance per year event – occurred today, about 12,000 residential properties would be impacted, 90,000 people would need to evacuate and the estimated damage would cost $5 billion.

By 2041, the numbers needing to evacuate in a 1 in 500 chance per year event could increase to at least 158,000, and the costs could increase to $7 billion, if population grows in line with current land use planning policy (INSW, 2017). Therefore, the degree and location of growth in the floodplain, and the scale of the evacuation task, needs to be strategically managed.

### *Limited application of land use planning controls*

The *Floodplain Development Manual* (NSW Government, 2005) defines a floodplain as including all sized floods up to the probable maximum flood (PMF). However, the *Guideline for Residential Development on Low Flood Risk Land* (an addendum to the 2005 Floodplain Development Manual, issued in 2007 and given effect under the *Environment and Planning Assessment Act 1979*) recommends the application of flood related controls for residential development to land roughly at the 1 in 100 chance per year flood level.

The application of the Guideline has resulted in a focus on the 1 in 100 chance per year flood for land use planning, rather than a risk-based approach that considers the full range of flood sizes. Given the large flood depth range between the 1 in 100 chance per year flood and the PMF in the Hawkesbury-Nepean Valley (**Figure 1.2**), the focus on the area below the 1 in 100 chance per year flood level does not adequately address flood risk. This increases the scale of emergency evacuations and does not provide for flood compatible buildings appropriate for the levels of risk.

### *Evacuation constraints and complexity*

Due to the potentially rapid, deep and extensive flooding in the valley, evacuating large numbers of people away from flood affected areas is the primary method of reducing the risk to life during a flood. In the approved emergency plan, the NSW State Emergency Service (NSW SES) identifies mass self-evacuation by private motor vehicles as the primary method for evacuation, as other transport options are highly vulnerable to floods or have limited capacity.

Currently, there is insufficient road capacity to safely evacuate the at-risk population within the limited flood forecast time available for evacuation, with multiple communities often relying on a regional network of common roads as their means of escape.

The undulating topography of the valley results in many key evacuation routes becoming flooded at low points long before population centres are inundated. Many of the significant urban centres such as McGraths Hill, Windsor, Bligh Park and Richmond are located on flood islands which can become fully submerged in more extreme flood events.

Reliable and timely flood forecasts and warnings are critical for evacuation. The Bureau of Meteorology (BoM) aims to provide up to 15-hour flood level predictions for large flood events (**Table 1.2**). However, the NSW SES requires more than 15 hours to evacuate some flood islands in the valley during large flood events (**Table 1.3**). This could force the NSW SES to issue evacuation orders based on uncertain flood forecasts using predicted rainfall. If the flood exceeds the prediction, lives could be at risk. Alternatively, if the flood does not reach the predicted level, large numbers of people could be evacuated unnecessarily, which could cause unnecessary disruption. As has been demonstrated in the valley and elsewhere, it also means that people may be reluctant to follow future evacuation orders, putting their lives at risk.

In 1961, during an approximately 1 in 40 chance per year flood, the township of Windsor became an island surrounded by rising floodwaters. In 1867, some two thousand people in Windsor were forced to crowd onto two small, shrinking islands at Windsor (Yeo et al., 2017). During that record event, floodwaters stretched for about 20 kilometres at their widest, and waves were reported to be between one and two metres high. Evacuation of flood islands must be completed before evacuation routes are flooded. With a large population, the risk of isolation and potentially dangerous weather conditions, rescue by boat or helicopter is not an option for this valley.

**Table 1.2 Target warning lead times for selected valley gauges**

| Forecast location | Time | Trigger height | Condition | 70% of peak forecasts within |
|---|---|---|---|---|
| **Wallacia Weir** | 12 hrs | >5.0 | | ± 0.3m |
| **Penrith** | 6 hrs | >8.9m | | ± 0.3m |
| | **8 hrs** | >11.3m | | |
| **North Richmond Bridge** | 6 hrs | >16m | | ± 0.3m |
| | **15 hrs** | >18m | | |
| **Windsor** | 6 hrs | >9.6m | If peak >16m | ± 0.3m |
| | **15 hrs** | >13.7m | If peak >16m | |
| | 12-18 hrs | Peak | | |
| **Sackville** | 18 hrs | >4.6m | | ± 0.3m |
| **Lower Portland** | 18 hrs | >4.6m | | ± 0.3m |
| **Wisemans Ferry** | 12 hrs | >3.5m | | ± 0.3m |

*Source:* Service Level Specification for Flood Forecasting and Warning Services for New South Wales and the Australian Capital Territory (BoM, 2017)

**Table 1.3 Indicative evacuation timings for key flood islands on the Richmond/Windsor floodplain**

| Sector | Estimated no. of vehicles requiring evacuation | Estimated time required for community to evacuate | Level at which evacuation route is cut (AHD) |
|---|---|---|---|
| **McGraths Hill** | 2,800 | 8.1 hrs | 13.5m |
| **Pitt Town** | 1,100 | 4.8 hrs | 16.0m |
| **Windsor** | 8,500 | 19.2 hrs | 17.3m |
| **Bligh Park** | 5,600 | 13.9 hrs | 18.5m |
| **Richmond** | 9,100 | 20.7 hrs | 20.2m |

*Source:* Adapted from *Hawkesbury Nepean Flood Plan* (NSW SES, 2015), Volume 3 Chapter 2 Table 5

*Note:* An additional six hours is required to mobilise NSW SES personnel in order to deliver warnings to dwellings

### *Low levels of awareness*

Risk to life depends in part on the community's awareness of floods and responsiveness to evacuation warnings and evacuation orders. The risk increases if people delay or refuse to evacuate or drive through floodwaters. In addition, the community's preparedness for flooding is expected to influence property damage because 'flood-ready' households may raise or relocate movable items, invest in flood-compatible building materials, and take out flood insurance.

Social research was undertaken to assess current levels of community awareness and preparedness in the Hawkesbury-Nepean Valley (Newgate Research, 2014a; 2014b). The research employed a mix of qualitative and quantitative methods. Some of the key statistics are summarised in **Figure 1.3**.

Importantly, levels of awareness of and preparedness for the flood risk are low. Many valley residents have no experience of a past flood in the region. Australian Bureau of Statistics (ABS) Census data indicate that 27% of the community was not living in the valley five years prior to 2011, and almost 1 in 10 were not living in the area only 12 months prior (**Figure 1.4**). Several factors may help explain why current levels of flood risk awareness in the valley are low:

- the changing population that live and work in the valley
- the lack of significant flood events since 1992
- a misconception that Warragamba Dam stops major floods
- the vastness of the floodplain meaning many dwellings at risk are located far from the river with its inherent visual cue of the potential for flooding
- local councils apply residential flood controls only to land below the 1 in 100 chance per year flood level, leading to a misperception in the community that there is no risk above this level. As described earlier, there is significant flood risk above this level in the Hawkesbury-Nepean Valley.

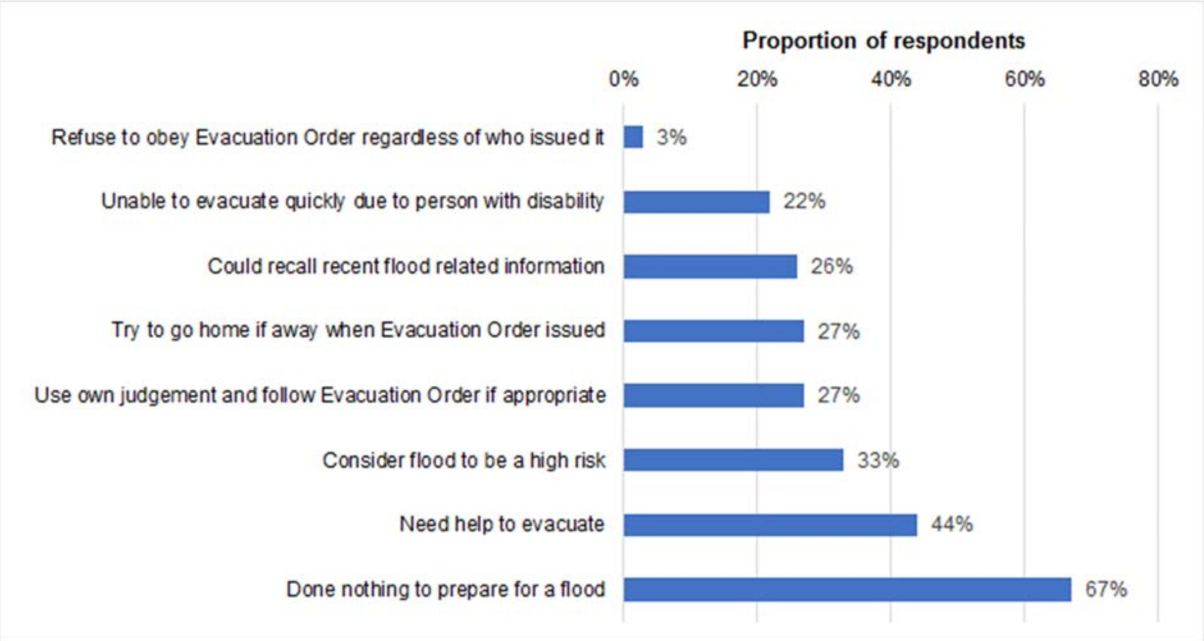



**Figure 1.3 Community flood awareness and preparedness**

*Source:* Adapted from Newgate Research (2014b)

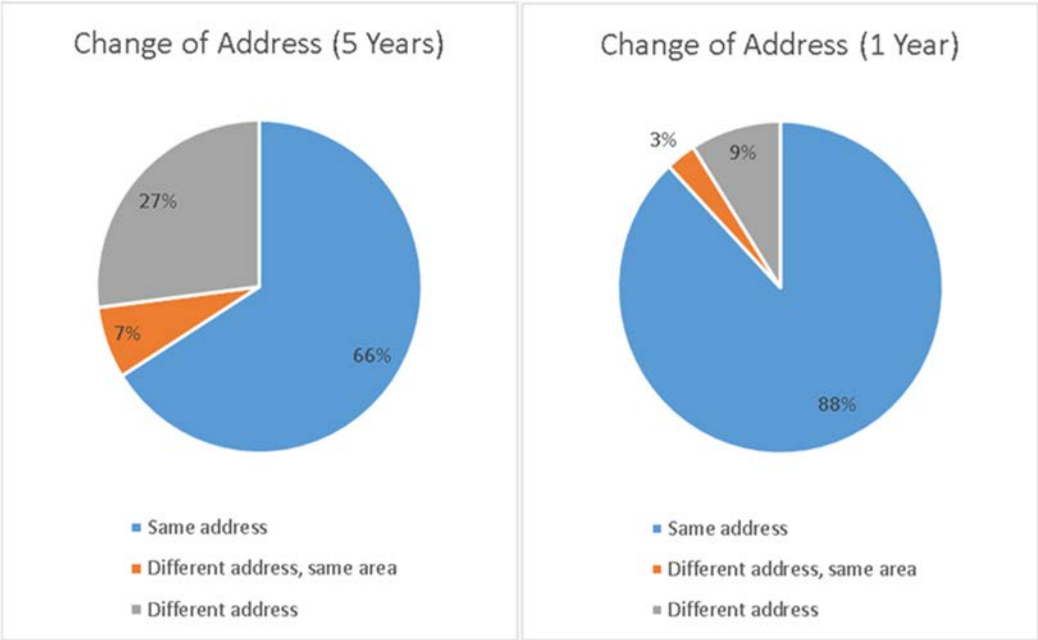



**Figure 1.4 Turnover of Hawkesbury-Nepean Valley residents**

*Note*: Data extracted for Hawkesbury-Nepean Valley floodplain by ABS from 2011 Census

In the event of an evacuation order being issued, a significant proportion of people report that they would exercise their own judgment in deciding whether to obey, and some people indicated they would refuse to evacuate under any circumstances. A significant proportion would attempt to return home – *into* the area under threat – if they were away when the order was issued.

The proportion of people needing assistance to evacuate, including family members with a disability, is high.

The research found that, if only 3% of the population do not evacuate, around 2,000 of the 64,000 people that currently need to evacuate in a 1 in 100 chance per year flood would be risking their lives. If about half of the people who would use their own judgement do not evacuate (15% total), almost 10,000 people would be risking their lives. The research highlights the challenges in ensuring people understand the need for evacuation, particularly from flood islands where early evacuation is required.

**Box 1.1 Findings of latest social research**

The most recent social research (2018) demonstrated community awareness of the significant flood risk in the Hawkesbury-Nepean Valley is very low.

Only 17% of those surveyed thought there was a high risk of flooding in the valley, 31% believed there was no risk of flooding in the valley at all, and 79% said they had done nothing to prepare for flooding.

The results of the survey confirmed that 3% of the population would not evacuate in a flood emergency and 26% would use their own judgement, rather than comply with evacuation orders.

One in two people would attempt to return home even if told access was cut due to an evacuation – particularly younger residents and those with children or pets.

## 1.2 Flood risk management framework

Flood risk is a combination of the likelihood of occurrence of a flood event and the consequences of that event when it occurs. It is the human interaction with a flood that results in a risk to the community from flooding. Flood risk varies according to the frequency of exposure to flooding, the severity of flooding, and the vulnerability of the community and its supporting infrastructure to the hazard (**Figure 1.5**). The assessment of flood risk requires an understanding of the interaction of the likelihood and consequences of flooding and how changes in hazard (e.g. through climate change or mitigation), exposure (e.g. through urban development) or vulnerability (e.g. through recovery plans) change the flood risk.

### *Flood risk management*

Flood risk management is a systematic process to identify, analyse, evaluate and treat flood risks, as described in AS/NZS ISO 31000:2018. Understanding risks is a key priority of the Australian Government's *National Strategy for Disaster Resilience* (COAG, 2011). It is also identified as a key priority for the *Sendai Framework for Disaster Risk Reduction 2015-2030*, together with investing in disaster risk reduction, enhancing disaster preparedness and strengthening disaster risk governance (UNISDR, 2015).

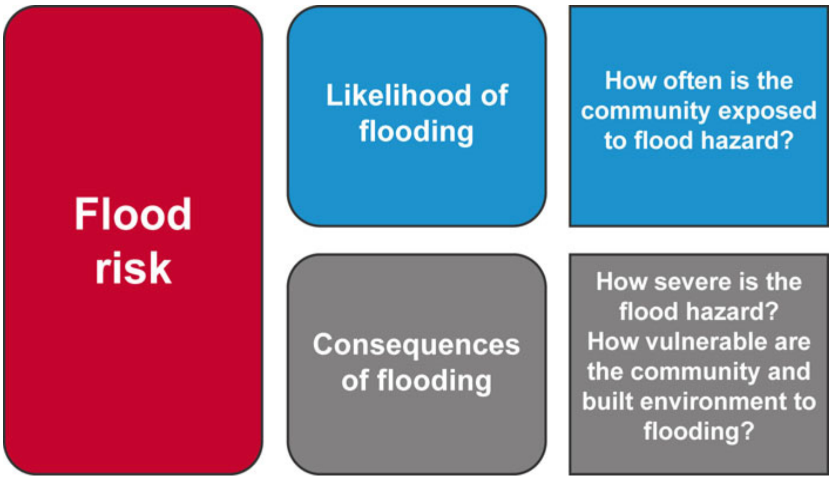



**Figure 1.5 Defining flood risk**

*Source:* D. McLuckie, OEH

In Australia, a range of guidance is available to support the process of flood risk management including the Australian Institute for Disaster Resilience Handbook 7, *Managing the Floodplain: A Guide to Best Practice in Flood Risk Management in Australia* (AIDR, 2017) and the *Floodplain Development Manual* (NSW Government, 2005). The Guide and Manual identify three types of risk to be managed in flooding:

- ***Existing flood risk*** – This is the risk associated with current development in the floodplain, which can be managed by modifying flood behaviour and reducing the exposure of people and property to flood hazards.

- ***Future flood risk*** – This is the risk associated with future development of the floodplain, which can be managed through strategic land use planning and associated development controls.
- ***Residual flood risk*** – This is the risk remaining, in both existing and future development areas, after management measures such as mitigation works, land use planning and development controls are implemented. Emergency management and recovery planning, supported by systems and infrastructure, can help reduce residual risk.

Strategic flood risk management recognises that a suite of treatment options will usually be required and that many of these actions will be interdependent.

### *Current flood risk management responsibilities in New South Wales*

As a multifaceted problem, addressing risk requires management across many areas of government and the community. The NSW Government's Flood Prone Land Policy recognises that the primary responsibility for floodplain risk management rests with local councils. Local councils carry out their functions for their service areas under a floodplain risk management process articulated in the *Floodplain Development Manual* (NSW Government, 2005). The process includes setting up a Floodplain Risk Management Committee to consult with community members and state agencies. This committee then oversees the preparation of flood studies to understand flood behaviour, floodplain risk management studies to evaluate options, and floodplain risk management plans to set out a recommended action plan to manage the risk.

The NSW Government also has a role, especially through:

- NSW Office of Environment and Heritage (OEH), which provides financial and technical support to local councils
- NSW Department of Planning and Environment, as it shapes strategic land use planning through legislation and policy
- Greater Sydney Commission, as it shapes urban development in the Hawkesbury-Nepean Valley through the *Western City District Plan* (GSC, 2018a) and *Central City District Plan* (GSC, 2018b)
- NSW State Emergency Service (NSW SES), responsible for leading the planning for response to flood events
- NSW Roads and Maritime Services, insofar as future road planning considers flood evacuation requirements
- NSW Office of Emergency Management, responsible for leading the planning for recovery from flood events.

The Commonwealth Government also has a role, particularly:

- Bureau of Meteorology, which provides weather predictions and flood forecasting services.

The *National Strategy for Disaster Resilience* (COAG, 2011) also emphasises the need for shared responsibility, such that flood prone communities, households and individuals are equipped to take appropriate action in the face of hazards.

It has been identified that the current responsibilities for flood risk management in the valley do not adequately support an integrated regional approach to land use, road and emergency planning. Eight councils in the Hawkesbury-Nepean Valley (**Figure 1.1**) have responsibility for floodplain management. The valley's flood risk problem requires an integrated, regional strategic approach.

## 1.3 Initiatives to manage the Hawkesbury-Nepean flood risk

Recognising the complexities of the flood problem and the need for a regional approach, the NSW Government has invested significantly to better manage the flood risk in the Hawkesbury-Nepean Valley. Some important investigations over the past 25 years are shown in **Figure 1.6**.

The process of investigation is outlined below. The studies up to 2012 are summarised at greater length in **Chapter 2**.

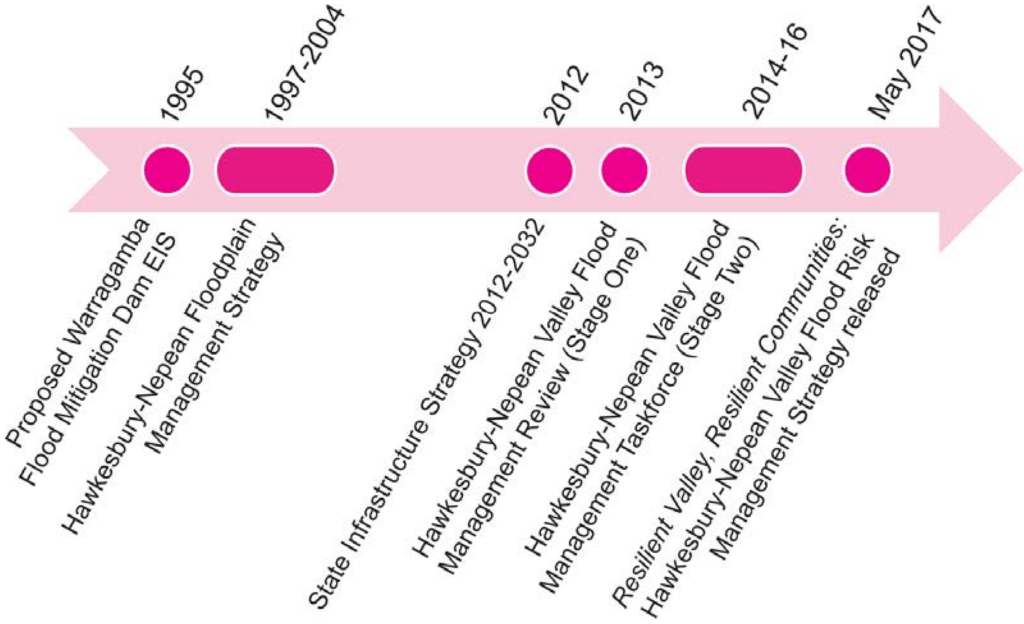



**Figure 1.6 Significant investigations of regional flood risk, Hawkesbury-Nepean Valley floodplain**

### *Pre-2012 initiatives*

During the 1980s and 1990s, evidence emerged that floods significantly larger than any yet recorded could occur in the valley.

The ability of Warragamba Dam to safely pass such extreme floods was investigated and found to not meet contemporary dam safety standards. As an interim measure, the risk to Warragamba Dam was partly mitigated in 1990 by strengthening and raising the dam wall by five metres. Despite the level of the dam crest being raised for dam safety, this extra five metres could not be used to create airspace for mitigation of downstream flood peaks because there was no change in the level of the central drum gate.

An Environmental Impact Statement (EIS) was prepared to assess further options for dam safety, as well as options to reduce the serious flood risk to people living and working in the valley (ERM

Mitchell McCotter, 1995). The EIS concluded that raising Warragamba Dam wall by 23 metres to temporarily store floodwater not only made the dam wall safe from the PMF, but would also reduce flood losses in the valley. The largest environmental impact of this option was the temporary inundation, upstream of the dam. The social and economic benefits to be gained from raising the dam wall were judged to outweigh the biophysical costs.

However, the incoming NSW Government in 1995 rejected raising the dam wall, instead deciding to mitigate the impact of flooding downstream through focussed town and emergency planning (HNFMAC, 1997; HNFMSC, 2004). This included upgrading evacuation routes to provide more time for the people in the valley to escape rising floods. However, not all the Hawkesbury-Nepean Floodplain Management Action Committee recommendations were fully implemented.

In order to satisfy dam safety requirements and to protect Sydney's water supply, an auxiliary spillway was completed at Warragamba Dam in 2002. This would divert floodwaters around the dam in a rare and extreme flood to protect the dam from overtopping and ensure it remains safe. The construction of the auxiliary spillway dealt only with dam safety issues. The auxiliary spillway does nothing to mitigate the existing and ongoing flood risk to people and businesses in the valley.

### *State Infrastructure Strategy 2012-2032*

Flooding in Queensland in 2011 renewed concern about flood risk in the Hawkesbury-Nepean Valley. In developing the *State Infrastructure Strategy 2012-2032* (INSW, 2012), Infrastructure NSW commissioned new modelling to provide up-to-date data on flood impact from both a flood damages and an economic impact perspective so that it could provide advice to Government (Molino Stewart, 2012). It was found that exposure to flooding in the valley had increased since earlier assessments, and with planned urban releases, was projected to increase further.

As a result, the *State Infrastructure Strategy 2012-2032* recommended that the NSW Government review all available major flood mitigation options, including raising Warragamba Dam wall, to significantly reduce the potential economic and social impact of flooding in the valley. If major flood mitigation was not provided, it was recommended that roads in the valley be upgraded to ensure people could evacuate in time.

The strategy also recommended a review of governance of flood management in New South Wales, with a view to ensuring a single entity with clear accountability for flood management within the NSW Government.

### *Hawkesbury-Nepean Valley Flood Management Review, 2013*

In response to the Government's adoption of the *State Infrastructure Strategy 2012-2032,* the *Hawkesbury-Nepean Valley Flood Management Review* (the Review) began in early 2013. The overarching objective of the Review was to develop a package of management actions that would ensure the Hawkesbury-Nepean Valley is strategically managed so the community is more resilient to flood risk.

The Review adopted a holistic approach that explored all options with the potential to reduce flood risk to life and property (includes homes, businesses and essential services), including governance arrangements, policy settings, planning tools, community education, and infrastructure.

The Review found that there is no simple or single solution that can completely address all of the existing flood risk in the Hawkesbury-Nepean Valley. This risk would continue to increase with population growth unless an integrated strategy incorporating both flood mitigation infrastructure, non-infrastructure and policy options was adopted.

The Review put forward 20 recommendations. Their implementation required detailed investigation to support an integrated approach to reduce overall flood risk.

Further information is available in the *Hawkesbury-Nepean Valley Flood Management Review* (NSW Office of Water, 2014a, 2014b).

### *Hawkesbury-Nepean Valley Flood Management Taskforce, 2014-2016*

The NSW Government established the Hawkesbury-Nepean Valley Flood Management Taskforce (the Taskforce) in early 2014 to implement the recommendations of the 2013 Review. The Taskforce's terms of reference are outlined in **Appendix A**.

The Taskforce was independently chaired by Mark Bethwaite AM and included senior representatives from:

- Infrastructure NSW
- Department of Premier & Cabinet
- Department of Primary Industries – Water
- WaterNSW (previously Sydney Catchment Authority)
- NSW State Emergency Service (NSW SES)
- Office of Emergency Management
- Department of Planning and Environment
- Office of Environment and Heritage (OEH)
- NSW Treasury
- Public Works Advisory (part of Department of Finance, Services and Innovation)
- Roads and Maritime Services.

A Stakeholder Reference Panel was established to enable collaboration with local councils located on the Penrith and Richmond/Windsor floodplains (Penrith City Council, Hawkesbury City Council, The Hills Shire Council and Blacktown City Council), Western Sydney Regional Organisation of Councils (WSROC), Sydney Water Corporation, Floodplain Management Australia and the Insurance Council of Australia.

The Taskforce developed a methodology to select the best mix of infrastructure and non-infrastructure measures for *Resilient Valley, Resilient Communities:* Hawkesbury-Nepean Valley Flood Risk Management Strategy (the Flood Strategy) (see **Chapter 3**). The Taskforce's extensive and detailed program of work included projects to investigate:

- flood mitigation infrastructure options
- flood risk governance and policy including land use planning
- flood modelling and information
- emergency management, evacuation and recovery
- social research and community engagement
- options analysis including cost-benefit analysis.

***Hawkesbury-Nepean Valley Flood Risk Management Strategy (Implementation Phase 1) 2016-2020***

The Taskforce's assessment of options to mitigate the flood risk culminated in the Flood Strategy, which was adopted by the NSW Government, and released in May 2017 (INSW, 2017).

The Flood Strategy includes a range of targeted actions designed to deliver nine outcomes:

- Outcome 1: Coordinated flood risk management across the valley now and in the future
- Outcome 2: Reduced flood risk in the valley by raising Warragamba Dam wall
- Outcome 3: Strategic and integrated land use and road planning
- Outcome 4: Accessible contemporary flood risk information
- Outcome 5: An aware, prepared and responsive community
- Outcome 6: Improved weather and flood predictions
- Outcome 7: Best practice emergency response and recovery
- Outcome 8: Adequate local roads for evacuation
- Outcome 9: Ongoing monitoring, evaluation, reporting and improvement of the Flood Strategy.

Phase 1 of the Flood Strategy's implementation is from 2016 to 2020, involving work across all nine outcomes, including preparation of a Warragamba Dam Raising Environmental Impact Statement and a final business case for the proposed dam raising.

## 1.4 Taskforce Options Assessment scope and purpose

This Taskforce Options Assessment Report details the investigations undertaken by the Taskforce from 2014 to 2016, which culminated in the release of the Flood Strategy. There is also some reference to the 2013 Review investigations and earlier work.

The primary purpose of this Options Assessment Report is to inform the Warragamba Dam Raising Environmental Impact Assessment, which commenced in July 2017. Considerable detail about alternative options for reducing and managing the flood risk is provided.

Investigations of flood risk in the Hawkesbury-Nepean Valley are continuing as part of the Phase 1 implementation of the Flood Strategy. Some material in this Options Assessment Report will be superseded by this ongoing work.

The data presented are based on information collated for the Taskforce. Population, risk to life, flood damages and relevant cost estimates will be updated for the Warragamba Dam Raising Environmental Impact Statement and the final business case.

Adaptive and flexible flood risk strategies are essential to managing the impact of future uncertainties such as climate change and urban development on the overall flood risk. In addition, data inputs and methods for modelling flood behaviour and the complexities of evacuation are continuously advancing.

The Taskforce assessments were conducted over a period of three years and reflect this process of increasingly sophisticated data and assessment methodologies. Ongoing investigations as part of the Warragamba Dam Raising Environmental Impact Assessment are using the latest data and methods.

## 1.5 Study area

The work of the Taskforce, and the resultant Flood Strategy, addresses flood risks associated with river or riverine flooding from the main Hawkesbury-Nepean River between Bents Basin, near Wallacia, to the Brooklyn Bridge. This is the area referred to as the Hawkesbury-Nepean Valley (the valley). The Flood Strategy does not address local catchment flooding that occurs independently of flooding in the Hawkesbury‑Nepean River.

The valley covers 425 square kilometres of floodplain (**Figure 1.1**). The extent of the floodplain is based on the largest flood that could reasonably occur (PMF). The key areas of the valley floodplain are at Wallacia, Penrith and Emu Plains, around Richmond and Windsor and numerous small pockets downstream of Sackville. The valley floodplain also includes the backwater effects (the river backing up) of flooding from the Hawkesbury-Nepean River, including in South Creek and Eastern Creek.

With a catchment area of 22,000 square kilometres, the Hawkesbury-Nepean Valley is one of the largest coastal basins in New South Wales. It includes extensive grazing areas in the southwest and large National Parks in the Blue Mountains to the northwest. Urban development in the catchment area includes country towns, such as Goulburn, Bowral and Lithgow and many outer suburbs of western Sydney, including Penrith, Richmond and Windsor.

The main river flows over 470 kilometres from its headwaters near Lake Bathurst (south of Goulburn) to Broken Bay. Its major sub-catchments are presented on **Figure 1.7**, and include the Wollondilly, Nattai, Kowmung, Coxs, Nepean, Grose, Colo, and Macdonald rivers.

More than 40% of the total Hawkesbury-Nepean Catchment to Broken Bay is upstream of Warragamba Dam. Four major rivers drain to the dam: Wollondilly, Nattai, Kowmung and Coxs. However, the Warragamba Catchment comprises around 80% of the catchment to Penrith and around 70% of the catchment to Windsor.

The Warragamba River joins the Nepean River some 3.3 kilometres below Warragamba Dam. The Nepean River at this point has a catchment area of approximately 1,760 square kilometres (which represents almost 20% of the total catchment area to Penrith). The Nepean Catchment includes high rainfall areas at the top of the Illawarra escarpment and the major WaterNSW dams at Avon, Cataract, Cordeaux and Nepean.

The Grose River is a major tributary which joins the Nepean River downstream at Yarramundi. While it has a catchment of only 650 square kilometres, it drains a high rainfall area located close to the Richmond/Windsor floodplain. Flood flows from the Grose River can sharply increase river levels downstream of Yarramundi before floodwaters arrive from the Nepean. This can potentially shorten the time available for evacuation in the lowest lying areas. Floodwaters from the Grose River alone can produce flooding of the Hawkesbury River downstream, though not to levels posing the greatest risk to life and property.

The Nepean River becomes the Hawkesbury River below the Grose River junction at Yarramundi.

South Creek joins the Hawkesbury River at Windsor. Although its catchment area of 640 square kilometres is virtually the same as the Grose River, it receives less rainfall and thus has less impact on flooding in the Hawkesbury River. Other large streams that join the river between Windsor and Lower Portland include Cattai, Little Cattai and Currency creeks.


**Figure 1.7 Sub-catchments of the Hawkesbury-Nepean River Catchment**

*Source*: INSW, NSW SES

At Lower Portland, the Hawkesbury River has a catchment area of about 13,500 square kilometres. It is joined there by the Colo River, the largest single tributary below the Warragamba River. The Colo drains an area of 4,640 square kilometres, which is equivalent to 35% of the Hawkesbury Catchment at this point. Although the Colo River joins the Hawkesbury River downstream of Windsor, the inability of floodwaters to swiftly pass Sackville Gorge can have a minor influence on flood levels upstream at Windsor.

The Macdonald River joins the Hawkesbury River at Wisemans Ferry. It drains a catchment area of approximately 1,910 square kilometres.

### *Greater Sydney's water supply system*

The Hawkesbury-Nepean Catchment began supplying Sydney with water in the 1880s with the construction of the Upper Nepean Scheme on the Nepean and Cataract rivers. Work continued in the Upper Nepean sub-catchment in the early part of the 20th century with the construction of Cataract, Cordeaux, Avon and Nepean dams.

Warragamba Dam, on the Warragamba River, was completed in 1960 and the Shoalhaven Scheme (connecting the Shoalhaven Catchment with the Hawkesbury-Nepean) was constructed in the 1970s. The water supply system was augmented in 2006 with the construction of deep-water pumping stations at Warragamba and Nepean dams enabling additional water low in the dams to be accessed in a severe drought. The Sydney Desalination Plant was completed in 2010.

Greater Sydney's water supply system comprises 21 dams and two weirs that collect water from the river systems of the Warragamba, Upper Nepean, Blue Mountains, Woronora and Shoalhaven. Water is transported via a largely interconnected network of rivers, pipes and canals to water filtration plants where it is treated and then provided to more than five million consumers in Sydney, Illawarra, the Shoalhaven, Goulburn, Blue Mountains and Southern Highlands. This water supply system is operated by WaterNSW, a NSW Government-owned corporation.

### *Upper Nepean dams*

The four Upper Nepean dams (Cataract, Cordeaux, Avon and Nepean) have limited potential to mitigate floods. While the Upper Nepean Catchment is a high rainfall area, the four dams cover 6% of the catchment to Penrith, and 5% to Windsor. In addition, the dams each have ungated spillways, which means that they cannot be proactively operated to reduce floods. Once the water levels in these dams are higher than the spillway levels, these dams spill.

### *Warragamba Dam*

Warragamba Dam is a post-tensioned concrete gravity dam constructed between 1948 and 1960 with the sole purpose of supplying water to the Sydney metropolitan area. It is Australia's largest concrete gravity dam.

The dam wall was originally completed to a height of 137 metres with a central gated spillway. The first stage of a dam safety upgrade was completed in 1990, raising the dam crest (that is, the roadway on top of the dam wall) by 5.1 metres and strengthening the dam walls, spillway training walls and energy dissipater.

In late 1998, work began on stage two of the dam safety program with the construction of a concrete-lined auxiliary spillway channel 700 metres long, 190 metres wide at the upstream end, 65 metres wide at the downstream end and with a maximum depth of 50 metres. This project also included modifications to the crest gates on the existing central spillway and further strengthening of the existing spillway training walls. The auxiliary spillway was completed in 2002. These works were designed to enable the dam to safely pass the most extreme flood, the PMF. **Figure 1.8** shows a comparison of Warragamba Dam before and after the construction of the auxiliary spillway in 2002. None of the dam safety upgrade work provided flood mitigation capacity or capability.

The dam's operating capacity is 2,027 gigalitres (GL). A gigalitre equals a billion litres.

**Figure 1.8 Warragamba Dam before and after construction of the auxiliary spillway**

*Source:* WaterNSW

Warragamba Dam is approximately 142 metres high by 351 metres long. It has a central gated spillway section approximately 90 metres wide and a concrete lined auxiliary fuse plug spillway located through the right abutment adjacent to the main dam section. The auxiliary spillway is approximately 190 metres wide at the main control section. The gates operate automatically to release water according to a pre-determined protocol, known as the H14 protocol. **Figure 1.9** illustrates the layout of the Warragamba Dam spillways and gates.

The central gated spillway is divided into five spans – one span comprises a central drum gate and the other four spans comprise radial gates.

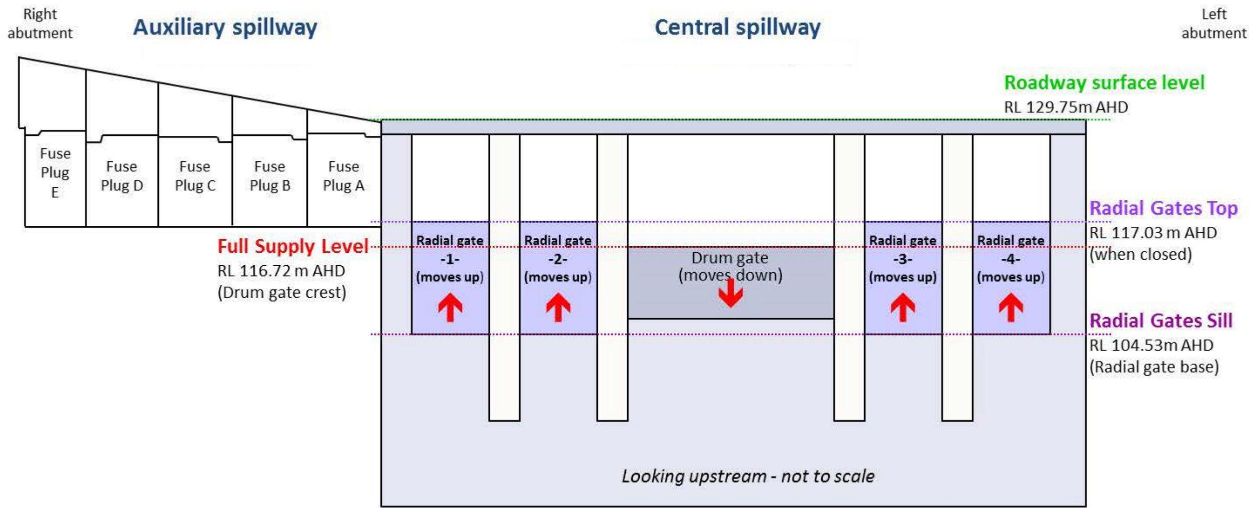



**Figure 1.9 Schematic of Warragamba Dam's spillways and gates looking upstream**

*Source*: WaterNSW

The central drum gate is 7.6 metres high and 27.4 metres wide and dictates the level of the full water supply level (FSL) in the dam. As shown in **Figure 1.10**, the drum gate is opened first to pass floating debris which could damage or block the radial gates. When the drum gate is partially open the flow over the drum gate is limited to a depth of 30 centimetres. This constraint is related to structural strength. The drum gate cannot be used to control flow over the dam spillway but offers a smooth passage to debris.

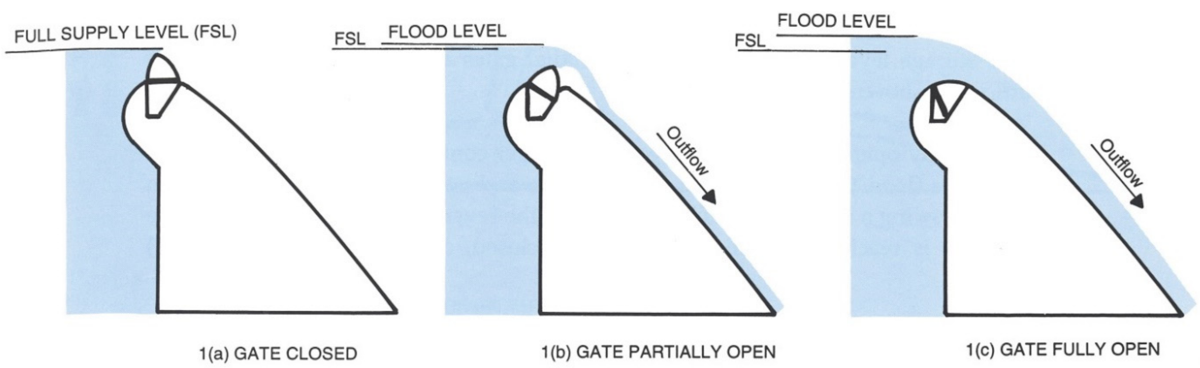



**Figure 1.10 Schematic operation of central drum gate within the central spillway**

*Source*: WaterNSW

When the storage level reaches 30 centimetres above FSL, the drum gate is completely lowered, the surface of the gate merges the spillway, and the flow over the gate is similar to free overflow. When fully lowered, there are no overtopping restrictions. The flow over the drum gate would be approximately 112 GL/day.

The four 12.5-metre-wide by 13.3-metre-high radial gates are located in the spans on either side of the drum gate (two on each side). The radial gates operate in pairs and are raised by winches.

The sill of the radial gates (that is, their lowest point) is at a level of 104.5 m AHD. This is the lowest level to which the dam can be drawn down using the crest gates. The radial gates hold back approximately 40% of the stored water (811 GL) when the dam is at FSL.

The radial gates are designed to control flow through the spillway. As shown in **Figure 1.11**, there are three stages in the operation of the radial gates:

- gate closed – there is no flow under or over the gate
- gate partially open with controlled flow – the bottom of the gate touches the flow and changing the gate opening can change the outflow
- gate fully open with uncontrolled outflow – the gate is lifted completely out of the water. There is free flow over the spillway. The flow over the spillway is not controlled when the gate is fully opened, with the flow rate only determined by the level of the water above spillway level.

The radial gates are required to open when the inflows to the dam cause water to rise above FSL as they are not designed to be overtopped.

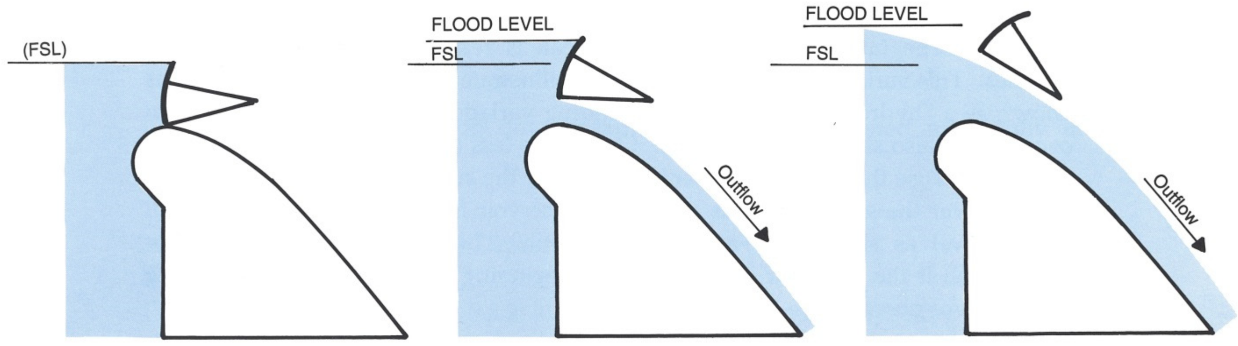



**Figure 1.11 Schematic operation of radial gates within the central spillway**

*Source:* WaterNSW

The auxiliary spillway is designed to safely pass floodwaters around the dam in severe and extreme flood events, protecting the dam from overtopping and possible failure. It protects the downstream valley from the catastrophic consequences of a dam failure, safeguards Sydney's water supply, and ensures that Warragamba Dam complies with the required safety standards.

The auxiliary spillway would only operate in about a 1 in 1,200 chance per year flood, which is considerably rarer than the 1867 flood, the largest flood on record. All floods less than this would be passed through the central gated spillway.

A series of erodible earth and clay walls or 'fuse plugs' – approximately 14 metres high built across the upstream opening of the auxiliary spillway – are designed to be sequentially washed away by the rising floodwaters. The auxiliary spillway would then divert excess floodwater around the dam. The 'flip bucket' at the downstream end of the auxiliary spillway manages the floodwaters entering the river at the point where they meet the flow from the central spillway. This minimises erosion of the riverbed and banks by dissipating the energy in the fast-flowing water.

### *Operation of the dam during inflow events*

Warragamba Dam contains around 80% of the total water storage capacity for the greater Sydney region. It supplies water directly from inlet pipes on the upstream face of the dam wall to Prospect, Orchard Hills, and Warragamba water filtration plants. In addition, Warragamba Dam releases water downstream for the North Richmond water filtration plant, which extracts water from the Hawkesbury River.

During inflow events including floods, large volumes of water come into the Warragamba Dam storage. As these inflows have elevated levels of nutrients and sediments, during these events WaterNSW models and tracks the location of these inflows within the storage. The level at which the incoming water sits in the storage will depend on the relative temperature and density of the incoming and stored water. As the dam storage is very large, it is able to handle most inflow events without any significant impact on the quality of water supplied to the filtration plants.

Other factors can affect water quality in the dam, independent of inflow events, for example, algal outbreaks and lake turnover events associated with temperature differences in the stored water. If necessary, the level of the water supply offtakes at the dam can be adjusted to maintain the quality of water being supplied, but this becomes more limited as the storage is drawn down.

Although the gates start opening whenever the water level rises above FSL, during flood events the upstream water levels can rise above the FSL. With the existing Warragamba Dam, under a PMF event, the water level upstream of the dam was modelled by the Taskforce to reach 13.7 metres above FSL.[1]

### *Environmental flows and other releases*

The New South Wales *Water Management Act 2000* recognises the need to allocate water as environmental flows for the health of our rivers and groundwater systems. Water sharing plans under the Act establish the rules for protecting and sharing water between the environmental needs of the river or aquifer and water users, and between different types of water users such as town supply, rural domestic supply, industry and irrigation. Environmental flow releases from dams are protected from extraction, and do not include those flows that spill over the dam when it is full.

The volume and pattern of water released for variable environmental flows attempts to mimic the natural inflows to partially mitigate the effect of large dams by restoring and protecting key elements of the flow. Typically, low flows pass through the dams, with a portion of the medium and high flows also released.

Variable environmental flows are already released by WaterNSW from Sydney's other water supply dams – on the Avon, Cataract, Cordeaux, Nepean, Wingecarribee, Woronora and Shoalhaven rivers. The environmental flow rules for this water are prescribed under the *Water Sharing Plan for the Greater Metropolitan Region Unregulated River Water Sources 2011*.

[1] PMF subject to refinement to comply with *Australian Rainfall and Runoff 2016* (Ball et al., 2016)

Variable environmental flows from Warragamba Dam were approved as part of the 2017 Metropolitan Water Plan (MWD, 2017). In the case of Warragamba, the dam infrastructure will need to be modified to allow for new environmental flow releases. These modifications would ideally be undertaken in conjunction with any significant modifications to the dam wall.

## 1.6 Options assessment overview

This Taskforce Options Assessment Report sets out all the flood risk management options assessed in the 2013 Review and under the Taskforce. The outline of the Report is as follows:

- Chapter 2 summarises previous studies up to the 2013 Review
- Chapter 3 presents the methods used to assess flood risks in the valley
- Chapter 4 provides an overview of the options assessment
- Chapters 5 to 9 detail the assessment of infrastructure and non-infrastructure options
- Chapter 10 presents the conclusion of the options assessment.

# 2 Previous studies

The flood risk in the Hawkesbury-Nepean Valley has long been recognised as a significant issue. Substantial work was done in the 1990s and 2000s to assess regional flood risk in the valley, and to identify and evaluate options to mitigate those risks. This chapter summarises investigations from the 1990s up until the 2013 Review. The 2013 Review considered this earlier work in the context of new and emerging methodologies and technologies available today.

## 2.1 Proposed Warragamba Flood Mitigation Dam Environmental Impact Statement (1995)

The *Warragamba Flood Mitigation Dam Environmental Impact Statement* (ERM Mitchell McCotter, 1995) was prepared to assess the impacts of a proposed flood mitigation dam at Warragamba. This involved a proposal to raise the crest of the existing Warragamba Dam by 23 metres and thicken the dam wall. The objective of the proposal was “to significantly reduce the impacts of flooding in the Hawkesbury-Nepean Valley to the degree which optimises the benefits against the costs, having regard to the environmental consequences of the project” (p.1.5). It was also noted that the dam raising proposal could address the dam safety issue but excluded altering the dam’s permanent water storage level.

An essential component of the Environmental Impact Statement (EIS) was the development of detailed computer-based hydrologic and hydraulic models to estimate the size and frequency of flooding at Warragamba Dam and in the Hawkesbury-Nepean Valley. The models and their results were reviewed by Australian and international experts who confirmed the validity of the work (see WMA, 1996).

Several strategies to mitigate the risk were considered in the 1995 EIS:

- ***permanent lowering of Lake Burragorang to provide airspace for temporary capture of floodwaters*** – rejected due to impacts on Sydney's water supply
- ***raising Warragamba Dam or building a new higher dam in its vicinity to provide airspace for temporary capture of floodwaters*** – preferred option
- ***drainage improvements such as channel dredging or channel straightening*** – rejected due to unacceptable financial and environmental costs
- ***floodplain works such as levees or flood proofing of buildings*** – rejected as not suitable for the majority of flood-prone houses, not effective in larger floods, and would disadvantage many people
- ***non-structural options such as property purchase*** – rejected due to the high financial, social and environmental costs of large-scale relocation of residential populations from the floodplain
- ***a combination of strategies*** – rejected because strategies joining two or more infrastructure options were found to have the combined financial, social and environmental costs of individual options, without overcoming their deficiencies.

Four options to raise Warragamba Dam to enable a flood storage function were considered: 15- metre raising, 23-metre raising, 30-metre raising and a new downstream rockfill dam

35 metres higher than the existing dam. The 23-metre option was ultimately selected as the preferred option, with a benefit cost ratio of 1.9 (ERM Mitchell McCotter, 1995).

With a change of Government policy, this crest raising proposal did not proceed. As an alternative dam safety measure, construction of an auxiliary spillway to safely pass the probable maximum flood (PMF) was completed in 2002.

## 2.2 Achieving a Hawkesbury-Nepean Floodplain Management Strategy (1997)

In April 1997, the NSW Government established the Hawkesbury-Nepean Flood Management Advisory Committee, to prepare the comprehensive report entitled *Achieving a Hawkesbury-Nepean Floodplain Management Strategy* (HNFMAC, 1997) to address the significant flood problem in areas of the Hawkesbury-Nepean Valley downstream of Warragamba Dam. The principal study area was defined as that part of the Hawkesbury-Nepean Valley downstream of Warragamba Dam to Spencer, including the creek and river catchments which are potentially affected by mainstream flooding of the Hawkesbury and Nepean Rivers.

Consultants were commissioned to undertake the following specialist technical studies to assist the Committee in preparing the 1997 Strategy:

- *Impacts of Flooding on Communities and Infrastructure* (Molino Stewart, 1997)
- *Engineering Studies to Modify Flood Behaviour* (WMA, 1997)
- *Land Use Planning and Development Control Measures* (Don Fox Planning and Bewsher Consulting, 1997)
- *Emergency Response Planning and Traffic Infrastructure* (Patterson Britton & Partners and Masson & Wilson, 1997).

The Committee drew upon the data and detailed findings presented in these studies when preparing the 1997 Strategy report. A brief overview of each of these studies is presented below.

### *2.2.1 Impacts of Flooding on Communities and Infrastructure (1997)*

*Impacts of Flooding on Communities and Infrastructure* (Molino Stewart, 1997) identified and evaluated the impacts and consequences of flooding on communities and infrastructure within the study area and proposed measures to mitigate those impacts.

The report found that more than half of the tangible average annual damages would be caused by flooding above the urban planning levels in the valley at the time. The magnitude of damages in any one of these floods would place a significant burden upon the local, regional and state economies.

The report recommended that flooding be considered in the planning, design and operation of all assets, in all floods, up to the PMF.

### 2.2.2 Engineering Studies to Modify Flood Behaviour (1997)

*Engineering Studies to Modify Flood Behaviour* (WMA, 1997) was undertaken to identify and evaluate various engineering works for the river system and floodplain as part of an overall strategy to mitigate flood hazards. This study used computer models to define flood behaviour for the full range of floods in the valley, and to evaluate a range of possible flood mitigation options to reduce flood hazards.

#### *Valley-wide options*

Consideration was given to major new flood mitigation dams, including on Wollondilly River, Coxs River, Nepean River, Grose River, South Creek and Colo River. (The potential to raise Warragamba Dam for use as a flood mitigation dam was not revisited as part of this study.) Preliminary model results showed that some mitigation dams could reduce flood levels in the valley, but the high economic and environmental costs involved would render them inappropriate.

Diversion channels would, in general, have less impact on flood levels, but would still involve high economic and environmental costs.

#### *Local options*

Options for site-specific flood behaviour modification were considered for communities at Wallacia, Penrith/Emu Plains, Richmond/Windsor and downstream of Sackville. These included levees, retarding basins, flow deflectors, emergency access, bank protection and channel improvements. Most options were considered impractical for economic, social and environmental reasons. Some were deemed worthy of further consideration by the relevant local councils, as part of the preparation of their floodplain risk management plans.

#### *Conclusions*

The *Engineering Studies to Modify Flood Behaviour* study concluded that the number of potentially viable structural engineering options was very limited due to the nature of the valley, the widespread urban development and the magnitude of the flood hazard.

### 2.2.3 Land Use Planning and Development Control Measures (1997)

*Land Use Planning and Development Control Measures* (Don Fox Planning and Bewsher Consulting, 1997) was carried out to:

- review current floodplain planning practice within the valley
- formulate and assess various land use planning options
- identify appropriate regional planning measures, policies and guidelines, to assist local floodplain management.

A key recommendation of the study was that land use planning measures provide the greatest opportunity to control future increases in risk. Floodplain management deals with occupying the floodplain and optimising its use in a manner which is compatible with the flood hazard and at a level of risk acceptable by the community.

The study recommended that the full range of flood risks up to the PMF be considered in metropolitan planning strategies, and that flood emergency response be considered when planning for urban development. To achieve sound floodplain management through strategic land use planning at the local government scale, the study recommended the preparation of best practice planning, subdivision and building design guidelines to assist councils to prepare local environmental plans and development control plans.

#### *2.2.4 Emergency Response Planning and Traffic Infrastructure (1997)*

*Emergency Response Planning and Traffic Infrastructure* (Danielson & Associates et al., 1997) reviewed flood emergency plans and the regional urban road network and its capacity to handle evacuation traffic. Communications, flood forecasting and flood warning systems, and interdependencies with utilities and relevant community support services in the valley, were also reviewed.

The report found that without any improvement in evacuation routes and if local flooding was occurring in the evacuation area, some tens of thousands of people would be unable to self-evacuate by road, and might rely upon limited rescue operations if floodwaters rose to inundate the flood islands.

The study identified many opportunities to improve the effectiveness of flood emergency plans in the valley, including to upgrade evacuation routes.

#### *2.2.5 Summary*

The primary objective of the Hawkesbury-Nepean Flood Management Advisory Committee was to prepare a comprehensive strategy for floodplain management in the Hawkesbury-Nepean Valley. The components and outcomes of the 1997 *Hawkesbury-Nepean Floodplain Management Strategy* are presented in **Figure 2.1**.

### 2.3 Implementation of the Hawkesbury-Nepean Floodplain Management Strategy (1998-2004)

#### *2.3.1 Hawkesbury-Nepean Floodplain Management Strategy Implementation report (2004)*

Following adoption of the 1997 Hawkesbury-Nepean Floodplain Management Strategy, the NSW Government committed $71 million over five years to implement the strategy. The *Hawkesbury-Nepean Floodplain Management Strategy Implementation* report (HNFMSC, 2004) provides details of the key outcomes and outputs of the strategy implementation between 1998 and 2004. These are summarised in **Table 2.1**, and some illustrations are provided in **Figure 2.2**.

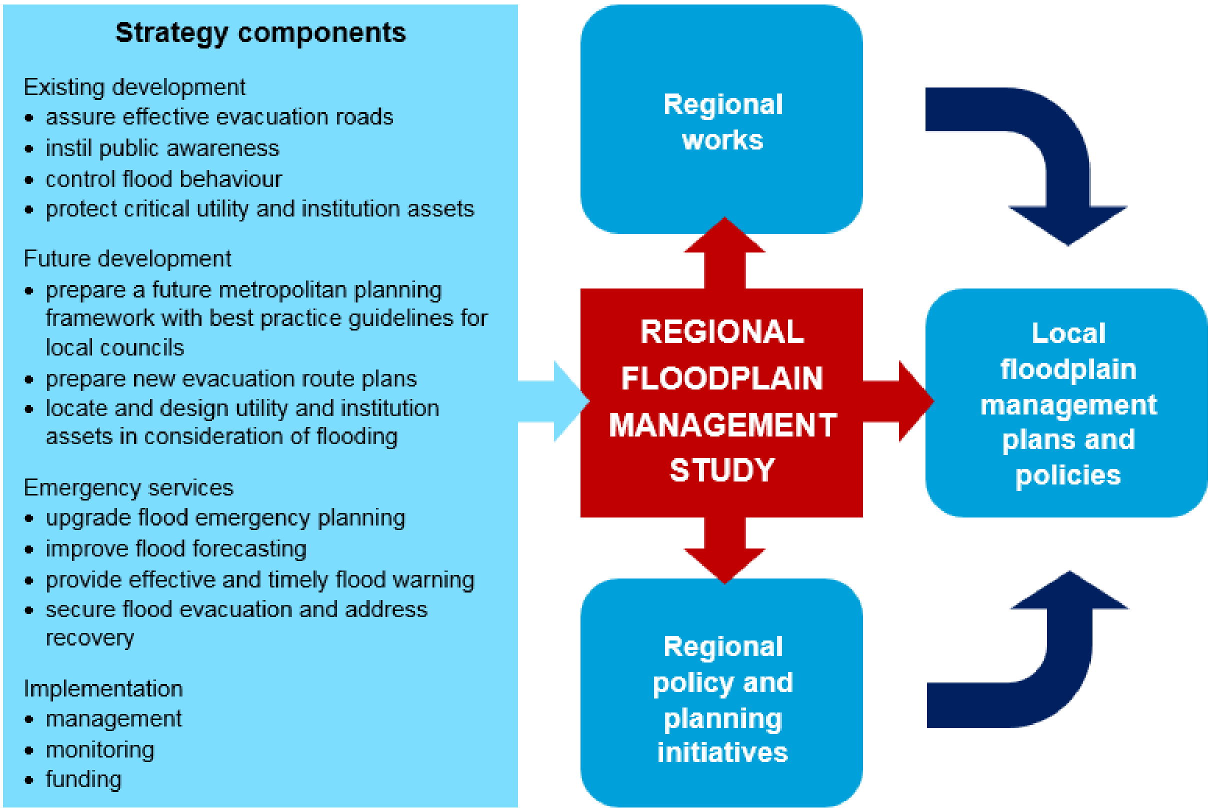



**Figure 2.1 The 1997 Hawkesbury-Nepean Floodplain Management Strategy**

*Source:* HNFMAC (1997)

**Table 2.1 Key outcomes of the Hawkesbury-Nepean Floodplain Management Strategy**

| Strategy initiative | Key outcomes | Expenditure (1998-2004) |
|---|---|---|
| **Improved evacuation routes** | Upgraded evacuation routes for five key towns | **$58.1 million** |
| **Better flood forecasting and warning** | Improved accuracy and reliability of flood forecasts | **$3.2 million** |
| **Enhanced emergency response to floods** | Improvements to emergency response operations | **$3.7 million** |
| **Faster recovery for affected communities** | Reduced potential for down-time of essential services; improved community support services for recovery | **$0.2 million** |
| **Increased awareness of flood risks** | Implementation of regional public awareness campaign targeting community and councils | **$4.0 million** |
| **Regional approach to flood planning** | Completion of the Regional Floodplain Management Study | **$0.3 million** |
| **Improved understanding of flood hazards** | Release of the computer-based Flood Hazard Definition Tool, together with workshops | **$0.3 million** |
| **Development of best practice land development guidelines** | Release of Land Use Planning, Subdivision and Building Guidelines | **$1.5 million** |
| | **TOTAL EXPENDITURE** | **$71.3 million** |

*Source:* HNFMSC (2004)

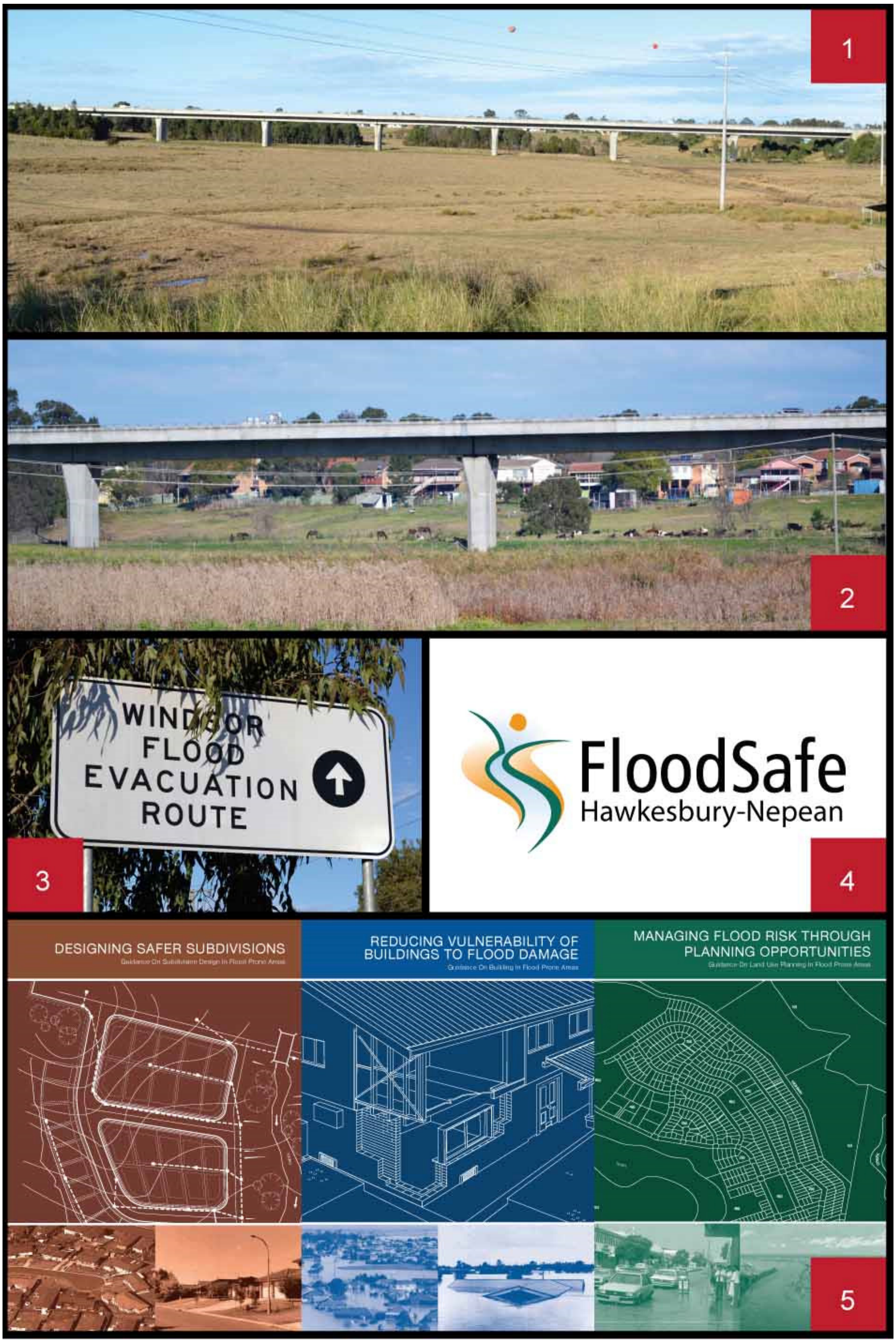



**Figure 2.2 Examples of outputs from Hawkesbury-Nepean Floodplain Management Strategy**

(1), (2): New Jim Anderson Bridge opened in 2007, flood evacuation route for Windsor across South Creek (completed as part of a larger road upgrade program); (3): Typical signage advising of flood evacuation routes; (4): FloodSafe community education and awareness program; (5): 2006 best practice guidelines

*Source:* NSW Office of Water

#### *2.3.2 Best practice land use planning, subdivision and building guidelines (2006)*

A key outcome of the *Hawkesbury-Nepean Floodplain Management Strategy* was the preparation of the following three best practice land development guidelines:

- ***Land Use Planning Guidelines** – Managing Flood Risk Through Planning Opportunities: Guidance on Land Use Planning in Flood Prone Areas* (Hawkesbury-Nepean Floodplain Management Steering Committee, 2006a)
- ***Subdivision Guidelines** – Designing Safer Subdivisions: Guidance on Subdivision Design in Flood Prone Areas* (Hawkesbury-Nepean Floodplain Management Steering Committee, 2006b)
- ***Building Guidelines** – Reducing the Vulnerability of Buildings to Flood Damage: Guidance on Building in Flood Prone Areas* (Hawkesbury-Nepean Floodplain Management Steering Committee, 2006c).

Together, the three guidelines provide comprehensive information on how finished landforms, road layouts, building design, construction methods and materials can affect the consequences from flooding and hence flood risk.

## 2.4 Hawkesbury Floodplain Risk Management Study and Plan (2012)

Hawkesbury City Council adopted the *Hawkesbury Floodplain Risk Management Study and Plan* (Hawkesbury FRMS&P) in 2012 (Bewsher Consulting, 2012). This was prepared in accordance with the floodplain risk management process outlined in the *Floodplain Development Manual* (NSW Government, 2005) with financial assistance from the NSW Government under the NSW Floodplain Management Program.

The Hawkesbury FRMS&P defined flood risks related to Hawkesbury River flooding within the Hawkesbury local government area, and evaluated local options to manage those risks. Investigation of regional flood mitigation measures such as changes to the operation of Warragamba Dam, raising of the dam wall or river dredging was excluded from the scope.

No new flood modelling was undertaken for the Hawkesbury FRMS&P. Nonetheless, flood maps were updated incorporating LiDAR terrain data captured in 2007-2008.

A principal output from the study was an action plan to manage existing and future flood risks within the Hawkesbury local government area. The plan recommended:

- measures to improve understanding of flood behaviour and evacuation capacities
- measures to promote risk-informed land use planning
- measures to increase community flood education and resilience
- measures to enhance community safety during floods
- McGraths Hill levee feasibility study
- voluntary house raising scoping study.

The Taskforce reviewed the investigations and recommendations of the Hawkesbury FRMS&P to inform the options assessment.

# 3 Flood risk assessment methodology

## 3.1 Introduction

A flood risk assessment is essential for defining the scale of the flood problem and for forming a base case against which the effectiveness of options to reduce the risk can be tested.

This chapter outlines the methodology formulated under the Taskforce for developing this base case both for current (2016) risk and for future (2041) risk. Two particular components of flood risk are assessed: the potential risk to life; and potential impacts on homes, businesses and critical assets. This methodology included:

1. flood modelling to quantify the likelihood and behaviour of floods
2. development of a floodplain assets database to define current and future exposure
3. quantifying the potential consequences from floods for the current and future base case flood risks by estimating the:
    - extent of potential danger to personal safety or risk to life using a flood evacuation model
    - potential impacts on homes, businesses and critical assets using a flood damages assessment.

These steps are outlined in further detail below.

## 3.2 Flood modelling

### *3.2.1 Introduction*

The Insurance Council of Australia has identified that the Hawkesbury-Nepean Valley has the most significant flood risk exposure in New South Wales, if not Australia.

The last regional flood studies were prepared more than 20 years ago, and there have been considerable advances in the science of flood modelling, as well as some changes to the valley landscape, since then. There is also a requirement to consider the possible impacts of climate change on flooding. For these reasons, and to ensure accessible and consistent flood risk information is available, the NSW Government commissioned specialist flood engineering firm, WMAwater Pty Ltd, to prepare a new Hawkesbury-Nepean Valley Regional Flood Study (Regional Flood Study). The new study was reviewed by a highly experienced, independent flood expert to check the validity and accuracy of the data, method and results.

The new Regional Flood Study is a technical document describing the flood behaviour of the main Hawkesbury-Nepean River from Bents Basin near Wallacia downstream to Brooklyn Bridge, and the backwater flooding associated with this main river flooding. It describes regional flood behaviour both for existing conditions and under projected climate change. The Regional Flood Study does not include shorter-duration local catchment flooding or overland flow inundation. It has multiple applications for a variety of users, including to inform:

- the evaluation and design of measures to reduce flood risk
- evacuation and emergency planning
- Hawkesbury-Nepean regional and local land use planning, development control processes and decision-making to improve flood resilience in the valley
- communities and stakeholders about current and future flood risk to increase flood awareness in the valley.

The new Regional Flood Study was progressed in stages, with advances in methods applied throughout the process consistent with evolving national best practice and guidelines.

The Warragamba Dam Raising Environmental Impact Statement and the final business case will draw upon the most up-to-date flood modelling. Some key features and results of the work are summarised below.

### *3.2.2 Method*

The new Regional Flood Study updates the 1996 flood study (WMA, 1996), which at the time was the most extensive flood study ever carried out in Australia. The 1996 study included a detailed analysis of primary flood data and used the most up-to-date technology at the time. It forms a foundation for the revised work.

As part of the new Regional Flood Study, the previous flood frequency analysis (FFA) was updated using current techniques and 22 years of additional data, albeit with no additional major floods over that period. The FFA was used to verify the probability of different size flood events occurring in the Monte Carlo simulations (see below).

Hydrology is the study of how rainfall is converted into runoff from a catchment over time. Differing combinations of rainfall (amounts, timing, location) and ground conditions influence flood behaviour. A hydrologic model (RORB) was developed to model the rainfall-runoff characteristics of the river systems feeding into the Hawkesbury-Nepean Valley. This represents a 22,000 square kilometre area, extending from Goulburn in the south to Wollemi in the north.

The hydrologic model was ‘calibrated’ and ‘verified’ by comparing the modelled results to seven actual, recorded historic flood events. Calibration sites included four stream gauging stations located upstream of Warragamba Dam, Warragamba Dam and various stations downstream. The model was used to estimate the flood flows from the various sub-catchments feeding into the Hawkesbury-Nepean River system for a range of rainfall events.

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), hazard and flows. A quasi two-dimensional hydraulic model (RUBICON) was developed to calculate peak flood levels resulting from the flood flows. This was calibrated and verified using 10 flood events.

A Monte Carlo framework was established to better replicate observed flood behaviour. Real flood events exhibit an enormous degree of variability, most of which is determined by exactly where and when rain falls. Flood events are also influenced by how wet the catchment is, and in the case of the Hawkesbury-Nepean floodplain, the levels in Warragamba Dam prior to an event. To better account for this variability, flood estimation in Australia is moving from deriving a single event (such as the 1 in 100 chance per year flood) to Monte Carlo modelling, where thousands of events are simulated and ranked. Understanding the potential variability of floods in the valley is critical to gaining an accurate estimate of the flood risk to life. For the current study, the variability in each of the following key input variables was estimated from observed events, and a Monte Carlo framework was established to randomly sample each variable from within the range of possible inputs:

- rainfall intensity/frequency/duration
- spatial pattern of rainfall – where in the catchment rain falls
- temporal pattern of rainfall – when in the event rain falls
- initial loss – rain 'lost' at the beginning of an event through infiltration into the soil
- pre-burst rainfall – rain that occurs before the most intense burst of the storm
- dam drawdown – the level of Warragamba Dam before the start of an event
- relative timings of tributary inflows
- tides.

In all, 19,500 model simulations were conducted, which represents the range of floods that could be experienced in about 200,000 years.

The variables from the Monte Carlo analysis were fed to the hydrological (rainfall-runoff) model, and the resultant flows, together with the other variables including relative timings of tributary inflows and tides, were fed into the hydraulic (river/floodplain flow behaviour) model. This was used to assess flood behaviour.

### *3.2.3 Results: existing flood behaviour*

The Regional Flood Study calculates flood levels, extents, depths, hazard and flood function for a series of 'design' events, which are representative of the frequency quantiles from the Monte Carlo modelling. The design events included are the 1 in 5, 1 in 10, 1 in 20, 1 in 50, 1 in 100, 1 in 200, 1 in 500, 1 in 1,000, 1 in 2,000, and 1 in 5,000 chance per year events, and the probable maximum flood (PMF), which is modelled using the probable maximum precipitation (PMP). For the purpose of floodplain management in the valley, the PMF is approximately a 1 in 100,000 chance per year flood event. The change in peak flood levels with distance upstream is presented in **Figure 3.1** and **Figure 3.2**.

Rate of rise, time to rise, rate of fall, time to fall, time above critical levels and travel time were also extracted from the model at a number of key locations. These results are primarily to inform emergency response and evacuation planning. An example of the outputs is shown in **Figure 3.3**, highlighting the natural variability in these parameters.

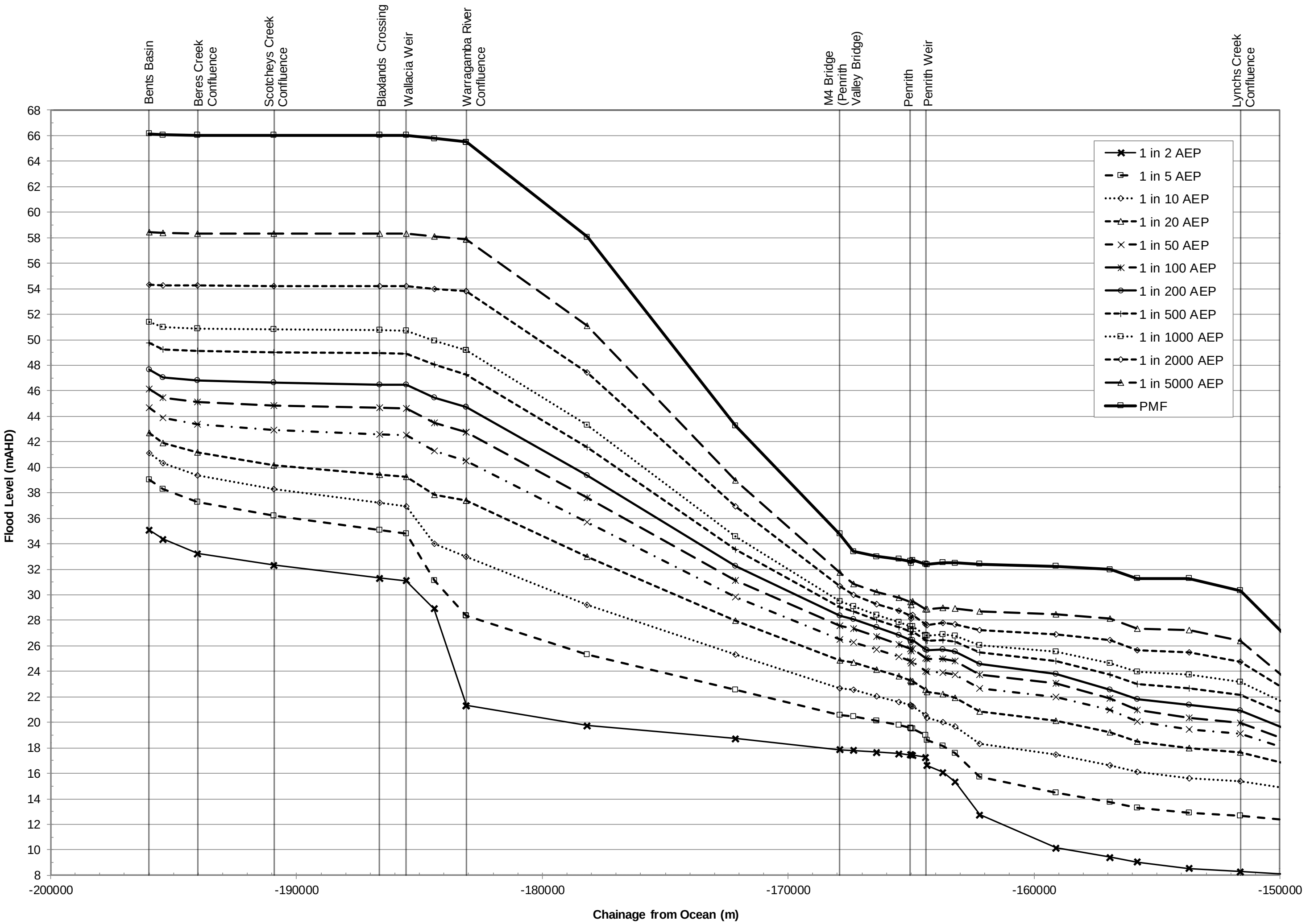
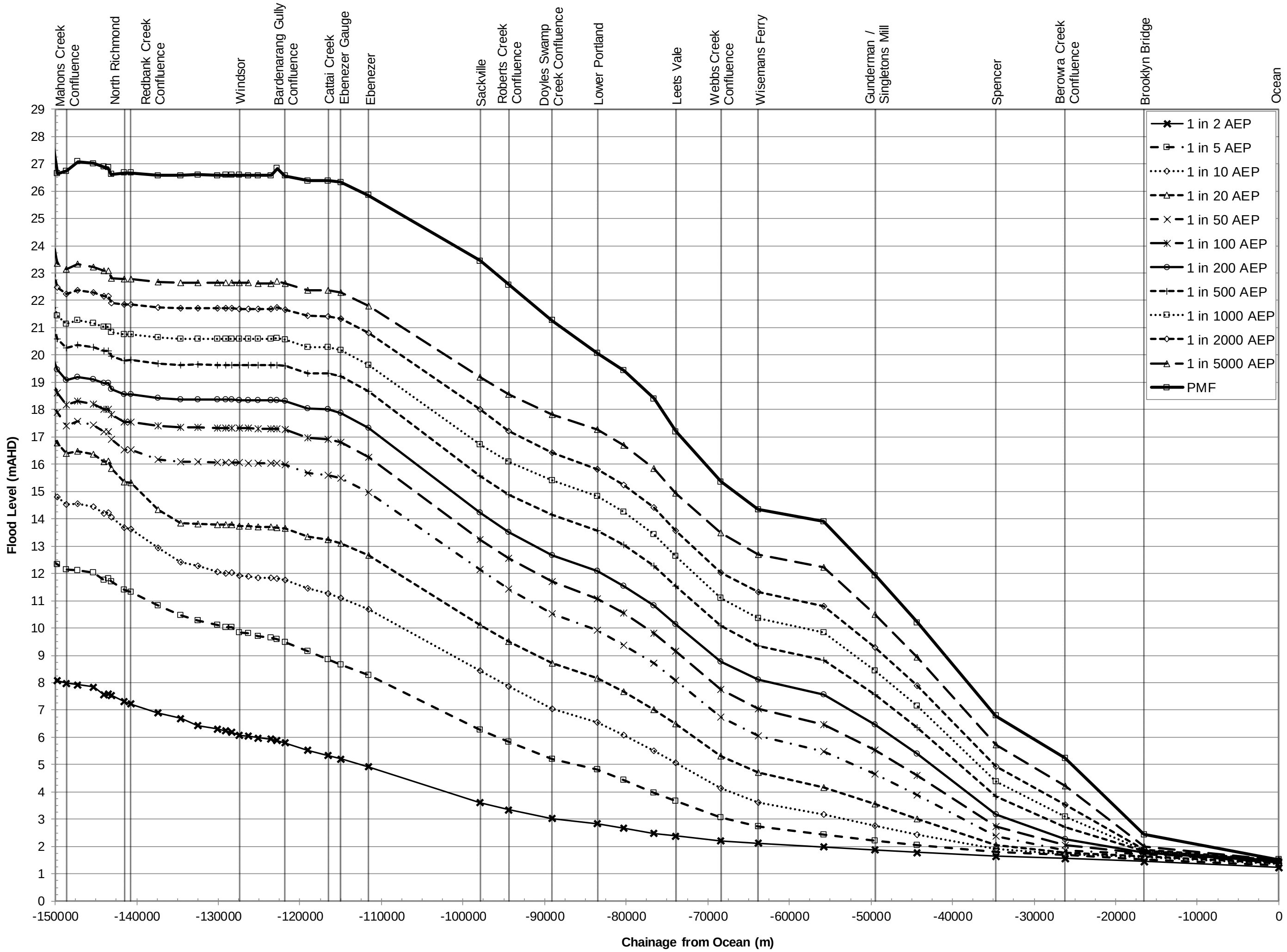



**Figure 3.1 Peak flood profiles, upstream**

*Source:* WMAwater for INSW




## Figure 3.2 Peak flood profiles, downstream

*Source:* WMAwater for INSW

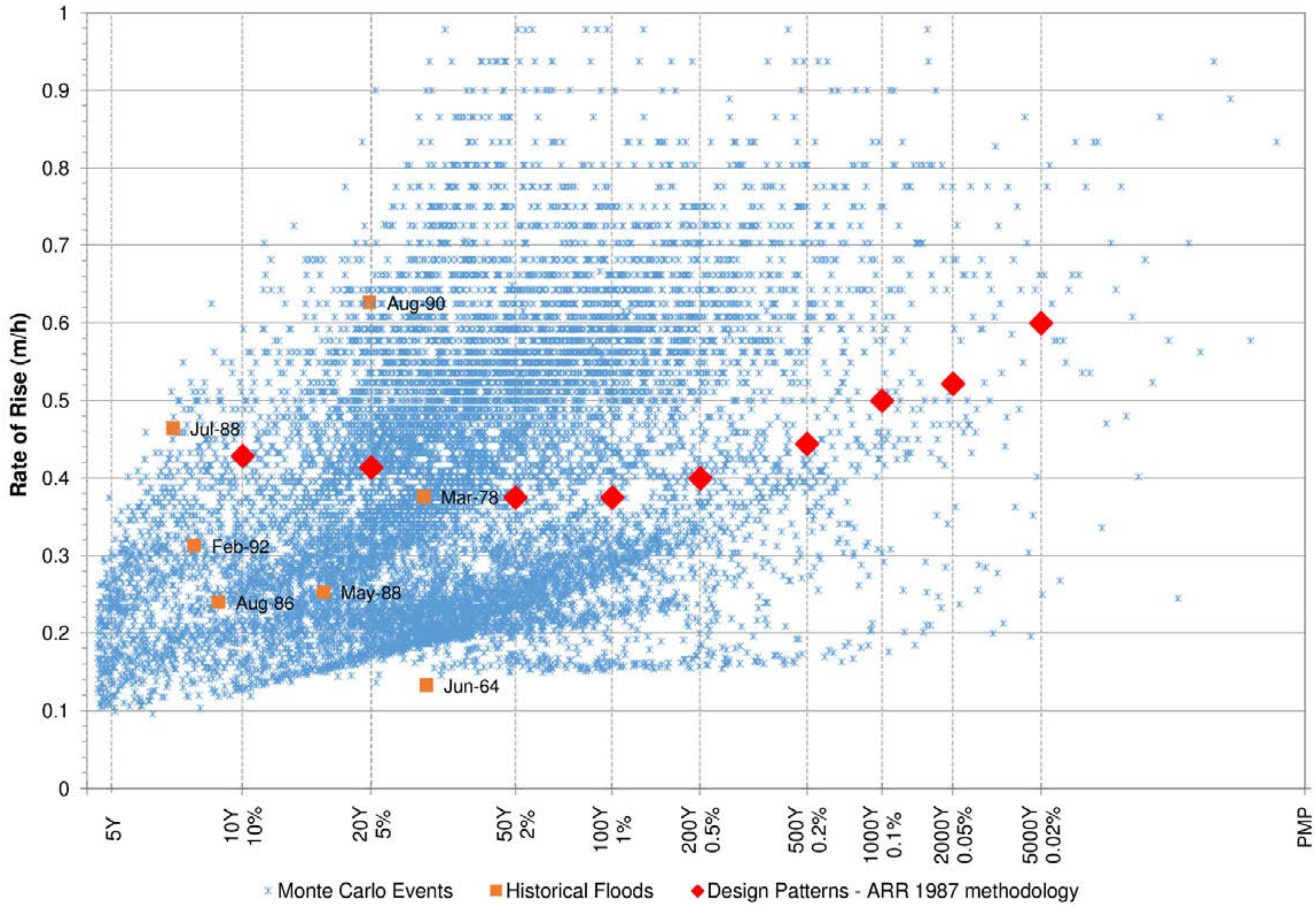



**Figure 3.3 Rate of rise between 4 and 10 metres versus the average frequency of the flood, Windsor**

*Source:* WMAwater for INSW

**Box 3.1 Nepean River Flood Study, 2018**

Penrith City Council's *Nepean River Flood Study* (Advisian, 2018) defines flood behaviour in the Nepean River floodplain within the Penrith Local Government Area. The flood modelling was undertaken using a two-dimensional hydrodynamic modelling package that covers the Nepean River floodplain between Glenbrook Creek and Yarramundi Bridge. The model is based on LiDAR terrain data largely captured in 2002 and contemporary representations of terrain in the Penrith Lakes Scheme and for several development sites.

The *Nepean River Flood Study* should be used to inform the setting of flood planning levels within its study limits. However, the Regional Flood Study is the best source of information for evacuation and risk to life assessments. This is because it applied a Monte Carlo approach to capture the real variability of floods, which is a critical determinant in emergency planning and response.

### *3.2.4 Climate change sensitivity tests*

Climate change can alter flood behaviour in the Hawkesbury-Nepean Valley by changing:

- rainfall intensity
- storm type frequency and seasonality
- rainfall spatial and temporal patterns
- antecedent catchment conditions
- dam levels prior to flood producing rainfall.

The interaction of these characteristics makes predicting the impact of climate change on flood behaviour complex.

Climate change predictions are made based on modelling changes to temperature and rainfall for various representative concentration pathways (RCPs), which consider projected increases in greenhouse gas concentrations.

*Australian Rainfall and Runoff 2016* recommends that RCP 4.5 and RCP 8.5 be used for impact assessment. Projected increases in temperature and rainfall for Sydney were extracted using CSIRO's Climate Futures tool.

The following rainfall increases were chosen for the assessment:

- 4.9 % (high emissions, 2030)
- 9.1% (low emissions, 2090)
- 13.9% (medium emissions, 2090)
- 18.6% (high emissions, 2090).

An increase in rainfall intensities of 9.1% would increase the 1 in 100 chance per year flood level by 1.3 metres at Wallacia, 0.5 metres at Penrith, 0.7 metres at North Richmond and Windsor, and 0.6 metres at Wisemans Ferry.

**Box 3.2 2018 climate change assessments**

Further assessment of the potential impacts of climate change is being conducted for the implementation phase of the Flood Strategy, including:

- potential effects on the location, intensity and seasonality of the East Coast Low weather systems that are responsible for the majority of flood rainfalls in the Hawkesbury-Nepean Valley
- use of downscaled climate change modelling (NARCLiM)
- potential effects of sea level rise.

## 3.3 Floodplain exposure dataset

In addition to information on flood likelihood and behaviour, the following information was needed for evacuation modelling and flood damages assessment:

- spatial and temporal distribution of assets (residential, commercial and other infrastructure including roads and utilities)
- spatial and temporal distribution of population and vehicles based on evacuation subsectors.

Current and future development scenarios for the valley were collated by Infrastructure NSW and NSW Department of Planning and Environment. The Australian Bureau of Statistics (ABS) 2011 Census was used to establish the base dataset for assets, population and vehicles. The 2011 Census data were extrapolated so that 2016 represented the current level of residential development. The 2011 Census was used as the most recent complete demographic data available for the Taskforce.

It is important to understand future flood risk associated with potential growth that could occur under the current land use planning arrangements. Future scenarios were developed to assess the impact of different growth projections on flood risk. Best practice requires consideration of future exposure to assess the efficacy of options to reduce flood risk.

For future development, 2041 was adopted as a reasonable point in time to represent the potential planned development that could take place under the current planning policy. Growth rates are difficult to predict as they vary according to the prevailing economic and demographic factors, and land use planning arrangements.

The year 2041 was selected as it represented a 30-year planning horizon from the 2011 Census and was the period over which reasonable projections were available. The cost benefit analysis extended to 2055 (30 years after the finalisation of construction of potential flood mitigation infrastructure) with the level of development assumed to stay constant at 2041 levels. The year 2026 was adopted to represent an intermediate level of development.

The 2041 development scenarios do not represent a growth target. They provided a means to test the sensitivity of future flood risk to growth, and to measure the effectiveness of potential flood mitigation options.

Future residential development in the floodplain assets database comprised the following components:

- ***Future development areas*** – future development areas is the collective term that includes the North West Growth Area, other urban release areas, large proposed subdivisions and other identified multi-level medium and high-density sites with any part of the area located below the PMF.
- ***Permissible infill development*** – permissible infill development includes additional residential dwellings such as dual occupancies and town house developments that could be constructed where the existing land zoning already permits that land use. This would result in an increased residential density below the PMF.

Given the uncertainty of the rate of future growth, two levels of permissible infill development were considered, a low and high level. These growth scenarios allowed for testing the sensitivity of the rate of infill development on evacuation capacity, flood damages, and the benefits of flood mitigation options.

The projected data were drawn from a number of sources including:

- NSW Department of Planning and Environment's growth forecasts and strategic land use planning data
- Bureau of Transport Statistics' (now Transport Performance Analytics, a part of Transport for NSW) residential and workforce travel analysis and forecasts
- estimates of future residential development data from the four main local councils (Blacktown, Hawkesbury, The Hills, and Penrith)
- NSW Land and Property Information's (now Spatial Services) aerial photography, ground level data (LiDAR), and datasets of utilities, infrastructure and other public assets.

The methodology used to collate this suite of information to develop a Floodplain Assets Database is described in **Appendix B**.

**Box 3.3 2018 floodplain exposure dataset**

The most current data and methodologies are being used to update the floodplain assets database for the Warragamba Dam Raising Environmental Impact Statement and preparation of the final business case. This includes updating 'existing' development from 2016 to 2018 using the latest Census data and 2018 aerial photography. In addition, 'future' development scenarios are being updated using the latest projection information from the Department of Planning and Environment and local councils.

## 3.4 Risk to life assessment

### *3.4.1 Introduction*

Large numbers of people live and work on the Hawkesbury-Nepean floodplain. In a 1 in 100 chance per year flood, around 64,000 people would need to evacuate.

For the purpose of the Taskforce assessment, the risk to life associated with flooding largely relates to the likelihood of people being trapped by floodwaters and unable to evacuate. The depth and extent of flooding means that sheltering in place during major flood events is not safe or feasible.

The *Hawkesbury Nepean Flood Plan* (NSW SES, 2015) identifies mass self-evacuation as the primary method of reducing the flood risk to life during major flood events. Self-evacuation by private vehicles is the primary method of evacuation during flood emergencies in the valley. Buses have limited capacity, and other transport modes in the valley, such as rail, are highly vulnerable to floods.

Many key settlements are located on flood islands, which are accessed by relatively low-level roads (**Figure 3.4**). During rising floods, these urban centres can be isolated and utilities cut. With continued rises, the communities can be entirely inundated. It is important that populations on flood islands such as McGraths Hill, Pitt Town and Windsor, are evacuated before evacuation roads are cut.

Significant evacuations in the valley are triggered when floods are predicted to cut the McGraths Hill regional flood evacuation route at 13.5 m AHD (see **Table 1.3**). The key evacuation route for Pitt Town is cut at 16.0 m AHD, and for Windsor and South Windsor (Jim Anderson Bridge) at about 17.3 m AHD (1 in 100 chance per year flood at Windsor). The last route for evacuating the flood islands is the Richmond regional flood evacuation route, which is cut at 20.2 m AHD. This corresponds to between a 1 in 500 and 1 in 1,000 chance per year flood. Most evacuation routes above this level have rising road access.

In the Hawkesbury-Nepean Valley, there is a limited number of inter-connected evacuation roads. Evacuation from Penrith can be affected by evacuations southwards from the Richmond/Windsor floodplain, and evacuations from Richmond/Windsor can be similarly affected by evacuation demand from the large urban population in the Penrith floodplain. The *Hawkesbury Nepean Flood Plan* (NSW SES, 2015) contains a sequenced evacuation of populations at greatest risk ahead of those areas that are higher or have rising road access.

Risk to life from floods can occur from people driving through floodwaters, or not responding to evacuation orders. The Taskforce focussed on road evacuation capacity to assess the relative efficacy of flood mitigation and evacuation road infrastructure options. The Taskforce also recognised that complementary management actions such as an appropriate flood risk planning framework and investment in flood risk awareness are essential to realise the benefits of any infrastructure options and for a flood-prepared community.

For the Taskforce, risk to life was assessed by:

1. developing a flood evacuation traffic model to measure the number of vehicles (and hence, people) unable to evacuate to dry ground within the available timeframes
2. estimating the potential loss of life for those people unable to evacuate.

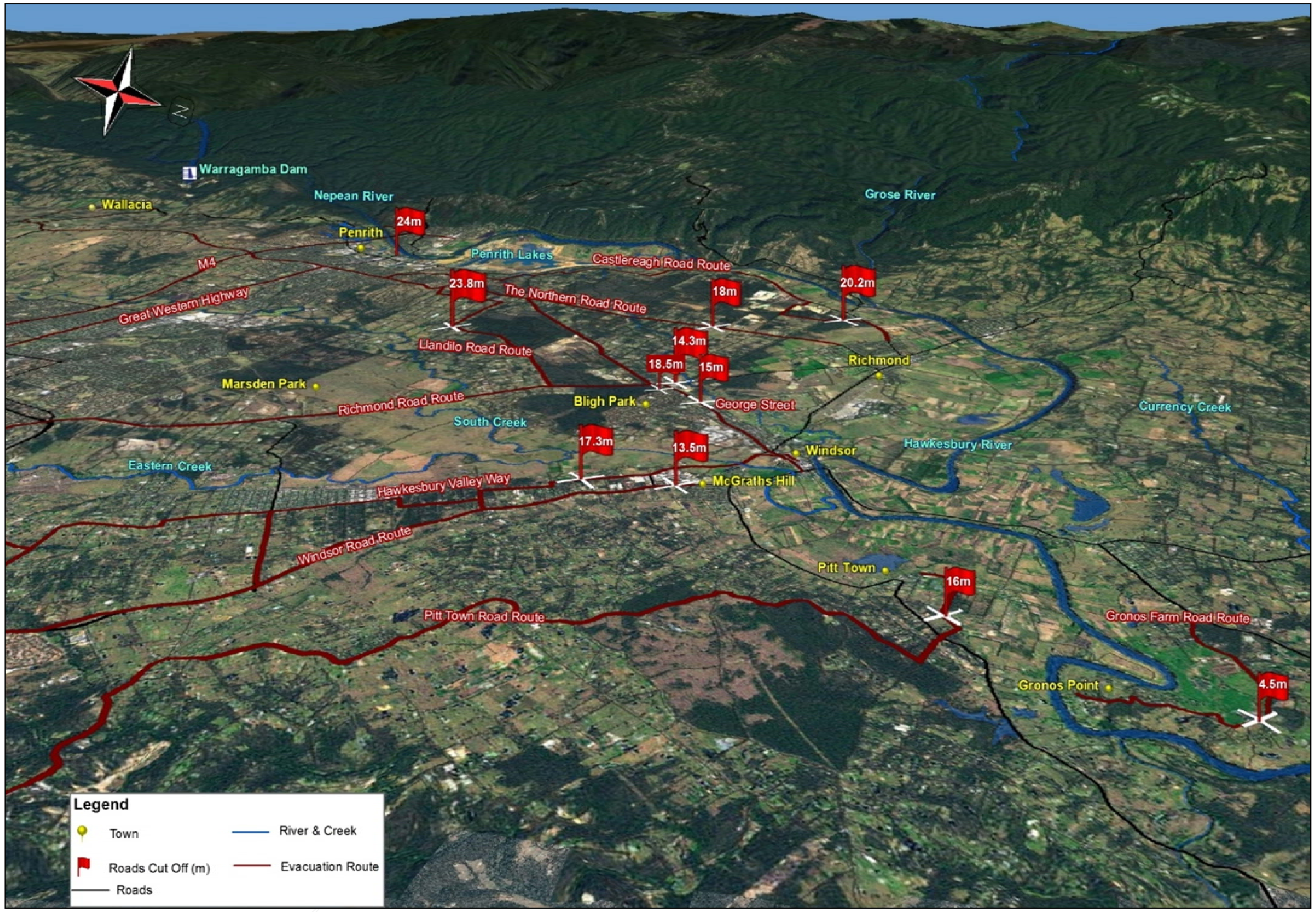



**Figure 3.4 Hawkesbury-Nepean Valley flood evacuation routes and the flood level (m AHD) at which the routes are cut**

*Source:* 2013 Review

### 3.4.2 Flood evacuation modelling

The Taskforce assessed risk to life for:

- the current time (2016)
- a projected future population and road network (2041)
- scenarios that included flood mitigation and/or road infrastructure upgrades.

Risk to life was quantified by simulating flood evacuations using a purpose-built, agent-based flood evacuation traffic model developed by National Information and Communication Technology Australia (NICTA, now the Data61 division of CSIRO). It considers evacuation of each vehicle from a range of flooded population sub-sectors travelling to a range of 'dry' destinations outside the Hawkesbury-Nepean Valley using NSW SES's designated regional evacuation routes.

The model uses 46 representative modelled flood events between 1 in 50 and 1 in 5,000 chance per year (at Windsor) from the 19,500 events generated by the Monte Carlo flood modelling. The sampling methodology was statistically analysed by Professor Dmitri Kavetski (University of Adelaide) to ensure that the samples were representative of the 19,500 modelled flood events.

The model is based on the *Hawkesbury Nepean Flood Plan* (NSW SES, 2015) evacuation timeline, with NSW SES subsectors progressively triggered to evacuate 15 hours before either the low point on the evacuation route is cut, or houses within the subsector are impacted by the flood event. A 15-hour flood level forecast is based on the current Bureau of Meteorology target for Windsor (see the Service Level Specifications in **Table 1.2**). The assumed available time is longer than the eight-hour forecast target for Penrith. In practice the NSW SES would order evacuation of areas with evacuation times greater than 15 hours based on more uncertain forecasts, taking the risk that some areas may be evacuated that, with the benefit of hindsight, did not need to be evacuated.

The model assumes a 100% community response to an order to evacuate, and that transport services would be provided for people without vehicles as per the *Hawkesbury Nepean Flood Plan*. It is recognised that an actual evacuation is very unlikely to occur with 100% response in this valley (see **Section 1.1.2**). The primary purpose of these evacuation simulations was as a comparative analysis for the benefits of infrastructure options, so an assumption of full compliance with an evacuation order was required to measure 'no-fault' risk to life.

Non-compliance rates up to 20% were applied to test the sensitivity of the model to different community responses to evacuation orders. Results from the social research (Newgate Research, 2014a; 2014b) found that 27% of respondents would apply their own judgment when deciding whether to follow an evacuation order. If half of these delay or decide not to evacuate, added to the 3% who said they would refuse to evacuate under any circumstances, then about 15% of the total population called to evacuate would not do so.

Research of global evacuation behaviours shows that responses to evacuation orders is highly variable, with between about 20% and 90% of populations evacuating (Gissing, 2015). A non-compliance rate of 15% is possibly optimistic, especially considering the absence of a major flood in the Hawkesbury-Nepean since 1990, and the very long times that can elapse between the rare floods that would trigger evacuations of higher flood islands such as Richmond and Pitt Town.

The risk to life was measured as the number of vehicles and people unable to self-evacuate before either the low point on the evacuation route is cut or houses within the subsector are flooded.

The risk to life assessment process is summarised in **Figure 3.5**.

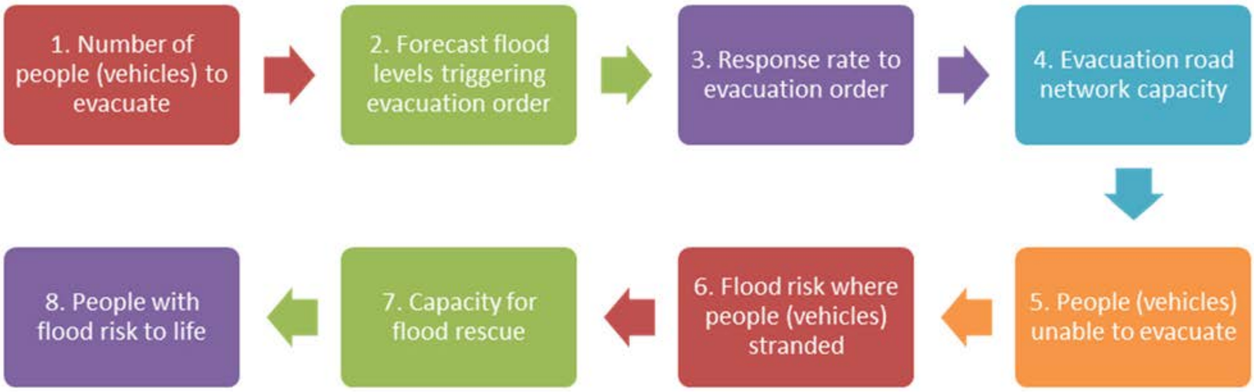



**Figure 3.5 Steps in estimating the flood risk to life**

More than 12,000 evacuation model runs were generated across the flood events, time horizons, and flood mitigation and road infrastructure options.

Emeritus Professor John Black (University of NSW) reviewed the Taskforce evacuation modelling. He found that inputs to the modelling process including hydrological data, the spatial distribution of population and the road network were of high quality. The application of the agent-based micro-simulation model MATsim to flood evacuation routes was judged to represent pioneering work that allowed simulations of thousands of scenarios.

The Taskforce evacuation modelling is being updated to inform the Warragamba Dam Raising Environmental Impact Statement and final business case.

### *3.4.3 Mortality rates*

The evacuation model quantified the number of people unable to evacuate (given limited time) in the base case and with various infrastructure options in place. The number of vehicles unable to evacuate in floods was used to estimate the danger to personal safety (risk to life), as mortality was assumed to be a sub-set of those unable to evacuate.

The NSW SES considered the potential rates of loss of life for those unable to evacuate based on the global research and local flood behaviour (see **Appendix C**). For most cases, it was assumed that the mortality rate for the population unable to evacuate was 1% (with sensitivity testing for 0.5% and 2%). Several urban settlements in valley, including Windsor and Richmond, are located on flood islands. For flood islands the mortality rate was assumed to be higher. This is because a flood island may be first isolated by floodwater and then overtopped by up to nine metres of relatively fast-rising floodwater. The mortality rate applied to these populations was modelled to increase up to 100% associated with increases in the depth of flooding.

## 3.5 Flood damages assessment

Floods have a number of adverse impacts, including direct and indirect damage to residential and commercial/industrial properties, damage to utilities and infrastructure, and the cost from loss of life and injury (**Table 3.1**). The Centre for International Economics (CIE) adapted the standard flood damages assessment methodology to quantify the economic costs, benefits and net economic benefits for different flood mitigation options compared to the base case (no flood mitigation options adopted).

Average annual damage (AAD) is a measure of the cost of flood damage that could be expected each year by the community, on average. It is a convenient yardstick to compare the economic benefits of various proposed mitigation measures with each other and the base case. AAD is equal to the total damage caused by all floods over a long period of time divided by the number of years in that period. It is equal to the area under a damage-probability curve. The CIE assessment was consistent with the approach set out in the *Floodplain Development Manual* (NSW Government, 2005), NSW Treasury guidelines, and the methods used by the insurance industry to establish flood insurance premiums.

**Table 3.1 Impacts of flooding**

| Category | Description |
|---|---|
| **Residential direct damage** | Damage to residential buildings, contents and costs to clean-up |
| **Commercial/industrial direct damage** | Damage to commercial and industrial buildings, contents and costs to clean-up |
| **Residential indirect damage** | Welfare loss from the change of circumstances because a residential property is flooded, largely reflecting welfare costs of not being able to live at home for some period |
| **Commercial/industrial indirect damage** | Loss of surplus for producers and workers at businesses that do not restart business for some period |
| **Electricity damage** | Damage to electric distribution systems |
| **Loss of life and injury** | Loss of life, injury and welfare impacts related to immediate evacuation |
| **Other damages** | Damages to other infrastructure (water, sewerage, telecommunications, roads) and other property (motor vehicles, agricultural land, caravans) |
| **Other unquantified** | • Costs related to response to flooding events (emergency services)<br>• Loss of memorabilia<br>• Damage to heritage items<br>• Environmental damage |

*Source:* CIE for the Taskforce

A description of the particular approaches adopted for the assessment of damages and avoided damages (benefits) with mitigation measures is outlined in **Table 3.2** for each category. Consistent with international practice, direct residential and commercial/industrial damages were related to the depth of above-floor inundation. Further information is set out in **Appendix D**. Indirect damages were estimated at 5% and 37.5% of direct residential and commercial/industrial damages, respectively.

### Table 3.2 Approaches to measuring flood damages

| Benefit | Measurement |
|---|---|
| **Residential buildings and property** | Stage damage curves developed by Geoscience Australia were used. These relate damage (both building fabric and contents) to flood depth for a variety of residential types. Flood modelling specialists WMAwater provided flood depths for a range of flood events for each property in the floodplain.<br>Results were also tested using Office of Environment & Heritage (OEH) stage damage curves. |
| **Commercial and industrial buildings and property** | Stage damage curves based on Middlesex University's Flood Hazard Research Centre's 2010 FloodSite Multi-Coloured Manual were used. These were scaled to 2013 and converted to AUD by Molino Stewart for the Taskforce. These relate damage to the building area in square metres. WMAwater provided flood depths for a range of flood levels for each property in the floodplain.<br>It is noted that commercial and industrial damages will be highly variable across types of activity, depending on how easily plant and machinery is damaged. |
| **Indirect residential damages** | Assumed to be 5% of direct residential damages, with low and high sensitivity tests of 0% and 25%.<br>There is no strong evidence about the magnitude of indirect residential damage, as this captures factors not easily observed, such as lost welfare from living in alternative accommodation/location. |
| **Indirect commercial and industrial damages** | This includes the loss impacts related to production. Conceptually, this is defined as lost producer surplus and losses in surplus for employees unable to work (wages less their reservation wage).<br>This was measured through reference to a business survey conducted after the 2011 Queensland floods and CIE adjustments to reflect economic cost only.<br>Indirect damages were assumed to be 37.5% of direct commercial/industrial damages, with a high sensitivity test of 100%. |
| **Electricity infrastructure damages** | Estimates of damage at different flood levels were provided by Endeavour Energy.<br>Damages were assumed to reduce at the same proportion as residential damage. |
| **Road pavement damages** | Estimated by Roads and Maritime Services, by classifying roads into condition, estimating how much road is damaged and the cost of repaving. |
| **Loss of life** | Loss of life was calculated as a subset of the number of people unable to be evacuated in available time with existing road capacity. The number of people unable to evacuate is a function of the number of vehicles unable to evacuate, as assessed through the road evacuation model developed by Data61. A 100% compliance with NSW SES orders to evacuate was assumed (with a high sensitivity test of 20% non-compliance).<br>Loss of life was estimated as 1% of people unable to evacuate, with low and high sensitivity tests of 0.5% and 2%. Recognising the difficulty of evacuating flood islands that can become fully inundated, a higher mortality function based on depth was applied in such areas.<br>For the purposes of cost-benefit analysis, the value of statistical life used in the central case was $6.8 million per person based on the NSW Government's *Principles and Guidelines for Economic Appraisal of Transport Investment and Initiatives* (TfNSW, 2016). This value was sensitivity tested with a value of $4.3 million per person based on the Australian Government's *Best Practice Regulation Guidance Note: Value of Statistical Life* (OBPR, 2014). |
| **Injury and welfare loss from evacuation** | Anyone evacuating was assumed to have a welfare cost ranging from $313 to $641 per person.<br>The range of costs per person unable to evacuate were assumed to be larger at $313 to $954.<br>These estimates are based on previous studies of costs for those in flooded areas (sourced from a literature review conducted by CIE). |
| **Other damages** (caravans, agriculture, motor vehicles, telecommunications, water and sewerage) | Estimates of damage at different flood levels were based on earlier damage assessments. Minor adjustments were made by CIE to reduce damages for agriculture. Estimates for damage to water and sewerage were cross-checked with Sydney Water and found to be sufficiently consistent.<br>Damages were assumed to be mitigated at the same proportion as residential damage. |

*Source:* CIE for the Taskforce

# 4 Options identification and evaluation overview

## 4.1 Options

The Taskforce confirmed the findings of the 2013 Review that there is no simple solution or single infrastructure option that can eliminate the high flood risk to existing communities in the Hawkesbury-Nepean Valley. A combination of infrastructure and policy or other initiatives is required to reduce flood risk by:

- changing the probability of different sized flood events
- reducing the exposure of the population, property and assets to flood risk
- increasing the certainty of time to safely evacuate areas exposed to forecast floods
- increasing the resilience of communities, property and public assets exposed to floods.

**Flood mitigation infrastructure options** reduce flood risk by lowering the probability or level of a flood event, reducing the exposure, and in some cases by increasing the certainty of time available for evacuation. These options significantly reduce but cannot eliminate the risk of flooding due to the large flood depths associated with flooding in the valley. Optimal options are those that would significantly reduce the flood risk to life and property and provide greater certainty of time for evacuation for those events that still trigger evacuation. The flood mitigation options assessed include:

- measures to temporarily capture or store floodwater upstream of the valley, which reduce and delay downstream flood peaks
    - operating Warragamba Dam differently
        - maximising the amount of water held back using the dam's radial gates (variously described in this report as the 'surcharge' or 'induced surcharge' method of gate operations)
        - pre-releases from the water storage to create airspace
        - lowering full water supply level (FSL) to create airspace
    - new sole-purpose flood mitigation dams
    - raising Warragamba Dam to create airspace.

  Most of these options involve the formation of airspace, or a 'flood mitigation zone' (FMZ), for the temporary capture of floodwaters. This concept is explained in **Box 4.1**.

- measures to divert flow or enhance drainage from the valley, which tend to reduce upstream flood peaks (but may increase downstream flood peaks)
    - Currency Creek diversion channel
    - Sackville diversion channels
    - river dredging.
- local structural works such as levees designed to protect urban areas from inundation up to a design height.

**Box 4.1 Flood mitigation zone concept**

Dams can be constructed for the sole purpose of modifying flood behaviour. These sole-purpose, flood detention dams are kept as empty as possible so that the maximum amount of floodwater can be stored and released at a controlled rate after or later in the flood event. While flood detention basins are common in urban areas, few sole purpose flood detention dams have been constructed in Australia.

Dual purpose water supply and flood mitigation dams do operate in Australia, including Wivenhoe and Somerset dams in Queensland and Burrendong and Glenbawn dams in New South Wales. These dams have additional storage capacity (airspace) between the normal full water supply level (FSL) and the maximum storage level that is reserved specifically for storing floodwaters. This airspace is often referred to as the flood mitigation zone (FMZ).

At the start of a flood event, incoming floodwaters are temporarily captured in the FMZ to help reduce the amount of flooding downstream. Once floodwaters exceed the capacity of the FMZ, floodwaters are discharged over the spillway to the downstream channel and floodplain. The dam water level will continue to rise when the dam is spilling until the inflows into the dam match the outflow from the spillway. Because of this temporary surcharge storage, a dam can continue to mitigate flood events even when the FMZ is full.

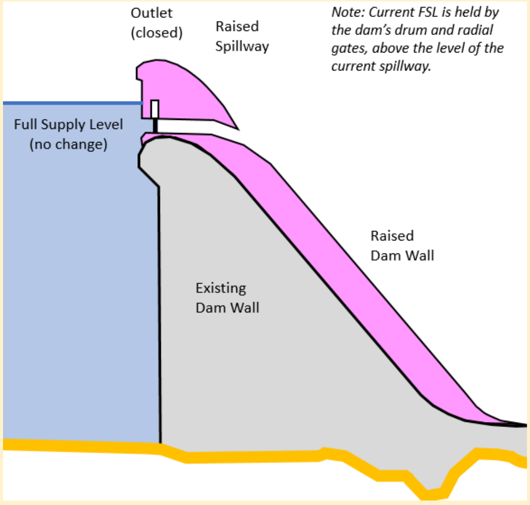
After the flood inflow peak has passed, the temporarily stored floodwaters are released from the dam until the FSL is reached, so that airspace is available to mitigate the next flood.

Several of the flood mitigation options discussed in following chapters involve making airspace to hold incoming floodwater behind Warragamba Dam wall. These include:

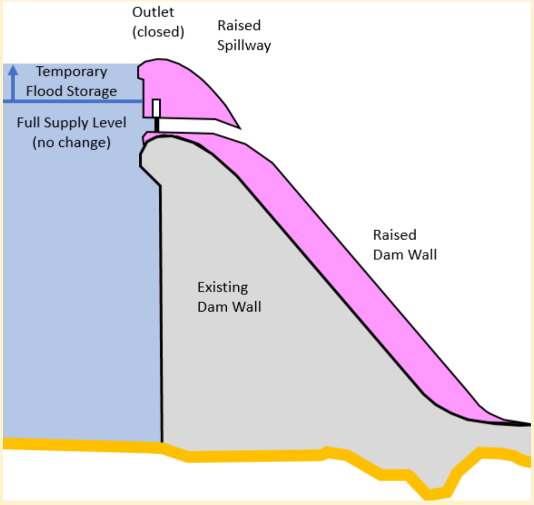
- pre-releases from the existing dam that reduce water supply to create a *temporary* airspace in anticipation of a flood
- permanently lowering Warragamba Dam FSL to create airspace between the lowered FSL and the existing dam crest
- raising the dam wall and spillways while retaining the existing FSL so that the created airspace functions as a permanent FMZ.

The following schematic diagrams depict a cross section through the central spillway, showing how a raised Warragamba Dam spillway would use airspace to temporarily capture floodwaters, which would be released at a controlled rate as the flood is receding.

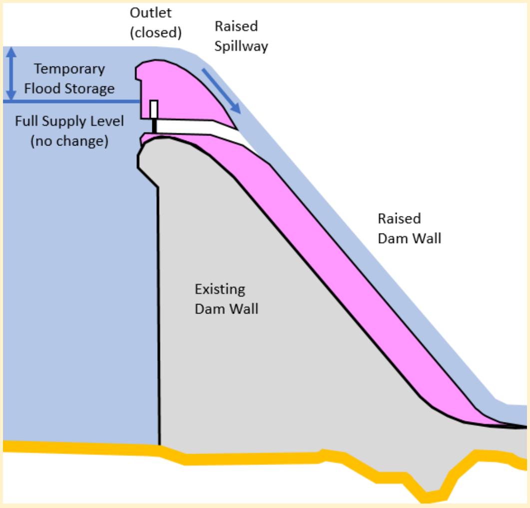
**Before a flood: Dam at or below full water supply level**



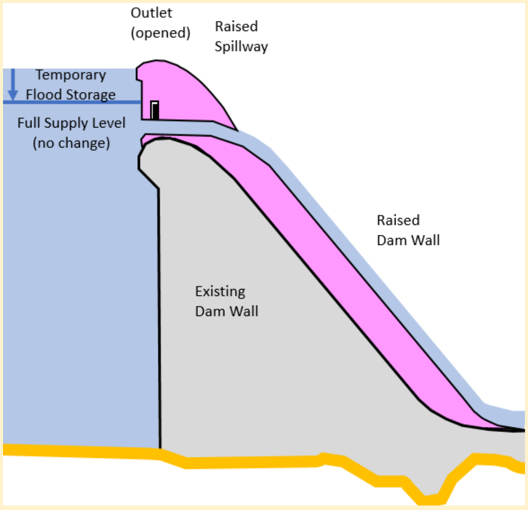

**During a flood #1: Rising flood storage level**



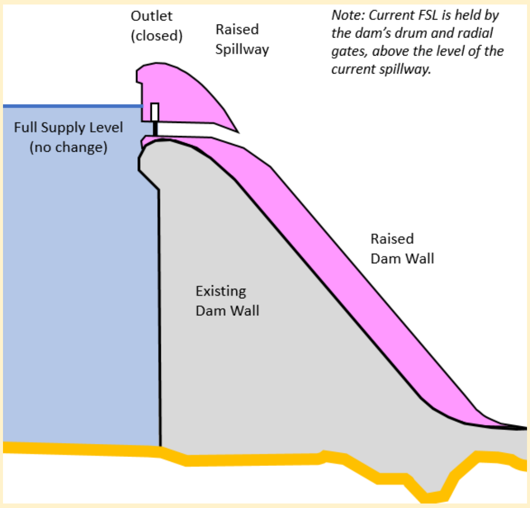

**During a flood #2: Flood storage level filling with uncontrolled releases via spillway**




**During a flood #3: Controlled releases when spill falls below spillway crest, to restore FMZ capacity**




**Between flood events: Dam at or below full water supply level**



**Road evacuation infrastructure options** do not change the likelihood of certain flood levels in the valley being reached by floods, so would offer no benefit for reducing damages to building structures or critical assets. However, upgrades to evacuation roads could provide additional road capacity, thereby decreasing the potential number of vehicles unable to evacuate during flood events and the risk to life from floods.

The Taskforce investigated a range of **non-infrastructure options**. These management measures address different elements of the flood risk management cycle (**Figure 2**) and are essential to manage ongoing risk. They can reduce the existing exposure of communities to floods as well as limit the future exposure of communities to floods by integrated land use, road and emergency planning. These options include:

- regional land use planning taking into consideration flood risk
- regional road planning taking into consideration flood risk
- voluntary house purchase
- voluntary house raising.

Non-infrastructure options also include those that are critical to help ensure the community is prepared, responsive and resilient to flood events that occur infrequently but have high social and economic consequences. These options include:

- improved flood forecasting and warning
- community engagement and information provision
- preparation for flood emergency and recovery
- improved governance to support integrated flood risk management.

## 4.2 Phased stages of evaluation

Recognising the significant risk to life and property in the Hawkesbury-Nepean floodplain, several regional studies have been conducted to identify and evaluate options to reduce the risk. Studies from the 1990s up to 2012 are summarised in **Chapter 2**.

The 2013 *Hawkesbury-Nepean Valley Flood Management Review* (NSW Office of Water, 2014a; 2014b) reconsidered many of these options and put forward a list of feasible options for further investigation as part of the Taskforce's work. The Taskforce evaluated these feasible options, with detailed investigation of the more feasible options. In effect, a shortlisting approach has been adopted (**Figure 1**), in which the most feasible alternatives have been narrowed through the course of the investigations commencing with the 2013 Review. This process led to the options recommended in the 2017 *Resilient Valley, Resilient Communities:* Hawkesbury-Nepean Valley Flood Risk Management Strategy (Flood Strategy) (INSW, 2017).

**Table 4.1** lists the options considered as part of this shortlisting process. It shows the stage at which the evaluation of each option was concluded if, following investigation, it was judged that sufficient work had been done to exclude that option from further investigation. The reasons for their exclusion are summarised in **Section 4.4**.

Some options have been or are being implemented as part of the Flood Strategy. The preferred and alternative flood mitigation options are being further investigated as part of the Warragamba Dam Raising Environmental Impact Assessment that commenced in July 2017.

**Table 4.1 Flood risk management option assessment by stage of Hawkesbury-Nepean Valley investigations**

**LEGEND:**

- Option assessed
- Option taken forward and/or implemented
- Option not considered further

| Option | Pre-2013 | 2013 Review | Taskforce (2014-16) | Flood Strategy Phase 1 (2016-20) |
|---|---|---|---|---|
| **FLOOD MITIGATION INFRASTRUCTURE OPTIONS** | | | | |
| **FLOOD CAPTURE/STORAGE** | | | | |
| ***Business-as-usual (H14 operating protocol)*** | | | | |
| ***Changes to operation of existing Warragamba Dam*** | | | | |
| **Surcharge method of gate operations** | | | | |
| **Pre-release 50-100 GL over one day** | | | | |
| **Pre-release <40 GL/d over three days** | | | | |
| **Pre-release <130 GL/d over three days** | | | | |
| **Lower FSL by 2m** | | | | |
| **Lower FSL by 5m** | | | | See note 1 |
| **Lower FSL by 12m** | | | | See note 1 |
| ***New flood mitigation dams*** | | | | |
| **New dams upstream of Warragamba** (Wollondilly River, Coxs River) | | | | |
| **New dams downstream of Warragamba** (Nepean River, Grose River, South Creek, Colo River) | | | | |
| **Large detention basin** (Richmond Lowlands) | | | | |
| ***Raise Warragamba Dam*** | | | | |
| **WD +23m** | | | | |
| **WD +12m to +30m (especially +15m, +23m)** | | | | |
| **WD +20m** | | | | |
| **WD +14m** | | | | |
| **DIVERSION CHANNELS OR ENHANCED WATER DRAINAGE FROM VALLEY** | | | | |
| ***Diversion and channel works*** | | | | |
| **Breakaway cut-off** (Freemans Reach–Wilberforce) | | | | |
| **Currency Creek diversion channel** | | | | |
| **Gronos Point diversion channel** | | | | |
| **Sackville cut-off (short diversion)** | | | | |
| **Sackville large diversion** | | | | |
| **Dredging between Windsor and Wisemans Ferry** | | | | |

| Option | Pre-2013 | 2013 Review | Taskforce (2014-16) | Flood Strategy Phase 1 (2016-20) |
|---|---|---|---|---|
| **LOCAL STRUCTURAL WORKS** | | | | |
| Wallacia levee | | | | |
| Emu Plains levee | | | | |
| Penrith levee | | | | |
| Regentville levee | | | | |
| Peachtree Creek levee | | | | |
| Penrith and Emu Plains deflection walls | | | | |
| Penrith and Emu Plains riverbank protection | | | | |
| Victoria Bridge pier replacement | | | | |
| Penrith weir removal or cleaning | | | | |
| North Richmond levee | | | | |
| Richmond levee | | | | |
| Windsor levee | | | | |
| Riverstone levee | | | | |
| Mulgrave levee | | | | |
| Bligh Park levee | | | | |
| McGraths Hill levee | | | | |
| Pitt Town levee | | | | |
| Wilberforce levee | | | | |
| Richmond to Windsor macro levee | | | | |
| Richmond to McGraths Hill macro levee | | | | |
| Wisemans Ferry, Spencer micro levees | | | | |
| **EVACUATION ROAD INFRASTRUCTURE OPTIONS** | | | | |
| Regional evacuation road upgrades | See note 2 | | See note 3 | |
| Local evacuation road upgrades | See note 2 | | | See note 3 |
| **NON-INFRASTRUCTURE OPTIONS** | | | | |
| **OPTIONS TO REDUCE EXPOSURE TO FLOOD RISK** | | | | |
| Risk-informed, regional land use planning | | | | |
| Risk-informed, regional road planning | | | | See note 3 |
| Voluntary house purchase | | | | |
| Voluntary house raising | | | | |
| **OPTIONS TO IMPROVE AWARENESS, PREPAREDNESS AND RESPONSIVENESS** | | | | |
| Improved flood forecasting and warning system | | | | |
| Community flood awareness, preparedness and responsiveness | | | | |
| Best practice emergency response and recovery | | | | |
| **IMPROVED GOVERNANCE** | | | | |
| Improved governance to support integrated flood risk management | | | | |
| Collection of post-event flood data/intelligence | | | | |

*Note:*

GL/d = gigalitres per day

[1] Options involving lowering of Warragamba Dam FSL were not supported in the Flood Strategy. These options will be updated as part of the feasible alternative options requirements under the Secretary's Environmental Assessment Requirements (SEARs) for the Warragamba Dam Raising Environmental Impact Statement.

[2] Works to improve regional evacuation roads were completed as an outcome of the 1998-2004 *Hawkesbury-Nepean Floodplain Management Strategy*. This included construction of the Windsor flood evacuation route with the building of Jim Anderson Bridge as part of a larger road upgrade program. Local evacuation route upgrades were also implemented, including the Thorley Street extension to improve evacuation from Bligh Park (see HNFMSC, 2004).

[3] The Taskforce determined that upgrades to major regional evacuation roads were not cost effective to address existing flood risk. A Regional Road Evacuation Master Plan is being developed to have flood risk considered when these regional roads are upgraded in response to growth in the valley. Also, business cases are being developed for around 40 targeted road upgrades to increase the capacity and reliability of evacuation routes identified in the NSW SES *Hawkesbury Nepean Flood Plan*.

It is also possible to consider options in combination. This is of value only where an individual option *complements* other options, that is, where the benefit of undertaking both options together is higher than the sum of the benefits of undertaking each by itself.

For the options considered in this study, most options are partial *substitutes* for most other options; that is, the benefit of undertaking both options together is lower than the sum of the benefits of undertaking each individually. The exceptions to this are non-infrastructure options such as land use planning and improved governance for integrated flood risk management, which complement flood mitigation measures.

Flood modelling evolved over the process of the 2013 Review and Taskforce investigations, in keeping with advances in national best practice through the revision of *Australian Rainfall and Runoff* (Ball et al., 2016). Options were assessed using the latest modelling outputs available at the time of their analysis.

Similarly, evacuation modelling evolved with increasing resolution over the process developed and implemented for the Review and Taskforce.

## 4.3 Method: assessment criteria

A range of factors were used to evaluate options, appropriate to the phase of analysis. At all times, the underlying principle was to obtain the best available evidence to inform the assessment. This section describes the criteria that were used for to evaluate options throughout the phased assessment.

### *4.3.1 Significant, regional reduction of flood risk*

The 2013 Review particularly considered the degree to which options would meet the objective to 'significantly reduce the potential economic and social impact of flooding in the Hawkesbury Nepean Valley' (SIS, 2012). Two aspects of this objective were critical for the assessment. Options needed to:

- *significantly* reduce the impact of flooding on risk to life and property damages
- provide *regional* benefit rather than localised benefit.

For flood mitigation options, one measure of effectiveness is the reduction of critical peak flood levels. This was assessed using hydrologic and hydraulic flood model results. To meet the objective of *significantly* reducing the impact of flooding, an option needed to make a substantial difference to floods in the range of 1 in 50 to 1 in 1,000 chance per year. The 1 in 50 to 1 in 500 chance per year flood range contributes about two-thirds of calculated current average annual flood damages (**Figure 4.1**). More frequent (smaller) flood events contribute only about 10% of current average annual flood damages. The critical range for flood risk reduction is extended to include the 1 in 1,000 chance per year flood because this incorporates the risk to life associated with the Richmond flood island being cut off and flooded (see **Section 4.3.2**). Therefore, options that most effectively reduce flood levels in the critical range of 1 in 50 to 1 in 1,000 chance per year flood will be the most effective for mitigating the flood risk.

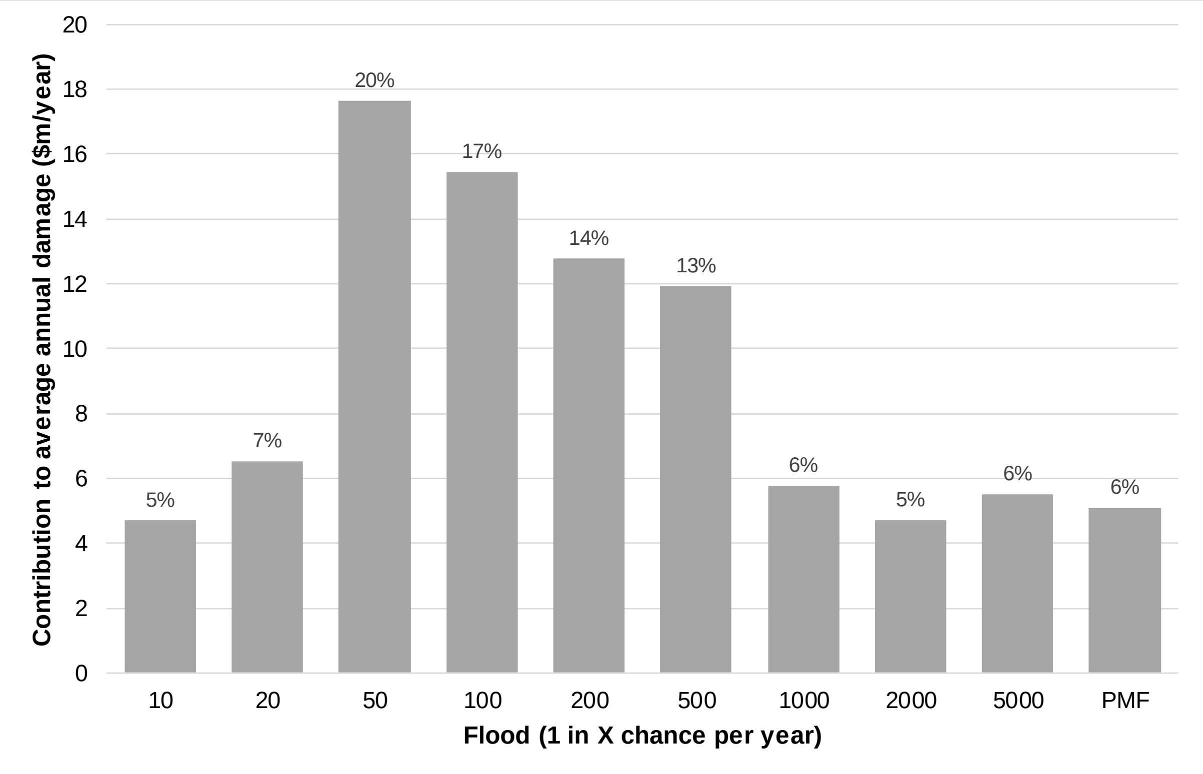



**Figure 4.1 Contribution of flood events to average annual flood damages in the valley, base case, 2015 development**

*Source:* INSW using data from CIE

*Note:* PMF = probable maximum flood

Significant flood impacts occur from around the current 1 in 50 chance per year event. This is because the 1 in 100 chance per year flood planning level was previously lower, allowing houses to be built at a level lower than would be permissible today. For example, in the 1990s, the flood planning level at Windsor was 16.0 m AHD compared to the current 1 in 100 year chance per year level of 17.3 m AHD.

Mitigating events greater than the current 1 in 1,000 chance per year flood becomes increasingly difficult and costly as it requires very large volumes of water to be stored upstream or very large diversions of floodwaters downstream of populated areas of the valley.

The flood risk is distributed unevenly in the valley. Infrastructure options can have high capital costs; therefore, investment decisions should provide the greatest net benefits for the region. To meet the objective of a *regional* reduction of flood risk, the Taskforce considered that options should demonstrate a substantial difference to floods for both the Penrith and Richmond/Windsor floodplains, since this is where the exposure to flooding (residential and commercial/industrial uses) is concentrated (see **Figure 4.10**). Options that reduced the impacts of floods primarily in the Richmond/Windsor floodplain, while offering limited benefits for the Penrith floodplain, or vice versa, were not considered optimal.

The Warragamba Catchment provides the greatest contribution of high flows causing significant flooding in the Hawkesbury-Nepean River system. Floods are highly variable with each flood behaving differently. Given the high proportion of the Warragamba Catchment to the total catchment areas to Penrith (80%) and Windsor (70%), the flood mitigation options most likely to offer regional flood mitigation benefits are those controlling floodwater from the Warragamba Catchment. **Figure 4.2** shows that the Warragamba Catchment was the main contributor of total floodwater at Windsor in historic floods. For all the Monte Carlo-modelled 1 in 100 chance per year events, the Warragamba Catchment contributes between 50% and 75% of the volume at Windsor and between 60% and 85% at Penrith. Therefore, options that mitigate flooding from the Warragamba Catchment provide efficient regional flood mitigation as they control the largest source of flows during large flood events.

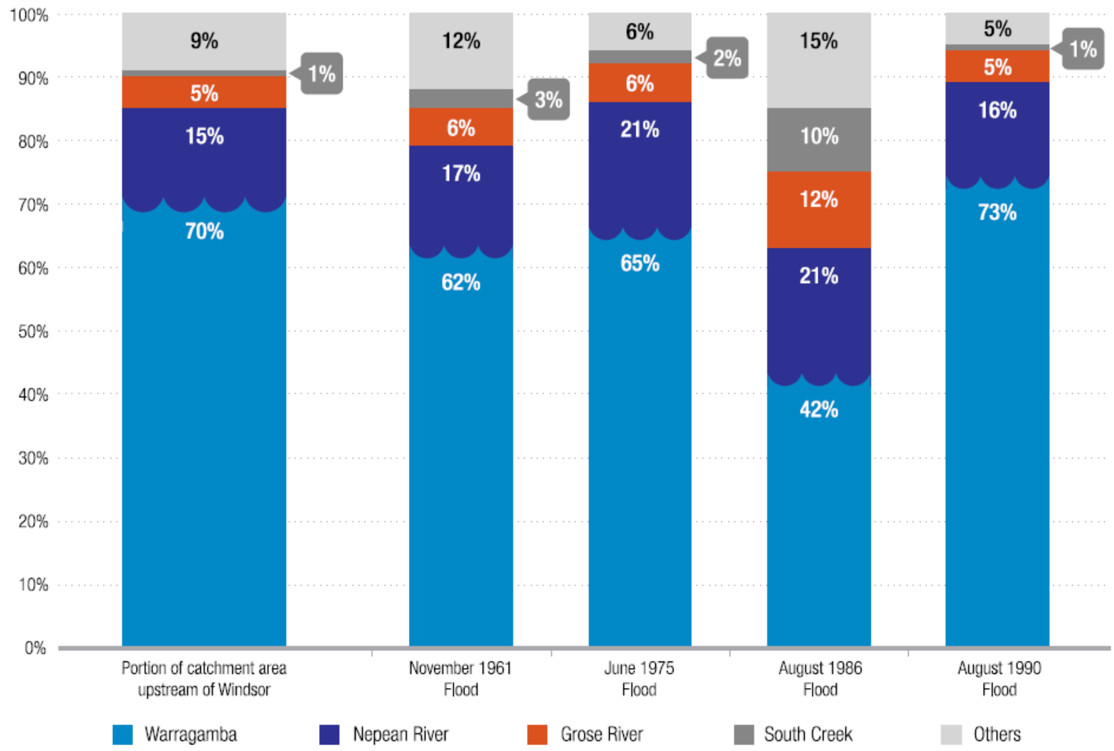



**Figure 4.2 Relative contribution at Windsor of flows from different river catchments in previous floods in the Hawkesbury-Nepean Valley**

*Source:* Flood Strategy (INSW, 2017)

*Note:* The August 1986 flood event was smaller than a 1 in 20 chance per year flood, with Warragamba Dam contributing only 42% of the total volume at Windsor. This is because Warragamba Dam storage level was relatively low and captured a large portion of the incoming flows thus delaying the downstream flows. If Warragamba Dam had been full, the Warragamba Catchment would have contributed 57% of the volume at Windsor.

### *4.3.2 Risk to life reduction*

A key component of reduced flood risk is the estimated reduction in the risk to life from flood events. The ability to reduce risk to life was assessed for dam and evacuation road infrastructure options that were carried through to latter stages of the Taskforce evaluations.

Optimal or preferred options would significantly reduce the frequency and timing of all the critical evacuation routes being cut. Therefore, the risk-to-life reducing benefits of options were assessed by three metrics:

- **Reduced exposure to floods**. Where a flood mitigation infrastructure measure reduces the frequency of floods at which properties will be inundated and evacuation roads will be cut, the risk to life will be directly reduced as many evacuations will no longer be required. This was assessed using the Monte Carlo suite of 19,500 possible floods.
- **Flood delay providing a longer window for evacuation**. Currently the time to evacuate some areas of the valley (**Table 1.3**) exceeds the flood forecast target time (eight to 15 hours), forcing NSW SES to order evacuations based on uncertain flood level predictions. This uncertainty is because the rapid flooding response in the valley requires the use of forecast rainfall rather than fallen rain or observed river level rises. If an infrastructure flood mitigation measure delays the time at which evacuation roads are cut until later in the rainfall event, it provides more certainty about the timing of flood levels. This makes it possible to safely evacuate more people from the floodplain, and minimise premature evacuations. Conversely, where a mitigation measure shortens the time at which evacuation roads are cut, the time available for evacuation following receipt of a warning reduces, increasing risk to life.
- **Average annual vehicles or population unable to evacuate due to flooding**. This metric provides a way of quantifying the risk-to-life benefits of reduced exposure and/or delay of peaks resulting from flood mitigation or evacuation road infrastructure measures. These measures include:
    - dam options that reduce and delay downstream flood rise and peaks
    - road options that increase evacuation capacity by raising, widening or expanding the evacuation road network, and
    - combinations of these options.

  The risk to life for alternative options was compared by simulating flood evacuations and measuring the number of vehicles and people unable to evacuate ahead of the flood event. The modelling included transport services for people without vehicles as per the *Hawkesbury Nepean Flood Plan* (NSW SES, 2015).

  A 100% response to the order to evacuate was assumed. This was necessary to test the capacity to evacuate the entire at-risk population within the approved evacuation timeline, for the base case and with options.

  The simulations were conducted using a flood evacuation traffic model developed by National Information and Communication Technology Australia (NICTA, now the Data61 division of CSIRO) for the Taskforce. The model is based on the *Hawkesbury Nepean Flood Plan* evacuation timeline, with NSW SES subsectors progressively triggered to evacuate 15 hours before either the low point on the evacuation route is cut, or houses within the subsector are impacted by the flood event. The model uses 46 representative modelled flood events between 1 in 50 and 1 in 5,000 chance per year (at Windsor) derived from the Monte Carlo suite of possible floods.

### *4.3.3 Economic assessment*

Another criterion was the economic costs and benefits of each option.

For some options, the direct cost relative to likely reduction in flood damages was sufficient reason to eliminate it from further consideration. For more feasible infrastructure options that were carried through to latter stages of the Taskforce evaluations, a full damages assessment was conducted to assess the benefits in terms of damages avoided for each option. This was then compared to estimated costs. This cost-benefit analysis is described further below.

#### *Measuring benefits*

The benefits were measured in terms of both reduced flood damages to property resulting from reduced peak flood levels (where applicable), and reduced risk to life resulting from a reduction of vehicles unable to evacuate (where applicable). Further detail is provided in **Table 3.2**.

#### *Measuring costs*

The capital and operating costs of the options are described in the relevant chapters, using applicable costs at the date of assessment. **Table 4.6** sets out the costs of infrastructure flood mitigation options carried through to the latter stages of Taskforce evaluations. These costs include construction costs, and for some options, costs to safeguard water security and water quality.

Options that lower the FSL of the existing Warragamba Dam have impacts on Sydney's water supply system. These impacts were measured by modelling the cost of meeting water security requirements under given flood mitigation options. These include costs of pumping water from the Shoalhaven River more frequently, running the Sydney Desalination Plant more often, increased time with restrictions on water use, and earlier construction of major infrastructure to augment supply. These were modelled using MetroNet, the NSW Government's hydro-economic model used for identifying optimal solutions for securing greater Sydney's water supply now and in the future.

Introducing a flood mitigation function to Warragamba Dam – either by lowering FSL or raising the dam wall – could also have implications for managing the quality of water supplied to water filtration plants. The potential incremental increases to treatment costs to either WaterNSW or Sydney Water were factored into the assessment.

Floods naturally occur now and provide important geomorphic and ecological functions. Quantifying and assigning a cost to the transient, incremental changes to natural flood disturbances is challenging with the available approaches. Environmental evaluation techniques including willingness-to-pay, benefit transfer and contingent evaluation were investigated, particularly for the assessment of the upstream impacts of raising Warragamba Dam for flood mitigation. Following an extensive review of national and international studies, none identified transferable monetary values applicable to the potential environmental impacts of infrequent, temporary inundation.

Given the above, and the stage of investigation, a risk-based approach was adopted to assess the impacts of changed flood behaviour associated with infrastructure options on socio-economic, environmental and cultural heritage (SECH) values (see **Section 4.3.4**).

In response to the Department of Planning and Environment Secretary's Environmental Assessment Requirements (SEARs), the impacts of raising Warragamba Dam wall by about 14 metres are being assessed and reported in detail as part of the Environmental Impact Statement. This process requires detailed survey and analysis to inform a quantification of costs and benefits, building on the work of the Taskforce.

### *Comparing benefits to costs*

A cost benefit analysis (CBA) requires assumptions about the time period for the evaluation and the discount rate, which converts future benefits and costs into their value today. The general CBA assumptions used for Taskforce options evaluation are set out in **Table 4.2**. The discount rate (7%) and time period assumptions (30 years) are in accordance with Treasury guidelines.

Modelling assumptions were developed using the best available information and expert opinion. Best practice requires an assessment of the sensitivity of the assumptions to test the robustness of options. Accordingly, the cost benefit analysis applied sensitivity analysis of the 'central case' assumptions using high and conservative assumptions (see **Table 4.2** for summary of assumptions). The 'central case' tends towards the conservative assumptions. The high sensitivity assumption would increase the favourability of potential flood mitigation options.

The overall results from cost benefit analysis were calculated and presented as the net benefit or net disbenefit (cost) of an option relative to the base case calculated as the discounted benefits less the discounted costs.

### *Non-infrastructure measures*

It is more challenging to quantify the benefits and costs of non-infrastructure measures that contribute to improving the preparedness, response and recovery phases of flood risk management. In the cost benefit analysis, the value of community engagement was estimated by increasing the community's compliance with evacuation orders, as informed by social research.

**Table 4.2 'Central case' and sensitivity assumptions for cost benefit analysis**

| Assumption | Central case | Low sensitivity | High sensitivity |
|---|---|---|---|
| Development path | Low infill * | Low infill * | High infill * |
| ***General assumptions*** | | | |
| Discount rate | 7% | 4% | 10% |
| Time period post construction | 30 years | 20 years | 40 years |
| ***Loss of life and injury assumptions*** | | | |
| Share of people not evacuating when requested | 0% | 0% | 20% |
| Default mortality rate for those not evacuated (not used for flood islands) | 1% | 0.5% | 2% |
| Statistical value of life | $6.8M | $4.3M | $6.8M |
| Cost per person requiring evacuation | $477 | $313 | $641 |
| Cost per person for those unable to evacuate | $641 | $313 | $974 |
| ***Damage assumptions*** | | | |
| Residential stage damage curves | Geosciences Australia | Geosciences Australia | OEH |
| Residential indirect damage as a share of direct damage | 5% | 0% | 25% |
| Commercial indirect damage as a share of direct damage | 37.5% | 37.5% | 100% |

*Source:* CIE for the Taskforce

*Note:* * Low and high infill development paths represent lower and upper ranges for increased dwellings in approved zoned residential areas where this type of development is permissible

### *4.3.4 Social, environmental and cultural heritage impacts*

A fourth criterion assessed the impact of flood mitigation options on socio-economic, environmental and cultural heritage (SECH) values. BMT WBM Pty Ltd was engaged to undertake a risk-based impact assessment, which included the following steps:

- establish baseline socio-economic, environmental and heritage values using a combination of desktop review, data collation and expert advice
- assess the potential adverse and beneficial impacts of each option on the identified SECH values and rate the impacts according to the impact's significance and likelihood
- identify potential strategies for managing or mitigating identified potential impacts and determine residual impacts following application of mitigation measures, and
- identify potential cumulative or consequential impacts on the values caused by the option, either in isolation or in combination with other known and identified projects, including consideration of the resilience of values to future impact.

The assessment methodology is consistent with the *National Water Quality Management Strategy* (ANZECC and ARMCANZ, 2000) and the *National Framework for Describing the Ecological Character of Australian Ramsar Wetlands* (DEWHA, 2008). It conformed to current best practice requirements and Environmental Impact Statement guidelines adopted throughout Australia.

BMT WBM's assessment was suitable for the Taskforce's detailed feasibility investigation. The Warragamba Dam Raising Environmental Impact Assessment is investigating these issues in further detail for the dam raising option.

As part of the shortlisting process, the impacts of options not taken forward to the SECH assessment were subject to a preliminary assessment.

### *4.3.5 Other factors*

A number of other factors are important for informing decisions on the feasibility of options. These include:

- maintaining dam safety
- maintaining water supply security and quality.

## 4.4 Results: summary

This section summarises the findings of the flood risk management options evaluation detailed from **Chapters 5** to **9**. **Table 4.3** sets out how each option performs against the assessment criteria described in **Section 4.3**. These criteria include:

- Significant regional reduction of flood peaks
    - reduction in downstream peak flood levels for the critical flood risk range of 1 in 50 to 1 in 1,000 chance per year at Windsor
    - extent of peak flood level reduction across the Hawkesbury-Nepean Valley
- Reduced risk to life
    - reduced exposure to floods
    - flood delay providing a longer window for evacuation
    - average annual vehicles/population unable to evacuate
- Economic costs and benefits
    - capital and operating costs
    - benefits in terms of avoided flood damages
    - net benefit
- Socio-economic, environmental and cultural heritage (SECH) impacts
- Other factors.

It is again reinforced that because the assessment of options has followed a progressive shortlisting approach from the 2013 Review, to the 2014-16 Taskforce, and to the 2016-20 Strategy, only the more feasible options were assessed using the more intensive methodologies including evacuation modelling to better understand relative risk to life.

**Table 4.3 Summary of options evaluation**

**LEGEND:**

- Does not meet evaluation criterion/objective
- Partially meets evaluation criterion/objective
- Meets evaluation criterion/objective
- Key reason(s) for option exclusion from Strategy
- Key reason(s) for option inclusion in Strategy

*Costs and benefits:*

| | |
|---|---|
| $ | $0M–$20M |
| $$ | $21M–$100M |
| $$$ | $101M–$500M |
| $$$$ | $501M-$1,000M |
| $$$$$ | >$1B |

*Note:* The process of options identification and evaluation followed a shortlisting process from the **2013 Review** through the **Taskforce** to the **Flood Strategy**. Only options that were carried forward to the latter stages of investigation were assessed using full hydrological, economic and evacuation modelling.

| Option | Stage excluded | Significant regional reduction in flood risk | | | | | Economic costs and benefits | | | Social, environmental & cultural heritage impacts | Other factors |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Flood peak reduction, 1 in 50 to 1 in 1000 AEP range (see note 1) | Reduced exposure to floods (see note 2) | More certainty of time for evacuation (see note 3) | Reduced risk to life (see note4) | Valley wide benefits | Cost | Benefit | Net benefit | | |
| **INFRASTRUCTURE MEASURES** | | | | | | | | | | | |
| **FLOOD CAPTURE/STORAGE** | | | | | | | | | | | |
| ***Change existing Dam operation*** | | | | | | | | | | | |
| **Surcharge gate operations** | Taskforce | **0.0 to 1.0 m Penrith 0.0 to 0.7 m Windsor** | 26% floods no longer reach 1 in 100 AEP level at Windsor | Few floods significantly delayed & some floods reach evacuation routes faster | Not assessed | Yes | $ | Low | Not assessed | Negligible-Low | Increased risk of radial gate failure |
| **Pre-release <40 GL/d over three days** | Taskforce | **0.0 to 0.2 m Penrith 0.1 to 0.3 m Windsor** | 14% floods no longer reach 1 in 100 AEP level at Windsor | Few floods significantly delayed & some floods reach evacuation routes faster | Not assessed | Yes | $ | Low | Not assessed | Low | Possible loss of water supply and impacts on water quality |
| **Pre-release <130 GL/d over three days** | Taskforce | **0.2 to 0.7 m Penrith 0.7 to 1.3 m Windsor** | 42% floods no longer reach 1 in 100 AEP level at Windsor | Few floods significantly delayed & some floods reach evacuation routes faster | Not assessed | Yes | $$ | Medium | Not assessed | Medium | **Increased risk of loss of water supply; impacts on water quality** |
| **Lower FSL by 2m** | 2013 Review | **Negligible reduction** | Not assessed | Not assessed | Not assessed | Not assessed | Not assessed | Not assessed | Not assessed | Negligible-Low | **Does not meet primary objective, high remaining risk** |
| **Lower FSL by 5m** | Taskforce | **0.1 to 0.4 m Penrith 0.4 to 0.9 m Windsor** | 32% floods no longer reach 1 in 100 AEP level at Windsor | Few floods significantly delayed | Provides some benefits but less effective than dam raising | Yes | $$$ | $$$ | $58M | Low-Medium | **Does not meet primary objective, high remaining risk** |
| **Lower FSL by 12m** | Taskforce | 0.5 to 1.9 m Penrith 1.3 to 2.6 m Windsor | 64% floods no longer reach 1 in 100 AEP level at Windsor | Most floods that still reach 1 in 100 AEP level at Windsor significantly delayed | Not assessed | Yes | $$$$$ | $$$$ | **-$505M** | Higher than FSL -5m | **High water security costs; less flexibility to manage airspace for sequential events** |

| Option | Stage excluded | Flood peak reduction | Reduced exposure to floods | More certainty of time for evacuation | Reduced risk to life | Valley wide benefits | Cost | Benefit | Net benefit | Social, environmental & cultural heritage impacts | Other factors |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ***New flood mitigation dams*** | | | | | | | | | | | |
| **New dams upstream of Warragamba** (combined Wollondilly and Coxs) (see note 5) | 2013 Review | 1.5 to 1.8 m Penrith 2.2 to 2.3 m Windsor (see note 5) | Not assessed | Not assessed | Not assessed | Yes | $$$$ | Not assessed | Not assessed | **High-extreme** | **No sites on Wollondilly and Coxs Rivers as well suited as Warragamba** |
| **New dam on Nepean River** (see note 5) | 2013 Review | 1.1 to 1.7 m Penrith 1.5 to 1.7 m Windsor (see note 5) | Not assessed | Not assessed | Not assessed | Yes, but increased flood risk in Camden area | $$$–$$$$ | Not assessed | Not assessed | **High-extreme** | **Does not mitigate predominant Warragamba Catchment floods** |
| **New dams downstream of Warragamba** (Grose or Colo) (see note 5) | 2013 Review | **0.0 m Penrith 0.2 to 0.5 m Windsor** (see note 5) | Not assessed | Not assessed | Not assessed | No mitigation at Penrith | $$$–$$$$ | Not assessed | Not assessed | High-extreme | **Does not mitigate predominant Warragamba Catchment floods** |

| Option | Stage excluded | Significant regional reduction in flood risk | | | | | Economic costs and benefits | | | Social, environmental & cultural heritage impacts | Other factors |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Flood peak reduction, 1 in 50 to 1 in 1000 AEP range (see note 1) | Reduced exposure to floods (see note 2) | More certainty of time for evacuation (see note 3) | Reduced risk to life (see note4) | Valley wide benefits | Cost | Benefit | Net benefit | | |
| ***Raise Warragamba Dam*** | | | | | | | | | | | |
| **WD +14m** | Not excluded | **0.9 to 4.8m Penrith 2.3 to 3.9m Windsor** | 83% floods no longer reach 1 in 100 AEP level at Windsor | Most floods that still reach 1 in 100 AEP level at Windsor significantly delayed | Significant reductions | Yes | $$$$ | $$$$ | **$166M** | High | **Highest net benefit** |
| **WD +20m** | Taskforce | 3.8 to 5.5m Penrith 4.0 to 4.6m Windsor | 94% floods no longer reach 1 in 100 AEP level at Windsor | Most floods that still reach 1 in 100 AEP level at Windsor significantly delayed | Best performing | Yes | $$$$ | $$$$ | **$52M (lower than WD +14m)** | **Higher than WD +14m** | **Emptying the FMZ within required timeframe more challenging** |
| **DIVERSION CHANNELS OR ENHANCED WATER DRAINAGE FROM VALLEY** | | | | | | | | | | | |
| **Currency Creek diversion channel** | Taskforce | **0.0m Penrith 0.3 to 0.8m Windsor** | Not assessed | Not assessed | Not assessed | No mitigation at Penrith; slightly higher floods at Wisemans Ferry | $$$$ | $$$ | **-$518M** | High-extreme | Limited benefits due to low reduction in flood peaks |
| **Sackville cut-off (short diversion)** | 2013 Review | **0.0m Penrith 0.1 to 0.2m Windsor** | Not assessed | Not assessed | Not assessed | No mitigation at Penrith; slightly higher floods at Wisemans Ferry | $$$ | Negligible | Negative due to low benefit | High | Limited benefits due to low reduction in flood peaks |
| **Sackville large diversion** | 2013 Review | **Minor reduction given multiple hydraulic constrictions** | Not assessed | Not assessed | Not assessed | Likely limited mitigation at Penrith & higher floods at Wisemans Ferry | **$$$$$** | Not assessed | Negative due to very high costs | Likely extreme | Limited benefits due to low reduction in flood peaks |
| **Dredging between Windsor and Wisemans Ferry** | Taskforce | 0.0m Penrith 2.0 to 2.2m Windsor | Not assessed | Not assessed | Not assessed | No mitigation at Penrith; higher floods at Wisemans Ferry | $$$$ | $$$ | **-$254M** | **High-extreme** | Dredging must be maintained to maintain benefit |
| **LOCAL STRUCTURAL WORKS** | | | | | | | | | | | |
| **Peachtree Creek levee** | Taskforce | Protection to 1 in 100 AEP level within levee | Reduced exposure up to levee height; population may still require evacuation but be less willing to evacuate | Not assessed | Not assessed | **No – localised benefit only** | $ | Preliminary assessment | Positive | Medium | May discourage evacuation and increase risk of catastrophe |
| **McGraths Hill levee** | Taskforce | Protection to 1 in 50 AEP level within levee | | Not assessed | Not assessed | | $ | Preliminary assessment | Positive | Medium | Exacerbates flood island with evacuation route below levee crest |
| **Pitt Town levee** | 2013 Review | Protection to 1 in 50 AEP level within levee | | Not assessed | Not assessed | | $ | Not assessed | Not assessed | Not assessed | May discourage evacuation and increase risk of catastrophe |
| **ROAD INFRASTRUCTURE** | | | | | | | | | | | |
| **Regional evacuation road upgrades** | Taskforce | No reduction in flood peaks | No reduction of exposed population | Increased capacity shortens evacuation time | Provides benefits but less effective than dam raising | Yes, but requires multiple roads to effect valley-wide benefit | $$$–$$$$$ | $$ | **-$908M (road widening)** | Not assessed | **Does not reduce damages to homes, businesses and critical assets** |
| **Local evacuation road upgrades** | Progressing | No reduction in flood peaks | No reduction of exposed population | Decreased risk of local flooding and congestion | Not modelled; reduces local evacuation risk | Yes, but requires multiple projects to effect valley-wide benefit | $$ | Not assessed | Not assessed | Not assessed | **Complements existing regional evacuation routes** |

| Option | Stage excluded | Significant regional reduction in flood risk | | | | | Economic costs and benefits | | | Social, environmental & cultural heritage impacts | Other factors |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Flood peak reduction, 1 in 50 to 1 in 1000 AEP range (see note 1) | Reduced exposure to floods (see note 2) | More certainty of time for evacuation (see note 3) | Reduced risk to life (see note4) | Valley wide benefits | Cost | Benefit | Net benefit | | |
| **NON-INFRASTRUCTURE MEASURES** | | | | | | | | | | | |
| **OPTIONS TO REDUCE EXPOSURE TO FLOOD RISK** | | | | | | | | | | | |
| **Flood risk-based regional land use planning** | Progressing | Not applicable | **Limits increase in future exposure** | Not applicable | Manages cumulative impact of growth on evacuation capacity | Yes, for new development or redevelopment | Not assessed | $$ | Not assessed | Not applicable | Risk increases with growth at and above current 1 in 100 AEP flood planning level (FPL); benefits of dam raising assume current 1 in 100 AEP FPL is maintained |
| **Flood risk-based regional road planning** | Progressing | Not applicable | Not applicable | Not applicable | **Yes, if new or upgraded to provide evacuation capacity** (see note 6) | Yes | Not assessed | Not assessed | Not assessed | Not applicable | Road Evacuation Master Plan will consider flood risk when regional roads are upgraded for growth in the valley |
| **Voluntary house purchase (VP)** | Taskforce | Not applicable | Effectiveness in reducing exposure depends on take up | Not applicable | Potentially reduces evacuation load | Yes, but requires multiple VP to effect valley-wide benefit | **$$$$$** (up to 1 in 100 AEP) | Not assessed | **Negative due to very high costs** | High social impact | **Take up rates uncertain** |
| **Voluntary house raising (VHR)** | Not formally assessed | Not applicable | No reduction of dwellings in floodplain; population still requires evacuation | Not applicable | No benefits | Limited due to large flood depths and house construction types | Not assessed | Not assessed | Not assessed | Some social and heritage impact | **Impractical** given house construction types and extreme flood depths in this valley; may discourage evacuation and increase risk of catastrophe |
| **OPTIONS TO IMPROVE AWARENESS, PREPAREDNESS AND RESPONSIVENESS** | | | | | | | | | | | |
| **Improved flood forecasting and warning system** | Progressing | Not applicable | Not applicable | Increased certainty of forecasts for evacuation | **Increased certainty of forecasts for evacuation** | Yes | $ | Not assessed | Not assessed | Not applicable | Level improvement uncertain; will need to validate after a flood event; complementary to infrastructure options; reduces remaining risk |
| **Community flood awareness, preparedness and responsiveness** | Progressing | Not applicable | **Increased evacuation compliance** | Not applicable | **Increased evacuation compliance** | Yes | $ | Indirectly assessed | Indirectly assessed | Not applicable | Critical component for successful evacuation and resilient communities |
| **Best practice emergency response and recovery** | Progressing | Not applicable | Not applicable | Not applicable | **Improved flood rescue and recovery capability** | Yes | $ | Not assessed | Not assessed | Not applicable | Optimum decision making; rescue capacity; efficient recovery etc |
| **IMPROVED GOVERANCE** | | | | | | | | | | | |
| **Improved governance to support integrated flood risk management** | Progressing | Not applicable | Not applicable | Not applicable | Not measurable | Yes | $ | Not assessed | Not assessed | Not applicable | **Coordination of flood risk management in valley** |
| **Collection of post-event flood data/intelligence** | Progressing | Not applicable | Not applicable | Not applicable | Not measurable | Yes | $ | Not assessed | Not assessed | Not applicable | **Continuous improvement for future floods** |

*Notes:*

AEP = annual exceedance probability; GL/d = gigalitres per day

1 To meet the evaluation criterion, an option needed to reduce the peak flood level at Windsor by at least 2.0 metres. A reduction of 1.0 to 2.0 metres partially satisfied the evaluation criterion.

2 For flood mitigation infrastructure measures, to meet the evaluation criterion, an option needed to reduce the number of floods reaching or exceeding the current 1 in 100 AEP flood level at Windsor (17.3 m AHD) by 50%. A reduction of 25-50% partially satisfied the evaluation criterion.

3 For flood mitigation infrastructure measures, to meet the evaluation criterion, an option needed to delay by >10 hours more than 50% of the remaining floods reaching or exceeding the 1 in 100 AEP flood level at Windsor, which is also the level of the Windsor flood evacuation route.

4 For selected infrastructure options, reduced risk to life was assessed on the basis of changes to average annual vehicles unable to evacuate.

5 The assessment of these new flood mitigation dam options assumed complete retention of floodwater, which is unrealistic but provides a maximum bound on the flood mitigation benefits that could be achieved (WMA, 1997). Only results for the 1 in 100 and 1 in 500 chance per year events were reported. The estimated costs in 1997 dollars were factored up to 2017 dollars using changes in CPI.

6 The Taskforce determined that although regional evacuation roads upgrades were not viable to address flood risk alone, there was opportunity to have flood risk considered when these regional roads are upgraded in response to growth in the valley.

### *4.4.1 Significant, regional reduction of flood risk*

Changes to downstream peak flood levels as a result of flood mitigation infrastructure options are summarised for Penrith and Windsor in **Figure 4.3** and **Figure 4.4**. Information for these sites plus Wallacia, North Richmond and Wisemans Ferry is tabulated in **Appendix E**.

Options to reduce downstream flood levels by changing the way the existing Warragamba Dam is operated mostly fail to meet the objective of a significant regional reduction of flood risk as defined in **Section 4.3.1**.

For example, changing the way the radial gates are operated to maximise the amount of water held back by the gates (the ‘surcharge’ method) would result in only relatively minor reductions in peak flood levels (maximum 0.7 metres) at Windsor, and only up to the 1 in 50 year event. It could also slightly *increase* some flood levels at Wallacia and Penrith if the gates have to be quickly raised for dam safety purposes for larger events.

Alternatively, pre-releasing water from Warragamba Dam to create temporary airspace to capture inflows would provide a maximum peak flood level reduction of 1.3 metres at Windsor within the critical range of 1 in 50 to 1 in 1,000 chance per year events, and so fails to satisfy the objective.

Another way to provide airspace for flood mitigation would be to permanently lower the current FSL. Lowering FSL by five metres would provide a maximum reduction of peak flood levels at Windsor by 0.9 metres within the critical range of floods, which fails to meet the key objective of a significant reduction of flood risk.

Lowering FSL by 12 metres would reduce the 1 in 100 chance per year peak flood levels at Penrith by 1.2 metres and Windsor by 1.9 metres. Although better than the -5m FSL option, it does not offer the same magnitude of peak flood level reductions for this and rarer floods as options involving dam wall raising (see **Figure 4.3** and **Figure 4.4**). The size of the FMZ formed by lowering FSL by 12 metres is less than that formed by raising the dam wall by 14 metres. The deep V-shaped valley at Warragamba Dam means that the volume of airspace created by raising the dam by 14 metres is about 30% more than the volume created by lowering FSL by 12 metres, as depicted in **Figure 4.5**. Also, for the FSL-lowering option, under the H14 operating rules designed to protect the dam, the existing gates must be fully raised at a point during the rising dam water level. This releases floodwater earlier and so lessens the degree of reduction of downstream flood levels compared to a 14-metre dam raising.

Constructing two new flood mitigation dams upstream of Warragamba Dam could, in combination, yield a 2.2-2.3 metres reduction in downstream peak flood levels at Windsor for the 1 in 100 and 1 in 500 chance per year events. However, this option would have unacceptably high economic and environmental costs. A flood mitigation dam on the Nepean River downstream of Camden would yield lesser flood-reducing benefits because it does not mitigate flows coming from the predominant Warragamba Catchment that contributes most to flooding at Penrith and Windsor. It also has unacceptably high combined social, economic and environmental impacts.

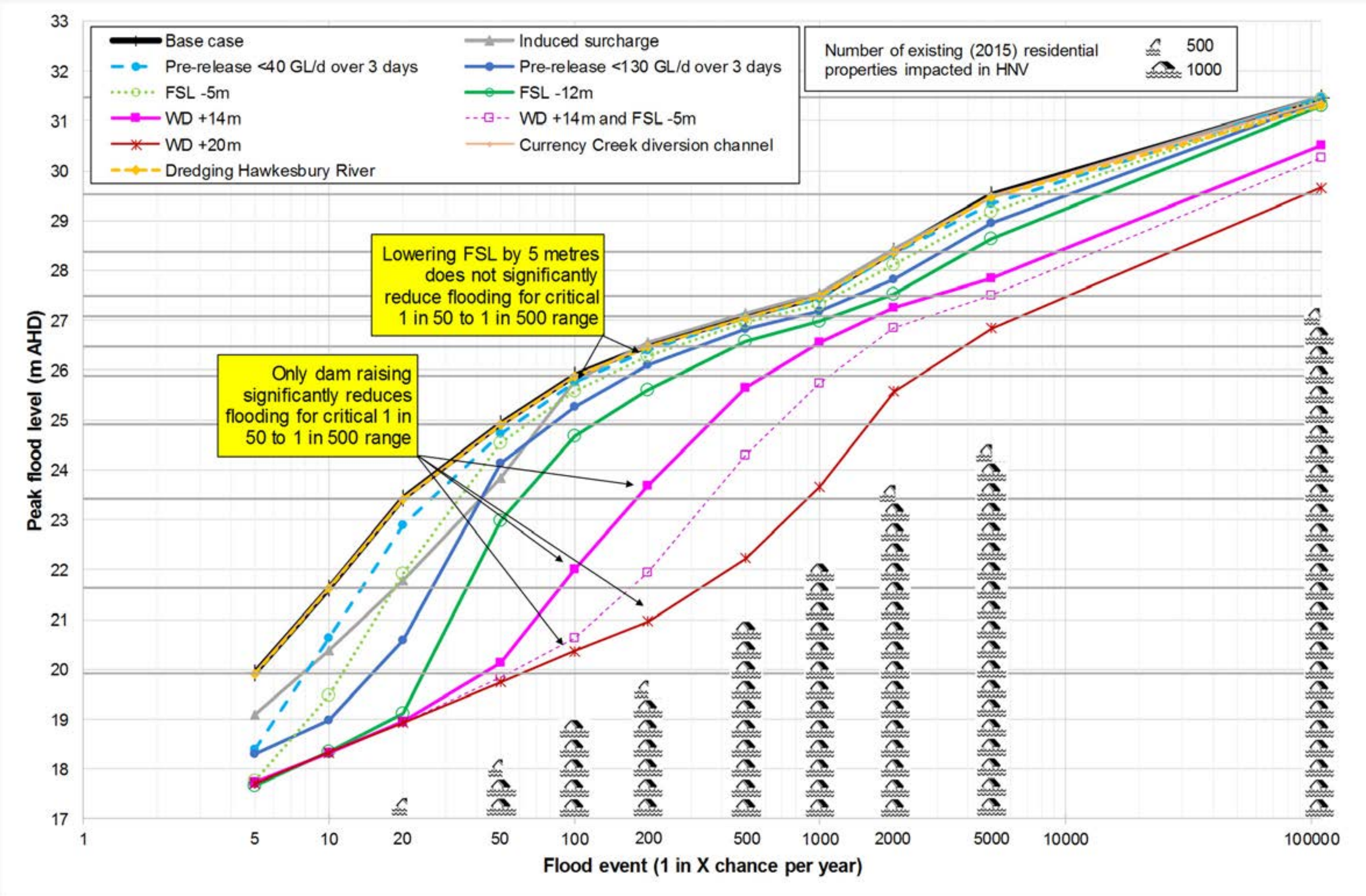



**Figure 4.3 Stage-frequency curve for flood mitigation infrastructure options, Penrith**

*Source:* INSW using data from WMAwater (2014 and 2016 model results)

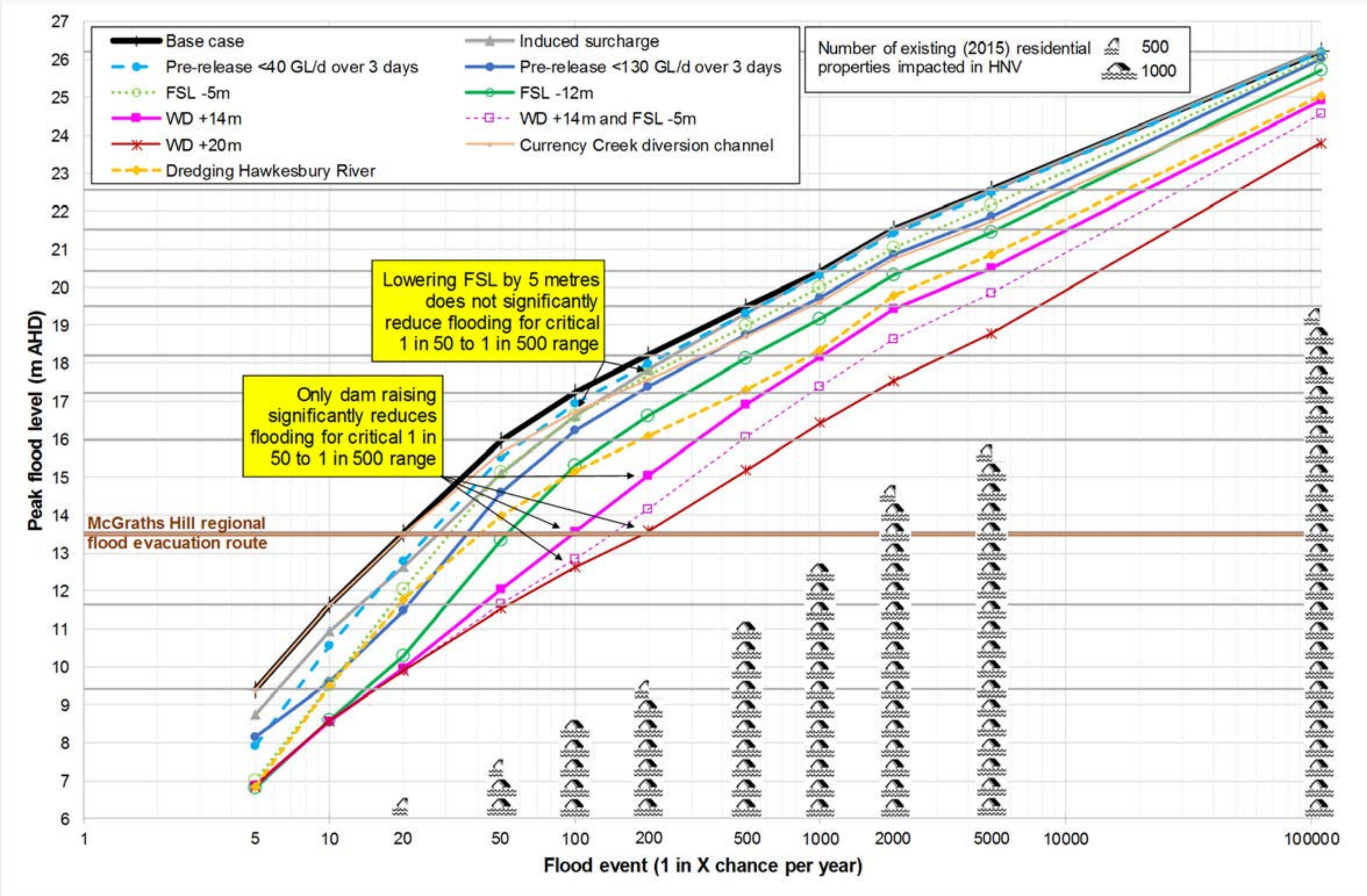



**Figure 4.4 Stage-frequency curve for flood mitigation infrastructure options, Windsor**

*Source:* INSW using data from WMAwater (2014 and 2016 model results)

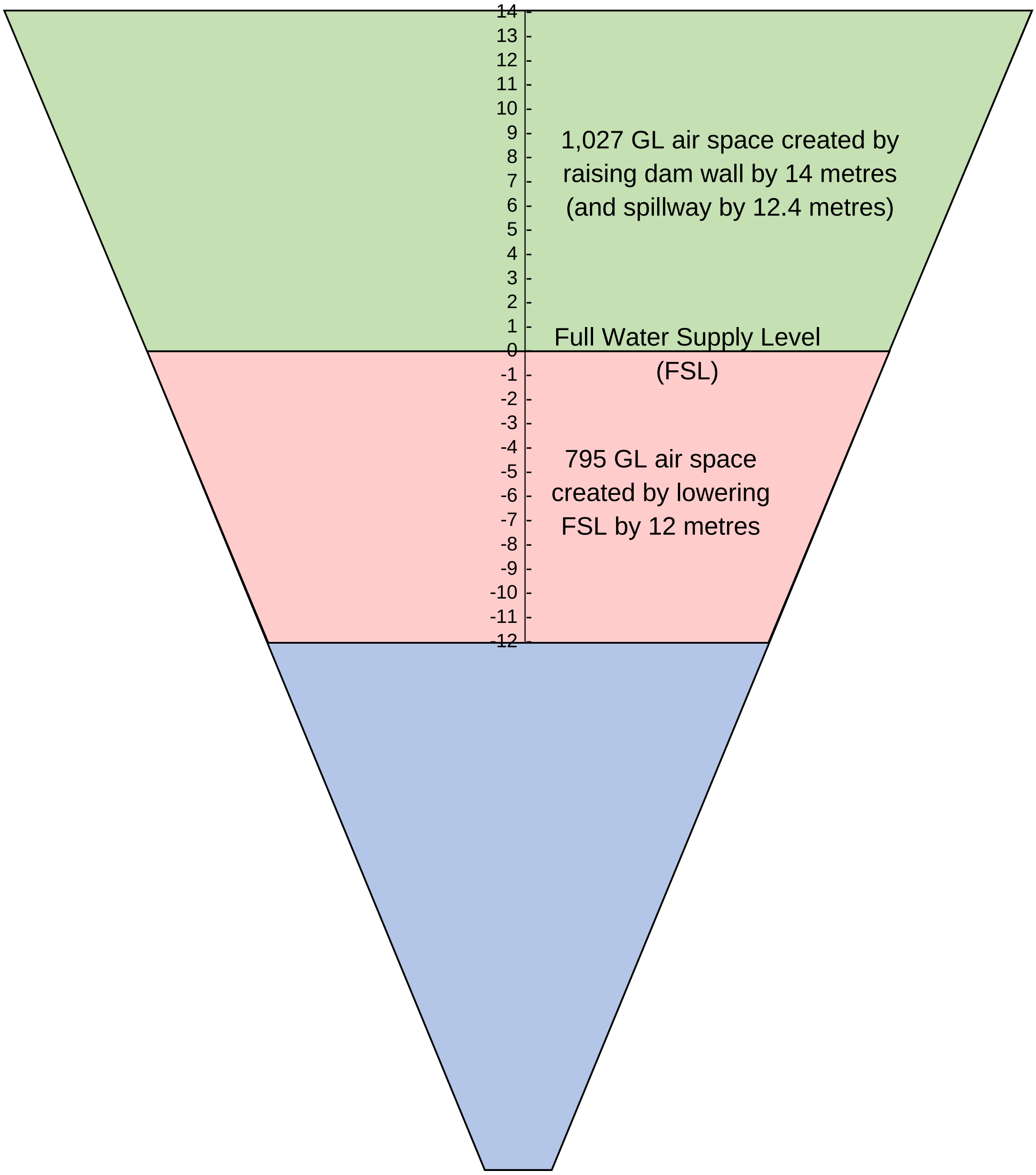



**Figure 4.5 Schematic comparison of airspaces created by lowering FSL and raising dam wall**

*Source*: INSW

*Note*: Airspaces subject to change with new bathymetry; mitigation would not cease when the raised dam commences spilling

With the exception of large-scale dredging of the Hawkesbury River, the investigated downstream flood mitigation infrastructure options – Currency Creek diversion channel and Sackville cut-off – would reduce peak flood levels within the critical range at Windsor by a maximum of only 0.8 metres, would provide no significant benefit to Penrith, and could increase flood levels at Wisemans Ferry. While the modelled dredging scenario does offer sizeable reductions to peak flooding upstream in the Richmond/Windsor floodplain, it also offers no significant benefit to Penrith, it generates higher floods at Wisemans Ferry, and modelling indicated salinity ingress upstream. Also, the downstream options do not delay the peak during the flood event compared to the Warragamba Dam raising options and lowering FSL by 12 metres.

The local levees at Peachtree Creek (Penrith), McGraths Hill and Pitt Town would protect areas within the levees up to the design flood limit (1 in 100 chance per year at Penrith, 1 in 50 chance per year at McGraths Hill and Pitt Town). Because they provide only limited and localised benefits, they were not included in the Flood Strategy. Nonetheless, Peachtree Creek levee was considered worthy of more detailed consideration as a local measure.

The option with the greatest regional reduction in downstream peak flood levels is raising Warragamba Dam wall. A 14-metre dam raising reduces peak flood levels at Windsor by more than 2.3 metres in the critical flood range (1 in 50 to 1 in 1,000 chance per year). The current 1 in 100 chance per year flood would be reduced by 3.7 metres, such that McGraths Hill regional evacuation route would not be cut during that event. A flood reaching the current level of the 1 in 100 chance per year flood at Windsor (17.3 m AHD) would be much less frequent – decreasing to a 1 in 580 chance per year event.

A 20-metre dam raising would offer even larger reductions of peak flood levels downstream for floods rarer than a 1 in 50 chance per year. A 20-metre raising reduces peak flood levels at Windsor by more than 4.0 metres in the critical flood range. The 1 in 100 chance per year flood would be reduced by 4.6 metres. A flood reaching the current level of the 1 in 100 year chance per year flood at Windsor (17.3 m AHD) would be close to a 1 in 2,000 chance per year event. While the 20-metre dam raising provides the greatest flood mitigation benefits, it has greater upstream inundation impacts and would require larger post flood releases which would prolong flooding of low-lying areas downstream.

### *4.4.2 Risk to life reduction*

Changes in the exposure of dwellings in the Hawkesbury-Nepean Valley with different flood risk management options are presented in **Figure 4.6** for current (2015) level of development, and in **Figure 4.7** for forecast development levels by 2041. These show that lowering Warragamba Dam FSL by five metres does not substantially reduce the number of dwellings exposed to floodwater. In contrast, raising Warragamba Dam by 14 metres or 20 metres would result in very substantial reductions.

Changes in both the probability of key regional evacuation roads being cut, and in the probability of greater lead time prior to the evacuation road being cut, are shown for different flood risk management options in **Figure 4.8** (for the McGraths Hill regional evacuation route) and **Figure 4.9** (for the Windsor regional evacuation route). These figures show that dam raising options perform best for reducing the frequency and delaying the inundation of evacuation routes. A 14-metre raising would prevent 80% of events that currently reach or exceed the McGraths Hills evacuation route (13.5 m AHD) reaching that level, and prevent 83% of events that currently reach or exceed the Windsor evacuation route (Jim Anderson Bridge, 17.3 m AHD) reaching that level. Of the floods that would still reach those evacuation routes, about 70% would be delayed by more than 10 hours, providing more opportunity for evacuation from the flood islands. A 20-metre raising would prevent 89% of events that currently reach or exceed the McGraths Hills evacuation route and 94% of events that currently reach or exceed the Windsor evacuation route, reaching those levels.

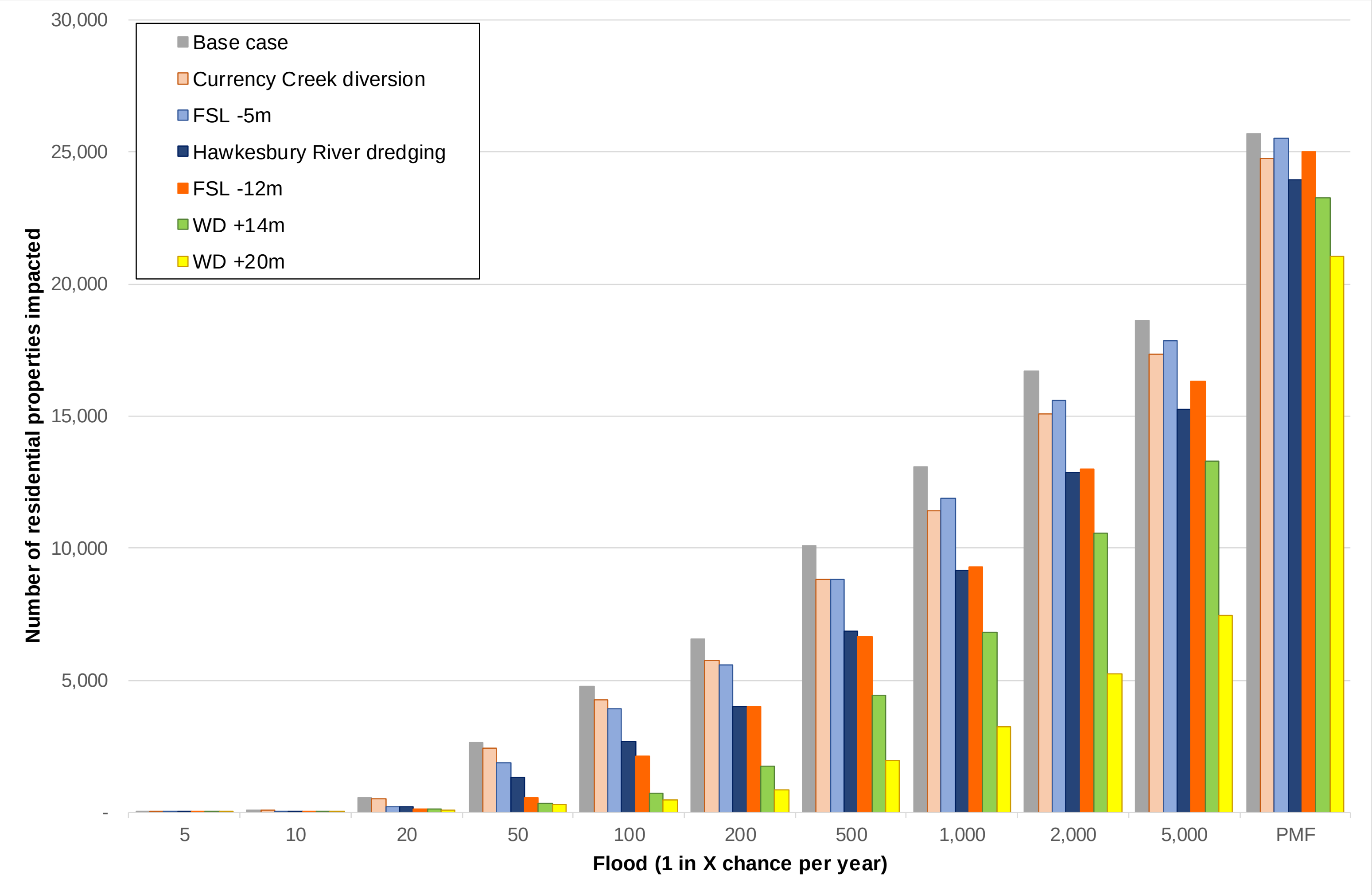



**Figure 4.6 Number of residential properties impacted in the valley, base case versus options, 2015 development**

*Source:* INSW using data from CIE

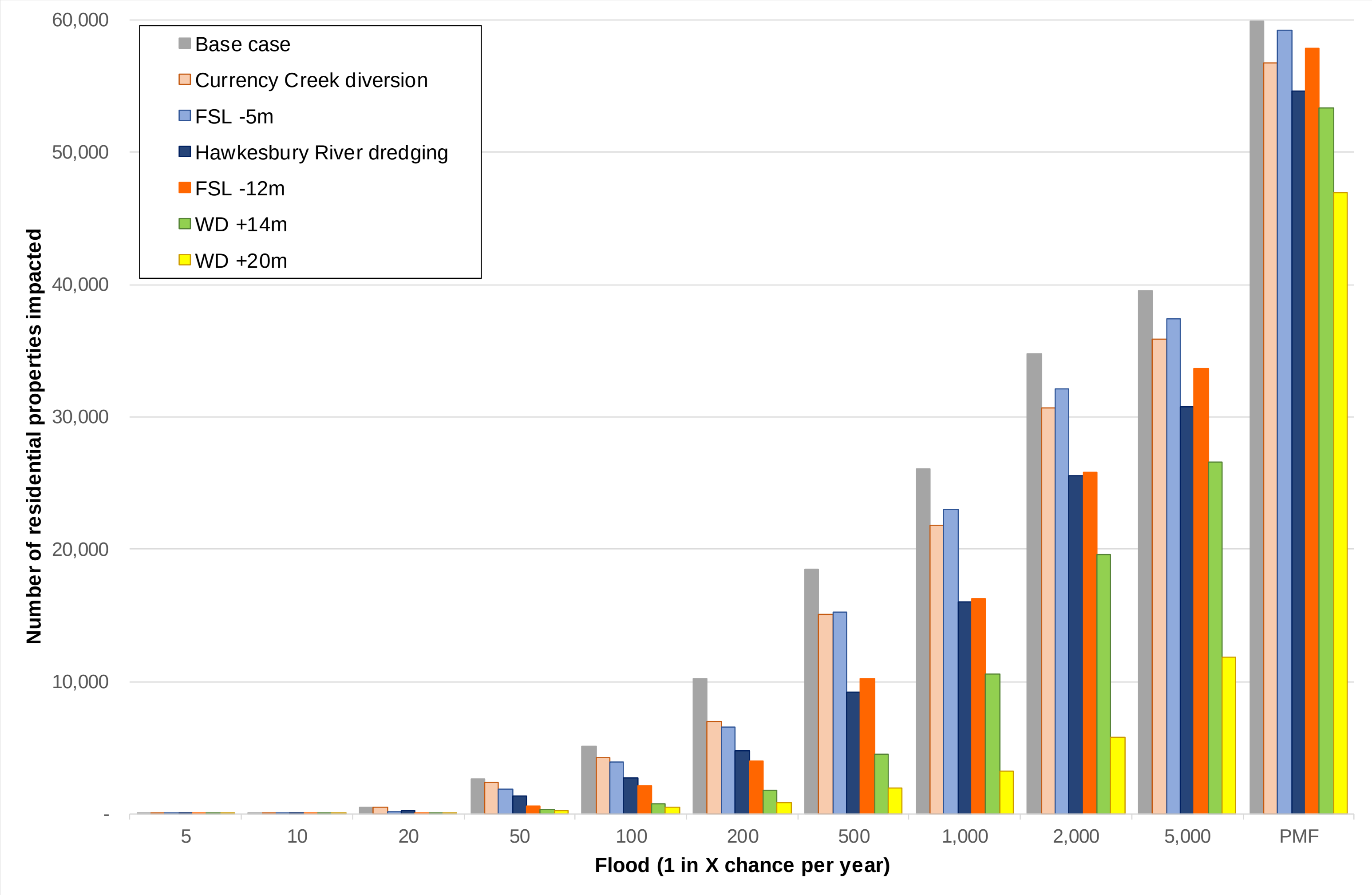



**Figure 4.7 Number of residential properties impacted in the valley, base case versus options, 2041 development**

*Source:* INSW using data from CIE

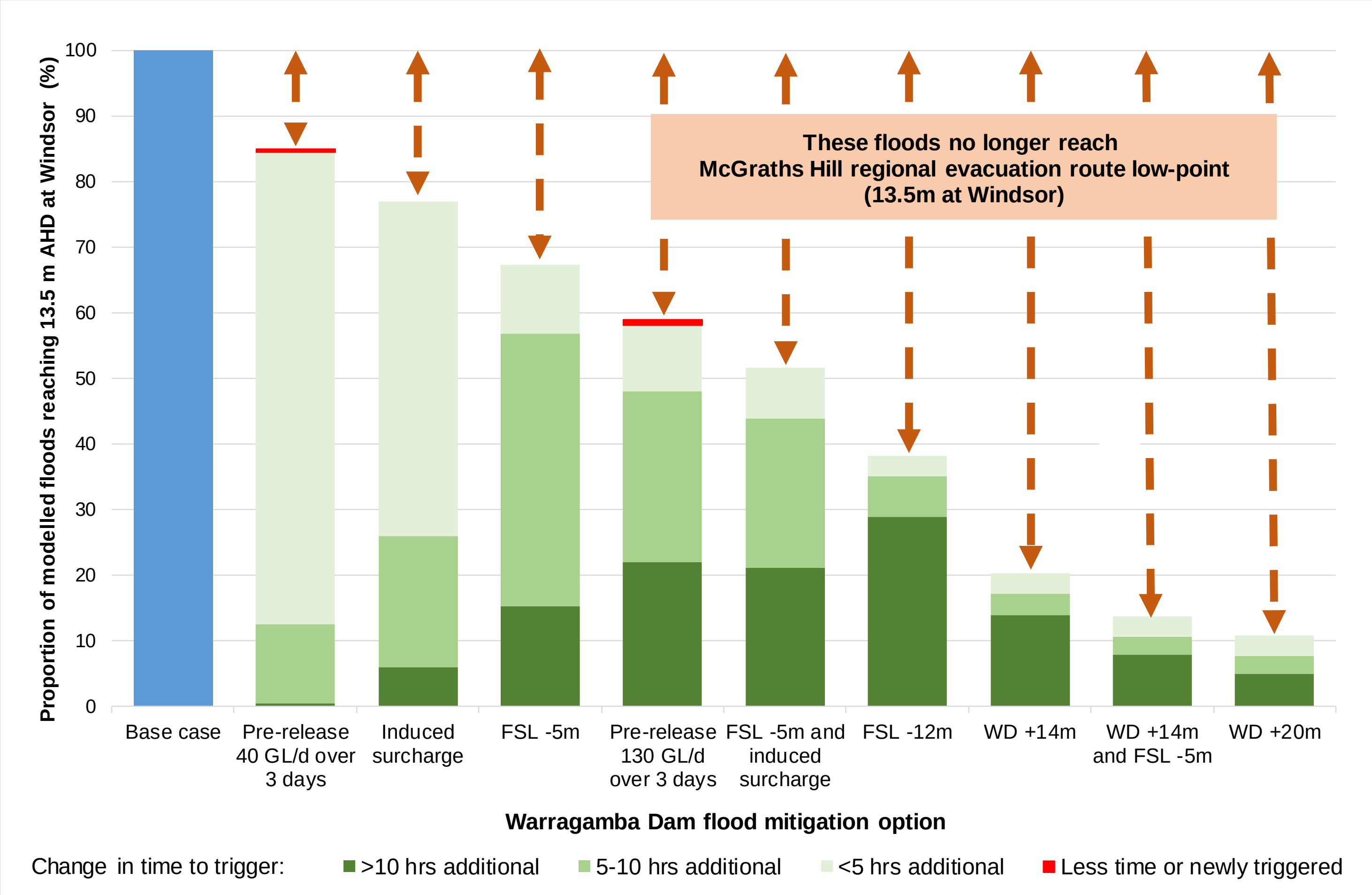



**Figure 4.8 Change in frequency and timing of events reaching and exceeding 13.5 m AHD level at Windsor with different Warragamba Dam infrastructure options**

*Source:* INSW using data from WMAwater (2014 and 2016 models)

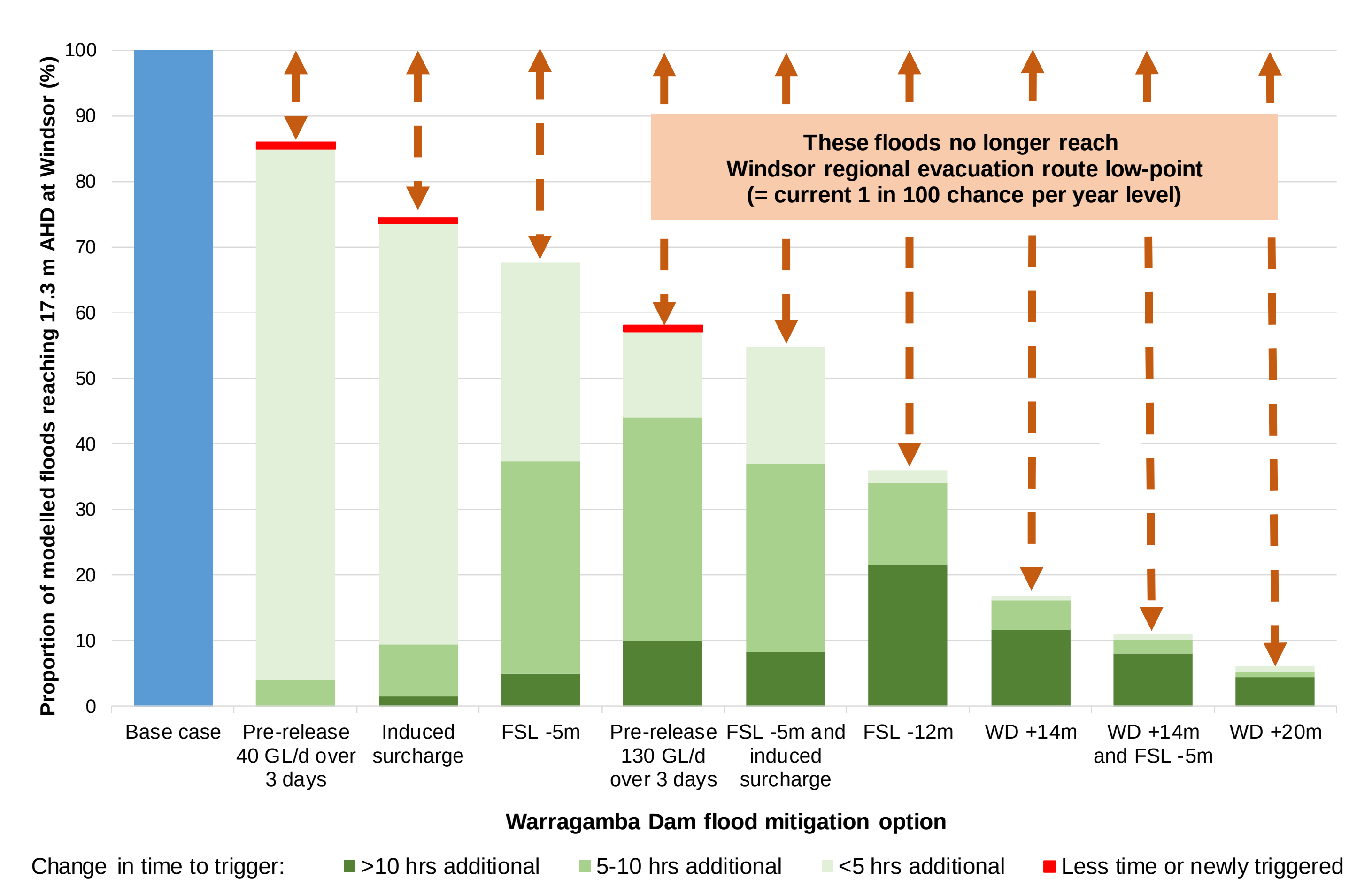



**Figure 4.9 Change in frequency and timing of events reaching and exceeding 17.3 m AHD level at Windsor with different Warragamba Dam infrastructure options**

*Source:* INSW using data from WMAwater (2014 and 2016 models)

None of the options involving changes to the operation of the existing Warragamba Dam – including lowering of FSL – provide the same quantum of benefits. Releasing water before a forecast event can *reduce* time available for evacuation in some instances (see the red components on **Figure 4.8** and **Figure 4.9**). Indeed, such pre-releases can have pronounced impacts on evacuation from lower-lying areas in the valley (up to about 11.0 m AHD at Windsor), especially at the higher outflow rates that are needed to achieve larger peak flood level reductions.

A preliminary assessment of average annual vehicles (and by extension, population) unable to evacuate was undertaken using the purpose-built flood evacuation traffic model (see **Section 4.3.2**). This allowed a comparison of the utility of various dam options and regional evacuation road options for reducing risk to life. It is important to note that this analysis considers the whole range of possible floods that trigger regional flood evacuations (based on 46 representative model flood events from 19,500 Monte Carlo simulations). This includes very rare floods anticipated to inundate large populated areas. The modelling reports the population unable to evacuate as an *average* per year. Annualization is a method that takes account of the frequency and consequences of the full range of possible floods, and allows comparative analysis between options. It is also noted that mortality is assessed as a subset of people unable to evacuate.

**Table 4.4** presents the Taskforce's preliminary assessment of average annual population unable to evacuate for the current (2011) population, for different dam options. This shows that dam raising performs significantly better than lowering FSL by five metres in terms of reduced average annual population unable to evacuate. This is because the dam raising options provide greater reductions of peak flood levels for the floods that pose most risk to life (rarer than 1 in 100 chance per year).

These results are conservative because the flood evacuation model assumed that even after dam raising, the adopted 15-hour forecast timeframe remained. In reality the dam raising would delay downstream flood peaks by 10 hours or more (**Figure 4.8**; **Figure 4.9**). This delay means the peak occurs later in the rainfall event that causes the flood, allowing for the flood peak forecast to be based more on *observed* rainfall and river levels and less on *forecast* rain. This would further increase the risk to life benefits of the dam raising. The benefit of the delay in the flood peak will be better quantified with the Bureau of Meteorology's improved flood forecasting upgrade project (see **Section 9.2.1**).

**Table 4.4 Taskforce's preliminary modelling of relative risk to life for current (2011) population, under different dam scenarios**

| | Current (2011) average annual population unable to evacuate by dam scenario | | | |
|---|---|---|---|---|
| **Evacuation roads scenario** | Current dam | FSL -5m | WD +14m | WD +20m |
| Current (2014) roads | | | | |

| **People** | 30 | 20 | 10 | 1 |
|---|---|---|---|---|

*Source*: Taskforce

*Note:* Evacuation simulations were conducted using the 2015 evacuation model and the 2011 population. This was a preliminary analysis for the purpose of comparing options. Evacuation modelling and data inputs continue to be refined for the Warragamba Dam Raising Enviornmental Impact Statement.

**Table 4.5** presents the Taskforce's preliminary assessment of average annual population unable to evacuate in 2041 – for different dam, road and population growth scenarios. There are several noteworthy features:

- The dam raising options perform significantly better than lowering FSL by five metres in terms of reduced average annual population unable to evacuate. This is because the dam raising options provide greater reductions of peak flood levels and greater delays of flooding for the floods that pose most risk to life (rarer than 1 in 100 chance per year).
- Evacuation road infrastructure options, in isolation, provide lower benefits than dam raising. The best performing road options are those packages involving capacity upgrades. Dam raising affords the benefit of controlling the largest contributor of floodwaters for the largest floods (the Warragamba Catchment), whereas road infrastructure upgrades must be applied across extensive parts of the floodplain.
- If the dam was raised, any subsequent regional evacuation road infrastructure upgrades would only provide modest *additional* benefits.
- The results are highly sensitive to the assumed population growth, with high growth significantly increasing the population unable to evacuate. This points to the imperative of integrated, regional land use planning and road planning to manage flood risk exposure in the valley.

### *4.4.3 Economic costs and benefits*

A preliminary assessment of the benefits of alternative flood mitigation options was conducted for the 2013 Review and presented in terms of reductions in average annual damages. Smaller, frequent floods cause less damage, and larger, rare floods cause greater damage. An assessment of average annual damages is a way of incorporating the probability and consequences of the full range of possible flood events into a single metric. The results are presented in **Figure 4.10**.

Given the minor reductions in flood peaks associated with many options (**Figure 4.3** and **Figure 4.4**), the corresponding reductions in average annual damages are also minor (**Figure 4.10**). The limited extent of benefit for several options is also apparent, with negligible benefits evident for the Penrith reach. The dam raising options were identified as providing the greatest flood risk mitigation in the 2013 Review assessment. These were therefore carried forward for more detailed Taskforce investigations, along with alternative options with strong community support.

**Section 4.3.3** describes the Taskforce method for assessing the costs and benefits of alternative flood risk management options.

Some options could be safely excluded from further consideration because of excessive costs and impacts. For example, constructing the Sackville large diversion channel from South Maroota to Leetsvale was estimated as part of the 2013 Review to cost in excess of $5 billion and to have extreme environmental impact.

## Table 4.5 Taskforce's preliminary modelling of relative risk to life by 2041 for different dam, road and population growth scenarios

| Evacuation roads scenario | Average annual population unable to evacuate by dam and 2041 population scenarios | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Current dam | | FSL -5m | | WD +14m | | WD +20m | |
| | 2041 Lower | 2041 Upper | 2041 Lower | 2041 Upper | 2041 Lower | 2041 Upper | 2041 Lower | 2041 Upper |
| Planned 2041 roads | | | | | | | | |
| Option 1 – Road height increases to 17.3 metres by 2041 | | | | | | | | |
| Option 2 – Road height increases to 18.5 metres by 2041 | | | | | | | | |
| Option 3 – Lane capacity increases by 2041 | | | | | | | | |
| Option 4 – Options 1 and 3 by 2041 | | | | | | | | |
| Option 5 – Options 2 and 3 by 2041 | | | | | | | | |
| Option 6 – Build Castlereagh Freeway at 17.3 metres by 2041 | | | | | | | | |
| Option 7 – Option 4 and Option 6 by 2041 | | | | | | | | |
| Option 8 – Option 5 and build Castlereagh Freeway at 18.5 metres by 2041 | | | | | | | | |
| Option 9 – Option 5 and build Castlereagh Freeway at 20.2 metres by 2041 | | | | | | | | |

| **People** | 1 | 5 | 10 | 20 | 50 | 100 | 200 |
|---|---|---|---|---|---|---|---|

*Source*: Taskforce

*Note:* Evacuation simulations were conducted using the 2015 evacuation model and the then projected 2041 'Lower' and 'Upper' populations, which reflect low and high growth development paths. This was a preliminary analysis for the purpose of comparing options. Evacuation modelling and data inputs continue to be refined for the Warragamba Dam Raising Enviornmental Impact Statement.

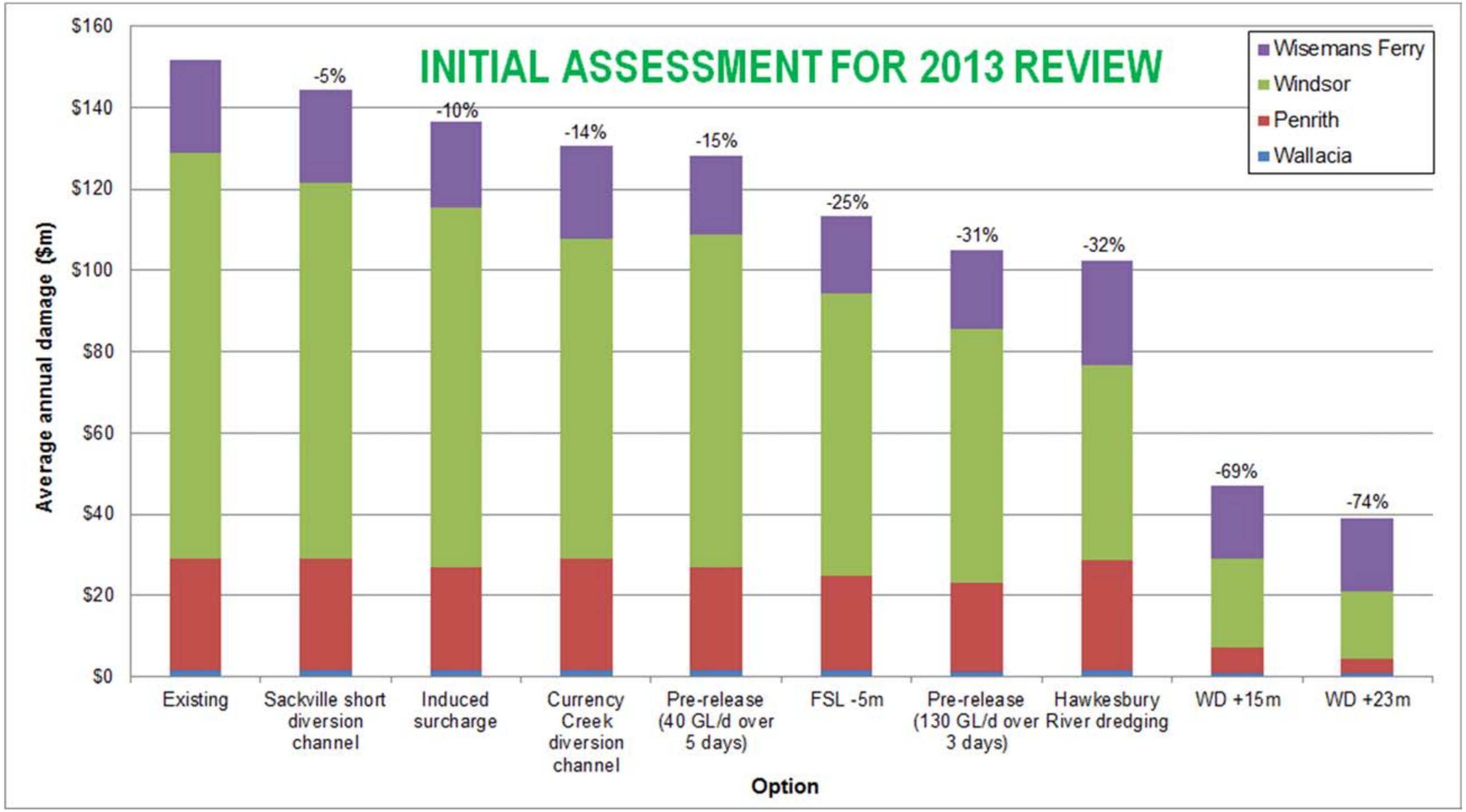



**Figure 4.10 The 2013 Review assessment of relative average annual damages of flooding in the valley with alternative options**

*Note:* This analysis was conducted as part of the 2013 Review. More detailed economic analysis of the preferred options was subsequently undertaken for the Taskforce, which with some changed assumptions resulted in a reduction of existing case average annual damages. Since the purpose of the 2013 Review's analysis was to understand the relative performance of alternative options, the results are considered to provide a valid comparison. The Review defined Wallacia reach as extending from Bents Basin to the Warragamba River, Penrith reach as extending from Warragamba River to Grose River, Windsor reach as extending from Grose River to Sackville (including backwater flooding up Rickabys Creek, South Creek and Eastern Creek), and Wisemans Ferry reach as extending from Sackville to Brooklyn (including backwater flooding up Colo River, Macdonald River and Mangrove Creek).

Purchasing existing houses costs less than 14-metre dam raising only if the scope of purchase was confined to dwellings impacted by the 1 in 20 chance per year or smaller floods (well below the 1 in 100 flood planning level). But limiting the scope of a scheme to this level of inundation would not provide a significant, regional reduction of flood risk, given that risk to property and life is concentrated in the 1 in 50 to 1 in 1,000 chance per year range. The large existing urban development in the valley, and high cost of purchase precludes house purchase as a feasible regional flood risk management option. It would also have a high social cost.

Levees at Peachtree Creek (Penrith) and McGraths Hill were identified as cost-effective options for providing local flood protection only.

**Table 4.6** presents the discounted benefits and costs and the net present benefit of options taken forward to the latter stages of the Taskforce evaluations. Under ‘central case’ assumptions (see **Table 4.2**), only the options to raise Warragamba Dam wall by 14 metres or 20 metres and the option to lower the dam FSL by five metres deliver net benefits to the community. This is also the case for low and high sensitivity tests of the economic assessment. The 14-metre dam raising is preferred to all other options under the ‘central case’, as highlighted in **Figure 4.11** and further explained below.

Even though the option to lower FSL by five metres has a net benefit due to its low cost, it does not meet the core objective of significantly reducing flood risk (**Section 4.4.1**). It does not substantially reduce the number of dwellings exposed to floods (**Section 4.4.2**) or provide the same quantum of benefits in terms of reduced and delayed inundation of evacuation routes as those made possible by dam raising (**Section 4.4.2**).

A comparison of reductions in average annual damages shows the relative ineffectiveness of the -5m FSL option on this metric too, since this option would reduce current average annual damages by only 27%, compared to 75% for a 14-metre raised dam and 85% for a 20-metre raised dam. **Figure 4.12** and **Figure 4.13** present the contribution to average annual damages across the range of floods, for 2015 and 2041 development scenarios, respectively. It confirms that lowering FSL by five metres fails to effectively target the critical 1 in 50 to 1 in 1,000 chance per year flood range that contributes most to average annual flood damages.

Other flood mitigation options such as dredging the Hawkesbury River and the Currency Creek diversion channel have significant net costs (**Table 4.6**).

Similarly, lowering the FSL by 12 metres also has a significant net cost, reflecting the fact that this would lead to higher costs associated with additional water supply infrastructure needed to meet Sydney’s future water supply needs. The cost in **Table 4.6** does not account for the fact that the -12m FSL option would likely preclude the intended release of environmental flows (e-flows) from the dam because the costs of the additional water lost to the water supply system would be unacceptably high. The e-flow benefits that would be foregone are in the order of $400 million. This would be an additional cost of adopting the -12m FSL option.

The major regional evacuation road infrastructure options also result in net costs, reflecting the relatively high construction costs compared to the benefits of reducing the risk to life for low probability but high consequence floods. Roads also do not reduce flood damages. The road infrastructure options were examined with a focus on upgrading roads for flood resilience, not for increasing capacity for day to day growth.

The flood infrastructure mitigation options are nearly all 'substitutes', which means that if an option does not have net benefits when assessed on a standalone basis, it will not have net benefits when undertaken in conjunction with other options.

**Table 4.6 Discounted benefits and costs and net benefits of selected options**

| Option | Discounted benefits | Discounted costs | Net benefits |
|---|---|---|---|
| | $m | $m | $m |
| **Flood mitigation options** | | | |
| -5m FSL | 320 | -262 | 58 |
| -12m FSL | 609 | -1114 | -505 |
| 14m dam wall raising | 768 | -603 | 165 |
| 14m dam wall raising and -5m FSL | 734 | -854 | -120 |
| 20m dam wall raising | 809 | -757 | 52 |
| Currency Creek diversion channel | 120 | -638 | -518 |
| Dredging Hawkesbury River | 389 | -643 | -254 |
| **Evacuation road infrastructure options** | | | |
| Option 1 – Road height increases to 17.3 metres by 2041 | -1 | -336 | -337 |
| Option 2 – Road height increases to 18.5 metres by 2041 | -5 | -353 | -358 |
| Option 3 – Lane capacity increases by 2041 | 43 | -951 | -908 |
| Option 4 – Options 1 and 3 by 2041 | 42 | -1279 | -1237 |
| Option 5 – Options 2 and 3 by 2041 | 35 | -1304 | -1269 |
| Option 6 – Build Castlereagh Freeway at 17.3 metres by 2041 | -13 | -1041 | -1054 |
| Option 7 – Option 4 and Option 6 by 2041 | 10 | -2066 | -2056 |
| Option 8 – Option 5 and build Castlereagh Freeway at 18.5 metres by 2041 | 14 | -2108 | -2094 |
| Option 9 – Option 5 and build Castlereagh Freeway at 20.2 metres by 2041 | 22 | -2247 | -2225 |

*Source:* CIE

*Note:* 'Central' case assumed; loss of life was not measured for dredging, Currency Creek diversion, -12m FSL and the combination of a raising of the dam wall by 14m and a -5m FSL, as these options performed less well than other options in early analysis. The analysis assumed construction of each option commenced in 2016.

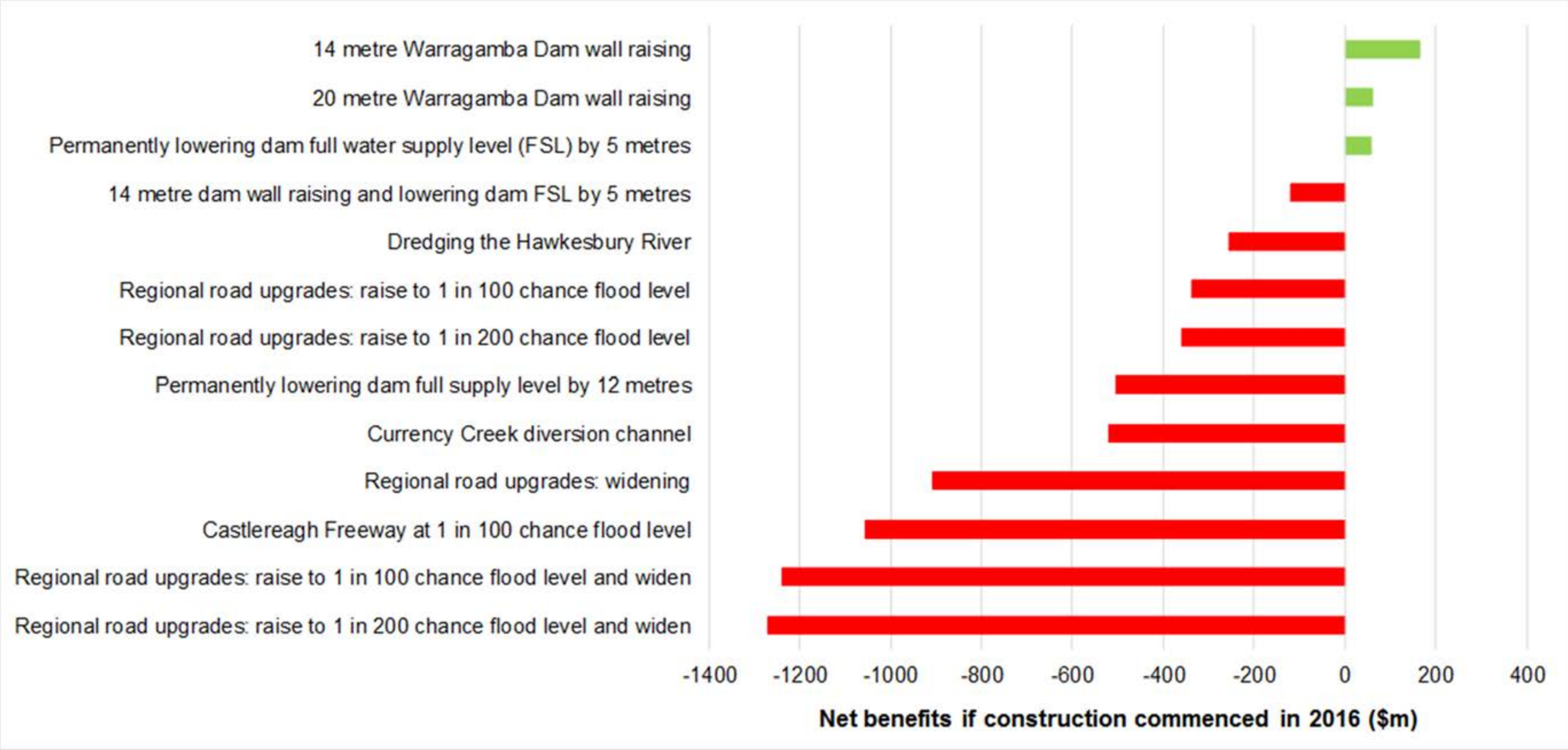



**Figure 4.11 Net benefits of flood mitigation and evacuation road infrastructure options**

*Source:* CIE

*Note:* 'Central' case assumed; loss of life was not measured for dredging, or the Currency Creek diversion, or -12m FSL or the combination of a raising of the dam wall by 14 metres and a -5m FSL, as these options performed less well than other options in early analysis. Additional Castlereagh Freeway options are not shown, and have greater net costs than the options shown. The analysis assumed construction of each option commenced in 2016.

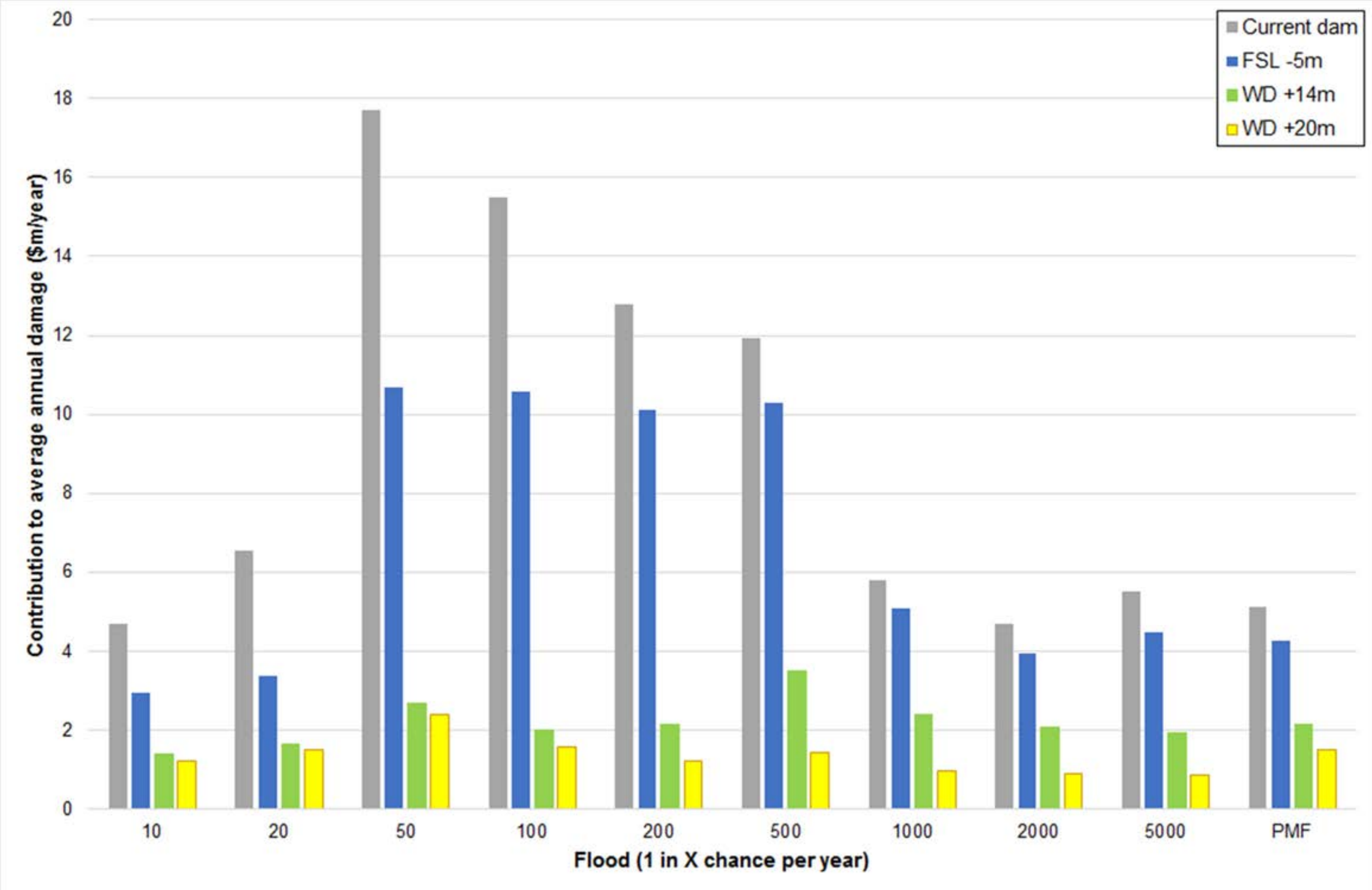



**Figure 4.12 Contribution of flood events to average annual flood damages in the valley, base case versus three options, 2015 development**

*Source:* CIE

*Note:* PMF = probable maximum flood

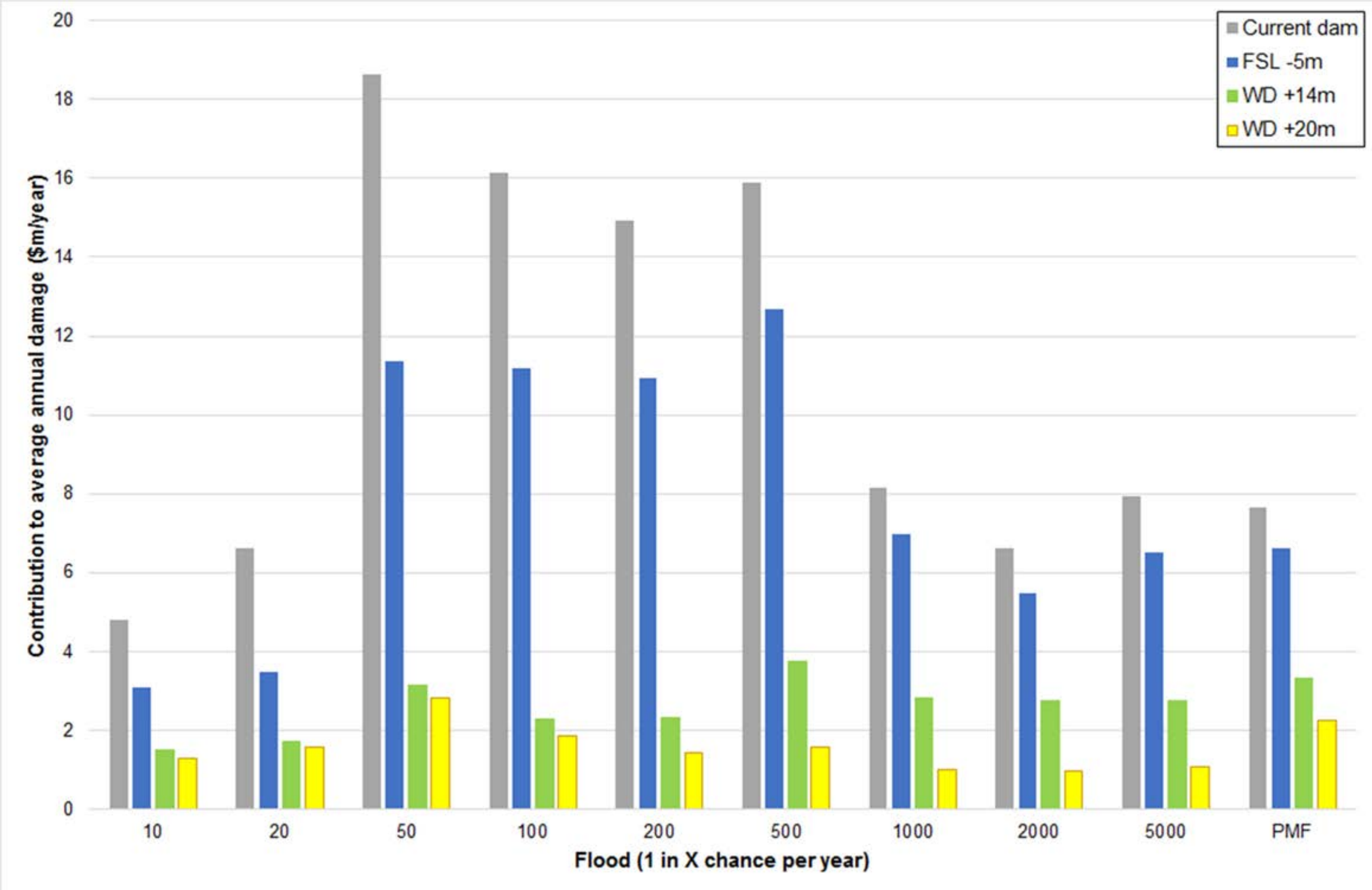



**Figure 4.13 Contribution of flood events to average annual flood damages in the valley, base case versus three options, 2041 development**

*Source:* CIE

*Note:* PMF = probable maximum flood

### *4.4.4 Social, environmental and cultural heritage impacts*

A preliminary socio-economic, environmental and cultural heritage (SECH) impact assessment was conducted for the following infrastructure flood mitigation options:

- lower Warragamba Dam FSL by five metres
- raise Warragamba Dam by 14 metres
- raise Warragamba Dam by 20 metres
- Currency Creek diversion channel
- Hawkesbury River dredging
- local levees at Peachtree Creek (Penrith) and McGraths Hill.

The SECH assessment examined impacts in three areas: upstream of the option, at the mitigation option site, and downstream of the option.

One particular area of impact relates to the operation of a flood mitigation dam. Temporarily capturing floodwaters behind a raised Warragamba Dam would result in a temporary increase in the duration and depth of inundation upstream, depending on the height of the raised spillways, the size of inflows, and the selected rate of outflows. This additional inundation – above the flooding that occurs in the upstream areas now – would have varying impacts on endangered ecological communities, World Heritage values, and sites of Aboriginal cultural heritage.

Post flood releases from the dam's FMZ may have impacts downstream, though these impacts would typically be much lower than those that currently occur without the benefit of a dam with a designated flood mitigation function. Raising Warragamba Dam to provide airspace would significantly reduce downstream floods that contribute most to property damage and risk to life, but would prolong low-level flooding up to about the 1 in 5 chance per year flood for some events.

These upstream and downstream impacts are schematically presented in **Figure 4.14**. There is a trade-off between upstream and downstream impacts, because upstream impacts are mitigated by higher releases from the FMZ, but could cause downstream impacts such as bridge closures from higher releases. Other downstream impacts might be more sensitive to the length of post flood releases.

The preliminary SECH assessment found that environmental and cultural heritage impacts of a 20-metre dam raising on the areas upstream of the dam, had low to medium risks. This was a high-level desktop risk assessment. Further detailed field surveys and research on how the ecological communities could respond to the increases in temporary inundation are needed to better understand the impacts. A detailed assessment of SECH values will be included in the Environmental Impact Statement for the Warragamba Dam Raising proposal.

The assessment identified some high temporary impacts at the dam and downstream, the latter related to the release of flows from the FMZ on downstream industrial and commercial uses. The Taskforce was provided with data associating flows to various downstream impacts (**Table 4.7**).

The Warragamba Dam Raising Environmental Impact Assessment is providing a more detailed assessment of the incremental upstream and downstream impacts associated with dam raising and the operation of a FMZ.

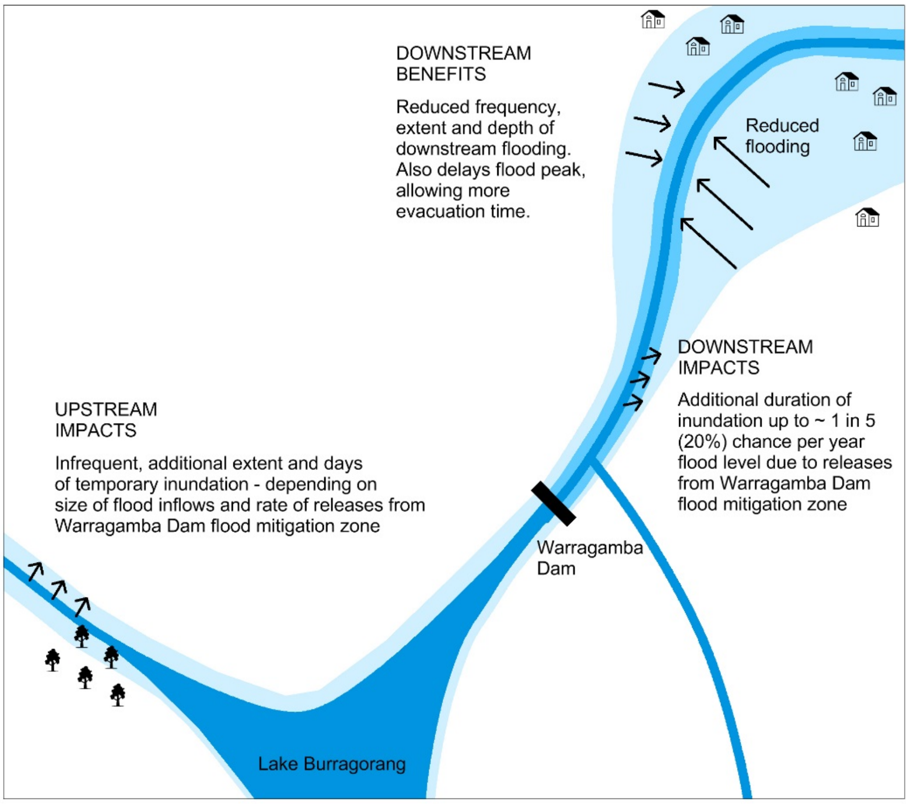



**Figure 4.14 Schematic depiction of upstream and downstream impacts from raising Warragamba Dam to provide flood mitigation capacity**

**Table 4.7 Approximate flow rates associated with impacts downstream of Warragamba Dam**

| Impact | Stakeholder | Local flow rate (GL/d) |
|---|---|---|
| Vehicle ferries closed | RMS | 50 |
| Yarramundi Bridge closed | RMS | 80 |
| Cattai Creek Bridge closed | council | 80 |
| McGraths Hill sewage treatment plant's treatment ponds flooded | council | 80 |
| North Richmond Bridge closed | RMS | 90 |
| Windsor Bridge closed | RMS | 100 |
| Four local bridges closed | council | 120 |
| Dwellings isolated in Pitt Town Bottoms, Cornwallis, Richmond Lowlands and Gronos Point | private owners | 200 |
| Parts of caravan and ski parks flooded | private owners | 200 |
| Three sewage pumping stations servicing McGraths Hill flooded | community | 200 |
| Some dwellings and caravans on low-lying land flooded | private owners | 230 |
| 21 local bridges closed | council | 230 |

*Source:* WaterNSW and RMS

*Note:* GL/d = gigalitres per day

No high or extreme risks were identified for the option of lowering Warragamba Dam FSL by five metres. Although not formally assessed, it is expected that compared to the -5m FSL option, lowering FSL by 12 metres would have relatively higher impacts upstream, at the dam and downstream, the latter related to the release of flows from a larger FMZ.

The SECH assessment found that extreme risks were associated with the Currency Creek diversion channel and Hawkesbury River dredging options.

The Taskforce did not formally assess the environmental impacts of new flood mitigation dams upstream of Warragamba Dam. It is considered that these dams would have extreme impacts associated with construction in remote parts of National Parks, including the impacts of new access roads (**Table 4.3**).

### *4.4.5 Other factors*

For some options, **Table 4.3** also identifies other factors of importance to the options evaluation.

Changing the operation of the existing Warragamba Dam to maximise surcharging behind the gates could increase the risk of radial gate failure.

Pre-releases from Warragamba Dam’s permanent storage could see a loss of water supply if the forecast flood does not eventuate. The risk is higher for larger pre-releases, which could also have severe impacts on the quality of water drawn to the North Richmond Water Filtration Plant.

Permanently lowering Warragamba Dam’s FSL by 12 metres would have severe impacts on water security and quality, and the costs to maintain water security were factored into the economic assessment of that option.

Some options are associated with a significant residual risk, which can increase losses when larger, rarer floods happen. Permanently lowering Warragamba Dam’s FSL by five metres reduces impacts for more frequent floods such as a 1 in 10 chance per year event, but provide little benefit for an 1867-type flood (estimated to be around a 1 in 500 chance per year event).

Levees, as well as house raising, can reduce people’s incentive to evacuate, thereby increasing the risk to life for events that overtop or breach a levee, or reach the floor of a raised house. The McGraths Hill levee would effectively create a low flood island, exacerbating the risk for anyone who failed to evacuate prior to cutting of the evacuation route.

While raising Warragamba Dam by 20 metres performs best in terms of reduced downstream flood levels, reduced inundation of dwellings and evacuation routes, and reduced average annual damages, it is not as cost effective as the 14-metre dam raising option. Also, a 20-metre dam raising could potentially have more extensive temporary inundation impacts upstream, and the need to evacuate the FMZ within the required timeframe in preparation for a potential subsequent event could cause substantial downstream impacts.

#### *4.4.6 Conclusion*

The Taskforce found that a 14-metre raising of Warragamba Dam to temporarily capture flood inflows is the preferred infrastructure option for reducing risk to property and risk to life in the Hawkesbury-Nepean Valley. Reducing floods at Windsor in the critical 1 in 50 to 1 in 1,000 chance per year flood range by about 2.5 to 4 metres, and with substantial reductions at Wallacia and Penrith, the 14-metre dam raising satisfies the key objective of a significant regional reduction of risk. It reduces risk to life by reducing floods to such an extent that many events would no longer reach urban areas or evacuation routes, and floods that still reach critical levels would do so more slowly, offering more time and certainty for evacuation operations. It reduces average annual damages by about 75% compared to the base case. Of all options considered, the 14-metre dam raising offers the highest net benefits.

The option of raising Warragamba Dam wall by 20 metres would increase the benefits in terms of reduced flood levels and exposure to floods downstream, but is not as cost effective as a 14-metre raising of the dam. Also, it would likely have relatively higher upstream impacts during a flood and downstream impacts when releasing temporarily held back flood inflows.

Of the options involving changes to the way the existing Warragamba Dam is operated, only lowering FSL by 12 metres provides reasonable regional reduction of flood risk, although it is less effective than dam raising. But the high cost, particularly related to maintaining security of water supply and water quality, mean that this option has a large net cost.

Lowering FSL by five metres has a net benefit due to the relative ease of implementation. However, it does not meet the core objective of significantly reducing flood risk (reducing peak flood levels in the critical range at Windsor by up to only 0.9 metres) because it does not provide sufficient airspace, and it does not provide the same quantum of benefits in terms of reduced exposure of houses, reduced and delayed inundation of evacuation routes, and reduced average annual damages, as achieved through dam raising.

New flood mitigation dams upstream of Warragamba were considered in the 2013 Review but would be less effective than dam raising and would have extreme environmental impact. A new flood mitigation dam on the Nepean River would provide only moderate benefit because it would not mitigate floods emanating from the predominant Warragamba River Catchment.

Downstream diversion channels and river dredging were considered by the Taskforce, but provided little reduction of flood levels, and/or were not cost effective.

While levees to protect discrete urban exposures up to a design limit may have some merit (especially the Peachtree Creek levee at Penrith), these were not included in the Flood Strategy because they provided local, not regional, benefits.

Options for targeted upgrades of regional evacuation roads were carefully evaluated. Evacuation modelling showed that capacity upgrades (road widening) could ease congestion on flood evacuation routes and so reduce the risk to life associated with vehicles unable to evacuate from flood islands during a flood operation. However, regional road upgrades are expensive. Many kilometres of road would need to be raised due to the relatively low gradients in the floodplain. The need to maintain access for many adjoining properties and roads would also be prohibitive. Road upgrades would not reduce damages to property. Dam raising was found to be more cost effective at reducing regional risk to life and property.

Voluntary house purchase to remove exposures from the floodplain was considered but was not cost effective and would cause significant social upheaval. Voluntary house raising is considered unlikely to be feasible as a regional strategy given house construction types unsuited to raising (often brick, slab-on-ground), the potential for extreme depths of flooding in the Hawkesbury, and the risk that house raising may discourage evacuation.

It is recognised that raising Warragamba Dam wall will significantly reduce the likelihood of major flood events, but will not eliminate the flood risk. There is no single or simple solution to the significant flood risk exposure in the valley. Therefore, a range of measures are required to manage the ongoing flood risk and for building a more flood-resilient community and valley. For this reason, the Flood Strategy includes several other initiatives:

- local evacuation road upgrades, which aim to treat local constrictions so that evacuating residents can more readily access the existing regional routes
- regional land use planning, which controls growth on the floodplain and is important to maintain the benefits of dam raising
- regional road planning, which considers flood evacuation needs when planning to expand the road network
- improved flood forecasting and warning system, to increase the certainty and time for evacuation
- initiatives to build and maintain community flood awareness, preparedness and responsiveness, especially to increase compliance with evacuation orders
- best practice emergency response and recovery
- improved governance to support integrated flood risk management.

# 5 Flood mitigation options – operating the existing Warragamba Dam for flood mitigation

Dams can provide flood mitigation by temporarily storing floodwaters, and reducing and delaying the downstream flood peak. This offers more certainty of time for evacuation operations, and can reduce flooding impacts on downstream homes, businesses and critical infrastructure. Dams are designed with spillways that allow flood inflows to pass through the reservoir without threatening the structural integrity (safety) of the dam. Floodwaters that pass over the spillway are waters that cannot be stored in the dam.

At the current time, there is no significant flood-specific mitigation infrastructure in the valley. The presence of Warragamba Dam and the Upper Nepean dams provide limited mitigation. For example, modelling shows that in a repeat of the 1867 flood of record, and assuming Warragamba Dam is at full water supply level (FSL), the flood peak at Windsor would be reduced by 0.4 metres from 19.7 m AHD to 19.3 m AHD. If the dam is below FSL, slightly larger reductions could be realised.

Although Warragamba Dam has gates, these are operated primarily for dam safety purposes. The Upper Nepean dams do not have gates meaning that they cannot be operated as flood mitigation dams.

This chapter describes the evaluation of a subset of flood mitigation infrastructure options that involve changing existing operational arrangements at Warragamba Dam to mitigate downstream floods, while maintaining its water supply function. These include:

- surcharge (or 'induced surcharge') method of gate operations
- pre-releases to create airspace
- permanently lowering FSL to create airspace.

## 5.1 Surcharge method of Warragamba Dam gate operations

### *5.1.1 Description of option*

This option involves maximising the amount of floodwater temporarily held back by the radial gates at Warragamba Dam.

#### *Current gate operation: the H14 protocol*

In February 1967, the then Metropolitan Water, Sewerage and Drainage Board adopted the 'H14 protocol' for operating the Warragamba Dam gates during time of flood by providing for an automatic gate opening sequence when the water level in the dam exceeds FSL. The H14 protocol remains the current operating protocol for this situation.

Under the H14 protocol, the gates only operate when the water level is above FSL. There is no drawdown of the dam (that is, pre-release of water) prior to a flood.

The drum gate starts to lower when the storage is 0.08 metres above FSL and continues to lower and is fully open when the water level reaches 0.3 metres above FSL.

The radial gates, which operate in symmetric pairs, begin to rise when the level in the dam gets to 0.23 metres above FSL. The gates operate relatively rapidly through the first 0.6 metres of opening and are lifted free of the water surface as soon as practical to minimise the risk of damage to the gates from floating debris and vibration.

All four radial gates are fully open when the dam level is at about 1.8 metres above FSL. Water levels in the dam have reached or exceeded this level on three occasions. At this level, the gates would be discharging about 580 gigalitres (billions of litres) per day (GL/d) from the dam. This is roughly equivalent to Sydney's annual water use.

Once this level is reached, there is no operational control or influence on the passage of floodwaters. If the level in the dam continues to rise as a result of upstream rain, then the discharge increases through the central spillway. This would continue until the water level in the dam reaches about 9.6 metres above FSL, when the first of the five fuse plugs on the auxiliary spillway would be activated. This was modelled to be about a 1 in 1,200 chance per year flood event.

The H14 protocol is not intended to maximise flood mitigation. Its purpose is to minimise the risk of damage to the gates or dam structure, by raising the gates relatively rapidly to reduce the risk of overtopping and gate failure. It is also designed not to exacerbate floods by ensuring that peak outflow is less than peak inflow, and to minimise the number of gate movements while opening the gates.

The H14 protocol is an automated process based on the known level of water in the storage.

### *Surcharging storage*

Dams with gated spillways, such as Warragamba Dam, can operate their gates to maximise the control of outflow and increase mitigation of downstream flooding. The sequence in which the spillway gates are opened during a flood can affect the depth, duration and rates of rise of downstream floods until they have to be fully raised to protect dam safety.

It is possible to operate Warragamba Dam's gates to maximise the surcharge storage, temporarily storing more floodwater in the dam longer. The surcharge storage (also known as temporary flood storage) is the difference between FSL and the water in the dam above FSL, and occurs whenever the storage levels are above FSL and the inflows into the dam exceed the outflows from the dam. Under the H14 dam operating rules the gates partially surcharge the floodwaters until the gates are fully raised when the dam levels reach 1.83 metres above FSL.

The volume of surcharge storage could be increased if the gates are not fully raised until the water level in the storage is more than 1.83 metres above FSL. Opening the gates more slowly maximises the surcharge storage and delays the release of the floodwaters downstream. This reduces the peak outflow and lowers downstream flood peaks, but prolongs low-level flood duration.

### *Previous reviews of the operation of Warragamba Dam's gates*

There have been a number of reviews to determine if the Warragamba Dam gates could be operated differently to provide better flood mitigation. While findings have suggested other procedures could be useful to improve flood mitigation, the H14 protocol has remained the method by which the Warragamba Dam gates are operated.

A review by the then Sydney Water Board in 1991 concluded that a rapid automated opening procedure (such as H14) offered the greatest security to the dam gates from overtopping. A slower operating procedure would provide greater flood attenuation, but longer durations and more rapid rises downstream once the gates open.

From 1998 to 2000, an investigation by Snowy Mountains Engineering Corporation (SMEC) considered alternative gate operating procedures, finding that with the current dam gates, the 'RELEASE' (now known as surcharging) method was the most effective for mitigating downstream floods. This involves opening the gates more slowly in the early part of a flood to temporarily store more water in the dam.

In 2012, Sinclair Knight Merz (SKM) conducted a review of the results of previous studies. Further study was recommended to reassess the benefits that could be achieved from the implementation of alternative gate operation procedures.

This section of the Options Assessment Report describes a Taskforce assessment of the surcharge method as a flood mitigation measure, based on the capability of existing infrastructure at Warragamba Dam.

### *5.1.2 Effects on flood behaviour*

The effects of surcharging on flood behaviour were tested using the Monte Carlo simulated flood events.

The option was modelled with the following parameters:

- freeboard (the height of the gate above the storage level) is to be no less than one metre. This is to reduce the likelihood that the gates will be overtopped by rising floodwaters or wave action
- while the gates are being used to control the flow, the maximum gate opening is to be two metres less than the depth of free overflow over the spillway (except when the gates are being raised completely out of the flow). This is to avoid problems with unstable and surging flow
- the maximum radial gate gap is 10 metres and the maximum water level at which flow can be controlled is 123 m AHD (FSL + 6.28 metres)
- the drum gate operates within its present constraints (according to the H14 protocol).

#### *Downstream peak outflows and flood levels*

The Monte Carlo simulated flood events were used to compare peak outflows from Warragamba Dam under the current H14 protocol with those with the induced surcharge method of gate operations. This assessment found that:

- for events less than about 430 GL/d, the surcharge method produces lower peak outflows most of the time
- when outflows are between about 430 GL/d and 690 GL/d, the surcharge method produces lower peak outflows

- for events between about 690 GL/d and 1300 GL/d, the existing H14 protocol produces lower peak outflows than the surcharge method.

The impact of induced surcharge on downstream peak flood levels at Wallacia, Penrith, North Richmond, Windsor and Wisemans Ferry is shown in **Table 5.1** (see also **Figure 4.3** and **Figure 4.4**). The results are summarised as follows:

- flood levels at Penrith would be reduced by up to 1.6 metres, for events up to the 1 in 50 chance per year frequency; however, floods within this range at Penrith are within the river banks so these reductions would accomplish minimal damage savings
- flood levels at North Richmond and Windsor would reduce by about 0.5 to 1.0 metre for events up to the 1 in 100 chance per year flood
- the surcharge method has limited mitigation benefits on floods greater than the 1 in 100 chance per year flood planning level, which is critical to reducing risk to life and property in the valley
- the surcharge method has the potential to perform a little worse than the H14 protocol for rare events when the limits of the operating envelope are reached and the gates need to be raised quickly for dam safety. While the magnitude of change is small, flood levels at Penrith and Wallacia are increased in events larger than the 1 in 200 chance per year flood. Flood levels at North Richmond and Windsor are not increased because they are more dependent on the volume of the flood as well as the peak flow.

These reductions of peak flood levels do not meet the key objective of providing significant regional reductions of flood risk as set out in **Section 4.3.1**.

### *Fuse plugs*

A series of erodible earth and clay walls or 'fuse plugs' are built across the upstream opening of Warragamba Dam's auxiliary spillway, which are designed to be washed away in a very rare flood (**Section 1.5**). The surcharge method uses surcharge storage more aggressively as a flood is rising and is consequently more likely to trigger a fuse plug erosion when a large inflow occurs. It trades off benefits in smaller floods for a slight increase in the probability of each fuse plug on the auxiliary spillway being eroded. The modelled frequency at which the first fuse plug is triggered changes from 1 in 1,260 chance per year for the H14 protocol to 1 in 1,120 chance per year for the surcharge method.[2]

It may be possible to refine the method so it is used only for events that are likely to be well below the fuse plug trigger levels, though information will be imperfect.

[2] WMAwater for the Taskforce, 2014 model

**Table 5.1 Impacts of induced surcharge method of gate operation on downstream flood levels**

| Flood event (chance of occurrence per year) | Wallacia | | Penrith | | North Richmond | | Windsor | | Wisemans Ferry | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Base case (m AHD) | Induced surcharge (Difference in m) | Base case (m AHD) | Induced surcharge (Difference in m) | Base case (m AHD) | Induced surcharge (Difference in m) | Base case (m AHD) | Induced surcharge (Difference in m) | Base case (m AHD) | Induced surcharge (Difference in m) |
| 1 in 5 | 35.2 | 0.0 | 19.9 | -0.5 | 11.2 | -0.4 | 9.4 | -0.2 | 1.2 | 0.0 |
| 1 in 10 | 37.3 | -0.2 | 21.6 | -1.0 | 13.6 | -0.9 | 11.6 | -0.4 | 2.4 | -0.2 |
| 1 in 20 | 39.5 | -0.5 | 23.4 | -1.6 | 15.3 | -1.1 | 13.5 | -0.7 | 3.8 | -0.2 |
| 1 in 50 | 42.6 | -1.0 | 24.9 | -1.0 | 16.5 | -0.4 | 16.0 | -0.7 | 5.4 | -0.1 |
| 1 in 100 | 44.6 | -0.4 | 25.9 | -0.1 | 17.5 | -0.5 | 17.2 | -0.5 | 6.5 | -0.1 |
| 1 in 200 | 46.3 | +0.2 | 26.5 | +0.1 | 18.4 | -0.3 | 18.2 | -0.3 | 7.5 | -0.1 |
| 1 in 500 | 48.7 | +0.3 | 27.1 | +0.1 | 19.7 | -0.1 | 19.5 | -0.1 | 9.1 | -0.1 |
| 1 in 1,000 | 50.4 | +0.2 | 27.5 | +0.1 | 20.6 | 0.0 | 20.4 | 0.0 | 10.2 | -0.1 |
| 1 in 2,000 | 54.4 | +0.1 | 28.4 | +0.1 | 21.7 | 0.0 | 21.5 | 0.0 | 11.2 | -0.1 |
| 1 in 5,000 | 58.6 | 0.0 | 29.5 | 0.0 | 22.7 | 0.0 | 22.6 | 0.0 | 12.5 | -0.2 |
| PMF | 62.3 | +0.1 | 31.5 | 0.0 | 26.3 | 0.0 | 26.2 | 0.0 | 14.6 | 0.0 |

**LEGEND**

Difference in m
- > +0.1
- -0.25 to -1.0
- -1.0 to -2.0

Critical range for flood risk

*Source:* WMAwater for the Taskforce (2014 model for option; 2016 model for base case)

*Note:* All scenarios allow for probabilistic drawdown; base case is for H14 protocol; PMF = probable maximum flood

### *Impact of exceeding the limit of the operating envelope*

Dam safety is the overriding principle in consideration of dam infrastructure or operational change options. Floods can generate large volumes of inflows in short periods of time. For the induced surcharge method of operating the gates, the upper limit of the operational envelope is reached at a water level of 123 m AHD, about six metres above FSL. The gates would then need to be opened, quickly increasing the outflow from about 700 GL/d to 900 GL/d. If the inflow exceeds 1,000 GL/d, the gates would need to be fully opened. This could significantly increase downstream flooding, cutting off evacuation routes.[3]

[3] WMAwater for the Taskforce, 2014 model

### *Upstream peak flood levels and duration*

Since surcharge operates by keeping water in the storage for longer, the maximum storage water level would be about 1.63 metres higher than if the gates were operated according to the H14 protocol. This occurs for a flood slightly smaller than a 1 in 100 chance per year flood. The maximum increase in the duration of upstream inundation with surcharge is 30 hours, for a 1 in 50 chance per year flood. The maximum water level above FSL, and the upstream inundation duration, is the same for both methods of operation when considering the probable maximum flood (PMF).[4]

## *5.1.3 Effects on evacuation timing*

Surcharge gate operations can affect the depth and timing of floods, and thereby impact evacuation. Every flood has a different timing even if the depth is the same. Flood modelling considered 19,500 events using Monte Carlo simulations. The impacts on evacuation timing were assessed by considering how the option would affect the probability of key evacuation thresholds being reached, as listed in the *Hawkesbury Nepean Flood Plan* (NSW SES, 2015).

With the surcharge method of gate operations, there would be an approximately 25% chance that the evacuation route trigger levels for McGraths Hill, Pitt Town and Windsor would no longer be reached (see **Figure 4.8** and **Figure 4.9**).

However, at Richmond there would be a newly-triggered 10% chance that the surcharge method would close the evacuation route compared to existing dam operations. Also, there would be an almost 10% chance of up to five hours *less* evacuation time before the Richmond evacuation route would be cut. This would result from a consequence of a sudden release of water when the upper limit of the operational envelope is reached and the radial gates are fully opened.

**Figure 4.8** and **Figure 4.9** show that induced surcharge is substantially less effective than other options at reducing and delaying floods that cut evacuation routes.

## *5.1.4 Economic assessment*

### *Benefits*

An economic assessment of induced surcharge gate operations across the full range of floods found that average annual damages would be reduced by 14%.[5]

### *Costs*

Capital costs to WaterNSW would include augmenting the water monitoring network, developing a flood model to better understand the effect of operations on downstream communities, and modifications to the SCADA dam operations monitoring and control system (totalling $2.75M). Recurring operations and maintenance costs are estimated at ~$1.15M/year.

---

[4] WMAwater for the Taskforce, 2014 model

[5] **Figure 4.10** presents the results of an earlier assessment conducted for the 2013 Review. The updated result described here relies upon revised (2014) flood modelling and some changed assumptions for the damages assessment.

### *5.1.5 Social, environmental and cultural heritage impact*

Induced surcharge did not satisfy the key objective of a significant, regional reduction of a flood risk. Therefore, it was not taken forward for a detailed socio-economic, environmental and cultural heritage (SECH) impact assessment. A preliminary assessment of possible impacts was undertaken.

Induced surcharge would incrementally increase areas of temporary inundation upstream of the dam, albeit for minor additional depths and durations (see **Section 5.1.2**).

For more frequent floods, induced surcharging would typically result in modest reductions of peak flood levels and extents downstream, and possibly prolong low-level flows on the tail-end of a flood.

### *5.1.6 Water supply system*

Surcharging the gates is not expected to have any significant impacts on the available water and storage levels, the yield-demand balance or drought response measures.

In the unlikely but catastrophic event of failure and loss of a radial gate, 39% of the Warragamba storage would be lost downstream as the sill of the radial gates would become the new maximum lake level until the radial gate was restored. This would have a very significant effect on water supply security for greater Sydney, particularly if the system was to then enter a drought period.

### *5.1.7 Water quality*

Surcharging the gates is not expected to result in any significant difference for water quality from current operations under the H14 protocol.

### *5.1.8 Dam operations and maintenance*

The induced surcharge method of gate operations could have implications for dam operations:

- ***Increased gate contact with water flow and increased gate movements***. Induced surcharge would place the radial gates in contact with water flow for much longer, and would require the gates to move more frequently than is the case with the H14 protocol gate operation. This could increase the risk of mechanical or electrical failure. Because the surcharge method also generally operates the gates with less freeboard, and hence less time to rectify any faults that do occur, the consequences of a failure are likely to be more severe. Maintenance regimes would need to be adjusted to account for these risks. There may also be a requirement to upgrade the gates.
- ***More complicated dam operations***. Inflows around the 1 in 100 chance per year probability present challenges for surcharge. This could result in a sudden jump in outflows when the end of the surcharge operating envelope is reached and the radial gates have to be raised quickly for dam safety. A modification to the method of gate opening may be required to transition from controlled to uncontrolled flow.

### *5.1.9 Findings – surcharge method*

The surcharging method of gate operations would not meet the key objective of *significantly* reducing the impact of flooding. It does not make a substantial difference to floods in the critical range for flood risk reduction of 1 in 50 to 1 in 1,000 chance per year.

Although surcharging could achieve some reductions in flood levels downstream of the dam there are a number of limitations that reduce its effectiveness and increase its risks. These are summarised as follows:

- ***benefits limited to more frequent flood events*** – the benefits of the surcharge method in reducing flood levels are limited to relatively small flood events (more frequent than 1 in 50 chance per year) with lesser reduction of flood levels in larger flood events. It is in these larger floods that the majority of flood damages and risk to life occurs.
- ***worsened flooding for some events*** – flood levels are slightly increased at Wallacia and Penrith for some events. The likelihood that the dam fuse plugs are triggered increases slightly. Also, the time for evacuation is reduced in a proportion of events, especially for Richmond.
- ***increased risk of radial gate failure*** – surcharging increases the loads on the gates, water is closer to the top of the gates, and water can rise relatively quickly.

## 5.2 Pre-releases from Warragamba Dam

### *5.2.1 Description of options*

This option involves the creation of a temporary 'flood mitigation zone' (FMZ) by releasing water from Warragamba Dam's water supply in advance of a forecast flood event. This temporary airspace would be used to capture incoming floodwaters (refer **Figure 5.1**). This mode of operation can be based on forecast or observed rainfall in the catchment.

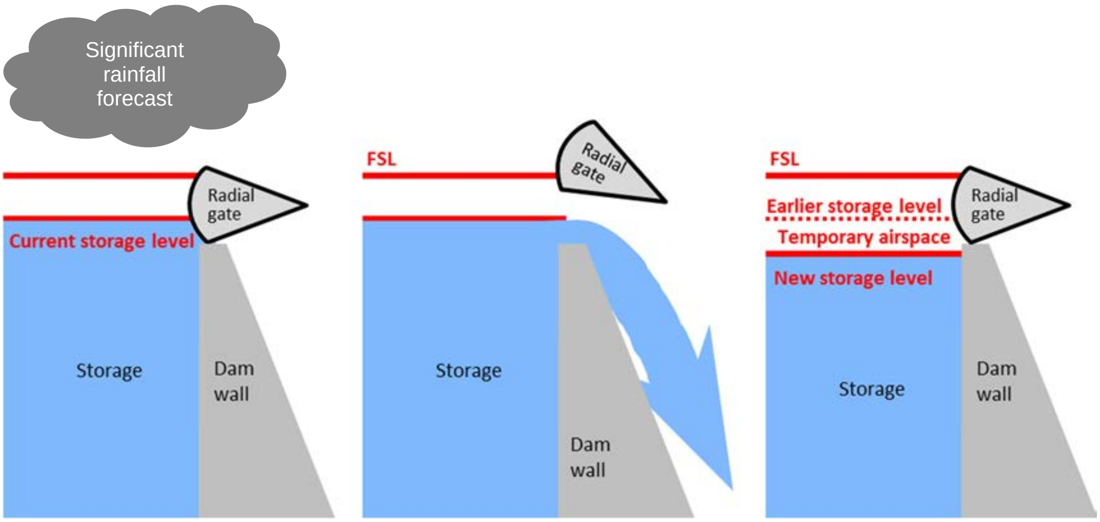



**Figure 5.1 Pre-release of water supply to create temporary airspace for flood mitigation**

*Source*: WaterNSW for the Taskforce

The time between rain falling on the catchment upstream of Warragamba Dam and the flow arriving at the dam storage is less than 24 hours. Flood forecasting is undertaken by the Bureau of Meteorology (BoM). Based on observed rainfall and water levels, the current *Service Level Specification for Flood Forecasting and Warning Services* (BoM, 2017) sets a target of 15 hours' lead time prior to 13.7 metres at the Windsor gauge, for events when flood peaks are expected to exceed 16.0 metres (**Table 1.2**). If pre-releases were made only after rain has fallen, the size of the temporary airspace that could be created would be limited.

Pre-releases for more than 24 hours before a flood event would rely on rain forecast by BoM. At the current time, for the purposes of flood warning, BoM can forecast rainfall events a number of days prior to the event with a certain level of confidence. These confidence levels increase as the event approaches. If a pre-release strategy was implemented, it may have to be activated before there is reasonable certainty that a major flood event would occur in the Warragamba Catchment. If actual rainfall was less than the predicted rainfall, or a slight shift in the location of the weather system meant that the heaviest rain fell outside the Warragamba Catchment, water supply could be lost. A case study of the June 2016 flood demonstrates this risk (**Box 5.1**).

Despite the challenges of forecasting more than 24 hours before a flood, the Taskforce adopted a three-day pre-release strategy to test flood mitigation benefits. Three days would be required to create a FMZ large enough to provide a minimum level of flood mitigation.

Pre-releasing water from Warragamba Dam will increase the flow and raise the level in the downstream river. This will have implications for downstream stakeholders. The critical flow rates for downstream water users are summarised in **Table 4.7**.

The Taskforce adopted pre-release rates of 40 GL/d and 130 GL/d based on preventing the closures of Yarramundi Bridge, and North Richmond and Windsor Bridges, respectively. These estimates allowed for inflows between Warragamba Dam and these bridges. NSW Roads and Maritime Services subsequently updated advice about bridge closures.

Based on the adopted three-day timeframe and maximum flow rates for pre-release, the following scenarios for pre-release of dam water storage to create temporary airspace for flood mitigation were used by the Taskforce:

- three days of pre-release at 40 GL/d, a total of 120 gigalitres
- three days of pre-release at 130 GL/d, a total of 390 gigalitres (see **Table 5.2**).

**Table 5.2 Potential airspace created from pre-releasing water supply from Warragamba Dam**

| Rate of pre-release | Duration of pre-release | Total airspace created | Equivalent reduction in FSL | Equivalent reduction in Warragamba storage |
|---|---|---|---|---|
| 40 GL/d | 3 days | 120 GL | -1.65 m | -6% |
| 130 GL/d | 3 days | 390 GL | -5.45 m | -19% |

*Source:* WaterNSW

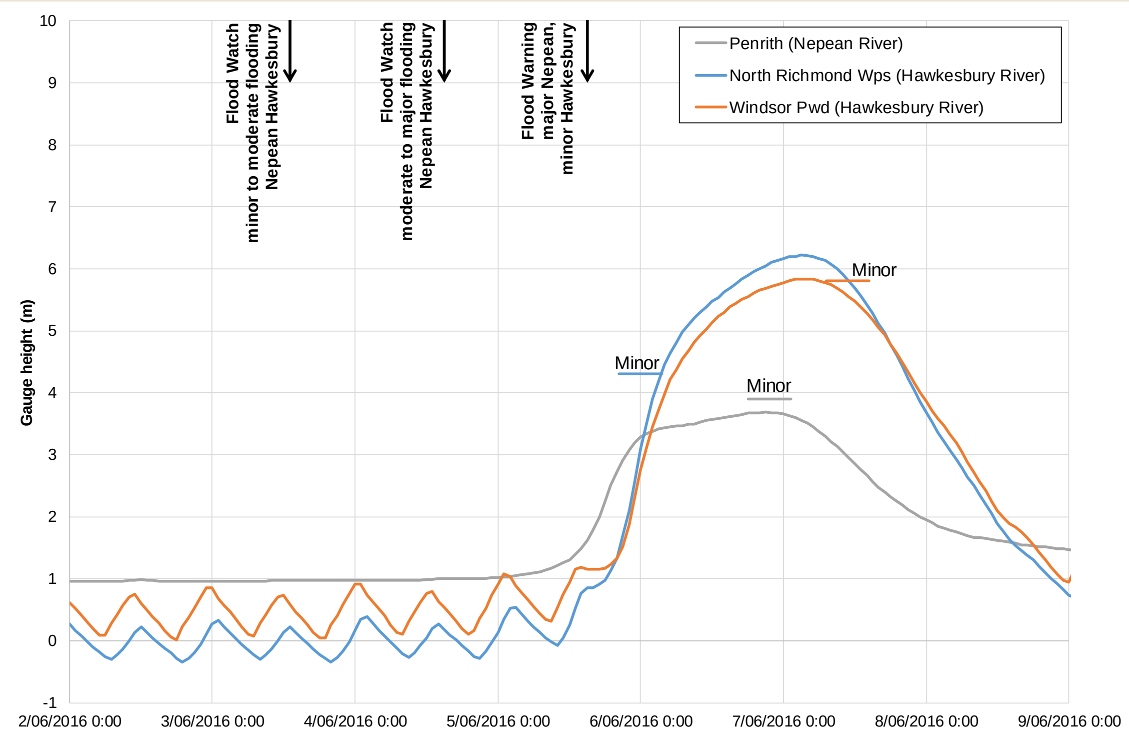
### Box 5.1 Forecasting challenges – case study of the June 2016 flood

At the current time, the ability of weather models to predict the spatial and temporal pattern of rainfall with the confidence required for implementing a pre-release strategy from a water supply dam is limited.

Weather models forecast development of an East Coast Low off the coast near the New South Wales-Queensland border late on Saturday 4 June 2016. The East Coast Low was expected to move southwards during Sunday 5 June and Monday 6 June, bringing heavy rainfall to the New South Wales coast. At 1 pm on Friday 3 June, BoM issued a Flood Watch covering catchments from the Tweed River in the north to Bega in the south. At this time, the Nepean and Hawkesbury Rivers were forecast to experience minor to moderate flooding and the Georges River was forecast to experience minor flooding. A later Flood Watch (3 pm, Saturday 4 June) forecast moderate to major flooding of the Nepean and Hawkesbury Rivers. A later Flood Watch (4 pm, Saturday 4 June) forecast moderate to major flooding of the Georges River.

As it turned out, heavier rain fell in the Georges River Catchment, resulting in major flooding at Milperra (peak about 4.4 metres). The Nepean River at Penrith failed to reach even minor flood level while the Hawkesbury River at North Richmond and Windsor reached minor flood levels (see below).

Had pre-releases from Warragamba Dam been made on the basis of the Flood Watch for moderate to major flooding of the Nepean and Hawkesbury Rivers, water supply would have been lost unnecessarily.




**Flood hydrographs for the June 2016 Nepean and Hawkesbury floods**

*Source:* BoM; flood classifications (minor, moderate, major) for respective gauges taken from NSW State Flood Plan

The design of Warragamba Dam limits the rate at which water can be released through the radial gates when the storage falls to certain levels below FSL:

- When Warragamba Dam is 9.0 metres below FSL, or 72% full, it cannot release more than 40 GL/d through the four radial gates. At this level, 629 GL of airspace is already available for capturing incoming floodwaters. Modelling shows that the dam is below -9m around 13% of the time.
- When Warragamba Dam is 5.5 metres below FSL, or 80.5% full, it cannot release more than 130 GL/d through the four radial gates. At this level, 395 GL of airspace is already available for capturing incoming floodwaters. Modelling shows the dam is below -5.5m around 26% of the time.

### *5.2.2 Effects on flood behaviour*

The effects of pre-releases on flood behaviour were tested using the Monte Carlo simulated flood events.

#### *Downstream peak flood levels*

Pre-releasing empties water supply to create temporary airspace in which flood inflows can be stored up to FSL. The impact on downstream peak flood levels at Wallacia, Penrith, North Richmond, Windsor and Wisemans Ferry is shown in **Table 5.3** (see also **Figure 4.3** and **Figure 4.4**). The results are summarised as follows:

- for a pre-release of 40 GL/d over three days:
    - for Penrith, North Richmond and Windsor, reductions in peak flood levels exceeding one metre would be achieved only in events smaller than a 1 in 10 chance per year flood.
    - for floods larger than a 1 in 50 chance per year – those with the potential to cause substantial damage given the concentration of risk exposure on the floodplain – negligible reductions would be achieved.
- for a pre-release of 130 GL/d over three days:
    - although peak flood levels reductions of about 2-3 metres would be achieved at Penrith, North Richmond and Windsor in the 1 in 20 chance per year flood, such floods are not critical for average annual damages or risk to life.
    - in a 1 in 100 chance per year flood, reductions in flood levels of only 0.6-0.9 metres would be achieved at Penrith, North Richmond and Windsor, which fails to significantly mitigate the critical range for risk.

These reductions of peak flood levels do not meet the key objective of providing significant regional reductions of flood risk as set out in **Section 4.3.1**.

**Table 5.3 Impacts of pre-release of water supply on downstream flood levels**

| Flood event (chance of occurrence per year) | Wallacia | | | Penrith | | | North Richmond | | | Windsor | | | Wisemans Ferry | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Base case (m AHD) | Pre-release <40 GL/d over three days (Difference in m) | Pre-release <130 GL/d over three days (Difference in m) | Base case (m AHD) | Pre-release <40 GL/d over three days (Difference in m) | Pre-release <130 GL/d over three days (Difference in m) | Base case (m AHD) | Pre-release <40 GL/d over three days (Difference in m) | Pre-release <130 GL/d over three days (Difference in m) | Base case (m AHD) | Pre-release <40 GL/d over three days (Difference in m) | Pre-release <130 GL/d over three days (Difference in m) | Base case (m AHD) | Pre-release <40 GL/d over three days (Difference in m) | Pre-release <130 GL/d over three days (Difference in m) |
| 1 in 5 | 35.2 | 0.0 | 0.0 | 19.9 | -1.2 | -1.3 | 11.2 | -1.4 | -1.2 | 9.4 | -1.0 | -0.8 | 1.2 | -0.1 | 0.0 |
| 1 in 10 | 37.3 | -0.1 | -0.1 | 21.6 | -0.8 | -2.4 | 13.6 | -1.0 | -2.4 | 11.6 | -0.8 | -1.8 | 2.4 | -0.2 | -0.2 |
| 1 in 20 | 39.5 | -0.3 | -0.5 | 23.4 | -0.4 | -2.7 | 15.3 | -0.4 | -2.2 | 13.5 | -0.5 | -1.8 | 3.8 | -0.2 | -0.3 |
| 1 in 50 | 42.6 | -0.3 | -1.0 | 24.9 | -0.2 | -0.7 | 16.5 | -0.1 | -0.6 | 16.0 | -0.3 | -1.3 | 5.4 | -0.1 | -0.3 |
| 1 in 100 | 44.6 | -0.2 | -1.0 | 25.9 | -0.1 | -0.6 | 17.5 | -0.2 | -0.8 | 17.2 | -0.2 | -0.9 | 6.5 | -0.1 | -0.3 |
| 1 in 200 | 46.3 | -0.2 | -0.9 | 26.5 | -0.1 | -0.4 | 18.4 | -0.2 | -0.8 | 18.2 | -0.2 | -0.8 | 7.5 | -0.1 | -0.1 |
| 1 in 500 | 48.7 | -0.1 | -0.8 | 27.1 | 0.0 | -0.2 | 19.7 | -0.1 | -0.7 | 19.5 | -0.1 | -0.7 | 9.1 | -0.1 | -0.3 |
| 1 in 1,000 | 50.4 | -0.1 | -1.0 | 27.5 | 0.0 | -0.3 | 20.6 | -0.1 | -0.7 | 20.4 | -0.1 | -0.7 | 10.2 | -0.1 | -0.4 |
| 1 in 2,000 | 54.4 | -0.2 | -2.5 | 28.4 | 0.0 | -0.5 | 21.7 | -0.1 | -0.6 | 21.5 | -0.1 | -0.6 | 11.2 | -0.1 | -0.4 |
| 1 in 5,000 | 58.6 | -0.3 | -1.7 | 29.5 | -0.1 | -0.5 | 22.7 | -0.1 | -0.7 | 22.6 | -0.1 | -0.7 | 12.5 | 0.0 | -0.4 |
| PMF | 62.3 | +0.1 | 0.0 | 31.5 | 0.0 | -0.1 | 26.3 | 0.0 | -0.2 | 26.2 | 0.0 | -0.2 | 14.6 | 0.0 | -0.2 |

**LEGEND**

Difference in m

- > +0.1
- -0.25 to -1.0
- -1.0 to -2.0
- -2.0 to -3.0

Critical range for flood risk

*Source:* WMAwater for the Taskforce (2014 model for options; 2016 model for base case)

*Note:* All scenarios allow for probabilistic drawdown; base case is for H14 protocol; PMF = probable maximum flood

#### *Downstream flood duration*

Pre-releasing would bring forward low-level flooding downstream of the dam, particularly at the higher rate of 130 GL/d. Under this scenario, riverboat operations at Penrith and Windsor would be disrupted earlier, vehicular ferries would also cease operating earlier, Yarramundi Bridge would close earlier, and low-lying areas around Richmond and Windsor would be inundated by backwater flooding up minor tributaries. For most modelled events, the duration of bridge inundation would be similar to existing conditions, but for some, it could be longer.

#### *Upstream peak flood levels and duration*

The early release of water will mean that flood levels upstream of Warragamba Dam will not rise as high and the duration of upstream flooding will be less than under current operations.

### *5.2.3 Effects on evacuation timing*

Pre-releases can bring forward inundation and thereby impact evacuation. Raising the river level means that once the dam spills, water will travel faster downstream, which can reduce evacuation times. Every flood has a different timing even if the depth is the same. Flood modelling considered 19,500 events using Monte Carlo simulations. The impacts on evacuation timing were assessed by considering how the option would affect the probability of key evacuation thresholds being reached, as listed in the *Hawkesbury Nepean Flood Plan* (NSW SES, 2015).

With pre-releases of 40 GL/d over three days, about 15% of modelled events would no longer cut evacuation routes from McGraths Hill, Pitt Town and Windsor (see **Figure 4.8** and **Figure 4.9**). However, an adverse impact of pre-releases is the potential for earlier flooding at lower levels, which could reduce the available evacuation time for a range of possible floods of 10 metres and less at Windsor. While this is not expected to affect the evacuation of the flood island sectors, it would make flood emergency response more difficult for the low-lying areas.

With pre-releases of 130 GL/d over three days, about 40% of modelled flood events would no longer cut evacuation routes from McGraths Hill, Pitt Town and Windsor (see **Figure 4.8** and **Figure 4.9**). However, this option would increase the probability that there will be less time available for evacuation for floods reaching levels of 10 metres and less at Windsor (e.g. 20% of modelled floods would reach 9.75 metres more quickly). There is also a small chance of less time for evacuating before the McGraths Hill evacuation route closes.

As pre-releases have the potential to reduce warning and evacuation timing, the NSW SES would need to carefully assess their plans and procedures with a pre-release strategy.

**Figure 4.8** and **Figure 4.9** show that pre-releases are less effective than other options at reducing and delaying floods that cut evacuation routes.

### *5.2.4 Economic assessment*

#### *Benefits*

An economic assessment of pre-releases across the full range of floods found that average annual damages would be reduced by:

- 13% for a pre-release of 40 GL/d over three days. There would be limited benefit at Penrith, because the riverbank levee is close to the 1 in 100 chance per year level and so little development would benefit from the peak level reductions to the 1 in 5 chance per year event provided by this option.
- 29% for a pre-release of 130 GL/d over three days. Most of the benefit would be in the Richmond/Windsor floodplain because of the reduction of 1.3 metres in the 1 in 50 chance per year flood. Land use below that level is primarily agriculture with some housing due to the historical settlement pattern.[6]

#### *Costs*

A significant potential cost is the loss of water supply if pre-releases are made on the basis of forecast rain that either does not fall or does not fall within the Warragamba Catchment, so the predicted inflows to the water storage fail to eventuate. There have been examples where larger floods were expected but did not eventuate.

Other impacts of pre-releases include earlier ferry and bridge closures, which would likely isolate populations on the western and northern sides of the Hawkesbury River.

Capital costs to WaterNSW would include augmenting the water monitoring network, development of an operations manual and communications protocols with downstream communities, and modifications to the SCADA system (totalling $2.75M). Recurring operations and maintenance costs are estimated at ~$1.15M/year.

### *5.2.5 Social, environmental and cultural heritage impact*

Pre-releases did not satisfy the key objective of a significant, regional reduction of a flood risk. Therefore, it was not taken forward for a detailed socio-economic, environmental and cultural heritage (SECH) impact assessment. A preliminary assessment of possible impacts was undertaken.

A pre-release of 130 GL/d over three days (total 390 GL) would expose 5.45 metres of Lake Burragorang's banks more quickly than through draw down from water supply. However, any erosion or impacts upon water quality would be short term. There would be some reduction in the peak level of temporary flood inundation above FSL.

A smaller pre-release of 40 GL/d from Warragamba Dam over three days (total 120 GL) could have similar impacts as above, albeit lower magnitude, with 1.65 metres of lake lowering.

If flooding does eventuate as predicted, pre-releases would bring forward low-level flooding downstream by up to three days, with associated social disruption to low-lying areas and access across the river.

### *5.2.6 Water supply*

The major risk of pre-releasing water supply from the dam based on expected flooding is that the flood does not eventuate (or is smaller than forecast), and the pre-released water is not partially

[6] **Figure 4.10** presents the results of an earlier assessment conducted for the 2013 Review. The updated result described here relies upon revised (2014) flood modelling and some changed assumptions for the damages assessment.

or fully replaced. To quantify the likelihood of loss of supply, the start level, maximum level and the ending level of the storage were extracted from the Monte Carlo simulations. For the purposes of this modelling exercise, it was assumed that pre-releases would be made three days in advance of the flood event regardless of the quantity of rainfall forecast (see **Section 5.2.1**).

Pre-releasing at 40 GL/d over three days resulted in estimated losses to the water supply system in approximately half of modelled flood events. Pre-releasing at 130 GL/d over three days resulted in estimated losses to the water supply system in approximately three-quarters of modelled flood events.

It is noted that all forecasts contain uncertainty, which increases with longer lead times. Precisely how a rainfall event will unfold three days out will be uncertain. There are examples of forecast east coast lows that ultimately produce less or more rain, or a different distribution of rain, than expected (see **Box 5.1**). At the current time, the ability of weather models to predict the spatial and temporal pattern of rainfall with the confidence required for implementing a pre-release strategy from a water supply dam is limited.

### 5.2.7 Water quality

A pre-release of 130 GL/d over three days could result in earlier impacts on river water quality, compared to flooding under current operating rules. This is critical for Sydney Water's North Richmond Water Filtration Plant (WFP), which draws upon river water and supplies approximately 44,000 people in the Richmond/Windsor area. The ability of the plant to meet the Australian Drinking Water Guidelines (ADWG) reduces as raw water quality deteriorates or if raw water quality changes rapidly. The North Richmond system storage reservoirs are capable of holding up to two to three days' supply when full and when system demands are low.

A pre-release of 130 GL/d over three days could also impact water quality in Lake Burragorang – the Warragamba Dam water supply reservoir. Good quality surface water would be released and potentially replaced with poor quality inflows.

The storage acts as a buffer with the stored waters providing internal resistance to the passage of the muddy water inflows, slowing them down and increasing the potential for suspended particles to drop out or the pollutant concentrations to be diluted.

The level of water in the storage has a significant impact on the ability of the storage to act as a buffer to these muddy water inflows. A pre-release is only likely to occur when the dam is reasonably full. At this level, Lake Burragorang is effective at buffering small to moderate inflow events.

A pre-release of 40 GL/d over three days could have similar impacts as above, albeit at a lower magnitude.

### 5.2.8 Dam operations

Pre-releasing water in advance of a flood would be a complex operation, with interfaces to be clarified between interpretation of weather forecasts, pre-flood operations, pre-releases, flood mitigation operations and post flood operations.

To realise significant flood mitigation benefits, pre-releases must be made based on a three-day rainfall forecast. However, the size, duration, intensity and location of the rainfall event would not be known three days before the event. Currently BoM's Service Level Specification for the

Hawkesbury-Nepean Valley only provides for a 15-hour target forecast (BoM, 2017). Extending this forecast capability to three days (72 hours) would be difficult, if not impossible, to attain, and would require many events to be validated.

If the rains are lower than forecast, significant water supply may be lost and the pre-releases may have caused unnecessary inconvenience due to low level flooding downstream. If pre-released water from Warragamba Dam reaches Windsor at the same time as floodwaters from downstream tributaries, then the flood levels would be greater due to the water from Warragamba.

### *5.2.9 Findings – pre-releases*

Pre-release of water supply from Warragamba Dam to create temporary airspace for flood mitigation could achieve some reductions in flood levels downstream of the dam. However, there are a number of limitations to pre-releasing that reduce its effectiveness as a flood risk management option for the valley. These are summarised as follows:

- ***benefits limited to more frequent flood events*** – even larger pre-releases do little to mitigate larger floods (> 1 in 50 chance per year) that contribute most to flood damages and risk to life. Pre-releases do not meet the key objective of providing a *significant*, regional reduction of flood risk.
- ***reliance on forecast rainfall*** – to be able to create sufficient airspace for flood mitigation, pre-releases need to be made over at least three days. Currently, only a 15-hour target forecast is available.
- ***potential impact on security of water supply*** – in the case of a pre-release of 130 GL/day over three days (390 GL), which was not replaced by flood inflows, about 19% of the dam's storage, which represents around two-thirds of Sydney's annual water supply would be lost.
- ***earlier flooding downstream*** – pre-releasing 130 GL/d over three days would close Yarramundi Bridge and inundate low-lying areas around Windsor and Richmond earlier than if pre-releasing did not occur. This would cause earlier disruption to low-lying communities and transport links (e.g. ferry crossings), compared to current operations.
- ***exacerbate flooding downstream*** – if pre-releases from Warragamba Dam arrive downstream at Windsor at the same time as floodwaters from downstream tributaries, flooding could be increased. Raising the river level also means that once the dam spills, water will travel faster downstream, which could impact upon evacuation operations.
- ***newly triggered low-level floods*** – in some cases, if the forecast rain does not eventuate, pre-releases would generate a flood that would not have occurred under the current operating regime.
- ***potential loss of water quality*** – a pre-release could impact water quality downstream, particularly turbidity, earlier than under current operations. This would have potential implications for water supply to North Richmond and nearby communities. Pre-releases could also result in the replacement of good quality surface water in Lake Burragorang with poor quality inflows.

## 5.3 Lowering Warragamba Dam's permanent storage

The provision of permanent airspace in a dam has significant benefits over the pre-release of water storage to create temporary airspace, including:

- guaranteed and larger flood mitigation capacity
- availability of flood mitigation independent of accurate rainfall and flood forecasting
- a delay in the rise of floodwaters downstream
- greater certainty in evacuation timing.

There are three ways of creating dedicated airspace or a 'flood mitigation zone' (FMZ) at Warragamba Dam:

- permanently lowering FSL
- raising the dam wall while maintaining the current FSL
- combining lowering the FSL and raising the wall.

The general operation of a FMZ is described in **Box 4.1**.

After a flood, it is important to evacuate the FMZ in time for the dam to be able to mitigate any subsequent flood event. A target of emptying the FMZ within 7-10 days was adopted, as this was considered to be the limit of forecasting a subsequent flood event.

In optimising outcomes, there are trade-offs between:

- Recovering airspace in preparation for any potential subsequent flood event (= rapid drawdown of the FMZ)
- Minimising the extent and duration of upstream inundation (= rapid drawdown of the FMZ)
- Minimising the downstream impact of post flood releases
  - o Reducing the extent of impacts (= slow drawdown of the FMZ)
  - o Reducing the duration of impacts (= rapid drawdown of the FMZ)

Once the FMZ has been evacuated, operational procedures need to be in place to maintain the water level at or below the nominated FSL.

This section considers options to lower FSL by either five metres or 12 metres.

### *5.3.1 Description of options*

The current FSL of Warragamba Dam is at 116.72 metres Australian Height Datum (m AHD is approximately equal to mean sea level). This level is dictated by the top of the central drum gate. The height of the dam crest was raised by five metres in 1990 for dam safety. This extra five metres could not be used to increase the water storage capacity of the dam nor could it be used for flood mitigation storage airspace as there was no change in the level of the central drum gate.

The sill of the base of the four central radial gates at Warragamba Dam is at 104.5 m AHD, 12.2 metres below FSL (**Figure 1.9**). This level is the limit to which the FSL can be lowered using the existing gate configuration at the dam.

The following three options to permanently lower the FSL of Warragamba Dam were considered as part of the 2013 Review:

- two metres to create 148 GL of airspace
- five metres to create 360 GL of airspace
- 12 metres to create 795 GL of airspace.

The proportion of Warragamba Dam's full storage capacity of 2,027 GL that would be lost to the water supply system under these options is shown in **Table 5.4**.

**Table 5.4 Potential airspace created from permanently lowering FSL at Warragamba Dam**

| Lowering of FSL | Total airspace created | Equivalent reduction in Warragamba storage |
|---|---|---|
| -2m | 148 GL | -7% |
| -5m | 360 GL | -18% |
| -12m | 795 GL | -39% |

*Source:* WaterNSW for the Taskforce

*Note:* Airspaces subject to change with new bathymetry

Following an initial assessment of these three options as part the 2013 Review, it was concluded that:

- ***lowering FSL by two metres*** – would not be considered further as it would not achieve a significant reduction in downstream flood levels
- ***lowering FSL by five metres*** – would be considered for detailed flood modelling and benefit cost analysis
- ***lowering FSL by 12 metres*** – would be considered for detailed flood modelling and benefit cost analysis.

**Figure 5.2** shows a schematic of Warragamba Dam with FSL permanently lowered by five metres to 111.72 m AHD and a new FMZ created.

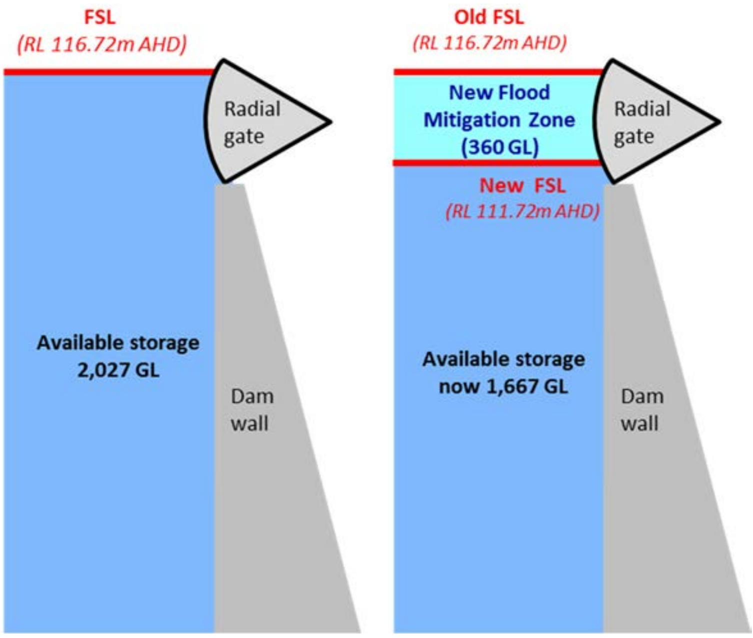



**Figure 5.2 Potential lowering of FSL of Warragamba Dam by five metres**

*Source*: WaterNSW for the Taskforce

## *5.3.2 Effects on flood behaviour*

The effects of lowering FSL on flood behaviour were tested using the Monte Carlo simulated flood events.

### *Downstream peak flood levels*

Lowering Warragamba Dam FSL would create airspace in which flood inflows can accumulate. The impact on downstream peak flood levels at Wallacia, Penrith, North Richmond, Windsor and Wisemans Ferry is shown in **Table 5.5**. The results are summarised as follows:

- lowering FSL by five metres:
  - for Penrith, North Richmond and Windsor, reductions in flood levels exceeding one metre would be achieved only in events up to a 1 in 20 chance per year flood
  - for floods larger than a 1 in 50 chance per year flood – those with the potential to cause substantial damage given the concentration of risk exposure on the floodplain – only modest flood level reductions of 0.3 metres at Penrith and up to 0.6 metres at North Richmond and Windsor would be achieved.
- lowering FSL by 12 metres:
  - substantial reductions in flood levels, that is about 3-4 metres, would be achieved at Penrith, North Richmond and Windsor in the 1 in 20 chance per year flood; however, this size of flood is not in the critical range for flood damages or risk to life (see **Section 4.3**).
  - in a 1 in 100 chance per year flood, would result in reductions in flood levels of 1.2 metres at Penrith, 1.3 metres at North Richmond and 1.9 metres at Windsor would be achieved.

**Table 5.5 Impacts of lowering Warragamba Dam FSL on downstream flood levels**

| Flood event (chance of occurrence per year) | Wallacia | | | Penrith | | | North Richmond | | | Windsor | | | Wisemans Ferry | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Base case (m AHD) | Lower FSL by 5m (Difference in m) | Lower FSL by 12m (Difference in m) | Base case (m AHD) | Lower FSL by 5m (Difference in m) | Lower FSL by 12m (Difference in m) | Base case (m AHD) | Lower FSL by 5m (Difference in m) | Lower FSL by 12m (Difference in m) | Base case (m AHD) | Lower FSL by 5m (Difference in m) | Lower FSL by 12m (Difference in m) | Base case (m AHD) | Lower FSL by 5m (Difference in m) | Lower FSL by 12m (Difference in m) |
| 1 in 5 | 35.2 | -0.1 | -0.1 | 19.9 | -2.2 | -2.3 | 11.2 | -2.9 | -3.1 | 9.4 | -2.4 | -2.6 | 1.2 | -0.3 | -0.4 |
| 1 in 10 | 37.3 | -0.1 | -0.2 | 21.6 | -2.2 | -3.3 | 13.6 | -2.7 | -3.8 | 11.6 | -2.1 | -3.0 | 2.4 | -0.4 | -0.6 |
| 1 in 20 | 39.5 | -0.5 | -0.7 | 23.4 | -1.5 | -4.3 | 15.3 | -1.3 | -3.8 | 13.5 | -1.5 | -3.2 | 3.8 | -0.4 | -0.6 |
| 1 in 50 | 42.6 | -0.6 | -1.6 | 24.9 | -0.4 | -1.9 | 16.5 | -0.4 | -1.4 | 16.0 | -0.9 | -2.6 | 5.4 | -0.4 | -0.7 |
| 1 in 100 | 44.6 | -0.5 | -1.8 | 25.9 | -0.3 | -1.2 | 17.5 | -0.6 | -1.3 | 17.2 | -0.6 | -1.9 | 6.5 | -0.4 | -0.7 |
| 1 in 200 | 46.3 | -0.5 | -1.8 | 26.5 | -0.2 | -0.9 | 18.4 | -0.5 | -1.5 | 18.2 | -0.5 | -1.6 | 7.5 | -0.4 | -0.5 |
| 1 in 500 | 48.7 | -0.5 | -1.7 | 27.1 | -0.1 | -0.5 | 19.7 | -0.5 | -1.4 | 19.5 | -0.5 | -1.4 | 9.1 | -0.4 | -0.7 |
| 1 in 1,000 | 50.4 | -0.5 | -1.9 | 27.5 | -0.2 | -0.5 | 20.6 | -0.4 | -1.3 | 20.4 | -0.4 | -1.3 | 10.2 | -0.4 | -0.7 |
| 1 in 2,000 | 54.4 | -1.2 | -3.5 | 28.4 | -0.3 | -0.8 | 21.7 | -0.5 | -1.2 | 21.5 | -0.5 | -1.2 | 11.2 | -0.4 | -0.7 |
| 1 in 5,000 | 58.6 | -0.8 | -3.1 | 29.5 | -0.3 | -0.9 | 22.7 | -0.4 | -1.1 | 22.6 | -0.4 | -1.1 | 12.5 | -0.3 | -0.6 |
| PMF | 62.3 | +0.1 | 0.0 | 31.5 | 0.0 | -0.2 | 26.3 | -0.1 | -0.5 | 26.2 | -0.1 | -0.5 | 14.6 | -0.2 | -0.5 |

**LEGEND**

Difference in m

- > +0.1
- -0.25 to -1.0
- -1.0 to -2.0
- -2.0 to -5.0

Critical range for flood risk

*Source:* WMAwater for the Taskforce (2016 model)

*Note:* All scenarios allow for probabilistic drawdown; base case is for H14 protocol; FSL lowering scenarios assume releases of 100 GL/d from FMZ; FSL = full water supply level; PMF = probable maximum flood

#### *Downstream flood duration*

Floodwater temporarily stored in the airspace would need to be released to restore the airspace. The downstream flood duration is sensitive to which post flood release strategy is implemented. Fixed post flood release rules were modelled to assess the impact of high (230 GL/d), moderate (100 GL/d) and low (40 GL/d) release rates on flood durations at nominated levels.

The time floodwaters exceeded 10 m AHD at Windsor was assessed using the Monte Carlo suite of 19,500 possible floods. This level was selected as an indicator of the upper end of flooding events that could be exacerbated through post flood releases. Land below 10 m AHD at Windsor is primarily land zoned for agricultural and recreational uses, without significant residential development.

For the -12m FSL option and a high release rate of 230 GL/d:

- most floods (68%) would no longer reach a level of 10 m AHD at Windsor
- about 16% of floods would have a shorter duration above 10 m AHD
- about 17% of floods would have a longer duration above 10 m AHD.

For the -12m FSL option and a moderate release rate of 100 GL/d:

- most floods (68%) would no longer reach a level of 10 m AHD at Windsor
- about 31% of floods would have a shorter duration above 10 m AHD
- about 1% of floods would have a longer duration above 10 m AHD.

For the -5m FSL option and a moderate release rate of 100 GL/d:

- many floods (48%) would no longer reach a level of 10 m AHD at Windsor
- about 47% of floods would have a shorter duration above 10 m AHD
- about 5% of floods would have a longer duration above 10 m AHD.

For the -5m FSL option and a low release rate of 40 GL/d:

- many floods (48%) would no longer reach a level of 10 m AHD at Windsor
- about 52% of floods would have a shorter duration above 10 m AHD
- fewer than 1% of floods would have a longer duration above 10 m AHD.

#### *Upstream peak flood levels and duration*

Lowering the FSL will decrease the level and duration of upstream flooding compared to the current dam operation.

### *5.3.3 Effects on evacuation timing*

Lowering Warragamba Dam's FSL to provide airspace for temporarily capturing flood inflows reduces and delays downstream flooding, with benefits for evacuation. Every flood has a different timing even if the depth is the same. Flood modelling considered 19,500 events using Monte Carlo simulations. The impacts on evacuation timing were assessed by considering how the option would affect the probability of key evacuation thresholds being reached, as listed in the *Hawkesbury Nepean Flood Plan* (NSW SES, 2015).

With a lowering of FSL by five metres, about one-third of modelled events would no longer cut evacuation routes from McGraths Hill, Pitt Town and Windsor, and the time at which the routes would be cut for floods still reaching those levels would be delayed (see **Figure 4.8** and **Figure 4.9**).

With a lowering of FSL by 12 metres, 62-64% of modelled events would no longer cut evacuation routes from McGraths Hill, Pitt Town and Windsor, and the time at which the routes would be cut for floods still reaching those levels would be significantly delayed (see **Figure 4.8** and **Figure 4.9**).

**Figure 4.8** and **Figure 4.9** show that lowering FSL is less effective than some other options at reducing and delaying floods that cut evacuation routes.

### *5.3.4 Economic assessment*

The Centre for International Economics assessed the benefits and costs of lowering FSL by either five metres or 12 metres.

#### *Benefits*

The benefits are described in **Table 5.6**. Reducing the FSL by 12 metres creates a larger FMZ, which has potential to reduce peak flood levels and associated damages more than reducing the FSL by five metres, even without counting benefits in terms of loss of life and injury avoided for the -12m FSL option.

**Table 5.6 Discounted benefits of options to lower FSL compared to base case**

| Benefit | -5m FSL | -12m FSL |
|---|---|---|
| | $m | $m |
| **Residential direct damage avoided** | 143 | 305 |
| **Residential indirect damage avoided** | 7 | 15 |
| **Commercial and industrial direct damage avoided** | 56 | 123 |
| **Commercial and industrial indirect damage avoided** | 21 | 46 |
| **Avoided electricity damage** | 6 | 14 |
| **Avoided other damages – roads, bridges, hospitals, etc** | 52 | 106 |
| **Loss of life and injury avoided** | 35 | not assessed (see note 1) |
| **TOTAL** | **320** | **609** |

*Source*: CIE for the Taskforce

*Note:* 'Central case' assumptions applied including 7% discount rate

[1] As part of the process of shortlisting options, lowering FSL by 12 metres was not taken forward due to the high costs that would be incurred to address impacts on water supply and quality. For this reason, the risk to life was not assessed using the evacuation modelling. The benefits would fall between the -5m FSL and WD +14m options. Regardless, there would still be a large net cost for the -12m FSL option.

### *Costs*

**Table 5.7** shows that the costs of lowering FSL by 12 metres are very high, especially accounting for the costs of bringing forward alternative supplies to meet greater Sydney's water needs, and to address water quality issues.

This cost does not account for modifications to the dam wall that would be required to effectively manage releases from the FMZ. To provide a similar level of control as for dam raising, a new outlet would be needed below the sill of the current gates, through the existing dam wall. This would be technically difficult and come at a high cost due to the size of the outlet required and high strength of the concrete of the existing dam.

This cost also does not account for the fact that the -12m FSL option would potentially preclude the scheduled release of environmental flows (e-flows) from the dam in order to maintain water security for Sydney. The e-flow benefits that would be foregone under this option are in the order of $400 million.

**Table 5.7 Discounted costs of options to lower FSL compared to base case**

| Cost | -5m FSL | -12m FSL |
|---|---|---|
| | $m | $m |
| **Capital and operating costs** | 26 | 28 |
| **Water quality impacts** | 61 | 61 |
| **Water security impacts** | 175 | 1025 |
| **TOTAL** | **262** | **1114** |

*Source*: CIE for the Taskforce

*Note:* 'Central case' assumptions applied including 7% discount rate

### *Benefit-cost*

Comparing the benefits to the costs shows that there is a net benefit of $58 million for the -5m FSL option under central case assumptions. The option to reduce FSL by five metres also delivers net benefits to the community under low and high assumptions (see **Section 4.4.3**). However, even though the option to lower FSL by five metres has a net benefit due to its low cost, it does not meet the core objective of significantly reducing regional flood risk (see **Section 4.4.1**), does not substantially reduce the number of dwellings exposed to floods, and does not provide the same quantum of benefits in terms of reduced and delayed inundation of evacuation routes as those made possible by dam raising (see **Section 4.4.2**).

Despite its greater flood mitigating benefits, the option to lower FSL by 12 metres has a net *cost* of $505 million due to the significant impacts on Sydney's water security.

### 5.3.5 Social, environmental and cultural heritage impact

#### Lowering FSL by five metres

BMT WBM Pty Ltd prepared a detailed socio-economic, environmental and cultural heritage (SECH) impact assessment for the -5m FSL option. No high or extreme impacts were identified upstream of the dam, at the dam, or downstream of the dam.

#### Lowering FSL by 12 metres

A preliminary socio-economic, environmental and cultural heritage (SECH) impact assessment of the -12m FSL option was undertaken for the Taskforce. The option was not taken forward to the detailed SECH impact assessment prepared by BMT WBM Pty Ltd, as it was eliminated due to the significant costs associated with impacts on water security.

Lowering FSL by 12 metres would have more extensive impacts than lowering FSL by five metres, especially due to the larger FMZ that would need to be evacuated following a flood.

Upstream of the dam, the newly exposed areas would initially have a higher potential for erosion, impacting water quality during rain events until the newly exposed areas are vegetated. Once ecological communities establish to the new FSL, they would be subject to temporary inundation through operation of the FMZ in much the same way as for a raised Warragamba Dam.

The overall impacts of post flood releases for the -12m FSL option, would be similar to those for dam raising (see **Section 4.4.4**). However, drawing the dam level all the way down to -12m could take a long time under the current dam outlet infrastructure. This would mean longer low-level upstream inundation and downstream flows compared to dam raising. Importantly, the FMZ may not be emptied in time to mitigate a subsequent event, with potential for greater risk to life as well as social and economic disruption.

### 5.3.6 Water supply

One of the most significant impacts of lowering Warragamba Dam's FSL to create a dedicated FMZ is a loss of water supply.

Lowering FSL by five metres would reduce the available storage at Warragamba Dam by 360 GL or about 18%. Lowering FSL by 12 metres would reduce the available storage at Warragamba Dam by 795 GL or 39%, or total system storage by 31%.

Lowering the FSL in Lake Burragorang would increase the frequency and duration of periods when the storage is relatively low. To estimate the impact of the reductions in FSL on the water level in Lake Burragorang over a range of climate conditions and sequences, WaterNSW used the WATHNET model. WATHNET estimates inflows using a daily Hydrological Simulation Program Fortran (HSPF) model. The water supply demand was estimated to be 580 GL per annum. The system configuration was consistent with the (then applicable) 2010 Metropolitan Water Plan settings. The model used 2,000 synthetic hydrological sequences based on hydrological data from 1909 to 2012.

Lowering FSL by five or 12 metres increases the likelihood that the level in Lake Burragorang will be notably lower more often than it is at present. For example, the proportion of time at which Warragamba Dam is less than half full (below -17.5m) would increase from about 2% with the current FSL, to 5% with a five-metre lowering of FSL, and to 15% with a 12-metre lowering of FSL.

Based on the current trigger for supplementing water supply for Greater Sydney from the Shoalhaven system (supply falling below 75% of total storage), lowering the FSL of Warragamba Dam by five metres would increase the frequency of time for which transfers are required from 18% to 38%. Lowering the FSL by 12 metres means the storage would always be below the level at which Shoalhaven transfers currently commence. Water transferred from the Shoalhaven is costlier to supply than dam water as it is necessary to pump the water up 620 vertical metres.

Based on the current trigger for supplementing water supply for Greater Sydney through operation of the Sydney Desalination Plant (supply falling below 60% of total storage), lowering the FSL of Warragamba Dam by five metres would increase the frequency of time for which the Sydney Desalination Plant is required to operate from 6% to 10%. Lowering the FSL by 12 metres would increase the frequency of time to 25%. The drinking water produced by the Sydney Desalination Plant is more expensive than water from Warragamba Dam.

Modelling also shows that water restrictions would be required more often with lowering of Warragamba Dam's FSL. The triggers for Shoalhaven pumping, desalination operation, and application of restrictions would all need to be revised to maintain agreed standards of service for the supply of water to greater Sydney.

In addition, a 31% reduction in total system storage capacity associated with the 12-metre lowering of FSL (in particular) would also bring forward the time at which major infrastructure augmentations of the water supply system would be required. Such measures could include a second desalination plant and the Burrawang to Avon Dam tunnel.

If either of these two options were adopted, planning for greater Sydney's water supply would need to be updated to take account of the increased costs associated with changing operating triggers and augmenting supply for current and future water security and reliability.

### *5.3.7 Water quality*

Lowering the FSL in Lake Burragorang to five metres below current FSL is expected to have a minor negative impact on the quality of the raw water supplies, while a 12-metre reduction would present significantly greater risks.

#### *Stratification and anoxia*

Changes in the FSL of the storage can affect the hydrodynamics (the behaviour of water) within the storage in terms of the intensity of stratification (the formation of layers based on temperature) and the development of anoxia (low levels of oxygen). However, both a five-metre and 12-metre reduction of FSL should have a minimal impact on stratification in the deeper waters. The risk of poor water quality driven by vertical mixing in the shallower zones of the lake should be comparable to the current situation.

#### *Inflow events*

Significant inflow events are typically the cause of major water quality issues in Lake Burragorang. However, the storage does act as a buffer with the stored waters providing internal resistance to the passage of the muddy water inflows, slowing them down and increasing the potential for suspended particles to drop out or the pollutant concentrations to be diluted. The level of water in the storage has a significant impact on the ability of the storage to act as a buffer to muddy water inflows in the following ways:

- when the lake is relatively full, it is very effective at buffering small to moderate inflow events. With a five-metre lower FSL, the buffering capacity will be slightly (although not significantly) diminished as the full storage volume is reduced.
- when the lake level is low, the buffering effect of the stored water on inflows is significantly reduced. Reducing the FSL in Lake Burragorang by 12 metres would significantly increase the frequency and duration of periods when the storage is relatively low, and therefore the probability of a moderate to large inflow event coinciding with a low storage volume, increasing the risk of poor water quality.

For most spring and summer events, the FMZ provides an opportunity to release poorer quality water, since these floods tend to deliver this water to the upper levels of the water column (as incoming flows are warmer and less dense than the stored water).

For autumn and winter events, floods are likely to deliver the poorer quality, colder water into the deeper zones of the lake, and the upper, higher quality water would be released through the gates. The potential for the poorer quality water to then mix into the surface layers (due to the weak stratification during autumn and winter) may increase, thereby reducing the overall water quality in Lake Burragorang post event. Lowering the FSL by 12 metres would increase this risk to water quality due to the reduced buffering effect.

#### *Cyanobacteria (Blue-green algae)*

Cyanobacteria blooms can be toxic to humans and can have a significant impact on the stored water quality in Lake Burragorang.

Investigations of historical events suggest that increased algal activity in the lake is more likely when a moderate to large inflow event occurs between April and August, and the total inflow is greater than half of the antecedent storage volume. There is a much greater likelihood of this situation occurring with the FSL lowered by 12 metres.

#### *Effectiveness of selective offtake for raw water supply*

WaterNSW uses a multi-level offtake facility at Warragamba Dam to draw the best available water quality for raw water supply. This aims to avoid Cyanobacteria in the upper layers, dissolved metals (iron and manganese) generated in the deeper layers, layers of poor water quality (high colour, high turbidity, etc.), and inflows, which may carry pathogens, such as cryptosporidium and giardia, and other pollutants.

Reducing FSL by five metres or 12 metres is not expected to have notable challenges for the screen selection and operating procedures when the storage is at or near the new FSL. However, during lower storage periods, the withdrawal options become increasingly limited and the risk of poorer quality water entering the raw water supplies increases as the water level drops.

The ideal operation of the outlet works is to have two outlets online at different levels at any one time. Lower water storage levels generally mean that only one outlet can be used. The ability to select from two outlets becomes limited when water level drops approximately 15 metres below current FSL, and substantially compromised when the level drops 20 metres below current FSL.

Under current operations the storage will be below -15 metres about 3% of the time. This would increase to approximately 6% of the time for the -5m FSL option and to approximately 28% of the time for the -12m FSL option. With the existing FSL, the storage is below -20 metres just under 2% of the time. This would increase to just under 4% of the time for the -5m FSL option and to over 10% of the time for the -12m FSL option. Thus, lowering FSL by 12 metres would constitute a major decrease in the effectiveness of this key mitigation capability for treating water quality risk.

#### *River water quality*

Releases from a FMZ could affect water quality (and supply), particularly with increased turbidity in water drawn from the Hawkesbury River supplying the North Richmond Water Filtration Plant (see **Section 5.2.7**).

#### *Summary*

Especially for the -12m FSL option, reducing the FSL in Lake Burragorang would increase the frequency and duration of periods when the storage is relatively low, and therefore increase the risk that WaterNSW will supply Sydney Water with lower quality water as a result of:

- a decrease in the effectiveness of the use of selective offtake to mitigate poor water quality
- diminished buffering capacity
- increased risk of algal activity.

These raw water quality impacts would increase the risk that Sydney Water would have treatment issues and increased costs at the water filtration plants, and increases the risk of not meeting the Australian Drinking Water Guidelines.

### *5.3.8 Dam operations*

#### *Warragamba pipelines and Deep Water Pumping Station*

Warragamba Dam typically supplies the majority of Sydney's water needs. Two gravity-feed pipelines from the dam are the primary method via which water is supplied to Sydney Water's water filtration plants at Orchard Hills and Prospect.

Lowering the FSL of Warragamba Dam would reduce the capacity of the Warragamba pipelines by 6% for the -5m FSL option and by 15% for the -12m FSL option. Pipeline capacity continues to reduce as the storage depletes due to the reduction in hydraulic head.

When the level in the dam falls to -33 metres, the flow to the pipelines cannot be delivered by gravity and the offline Deep Water Pumping Station would need to be brought into service. The operation of this facility turns a gravity system into a pumped system and is a major undertaking with considerable cost.

Lowering the FSL by five metres would double the likelihood of reaching the level at which the Deep Water Pumping Station is required. Lowering the FSL by 12 metres would increase this likelihood by more than 20 times.

### *5.3.9 Maintenance*

Lowering the FSL would lower the average water level, with implications for the operation and maintenance of WaterNSW's assets.

#### *Gates*

Regular, planned exercising of the radial gates and their associated systems is an essential component of ensuring the reliable operation of the gates. The radial gates can be exercised irrespective of the lake level. However, it is important that radial gates are exercised under full hydrostatic load (that is, with water against the gates).

Lowering the FSL will reduce the opportunity for WaterNSW to fully exercise the gates under load in non-drought periods, since the new FSL would be partway down the gates. This means that the only time the gates would be operating under full load would be during or after a flood event.

The drum gate lowers into a chamber in the dam crest and requires a minimum water level (7.43 metres below FSL) to operate. It can be readily exercised when the lake level is between the current FSL and approximately seven metres below FSL. The drum gate has been designed to float and when not in flotation mode must be manually kept closed. This is achieved by 'strutting' the drum gate, which means the drum gate struts are extended to support the drum gate when the flotation chamber is empty of water.

Lowering the FSL by five metres was modelled to result in the lake level being below the minimum level for drum gate flotation approximately 65% of the time. Lowering the FSL by 12 metres would require permanent strutting of the drum gate, which could not be operated apart from inflow events that raised the storage above the level of the flotation chamber. WaterNSW's ability to exercise and maintain the drum gate could be significantly impaired.

#### *Warragamba pipelines*

WaterNSW has implemented an ongoing maintenance regime for the Warragamba pipelines and associated infrastructure. This maintenance regime is sensitive to the lake level at Warragamba. When the lake level is lower, specific maintenance outages cannot be undertaken as insufficient water can be supplied at the Warragamba Pipeline Outlet Works to meet demand requirements from Prospect and Orchard Hills water filtration plants.

Lowering FSL by 12 metres would have significant implications for the defined exercise and maintenance regime on the Warragamba pipelines. This would significantly and adversely impact WaterNSW's risk profile as these pipelines supply around 70% to 80% of Sydney's daily water demands. Lowering FSL by five metres would have less impact but has some potential to adversely affect WaterNSW's risk profile.

### *5.3.10 Findings – lowering permanent storage*

Lowering the FSL of Warragamba Dam to create permanent airspace for flood mitigation would achieve some reductions in flood levels downstream of the dam. However, there are a number of issues relating to lowering the FSL. These are summarised as follows:

- ***benefits limited to small flood events*** – although a five-metre lowering of FSL has a net benefit due to its low cost, it does not meet the core objective of significantly reducing flood risk since it reduces peak flood levels at Windsor by a maximum of 0.9 metres for the critical range for flood risk reduction of 1 in 50 to 1 in 1,000 chance per year. In comparison to the dam raising options, a five-metre lowering of FSL also does not substantially reduce the number of dwellings exposed to floods, does not provide the same quantum of benefits in terms of reduced and delayed inundation of evacuation routes, and does not substantially reduce average annual damages.

As a five-metre lowering of FSL does not meet the key flood risk reduction objectives, it is clear that an earlier-rejected option of a two-metre lowering of FSL would also offer inadequate airspace.

Although a 12-metre lowering of FSL offers moderate reduction of peak flood levels, it is significantly less effective than the dam raising options for the 1 in 50 chance per year flood and larger events, which are those critical for risk to life and property in the valley.

- ***loss of water supply storage*** – any lowering of FSL would result in a permanent reduction in security of Sydney's water supply, with a 12-metre lowering having a very significant impact. As a consequence, the water supply system would become much more dependent upon the Upper Nepean dams, the Shoalhaven transfer system and the Sydney Desalination Plant. With a 12-metre lowering, new water supply infrastructure would also be needed to secure current and future supplies for greater Sydney. This has costs relating to:
    - increased operational and maintenance costs associated with increased reliance on the Upper Nepean dams and associated transfer infrastructure
    - increased electricity costs associated with increased reliance on transfers from the Shoalhaven system
    - increased use of the Sydney Desalination Plant, which is a more expensive source of water to consumers than dam water
    - construction of major new water supply infrastructure.
- ***potential loss of water quality*** – a 12-metre lowering of FSL increases the risk of poor water quality in the storage and provides less operational flexibility to make the best quality water available to the water supply system
- ***poor cost effectiveness*** – the high costs of maintaining water security and water quality mean that lowering FSL by 12 metres does not provide a net benefit to society, since the costs exceed the flood mitigation benefits.

The following recommendations relate to the permanent lowering of FSL at Warragamba Dam:

- ***lowering FSL by two metres*** was not recommended as there would be only very minor benefits from reduction of downstream flood levels
- ***lowering FSL by five metres*** was not recommended because, despite offering net benefit, it did not sufficiently reduce floods in the critical range for risk to life and property
- ***lowering FSL by 12 metres*** was not recommended because the costs substantially exceed the benefits.

## 5.4 Combined options

### *5.4.1 Description of options*

Two combinations of options were considered to assess the maximum feasible benefit that could be obtained by operating the existing Warragamba Dam for flood mitigation. These were:

- lowering FSL by five metres, *and* applying the surcharge method of Warragamba Dam gate operations
- lowering FSL by five metres, *and* pre-releasing 40 GL/d over three days (to keep Yarramundi Bridge open), *and* applying the surcharge method of Warragamba Dam gate operations.

### *5.4.2 Effects on flood behaviour*

#### *Downstream peak flood levels*

**Table 5.8** shows that for these two combined options, reductions in downstream peak flood levels of more than two metres are limited to the 1 in 50 chance per year flood and more frequent events (excluding Wallacia). For the 1 in 100 chance per year flood, reductions of more than one metre would be achieved for all reference sites excluding Wisemans Ferry.

The benefits of these combined options decrease with increases in flood magnitude, with less than 0.5 metres reduction for Penrith in events rarer than the 1 in 100 chance per year flood. Little benefit would be achieved for the critical range of floods (1 in 50 to 1 in 1,000 chance per year) where the risk to life and property is concentrated.

#### *Downstream flood duration*

Downstream levels may remain elevated while the FMZ formed by lowering the FSL is emptied, potentially prolonging low-level inundation depending on the rate of post flood releases.

#### *Upstream peak flood levels and duration*

Surcharging, in combination with a lowering of FSL by five metres, increases the level and duration of upstream flooding, albeit to a lesser extent than with surcharging alone. The maximum difference between upstream flood levels for this combined option and existing conditions is 0.55m (for a flood a bit smaller than a 1 in 100 chance per year), and no more than an additional 20 hours of inundation (for a 1 in 50 chance per year flood). The level and duration of upstream flooding is the same for both methods of operation for the PMF.[7]

The combined option of lowering FSL by five metres, a pre-release of 40 GL/d over three days, and surcharge, although having a surcharge component, has a minimal, almost negligible increase in the level of upstream flooding compared to existing conditions, which occurs for no more than nine hours.[8]

---

[7] WaterNSW for Taskforce, 2014 model

[8] WaterNSW for Taskforce, 2014 model

**Table 5.8 Impacts of combination of Warragamba Dam operating options on downstream flood levels**

| Flood event (chance of occurrence per year) | Wallacia | | | Penrith | | | North Richmond | | | Windsor | | | Wisemans Ferry | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Base case (m AHD) | Induced surcharge and -5m FSL (Difference in m) | Induced surcharge, -5m FSL and pre-release of 40 GL/d (Difference in m) | Base case (m AHD) | Induced surcharge and -5m FSL (Difference in m) | Induced surcharge, -5m FSL and pre-release of 40 GL/d (Difference in m) | Base case (m AHD) | Induced surcharge and -5m FSL (Difference in m) | Induced surcharge, -5m FSL and pre-release of 40 GL/d (Difference in m) | Base case (m AHD) | Induced surcharge and -5m FSL (Difference in m) | Induced surcharge, -5m FSL and pre-release of 40 GL/d (Difference in m) | Base case (m AHD) | Induced surcharge and -5m FSL (Difference in m) | Induced surcharge, -5m FSL and pre-release of 40 GL/d (Difference in m) |
| *Model stage* | 2016 | 2016 | 2014 | 2016 | 2016 | 2014 | 2016 | 2016 | 2014 | 2016 | 2016 | 2014 | 2016 | 2016 | 2014 |
| 1 in 5 | 35.2 | -0.1 | -0.1 | 19.9 | -2.2 | -1.7 | 11.2 | -2.9 | -2.1 | 9.4 | -2.4 | -1.7 | 1.2 | -0.3 | -0.2 |
| 1 in 10 | 37.3 | -0.2 | -0.2 | 21.6 | -2.5 | -2.8 | 13.6 | -3.0 | -3.0 | 11.6 | -2.3 | -2.4 | 2.4 | -0.5 | -0.4 |
| 1 in 20 | 39.5 | -0.7 | -0.6 | 23.4 | -2.6 | -3.3 | 15.3 | -2.3 | -3.0 | 13.5 | -2.1 | -2.3 | 3.8 | -0.5 | -0.5 |
| 1 in 50 | 42.6 | -1.6 | -1.6 | 24.9 | -1.8 | -2.1 | 16.5 | -1.1 | -1.3 | 16.0 | -1.7 | -2.1 | 5.4 | -0.5 | -0.5 |
| 1 in 100 | 44.6 | -1.6 | -1.8 | 25.9 | -1.3 | -1.6 | 17.5 | -1.0 | -1.2 | 17.2 | -1.3 | -1.6 | 6.5 | -0.5 | -0.5 |
| 1 in 200 | 46.3 | -0.9 | -1.3 | 26.5 | -0.2 | -0.4 | 18.4 | -0.8 | -1.1 | 18.2 | -0.8 | -1.1 | 7.5 | -0.4 | -0.3 |
| 1 in 500 | 48.7 | -0.2 | -0.9 | 27.1 | 0.0 | -0.2 | 19.7 | -0.6 | -0.8 | 19.5 | -0.6 | -0.8 | 9.1 | -0.4 | -0.4 |
| 1 in 1,000 | 50.4 | -0.3 | -1.0 | 27.5 | -0.1 | -0.2 | 20.6 | -0.4 | -0.7 | 20.4 | -0.4 | -0.7 | 10.2 | -0.5 | -0.5 |
| 1 in 2,000 | 54.4 | -0.3 | -2.2 | 28.4 | -0.1 | -0.5 | 21.7 | -0.3 | -0.6 | 21.5 | -0.3 | -0.7 | 11.2 | -0.5 | -0.4 |
| 1 in 5,000 | 58.6 | -0.6 | -1.6 | 29.5 | -0.3 | -0.4 | 22.7 | -0.3 | -0.6 | 22.6 | -0.3 | -0.6 | 12.5 | -0.4 | -0.3 |
| PMF | 62.3 | +0.2 | 0.0 | 31.5 | 0.0 | -0.1 | 26.3 | -0.1 | -0.3 | 26.2 | -0.1 | -0.3 | 14.6 | -0.1 | -0.3 |

**LEGEND**

Difference in m

- > +0.1
- -0.25 to -1.0
- -1.0 to -2.0
- -2.0 to -4.0

Critical range for flood risk

*Sources:* WMAwater for the Taskforce

*Note:* All scenarios allow for probabilistic drawdown; base case is for H14 protocol; combined option for induced surcharge and -5m FSL assumes releases of 100 GL/d from FMZ; FSL = full water supply level; PMF = probable maximum flood

Unlike for surcharge alone, the combined options with -5m FSL do not result in the activation of the fuse plugs earlier than under current (H14) operations.

### 5.4.3 Effects on evacuation timing

While for many of the Monte Carlo events these combined options result in evacuation triggers no longer being reached or delayed, there are some events where implementation of the options could result in worse timing:

- for the combined option of lowering FSL by five metres and surcharge gate operation, in about 10% of modelled events, evacuation of Richmond would be required, when it is not required for the base case.
- for the combined option of lowering FSL by five metres, pre-releases of 40 GL/d and surcharge gate operation, the time to reach the moderate flood level of 8.25 m AHD at Windsor would occur earlier for 20% of modelled floods.[9]

### 5.4.4 Economic assessment

#### *Benefits*

An economic assessment of these combined options across the full range of floods found that average annual damages would be reduced by:

- 38% for the combined option of lowering FSL by five metres and surcharging of the gates
- 45% for the combined option of lowering FSL by five metres, a pre-release of 40 GL/d over three days, and surcharging the gates.[10]

#### *Costs*

The costs of these combined options would be a little higher than those for the -5m FSL option alone (**Table 5.7**).

### 5.4.5 Other issues

Environmental impacts would be similar to those described for the -5m FSL and surcharging options.

Lowering FSL by five metres entails a permanent loss of 18% of Warragamba Dam's storage volume. A pre-release of 40/GL day over three days entails the removal of 6% of the storage volume with a risk that it may not be fully replenished by the predicted rains. Therefore, combining the two options is judged to have a major impact upon water supply. Regardless of the risk to water security, at the current time, the ability of weather models to predict the spatial and temporal pattern of rainfall with the resolution and confidence required for implementing a pre-release strategy from a water supply dam is limited.

---

[9] WaterNSW for Taskforce, 2014 model

[10] **Figure 4.10** presents the results of an earlier assessment conducted for the 2013 Review. The updated result described here relies upon revised (2014) flood modelling and some changed assumptions for the damages assessment.

This combination of options would also be highly complex for operations, with an increased risk of mechanical, electrical, controls or operator error.

The risk to the radial gates would be the same as that described for the surcharging option in isolation.

### *5.4.6 Findings – combined options*

A combination of lowering FSL by five metres, surcharging the gates (and, in one scenario, pre-releasing 40 GL/d over three days) does result in a greater reduction of flood levels downstream, and for somewhat rarer events, than for the -5m FSL option in isolation. However, the combined options still fall well short of the significant reductions achieved by raising Warragamba Dam. Also, the issues associated with surcharging and pre-releases are problematic for options that incorporate them, including:

- loss of evacuation time for some events
- increased risk of loss of water supply
- high complexity of dam operations
- an increased risk to the radial gates.

Accordingly, these two combined options are not recommended.

## 5.5 Conclusion

Options to reduce downstream flood levels by changing the way the existing Warragamba Dam is operated mostly fail to meet the objective of a significant regional reduction of flood risk (see **Table 4.3**).

The best performing of this suite of options for reducing downstream peak flood levels is lowering FSL by 12 metres, which mitigates the 1 in 100 chance per year flood at Windsor by almost two metres. However, the high cost means that this option has a large net cost. This is because 12-metre lowering reduces the dam's water supply capacity by nearly 40% and Sydney's total water supply by around one third.

This would have a very significant impact on water security for greater Sydney. Before this option could be implemented, major new sources of water would need to be built and the current desalination plant would need to be continuously operated at maximum effective capacity. Further, a 12-metre lowering would present a range of water quality issues that would need to be mitigated, as described above.

None of the options to modify the operation of the existing Warragamba Dam for flood mitigation, or combination of options, provide the same quantum of flood risk reduction benefits as would be achieved through dam raising options.

# 6 Flood mitigation infrastructure options – new or raised dams

A number of rivers and creeks contribute to flooding in the Hawkesbury-Nepean Valley and it would be technically possible to construct flood mitigation dams on one or more of these. Floodwater would be detained upstream of the Hawkesbury-Nepean floodplain then released at a controlled rate after the risk of severe flooding had passed. Not only would these options reduce flood peaks but they would also delay the peak, giving emergency services personnel more certainty of time to evacuate the floodplain.

Options include constructing flood mitigation dams at new sites in the catchment, or raising Warragamba Dam while retaining the existing full water supply level (FSL) to create airspace for the temporary capture of floodwaters (see **Box 4.1**). **Figure 6.1** illustrates flood mitigation dam sites that were reconsidered in the *Hawkesbury-Nepean Valley Flood Management Review* (2013 Review).

## 6.1 New flood mitigation dams

As part of the *Warragamba Dam Flood Protection Program* in the 1980s and 1990s, the feasibility of constructing sole purpose flood mitigation dams was investigated across the Hawkesbury-Nepean Valley. These flood mitigation dams would be kept empty except during flood events when they would temporarily hold back floodwaters before releasing the floodwaters at a controlled rate.

These flood mitigation dams can be categorised as those upstream or downstream of Warragamba Dam.

### *6.1.1 Upstream of Warragamba Dam*

In the *Proposed Warragamba Flood Mitigation Dam Environmental Impact Statement* (the 1995 EIS) (ERM Mitchell McCotter, 1995), large flood mitigation dams upstream of Warragamba Dam were investigated primarily as an option to meet new dam safety requirements. (The issue of dam safety was ultimately addressed by construction of an auxiliary spillway from 1998 to 2002.) Two new dams upstream of Warragamba Dam were investigated:

- ***Wollondilly River at Jooriland*** – this dam site is located in remote bushland northwest of Mittagong, making access to the site difficult. Significant environmental impacts were identified both during construction and from temporary inundation of surrounding bushland and National Park during floods. This dam option would have about 50% larger capacity and a dam wall height about 50 metres higher, compared to the existing Warragamba Dam.
- ***Coxs River at Kelpie Point*** – this dam site is located in remote bushland on the Coxs River within the Blue Mountains National Park (now part of the Greater Blue Mountains World Heritage Area). Significant environmental impacts were identified both during construction and from temporary inundation during floods. The proposed dam would have about 35% the capacity of Warragamba Dam, with a slightly higher dam wall.

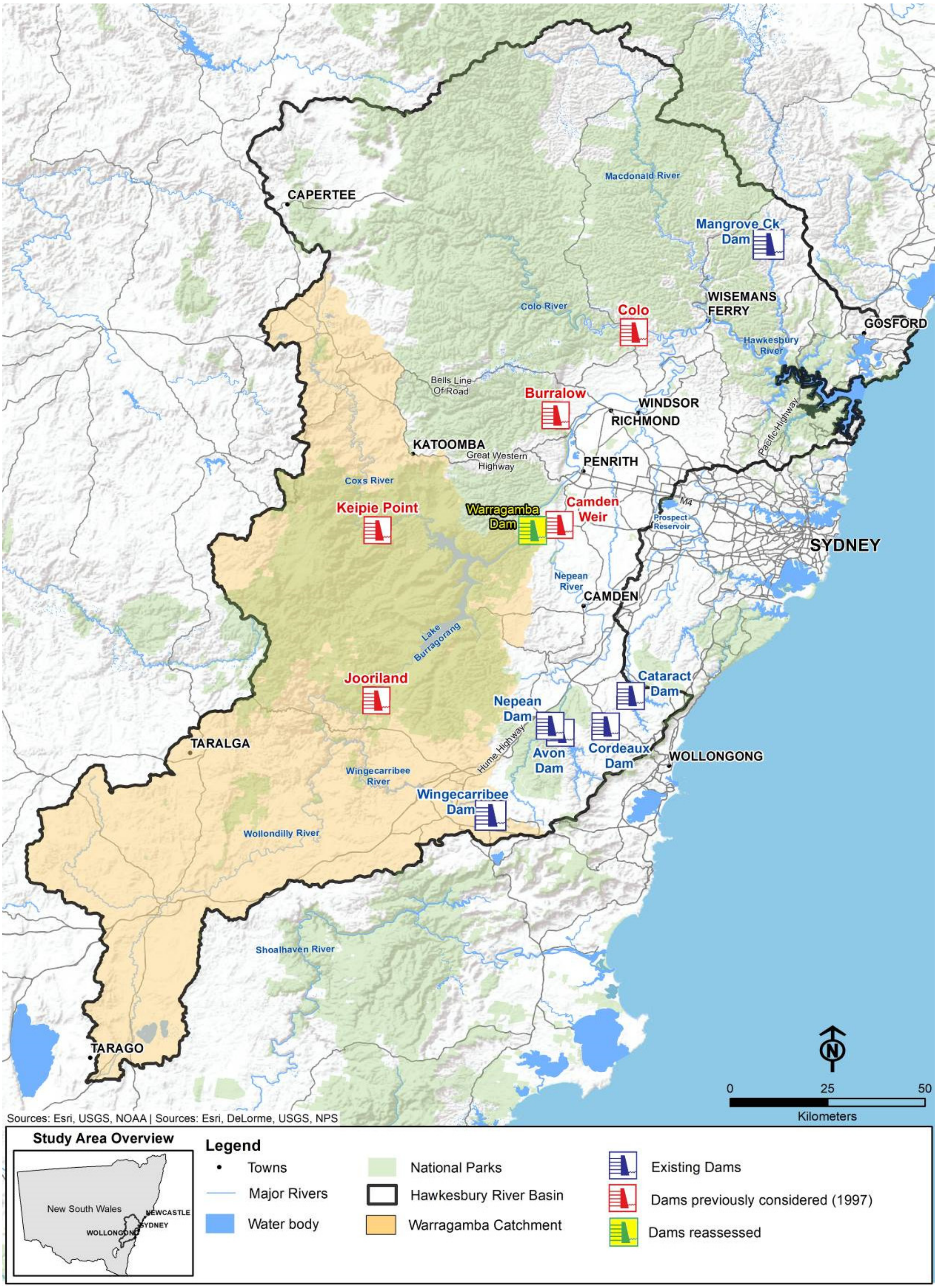



**Figure 6.1 Flood mitigation dam options in the Hawkesbury-Nepean Catchment**

*Source*: INSW; NSW SES

The two dams were estimated to cost in the order of $500 million in 1995. The two dams could temporarily store all floodwaters from their respective catchments up to a 1 in 100 chance per year flood.

In 1988, NSW Public Works concluded that the high cost and the environmental impacts associated with building large dams at these sites meant that further investigation was not warranted. Similar conclusions were made by the Warragamba Inter-Departmental Committee in 1990 and again in the 1995 EIS.

As part of *Achieving a Hawkesbury-Nepean Floodplain Management Strategy* (the 1997 study) (HNFMAC, 1997), a much smaller flood mitigation dam was investigated at the Wollondilly River site at Jooriland. Because the auxiliary spillway at Warragamba Dam had been approved, the aim of this smaller flood mitigation dam was to mitigate downstream flooding, not for dam safety requirements.

Being a much smaller dam, this option was found to have only limited benefit in reducing downstream flood levels. In a 1 in 100 chance per year flood, a reduction of only 0.5-0.7 metres would be expected between Penrith and Sackville, while in a 1 in 500 chance per year flood a reduction of only 0.2-0.5 metres in flood levels could be achieved (WMA, 1997).

Although smaller, the difficulties of accessing the site would result in very high construction costs. The environmental impacts associated with building a new dam were still found to be significant. It was concluded that this smaller flood mitigation dam on the Wollondilly River at Jooriland would not be feasible on economic and environmental grounds.

The 1997 study also considered the impact of totally blocking flow with two new dams at both the Wollondilly River and Coxs River sites. This is not a practical option since it would require very high and wide dams with very large inundation areas. However, it provides an indicative upper limit to the effects of dams at these locations. This scenario was modelled to reduce peak flood levels by 2.2-2.3 metres at Windsor for the 1 in 100 and 1 in 500 chance per year floods (WMA, 1997; **Table 4.3**).

The economic and environmental costs of both dams would also be prohibitive.

### *6.1.2 Downstream of Warragamba Dam*

As part of developing the 1995 EIS, other significant tributaries of the Hawkesbury-Nepean Catchment were investigated for sites that may be suitable for flood mitigation dams. The benefits of flood mitigation dams at these sites in reducing downstream flood levels were also investigated as part of the 1997 study.

The following sites were considered:

- ***Nepean River between Camden and Bents Basin (Camden Weir)*** – assuming it retained all flood inflows (unlikely to be achieved), a flood mitigation dam at this location was modelled to reduce flood levels by 1.7 metres at Penrith and 1.5 metres at Windsor in a 1 in 100 chance per year flood and reduce flood levels by 1.1 metres at Penrith and 1.7 metres at Windsor in a 1 in 500 chance per year flood (**Table 4.3**). However, during a flood, levels at Camden would be increased with a flood mitigation dam at this location (WMA, 1997).
- ***Grose River at Burralow*** – assuming it retained all flood inflows (unlikely to be achieved), a flood mitigation dam at this location would have no impact on flood levels at

Penrith, while a reduction in flood levels of about 0.4-0.5 metres between North Richmond and Sackville could be achieved in the 1 in 100 and 1 in 500 chance per year floods (WMA, 1997).

- ***Colo River at the confluence of the Hawkesbury River*** – the catchment of a flood mitigation dam at this site would be very large. Assuming it retained all flood inflows (unlikely to be achieved), a reduction of flood levels of 0.1-0.5 metres between North Richmond and Sackville could be achieved in the 1 in 100 and 1 in 500 chance per year floods, with no change at Penrith (WMA, 1997).

Each of these dams were estimated to cost in excess of $200 million in 1995.

The 1995 EIS found that while the combination of all three dams would have benefits at Windsor, the financial and environmental costs would be prohibitive. Consequently, the combination of these options was not considered further.

The 1997 study concluded that none of these flood mitigation dams were feasible for the following reasons:

- ***Nepean River between Camden and Bents Basin (Camden Weir)*** – would require significant land resumption, would result in significant environmental impacts, and would increase flood levels at Camden
- ***Grose River at Burralow*** – would have minimal flood mitigation benefits, would only be of benefit if flooding originated from the Grose River, inaccessible terrain, and there would be significant environmental impacts arising from the construction and operation of a dam in a National Park
- ***Colo River at the confluence of the Hawkesbury River*** – would have very little influence on flood levels in the Hawkesbury River upstream of its confluence with the Colo River, downstream development is relatively sparse and would not provide economic justification for this option, and environmental impacts would be significant.

### 6.1.3 Findings – new flood mitigation dams

All previous investigations into new, sole purpose flood mitigation dams, both upstream and downstream of Warragamba Dam, concluded that these are not feasible flood risk management options for the Hawkesbury-Nepean Valley based on economic, social and environmental considerations. The 2013 Review considered and concurred with the findings of these earlier investigations as contributing factors to the previous conclusions had not changed.

## 6.2 Warragamba Dam wall raising

### 6.2.1 Description of options

Completed in 1960, Warragamba Dam is a water supply dam that provides around 80% of Sydney's supply. It was not designed and is not operated for flood mitigation. Nonetheless, it occupies a site with significant potential to provide regional flood mitigation benefits, given the high proportion of the Warragamba Catchment to the catchment areas to Penrith (80%) and Windsor (70%) (**Figure 4.2**).

One way of providing a significant flood mitigation function is to raise Warragamba Dam wall without raising FSL. The airspace this would create would be available to capture and temporarily detain floodwaters until the downstream flood peak has passed. Investigations into raising Warragamba Dam for flood mitigation in the valley go back to the 1980s. The option was reassessed for the 2013 Review and the Hawkesbury-Nepean Valley Flood Management Taskforce, and was endorsed by the Government for further development under the auspices of Phase 1 of the Flood Strategy (see **Figure 6.2**).

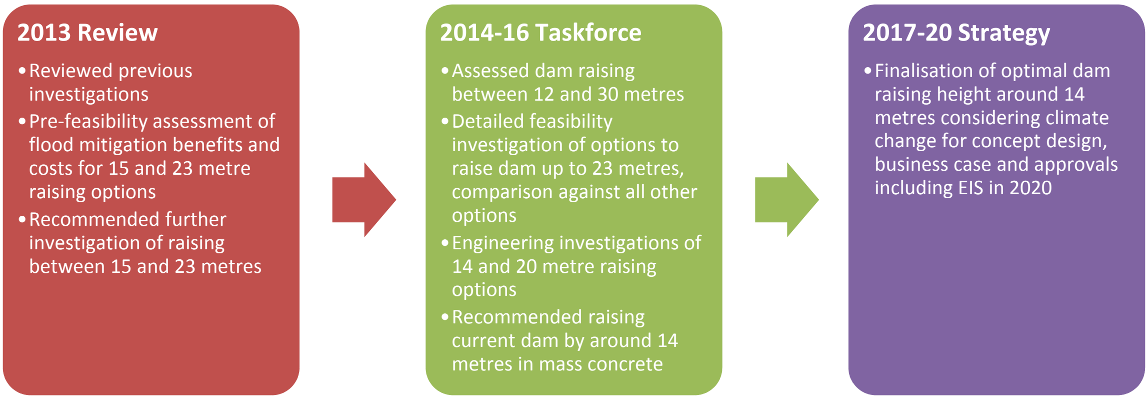



**Figure 6.2 Progressive investigations of Warragamba Dam raising options**

The 1995 EIS considered three dam raising options (15, 23 and 30 metres) and recommended raising Warragamba Dam by 23 metres for dam safety and flood mitigation downstream. Extensive engineering and environmental investigations had been undertaken leading up to the 1995 EIS. This proposal was not taken forward with a change of Government in 1995. The dam was subsequently modified (1998-2002) to safely pass the probable maximum flood (PMF) by installing an auxiliary spillway. The auxiliary spillway does not mitigate downstream floods (except in the case of PMF dam failure).

The 2013 Review revisited options for raising Warragamba Dam for flood mitigation to reduce risk to life and average flood damages downstream. Two dam raising options were investigated – 15 and 23 metres. These were considered appropriate for testing lower and upper flood mitigation potential. Different construction options for raising the dam (downstream concrete buttressing, downstream embankment raisings, downstream fill buttressing) were considered. Downstream concrete gravity buttressing (either conventional mass concrete or roller compacted concrete) was selected as the preferred raising option.

A pre-feasibility assessment of the flood mitigation benefits and the costs for these two options was undertaken. Modelling revealed significant reductions in downstream peak flood levels for both options. Dam raising was also found to significantly delay the flood peaks at Penrith and Windsor, providing more certainty for evacuation.

The Review recommended that further detailed investigation was required to optimise the configuration and height of a raised Warragamba Dam (considered likely to be between 15 and 23 metres), and to identify and assess a range of engineering, economic, environmental and social impacts of such a major infrastructure proposal.

The Taskforce, as part of its due diligence, considered a wider range of dam raising options from 12 to 30 metres, to reconfirm the lower and upper bounds of flood mitigation and to take account of contemporary construction technologies. The dam raising options were evaluated against the criteria of reducing the risk to life and reducing economic damages for both the existing population and projected growth (to 2041). The assessment included:

- modelling flood releases from Warragamba Dam for a range of dam raising heights, spillway configurations, flood events and durations
- modelling evacuation benefits for a range of dam and flood scenarios
- the economic damages associated with a range of dam and flood scenarios.

### *Hydrologic and hydraulic evaluation*

*Flood mitigation zone (FMZ) size options*

A multi-criteria analysis was applied to identify the optimal range of heights to raise the dam. Two heights, 14 and 20 metres, were chosen as representing the upper and lower bounds of feasible dam raising. For the work of the Taskforce, these heights refer to the raising of the abutments to prevent overtopping under the critical PMF event. The levels of the spillways are then set to ensure that the critical PMF is able to be safely passed over the spillways without overtopping the raised abutments, with an allowance or 'freeboard' for wave action and other factors.

Effective FMZs would be formed between the raised spillways and the existing FSL – estimated by the Taskforce to be 1,027 billion litres (GL) for a 14-metre raising, and 1,723 GL for a 20-metre raising. These FMZ volume estimates are subject to refinement as the design progresses and to meet any updated survey and guidelines.

Preliminary assessment of evacuation risk indicated that raising Warragamba Dam between 14 and 20 metres should allow for the evacuation of the population from flood islands in the valley for the critical flood range, using the forecast target of 15 hours. These heights were set as the lower and upper bounds of dam raising, for more detailed investigation.

*Spillway options*

Consideration was also given to having a 'slotted' spillway rather than gated outlet conduits. Compared to a gated spillway, this has the attraction of simpler operation, because the dam would commence spilling through the 'slot' when the FSL is exceeded.

*Post flood release options*

Various post flood release rate options were modelled to inform the initial design and operation of dam gates, and to quantify the upstream and downstream impacts. Three fixed post flood release rules were modelled:

- a low release rate of 40 GL/d targeted to keep Yarramundi Bridge open
- a moderate release rate of 100 GL/d targeted to keep Windsor and North Richmond bridges open
- a high release rate 230 GL/d to efficiently recover airspace in the FMZ and minimise upstream impacts.

### *Dam construction options*

The Taskforce engaged NSW Public Works and international consultants MWH to investigate a broad range of construction options for raising Warragamba Dam. In an iterative process and based on the outcomes of the hydrologic and hydraulic investigations, the following analyses were undertaken:

- progress the pre-feasibility 2013 Review mass concrete raising estimates to a detailed feasibility level for a 14 and 20 metre raising (NSW Public Works)
- assess potential alternative raising options to identify a preferred alternate raising option (MWH)
- progress the preferred alternate raising option (considering world best practice since the 1980s and 1990s reports) to a detailed feasibility level for a 14-metre raising (MWH)
- identify a preferred raising option (NSW Public Works, MWH, independent dam experts).

Sixteen alternative options were considered (**Table 6.1**) – four options involving raising of the existing dam with buttressing, and six new embankment options at each of two sites 800 metres and 1,300 metres downstream of the existing dam. Investigated dam types for the new embankments were gravity hardfill, gravity roller compacted concrete, concrete faced rockfill and asphaltic core rockfill.

A multi-criteria analysis of the alternative options was undertaken using three main objectives: cost, environmental impact, and operational impact. Scores were assigned on a scale of 0 to 10, with 1 the most favourable and 10 the least favourable to meet the objective. A sensitivity check was undertaken of the weighting given to each objective. The outcome of the scoring is shown in **Figure 6.3**. Options involving buttressing of the existing dam ranked more highly than new embankments downstream. The lowest scoring option (best able to meet the objectives) was a hardfill buttress at the existing dam wall utilising a central spillway and the existing auxiliary spillway. This was estimated to cost about $1.2 billion (2015 dollars), including a 25% contingency, which is significantly more expensive than the estimate for a 14-metre mass concrete dam raising ($692 million).

On the basis of estimated project cost, potential environmental and social impact from construction, and technical issues involved in raising, a mass concrete (concrete gravity) raising of the current dam was the recommended raising option.

### *Preferred option*

Adopting the recommended construction technique, the 14 and 20 metre dam raising options were investigated to detailed feasibility stage. Some of the features of the Taskforce's detailed feasibility designs are presented in **Table 6.2**.

**Figure 6.4** shows an indicative schematic for a 14-metre raising in mass concrete. The current FSL would be unchanged (116.72 m AHD). The current central drum gate and radial gates would be replaced by a raised central spillway crest. The current fuse plug auxiliary spillway would be replaced by a concrete auxiliary spillway. Eight submerged gated conduits would be provided to enable post flood releases from the FMZ. Raising the height of the dam also requires 'buttressing' or thickening the dam wall, as illustrated in **Figure 6.5**.

The purpose of the preliminary designs was to inform the Taskforce recommendations. The dam raising design is being further developed for the Warragamba Dam Raising Environmental Impact Statement and final business case.

**Table 6.1 Alternative 14-metre construction options**

| Site | ID | Dam type | Spillway solution |
|---|---|---|---|
| **3B** (existing dam) | A | Concrete faced rockfill dam | New 90 m abutment spillway + aux spillway |
| | B | Fill buttress | New 90 m abutment spillway + aux spillway |
| | C | Hardfill buttress | New 90 m abutment spillway + aux spillway |
| | D | | Spillway in dam + Existing aux spillway |
| **3A** (800 metres downstream of existing dam) | E | Concrete faced rockfill dam | Spillway in abutment |
| | F | Asphaltic core rockfill dam | Spillway in abutment |
| | G | Hardfill buttress | Spillway in abutment |
| | H | | Spillway in dam + abutment |
| | I | Roller compacted concrete | Spillway in abutment |
| | J | | Spillway in dam + abutment |
| **3** (1300 metres downstream of existing dam, at weir) | K | Concrete faced rockfill dam | Spillway in abutment |
| | L | Asphaltic core rockfill dam | Spillway in abutment |
| | M | Hardfill buttress | Spillway in abutment |
| | N | | Spillway in dam + abutment |
| | O | Roller compacted concrete | Spillway in abutment |
| | P | | Spillway in dam + abutment |

*Source:* MWH for the Taskforce

*Note*: See **Figure 6.3** for comparison of options

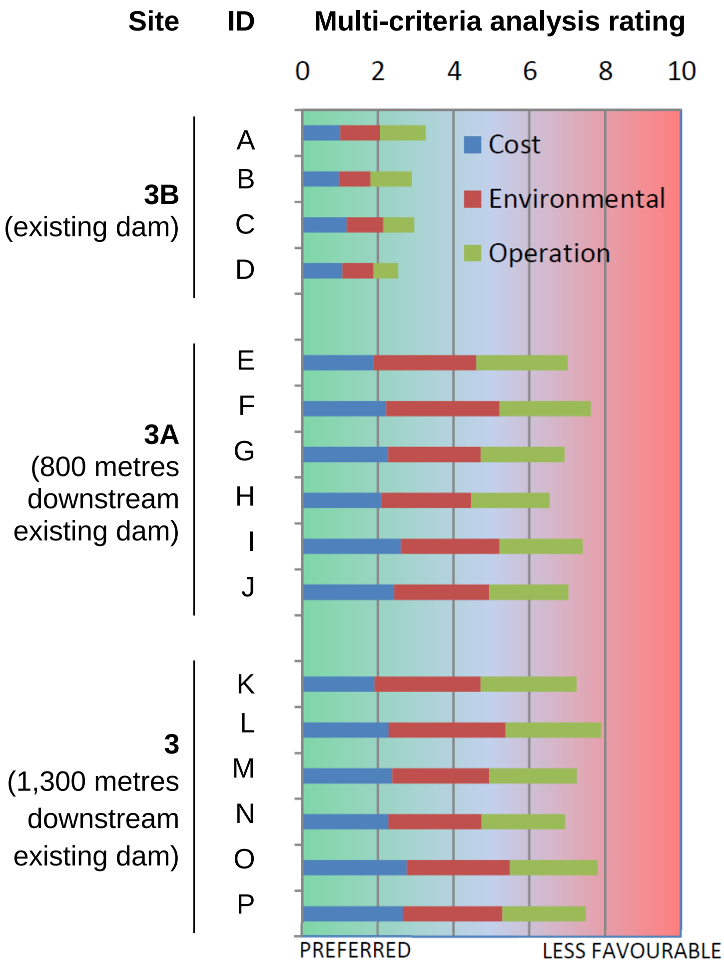



**Figure 6.3 Comparison of alternative 14-metre dam raising options**

*Source*: MWH for the Taskforce

*Note*: See **Table 6.1** for identification of options

**Table 6.2 Taskforce detailed feasibility dam raising design specifications (subject to change with detailed concept design and revised hydrology)**

| | WD +14m | WD +20m |
|---|---|---|
| Full water supply level (FSL) | RL 116.72<br>(same as existing) | RL 116.72<br>(same as existing) |
| Raised dam crest level, in order to ensure the PMF does not overtop the abutments | RL 144.2<br>(13.73 m above existing) | RL 150.2<br>(~20 m above existing) |
| Raised central spillway crest level, replacing the existing central spillway radial and drum gates | RL 128.45 | RL 136.17 |
| Auxiliary spillway crest level, replacing the five existing erodible fuse plugs | RL 128.45 | RL 136.17 |
| Buttress thickness (central spillway section) | 14.5 m | 18.6 m |
| Gated conduits within central spillway | Eight 4.5 m x 4.5 m | Eight 4.5 m x 4.5 m |
| Cost (2015 dollars incl. 25% contingency) | $692 million | $865 million |
| Additional temporary flood capture volume | 1,027 GL | 1,723 GL |
| Flood inflows able to be contained | Approx. 1 in 40 chance per year | Almost to approx. 1 in 200 chance per year |

*Source:* adapted from NSW Public Works for the Taskforce

*Notes*: GL = gigalitres; RL = reduced level

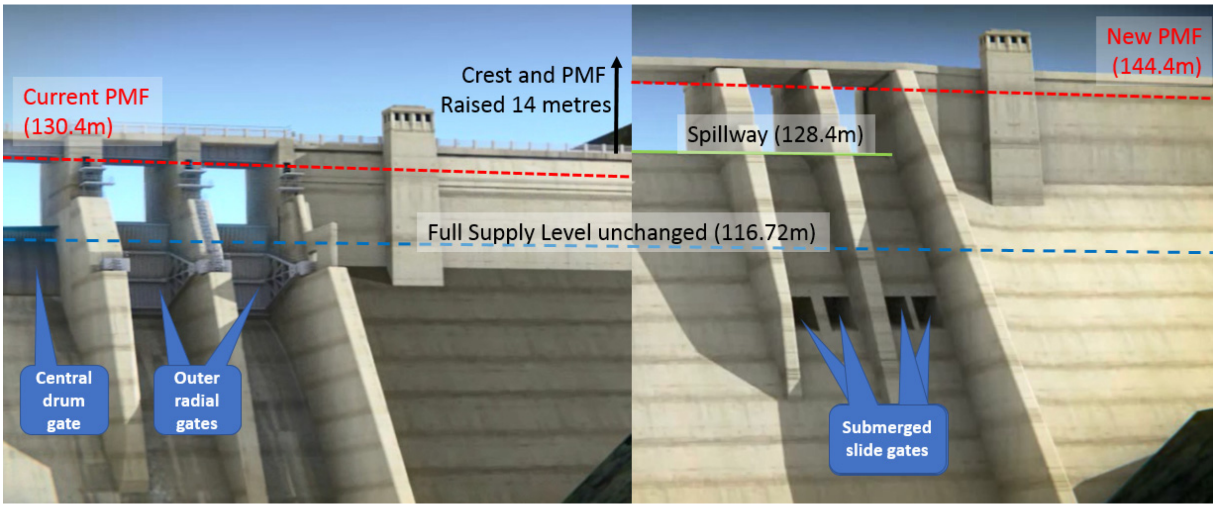



**Figure 6.4 Taskforce schematic comparing existing Warragamba Dam to indicative 14-metre raised dam (subject to change with detailed concept design and revised hydrology)**

*Source*: INSW

*Note*: PMF subject to change to comply with *Australian Rainfall and Runoff 2016* (Ball et al., 2016)

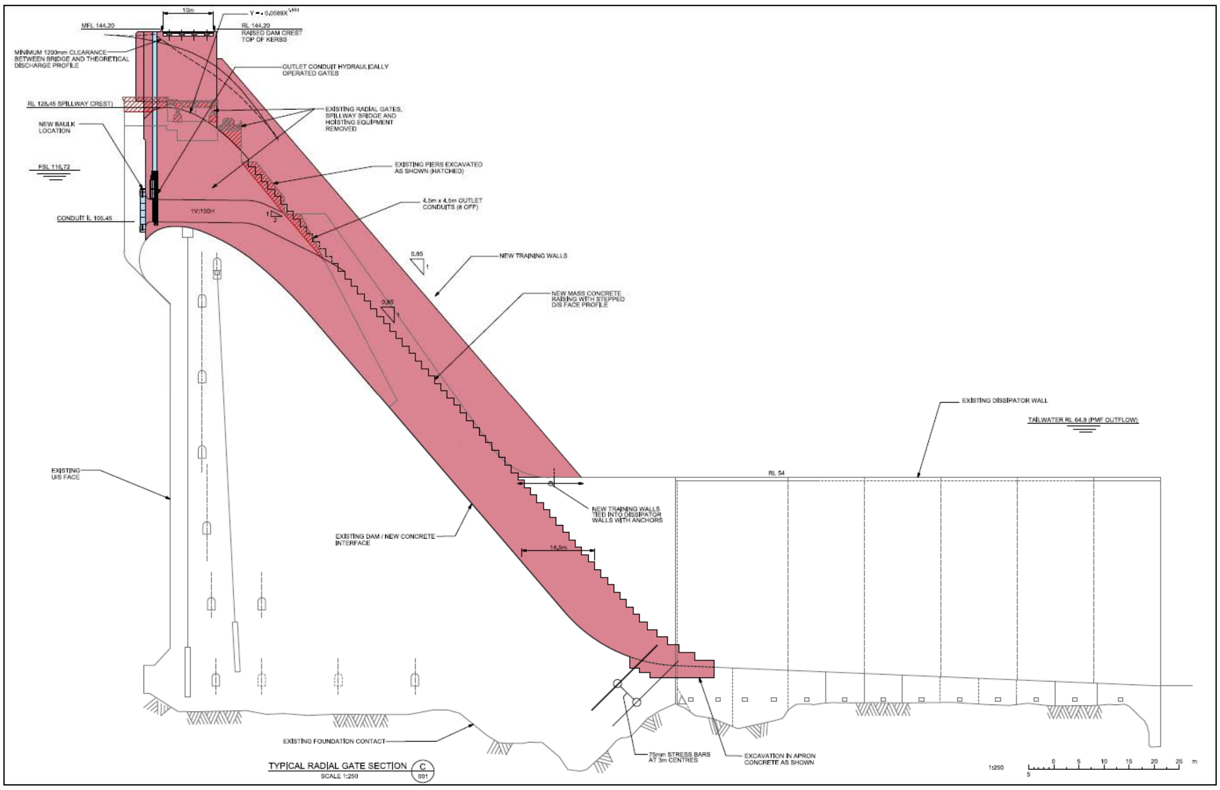



**Figure 6.5 Cross section of a 14-metre raised Warragamba Dam showing buttressed spillway with a stepped face and raised training wall**

*Source*: NSW Public Works for the Taskforce

### 6.2.2 Effects on flood behaviour

The effects of the 14 and 20 metre dam raising options on flood behaviour were tested using the Monte Carlo simulated flood events.

#### *Downstream peak flood levels*

Raising the wall of Warragamba Dam creates airspace in which flood inflows can temporarily be held. This significantly reduces the magnitude and frequency of downstream floods. No other flood mitigation infrastructure options provide the same quantum of benefits (**Figure 4.3** and **Figure 4.4**). Peak flood level reductions at Wallacia, Penrith, North Richmond, Windsor and Wisemans Ferry are shown in **Table 6.3**.

The results are summarised as follows:

- raising Warragamba Dam wall by 14 metres:
    - for Wallacia, reductions of more than 2.0 metres for floods rarer than the 1 in 20 chance per year flood, including a reduction of more than 6.0 metres for the 1 in 5,000 chance per year flood
    - for Penrith, reductions of more than 2.0 metres (up to 4.8 metres) for floods up to and including the 1 in 200 chance per year flood
    - for North Richmond and Windsor, reductions of more than 2.0 metres (up to 4.1 metres) for events up to and including the 1 in 5,000 chance per year flood
    - for Wisemans Ferry, reductions of about 0.5 to 1.0 metre for all modelled floods
- raising Warragamba Dam wall by 20 metres:
    - for Wallacia, reductions of more than 2.0 metres for floods rarer than the 1 in 20 chance per year flood, including a reduction of more than 10.0 metres for the 1 in 5,000 chance per year flood
    - for Penrith, reductions of more than 2.0 metres for floods up to and including the 1 in 5,000 chance per year flood (and exceeding 5.0 metres for floods between 1 in 50 and 1 in 200 chance per year)
    - for North Richmond and Windsor, reductions of more than 2.0 metres for all modelled events including the PMF (up to 4.6 metres for the 1 in 100 and 1 in 200 chance per year floods at Windsor)
    - for Wisemans Ferry, reductions of about 0.5 to 1.0 metre for most modelled floods.

Raising Warragamba Dam by 20 metres provides more flood mitigation benefit than raising the dam by 14 metres due to the increased capacity to temporarily store flood inflows. This additional storage only comes into play for events rarer than about a 1 in 50 chance per year flood.

The 14-metre dam raising option was modelled to change the frequency of flooding reaching the current 1 in 100 chance per year flood level (17.3 m AHD) at Windsor to a 1 in 580 chance per year event. The level of flooding experienced in the 1867 flood (similar to a 1 in 500 chance per year event) would be mitigated to a frequency of nearly a 1 in 2,000 chance per year event at Windsor. If the Warragamba Dam wall raising project proceeds, it will be important to maintain its risk-reducing benefits. This means that areas subject to current flood-related development controls based on the 1 in 100 chance per year flood level would need to continue to be subject to controls following dam raising (see **Section 9.1.1**).

Post flood release strategies can have some effect on downstream peak flood levels. **Figure 6.6** and **Figure 6.7** relate peak flood levels to frequency, for the 14-metre dam raising and the three assessed post flood release options, for Penrith and Windsor respectively. All three options show improvement from the existing case except for a high post flood release rate of 230 GL/d for very small floods (up to about a 1 in 3 chance per year). A 230 GL/d release rate would produce higher flood levels than moderate or low release rates, for floods smaller than about a 1 in 50 chance per year event.

Taskforce modelling of the 14-metre and 20-metre dam raising options with a slotted spillway showed that, in some events, the slotted spillway produces higher downstream flood levels than the gated option.

### *Downstream flood duration*

Flood inflows temporarily stored in the airspace would need to be released to restore the airspace ready for any subsequent flood event. The downstream flood duration is sensitive to which post flood release strategy is implemented.

The time that floodwaters exceeded 10 m AHD at Windsor was assessed using the Monte Carlo suite of 19,500 possible floods. This level was selected as an indicator of the upper end of flooding events that could be exacerbated through post flood releases. Land below 10 m AHD at Windsor is primarily land zoned for agricultural and recreational uses, without significant residential development.

For dam raising (either 14 or 20 metres) and a high release rate of 230 GL/d:

- most floods (64%) would no longer reach a level of 10 m AHD at Windsor
- about 23% of floods would have a shorter duration above 10 m AHD
- about 13% of floods would have a longer duration above 10 m AHD.

For dam raising (either 14 or 20 metres) and a moderate release rate of 100 GL/d:

- most floods (71%) would no longer reach a level of 10 m AHD at Windsor
- about 28% of floods would have a shorter duration above 10 m AHD
- fewer than 1% of floods would have a longer duration above 10 m AHD.

The optimisation of post flood releases will be developed as part of the Warragamba Dam Raising Environmental Impact Statement and subject to public consultation.

**Table 6.3 Impacts of Warragamba Dam raising options on downstream flood levels**

| Flood event (chance of occurrence per year) | Wallacia | | | Penrith | | | North Richmond | | | Windsor | | | Wisemans Ferry | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Base case (m AHD) | Raise WD by 14m (Difference in m) | Raise WD by 20m (Difference in m) | Base case (m AHD) | Raise WD by 14m (Difference in m) | Raise WD by 20m (Difference in m) | Base case (m AHD) | Raise WD by 14m (Difference in m) | Raise WD by 20m (Difference in m) | Base case (m AHD) | Raise WD by 14m (Difference in m) | Raise WD by 20m (Difference in m) | Base case (m AHD) | Raise WD by 14m (Difference in m) | Raise WD by 20m (Difference in m) |
| 1 in 5 | 35.2 | -0.1 | -0.1 | 19.9 | -2.2 | -2.2 | 11.2 | -3.1 | -3.1 | 9.4 | -2.5 | -2.6 | 1.2 | -0.4 | -0.4 |
| 1 in 10 | 37.3 | -0.2 | -0.2 | 21.6 | -3.3 | -3.3 | 13.6 | -3.8 | -3.8 | 11.6 | -3.1 | -3.1 | 2.4 | -0.6 | -0.6 |
| 1 in 20 | 39.5 | -0.7 | -0.7 | 23.4 | -4.5 | -4.5 | 15.3 | -4.1 | -4.2 | 13.5 | -3.6 | -3.6 | 3.8 | -0.8 | -0.8 |
| 1 in 50 | 42.6 | -2.0 | -2.0 | 24.9 | -4.8 | -5.2 | 16.5 | -3.2 | -3.7 | 16.0 | -3.9 | -4.4 | 5.4 | -0.8 | -0.8 |
| 1 in 100 | 44.6 | -2.7 | -2.9 | 25.9 | -3.9 | -5.5 | 17.5 | -2.7 | -3.8 | 17.2 | -3.7 | -4.6 | 6.5 | -0.7 | -0.8 |
| 1 in 200 | 46.3 | -3.1 | -3.5 | 26.5 | -2.8 | -5.5 | 18.4 | -2.5 | -3.8 | 18.2 | -3.2 | -4.6 | 7.5 | -0.5 | -0.6 |
| 1 in 500 | 48.7 | -3.4 | -4.6 | 27.1 | -1.4 | -4.9 | 19.7 | -2.5 | -3.9 | 19.5 | -2.6 | -4.3 | 9.1 | -0.9 | -1.0 |
| 1 in 1,000 | 50.4 | -3.4 | -5.2 | 27.5 | -0.9 | -3.8 | 20.6 | -2.3 | -3.9 | 20.4 | -2.3 | -4.0 | 10.2 | -0.8 | -0.9 |
| 1 in 2,000 | 54.4 | -4.9 | -8.2 | 28.4 | -1.1 | -2.8 | 21.7 | -2.1 | -4.0 | 21.5 | -2.1 | -4.0 | 11.2 | -0.8 | -0.9 |
| 1 in 5,000 | 58.6 | -6.2 | -10.4 | 29.5 | -1.7 | -2.7 | 22.7 | -2.1 | -3.8 | 22.6 | -2.1 | -3.8 | 12.5 | -0.7 | -0.9 |
| PMF | 62.3 | -2.0 | -4.2 | 31.5 | -0.9 | -1.8 | 26.3 | -1.3 | -2.4 | 26.2 | -1.3 | -2.4 | 14.6 | -1.2 | -2.3 |

**LEGEND**

Difference in m

- > +0.1
- -0.25 to -1.0
- -1.0 to -2.0
- -2.0 to -11.0

Critical range for flood risk

*Source:* WMAwater for the Taskforce (2016 model)

*Note:* All scenarios allow for probabilistic drawdown; base case is for H14 protocol; all dam raising scenarios allow for post flood release of 100 GL/d from FMZ; PMF = probable maximum flood

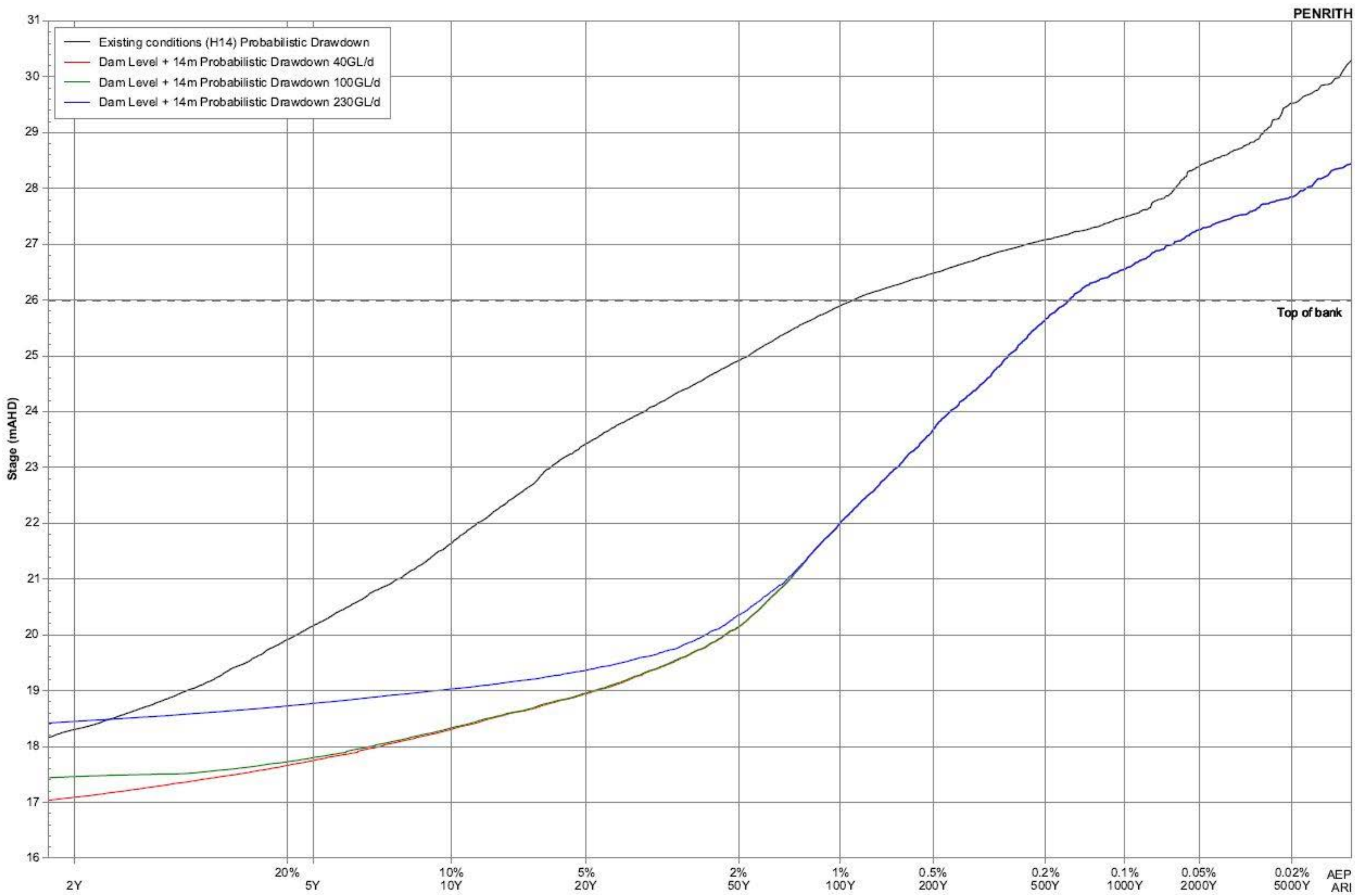



**Figure 6.6 Stage-frequency curve for 14-metre dam raising and different post flood release strategies, Penrith**

*Source:* WMAwater for the Taskforce (2016 model)

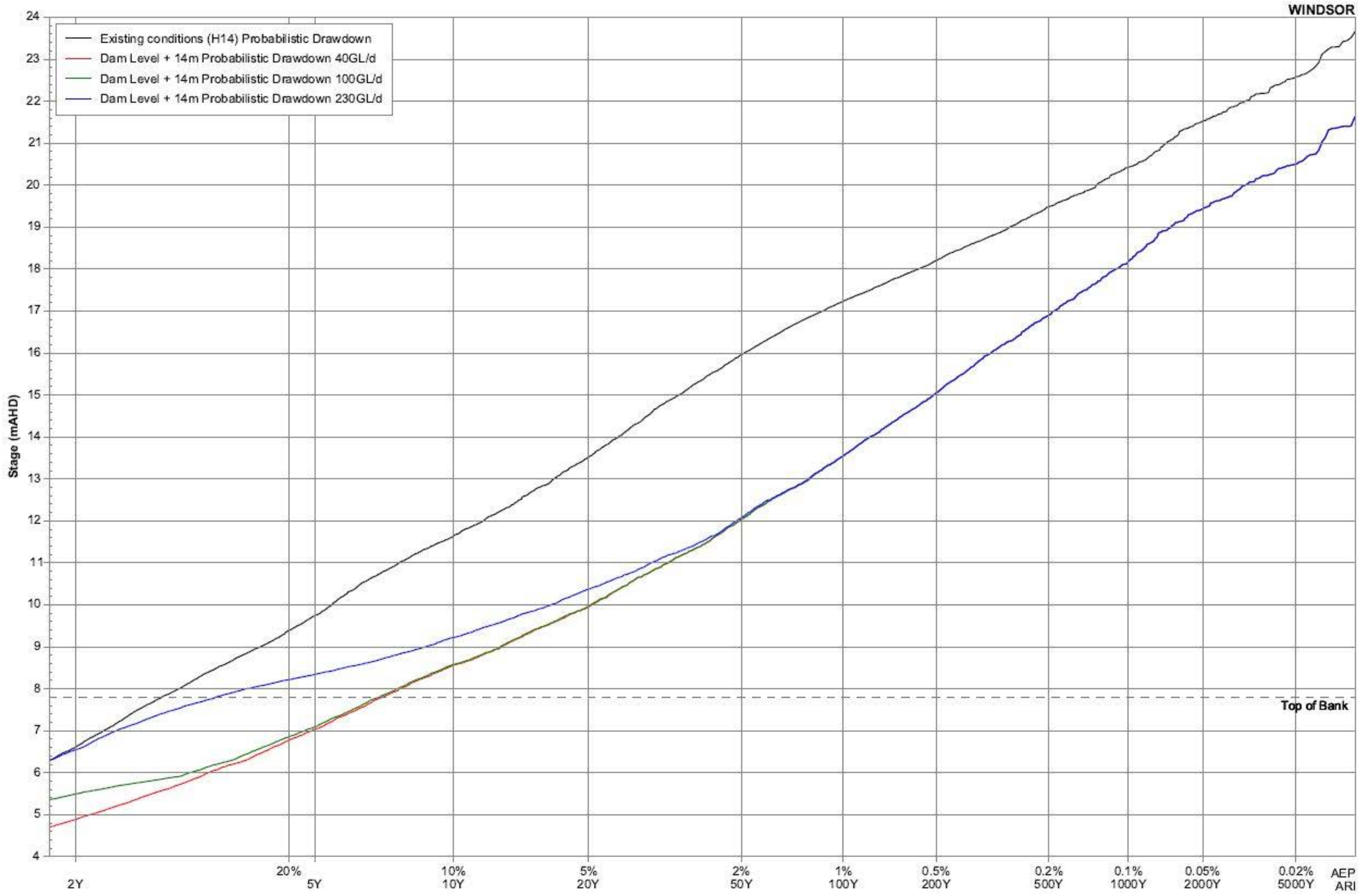



**Figure 6.7 Stage-frequency curve for 14-metre dam raising and different post flood release strategies, Windsor**

*Source:* WMAwater for the Taskforce (2016 model)

### *Upstream peak levels and duration*

Areas upstream of Warragamba Dam are inundated up to 13.7 metres above FSL now during floods.[11] The peak levels and duration of additional temporary inundation upstream of a raised Warragamba Dam would be a function of:

- the height of the spillway
- the size of inflows to the dam
- the rate at which the flood inflows into the dam are drawn down through the outlet conduits.

The Taskforce commissioned modelling of various combinations of flood frequencies, dam raisings, spillway heights and release strategies to assess the depth and duration of upstream inundation. This is an important consideration to assess the impact on endangered ecological communities (EECs) located within the footprint of a raised dam.

The EECs upstream of Warragamba Dam are situated on localised, sheltered river flats between hills, rather than the large open floodplains that comprised the majority of the original habitat. One community is known as the Hinterland River-flat Eucalypt Forest, which is a component of *River-Flat Eucalypt Forest on Coastal Floodplains of the NSW North Coast, Sydney Basin and South East Corner Bioregions*. The dominant vegetation communities have established in response to the prevailing climatic conditions and periodic disturbance events such as flood, drought and bushfire.

The largest known remnant population of the vulnerable species Camden White Gum (*E. benthamii*) is located in the Kedumba Valley, with approximately 6,550 trees (Corringham, 1988). While other species within the EEC will have varied ecological drivers for their recruitment, establishment and regeneration, the Camden White Gum was selected as a suitable indicator species of flood tolerance given its restricted distribution and recognised importance. The 1995 EIS adopted a 14-day inundation tolerance for Camden White Gums based on laboratory experiments for germination success. The Taskforce adopted this as the best available information, noting that this would need to be further assessed for the Warragamba Dam Raising Environmental Impact Statement.

Preliminary surveys conducted by the Taskforce found that the lowest observed stand of Camden White Gum is located at 120 m AHD. Some Camden White Gums may exist below this level in other locations. However, the large population in the Kedumba Valley exists above this level. This will be confirmed by more detailed field work as part of the Warragamba Dam raising environmental impact assessment, which will refine understanding of the spatial distribution of this species. For the purpose of the Taskforce assessment, 120 m AHD was adopted as an initial threshold to measure changes in temporary inundation of this species, compared to flooding that can already occur.

The preliminary results of the flood modelling show that even with the existing dam, inundation to 120 m AHD will be exceeded on rare occasions for a few days. This level would be exceeded more frequently with a 14-metre raised dam, but the duration of inundation would not exceed the 14-day threshold. These are preliminary estimates and will be refined as part of the dam design

[11] 13.7 metres is for PMF, which is subject to refinement to comply with *Australian Rainfall and Runoff 2016* (Ball et al., 2016)

and operation being developed for the Warragamba Dam Raising Environmental Impact Statement.

Another way of assessing comparative changes in upstream temporary inundation is to consider average annual days of inundation above particular levels. Average days per year is based on the whole range of 19,500 Monte Carlo-modelled floods. It does not mean that it will be inundated by this number of days every year, since floods are random events. There may be many years and several decades without a flood, followed by years and decades with multiple floods.

With the current dam and operating rules, Warragamba Dam FSL is exceeded about 0.5 days per year on average. With a 14-metre dam raising, and a variable post flood release regime, this would rise to about 4.2 days per year on average – an increase of 3.7 days per year on average. With a 14-metre dam raising, the number of days above 120 m AHD would increase by 1.2 days a year on average.

This initial assessment of upstream inundation shows that raising Warragamba Dam by 14 metres, with outflows of 100 GL/d or higher, is able to empty the FMZ within a 14-day period.

While a 14-day threshold was adopted as an environmental objective for upstream inundation, a second objective was to empty the FMZ within a reasonable timeframe to mitigate any potential subsequent event. Ten days was selected as the threshold for emptying the FMZ, as this is the limit of current forecasting capacities for flood-producing weather systems.

The final operating release rules would be more complex and determined by the final spillway configuration, peak spill rate, inflows to the dam, flow in the river and forecasts for any subsequent event to achieve a target of emptying the FMZ within 10 days.

The assessment found that meeting the above objectives for a 20-metre dam raising would be more difficult to achieve without those releases causing significant downstream impacts, given the larger volume of water to empty.

### *6.2.3 Effects on evacuation timing*

Raising Warragamba Dam to provide airspace for temporarily capturing flood inflows reduces and delays downstream flooding, with benefits for evacuation. Every flood has a different timing even if the depth is the same. Flood modelling considered 19,500 events using Monte Carlo simulations. The impacts on evacuation timing were assessed by considering how the option would affect the probability of key evacuation thresholds being reached, as listed in the Hawkesbury Nepean Flood Plan (NSW SES, 2015).

With a 14-metre dam raising, about 80-84% of modelled events would no longer cut evacuation routes from McGraths Hill, Pitt Town and Windsor, and the time at which the routes would be cut for floods still reaching those levels would be significantly delayed (see **Figure 4.8** and **Figure 4.9**).

With a 20-metre dam raising, about 89-94% of modelled events would no longer cut evacuation routes from McGraths Hill, Pitt Town and Windsor, and the time at which the routes would be cut for floods still reaching those levels would be significantly delayed (see **Figure 4.8** and **Figure 4.9**).

The benefits of dam raising for reduced and delayed inundation of these evacuation routes are not sensitive to the rate of post flood releases as these roads are cut when the dam is spilling, not during the managed post flood releases.

**Figure 4.8** and **Figure 4.9** show that dam raising performs best of all the assessed dam options at reducing and delaying floods that cut evacuation routes.

### *6.2.4 Economic assessment*

The Centre for International Economics (CIE) assessed the benefits and costs of raising Warragamba Dam by either 14 metres or 20 metres.

#### *Benefits*

The benefits are described in **Table 6.4**. Raising Warragamba Dam by 20 metres would create a larger FMZ so has potential to reduce peak flood levels and associated damages more than raising Warragamba Dam by 14 metres.

**Table 6.4 Discounted benefits of options to raise Warragamba Dam compared to base case**

| Benefit | Dam raising:<br>Post flood release: | WD +14m<br>100 GL/d | WD +20m<br>100 GL/d |
|---|---|---|---|
| | | $m | $m |
| **Residential direct damage avoided** | | 337 | 358 |
| **Residential indirect damage avoided** | | 17 | 18 |
| **Commercial and industrial direct damage avoided** | | 135 | 145 |
| **Commercial and industrial indirect damage avoided** | | 51 | 54 |
| **Avoided electricity damage** | | 15 | 16 |
| **Avoided other damages – roads, bridges, hospitals, etc** | | 119 | 124 |
| **Loss of life and injury avoided** | | 85 | 86 |
| **Other costs avoided** | | 9 | 9 |
| **TOTAL** | | **768** | **810** |

*Source*: CIE for the Taskforce

*Note:* 'Central case' assumptions applied including 7% discount rate and 100% response to evacuation order

#### *Costs*

The Taskforce progressed detailed feasibility costing for 14-metre and 20-metre dam wall raising options, including two different construction methods (mass concrete and hardfill). The costings included contingency for unforeseen or unquantified items representing 25% of the total cost (appropriate for this phase of the project). NSW Public Works cost estimates were compared to

MWH cost estimates. The costing methodology was reviewed by construction contractor, John Holland Group, the Taskforce and its experts.

The preferred construction method of mass concrete buttressing was estimated to cost $692 million for a 14-metre raising and $865 million for a 20-metre raising (2015 dollars).

The discounted costs of the dam raising options are set out in **Table 6.5**, assuming construction commenced in 2016 and took four to five years to complete. It is noted that CIE did not account for environmental costs, which will be factored into costs as part of the Environmental Impact Statement and full business case.

**Table 6.5 Discounted costs of options to raise Warragamba Dam compared to base case**

| Cost | Dam raising: Post flood release: | WD +14m 100 GL/d | WD +20m 100 GL/d |
|---|---|---|---|
| | | $m | $m |
| **Capital and operating costs** | | 592 | 738 |
| **Water quality impacts** | | 11 | 11 |
| **Water security impacts** | | 0 | 0 |
| **TOTAL** | | **603** | **749** |

*Source*: CIE for the Taskforce

*Note:* 'Central case' assumptions applied including 7% discount rate. The cost of addressing water quality impacts relates to improvements for North Richmond water supply. There are no costs for water security since the dam raising options maintain current FSL in Warragamba Dam.

### *Benefit-cost*

For the option to raise Warragamba Dam by 14 metres, comparing the benefits to the costs shows that there is a net benefit of $165 million. The net benefit is retained under low and high assumptions (see **Section 4.3.3**).

For the option to raise Warragamba Dam by 20 metres, comparing the benefits to the costs shows that there is a net benefit of $61 million. The net benefit is retained under low and high assumptions.

Based on the economic assessment, the 14-metre dam raising is preferred to the 20-metre dam raising because it has higher net benefits under the 'central case' conservative assumptions and using a discount rate of 7% per year.

### *Impact on insurance premiums*

In 2015, the Insurance Council of Australia (ICA) conducted a preliminary analysis on the potential impact of dam raising options on insurance premiums. The Taskforce supplied baseline and (unidentified) options flood data to ICA, who completed the assessment in parallel with two insurers and a third actuarial resource. Each of these parties completed the analysis independently and these results reflect the median point derived from all four analytical outcomes.

The results of the assessment were expressed as average annual damages. This is a proxy for the flood 'technical premium' and is suitable to indicate the magnitude of potential changes as a result of mitigation, that may be possible from some insurers. The flood technical premium is typically inclusive of predicted repair and rebuild costs, temporary accommodation, post-event inflation and other direct economic costs arising from predicted flood damage. The flood technical premium is less than the retail flood premium ultimately offered to a customer.

The ICA analysis found that, for a 14-metre dam wall raising, there would be a 76% reduction in average annual damages (AAD) for the region and for a 20-metre dam there would be an 87% reduction in AAD for the region. This result is consistent with the economic assessment conducted for the Taskforce by CIE.

The ICA concluded that both options offer significant potential to reduce the insurance premiums for property owners who are currently exposed. They indicated that any reduction in flood risk at individual properties will be considered by insurers, and will typically result in reduced premiums.

The ICA also notes that, where effective flood mitigation has been implemented in other states, there have been significant reductions in insurance premiums.

### *6.2.5 Social, environmental and cultural heritage impact*

BMT WBM Pty Ltd prepared a preliminary socio-economic, environmental and cultural heritage (SECH) impact assessment for the Taskforce for the option of raising Warragamba Dam to create a FMZ. The assessment focussed on risks for the 20-metre dam raising option, since this was expected to produce the greater impacts. A residual risk rating was also provided for the 14-metre dam raising option. Impacts were considered for three sites: at-dam, upstream, and downstream.

A more detailed investigation is being undertaken for the Warragamba Dam Raising Environmental Impact Statement.

#### *At-dam*

For a 20-metre dam raising, the preliminary assessment identified high risks at the dam site, even after implementation of potential mitigation measures, for:

- European heritage, since Warragamba Dam is heritage listed and is one of the best examples of a steep concrete dam wall in Australia. As part of the dam raising, the concrete buttressing and spillway construction works would require modification and/or loss of some high value heritage items including the main dam wall, apron drainage system, crest gates, dam outlets, hydro-electric power station and part of the valve house.
- visual landscape (built environment), associated with the changed appearance of Warragamba Dam wall
- amenity during the construction period, related to possible increased traffic, noise and air quality impacts at Warragamba township
- recreational uses during the construction period, such as possible interruptions to self-guided walks, school tours, lookouts and picnic activities.

For the at-dam impacts, the residual risk rating for a 14-metre dam raising would be similar.

Water security could be affected during construction of a raised dam, since the FSL may need to be lowered. Construction is expected to take up to four years. The reduced FSL would then need to be managed until the dam returns to normal FSL, which may take several years if there is an extended dry period. During the period of reduced storage, various measures would need to be considered including additional supply from the Shoalhaven and possibly raising the trigger for operating the desalination plant, and management of demand.

### *Upstream*

Dam raising for flood mitigation would incrementally increase the extent, depth and duration of temporary inundation compared to current upstream flooding impacts (**Section 6.2.2**). The significance of incremental temporary flood impact is not well understood and is difficult to quantify.

The preliminary assessment estimated that additional temporary inundation of small parts of the Greater Blue Mountains World Heritage Area and wilderness areas as a result of raising Warragamba Dam for flood mitigation could have a high impact in those areas upstream.

*Flora and fauna*

The residual risk rating for terrestrial flora and fauna was rated medium. This preliminary assessment found that temporary inundation upstream could impact the vulnerable listed *Eucalyptus benthamii* (Camden White Gum) and the Endangered Ecological Community *River-Flat Eucalypt Forest on Coastal Floodplains of the NSW North Coast, Sydney Basin and South East Corner Bioregions* (River-flat Eucalypt Forest). Although these communities rely on flood disturbance for their recruitment and distribution, there is a limited understanding of the flood tolerance levels for individual species and communities. Each species has different ecophysiological requirements and resilience to flood disturbance events. Resilience of critical biodiversity values will depend on:

- the antecedent conditions (long term climatic conditions)
- the frequency of the natural disturbance events such as floods and bushfires
- individual species response/regeneration strategies and recovery period.

These aspects are being further investigated as part of the Warragamba Dam raising environmental impact assessment and will be documented in the EIS.

*Cultural heritage*

Areas upstream of Warragamba Dam are subject to an indigenous land use agreement (ILUA) between the Gundungarra traditional owners and various NSW Government agencies, including WaterNSW. These lands and waters include Lake Burragorang and the Warragamba Special Area. The ILUA Consultative Committee is a key instrument to support the management of these lands and waters.

The preliminary impact assessment of Aboriginal cultural heritage values was based on previous studies and a search of the Office of Environment and Heritage's Aboriginal Heritage Information Management System (AHIMS).

Based on the desktop assessment, Aboriginal sites were identified in close proximity to Lake Burragorang. Depending on the storage level, some sites are located within the existing reservoir. Others are situated along the fringes of the lake.

Both dam wall raising options would temporarily inundate Aboriginal sites above FSL during large and infrequent flood events when the FMZ is filled. Those sites located close to major rivers and creeks draining into Lake Burragorang (and where steep terrain is not present) could be most at risk of increased temporary inundation above what happens now.

The Warragamba Dam Raising Environmental Impact Statement (EIS) will include a full Aboriginal cultural heritage assessment and consultation in accordance with the Office of Environment and Heritage's Guidelines, *Aboriginal Cultural Heritage Consultation Requirements for Proponents 2010*. The guidelines establish the requirements for consultation with registered Aboriginal parties as part of the heritage assessment process to determine potential impacts of proposed activities on Aboriginal objects and places, and to inform decision making.

Based on preliminary flood modelling, except for extremely rare events, European heritage values are not expected to be affected by the incremental increases in temporary inundation associated with the proposed dam raising. All potential impacts on heritage values will be investigated and reported in the Warragamba Dam Raising EIS.

#### *Downstream*

Downstream impacts of dam raising are associated with the changed flood regime, including reduced frequency and magnitude of major floods and an increased duration of low-level inundation as the FMZ is evacuated as the flood is falling.

There is a trade-off between the size of post flood releases and the magnitude and duration of low-level downstream flooding. A high release rate will lead to a shorter duration of downstream flooding than a lower release rate, but the downstream inundation extents and depths would be greater. A low release rate may prolong downstream flooding but the intensity of downstream impact is expected to be less. If the release rate is so slow that the mitigation storage is not empty when a subsequent flood event occurs, the inundation from the second event could be increased.

The timing and volume of released floodwaters impacts the duration and extent of temporary inundation upstream and downstream of the dam. There is a trade-off between minimising the additional temporary inundation of the endangered ecological communities, World Heritage Area, National Park and Aboriginal cultural heritage values upstream of the dam wall, and minimising the impact of flood releases downstream on the river-dependent users and the lowlands adjacent to the river.

The river downstream of Warragamba River in the lower Nepean and Hawkesbury rivers has been significantly modified with the building of Penrith Weir pool and extensive sand and gravel extraction from the river and floodplain. Sections of the river are in disequilibrium, that is, the river is adjusting to the reduced flows from the major water supply dams and changed channel morphology from sand and gravel extraction over 50 to 100 years. Areas along the Hawkesbury-Nepean River already experience river bank erosion under current conditions. The preliminary impact assessment rated downstream geomorphic impacts such as river bank erosion as a medium risk. Where post flood releases prolong low-level downstream flooding, this could exacerbate current river bank erosion. Large floods are important for geomorphic functions such as resetting the erosional and depositional environment. Further work is needed to ascertain the impacts of altered flow on river bank stability.

Releases from a FMZ could affect water quality (and supply), particularly with increased turbidity in water drawn from the Hawkesbury River supplying the North Richmond Water Filtration Plant (see **Section 5.2.7**).

**Box 6.1 Ongoing assessment of social, environmental and cultural heritage impacts for proposal to raise Warragamba Dam for downstream flood mitigation**

In response to the Flood Strategy, WaterNSW, as the owner and operator of Warragamba Dam, is preparing a comprehensive environmental impact statement (EIS) and detailed concept designs for the proposal to raise the dam for flood mitigation. The project is considered state significant infrastructure under NSW legislation. The NSW Secretary of the Department of Planning and Environment has issued a detailed set of assessment requirements.

Modelling, surveys, technical studies and analysis are underway to inform the EIS, including Aboriginal Cultural Heritage Assessment in consultation with traditional owners, and detailed flora and fauna surveys and assessments. Community and stakeholder consultation is an important part of the process.

The proposal is also considered a ‘controlled action’ by the Australian Government under the Environment Protection and Biodiversity Conservation Act 1999, and will be assessed in relation to matters of World Heritage, National Heritage and threatened species and communities.

The EIS for the Warragamba Dam Raising proposal is scheduled to be exhibited in 2019. Subject to environmental and planning approvals, a final business case will be prepared for consideration by the NSW Government in 2020. If approved, it is estimated construction would take approximately four years.

### *6.2.6 Findings – raising Warragamba Dam wall*

Multiple lines of evidence were used to evaluate options to reduce existing and future flood risk in the Hawkesbury-Nepean Valley. There is no single or simple solution to the significant flood risk in the valley. Both the 2013 Review and Taskforce recognised that a mix of measures was required, with nine complementary outcomes included in the Flood Strategy (INSW, 2017). Raising Warragamba Dam wall by around 14 metres was identified as the key infrastructure flood mitigation measure in the Flood Strategy to reduce the significant existing risk. Dam raising would reduce flood risk by creating airspace in the dam to temporarily hold back and slowly release flood inflows coming from the Warragamba River Catchment. The evidence for this recommendation is summarised below.

#### *Effective flood control*

As discussed in **Section 4.3.1**, the Warragamba Catchment provides the greatest contribution of high flows causing significant flooding in the Hawkesbury-Nepean River system. Given the high proportion of the Warragamba Catchment to the total catchment areas to Penrith (80%) and Windsor (70%), the flood mitigation options that offer the greatest regional flood mitigation benefits are those controlling floodwater from the Warragamba Catchment.

Raising Warragamba Dam controls the largest contributor to flood risk. The narrow sandstone gorge at Warragamba Dam provides efficient flood mitigation as it is a control point for the majority of flows during large flood events. Although flooding can be generated from the Upper Nepean River, Grose River and South Creek catchments, without inflows from Warragamba Dam the chance of a flood reaching or exceeding the current 1 in 100 chance per year flood level at Windsor is highly unlikely.

### *Substantial airspace for flood detention*

As shown in **Figure 4.5**, the location of Warragamba Dam in a deep V-shaped sandstone gorge means that a disproportionate volume of water is stored in the higher part of the dam. This is one reason why dam raising to create airspace above the current FSL outperforms lowering the current FSL to create airspace.

The volume of airspace created by raising the dam by 14 metres is about 30% more than the volume created by lowering FSL by 12 metres. To fully utilise a FMZ formed by lowering FSL by 12 metres, the current dam infrastructure would also need to be significantly modified, at substantial cost. Lowering FSL by 12 metres would also involve the loss of 39% of Warragamba Dam's water supply storage, which would be very costly to make up.

### *The 'Goldilocks' Principle*

Rare to extreme flood events have a low probability but very high social and economic consequences, particularly in this valley. An optimal solution is one that balances multiple objectives:

- provide regional flood risk reduction for floods that pose greatest risk to lives, homes, businesses and critical assets
- empty the FMZ efficiently to accommodate the possibility of a second or subsequent flood
- minimise the upstream impacts of temporary flood inundation above what already happens
- minimise the downstream impacts of post flood releases
- cost effectiveness.

No dam height will entirely eliminate the existing flood risk in this valley; however, dam raising will significantly reduce this risk.

The 'Goldilocks' Principle was applied to optimising the height of dam raising to meet the objectives, that is, the created airspace should be large enough to achieve regional flood risk reduction and cost effectiveness but small enough to minimise incremental inundation impacts. The optimal height was considered between 14 and 20 metres. While a larger dam raising provides greater regional flood mitigation benefits downstream, it presents greater challenges for minimising impacts.

The modelling also indicated diminishing returns with increasing dam height. It becomes progressively more difficult to mitigate floods above 1 in 2,000 chance per year without great additional expense. For these reasons, raising Warragamba Dam by about 14 metres was preferred to the 20-metre option. The 14-metre dam raising was included in the Flood Strategy for detailed investigation in the Warragamba Dam Raising Environmental Impact Statement.

## 6.3 Combined option

### *6.3.1 Description of option*

A combined option of raising Warragamba Dam by 14 metres and lowering the existing Warragamba Dam FSL by five metres was assessed.

### *6.3.2 Effects on flood behaviour*

#### *Downstream peak flood levels*

**Table 6.6** presents changes in downstream peak flood levels for the combined option. The combined option achieves slightly larger reductions for the 1 in 50 chance per year flood and rarer events at Penrith, North Richmond and Windsor, when compared to the 14-metre dam raising. However, the reductions are not as large as those that would be achieved with a 20-metre dam raising.

#### *Downstream flood duration*

The combined option reduces inundation above 10 m AHD at Windsor Bridge similar to a 20-metre dam raising (see **Section 6.2.2**).

### *6.3.3 Evacuation timing*

If Warragamba Dam is raised by 14 metres and FSL is lowered by five metres, about 86-90% of modelled events would no longer cut evacuation routes from McGraths Hill, Pitt Town and Windsor. The remaining floods that would still reach the evacuation routes would be significantly delayed (see **Figure 4.8** and **Figure 4.9**). The benefits of this option fall between the 14- and 20-metre dam raising options.

### *6.3.4 Economic assessment*

Discounted benefits for this combined option were calculated at $734 million, but did not include the monetised estimate associated with avoided loss of life.

The cost was estimated at $854 million (discounted, 2015 dollars). This is more expensive than raising the wall alone due to the costs for water security and water quality associated with options to lower FSL, plus some additional capital/operating costs.

The combined option yields a net cost of $120 million, whereas the standalone options of lowering FSL by five metres, or raising the dam by 14 metres, or raising the dam by 20 metres yield net benefits (**Figure 4.11**).

**Table 6.6 Impacts of combined 14-metre raising of Warragamba Dam and five-metre lowering of FSL on downstream flood levels**

| Flood event (chance of occurrence per year) | Wallacia | | Penrith | | North Richmond | | Windsor | | Wisemans Ferry | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Base case (m AHD) | Raise WD by 14m and -5m FSL (Difference in m) | Base case (m AHD) | Raise WD by 14m and -5m FSL (Difference in m) | Base case (m AHD) | Raise WD by 14m and -5m FSL (Difference in m) | Base case (m AHD) | Raise WD by 14m and -5m FSL (Difference in m) | Base case (m AHD) | Raise WD by 14m and -5m FSL (Difference in m) |
| 1 in 5 | 35.2 | -0.1 | 19.9 | -2.2 | 11.2 | -3.1 | 9.4 | -2.5 | 1.2 | -0.4 |
| 1 in 10 | 37.3 | -0.2 | 21.6 | -3.3 | 13.6 | -3.8 | 11.6 | -3.1 | 2.4 | -0.6 |
| 1 in 20 | 39.5 | -0.7 | 23.4 | -4.5 | 15.3 | -4.2 | 13.5 | -3.6 | 3.8 | -0.8 |
| 1 in 50 | 42.6 | -2.0 | 24.9 | -5.1 | 16.5 | -3.6 | 16.0 | -4.3 | 5.4 | -0.8 |
| 1 in 100 | 44.6 | -2.8 | 25.9 | -5.3 | 17.5 | -3.5 | 17.2 | -4.4 | 6.5 | -0.8 |
| 1 in 200 | 46.3 | -3.4 | 26.5 | -4.6 | 18.4 | -3.3 | 18.2 | -4.1 | 7.5 | -0.6 |
| 1 in 500 | 48.7 | -4.2 | 27.1 | -2.8 | 19.7 | -3.2 | 19.5 | -3.5 | 9.1 | -0.9 |
| 1 in 1,000 | 50.4 | -4.6 | 27.5 | -1.7 | 20.6 | -3.0 | 20.4 | -3.1 | 10.2 | -0.8 |
| 1 in 2,000 | 54.4 | -6.5 | 28.4 | -1.5 | 21.7 | -2.9 | 21.5 | -2.9 | 11.2 | -0.8 |
| 1 in 5,000 | 58.6 | -7.9 | 29.5 | -2.0 | 22.7 | -2.7 | 22.6 | -2.7 | 12.5 | -0.9 |
| PMF | 62.3 | -2.5 | 31.5 | -1.2 | 26.3 | -1.6 | 26.2 | -1.7 | 14.6 | -1.6 |

**LEGEND**

Difference in m

- > +0.1
- -0.25 to -1.0
- -1.0 to -2.0
- -2.0 to -8.0

Critical range for flood risk

*Source:* WMAwater for the Taskforce (2016 model)

*Note:* All scenarios allow for probabilistic drawdown; base case is for H14 protocol; all dam raising scenarios allow for post flood release of 100 GL/d from FMZ; PMF = probable maximum flood

### 6.3.5 Findings – combined option

A combination of raising Warragamba Dam by 14 metres and lowering FSL by five metres does result in a greater reduction of flood levels downstream than raising the dam by 14 metres alone. However, it does not reach the reductions achieved by raising the dam by 20 metres. Also, the increased costs due to water security and water quality, and the only marginally increased benefits, mean that there is a net cost for the combined option. This is the main reason why this option was not supported.

## 6.4 Summary of options to build new flood mitigation dams or raise Warragamba Dam

Each flood mitigation option involving new infrastructure to provide flood mitigation is summarised below.

### 6.4.1 New flood mitigation dams

New flood mitigation dams upstream of Warragamba Dam were considered as part of the 2013 Review. No sites were found to be as effective in mitigating floods as the site of Warragamba Dam (**Table 4.3**). Also, it was considered that there would be significant economic costs and major environmental impacts for constructing new dams and associated infrastructure upstream of Warragamba Dam.

A new flood mitigation dam on the Upper Nepean River upstream of Bents Basin was also considered as part of the 2013 Review. Since this does not mitigate floods from the predominant Warragamba Catchment, its ability to reduce peak flood levels downstream is reduced in comparison to options involving raising of Warragamba Dam wall (**Table 4.3**). A dam at this site could also make flooding worse at Camden. Also, the footprint of the dam would cover much private land, acquisition of which would be too costly.

### 6.4.2 Warragamba Dam wall raising

No options provide the same degree of reduction of downstream peak flood levels as raising Warragamba Dam wall, particularly within the critical range for flood damage and risk to life reduction of 1 in 50 to 1 in 1,000 chance per year. This is demonstrated for Penrith and Windsor in **Figure 4.3** and **Figure 4.4**.

Of all options investigated, dam raising provides the largest reductions to inundation of dwellings (**Figure 4.6**, **Figure 4.7**), the largest reductions and delays to inundation of regional evacuation routes (**Figure 4.8**, **Figure 4.9**), and the largest reduction in average annual damages (**Figure 4.10**, **Figure 4.12**, **Figure 4.13**).

Only dam raising and lowering FSL by five metres provide net benefits, that is, the benefits exceed the costs. But the option to lower FSL by five metres does not meet the key objective of providing significant benefits, within the critical range. Lowering FSL by 12 metres provides significantly less airspace than a 14-metre dam raising, so is less effective at mitigating rare floods. It is also more costly given the high costs for maintaining water security.

Of the two dam raising options considered, raising Warragamba Dam by 14 metres yields the highest net benefit (**Figure 4.11**). The volume of airspace created to temporarily capture floodwaters is well targeted to mitigating downstream flood peaks in the critical range for flood damages, and was judged to provide adequate delays to the peaks for evacuation of the critical low flood islands. Although a 20-metre dam raising provides larger downstream peak flood level reductions, the additional benefits do not offset the additional costs, so the net benefit is lower than for a 14-metre dam raising. Furthermore, the larger FMZ created by a 20-metre dam raising poses greater challenges to meet the objectives of:

- efficiently restoring airspace behind the dam in preparation for the next flood
- minimising upstream impacts associated with temporary, incremental inundation above the flooding that can occur now
- minimising downstream impacts.

### *6.4.3 Combined Warragamba Dam wall raising and lowering FSL*

Although the combined option to raise Warragamba Dam by 14 metres and lower FSL by five metres does result in increased reductions to downstream peak flood levels than a 14-metre dam raising in isolation, the increased benefits are not sufficient to offset the increased costs especially for water security. This combined option has a net cost (**Figure 4.11**).

### *6.4.4 Conclusion*

The Taskforce found that raising the Warragamba Dam wall by around 14 metres is the infrastructure option with the highest benefit. This would reduce flood risk by creating airspace in the dam to temporarily hold back and slowly release floodwaters coming from the Warragamba River Catchment.

Raising the Warragamba Dam wall would reduce average annual flood damages by 75%. It would reduce the flood damages for a 1 in 500 chance per year flood (similar to the 1867 flood) for current levels of urban development from $5 billion to $2 billion. In 2041, it would reduce flood damages for a 1 in 500 chance per year flood from $7 billion to $2 billion (INSW, 2017).

While raising the Warragamba Dam wall would make a significant difference to the existing flood risk in the valley, no combination of infrastructure options can eliminate the risk. Regardless of any infrastructure option, non-infrastructure options including risk-informed land use planning must be part of the solution for managing ongoing flood risk.

As outlined above, there is a range of social, environmental and cultural heritage impacts associated with the preferred dam raising proposal. These are being investigated in detail as part of the Warragamba Dam Raising environmental impact assessment and will be documented in the EIS for public review and comment.

# 7 Flood mitigation infrastructure options – downstream measures to enhance drainage or to protect communities

This chapter describes the evaluation of a subset of flood mitigation infrastructure options that involve either enhancing drainage from the valley, or protecting communities from flooding to mitigate downstream floods. These include:

- Currency Creek diversion channel
- Sackville diversion channels
- river dredging
- local structural works.

As described in **Appendix F**, as part of the 2013 Review, an assessment was conducted to shortlist the most viable non-Warragamba Dam infrastructure measures for more detailed assessment. Selected higher ranking options were subject to a pre-feasibility assessment as part of the Review.

The Taskforce approach was to assess these downstream flood mitigation options at the scale necessary to achieve significant mitigation for floods that impact evacuation risk to life as well as significant numbers of residential properties. In the Richmond/Windsor floodplain, these are floods with a minimum frequency of a 1 in 50 chance per year. In the Penrith floodplain, options would need to significantly mitigate at least a 1 in 100 chance per year event. If options could meet this objective, preliminary designs were prepared and the options were modelled to quantify the flood mitigation benefits for the full range of floods.

## 7.1 Currency Creek diversion channel

### 7.1.1 Description of option

The Currency Creek diversion channel option was reviewed in *Engineering Studies to Modify Flood Behaviour* (WMA, 1997) and further considered in the *Hawkesbury Floodplain Risk Management Study & Plan* (Bewsher Consulting, 2012). The option was assessed during the 2013 Review, and was investigated in detail under the program of the Taskforce.

Just downstream of Wilberforce, floodwaters from the Hawkesbury River naturally spill over a saddle into Chain of Ponds, which is a tributary of Currency Creek joining the Hawkesbury River near the Sackville Ferry. This natural spilling of floodwaters occurs when floods reach or exceed a level of about 19.0 metres on the Windsor gauge, which corresponds to between about a 1 in 200 and 1 in 500 chance per year event. Mapping prepared by Josephson (1885) indicates that this floodway was active during the 1867 flood of record.

The diversion option involves constructing a low-level channel through the saddle to allow floodwater from the Hawkesbury River to discharge into the Currency Creek system more frequently. To ensure the effectiveness of the diversion, the Taskforce proposal was a 200-metre wide channel excavated to 2.1-3.0 m AHD (AHD roughly equal to mean sea level). To prevent this diversion channel being used in minor flood events, erodible fuse plugs were proposed so the floodway would be activated in a 1 in 20 chance per year event or larger. This would mean that when activated, 22 kilometres of river between Pitt Town and Sackville would be short-circuited with a seven-kilometre bypass. Provided the channel was of sufficient size, it could have capacity to carry a considerable volume of flood flows on a more direct route and in a more hydraulically efficient manner than provided by the existing river channel. This could reduce flood levels in the Richmond/Windsor floodplain.

The general route of the Currency Creek diversion channel is shown in **Figure 7.1**, while **Figure 7.2** shows a concept plan. The route would require excavation in soil for the first and last segments of channel, and a cut through sandstone and shale hills in the middle reaches of the channel. The alignment was chosen to avoid property and infrastructure. Where key roads intersect the diversion channel route, dual lane bridges would be provided to maintain access across the channel and floodplain.

Construction of a large trapezoidal channel with an average base width of 200 metres was assumed for the assessments. It would be around five kilometres in length with a final footprint of approximately 95 hectares. Fuse plugs would be constructed at the upstream end of the diversion channel preventing activation of the channel for flood events with a magnitude of less than 1 in 20 chance per year.

The Currency Creek diversion channel has the following basic design features:

- design invert reduced levels (RLs) between 2.1-3.0 m AHD
- total volume of excavation (other than rock) of 3,750,000 $m^3$
- total volume of excavation (rock) of 5,400,000 $m^3$
- two bridges over Sackville Road and Argent Road, and minor roadwork at Stannix Park Road.

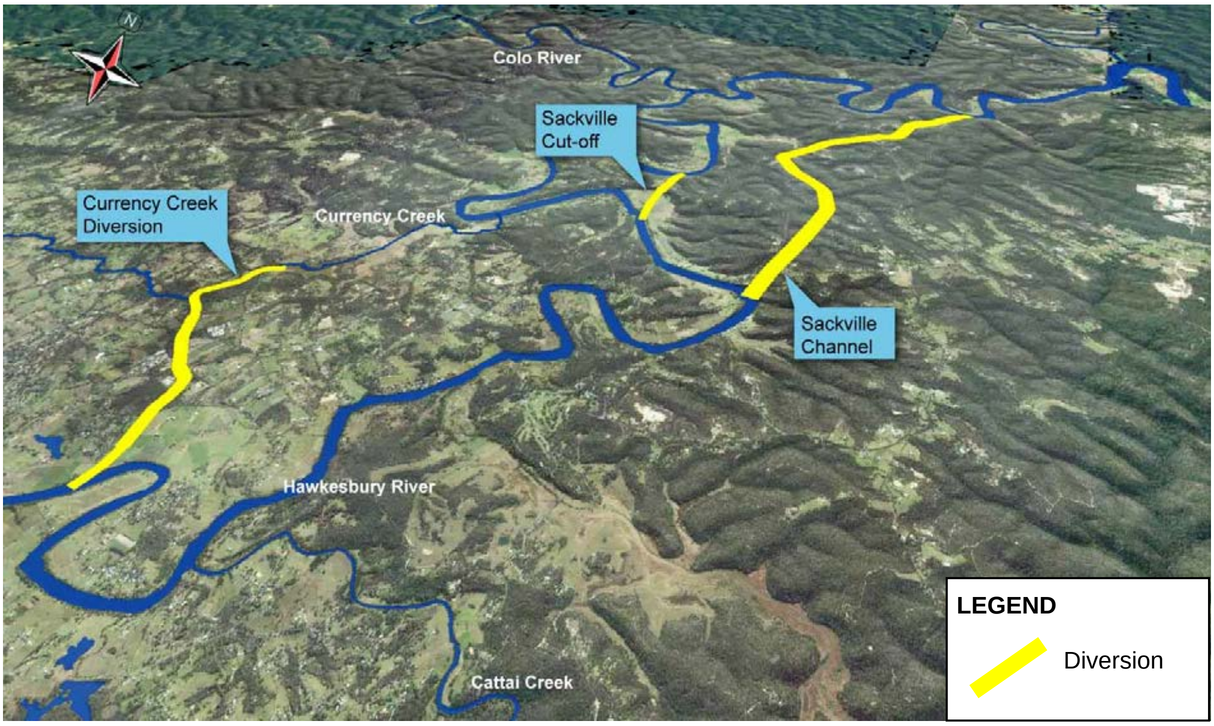



**Figure 7.1 Indicative layout of potential river diversion works**

*Source:* INSW

### *7.1.2 Effects on flood behaviour*

**Table 7.1** shows the difference in flood levels at Penrith, North Richmond, Windsor and Wisemans Ferry assuming the construction of the Currency Creek diversion channel.

The results can be summarised as follows:

- the Currency Creek bypass would have no impact on flood levels at Penrith
- as the Currency Creek bypass does not operate until a 1 in 20 chance per year event, it would provide negligible reductions in flood levels at North Richmond and Windsor in a 1 in 20 chance per year event
- in floods with a 1 in 100 to 1 in 200 chance per year, North Richmond and Windsor could expect a 0.4-0.6 metres reduction in flood levels. In all floods larger than this, flood levels would be reduced by 0.7-0.8 metres
- flood levels were modelled to *increase* slightly downstream at Wisemans Ferry.

This scale of reductions of peak flood levels fails to meet the objective of a significant reduction of flood risk as defined in **Section 4.3.1**.

In addition, as the flood levels have to be elevated in the Richmond/Windsor floodplain to drive floodwaters through the diversion, the delay in rise and peak in this floodplain would be significantly less than for the upstream flood mitigation options. Downstream of Currency Creek, the diversion could result in earlier flooding.


**Figure 7.2 Currency Creek diversion channel concept plan**

*Source*: NSW Public Works for the Taskforce

**Table 7.1 Impacts of Currency Creek diversion channel on flood levels**

| **Flood event** (chance of occurrence per year) | **Penrith** | | **North Richmond** | | **Windsor** | | **Wisemans Ferry** | |
|---|---|---|---|---|---|---|---|---|
| | **Base case** (m AHD) | **Currency Creek diversion channel** (Difference in metres) | **Base case** (m AHD) | **Currency Creek diversion channel** (Difference in metres) | **Base case** (m AHD) | **Currency Creek diversion channel** (Difference in metres) | **Base case** (m AHD) | **Currency Creek diversion channel** (Difference in metres) |
| 1 in 5 | 19.9 | 0.0 | 11.2 | 0.0 | 9.4 | 0.0 | 1.2 | 0.0 |
| 1 in 10 | 21.6 | 0.0 | 13.6 | 0.0 | 11.6 | 0.0 | 2.4 | 0.0 |
| 1 in 20 | 23.4 | 0.0 | 15.3 | 0.0 | 13.5 | -0.1 | 3.8 | +0.1 |
| 1 in 50 | 24.9 | 0.0 | 16.5 | -0.1 | 16.0 | -0.3 | 5.4 | +0.1 |
| 1 in 100 | 25.9 | 0.0 | 17.5 | -0.4 | 17.2 | -0.5 | 6.5 | +0.2 |
| 1 in 200 | 26.5 | 0.0 | 18.4 | -0.5 | 18.2 | -0.6 | 7.5 | +0.1 |
| 1 in 500 | 27.1 | 0.0 | 19.7 | -0.7 | 19.5 | -0.8 | 9.1 | +0.2 |
| 1 in 1,000 | 27.5 | 0.0 | 20.6 | -0.7 | 20.4 | -0.8 | 10.2 | +0.2 |
| 1 in 2,000 | 28.4 | 0.0 | 21.7 | -0.7 | 21.5 | -0.8 | 11.2 | +0.2 |
| 1 in 5,000 | 29.5 | 0.0 | 22.7 | -0.8 | 22.6 | -0.8 | 12.5 | +0.2 |
| PMF | 31.5 | -0.1 | 26.3 | -0.7 | 26.2 | -0.7 | 14.6 | +0.3 |

**LEGEND:** > +0.10 m; -0.25 to -1.0m; Critical range for flood risk

*Source:* WMAwater for the Taskforce (2016 model)

*Note:* Both scenarios allow for probabilistic drawdown and H14 protocol; PMF = probable maximum flood; Currency Creek diversion channel is modelled to have negligible effect on peak flood levels at Wallacia

## *7.1.3 Economic assessment*

### *Benefits*

The reduction of flood levels in the Richmond/Windsor floodplain through implementation of the Currency Creek diversion channel is estimated to reduce flood damages (produce a benefit) of approximately $120 million (**Table 7.2**). The risk to life benefits of this option were not modelled as it did not meet the performance criteria of regional benefits and significant reduction in the critical range of floods.

**Table 7.2 Discounted benefits of Currency Creek diversion compared to base case**

| Benefit | Currency Creek diversion |
|---|---|
| | $m |
| **Residential direct damage avoided** | 59 |
| **Residential indirect damage avoided** | 3 |
| **Commercial and industrial direct damage avoided** | 30 |
| **Commercial and industrial indirect damage avoided** | 11 |
| **Avoided electricity damage** | 3 |
| **Avoided other damages – roads, bridges, hospitals etc** | 14 |
| **Loss of life and injury avoided** | Not considered for evacuation assessment |
| **TOTAL** | **120** |

*Source:* CIE for the Taskforce

*Note:* 'Central case' assumptions applied including 7% discount rate

### *Costs*

WorleyParsons (2015) estimated the cost of the diversion channel at $753 million (2015 dollars). This includes construction costs, land acquisition costs, maintenance costs – including for removal of sediment deposited in the channel during floods and reinstatement of the fuse plug spillway after every flood exceeding the 1 in 20 chance per year event – and a 40% contingency appropriate for a pre-feasibility level of investigation. There is uncertainty about the cost of drill and blast excavation in rock and the cost of disposing or reusing the excavated earth and rock, so costs could potentially be higher.

The WorleyParsons cost estimate was significantly higher than an earlier estimate by NSW Public Works (~$508 million), mainly due to higher adopted rates for excavation and disposal of soil and rock to form the channel. The WorleyParsons-adopted excavation and disposal rates were consistent with those provided in the *Australian Construction Handbook* (Rawlinsons, 2012).

The discounted cost of construction (over 30 years) if construction had commenced in 2016 was $638 million (**Table 4.6**).

### *Benefit-cost*

Comparing the discounted benefit of $120 million to the discounted cost of $638 million yields a net *cost* of $518 million, based on central case assumptions (see **Section 4.4.3**). The result is little changed for the low and high assumption scenarios.

### 7.1.4 Social, environmental and cultural heritage impact

A preliminary socio-economic, environmental and cultural heritage (SECH) impact assessment was prepared for the Currency Creek diversion channel option.

Construction of the floodway was judged to pose an extreme risk – even after implementation of potential mitigation measures – to terrestrial flora and ecological communities, with irreversible loss of one endangered ecological community, the critically endangered Shale Sandstone Transition Forest. A high risk was identified for visual landscape, with the semi-rural and bushland vista permanently interrupted by the typically empty channel cut across the landscape. A high risk was also identified for recreational uses, since the floodway route intersects with Chain of Ponds Reserve in Ebenezer. During floods rarer than a 1 in 20 chance per year event, it is likely that this option would cause erosion at the outlet and lower reaches of Currency Creek as the channel adjusts to increased flows.

### 7.1.5 Findings – Currency Creek diversion channel

Assessment of the Currency Creek diversion channel showed that it would achieve relatively small reductions in flood levels in the Richmond/Windsor floodplain for the 1 in 100 chance per year flood and rarer events. It would slightly increase flood levels downstream at Wisemans Ferry.

The cost of constructing and maintaining the channel are significant, and not matched by the benefits, yielding a net cost of $518 million. There are also some extreme environmental impacts and high social impacts that would be difficult to mitigate.

In respect of the extent and magnitude of flood level reductions and the net benefits, the Currency Creek diversion channel compares unfavourably to the option of raising Warragamba Dam wall by 14 metres. The Currency Creek diversion channel was therefore not included in the 2017 Flood Strategy.

## 7.2 Sackville diversion channels

### 7.2.1 Description of options

One of the main controls over flooding behaviour in the Richmond/Windsor floodplain is the approximately 80-kilometre long, narrow, incised sandstone gorges between Sackville and Brooklyn. The series of gorges constricts the discharge of floodwaters from the valley, causing floodwaters upstream to back up to great depths and for prolonged periods. Proposals to lessen this constricting effect are considered in this section.

Diversion of the Hawkesbury River in the vicinity of Sackville was investigated as part of the *Engineering Studies to Modify Flood Behaviour* investigation (WMA, 1997). Two large scale diversion works were considered as part of the 2013 Review: a short diversion channel similar to that described in the 1997 WMA report, and another much larger scale option to gauge the maximum reduction in flood levels that could conceivably be achieved. These options are respectively described as:

- Sackville cut-off (or short diversion channel)
- Sackville large diversion channel.

The indicative route of these two options is shown on **Figure 7.1**. Although these options ranked lower in the shortlisting assessment conducted for the 2013 Review (see **Appendix F**), they received support from some members of the local community as possible means to providing flood mitigation benefits to the valley without raising Warragamba Dam.

The Review assessed these options to a pre-feasibility level of investigation. Aerial photography, property boundary information and ground surface levels based on 2011 LiDAR were provided by NSW Land and Property Information (LPI) to facilitate assessment of the options.

### *Sackville cut-off (short diversion channel)*

A concept plan for the short diversion channel is shown in **Figure 7.3**. Key attributes of the short diversion channel at Sackville considered as part of the 2013 Review are as follows:

- this option involves the construction of a large trapezoidal channel through a large hill, effectively cutting off a constricting meander that acts as hydraulic obstruction at Sackville. The total length of the works would be about 1.7 kilometres, with the offtake from the Hawkesbury River just upstream of Sackville North, bypassing some 10.5 river kilometres of the Hawkesbury River.
- at the offtake from the Hawkesbury River, a fuse plug would be built at a height equivalent to a 1 in 20 chance per year flood so that, for normal river flows and minor and moderate floods, flows would still travel down the main river and not 'short-cut' through the diversion channel.
- out of the 1.7 kilometres of works, about 450 metres of the channel would have to be excavated in sandstone.
- the base of the excavated trapezoidal channel would be 140 metres wide on the floodplain and 200 metres wide in the rock cuttings, with the bottom of the channel at 0 m AHD.
- excavation of the channel would involve removal of nearly six million cubic metres of rock and just over one million cubic metres of other materials. All this material would have to be disposed of securely.
- a bridge over the formed channel would be required for Sackville Ferry Road.
- the depth of flow in a 1 in 20 chance per year flood would be about 10 metres, while in a 1 in 100 chance per year flood, the depth would be about 13 metres.

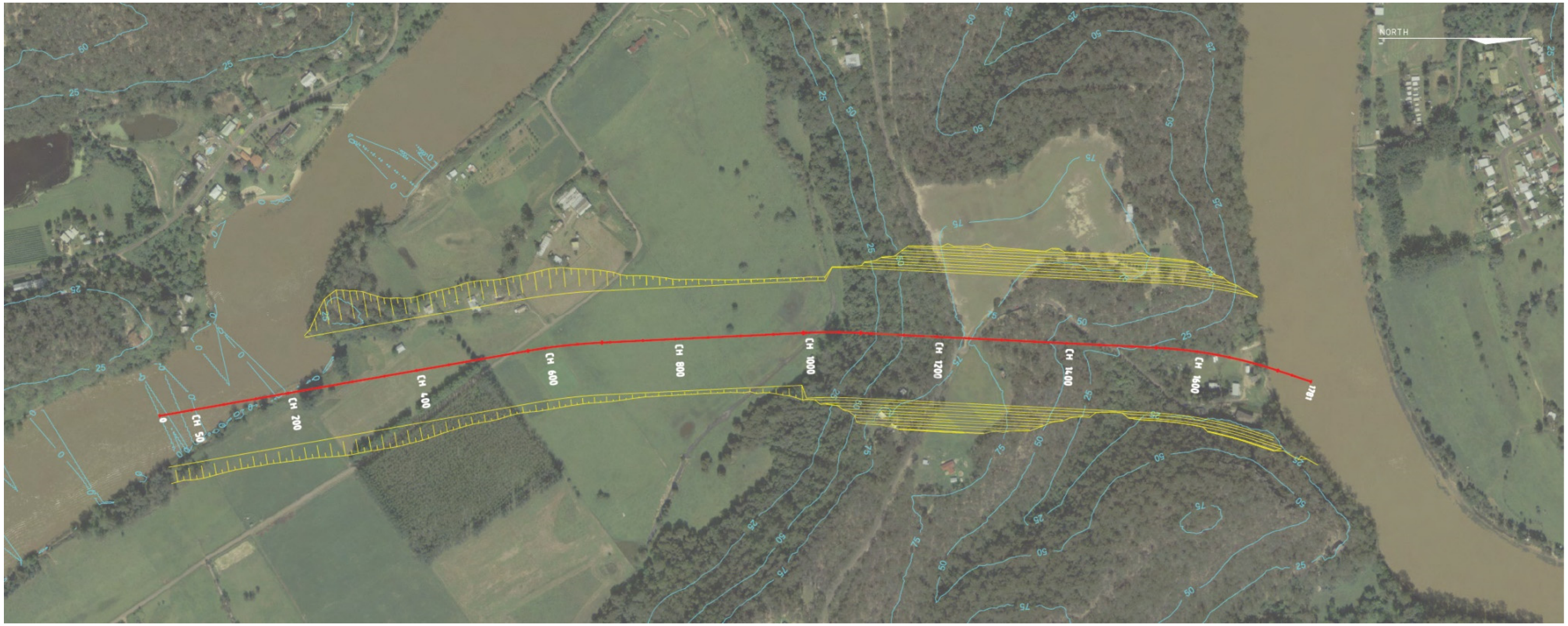



**Figure 7.3 Sackville short diversion channel concept plan**

*Source*: NSW Public Works for the Taskforce

### *Sackville large diversion*

A limited investigation of the Sackville long diversion channel option was carried out as part of the 2013 Review. Key attributes of this option are described below.

- this option involves the construction of a large trapezoidal channel that diverts flow from the Hawkesbury River immediately downstream of Pacific Park Water Ski Gardens at South Maroota, in a northerly direction through sandstone escarpments and valleys, reconnecting with the Hawkesbury River at Leetsvale Caravan Park. The estimated length of the Sackville large diversion is around 10.2 kilometres, compared to the 33.8 kilometres distance currently required for flows to travel to the same downstream location. The channel therefore offers significant improvement in hydraulic performance as water leaves the lower Hawkesbury floodplain.
- at the offtake from the Hawkesbury River, a fuse plug would be constructed at a height equivalent to a 1 in 20 chance per year flood so that, for normal river flows and minor and moderate floods, flows would still travel down the main river and not 'short-cut' through the diversion channel.
- in the absence of geotechnical information, it was assumed that the majority of the channel would have to be excavated in sandstone.
- the base of the excavated trapezoidal channel would be 270 metres wide, with the bottom of the channel set to 3.0 m AHD at the offtake and 1.65 m AHD downstream.
- Excavation of the channel would involve removal of nearly 100 million $m^3$ of material, approximately 90% of which is assumed to be rock. All this material would have to be disposed securely.
- The works would require the construction of at least two bridges over the channel, one bridge at Sackville Ferry Road with a span of about 670 metres and another bridge at Cliftonville Road with a span of 410 metres (by way of comparison, the span of the arch of Sydney Harbour Bridge is about 500 metres).
- The depth of flow in a 1 in 20 chance per year flood would be about seven metres, while in a 1 in 100 chance per year flood, the depth would be about 10 metres.

## *7.2.2 Effects on flood behaviour*

### *Sackville cut-off (short diversion channel)*

Flood modelling developed for the 2013 Review shows the difference in flood levels at Penrith, North Richmond and Windsor with the construction of a short diversion channel at Sackville (**Table 7.3**).

**Table 7.3 Impacts of short diversion channel at Sackville on flood levels**

| **Flood event** (chance of occurrence per year) | **Penrith** | | **North Richmond** | | **Windsor** | |
|---|---|---|---|---|---|---|
| | **Base case** (m AHD) | **Sackville short bypass** (Difference in metres) | **Base case** (m AHD) | **Sackville short bypass** (Difference in metres) | **Base case** (m AHD) | **Sackville short bypass** (Difference in metres) |
| 1 in 5 | 19.9 | 0.0 | 11.2 | 0.0 | 9.4 | 0.0 |
| 1 in 10 | 21.6 | 0.0 | 13.6 | 0.0 | 11.6 | 0.0 |
| 1 in 20 | 23.4 | 0.0 | 15.3 | 0.0 | 13.5 | 0.0 |
| 1 in 50 | 24.9 | 0.0 | 16.5 | 0.0 | 16.0 | -0.1 |
| 1 in 100 | 25.9 | 0.0 | 17.5 | -0.1 | 17.2 | -0.1 |
| 1 in 200 | 26.5 | 0.0 | 18.4 | -0.2 | 18.2 | -0.2 |
| 1 in 500 | 27.1 | 0.0 | 19.7 | -0.2 | 19.5 | -0.2 |
| 1 in 1,000 | 27.5 | 0.0 | 20.6 | -0.2 | 20.4 | -0.2 |
| 1 in 2,000 | 28.4 | 0.0 | 21.7 | -0.2 | 21.5 | -0.2 |
| 1 in 5,000 | 29.5 | 0.0 | 22.7 | -0.2 | 22.6 | -0.3 |
| PMF | 31.5 | 0.0 | 26.3 | -0.4 | 26.2 | -0.4 |

**LEGEND:** -0.25 to -1.0m; Critical range for flood risk

*Source:* WMAwater for the Taskforce (2013 model for option; 2016 model for base case)

*Note:* Base case allows for probabilistic drawdown; both scenarios assume H14 protocol; PMF = probable maximum flood; no results available for Wallacia or Wisemans Ferry

The results in **Table 7.3** are summarised below.

- the cut-off channel (short diversion channel) at Sackville gorge would have no impact on flood levels at Penrith.
- there would be negligible or zero reductions in flood levels at North Richmond and Windsor during floods smaller than a 1 in 100 chance per year event.
- in floods larger than a 1 in 200 chance per year event, North Richmond and Windsor could expect only a 0.2-0.4 metres reduction in flood levels.
- most of the benefits of this option would be limited to the areas just upstream of Sackville, where there is little urban development.
- there would be limited benefits upstream in the Richmond/Windsor floodplain because, with multiple bedrock constrictions extending downstream towards Brooklyn, cutting off just one of those constructions would not eliminate the broader hydraulic control that results in the 'bathtub' effect upstream.

Preliminary modelling undertaken as part of the *Engineering Studies to Modify Flood Behaviour* (WMA, 1997) investigation indicated similar results to **Table 7.3**, but also noted that *increases* in flood levels of up to 0.2 metre could be expected downstream as far as Wisemans Ferry.

#### *Sackville large diversion*

Because of the significant costs of the Sackville long diversion channel, this option was not modelled and so the impacts on flood behaviour have not been explicitly quantified. Nonetheless, expert opinion drawn on by the Taskforce judged that upstream flood level reductions would be limited as even this long diversion channel would still not bypass all the hydraulic constrictions between Sackville and Brooklyn. From the results of modelling the short diversion channel (meander cut-off), it is also likely that there would be increases in flood levels downstream of the works.

### *7.2.3 Economic assessment*

A pre-feasibility economic assessment of the Sackville cut-off was conducted as part of the 2013 Review.

#### *Sackville cut-off*

In 2013, NSW Public Works estimated the cost of the Sackville short diversion channel at about $420 million, including about $250 million for excavation, nearly $6 million for a bridge with a 200-metre span, $3 million for a fuse plug, and a 40% contingency appropriate for a pre-feasibility level of investigation. For costing purposes, it was assumed that all the excavated material could be disposed of within a few kilometres of the excavation. Whether such disposal areas would be available has not been confirmed.

The very limited flood level reductions of this option indicate that there would be negligible benefits in terms of avoided flood damages.

Accordingly, the net benefit of this option would be highly unfavourable.

#### *Sackville large diversion*

In 2013, NSW Public Works estimated the cost of the long diversion channel at about $5.5 billion, including about $3,850 million for excavation, $34 million for bridges, $1.4 million for a fuse plug, and a 40% contingency. For costing purposes, it was assumed that all the material could be disposed of within a few kilometres of the excavation. Whether such disposal areas would be available has not been confirmed.

The prohibitively high costs of this option meant that it was not modelled and so any benefits in terms of damages avoided upstream were not assessed.

Nonetheless, the very high costs, and likely modest benefits given the downstream hydraulic obstructions that wouldn't be addressed by the Sackville large diversion, together point to a net disbenefit.

### *7.2.4 Social, environmental and cultural heritage impact*

It is likely that the social, environmental and cultural heritage (SECH) impacts of the Sackville diversion channel options would be high to extreme. Since these options were not supported on other grounds – the limited flood mitigation benefits compared to the high costs – the specific SECH impacts were not assessed.

### *7.2.5 Findings – Sackville diversion channels*

The 2013 Review conducted an engineering pre-feasibility of two channel diversion options at Sackville, which would reduce the hydraulic constriction caused by Sackville Gorge during events exceeding the 1 in 20 chance per year flood, reducing flood levels upstream, but by only modest depths. Flood levels downstream at Wisemans Ferry would increase slightly.

The high to very high capital cost of these options, and the limited benefit in terms of reduced flood levels upstream, were sufficient reasons to exclude these options from further consideration, even without assessment of environmental, socio-economic and cultural heritage impacts, which would likely also be significant given the scale of works.

## 7.3 Dredging of the lower Hawkesbury River

### *7.3.1 Description of option*

A larger river channel is able to convey a greater volume of flows. Dredging rivers to remove sands and silts from the river bed has potential to increase the capacity to convey floodwaters. Dredging of the Hawkesbury River has been considered in several previous investigations as an option for mitigating floods.

Dredging of the main Hawkesbury River channel was investigated as part of the *Engineering Studies to Modify Flood Behaviour* investigation (WMA, 1997). This report concluded that, although significant reduction in flood levels could theoretically be achieved upstream of the works, there would be major environmental impacts from the works including issues associated with stability of the river banks, erosion and water quality. Flood levels downstream of the works would also be likely to increase.

Dredging was assessed again during the 2013 Review and under the Taskforce program. The potential benefits of dredging were assessed using a simplified design, which assumed a typical channel size for a particular length of channel, to gauge the maximum reduction in flood levels that could conceivably be achieved. Key attributes of the simplified design of the potential dredging option are set out below:

- the total length of the works was assumed to be about 66 kilometres of the Hawkesbury River between Windsor and Wisemans Ferry.
- it was assumed that the bed of the natural river, which is currently between 150 metres and 250 metres wide, would be lowered by a maximum of 10 metres below the current thalweg (line of lowest elevation within the channel), with 1:3 side slopes (see **Figure 7.4**).

- the works would require the excavation (as well as dewatering and potentially stockpiling) in the order of 39 cubic metres tonnes of sand, silt and other sediments (Neville, 1976, p.16).
- the project is estimated to take 10 years to complete.
- any dredging operations would need to be ongoing to maintain any flood mitigation benefits achieved. This is confirmed by a recent report into the potential of dredging the Hawkesbury River (WorleyParsons, 2012) which found that, on average, about one million tonnes of sand is deposited in the Hawkesbury River every year.

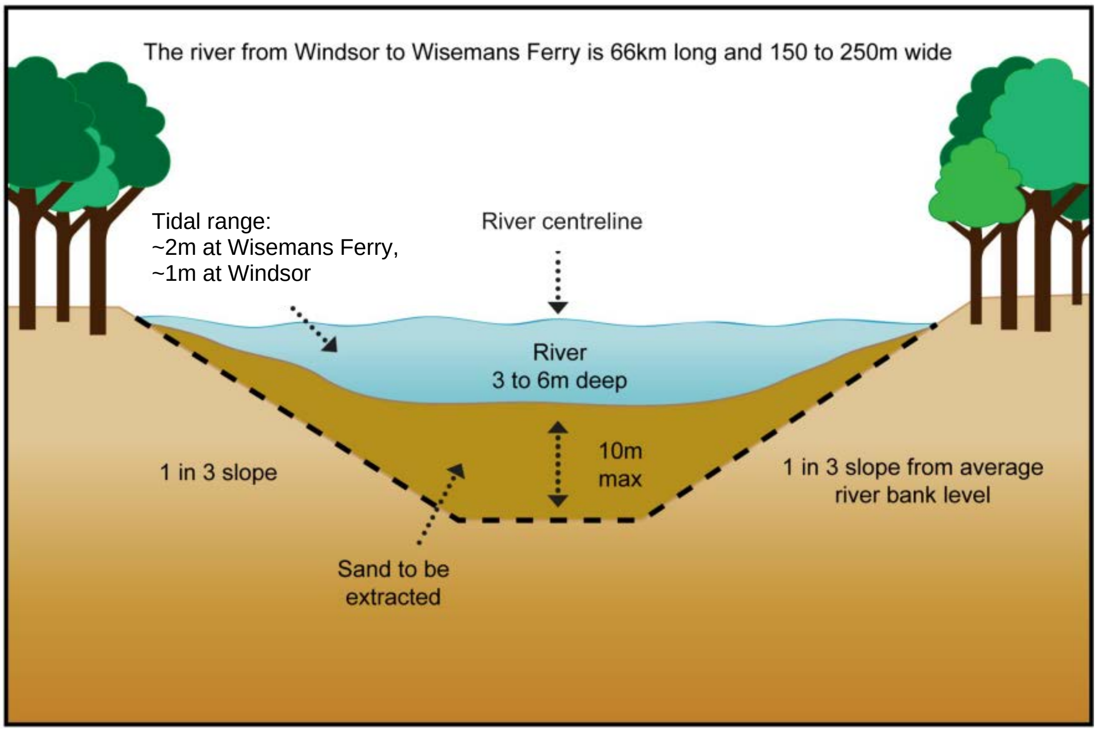



**Figure 7.4 Concept design for the lower Hawkesbury River dredging option**

### *7.3.2 Effects on flood behaviour*

**Table 7.4** shows the difference in flood levels at Penrith, North Richmond, Windsor and Wisemans Ferry assuming dredging of the Hawkesbury River between Windsor and Wisemans Ferry.

The results can be summarised as follows:

- dredging of the Hawkesbury River would have negligible impact on flood levels at Penrith
- at North Richmond (near the upstream of the limit of dredging), dredging would reduce peak flood levels by a maximum of 0.7 metres for events up to and including the 1 in 50 chance per year flood, increasing to 2.0 metres for the 1 in 500 chance per year flood

- at Windsor (the upstream limit of dredging), dredging would reduce peak flood levels by 1.2-2.6 metres over the entire range of floods
- at Wisemans Ferry (the downstream limit of dredging), dredging would *increase* peak flood levels by up to 0.5 metres for all floods more frequent than 1 in 500 chance per year.

**Table 7.4 Impacts of dredging of Hawkesbury River between Windsor and Wisemans Ferry on flood levels**

| **Flood event** (chance of occurrence per year) | **Penrith** | | **North Richmond** | | **Windsor** | | **Wisemans Ferry** | |
|---|---|---|---|---|---|---|---|---|
| | **Base case** (m AHD) | **Dredging Hawkesbury River** (Difference in metres) | **Base case** (m AHD) | **Dredging Hawkesbury River** (Difference in metres) | **Base case** (m AHD) | **Dredging Hawkesbury River** (Difference in metres) | **Base case** (m AHD) | **Dredging Hawkesbury River** (Difference in metres) |
| 1 in 5 | 19.9 | 0.0 | 11.2 | -0.7 | 9.4 | -2.6 | 1.2 | +0.4 |
| 1 in 10 | 21.6 | 0.0 | 13.6 | -0.6 | 11.6 | -2.1 | 2.4 | +0.4 |
| 1 in 20 | 23.4 | 0.0 | 15.3 | -0.2 | 13.5 | -1.8 | 3.8 | +0.5 |
| 1 in 50 | 24.9 | 0.0 | 16.5 | -0.5 | 16.0 | -2.0 | 5.4 | +0.4 |
| 1 in 100 | 25.9 | 0.0 | 17.5 | -1.1 | 17.2 | -2.1 | 6.5 | +0.3 |
| 1 in 200 | 26.5 | 0.0 | 18.4 | -1.6 | 18.2 | -2.1 | 7.5 | +0.3 |
| 1 in 500 | 27.1 | 0.0 | 19.7 | -2.0 | 19.5 | -2.2 | 9.1 | 0.0 |
| 1 in 1,000 | 27.5 | 0.0 | 20.6 | -1.9 | 20.4 | -2.1 | 10.2 | -0.2 |
| 1 in 2,000 | 28.4 | 0.0 | 21.7 | -1.6 | 21.5 | -1.8 | 11.2 | -0.2 |
| 1 in 5,000 | 29.5 | -0.1 | 22.7 | -1.6 | 22.6 | -1.7 | 12.5 | -0.1 |
| PMF | 31.5 | -0.2 | 26.3 | -1.1 | 26.2 | -1.2 | 14.6 | +0.4 |

**LEGEND:** > +0.10 m; -0.25 to -1.0m; -1.0 to -2.0m; > -2.0m; Critical range for flood risk

*Source:* WMAwater for the Taskforce (2016 model)

*Note:* Both scenarios allow for probabilistic drawdown and H14 protocol; PMF = probable maximum flood; Hawkesbury River dredging option is modelled to have negligible effect on peak flood levels at Wallacia

## *7.3.3 Economic assessment*

### *Benefits*

The reduction of flood levels in the Richmond/Windsor floodplain through the Hawkesbury River dredging option is estimated to reduce flood damages (produce a benefit) by approximately $389 million (**Table 7.5**). The risk to life benefits of this option were not modelled because it was eliminated at an earlier stage on investigation.

**Table 7.5 Discounted benefits of Hawkesbury River dredging compared to base case**

| Benefit | Hawkesbury River dredging |
|---|---|
| | $m |
| **Residential direct damage avoided** | 198 |
| **Residential indirect damage avoided** | 10 |
| **Commercial and industrial direct damage avoided** | 87 |
| **Commercial and industrial indirect damage avoided** | 32 |
| **Avoided electricity damage** | 9 |
| **Avoided other damages – roads, bridges, hospitals, etc** | 53 |
| **Loss of life and injury avoided** | Not considered for evacuation assessment |
| **TOTAL** | **389** |

*Source*: CIE for the Taskforce

*Note:* 'Central case' assumptions applied including 7% discount rate

### *Costs*

WorleyParsons (2015) estimated the cost of dredging at $916 million (2015 dollars). This includes the cost of dredging, transport and processing of dredge material, including a 40% contingency appropriate for a pre-feasibility level of investigation. The cost is partially offset by the sale of sand to the Sydney construction market, but an oversupply of sand to the market could drive prices down and lessen the offset. The cost estimate prepared by WorleyParsons was significantly higher than an earlier estimate by NSW Public Works (~$446 million) due to the higher costs associated with processing and stockpiling the dredged material adopted by WorleyParsons, primarily a function of uncertainty in the rates and quantities of material.

The discounted cost of construction (over 30 years) if construction had begun in 2016 was $643 million (**Table 4.6**).

### *Benefit-cost*

Comparing the discounted benefit of $389 million to the discounted cost of $643 million yields a net *cost* of $254 million, based on central case assumptions (see **Section 4.4.3**). The result is little changed for the low and high assumption scenarios.

### 7.3.4 Social, environmental and cultural heritage impact

A preliminary socio-economic, environmental and cultural heritage (SECH) impact assessment was prepared for the Hawkesbury River dredging option.

Extreme risks, even after implementation of potential mitigation measures, were identified for geomorphic impacts associated with the changed longitudinal riverbed profile by the instream dredging operation.

High risks, even after implementation of potential mitigation measures, were identified for:

- bank slumping and vegetation loss due to altered hydrodynamics
- water quality impacts, including algal blooms
- loss of prey resources and habitat changes resulting in flow-on effects to fisheries resource values
- changes in estuarine communities due to alterations in water quality and habitats resulting in loss of fisheries production
- impacts to fish and prawn habitat post-dredging.

A detailed assessment of the potential impacts of the river dredging option on hydrodynamics and water quality in the Hawkesbury-Nepean estuary was undertaken using Sydney Water's Hawkesbury-Nepean Receiving Water Quality Model.

Overall, the modelling assessment indicates that the proposed dredging scenario is likely to have significant impacts on both hydrodynamics and water quality within the Hawkesbury-Nepean River, but that these impacts will be broadly limited to the dredged reaches. In these areas, velocities are likely to decrease and tidal flows are likely to increase, with an associated increase in tidal flushing. As a result of the increased influence of marine water, it is expected that salinities in the dredged section of the Hawkesbury River would rise, and dissolved oxygen, total nitrogen and total phosphorus concentrations would fall. The rise in salinities could have an adverse impact on the ability of irrigators to make use of water extracted from the reach of the Hawkesbury River stretching from Windsor to Sackville.

### 7.3.5 Findings – dredging Hawkesbury River

The dredging option modelled was of a scale suitable to assess the maximum conceivable enhancements to drainage of floodwater from the Hawkesbury-Nepean Valley. The modelled scenario would achieve considerable reductions in flood levels at Windsor for the full range of floods. However, it would increase flood levels downstream at Wisemans Ferry. The option does not provide flood mitigation benefits to the Penrith floodplain.

The cost of dredging the channel is significant, and not matched by the benefits, yielding a net *cost* of $254 million. There are also some extreme environmental impacts and high economic impacts that would be difficult to mitigate. Furthermore, dredging would require regular maintenance to prevent the dredged river channel from refilling.

In terms of the extent and magnitude of flood level reductions, the cost, and the net benefits, the Hawkesbury River dredging option compares unfavourably to the option of raising Warragamba Dam wall by 14 metres. The dredging option was therefore not included in the Flood Strategy.

## 7.4 Local structural works

### *7.4.1 Description of options*

Levee banks are artificial embankments that prevent inundation of the protected area up to the design limit. When floods exceed the levee design level, inundation can be rapid and flood risk to life and property losses can be large.

As described in **Appendix F**, as part of the 2013 Review, an assessment was conducted to shortlist the most viable non-Warragamba Dam infrastructure measures for more detailed assessment. Levee banks at Peachtree Creek at Penrith, McGraths Hill and Pitt Town were selected for further investigation as the most viable from a list of potential levee options.

Preliminary concept plans of the levees are illustrated in **Figure 7.5** for Peachtree Creek, **Figure 7.6** for McGraths Hill, and **Figure 7.7** for Pitt Town, with details in **Table 7.6**.

The 2013 Review found there to be limited potential for localised flood mitigation using levees, due to the extreme depth of flooding in the valley, particularly in the Richmond-Windsor area. A flood levee on Peachtree Creek at Penrith was considered viable. The 2013 Review concluded that levees in Richmond-Windsor floodplain would have to be very high to provide any significant flood mitigation, and their impact on local amenity was not likely to be acceptable.

The Peachtree Creek levee was further assessed during the Taskforce investigations for its potential capacity to mitigate backwater flooding in an important commercial and residential area. The McGraths Hill levee was also further assessed as it was considered that a levee could protect local roads from very frequent flooding and therefore assist regional evacuations from this established suburb. While the Pitt Town levee was not further investigated by the Taskforce, details of the earlier work are included in this report for completeness.

If a levee-based flood mitigation strategy was adopted, each levee would need to be developed with its own design, environmental impact assessment, cost-benefit analysis and business case.

#### *Peachtree Creek levee*

Flooding on the eastern bank of the Nepean River at Penrith occurs via backwaters from the Nepean River through Boundary Creek and Peachtree Creek. Peachtree Creek is fed by Surveyor Creek to the south which collectively drains parts of Glenmore Park, South Penrith and Jamisontown, and joins with Boundary Creek and the Nepean River a short distance downstream of Penrith Weir. During a flood, commercial properties on the banks of Peachtree Creek as well as low lying areas around the sewage treatment works on Boundary Creek are affected.

The Peachtree Creek levee scheme proposes to protect properties situated between the Nepean River and Penrith CBD from backwater flooding with an earthen levee, a retaining wall and floodgates. It would be designed to prevent backwater flooding of about 200 commercial and residential properties in the Penrith area up to the 1 in 100 chance per year flood.

The concept design consists of three discrete levees that would occupy a combined area of approximately 0.6 hectares. These include:

- Peachtree Creek Main levee, including floodgates over Boundary Creek
- Old Ferry Road levee
- Tennis Court levee.

The levee design is a standard earth-fill embankment design with a total length of approximately one kilometre and design crest levels of between 26.5 m AHD and 26.7 m AHD. In a section of the Main levee close to Peachtree Creek, retaining wall type levees would likely be required to minimise the footprint within areas identified with potential bank stabilisation problems and space restrictions. It is estimated that the total volume of compacted clay fill required is 2,500 cubic metres and the total volume of the concrete retaining wall is 200 cubic metres.

#### *McGraths Hill levee*

A majority of McGraths Hill is inundated during a 1 in 50 chance per year event (576 dwellings) and nearly all of the area during a 1 in 100 chance per year event (913 dwellings) (Bewsher Consulting, 2012). A levee at this location would be designed to protect relatively recent (circa 1980s) dense housing development by blocking flows that enter the suburb through low lying areas predominately to the south and east, with small pockets of low areas to the north.

The concept design would protect residential properties in McGraths Hill against flooding up to the 1 in 50 chance per year event. A higher levee to protect up to the 1 in 100 chance per year flood level would not be practical due to the greater depth of flooding, requiring a very large imposing structure at significant expense.

The levee would be constructed as an earth embankment with a total length of approximately 3.7 kilometres (levee not required at all locations along this length). The crest height of the levee would be constructed to a level of 16.0 m AHD requiring three road ramps at key road crossings. The footprint of the final levee would occupy an area of approximately 5.6 hectares and the total volume of compacted clay fill required is estimated to be 200,000 cubic metres.

#### *Pitt Town levee*

A significant area of Pitt Town is inundated during a 1 in 50 chance per year event (177 dwellings) (Bewsher Consulting, 2012). A levee at this location would be designed to protect residential areas within the town by blocking flows that enter the town through low lying areas predominantly to the south and east. The levee concept would protect residential properties within the town against flooding up to the 1 in 50 chance per year event. The levee would be constructed as an earth embankment with a total length of approximately 1.7 kilometres.

### *7.4.2 Effects on flood behaviour*

Levees protect the area within the levee up to the design height. When floodwater exceeds the design height, the area within the levee will be inundated.

Given the size of the proposed local levees, relative to the floodplains, they are not expected to have significant effects on flood behaviour outside the levees, and so were not modelled.

**Table 7.6 Summary of levee options at Peachtree Creek, McGraths Hill and Pitt Town**

| Levee attributes | Peachtree Creek levee (Penrith) | McGraths Hill levee | Pitt Town levee |
|---|---|---|---|
| **Type of levee example** | protection of commercial development (up to design level) | protection of suburban residential area (up to design level) | protection of historic rural township (up to design level) |
| **Level of flood protection – flood size** | 1 in 100 chance per year flood plus 0.5 m freeboard | 1 in 50 chance per year flood | 1 in 50 chance per year flood |
| **Level of flood protection – level of top of levee** | 26.5-26.7 m AHD | 16.0 m AHD | 16.0 m AHD |
| **Approximate number of properties protected** | 200 (commercial and residential) | 576 (mainly residential) | 177 (mainly residential) |
| **Total length of levee** (includes some high ground where no levee required) | Main Levee: 900 metres<br>Old Ferry Road Levee: 50 metres<br>Tennis Court Levee: 100 metres | 3,700 metres | 1,700 metres |
| **Length of earthen embankment levee** | 460 metres | 2,300 metres | 1,700 metres |
| **Length of concrete retaining wall levee** | 340 metres | nil | nil |
| **Typical height of levee** | Concrete retaining wall: 1.6 metres<br>Earthen embankment: 2.5 metres | 1-2 metres | 1-3 metres |
| **Volume of earthworks**<br>• compacted clay fill<br>• concrete retaining wall | 2,500 cubic metres<br>200 cubic metres | 200,000 cubic metres<br>nil | 160,000 cubic metres<br>nil |
| **Creek crossings with pipes and floodgates** | Boundary Creek | nil | nil |
| **Road crossings** | nil | Wolseley Road<br>Ilma Crescent<br>Windsor Road | Lagoon Road<br>Bathurst Street<br>Cattai Road<br>Eldon Street<br>one private property |

*Source:* WMA (1997); NSW Public Works for the 2013 Review

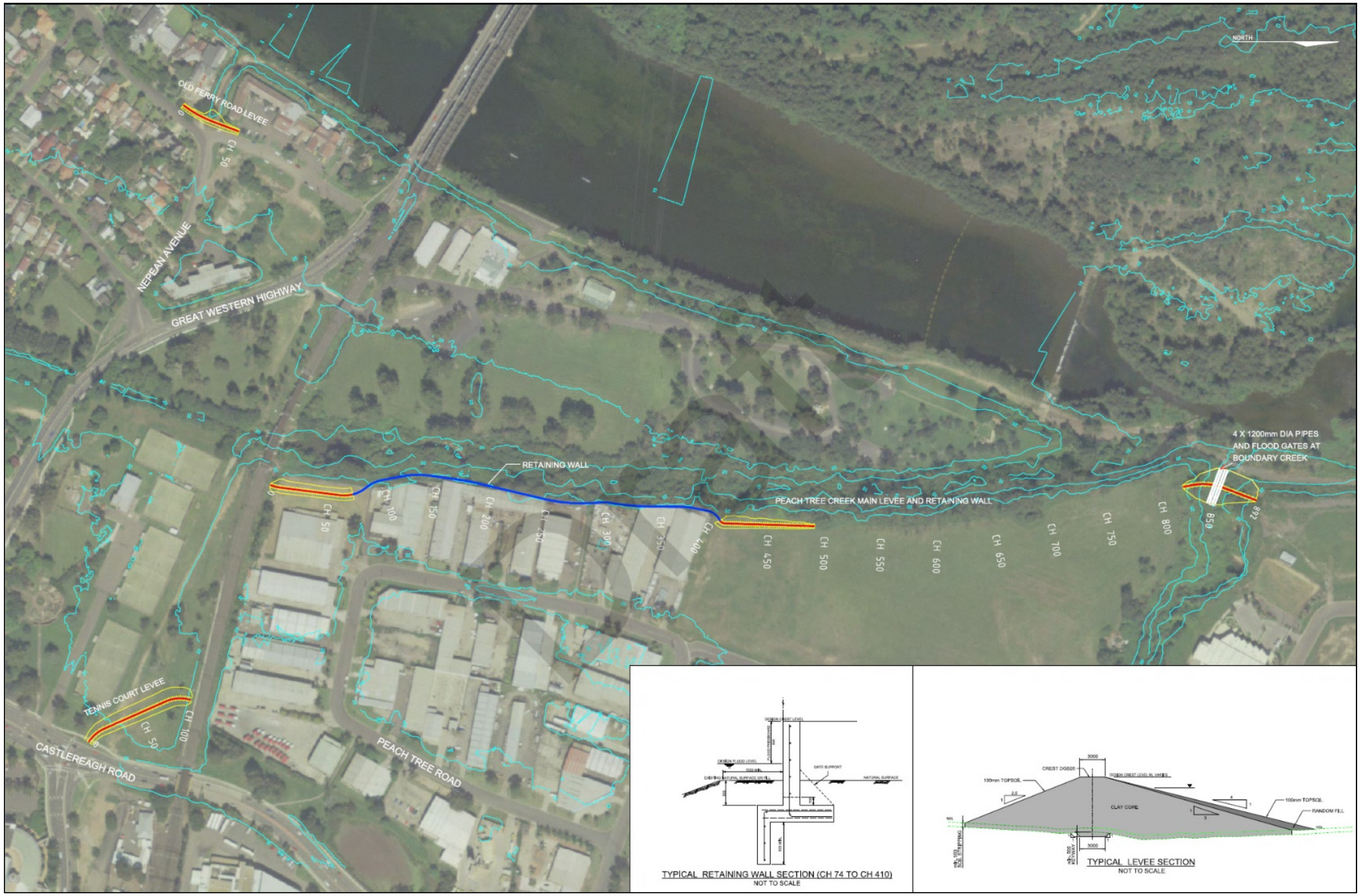



**Figure 7.5 Peachtree Creek levee concept plan**

*Source*: NSW Public Works


**Figure 7.6 McGraths Hill levee concept plan**

*Source*: NSW Public Works


**Figure 7.7 Pitt Town levee concept plan**

*Source*: NSW Public Works

### 7.4.3 Economic assessment

#### *Peachtree Creek levee*

WorleyParsons (2015) estimated the cost of the Peachtree Creek levee at $1.2 million (2015 dollars), including a concrete retaining wall, flood gates and a 40% contingency appropriate for a pre-feasibility level of investigation. The cost estimate prepared by WorleyParsons was significantly lower than an earlier estimate by NSW Public Works (~$4 million), mainly due to different estimates of the cost of installing the reinforced concrete wall.

The Peachtree Creek levee was identified as a cost-effective option as a potential local measure.

#### *McGraths Hill levee*

WorleyParsons (2015) estimated the cost of the McGraths Hill levee at $7.2 million (2015 dollars), including construction of a new earth levee, ramp roadworks and a 40% contingency appropriate for a pre-feasibility level of investigation. The cost estimate prepared by WorleyParsons was significantly lower than an earlier estimate by NSW Public Works (~$10.5 million), mainly due to different estimates of the costs of levee earthworks, especially the rate for winning, haulage and compaction of clay for the levee core.

The McGraths Hill levee was identified as a cost-effective option as a potential local measure.

#### *Pitt Town levee*

NSW Public Works estimated the cost of the Pitt Town levee at $8.3 million in 2013, including $4.5 million for earthworks, about $0.2 million for levee roadworks, and a 40% contingency.

As described earlier, the Pitt Town levee was not carried forward to the Taskforce investigations and so was not subject to cost-benefit analysis.

### 7.4.4 Social, environmental and cultural heritage impact

The Taskforce prepared a preliminary socio-economic, environmental and cultural heritage (SECH) impact assessment for the Peachtree Creek and McGraths Hill levee options.

Following mitigation, no extreme or high risks were identified.

Nonetheless, there are a number of key issues to consider in relation to levees:

- ***false sense of security of 'protected' community*** – while levees provide protection up to their design level, it is certain that at some time in the future, a larger flood will occur. The construction of levees can create a 'false sense of security' amongst the residents and businesses behind the levee, engendering a misconception that the levee protects them from all events. When a flood large enough to overtop the levee occurs, those sheltering behind the levee may be caught unawares in a very dangerous situation.

  The effect of levees on human behaviours may be particularly problematic for the flood islands. The McGraths Hill evacuation route is cut at 13.5 m AHD, before much of McGraths Hill is inundated (NSW SES, 2015). A levee built to prevent inundation up to 16.0 m AHD would make the suburb even more of an 'island' in floods and would likely act as a disincentive for residents to evacuate. However, evacuation would likely still be required due to the dangers of sheltering in place and the risks of levee failure or overtopping.

Similarly, Pitt Town needs to be evacuated before 16.0 m AHD (NSW SES, 2015), so having a levee built to that same level would likely lead to delayed evacuations. The evacuation route would be particularly unsafe as soon as inundated given the potential for high velocity floodwaters in this location.

- ***increased risk to life and property damage once levee is overtopped*** – once the water level exceeds the height of the levee, or the levee embankment fails, the inundation resulting from overtopping is often sudden and unexpected, with rapid rises in water level to considerable depths and high velocities of flow.
- ***need to manage drainage inside the levee*** – while a levee is designed to keep floodwaters of the main river out, there will often be stormwater runoff that is trapped inside the levee and cannot flow out during floods. This 'internal drainage' must be managed including setting aside areas inside the levee to pond stormwater runoff during the flood, pumping this stormwater runoff over the levee if required, and draining the runoff back to the river after the flood.
- ***need for on-going maintenance*** – while capital costs for levees may be cost-effective, a genuine long-term program of maintenance is critical to ensure levees operate as they are designed, when they are needed during times of flood.
- ***visual and amenity impacts*** – often a levee is not favoured by a local community because of its visual impacts in blocking views, as well as the severance impacts on existing land parcels and activities.

### *7.4.5 Findings – local structural works*

Based on the recommendations of the 2013 Review, levees at Peachtree Creek and McGraths Hill were identified as cost-effective options for providing local flood protection. But because they provide only localised and limited benefits (McGraths Hill up to only the 1 in 50 year chance per year event), they were not taken forward into the regional Flood Strategy.

Penrith City Council may wish to evaluate the Peachtree Creek levee option further in its Nepean River Floodplain Risk Management Study. Hawkesbury City Council's *Hawkesbury Floodplain Risk Management Plan* (Bewsher Consulting, 2012) recommended a feasibility study of the McGraths Hill levee be undertaken, including community engagement to ascertain levels of acceptance.

# 8 Evacuation road infrastructure options

Upgrades to evacuation roads do not mitigate flooding. While road infrastructure upgrades would not reduce damages to homes, businesses and critical assets, they are important for providing evacuation capacity during floods and hence reduce the risk to life. This chapter describes the identification and evaluation of evacuation road infrastructure options.

## 8.1 Regional evacuation road infrastructure

### *8.1.1 Description of options*

As described in **Sections 1.1.2** and **3.4.1**, mass self-evacuation by private motor vehicles is the primary method for evacuating the Hawkesbury-Nepean floodplain in advance of a flood event. The existing road evacuation network is shown in **Figure 8.1**.

Congestion during floods arises due to the large numbers of people requiring evacuation, and limited and sometimes low-set flood evacuation routes which are progressively cut by rising floodwaters.

The indicative evacuation timings for the critical flood islands range up to 20.65 hours for the Richmond sector (see **Table 1.3**). According to the *Service Level Specifications* (BoM, 2017), the Bureau of Meteorology aims to provide around 15 hours' warning of significant floods in the Richmond/Windsor floodplain. This means that there is currently insufficient road capacity to safely evacuate the whole population using reliable flood forecasts. This forces the NSW SES to order mass evacuations on more uncertain flood forecasts that may not eventuate. This is likely to reduce the response rate to an evacuation order in a subsequent event.

By 2041, it is anticipated that as part of business-as-usual, various road network improvements will be undertaken, including increased flood immunity of some routes, subject to funding (see **Figure 8.2**). Planned projects include upgrades on the M4, The Northern Road, Richmond Road, Garfield Road East and West, Schofields Road, Bandon Road, Andrews Road, Vincent Road, Llandilo Road, and Fourth Avenue (for more information see **Appendix G**). For evacuation modelling, all these planned upgrades were included in the 2041 base case.

The Taskforce assessed nine regional road infrastructure options or combinations of options for their impacts on evacuation in response to a rising flood, compared to the 2041 base case. These packages focus on building flood resilience and not providing capacity for everyday traffic. The options are outlined in **Table 8.1** and described in more detail in **Appendix G**:

- Options 1 and 2 involve raising roads to higher levels
- Option 3 involves increasing the capacity of selected roads to alleviate congestion at identified bottlenecks
- Options 4 and 5 combine both road level and capacity increases
- Options 6 to 9 involve construction of a new Bells Line of Road–Castlereagh Connection (previously known as the Castlereagh Freeway). Delivery of the Connection is a long-term, major project driven principally by daily traffic demand congestion benefits, rather than by intermittent evacuation benefits.

**Table 8.1 Regional road evacuation infrastructure options**

| Option | Description |
|---|---|
| **0** | Base case road network by 2041 |
| **1** | Road height increases to 1 in 100 chance per year by 2041 (to Garfield Road West, Londonderry Road, The Northern Road, The Driftway, Castlereagh Road, Great Western Highway, Park Road at Wallacia, and Wallace Road at Vineyard) |
| **2** | Road height increases to 1 in 200 chance per year by 2041 (to much the same list of roads as listed for Option 1 above) |
| **3** | Lane capacity increases by 2041 (to various roads including The Northern Road, Londonderry Road, The Driftway, Jockbet Road, Wilshire Road, Castlereagh Road, Great Western Highway, Richmond Road, and Wallace Road extension at Vineyard) |
| **4** | Options 1 and 3 by 2041 |
| **5** | Options 2 and 3 by 2041 |
| **6** | Build Castlereagh Freeway to 1 in 100 chance per year (17.3 m AHD) by 2041 |
| **7** | Option 4 and Option 6 by 2041 |
| **8** | Option 5 and build Castlereagh Freeway to 1 in 200 chance per year (18.5 m AHD) by 2041 |
| **9** | Option 5 and build Castlereagh Freeway at >1 in 200 chance per year (20.2 m AHD) by 2041 |

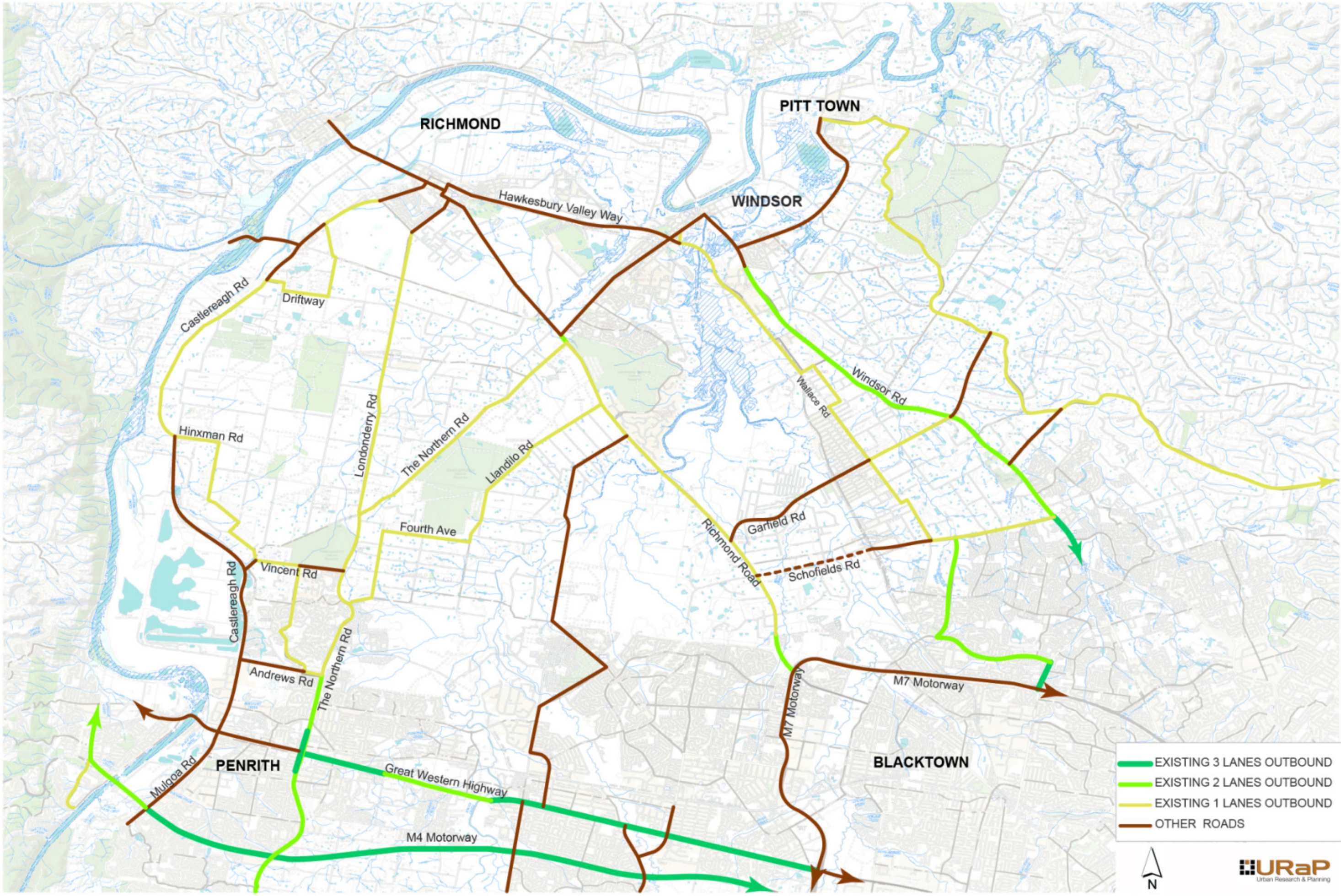



**Figure 8.1 Existing (2014) evacuation network**

*Source:* URaP and RMS for the Taskforce

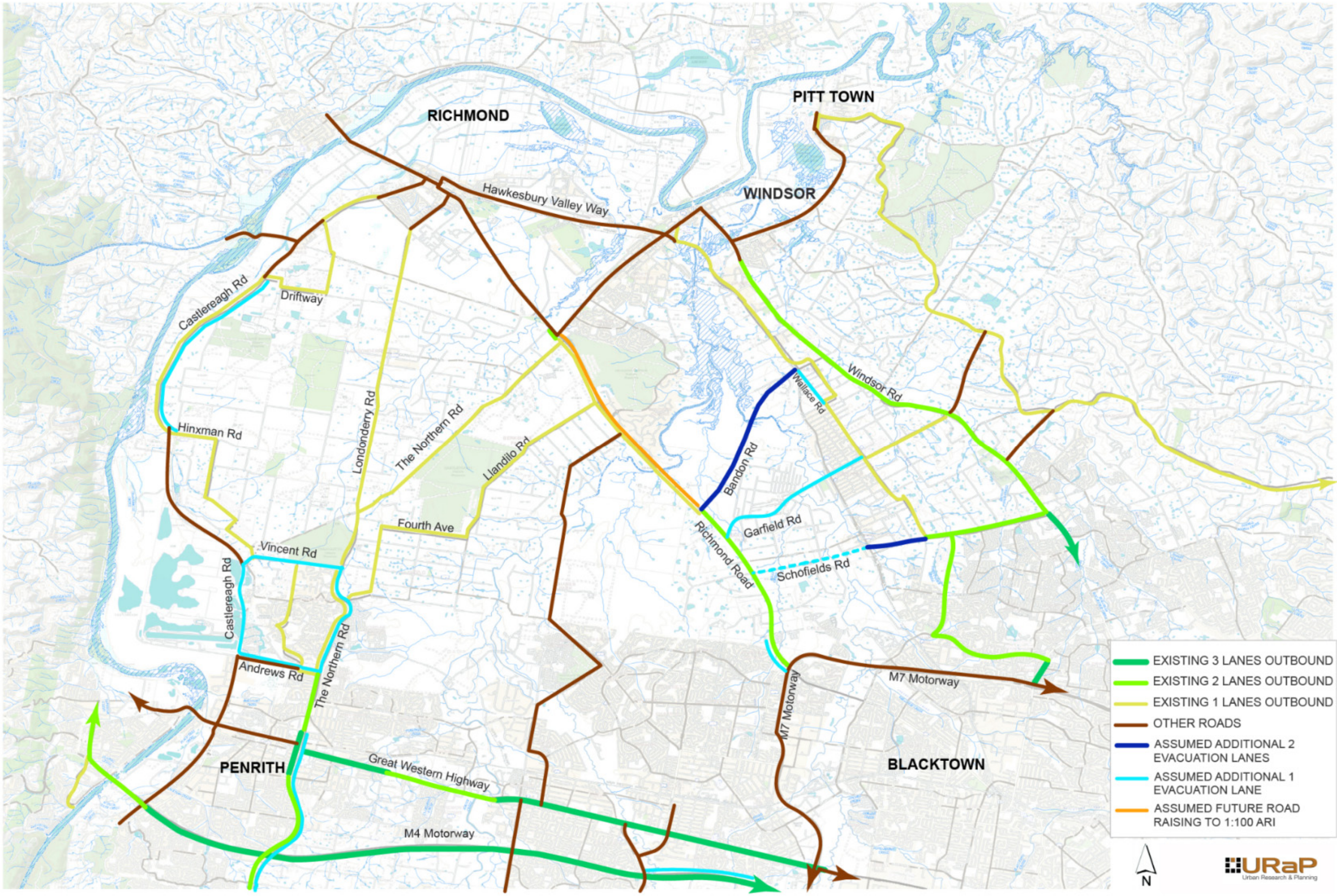



**Figure 8.2 Assumed 2041 evacuation network**

*Source:* URaP and RMS for the Taskforce

### *8.1.2 Risk to life assessment*

The Taskforce modelled vehicles isolated by floodwaters (unable to evacuate) for the 2041 base case road network. This base case was compared to various road infrastructure options, either as standalone options, or in combination with various flood mitigation infrastructure options (lowering the full water supply level or FSL by five metres, or raising the dam by either 14 or 20 metres). Assuming 100% compliance with evacuation orders (see **Section 4.3.2**), the results for two development pathways are presented in **Table 4.5**. There are several noteworthy features:

- Options 1 and 2 – elevating regional evacuation roads – provide negligible benefit in terms of number of vehicles isolated (unable to evacuate) when compared to the 2041 base case. While the individual projects may free up particular locations, resulting in a rescheduling of evacuation of different subsectors, the results point to widespread convergence and congestion of traffic from different subsectors. This suggests that greater physical capacity on a number of converging or critical evacuation roads would be necessary to improve evacuation performance, possibly along with select road elevation increases.
- Option 3 – road capacity upgrades – performs best of the tested road upgrade options for reduced risk to life, but not as well as dam raising. If implemented after dam raising, Option 3 would provide small additional benefits.
- The development of the Castlereagh/Bells Line of Road Connection between the M7 Motorway and Londonderry shows potential to enhance evacuation capacity either with or without dam raising. The higher the elevation of the Connection, the greater the evacuation potential as can be seen by the decreasing numbers of isolated vehicles. However, on its own, at much greater expense, it provides lower risk to life benefits compared to the raising the dam by 14 metres.
- Evacuation road infrastructure options, in isolation, provide lower benefits than dam raising for risk to life. Raising Warragamba Dam controls the largest contributor of floodwaters (the Warragamba Catchment) for larger events, whereas road infrastructure upgrades must be applied across extensive parts of the floodplain.
- If the dam is raised, any subsequent regional evacuation road infrastructure upgrades would only provide modest *additional* benefits.
- The results are highly sensitive to the assumed population growth. High growth significantly increases the population unable to evacuate. This highlights the importance of integrated, regional land use and road planning to manage flood risk exposure.
- As discussed in **Section 4.4.2**, the risk to life results for dam raising are conservative because the flood evacuation model assumed that even after dam raising, the 15-hour forecast timeframe remained. In reality, the dam raising would delay most downstream flood peaks by 10 hours or more. This will further increase the risk to life benefits of the dam raising. The benefit of the delay in the flood peak will be better quantified with the Bureau of Meteorology's improved flood forecasting upgrade project (see **Section 9.2.1**) and be included in an upgraded flood evacuation model being developed to quantify the interaction of road and dam options at different development timeframes.

### *8.1.3 Economic assessment*

The Centre for International Economics (CIE) assessed the benefits and costs of the nine regional evacuation road upgrades.

The focus of the road packages was flood resilience not building capacity for day to day traffic. The upgrades included raising low points, and limited road widenings such as an additional lane only in the direction of the flood evacuation. Benefits for day to day traffic would exist to some degree, but not to a level that would ordinarily justify them on their own. For this analysis, the benefits were estimated by comparing the base case to the average annual number of vehicles (and people) unable to evacuate after implementation of the road upgrade.

The costs of road upgrades were estimated by Urban Research and Planning (URaP) and reviewed by RMS Infrastructure Delivery, based on strategic level designs, associated quantities and applicable rates for circa 2014.

The results in **Table 4.6** show that *none* of the options for evacuation road upgrades yield a net benefit. The evacuation road infrastructure option that yields the most benefit (Option 3 – lane capacity increases) yields a net *cost* of $908 million. This is partly because the benefits of upgrading evacuation roads are confined to reduced risk to life and do nothing to reduce the flood damages caused by inundation of homes and businesses.

## 8.2 Local evacuation road infrastructure upgrades

Local roads are generally those roads, managed by local council, that connect the population to major regional evacuation roads. Upgrades to local evacuation roads aim to prevent premature closure due to flash floods or to provide additional capacity to allow evacuating communities to access the major regional evacuation routes.

A working group led by Roads and Maritimes Services (RMS) in consultation with local councils in the valley, NSW SES and other stakeholders was convened to identify and prioritise potential upgrades. Previous reports were reviewed, site inspections were undertaken, and assessment criteria were developed to evaluate potential local road upgrades.

Five assessment criteria were developed:

- ***Population*** – a higher score was allocated for projects servicing larger evacuation populations
- ***Evacuation constraints*** – higher scores were allocated for local road upgrades servicing evacuation subsectors classified as ‘flood island’ or ‘trapped perimeter’ than ‘overland escape route’ or ‘rising road access’ (see **Appendix C**)
- ***Local flooding*** – a higher score was allocated to a project that addresses a site subject to local flooding prior to it being affected by backwater from the probable maximum flood (PMF)
- ***Road capacity*** – projects increasing road capacity by widening at a location or/and improving road safety or/and removing a pinch point that will derive economic benefits apart from flood immunity, were allocated a higher score
- ***Alternatives*** – a higher score was allocated to projects for which there was no alternative evacuation road option.

Around 40 high priority local evacuation road upgrades were identified as essential to maintain access to major regional evacuation routes. These were selected from a list of 177 potential projects.

The general objectives of proposed upgrades are to either:

- provide a suitably wide road surface to allow three lanes of traffic to operate during emergencies (two lanes outbound, one lane inbound) as opposed to two normally
- remove impediments to suitable width being provided at intersections for side road traffic to enter and merge into the outbound traffic lanes
- remedy sag points and drainage constraints on the road network so that the local flood evacuation roads are not cut off prematurely and rendered unusable by rising floodwater or local rainfall and runoff.

Potential treatments that would achieve these objectives include:

- widening and sealing of road shoulders to provide sufficient road width for sector traffic
- widening of drainage culverts and other constrained locations to allow the road to be widened to provide sufficient road width
- modifying traffic calming treatment such as medians at roundabouts to allow sufficient number of informal lanes to form for outbound traffic
- increasing the capacity of drains to prevent localised overflow blocking the road.

The preliminary cost for this package of local evacuation road upgrades was estimated to be around $90 million in 2016. However, more detailed field investigations are required to confirm the packages and cost.

## 8.3 Findings – evacuation road upgrades

***Regional evacuation road infrastructure***

Roads are critical for evacuating a large number of people during a flood event. The scale of the evacuation task for existing and future development scenarios was described in **Section 1.1.2**. To determine the best mix of infrastructure options to reduce the risk to life it was important to understand the relative contributions of roads and/or the dam. Nine evacuation road upgrade packages in addition to an assumed road delivery programme to 2041 were tested to determine the optimal combinations of infrastructure.

The road options that increase traffic carrying capacity at pinch points or bottlenecks, rather than road-raising improvements, provided greatest overall benefit to evacuation risk-to-life outcomes. However, even with multiple major road upgrades, they would still be less effective at reducing regional risk to life than dam raising, and were also less cost effective.

The road options do not reduce flood damages because, unlike dam raising, they do not change flood behaviour.

While major road upgrades were not taken forward in the Flood Strategy for the above reasons, a Regional Evacuation Road Master Plan in conjunction with a Regional Land Use Planning

Framework were identified as key actions to ensure that evacuation requirements are considered when regional roads are upgraded over time.

### *Local evacuation road infrastructure*

In the Taskforce's evaluation of local evacuation road infrastructure options, around 40 high priority local evacuation road upgrade projects were identified as important to maintain access to major regional evacuation routes. These were included as a short-term measure in the Flood Strategy and will be subject to detailed investigation and business cases.

# 9 Non-infrastructure options

This section outlines the approaches, investigations and analyses undertaken to support consideration of non-infrastructure options for potential inclusion in the Flood Strategy.

For the purposes of the Taskforce, **non-infrastructure options** were taken to include all management options with the potential to reduce existing, future or ongoing flood risk apart from flood mitigation and evacuation road infrastructure options. These measures include non-infrastructure approaches to reducing exposure, and improving preparedness, responsiveness and recovery from floods (**Figure 2**). They can complement flood mitigation infrastructure options and include management actions that can be implemented in the shorter term.

The non-infrastructure measures fall under three categories.

The first category includes options to reduce the existing exposure to floods of buildings, contents and people living and working on the floodplain, through removal or modification of existing dwellings located on floodplains, or by limiting future exposure of communities to floods by appropriate land use, road and emergency planning.

In this category, the following options were considered:

- regional land use planning taking into consideration flood risk
- regional road planning taking into consideration flood risk
- voluntary house purchase
- voluntary house raising.

The second category includes options that are critical to help ensure that the community is aware, prepared, and responsive to flood events that occur infrequently but have high social and economic consequences. In this category, the following options were considered:

- improved flood forecasting and warning
- community engagement and information provision
- planning and preparation for flood emergency and recovery.

The third category includes measures to improve the governance of flood risk.

The impacts of non-infrastructure measures can be broad and include:

- reduced risk to life by:
    - controlling the growth of development in floodplains
    - planning regional roads that consider flood risk
    - providing more certain warnings for evacuations
    - increasing people’s responsiveness to evacuation orders
    - improving information available to the NSW SES to plan evacuations
    - improving NSW SES rescue capabilities to benefit those who do not evacuate
- reduced flood damages by:
    - controlling the growth of development in floodplains
    - applying appropriate development controls to buildings
    - improving information available to community to prepare their properties for flood

- o improving information available to insurers, which may lead to risk being better priced and individuals taking risk mitigation measures (e.g. knock down and rebuild with higher floor levels following floods).

## 9.1 Options to reduce existing or future exposure to flood risk

### *9.1.1 Strategic floodplain land use planning*

It is recognised that risk-informed land use planning has the potential to significantly shape the risk exposure profile, especially for future development. To a lesser extent it can also change the risk profile for existing development, as redevelopment affords the opportunity to incorporate contemporary flood information into building designs.

Strategic floodplain land use planning is especially important in the Hawkesbury-Nepean Valley because of the population exposed to risk, and the large flood height range for events rarer than the 1 in 100 chance per year flood – which typically forms the flood planning level that sets minimum floor levels for houses.

The difference between the 1 in 100 chance per year flood and the probable maximum flood (PMF) is about nine metres at Windsor, compared to two to three metres in most other floodplains in New South Wales. This means that, in this valley, great depths of flooding can be experienced during floods only a little rarer than the 1 in 100 chance per year flood. While some other coastal New South Wales river valleys have significant flood depths, none have the same exposure to floods as the Hawkesbury-Nepean Valley.

Another factor requiring special consideration in relation to land use planning in the Hawkesbury-Nepean Valley is the ability to evacuate large and increasing numbers of people from land that becomes isolated before being inundated ('flood islands' see **Figure 3.4**).

#### *Previous studies*

The need for strategic land use planning has long been recognised for the Hawkesbury-Nepean floodplain, including in the following reports:

- *Hawkesbury-Nepean Flood Management Strategy – Land Use Planning and Development Control Measures* (Don Fox Planning and Bewsher Consulting, 1997)
- *Managing Flood Risk through Planning Opportunities – Guidance on Land Use Planning in Flood Prone Areas* (HNFMSC, 2006a)
- *Hawkesbury Floodplain Risk Management Study and Plan* (Bewsher Consulting, 2012).

Although the need has been long identified, policies to manage growth in the floodplain have to date had limited application and effectiveness.

The 2013 Review identified insufficient integration between state-level policies for land use planning, road planning, and emergency and recovery planning in relation to flood risk management. This resulted in inconsistent approaches to the way flood risks were incorporated into land use planning between various jurisdictions.

The Review identified that the 2007 *Guideline for Residential Development on Low Flood Risk Land* made it more difficult for councils to apply development controls for residential development on land above the 1 in 100 chance per year flood level (plus freeboard). Development controls above the 1 in 100 chance per year may be required in this valley to improve the resilience of the built urban form.

In response to the identified issues, the Review recommended the improvement of land use planning policies and practices for flood prone land. The Review also recommended improved land use planning tools for managing flood prone land. Such a tool – *Flood Information to Support Land-use Planning* – has since been prepared under the auspices of the Australian Institute for Disaster Resilience. The Review also recommended a regional approach to development to manage the cumulative effect of evacuation constraints.

### *Taskforce assessments*

A Taskforce working group progressed strategic floodplain land use planning solutions to manage the exposure of people and assets to floods. The work included:

- high level analysis of the existing planning instruments and policy tools, and a series of interviews with a wide variety of senior NSW Government and Floodplain Management Australia (FMA) representatives, to identify solutions to:
    - improve consideration of flood risk in land use planning
    - maintain benefits associated with investment in flood mitigation infrastructure at Warragamba Dam
- workshops to draft strategic land use planning solutions to respond to current and future projected flood risk.

The following key issues were raised by interview participants.

*Inadequate consideration of the full range of flood risk*

In New South Wales, control of residential development below the level of a 1 in 100 chance per year flood plus 0.5 metres freeboard is generally accepted to mitigate flood risk to dwellings to an acceptable level (e.g. *Floodplain Development Manual*, 2005, p.2). This policy is enforced through Direction 4.3 (Flood Prone Land) under the *Environmental Planning and Assessment Act 1979* (Section 9.1) and the 2007 *Guideline on Development Controls on Low Flood Risk Areas* prepared by NSW Department of Planning and Environment.

The existing policy approach does not adequately reflect the risk for the Hawkesbury-Nepean Valley given the extreme depths of flooding that can occur. Floods only moderately rarer than the 1 in 100 chance per year flood – such as the 1867 flood – can be much deeper, causing severe damages to dwellings and other businesses built at the 1 in 100 chance per year flood planning level. The 1867 flood reached a level 2.4 metres above the current flood planning level (17.3 m AHD) at Windsor.

*Unassigned responsibility for managing cumulative impacts of development on evacuation capacity and hydrology*

As a key concern, all interview participants identified the lack of consideration of flood inundation and evacuation issues on a cumulative basis across the valley. Constrained road evacuation capacity caused by development in high risk areas is a key factor in increased flood risk to life. Evacuation is a consideration of the strategic land use planning process at a regional level and also as part of the precinct planning process in the designated growth areas. However, evacuation capacity constraints generally have not been considered in strategic planning or in planning applications on a cumulative basis across the region. This is because, in the absence of a regional framework and tool to assess the impact of growth on evacuation capacity, flood risk advice from the Office of Environment and Heritage (OEH) and NSW SES has been provided across multiple planning authorities.

It is also important to consider the cumulative impacts of filling the floodplain to above the 1 in 100 year chance per year flood level on the behaviour of floods. Changes to the landscape such as filling can increase flood levels elsewhere.

*Coordinated and strategic management of flood risk in land use planning*

Local councils have primary responsibility for flood risk management in New South Wales. With eight local government areas covering the valley, achieving a coordinated and strategic management of flood risk holistically across the region is difficult. **Table 9.1** summarises current approaches to flood risk management in the various council local environmental plans (LEPs).

**Table 9.1 Flood provisions in Local Environmental Plans relevant to the study area**

| LEP | Flood planning clause | Land to which flood planning clause applies | Floodplain risk management clause (for land between FPL and PMF) | FPA Map with LEP |
|---|---|---|---|---|
| **Blacktown LEP 2015** | ✓ | At or below 1:100 ARI + 0.5m freeboard OR highest historical flood event (1867) | x | x |
| **Gosford LEP 2014** | ✓ | At or below FPL as defined by FDM | ✓ | x |
| **Hawkesbury LEP 2012** | ✓ | At or below 1:100 ARI | x | x |
| **Hornsby LEP 2013** | ✓ | At or below 1:100 ARI + 0.5m freeboard OR identified as ‘flood planning area’ on flood planning map | x | ✓ |
| **Liverpool LEP 2008** | ✓ | At or below FPL as defined by FDM | ✓ | x |
| **Penrith LEP 2010** | ✓ | At or below 1:100 ARI + 0.5m freeboard OR identified as ‘flood planning land’ on clause application map | x | ✓ |
| **The Hills LEP 2012** | ✓ | At or below 1:100 ARI + 0.5m freeboard | x | x |
| **Wollondilly LEP 2011** | ✓ | At or below 1:100 ARI + 0.5m freeboard | x | x |

All eight councils have a flood planning clause in their LEPs, but the land to which the flood planning clause applies is defined variously:

- most often, to the level of the 1 in 100 chance per year flood plus 0.5 metres freeboard
- for Hawkesbury City Council, without freeboard

- for Blacktown City Council, with either the standard 1 in 100 chance per year plus 0.5 metres freeboard definition, or extending to the limit of the flood of record (1867).

Two councils have a second floodplain risk management clause in their LEP, which applies to land between the flood planning level and the PMF extent. This controls development for certain land uses to promote the safe occupation of, and evacuation from, land in floods that exceed the flood planning level.

No councils in the valley apply a floodplain risk management clause for floods above the flood planning level to standard residential dwellings, which would require a successful application for 'adequate justification' under Direction No. 4.3 or 'exceptional circumstances' under the *Guideline on Development Controls on Low Flood Risk Areas*.

Two councils include flood planning area maps as part of their LEPs.

Despite Standard Instrument LEP Provisions and model clauses, the identified differences revealed from the comparison of LEP clauses highlighted the need for a more coordinated approach to the management of flood risk in land use planning in the valley.

An additional layer of complexity is added where authority for consent and strategic planning operates at a state level, such as through the application of some State Environmental Planning Policies (SEPPs).

The review of existing land use policies is summarised in **Table 9.2**.

**Box 9.1 Ongoing progress towards risk-informed land use planning in the valley**

Since the completion of the work of the Taskforce in 2016, a number of relevant land use policies were introduced and are included in the table. These include the *Greater Sydney Region Plan: A Metropolis of Three Cities, 2018* which provides broad direction and objectives in relation to future development within greater Sydney and has specific objectives for resilient and socially connected communities (no. 7), for adaptation to climate change (no. 36) and for reduced exposure to natural hazards (no. 37). The objectives of the plan have been given effect in draft principles for the consideration of flood risk in the Hawkesbury-Nepean Valley in the *Western City District Plan* and the *Central City District Plan*.

**Table 9.2 Taskforce assessment of existing land use planning policies and tools**

Note: A number of updates were made to bring this assessment up to 2018

| Type | Planning instruments & policies | Attributes | Benefits | Issues (drawing on interviews) |
|---|---|---|---|---|
| **State guidelines** | • Floodplain Development Manual 2005<br>• Guideline on Development Controls on Low Flood Risk Areas (2007)<br>• NSW Flood Prone Land Policy 1984 | • These documents provide detailed guidelines on floodplain risk management and are used by councils in part to fulfil Local Government requirements under the *Local Government Act 1993.*<br>• In particular, the Manual is a key consideration in *Local Direction 4.3 Flood Prone Land*, when considering rezoning land that affects flood prone land<br>• The Guideline sets the policy position of the 1 in 100 chance per year flood level as the flood planning level for residential development, unless there are exceptional circumstances | • The Manual provides a comprehensive guideline on the floodplain risk management process, primarily on how to prepare and implement a floodplain risk management plan | • The Guideline was seen to not facilitate risk-based land use planning, as it focuses on risk to the 1 in 100 chance per year flood level |
| **State strategies** | • State Infrastructure Strategy 2018 | • The 2018 State Infrastructure Strategy sets out Infrastructure NSW's independent advice on the current state of NSW's infrastructure and the needs and priorities over the following 20 years – it identifies policies and strategies needed to provide infrastructure that meets the needs of a growing population and a growing economy | • Recommendation 19 of the 2018 State Infrastructure Strategy recommends a Natural Hazards Policy to be developed by the Department of Planning, and broader strategic process to embed resilience considerations into land use planning. The recommendation was supported in principle by the NSW Government. | |

| Type | Planning instruments & policies | Attributes | Benefits | Issues (drawing on interviews) |
|---|---|---|---|---|
| **Regional strategies & plans** | • Greater Sydney Region Plan: A Metropolis of Three Cities, 2018 | • This strategy provides broad direction and objectives in relation to future development within Greater Sydney<br>• In particular, *the Greater Sydney Region Plan* has objectives for resilient and socially connected communities (7), for adaptation to climate change (36) and for reduced exposure to natural hazards (37) including in the Hawkesbury-Nepean Valley | • Provides guidance and broad policy direction for councils when preparing LEPs<br>• *The Greater Sydney Region Plan* has specific strategies to avoid locating new development in areas exposed to natural hazards (37.1) and to respond to the direction for managing flood risk in the Hawkesbury-Nepean Valley as set out in *Resilient Valley, Resilient Communities* (37.2). This elevates the issue in the planning system. | |
| | • Western City District Plan, 2018<br>• Central City District Plan, 2018 | • Planning Priority W20 gives effect to the objective to reduce exposure to natural hazards described in the Region Plan<br>• The District Plans describes the need for a risk-based approach in the Hawkesbury-Nepean Valley that considers the full range of flood sizes up to the PMF | • Provides guidance and broad policy direction for councils when preparing LEPs<br>• Describes (p.137 Western City, p.122 Central City) interim planning principles to be applied to both local strategic planning and development decisions | • Councils have two years to update their LEPs following finalisation of this District Plan, other than Hawkesbury City Council which has three years |
| **Local directions for LEPs** | • S9.1 (formerly S117) Direction: Flood Prone Land<br>• Model local provision for flood planning | • This direction requires the relevant planning authority to consider the Floodplain Development Manual and Guideline when rezoning land in a flood prone area<br>• The model local provision provides a standard clause on flood prone land which is used in council LEPs | • The S9.1 Direction proscribes planning proposals from containing provisions that apply to flood planning areas which permit development in floodways, or permit development that will result in significant flood impacts to other properties, or permit a significant increase in development of that land, or is likely result in a substantially increased requirement for government spending, etc<br>• The model provision allows for standard clauses and certainty in LEPs when adopted by councils | • The S9.1 Direction proscribes the imposition of flood related development controls for residential development on land above the 1 in 100 chance per year flood, unless there is adequate justification for such controls. This was seen to not facilitate risk-based land use planning |

| Type | Planning instruments & policies | Attributes | Benefits | Issues (drawing on interviews) |
|---|---|---|---|---|
| **SEPPs** | • SEPP [Exempt and Complying] 2008<br>• SEPP [Growth Centres] 2006<br>• SEPP [Infrastructure] 2007<br>• SEPP [Major Development] 2005<br>• SEPP [Penrith Lakes] 1989<br>• SEPP [Seniors Housing] 2004<br>• SEPP [Western Sydney Employment Area] 2009<br>• SEPP [Western Sydney Parklands] 2009<br>• SEPP 30 – Intensive Agriculture<br>• SEPP 55 – Remediation of land<br>• SREP 20 – Hawkesbury-Nepean River<br>• SREP 25 – Orchard Hills | • SEPPs guide new LEPs as well as specific development types and/or nominated areas<br>• SEPPs provide broad direction and objectives including heads of consideration for a range of developments in flood prone areas in a number of scenarios including development assessment and preparation of DCPs<br>• SEPPs can also provide detailed planning controls (e.g. Exempt and Complying SEPP) delivering well defined development outcomes | • SEPPs are higher order Environmental Planning Instruments with the ability to directly influence development outcomes | • The current SEPPs include flood planning as relevant considerations under a variety of circumstances with reference to the Manual<br>• The Codes SEPP 2008 is not set up to consider the effects of cumulative development on evacuation capacity |
| **Other state plans** | • NSW State Flood Sub Plan<br>• NSW State Storm Plan<br>• NSW Emergency Management Plan | • These Government Plans provide strategies and policy for emergency agencies in the event of an emergency<br>• They set out prevention, preparation, response and recovery arrangements for emergency events as well as coordination of emergency management services<br>• The Flood Sub Plan plans also ensure that relevant agencies have sufficient input into the flood risk management plans and are represented on floodplain risk management committees | • These plans provide comprehensive plans on dealing with natural disaster management | • Insufficient consideration of these plans in the land use planning system |

| Type | Planning instruments & policies | Attributes | Benefits | Issues (drawing on interviews) |
|---|---|---|---|---|
| **LEPs** | • Blacktown LEP 1988<br>• Gosford LEP 2014<br>• Hawkesbury LEP 2012<br>• Hornsby LEP 2013<br>• Penrith LEP 2010<br>• The Hills LEP 2012<br>• Note: DP&E advise that are a large number of additional LEPs that still apply to areas of the LGAs concerned because of deferred matters or only partial coverage of the instruments | • The LEPs provide varying degrees of controls in relation to flood prone land within each LGA<br>• The LEPs primarily utilised the model provision clause which sets out heads of consideration for development within an identified flood prone land as well as determining the appropriate flood planning level (FPL)<br>• Some of the LEPs also provide flood risk management provisions for land between FPL and PMF – heads of consideration for DA assessment<br>• The Hawkesbury LEP 2012 provides the most comprehensive provisions, prohibiting certain development in relation to flood issues | • LEPs provide the basis for land use management in the LGAs<br>• Current adoption of the standard clause by councils in the Hawkesbury-Nepean Valley ensures that flooding is a consideration at a development application stage for urban development and subdivision<br>• Adoption of standard definitions within the Manual provides certainty on land considered impacted by flooding | • Slightly different flood planning areas are used throughout the valley (see **Table 9.1**)<br>• Evacuation is specifically referenced in the flood planning clause only in Penrith LEP<br>• Addressing cumulative impacts on evacuation is challenging through LEPs alone |
| **DCPs** | Growth Centres Precinct DCP; Riverstone West Precinct DCP; Blacktown DCP 2006; Hawkesbury DCP 2002; Hornsby DCP 2013; Penrith DCP 2006/2010; The Hills DCP 2012 | • The DCPs provide more detailed planning and building controls for development impacted by flooding<br>• DCPs are prepared by local councils and/or the DP&E in the growth areas | • DCPs provide more detailed development controls to ensure appropriate at the development assessment and building stage in the development process<br>• The DCP can be a valuable tool when dealing with local flooding matters | |
| **Local guidelines, policies and strategies** | Blacktown Engineering Guide for Development 2005; Hawkesbury Development on Flood Liable Land Policy 2012; Hawkesbury Floodplain Risk Management Study 2012; Penrith Rural Lands Study 2001; Penrith Rural Lands Strategy 2003 | • These guidelines provide additional detailed policy, emergency plans and background studies in relation to flood impacts | | |

The Taskforce recommended a variety of approaches to meet the identified needs of 1) consideration of the full range of flood risk, 2) management of the cumulative impacts of development on evacuation and flooding, and 3) more coordinated and strategic flood risk management with clearer accountabilities and responsibilities:

- development and implementation of a long-term regional land use planning framework to monitor and manage the cumulative impact of development (greenfield and infill) on road evacuation capacity and potential flood damages. This would allow regional evacuation infrastructure requirements to be considered alongside the assessment of new development applications and planning proposals
- as an interim measure in advance of completing the regional approach, coordination with NSW SES, Roads and Maritime Services (RMS) and OEH to provide road evacuation capacity advice to Department of Planning & Environment for major proposals or rezonings
- development and implementation of an immediate planning response to manage permissibility in existing evacuation constrained hotspots.

These land use planning approaches depend on the availability of comprehensive, quality assured and maintained regional flood risk information, including the development of:

- a regional flood study to identify the current flood hazards from riverine flooding
- a fit for purpose regional evacuation model that identifies evacuation capacity constraints for different areas in the valley
- an asset database across the valley to inform evacuation and damages assessments.

### *Ability to maintain benefits of investment in dam raising*

Under the current land use planning system, the 1 in 100 chance per year flood level is the default planning level for local councils to set flood planning controls for residential development, unless they apply for and receive approval to impose more stringent flood controls under ‘exceptional circumstances’ as per the 2007 *Guideline on Development Controls on Low Flood Risk Areas*.

If Warragamba Dam wall was raised by around 14 metres, the water level corresponding to the 1 in 100 chance per year flood would change. For example, with a 14-metre dam wall raising, the 1 in 100 chance per year flood level at Windsor would reduce from 17.3 m AHD to about 13.5 m AHD. Expressed another way, a 14-metre dam wall raising would change the probability of a flood at Windsor reaching 17.3 metres from 1 in 100 chance per year to around 1 in 600 chance per year. Dam raising would significantly reduce but not eliminate the flood risk.

A change in the 1 in 100 chance per year flood level following flood mitigation infrastructure investment would mean that – under current policy – some areas of land currently subject to flood planning controls could be free of those controls.

All the Taskforce’s assessment of risk to life and economic damage is predicated on the *current* 1 in 100 chance per year flood planning level continuing to control residential development after the dam is raised. Therefore, changing the current flood planning level to reflect the reduced risk associated with the dam raising would undermine those flood mitigation benefits.

Based on the work of the Taskforce, the Flood Strategy contains measures to develop a suitable planning instrument so that flood-related controls continue to apply over the same area they currently apply. This instrument would be integrated with a long-term regional land use planning framework as described above.

### *9.1.2 Strategic floodplain road planning*

While options to upgrade evacuation road infrastructure were assessed to inform the Flood Strategy (see **Chapter 8**), the Review identified the need for improved strategic floodplain road planning.

The evacuation routes identified by the NSW SES for the Hawkesbury-Nepean Valley include a mixture of local, regional and state roads. The management of the roads is separated between local councils and state government (RMS). In both jurisdictions, road design and economic assessment is primarily based on projected day-to-day use requirements. There is no statutory obligation to consider:

- flood risk associated with inundation of road low points
- capacity of routes during flood evacuation
- consequential potential isolation of communities and road users in the management of these roads.

The Taskforce identified the need to develop a regional master planning approach that:

- identifies the evacuation road network
- documents the assumptions for business-as-usual road update
- sets suitable flood design standards for these roads.

The new road planning framework would also set out a process for ongoing assessment of the cumulative impacts of population growth and of the effectiveness of possible road infrastructure proposals to address the impact on flood evacuation capacities.

### *9.1.3 Voluntary house purchase*

Voluntary house purchase (VP) was considered by the Taskforce as a potential option to reduce existing exposure on the floodplain. VP can be achieved through making available funds to purchase dwellings, demolishing them, and rezoning the vacant land to a recreational or other use. Given the expense of this option, it is generally reserved only for dwellings subject to highly hazardous flood conditions and where no other feasible options are available to address the risk to life (OEH, 2013). In the Hawkesbury-Nepean Valley, other feasible options are available to mitigate the risk to life.

VP is also, by definition, voluntary – contingent for its effectiveness on the willingness of owners to sell to the Government. Residents' appetite for participating in a VP scheme is considered likely to be low in the current climate, with over 25 years since even moderate flooding was experienced in the valley, and the high demand for housing in greater Sydney. Residents' willingness to sell is likely to be increasingly lower for dwellings exposed only to increasingly rarer floods.

Another issue with any large-scale VP scheme would be the social dislocation of large numbers of households, and the associated need for new housing to accommodate them.

Despite these limitations, an assessment was undertaken to estimate the cost of purchasing all existing dwellings in the Hawkesbury-Nepean Valley modelled to be impacted by floodwater for different frequencies of flooding (see **Figure 4.6**). These costs exclude the cost of demolition and landscaping.

**Figure 9.1** shows that the cost of purchasing dwellings impacted in the 1 in 100 chance per year flood approaches $3.8 billion (2017 dollars). House purchase is cheaper than a 14-metre dam raising only if the scope of VP is confined to dwellings impacted by the 1 in 20 chance per year event or smaller floods. As risk to property and life is concentrated in the 1 in 50 to 1 in 1,000 chance per year range, limiting the scope of a VP scheme to this level of inundation would not provide a significant, regional reduction of flood risk.

The large existing urban development in the valley, the high financial and social cost, and voluntary nature of VP, precludes it as a feasible regional flood risk management option (**Table 4.3**).

### *9.1.4 Voluntary house raising*

An alternative way of reducing the risk to property is to raise the floor levels of low-set houses. One significant constraint on this option is the suitability of dwellings to be raised. Many newer dwellings in the valley are brick/slab-on-ground, which are costly or impossible to raise. Multi-storey buildings cannot readily be raised. A number of older houses in the valley are heritage listed, which also places constraints on structural changes.

The large flood height range in this valley means that for some existing houses with floor levels near the 1 in 20 year chance per year flood level, about four metres' raising would be required to elevate habitable floor levels to the level of the 1 in 100 chance per year flood (plus freeboard). This level of raising – even for dwellings identified as suitable to raise – is expected to add to costs including to ensure structural stability during large floods. Such a high level of raising may also be unacceptable to house owners due to the impacts on access, especially for the elderly or people with a disability.

Even if raised to the 1 in 100 chance per year flood level, the extreme depths of flooding for rarer floods in this valley means the dwellings would still be exposed to very serious flooding in events such as the worst flood on record (1867 flood). People in the valley would still need to evacuate their dwellings if their properties were predicted to be flooded.

The experience of flooding elsewhere shows that a certain proportion of the population will attempt to 'sit it out' in a raised house, which presents heightened risks, including: belated and dangerous attempts to evacuate through floodwater; floodwater reaching the raised floor; floodwater causing structural collapse; isolation, likely without functioning utilities; and difficulties servicing medical or fire emergencies.

The impracticality of house raising given dwelling types and the flood height range in the valley, together with disincentive for early evacuation which could exacerbate risk to life in extreme floods, means this option was not considered feasible as a regional measure for reducing flood risk.

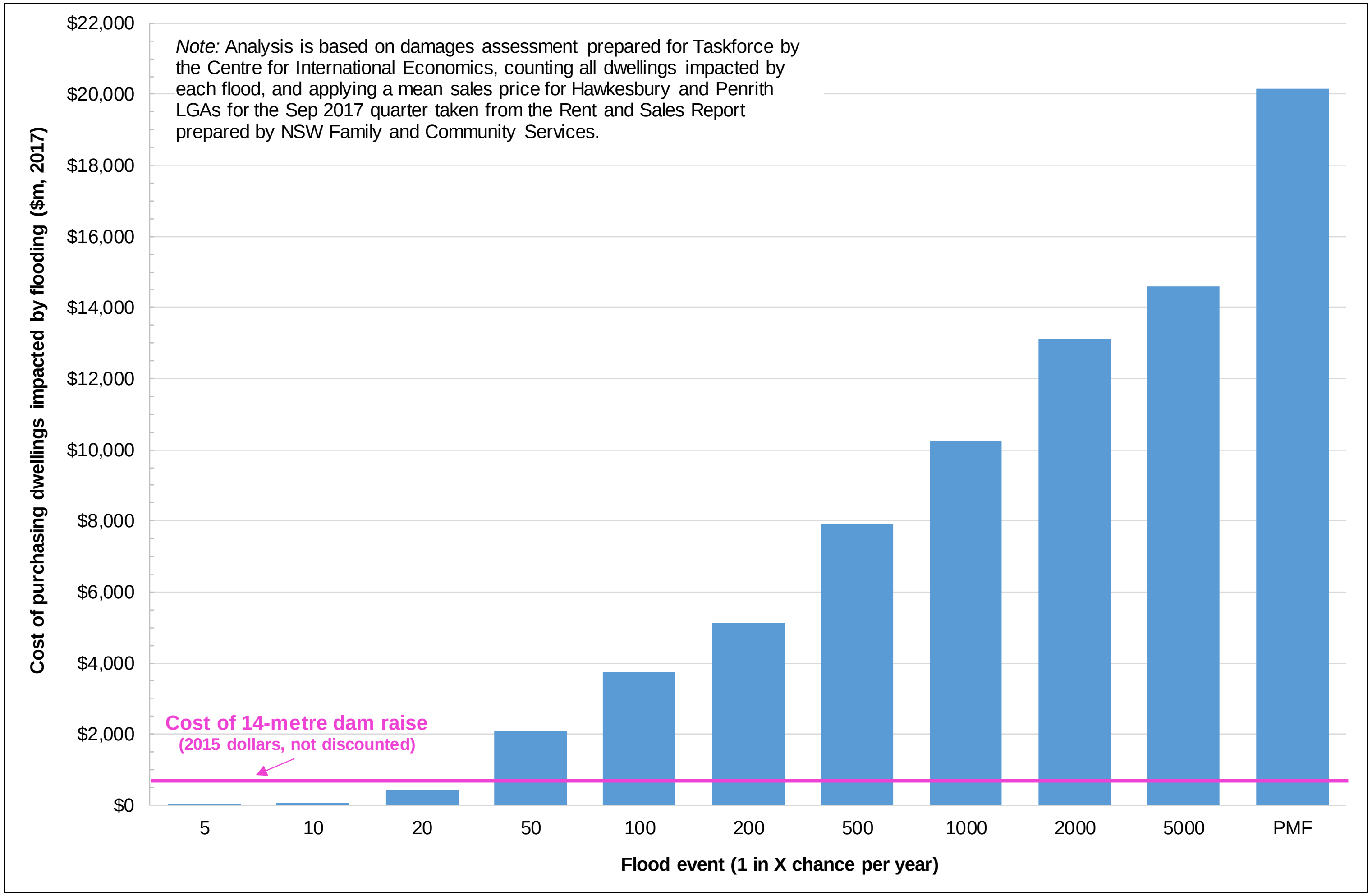



**Figure 9.1 Cost of house purchase for all dwellings in valley impacted by flood events**

*Source:* INSW

## 9.2 Options to improve awareness, preparedness and responsiveness

### *9.2.1 Improved flood forecasting and warning*

Evacuating people away from flood affected areas is critical for reducing the risk to life during a flood in the Hawkesbury-Nepean Valley. With a broad geographic area and large existing population, the NSW SES identifies mass self-evacuation by private motor vehicles as the primary method for evacuation.

Currently, there is not enough road capacity to safely evacuate the at-risk population on time, with multiple communities relying on common, constrained and congested road links as their means of evacuation. The undulating topography of the valley results in key evacuation routes becoming flooded at low points before population centres are inundated, creating flood islands. If floodwater continues to rise, these islands can be completely inundated.

Reliable and timely flood forecasts and warnings are critical for evacuation. Currently the Bureau of Meteorology (BoM) aims to provide up to 15 hours' lead time before regional flood evacuation routes from Windsor are cut (**Table 1.2**). The BoM may need to rely on forecast rather than observed rainfall to meet that target, depending on where in the catchment the rain falls and the storage level in the dams.

However, during large flood events, the NSW SES requires more than 15 hours to evacuate some flood islands in the valley (**Table 1.3**). This could force the NSW SES to issue evacuation orders based on more uncertain flood predictions. If the flood exceeds the prediction, lives could be at risk. Alternatively, if the flood does not reach the predicted level, large numbers of people could be evacuated unnecessarily, which could mean people may be reluctant to follow future evacuation orders.

The 2013 Review identified that the 15 hours' target lead time for BoM to forecast significant flooding at Windsor Bridge, and eight hours' lead time at Penrith Weir, was insufficient for a complete and safe evacuation of flood prone communities in the Hawkesbury-Nepean Valley. **Table 1.3** indicates that more than 20 hours would be required for some sectors of the floodplain.

The Taskforce therefore recommended that the BoM update their Hawkesbury-Nepean forecasting model to improve the accuracy and timeliness of flood predictions, to assist with emergency response and evacuation planning. The model would be updated through the accelerated application of the most advanced science and technology available to BoM. This work would also include:

- ensuring that accurate and reliable radar, rainfall and river observations underpin the forecasting models. With respect to the observations network, several federal, state and local government agencies operate monitoring sites in the valley to address specific agency-related management issues. A separate Flood Monitoring Working Group, established under the Review, was included in the Flood Strategy to continue to coordinate oversight of the flood warning network and to report on any potential removal of monitoring sites
- new rainfall ensemble forecasts so that the uncertainty of rainfall forecasts at longer lead times can be assessed and understood by decision makers

- improved hydrological flood forecasting models for the valley that utilise the new ensemble rainfall forecasts
- the development of tailored flood guidance products that are aligned to the needs of stakeholders.

### 9.2.2 Community engagement to increase resilience

Risk to life depends in part on the community's awareness of floods and responsiveness to evacuation warnings and evacuation orders. The risk increases if people delay or refuse to evacuate, drive through floodwaters or sightsee in flooded areas. In addition, the community's awareness and preparedness for flooding is expected to influence property damage, because 'flood-ready' households may raise or relocate movable items, invest in flood-compatible building materials, and take out flood insurance.

Community engagement and capacity building offers potential to improve community resilience through increased awareness, preparedness and responsiveness to floods. Current and reliable information is also vital to ensuring the right investments are made in infrastructure and non-infrastructure options to mitigate flood risk in the valley.

It was difficult to monetise the benefits of community engagement and information provision. The Centre for International Economics tested the benefits by considering modelled loss of life outcomes under different assumptions about behaviour response. It was found that reducing the level of non-compliance with evacuation orders from 15% to 10%, or further to 5%, would have benefits over five years of ~$150-$300 million (net present value). The benefits would be larger over a longer period.

Estimating how community engagement and education programs will change behaviour is not easy. Nonetheless, the magnitude of benefits described above, and the modest costs for providing a sustained staff resource to build and maintain community awareness, preparedness and responsiveness in the valley, indicates that the benefits comfortably outweigh the costs.

The Flood Strategy identified a number of actions to be taken to promote the goal of aware, prepared and responsive communities, including:

- develop a regional communication and engagement strategy
- upgrade evacuation route signage
- map and make available flood risk information.

#### *Regional communication and engagement strategy*

As discussed in **Section 1.1.2**, social research undertaken by the Taskforce found that the valley has a diverse population, which generally has a low level of awareness of and preparedness for flooding.

A *Communications and Community Engagement Strategy* was developed to address the findings of the social research. The Taskforce recommended a coordinated, multi-agency approach to deliver the strategic objectives of this strategy, as the task at hand requires involvement of a large number of agencies, organisations, and individuals.

The goal of the *Communications and Community Engagement Strategy* is to increase the Hawkesbury-Nepean Valley community's resilience against future flood to minimise the impact on people and property during an emergency and accelerate the recovery process. The implementation of this work was included in the Flood Strategy. The following objectives aim to achieve the overarching goal:

- improved flood information
- community capacity to prepare and respond to floods
- shared responsibility through partnerships
- support community and engagement activities for the Warragamba Dam Raising project
- strengthen government coordination
- build and grow knowledge base.

### *Upgraded evacuation signage*

As described in **Section 1.1.2**, mass self-evacuation by private motor vehicles is the primary method for evacuation in the valley. The Taskforce identified upgrading of evacuation route signage in the valley as an early priority to assist the NSW SES in improving road evacuation in case of flood. Existing flood evacuation signage, which is situated on both local and state government roads, is limited to the start of the evacuation routes, leaving drivers to largely find their own way out of the floodplain.

A new signage system would inform and guide the local population and workforce along designated evacuation routes and out of the inundation zone towards elevated population centres and formal evacuation centres.

The more comprehensive signage approach would provide consistent guidance and reassurance to evacuating motorists when they leave the district during flood emergencies, as well as playing a part in raising community awareness at other times.

**Box 9.2 Road evacuation signage**

As part of the Flood Strategy, more than 150 new signs have now been installed across the Hawkesbury-Nepean Valley. The project represents the first strategic regional approach to flood evacuation signage in New South Wales and has been a collaboration between state agencies and local government.

The design of the signage system was tested on 100 local residents using driving simulators before it was rolled out, while specific locations for the signs were selected in consultation with the NSW SES.

### *Flood risk information*

*Regional flood study, model and information platform*

Effective land use planning, flood mitigation, emergency response and community flood resilience in the valley needs to be underpinned by the best available flood risk information and mapping. The last regional flood study for the valley was done in the 1990s, and regional information on flood risk exposure of homes, businesses and critical assets had not been maintained.

The 2013 Review undertook a preliminary damages assessment to update understanding of the assets within the floodplain and associated flood risk. In light of this, the Taskforce recommended the development and maintenance of comprehensive and integrated:

- regional flood model and flood study
- spatial asset database.

A new flood study would define mainstream flood behaviour (including frequency, extent, depth, velocity, duration and rate-of-rise of floods) between Bents Basin down and Brooklyn Bridge (see **Section 3.2**).

To complement the flood study, an action was identified to develop a spatial asset database to inform assessments of risk to life and property (see **Section 3.3**).

*Web-based flood risk information access tool at property scale*

The *National Strategy for Disaster Resilience* (COAG, 2011) recognises the fundamental role of knowledge to enable everyone in the community to determine their hazards and risk and to inform preparation and mitigation activities.

The Taskforce recognised the priority of public access to quality-assured flood risk information in an understandable format. To be most effective in improving community resilience, this information needs to be linked to community education activities that help people plan for floods.

Ready access to reliable flood risk information is also required for local government, state government agencies, other infrastructure and utility providers and the insurance industry.

The Flood Strategy therefore includes an action to develop a web-based flood risk information access tool at the property scale.

*Evacuation model framework*

The Taskforce's framework and methodology to assess risk to life was informed by the purpose-built agent based (modelling individual vehicles) evacuation model by Data61 (see Section 3.4). Contemporary regional risk to life information was a key output of this work. Further refinement of the evacuation model, including better capturing the increase in flood forecast time made available via delays of flood peak, was included as an action in the Flood Strategy. This refined model would be used for:

- optimising Warragamba Dam design to maximise downstream evacuation benefits
- scenario planning for assessing cumulative impact of growth on flood evacuation capacity
- supporting information underpinning the Flood Strategy and Department of Planning & Environment's District Plans
- informing the operational use by NSW SES, RMS and Transport Management Centre during actual/training flood evacuation events and subsequent revision of the Hawkesbury Nepean Flood Plan.

*Develop and implement information management protocols*

Developing and implementing information management protocols is key to maintaining accessible and reliable flood risk information. This helps ensure the most current and verified data are available to support a range of flood risk management activities.

The Taskforce recommended ongoing monitoring, review, maintenance and updating of:

- the regional flood model, including data transfer of technical outputs to various end-users for use in local flood models
- floodplain assets database and flood damages model
- flood risk information including mapping.

*Post flood physical data collection*

Collecting physical post flood event data is essential for calibrating flood models against actual events. The 2013 Review highlighted the need for improved coordination in the collection of these data. In addition, a new regional flood model will require calibration based on contemporary regional post flood physical data.

Under the Flood Strategy, the governance and resourcing of post flood data collection is being considered in the context of an ongoing monitoring, evaluation, review and improvement framework.

### 9.2.3 Preparation for flood emergency and recovery

#### *Emergency planning*

Ensuring the capability of the emergency services to plan for and respond to infrequent floods that have high social and economic consequences is an ongoing challenge. The 2013 Review confirmed it was critical that the NSW SES should have the capacity to plan for, respond to, and manage the full range of floods in the valley.

As part of the Taskforce's work, the NSW SES conducted a series of capability exercises to test the *Hawkesbury Nepean Flood Plan*. These exercises highlighted that the emergency response to any severe flood in the valley is a resource intensive and complex operation. Specifically, to reduce risk to life, the NSW SES requires a sustained increase in its capacity and capability to plan for and manage complex emergency management operations, engage with the community, and contribute to land use planning decision-making.

The following actions are required to support ongoing capacity and capability for improved emergency response:

- review the *Hawkesbury Nepean Flood Plan* (NSW SES, 2015) for the Hawkesbury-Nepean Valley taking into account:
  - regional flood study and model outputs
  - evacuation strategy and model outputs
  - linkages with the Hawkesbury-Nepean Valley Flood Recovery Strategy
- ongoing capability assessment of the NSW SES to help ensure it has adequate resources and expertise to effectively manage and prepare for flood incidents in the valley
- test and rehearse emergency response and recovery plans and arrangements with regular exercises.

***Recovery planning***

As has been demonstrated in flooding experienced in recent years in Australia and internationally, community recovery from major floods can be prolonged and highly complex to coordinate. The impacts of these floods are felt by communities and individuals for years after the event, and in some cases, communities never fully recover.

The 2013 Review found that current flood recovery strategies for the Hawkesbury-Nepean Valley may not adequately reflect the potential short- and long-term impacts of severe flood events.

The Taskforce further investigated the adequacy of recovery planning for the valley and confirmed the need for adequate, understood and well-rehearsed recovery arrangements. It was recommended that the NSW Office of Emergency Management lead:

- development of NSW recovery arrangements for catastrophic disasters using the valley flood scenario as a case study
- implementation of a Hawkesbury-Nepean Valley flood recovery strategy (including approval from the State Emergency Management Committee).

## 9.3 Improved governance

As described in **Section 1.2**, multiple agencies are responsible for aspects of flood risk management across, national, state and local government. In New South Wales, the primary responsibility for floodplain risk management rests with local councils. However, the regional extent of flooding in the Hawkesbury-Nepean Valley impacts eight local government areas. This requires coordinated management that supports an integrated, regional strategic approach.

The 2013 Review audited roles, responsibilities and resources in relation to flood risk management in the valley. It identified a need for improved governance arrangements that support an integrated and effective approach to flood risk management in all stages of disaster management (prevention, preparedness, response and recovery).

The Taskforce further investigated accountabilities and responsibilities for flood risk management. Stakeholder interviews and workshops were held to assess in more detail agency functions, resources, gaps and potential options for improved coordination and support. The Taskforce considered the following solutions:

- establishing a special-purpose agency to lead flood risk management in the valley with dedicated legislation
- enhancing current arrangements with a dedicated group to provide coordination and oversight
- specific legislation akin to the *NSW Rural Fires Act 1997* to define responsibilities and accountability and provide appropriate powers of direction.

The Taskforce recommended the preferred approach for improving governance of flood risk management in the Hawkesbury-Nepean Valley involving a range of measures:

- enhance the current arrangements, noting the NSW Government's goal to reduce the legislative burden and a legislative approach would have state wide implications
- establish the Hawkesbury-Nepean Valley Flood Risk Management Directorate to:

- oversee implementation of a whole-of-government approach to implementing Phase 1 of the Flood Strategy (2016-2020)
- put in place a monitoring, evaluation, reporting and improvement (MERI) framework for Flood Strategy implementation to support adaptive management of flood risk in the Hawkesbury-Nepean Valley over time
- develop a final business case for the proposal to raise Warragamba Dam for flood mitigation
- make recommendations to the NSW Government for the ongoing governance and resourcing of flood risk management for the valley.

# 10 Conclusion and strategy

## 10.1 Flood problem

The Hawkesbury-Nepean Valley has a long history of widespread flooding. There have been about 130 moderate to major floods at Windsor since the 1790s. The valley has the highest flood exposure in NSW, if not Australia. This is because the unique landscape can create deep and extensive floods, with a large existing urban population exposed to inundation. In a 1 in 500 chance per year flood – similar to the flood of record in 1867 – about 12,000 residential properties would be impacted, 90,000 people would need to evacuate and the estimated damage would cost $5 billion, representing a significant impact on the New South Wales economy.

The undulating topography of the valley results in many key evacuation routes becoming flooded at low points long before population centres are inundated. Reliable and timely flood forecasts and warnings are critical for evacuation.

There hasn't been a major flood in the valley since 1990. The size and nature of the population has changed significantly since then, and a whole generation of young people has grown up without experiencing a flood.

The Bureau of Meteorology (BoM) aims to provide up to 15-hour flood level predictions for large flood events. However, the NSW SES requires more than 15 hours to evacuate some flood islands in the valley during large flood events. This could force the NSW SES to issue evacuation orders based on uncertain flood forecasts. If the flood exceeds the prediction, lives could be at risk. Alternatively, if the flood does not reach the predicted level, large numbers of people could be evacuated unnecessarily, which could cause unnecessary disruption and mean that people may be reluctant to follow future evacuation orders, putting their lives at risk. Social research shows that about 3% of people in the valley would refuse to evacuate and 27% would exercise their own judgment in deciding whether to evacuate. If only 3% of people fail to evacuate, in a 1 in 500 year chance per year flood, several hundred people would be putting their lives at risk.

The valley's high flood hazard is predicted to increase in the future as a result of climate change. Climate change has the potential to alter the frequency and severity of rainfall extremes, change rainfall patterns and increase the likelihood of flooding in the valley.

## 10.2 Assessment methods

Over four years, commencing with the 2013 Review and followed by the 2014-16 Taskforce, the NSW Government has investigated options to manage the Hawkesbury-Nepean flood problem. Consistent with a project of this complexity, some options were investigated to a pre-feasibility stage, others to a feasibility stage, and others to a detailed feasibility stage. This Taskforce Options Assessment Report brings together the results of these phased assessments into one report. It is noted that some options continue to be investigated for the Warragamba Dam Raising Environmental Impact Statement and the final business case for the NSW Government.

To facilitate the options assessment, various datasets and decision-support tools were developed, including a new regional flood study, a floodplain exposure dataset, a tailored agent-based evacuation model, and a flood damages assessment methodology (see **Chapter 3**).

In addition, key assessment criteria were established (see **Section 4.3**):

- significant, regional reduction of flood risk
- reduced risk to life
- economic costs and benefits
- social-economic, environmental and cultural heritage impacts.

## 10.3 Options assessment

A large number of infrastructure and non-infrastructure measures were considered over the years of these investigations. Infrastructure options can significantly reduce flood risk by lowering the chance of a flood event, reducing the exposure of homes and businesses to flooding, and with some options, increasing the certainty of time for evacuation. Infrastructure options considered include:

- controlling flows into the floodplains (upstream dams)
- reducing the constriction of the sandstone gorges (diversion channels, river dredging)
- protecting areas within the floodplains (levees)
- increasing evacuation capacity (road upgrades).

Non-infrastructure options can reduce the existing exposure of communities to floods through removal or modification of existing dwellings located on floodplains, or limit the future exposure of communities to floods by integrated land use, road and emergency planning. They also include measures to help ensure that the community is prepared, responsive and resilient to flood events that occur infrequently but have high social and economic consequences. Non-infrastructure options considered were:

- helping to prevent exposure through integrated land use planning and appropriate flood planning controls
- reducing existing flood risk exposure (voluntary house purchase)
- increasing community awareness, preparedness and response
- enhancing flood forecasting capability
- improving emergency and recovery planning and response
- strengthening the integration and coordination of organisations responsible for floodplain management.

**Table 10.1** summarises the findings of the options assessments. The key findings are summarised below.

**Table 10.1 Summary of options assessment**

| Option | Prevent* | Prepare | Respond | Recover | Finding | Key reason(s) |
|---|---|---|---|---|---|---|
| **Infrastructure measures** | | | | | | |
| Surcharge existing Warragamba Dam gates during floods | ✓ | | | | Not supported | Does not provide significant, regional reduction of flood risk |
| Pre-release water from Warragamba Dam before forecast flood events | ✓ | | | | Not supported | Does not provide significant, regional reduction of flood risk; risk of loss of water supply |
| Permanently lower Warragamba Dam full water supply level by 5m | ✓ | | | | Not supported | Does not provide significant, regional reduction of flood risk |
| Permanently lower Warragamba Dam full water supply level by 12m | ✓ | | | | Not supported | Provides moderate regional benefits in critical flood range but has high net cost due to high costs of addressing water supply security and water quality |
| New flood mitigation dams upstream of Warragamba | ✓ | | | | Not supported | High social, environmental and cultural heritage impacts; no sites as well suited as Warragamba |
| New flood mitigation dams downstream of Warragamba | ✓ | | | | Not supported | Does not mitigate predominant Warragamba Catchment floods |
| Raise Warragamba Dam wall by about 14m | ✓ | | | | **Supported** | Provides significant, regional reduction of flood risk; highest net benefit of all options considered |
| Raise Warragamba Dam wall by 20m | ✓ | | | | Not supported | Provides greatest flood mitigation but has lower net benefit than WD +14m; potentially higher impacts from temporary upstream inundation and downstream releases |
| Currency Creek diversion channel | ✓ | | | | Not supported | Does not provide significant, regional reduction of flood risk; high net cost; high to extreme environmental impact |
| Sackville cut-off (short diversion) | ✓ | | | | Not supported | Does not provide significant, regional reduction of flood risk |
| Sackville large diversion | ✓ | | | | Not supported | Does not provide significant, regional reduction of flood risk; extreme cost; likely extreme environmental impact |
| Dredging between Windsor and Wisemans Ferry | ✓ | | | | Not supported | High net cost; high to extreme environmental impact; must be maintained for ongoing flood mitigation |
| Levees (Peachtree Creek, McGraths Hill, Pitt Town) | ✓ | | | | Not supported | Provides local benefit only and not for severe or catastrophic floods; may discourage evacuation and increase risk of catastrophe if overtopped |
| Regional evacuation road upgrades | | | ✓ | | Not supported | Even with multiple major road upgrades, less effective at reducing risk to life than dam raising; high net cost due to large scale of upgrades; provides capacity for evacuation only – does not reduce property damages |
| Local evacuation road upgrades | | | ✓ | | **Supported** | Improves local evacuation, complementing existing regional evacuation routes |

| Option | Prevent* | Prepare | Respond | Recover | Finding | Key reason(s) |
|---|---|---|---|---|---|---|
| **Non-infrastructure measures** | | | | | | |
| Flood risk-based regional land use planning and development control | ✓ | ✓ | | | **Supported** | Essential and complementary to infrastructure measures; limits increase in future exposure; manages impact of growth on evacuation capacity |
| Flood risk-based regional road planning | | | ✓ | | **Supported** | Road evacuation master planning necessary to take account of flood evacuation risk when regional roads are upgraded for growth |
| Voluntary house purchase (VP) | ✓ | | | | Not supported | Extreme cost (billions) to significantly reduce flood risk; extreme social disruption requiring mass relocation |
| Voluntary house raising (VHR) | ✓ | | | | Not supported | Impractical due to house construction types and extreme flood depths |
| Improved flood forecasting and warning system | | | ✓ | | **Supported** | Complementary to infrastructure measures; provides increased certainty of time for evacuation |
| Community flood awareness, preparedness, responsiveness | | ✓ | ✓ | | **Supported** | Complementary to infrastructure measures; critical component for successful evacuation and resilient communities |
| Best practice emergency response and recovery | | ✓ | ✓ | ✓ | **Supported** | Complementary to infrastructure measures; critical for optimum decision-making, rescue capacity, efficient recovery |
| Improved governance of flood risk management (FRM) | ✓ | ✓ | ✓ | ✓ | **Supported** | Essential for coordination and integration of FRM and maintenance of risk reduction in valley over time |
| Collection of post-event flood data/intelligence | ✓ | ✓ | ✓ | ✓ | **Supported** | Underpins continuous improvement of flood models, emergency response and recovery plans |

* In the strict sense, flood mitigation measures and measures that target exposure such as land use planning can reduce or manage the risk but not prevent it.

### *10.3.1 Infrastructure options*

Flood mitigation infrastructure options that provide the greatest, regional benefit are those controlling floodwater from the Warragamba Catchment (**Section 4.3.1**). This is because the Warragamba Catchment provides the greatest contribution of high flows causing significant flooding in the Hawkesbury-Nepean River system. It makes up 80% of the catchment area to Penrith and 70% to Windsor, where most of the valley's flood risk is concentrated.

Raising Warragamba Dam while retaining the current full supply level (FSL) would significantly reduce flood risk by creating airspace ('flood mitigation zone' or FMZ) in the dam to temporarily hold back and slowly release floodwaters coming from the Warragamba Catchment. Several dam-raising options were examined.

Raising the dam wall by about 14 metres was taken forward in the Flood Strategy because it:

- significantly reduces risk to life by substantially reducing flood peaks in the critical flood range of 1 in 50 to 1 in 1,000 chance per year events. For example, 83% of flood events that currently reach or exceed the 1 in 100 chance per year flood level at Windsor would be prevented from reaching this critical level. This means the number of people requiring evacuation for any given event would be significantly reduced. In addition, floods would be delayed, increasing the certainty of time for people to evacuate.
- reduces damages to homes, businesses and critical assets by an average 75% per year, which is also expected to reduce insurance premiums
- provides the highest net benefit of all infrastructure options
- achieves a balance between downstream benefits and upstream impacts.

A 20-metre dam raising would provide greater mitigation of downstream flood peaks, but is less cost effective than a 14-metre dam raising. The larger FMZ created by a 20-metre dam raising poses greater challenges to meet the objectives of:

- efficiently restoring airspace behind the dam in preparation for the next flood
- minimising upstream impacts associated with temporary, incremental inundation above the flooding that can occur now
- minimising downstream impacts from releases of floodwater.

The volume of airspace created by raising the dam by 14 metres is about 30% more than the volume created by lowering FSL by 12 metres. This reflects the V-shaped valley (see **Figure 4.5**). Dam raising performs better then FSL-lowering in reducing downstream peak flood levels in the critical flood range partly due to the difference in airspace volumes.

Lowering FSL by 12 metres would also involve the loss of 39% of Warragamba Dam's water supply storage which equates to around one third of greater Sydney's storage. This would have a very significant impact on water security. Before this option could be implemented, major new sources of water would need to be built and the current desalination plant would need to be continuously operated at maximum effective capacity, with high capital and ongoing costs.

A lower FSL would also increase the risk of poor water quality in Lake Burragorang, as the reduced level of water in the dam would have a significant impact on the ability of the storage to act as a buffer to muddy water inflows.

Due to its impacts on water security and water quality, lowering FSL by 12 metres has a high net cost. This does not include the cost of significant modifications to the existing dam wall that would be required to effectively manage releases from a FMZ formed by lowering FSL.

Regional road upgrades were carefully evaluated to determine the best mix of infrastructure options to reduce the risk to life during floods, not for normal traffic conditions. Nine evacuation road upgrade packages in addition to an assumed road delivery programme to 2041 were tested.

The road options that increase traffic carrying capacity at pinch points or bottlenecks, rather than road-raising improvements, provided greatest overall benefit. However, road upgrade packages were more expensive and less effective at reducing risk to life when compared to the dam-raising options. The road upgrades also do not reduce potential flood damages to homes, businesses and critical assets because, unlike dam raising, they do not change flood behaviour. For these reasons, no major regional evacuation road options were selected for the Flood Strategy.

While dam raising was more effective than major road upgrades for reducing the existing risk, a Regional Evacuation Road Master Plan was identified as a key action to ensure that evacuation requirements are considered when the regional road network is upgraded over time.

The Taskforce identified the need for more detailed investigation of around 40 local road upgrade packages. These would address drainage and other minor constrictions in the existing evacuation road network enabling more reliable access to the regional evacuation routes.

### *10.3.2 Non-infrastructure options*

The Taskforce recognised the criticality of non-infrastructure measures for an integrated and sustainable approach to managing flood risk in the Hawkesbury-Nepean Valley.

Such an approach must include actions to integrate land use and road planning to adapt to and manage flood risk in the valley. One key measure is to review the current planning policy arrangements to account for the high flood risk above the 1 in 100 chance per year flood level in the valley. The result will be a new Regional Land Use Planning Framework, that will take account of the cumulative impacts of growth on evacuation capacity, and a Regional Evacuation Roads Master Plan. These will be critical to managing ongoing flood risk and to ensuring that the benefits of any infrastructure investment, such as the proposed raising of Warragamba Dam, are maintained in the longer term.

The Taskforce recommendations also included actions to deliver ‘an aware, prepared and responsive community’ through a coordinated and comprehensive community engagement and education program. To build their resilience to natural hazards, activities target communities of concern who are at greater flood risk, as well as the broader floodplain communities.

The Flood Strategy also has an outcome to provide ‘accessible contemporary flood risk information’. This includes the release of a new Regional Flood Study for the Hawkesbury-Nepean Valley to help local communities understand their flood risk, inform land use, road and emergency planning, and allow for more accurate pricing of flood risk.

These activities are vital given the diversity of communities and growth that has occurred since in the last major flood in 1990. Community research has shown very low levels of flood risk awareness and preparedness. If only a small percentage of residents don’t comply with evacuation orders during a major flood, many hundreds of lives will be at risk.

The Taskforce identified the need for improved flood forecasting to support emergency planning and response. The Flood Strategy also has an action for the Bureau of Meteorology to enhance their flood forecasting capability for the Hawkesbury-Nepean Valley. This will provide greater clarity about the height and timing of floods.

The Taskforce also identified a need for improved governance arrangements that support an integrated and effective approach to flood risk management in all stages of disaster management (prevention, preparedness, response and recovery). Under the Flood Strategy, new governance arrangements will support short- and long-term floodplain risk management.

The Taskforce considered voluntary purchase of flood prone dwellings as an option to reduce people’s exposure to flooding. However, as this would have very high financial and social cost, it was not taken forward into the Flood Strategy.

### *10.3.3 In conclusion*

There is no single or simple solution to the significant flood risk in the valley. Both the 2013 Review and the Taskforce recognised that an integrated mix of measures was required. The result of the options assessment was *Resilient Valley, Resilient Communities*: Hawkesbury-Nepean Valley Flood Risk Management Strategy, released in May 2017.

Nine complementary outcomes are included in the Flood Strategy (INSW, 2017; see **Section 1.3**), covering all aspects of the disaster resilience spectrum (see **Figure 10.1**). Consistent with the recommendations of the *Inquiry into Natural Disaster Funding Arrangements* (Productivity Commission, 2014), the Flood Strategy prioritises risk mitigation/management, to minimise post-disaster recovery and reconstruction.

The Flood Strategy sets out how the NSW Government, local councils, businesses and the community will work together to reduce and manage flood risk. Using this integrated and coordinated approach, Phase 1 of the Flood Strategy is currently being implemented. Under an adaptive management framework, ongoing implementation will be monitored, evaluated, reviewed and improved to better protect the communities of the Hawkesbury-Nepean Valley from the very real risks posed by major floods.

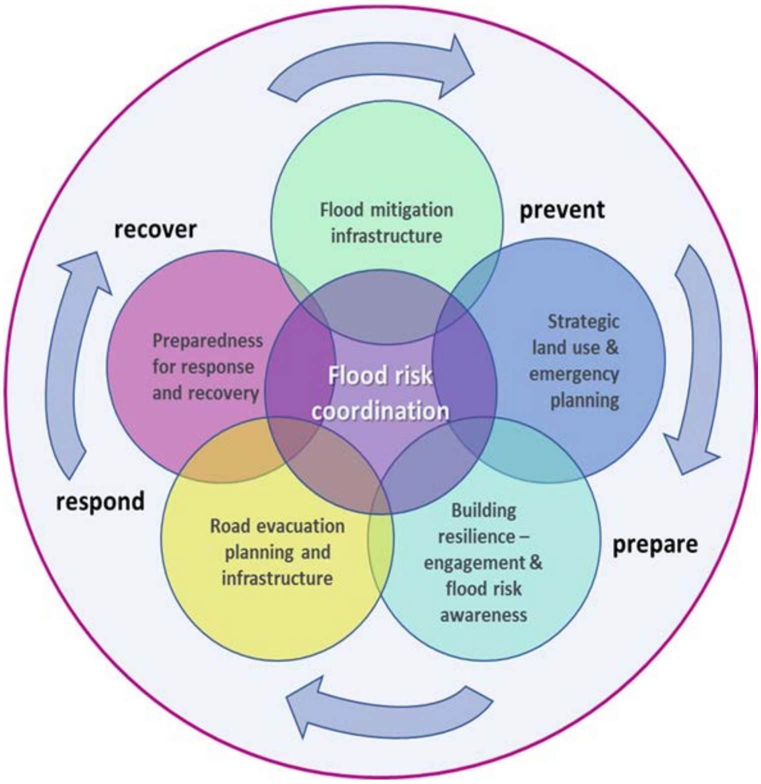



**Figure 10.1 Interaction of Flood Strategy components with emergency management framework**

*Source:* INSW

# References

Advisian (2018). *Nepean River Flood Study*, Final Report, prepared for Penrith City Council, November 2018.

AIDR (Australian Institute for Disaster Resilience) (2017). *Australian Disaster Resilience Handbook 7, Managing the Floodplain: A Guide to Best Practice in Flood Risk Management in Australia*, 3rd edition. AIDR, East Melbourne.

ANZECC (Australian and New Zealand Environment Conservation Council) and ARMCANZ (Agriculture and Resource Management Council of Australia and New Zealand) (2000). *National Water Quality Management Strategy*.

AWACS (Australian Water and Coastal Studies Pty Ltd) (1997). *Lower Hawkesbury River Flood Study*, Final Draft, prepared for Department of Land and Water Conservation, April 1997.

Ball, J., Babister, M., Nathan, R., Weeks, W., Weinmann, E., Retallick, M., Testoni, I. (eds) (2016). *Australian Rainfall and Runoff: A Guide to Flood Estimation*, Commonwealth of Australia.

Bewsher Consulting (2012). Hawkesbury Floodplain Risk Management Study and Plan: Volume 1: Main Report; Volume 2: Town Planning Issues; Volume 3: Flood Maps and Annotated Bibliography. Sydney NSW.: Report prepared for Hawkesbury City Council's Floodplain Risk Management Advisory Committee. December 2012.

BoM (Bureau of Meteorology) (2017). *Service Level Specification for Flood Forecasting and Warning Services for New South Wales and the Australian Capital Territory – Version 3.0*, February 2017.

Bracewell, M.G. & McDermott, G.E. 1985, *Report on the 1867 Flood*, Metropolitan Water Sewerage and Drainage Board.

COAG (Council of Australian Governments) (2011). *National Strategy for Disaster Resilience: Building the Resilience of Our Nation to Disasters*, Attorney General's Department, Canberra.

Corringham, R. (1988). Preliminary survey of *Eucalyptus benthamii* in Kedumba Valley. Prepared for Sydney Water Board.

Danielson & Associates, Patterson Britton & Partners and Masson & Wilson (1997). *Emergency Response and Traffic Infrastructure*, prepared for Hawkesbury-Nepean Flood Management Advisory Committee, September 1997.

DEWHA (Department of the Environment, Water, Heritage and the Arts) (2008). *National Framework for Describing the Ecological Character of Australian Ramsar Wetlands*.

Don Fox Planning and Bewsher Consulting (1997). *Land Use Planning and Development Control Measures*, prepared for Hawkesbury-Nepean Flood Management Advisory Committee, October 1997.

ERM Mitchell McCotter (1995). *Proposed Warragamba Flood Mitigation Dam – Environmental Impact Statement* (Volumes 1, 2 and 3). Report prepared for the Warragamba Dam Flood Mitigation Program, managed on behalf of the NSW Government by Sydney Water Corporation Ltd. July 1995.

Gissing, A. (2015). 'Human behaviour during natural hazard emergency evacuations', Briefing Note No. 301, Risk Frontiers, Sydney.

GSC (Greater Sydney Commission) (2018a). *Western City District Plan – connecting communities*. March 2018.

GSC (Greater Sydney Commission) (2018b). *Central City District Plan – connecting communities*. March 2018.

HNFMAC (Hawkesbury-Nepean Flood Management Advisory Committee) (1997). *Achieving a Hawkesbury-Nepean Floodplain Management Strategy*, November 1997.

HNFMSC (Hawkesbury-Nepean Floodplain Management Steering Committee) (2004). *Hawkesbury-Nepean Floodplain Management Strategy Implementation*, October 2004.

HNFMSC (Hawkesbury-Nepean Floodplain Management Steering Committee) (2006a). *Managing Flood Risk through Planning Opportunities – Guidance on Land Use Planning in Flood Prone Areas.* Parramatta, NSW: HNFMSC. June 2006.

HNFMSC (Hawkesbury-Nepean Floodplain Management Steering Committee) (2006b). *Designing Safer Subdivisions – Guidance on Subdivision Design in Flood Prone Areas.* Parramatta, NSW: HNFMSC. June 2006.

HNFMSC (Hawkesbury-Nepean Floodplain Management Steering Committee) (2006c). *Reducing the Vulnerability of Buildings to Flood Damage – Guidance on Building in Flood Prone Areas.* Parramatta, NSW: HNFMSC. June 2006.

Hunter, J. (1793). *An Historical Journal of Events at Sydney and at Sea 1787-1792*, ed. John Bach (1793; repr., Sydney: Angus and Robertson, 1968), 105-6.

Hunter, Governor J. (1799). Letter to Duke of Portland, 1 May 1799, *Historical Records of New South Wales*, vol. 3, p.668.

INSW (Infrastructure NSW) (2012). *First Things First – The State Infrastructure Strategy 2012–2032*, October 2012.

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

Josephson, J.P. (1885). 'History of floods in the Hawkesbury River', *Journal of the Royal Society of New South Wales*, 19, 97-107.

Karskens, G. (2016). 'Floods and flood mindedness in early colonial Australia', *Environmental History*, 21, 315-342.

King, Governor P.G. (1806). Letter to Earl Camden, 7 April 1806, *Historical Records of New South Wales*, vol. 6, p.61.

MWD (Metropolitan Water Directorate) (2017). *2017 Metropolitan Water Plan: Water for a Liveable, Growing and Resilient Greater Sydney*, Department of Industry, Skills and Regional Development.

Molino Stewart (1997). *Impacts of Flooding on Communities and Infrastructure*, prepared for Hawkesbury-Nepean Flood Management Advisory Committee, September 1997.

Molino Stewart (2012). *Hawkesbury-Nepean Flood Damages Assessment*, prepared for Infrastructure NSW, September 2012.

Neville, M.J. (1976). *Sand Resources of the Hawkesbury River System between Windsor and Brooklyn*. Sydney: Geological Survey of NSW, Department of Mines. September 1976.

Newgate Research (2014a). *Social Research on Floods in the Hawkesbury Nepean Valley. Qualitative Research Report*, September 2014.

Newgate Research (2014b). *Social Research on Floods in the Hawkesbury Nepean Valley. Quantitative Research Report*, September 2014.

NSW Government (2005). *Floodplain Development Manual: The Management of Flood Liable Land*, April 2005.

NSW Office of Water (2014a). Hawkesbury-Nepean Valley Flood Management Review - Stage One: Summary Report. Sydney, NSW: NSW Department of Primary Industries, Office of Water. March 2014.

NSW Office of Water (2014b). Hawkesbury-Nepean Valley Flood Management Review - Stage One: Review Report. Sydney NSW: NSW Department of Primary Industries, Office of Water. March 2014.

NSW SES (State Emergency Service) (2015). *Hawkesbury Nepean Flood Plan: A Sub Plan of the State Emergency Management Plan* (SEMP). September 2015.

OBPR (Office of Best Practice Regulation, Department of the Prime Minister and Cabinet) (2014). *Best Practice Regulation Guidance Note Value of Statistical Life*. https://www.pmc.gov.au/sites/default/files/publications/Value_of_Statistical_Life_guidance_note.pdf

OEH (Office of Environment and Heritage) (2013). *Floodplain Management Program Guidelines for voluntary purchase schemes*, OEH 2013/0055, February 2013.

Productivity Commission (2014). *Natural Disaster Funding Arrangements*, Inquiry Report no. 74, Canberra.

Rawlinsons (2012). *Australian Construction Handbook*, Rawlhouse Publishing.

Saynor, M.J and Erskine, W.D. (1993). Characteristics and implications of high-level slackwater deposits in the Fairlight Gorge, Nepean River, Australia. *Australian Journal of Marine and Freshwater Research* 44(5) 735-747.

TfNSW (Transport for NSW) (2016). *Principles and Guidelines for Economic Appraisal of Transport Investment and Initiatives,* Transport Economic Appraisal Guidelines. https://www.transport.nsw.gov.au/sites/default/files/media/documents/2017/principles-and-guidelines-for-economic-appraisal-of-transport-investment.pdf

UNISDR (The United Nations Office for Disaster Risk Reduction) (2015). *Sendai Framework for Disaster Risk Reduction 2015-2030*, Geneva, Switzerland.

Warner, R.F. (2009). 'Secular Regime Shifts, Global Warming and Sydney's Water Supply', *Geographical Research*, 47(3), 227-241.

WMA (Webb, McKeown & Associates) (1996). *Warragamba Dam Auxiliary Spillway Environmental Impact Study – Flood Study*.

WMA (Webb, McKeown & Associates) (1997). *Engineering Studies to Modify Flood Behaviour*. prepared for Hawkesbury-Nepean Flood Management Advisory Committee, September 1997.

WorleyParsons (2012). Hawkesbury River Dredging Investigations Summary Report, prepared for Hawkesbury City Council, August 2012.

WorleyParsons (2015). Hawkesbury Nepean Valley Flood Management Review. Review of Non-Dam Flood Mitigation Option Cost Estimates, prepared for the Taskforce.

Yeo, S., Bewsher, D., Robinson, J. and Cinque, P. (2017). 'The June 1867 floods in NSW: causes, characteristics, impacts and lessons', paper presented to 2017 Floodplain Management Australia National Conference, Newcastle.

# Glossary of terms

| | |
|---|---|
| 2013 Review | The Hawkesbury-Nepean Valley Flood Management Review. |
| Australian Height Datum (AHD) | A common national surface level datum corresponding approximately to mean sea level. It is used to measure height above sea level throughout Australia. It is also used to express the level or height of flooding associated with each chance per year flood. |
| Chance per year | Refers to the chance of a certain level of flooding occurring in any one year. The chance that a certain level of flooding occurs in any one year is not related to the timing of other floods.<br>For example, a 1 in 100 chance per year flood refers to a level of flooding with a 1 in 100 (or 1%) chance of occurring or being exceeded in any one year, regardless of whether that level or other levels of flooding have occurred in that year. |
| Flood mitigation zone (FMZ) | The airspace in a dam between the normal full water supply level (FSL) and the maximum storage level, reserved specifically for temporarily storing flood inflows. |
| Flood risk | Flood risk is a combination of the likelihood of occurrence of a flood event and the consequences of that event when it occurs. |
| Flood level | The level or height of flooding associated with each chance per year flood. This is often expressed in metres above mean sea level (AHD). |
| Flood Strategy | Hawkesbury-Nepean Valley Flood Risk Management Strategy released in May 2017. |
| Floodplain Development Manual 2005 | The NSW Government's Manual relating to the management of flood prone land in accordance with section 733, *Local Government Act 1993*. |
| Full water supply level (FSL) | Refers to full water supply level of Warragamba Dam. |
| Gigalitres (GL) | 1 GL = 1 billion litres of water or 1000 megalitres of water |

| | |
|---|---|
| Major, moderate and minor flooding | Both the NSW SES and the Bureau of Meteorology use the following definitions in flood warnings to give a general indication of the types of problems expected with a flood.<br>major flooding (≥12.2m at Windsor gauge): appreciable urban areas are flooded and/or extensive rural areas are flooded. Properties, villages and towns can be isolated.<br>moderate flooding (7.0-12.1m at Windsor gauge): low-lying areas are inundated requiring removal of stock and/or evacuation of some houses. Main traffic routes may be covered.<br>minor flooding (5.8-6.9m at Windsor gauge): causes inconvenience such as closing of minor roads and the submergence of low-level bridges. The lower limit of this class of flooding on the reference gauge is the initial flood level at which landholders and townspeople begin to be flooded. |
| Probable maximum flood (PMF) | The largest flood that could reasonably occur at a particular location (see *Floodplain Development Manual* and associated guidance). |
| Quantile | A defined probability. |
| Reduced Level (RL) | Refers to metres AHD unless otherwise indicated. |
| Taskforce | The Hawkesbury-Nepean Valley Flood Risk Management Taskforce (2014-2016), which progressed the work and recommendations of the 2013 Review. |

# Appendices

# Appendix A Taskforce Terms of Reference

The terms of reference include the following objectives:

1. Deliver a Hawkesbury-Nepean Flood Risk Management Strategy to reduce the risk to life and potential impact on the economy
2. Undertake cost benefit analysis of flood mitigation infrastructure options (road evacuation and flood mitigation infrastructure investment)
3. Investigate community education programs and further investigate community response to flood risk
4. Develop an evacuation modelling decision support tool to enable development of a road evacuation strategy
5. Identify local road upgrades that could provide improvements in the short term to evacuation capacity
6. Identify regional road upgrades that could provide improvements in the longer term to evacuation capacity
7. Identify current and approved future development in the floodplain to inform the cost benefit analysis
8. Strategically consider flood risk management in land use planning to minimise risk associated with ongoing development
9. Develop governance reforms to create an enduring and effective whole of NSW Government response to flood risk for Hawkesbury-Nepean Floodplain
10. Seek an agreed approach and consistent use of flood modelling and other data for the region
11. Contribute to the development of the Department of Planning and Environment’s natural hazards planning policy
12. Investigate options for changed operation of the existing Warragamba Dam for flood mitigation
13. Consider linkages with related government processes (including Metropolitan Water Supply Plan and Penrith Lakes Scheme)
14. Develop a Hawkesbury-Nepean Flood Recovery Plan including plans for reconstruction of essential infrastructure
15. Review Hawkesbury-Nepean Flood Emergency Sub Plan
16. Capability assessment of gaps in emergency evacuation plans

# Appendix B Taskforce floodplain assets database – methodology and assumptions for describing current and future exposure in Hawkesbury-Nepean floodplain

## *Introduction*

This Appendix documents the assumptions and methodology for assessing ‘existing’ and ‘future’ development, which were used across all projects undertaken by the Hawkesbury-Nepean Valley Flood Management Taskforce (the Taskforce), particularly:

- collating a suite of information relating to ‘existing’ and ‘future’ development in the Hawkesbury-Nepean Valley in and near the floodplain
- developing a methodology by which the impacts of ‘existing’ and ‘future’ development on flood risk can be assessed through a number of different numerical models.

The information required for Taskforce projects included those assets that would be affected by flooding up to the level of a probable maximum flood (PMF), whether by direct inundation or through isolation during a flood event. A PMF is the largest flood that could reasonably occur. The floodplain or flood prone land is defined as those areas inundated by a PMF. The information required by Taskforce projects was divided into the following four categories:

- **residential dwellings, population and vehicles** – this includes ‘existing’ development and ‘future’ development including the North West Growth Area, other large urban release areas and infill development
- **employment lands** – this covers all business, commercial and industrial land uses, including commercial and industrial buildings, businesses, employees and vehicles
- **utilities, infrastructure and other public assets** – such as schools, hospitals, water and sewerage infrastructure
- **roads**.

The focus of this Appendix is the ‘existing’ and ‘future’ development on residential lands, employment lands and utilities, infrastructure and other public assets. Information for the roads component of the floodplain assets database was collated and addressed separately.

## *Hawkesbury-Nepean Floodplain Assets Database*

The information gathered under the four categories above is collectively known as the ‘floodplain assets’ with the information held about each asset contained within the **Hawkesbury-Nepean Floodplain Assets Database** (the floodplain assets database). The structure of the floodplain asset database is shown in **Figure B.1**.

The floodplain assets database comprises two key datasets:

- ***evacuation modelling dataset*** – the key output of this dataset is the number of vehicles (and population) from residential and employment lands that require evacuation planning at a NSW SES subsector scale for the purposes of evacuation modelling. Those vehicles requiring evacuation planning are defined as those from residential properties and businesses below the level of a PMF in the Hawkesbury-Nepean floodplain or isolated in a PMF in the Hawkesbury-Nepean floodplain

- ***flood damages dataset*** – the key output of this dataset is the spatial location and associated property characteristics of individual residential dwellings and buildings on employment lands, utilities and infrastructure below the level of a PMF in the Hawkesbury-Nepean floodplain for the purposes of the flood damages assessment.

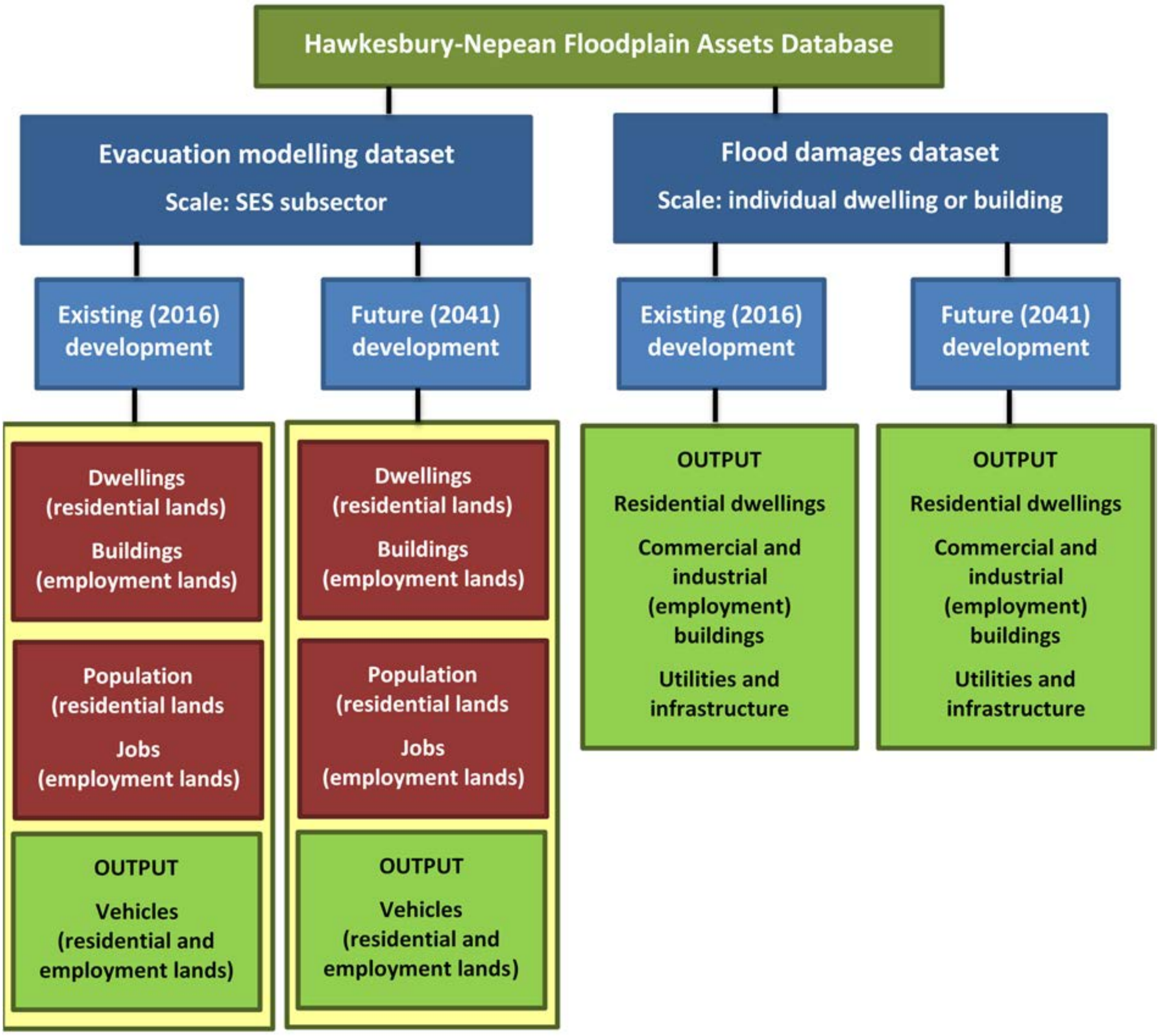



**Figure B.1 Structure of Hawkesbury-Nepean Floodplain Assets Database**

*Source*: INSW

An important consideration in the collation of information of ‘existing’ and ‘future’ development was to define when ‘existing’ development ends and ‘future’ development starts. At the time of the Taskforce projects around 2014-2015, much of the available information for ‘existing’ development was based on 2011 Census data and so the floodplain assets database was established with 'existing' development based to the level of development in 2011. The 2011 level of 'existing' residential development was later extrapolated so that 2016 represented the level of 'existing' residential development.

For 'future' development, 2041 was adopted to represent the potential development of the floodplain. The year 2026 was adopted to represent an intermediate level of development.

For the evacuation modelling dataset, the key output is the number of vehicles that would require evacuation planning on a NSW SES subsector scale. It was concluded that a direct spatial count of vehicles would not be available in the time available therefore the methodology outlined in **Figure B.2** was used to estimate the final vehicle numbers.

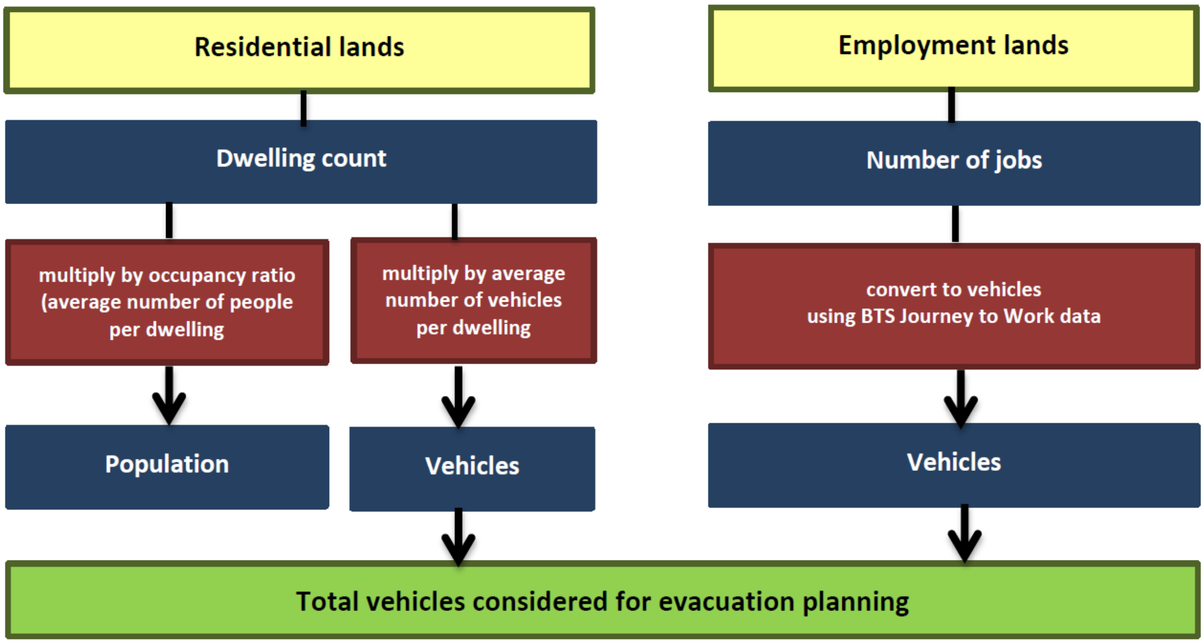



**Figure B.2 Overview of methodology for developing evacuation modelling datasets**

*Source*: INSW

An extensive review of all available data across state and local government sources was undertaken to establish both the evacuation modelling dataset and flood damages dataset. Outputs from each dataset were developed using a broad range of sources including Blacktown, Hawkesbury, Penrith and The Hills Councils, NSW Bureau of Transport Statistics (BTS), NSW Planning and Environment and previous data collection projects undertaken by Molino Stewart Pty Ltd.

Following a review of spatial mapping information available the following base mapping data were used and developed for the floodplain assets database:

- Modelling prepared by WMAwater (supplied to the Taskforce in 2014) was used as the sole source of information for determining the *extent* of the flood assets database, including the total number of vehicles for evacuation modelling.

- Modelling prepared by WMAwater (supplied to the Taskforce in 2015) was used as the sole source of information for determining *flood levels* for individual properties with and without flood mitigation options. The results were also used for hydrographs at key locations on the road network for evacuation modelling.
- The 2011 LPI aerial photography (and 2008 aerial photography in the downstream areas of the study area) was used as the principal source of data for Taskforce projects. The 2013 LPI aerial photography was used in limited situations as a comparison to the 2011 photography. Google Maps© and Google Street View© (October 2015) were used to extrapolate the 2011 residential dataset to the 2016 dataset.
- The 2011 LPI LiDAR was used as the sole source of topographical data for Taskforce projects.
- Zoning and land use information from Department of Planning & Environment (PDF and GIS) were used as the sole source of data for Taskforce projects.
- Many of the geo-spatial layers (particularly the fundamental, locational and infrastructure layers) of the Emergency Information Coordination Unit (EICU) Emergency Services Spatial Information Library (ESSIL) dataset, licensed to the NSW SES, were used as the sole source of data for Taskforce projects.
- The EICU ESSIL dataset was the primary source of cadastral and property information for Taskforce projects.

## *'Existing' development datasets*

### *Residential*

The principal source of data for existing residential development was the 2011 Data Collection Project (developed for Infrastructure NSW by Molino Stewart Pty Ltd), supplemented by additional data collated by the Taskforce. The 2011 Data Collection Project updated and expanded a dataset prepared by the Australian National University in 1988 as part of the 1995 *Warragamba Flood Mitigation Dam Environmental Impact Statement* (ERM Mitchell McCotter, 1995). It was used to determine the following attributes for each dwelling in the floodplain:

- spatial locations of residential buildings
- property characteristics such the construction materials, number of storeys, relative size of the dwelling
- floor height above ground level – using the 2011 LIDAR for ground levels at individual dwellings, the 'floor height above ground level' was based on a combination of:
  - field estimations of 'floor height above ground level' for individual properties
  - estimations of 'floor height above ground level' using Google Street View
  - three-dimensional vehicle laser survey (FAST Survey™)
  - relationship of typical 'floor height above ground level' developed from the FAST Survey™.

Occupancy ratios (number of people per dwelling) and the number of vehicles per dwelling were derived from the 2011 Census at a suburb scale and then applied at a NSW SES subsector scale.

### *Commercial/industrial*

The 2011 Data Collection Project was also used to develop a dataset of commercial/industrial properties, used for flood damages assessment. Attributes for each property included:

- building footprint area in square metres
- commercial or industrial categorisation based on land zoning information
- number of storeys
- floor height above ground level – assumed to be zero for the ground floor. The floor height above ground level for buildings with multiple levels was calculated assuming the height between building levels is three metres.

### *Evacuation from employment lands*

The principal source of data for estimating existing and future jobs, and hence the number of vehicles from employment lands for evacuation planning at a NSW SES subsector scale, was the 2011 BTS Employment Forecasts. The main input to the employment forecasts is the ABS Census 'Journey to Work' data. The Taskforce concluded that the BTS data, combined with current zoning of employment-related land, provided the best base data to estimate the number of vehicles from employment lands for evacuation planning.

BTS has divided the Greater Sydney Metropolitan Area into nearly 3,000 Travel Zones, of which nearly 200 Travel Zones cover the Hawkesbury-Nepean floodplain. BTS provides forecasts of employment (jobs), population and dwellings at a Travel Zone scale across 34 industry categories for each Census year from 2011 to 2041 (BTS, December 2014). Using the BTS data, it was necessary to develop a simplified method for estimating the number of jobs for each NSW SES subsector across the floodplain, as follows:

- aggregate the approximately 20 employment-related land use zones into one of the following four categories: business, industrial, education/health/recreation or rural
- aggregate the 34 different BTS industry categories into the same four categories – the BTS employment data includes jobs for utilities and infrastructure where jobs are associated with that asset such as hospitals, schools and emergency services
- apportion the BTS data spatially to the relevant NSW SES subsector based on the proportion of the area of the Travel Zone within each subsector affected by a PMF.

For the evacuation modelling dataset, the number of vehicles that need evacuation planning was required on a NSW SES subsector scale. The most conservative assumption would be to assume that for every job in the floodplain, there would be one vehicle requiring evacuation planning. However, the Taskforce / NSW SES agreed that this assumption was too conservative and so a methodology was required to estimate the number of vehicles requiring evacuation from the number of jobs in the floodplain. An analysis of the BTS Journey to Work data was undertaken to estimate the likely number of vehicles per job that could be expected within the Hawkesbury-Nepean floodplain. It was found that:

- 67,800 of employees live and/or work in a travel zone that is at least 50% affected by a PMF.
    - Around 55% (37,300) of these employees live in a travel zone which is less than 50% affected in a PMF but work in a travel zone that is more than 50% affected by a PMF. This means that the main flow of journeys to work is from an area of lower flood risk to an area of higher flood risk.
    - Around 29% (19,400) of these employees live in a travel zone which is more than 50% affected by a PMF but work in a travel zone that is less than 50% affected by a PMF, that is a flow of journeys to work from an area of higher flood risk to an area of lower flood risk.
    - Only 16% (11,100) of these employees live and work within travel zones that are at least 50% affected by a PMF.

The analysis of journey to work data also found that approximately two-thirds of the 30,500 people who live in a travel zone at least 50% affected by a PMF, travel to work as a 'single driver', that is, one person in a car. The next popular mode of travel is 'passenger in car', followed by public transport and cycling and walking.

Using the results of the analysis of the BTS Journey to Work data, the following conclusions were made:

- The 45% (30,500) of employees who live in the more flood-affected travel zones (at least 50% affected by a PMF) are not likely to go to work in a flood event.
- The remaining 55% of employees who live in less flood-affected travel zones (less than 50% affected by a PMF) will add to the evacuation planning requirements of the valley.
- If two-thirds of the employees who will add to the evacuation planning requirements travel to work as a 'single driver', then the total number of vehicles from employment lands to be included in evacuation planning is approximately 40% (two-thirds of 55%) of the total number of employees.
- It was therefore assumed for evacuation modelling purposes that the total number of vehicles from employment lands to be included in evacuation planning is 40% of the total number of employees, or 1 job = 0.4 vehicles requiring evacuation planning.

## *'Future' Development (2026 and 2041) datasets*

### *Residential*

'Future' residential development in the floodplain assets database comprised the following two components as shown on **Figure B.3**:

- ***Future Development Areas*** – Future Development Areas is the collective term that includes the North West Growth Area, other urban release areas, large proposed subdivisions and other identified multi-level medium and high-density sites with any part of the area located below the PMF
- ***permissible infill development*** – for the purposes of Taskforce projects, permissible infill development included additional residential dwellings such as dual occupancies and town house developments that could be constructed within existing urban areas in

locations where the existing land zoning already permits that land use with an increased density below the level of the PMF.

It was assumed that infill development would not occur on lands that would have to be rezoned for that development to occur and that any infill development would occur under the current state government policy framework. Secondary dwellings and granny flats were not included in permissible infill development.

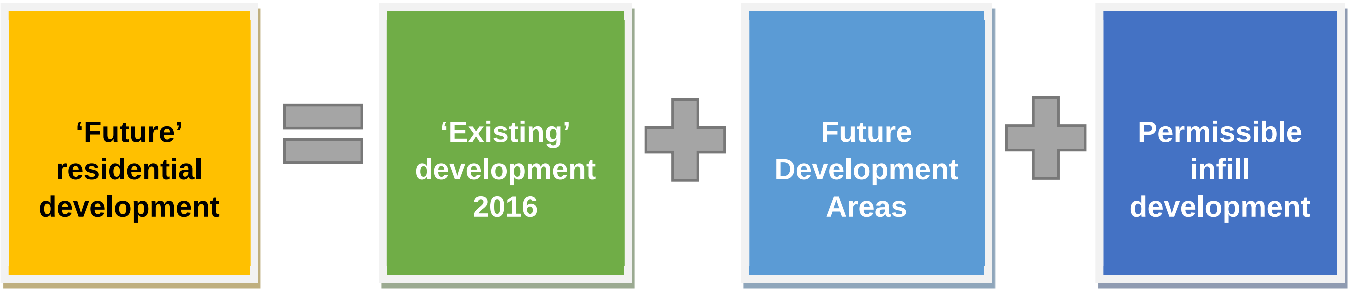



**Figure B.3 Components of 'future' residential development**

*Source*: INSW

For future development, 2041 was adopted as a reasonable point in time to represent the potential development of the floodplain that could occur under current planning policies and various growth rates. The 2041 development scenarios do not represent a growth target but provided a means to test the sensitivity of future flood risk to growth, and to measure the effectiveness of potential flood mitigation options. The year 2026 was adopted to represent an intermediate level of development.

The overlying aim for future residential development in the floodplain assets database was to estimate a hypothetical spatial location for every future dwelling within the Hawkesbury-Nepean floodplain, both below the PMF and isolated in a PMF.

A review of relevant available information at the commencement of the project concluded that no single data source for future residential development was suitable for direct use by Taskforce projects. Despite limitations of each of the data sources to be used directly, valuable information from each contributed to the development of datasets for future residential development.

Therefore, separate methodologies were developed for Future Development Areas and permissible infill development to determine these spatial datasets. These methodologies are summarised below.

### *Future Development Areas*

The following additional data collection, value-adding and data development tasks were undertaken by the Taskforce to develop the Future Development Areas datasets:

1. develop master list of Future Development Areas
2. review master list of Future Development Areas to determine those included in Taskforce projects

3. categorise each of the Future Development Areas into one of the following:
    - permissible development – this included all lands that were zoned for development, or which had development approval but were not yet constructed, as at December 2014. Those precincts within the North West Growth Centre covered by an Indicative Layout Plan were included as 'permissible' development.
    - potential development – this includes all lands that were formally identified and/or were in the planning process but were yet to be rezoned as at December 2014. Those precincts within the North West Growth Centre that were not covered by an Indicative Layout Plan at December 2014 (either they have not been released or are in Precinct Planning Phase) were included as 'potential' development including Marsden Park North, Riverstone East, Schofields West, Shanes Park and Vineyard.
    - possible development – this includes residential and employment lands that were identified as long-term options and are more speculative in nature. This includes 'future' development areas that were formally identified as having flood evacuation constraints, for example, Penrith Lakes Parklands and Bligh Park North.
4. develop methods to estimate the 'hypothetical' spatial location of future dwellings for each Future Development Area. Four methods were used depending on the amount of information available:
    - dwellings per hectare was available as a spatial layer
    - hard copy subdivision layout was available, which was scanned and geo-referenced
    - only the precinct boundary was available as a spatial layer with the assumption that there would be only one level of dwelling on a land parcel
    - only the precinct boundary was available as a spatial layer with the assumption that there would be more than one level of dwelling on a land parcel
5. complete dwelling count of future dwellings within Future Development Areas
6. estimate occupancy ratios for future (2041) residential development (by scaling the values used for 2011 by the difference between 2011 and 2041 BTS data from their Population Forecasts)
7. apply a constant value of 0.4 vehicles per dwelling for Future Development Areas.

### *Permissible infill development*

A separate methodology was developed for estimating projected levels of infill urban development to test the sensitivity of different rates of infill development on evacuation capacity and flood damages. Many factors affect the rate of infill development, particularly the state of the economy and policy drivers.

The aim for the infill development component of the floodplain assets database was to estimate the spatial location of permissible infill development below a PMF event and isolated in a PMF. During the course of the Taskforce assessments, it was identified that the calculated level of infill development may be an over-estimate. To test the sensitivity of changes in the rates of infill development between 2011 and 2041 on evacuation capacity and flood damages, a ‘lower level’ of permissible infill development was also calculated. The lower level of permissible infill development was determined using historical housing completion data using a method developed and agreed between the Taskforce and NSW Department of Planning and Environment.

### *Employment*

As described above, the principal source of data for estimating existing and future jobs, and hence the number of vehicles from employment lands for evacuation planning at NSW SES subsector scale, was the 2011 BTS Employment Forecasts. Due to the Taskforce’s time constraints, the dataset for utilities and infrastructure was not complete and was not fully reviewed.

# Appendix C Taskforce methodology for estimating loss of life from floods in the Hawkesbury-Nepean Valley (NSW SES)

This Appendix contains extracts from a paper prepared for the Taskforce in February 2016. Some content has been revised to update the paper to mid-2018.

### *Introduction*

The unique geography of the Hawkesbury-Nepean Valley generates extensive, rapid and prolonged flooding with extreme depths over the default flood planning level of a 1 in 100 chance per year flood. In addition, the large and growing population, and limited and flood-prone public transport in the valley means that mass, progressive self-evacuation by private vehicles is the primary method of reducing the flood risk to life during major flood events (NSW SES, 2015).

Risk to life in floods mainly results from:

- people being unable to evacuate within planned evacuation timeframes due to insufficient transport capacity
- people deciding not to evacuate and being exposed to floodwaters.

There is no readily available dataset for lives lost, or for the proportion of lives lost given the respective populations-at-risk, in past floods in the valley. This makes it difficult to provide a benchmark based on empirical data. In addition, there has been considerable growth and development in the floodplain. These factors together result in the need to review methods for estimating loss of life in floods in the context of the unique characteristics of flooding in the Hawkesbury-Nepean Valley.

This Appendix provides a short overview of various methods for estimating loss of life in floods and outlines a method for a first order estimate of loss of life arising from floods in the Hawkesbury-Nepean Valley. This method is based on the general approach and mortality functions proposed by Jonkman (2007), Jonkman and Vrijling (2008) and Jonkman et al. (2008, 2011, 2018), in combination with the NSW SES flood area classification scheme.

Providing better estimates of loss of life requires further research into the applicability of various loss of life estimation methods to the Hawkesbury-Nepean Valley.

### *Flood emergency response classification of communities*

The NSW SES uses the following flood classifications for areas in the Hawkesbury-Nepean Valley (see Annex):

- High Flood Island
- Low Flood Island
- High Trapped Perimeter
- Low Trapped Perimeter
- Overland Access
- Rising Road Access.

Bligh Park is an overland access area but the walk-out route is through very dense bush. For NSW SES purposes, it is therefore effectively treated as a low flood island.

Low flood islands, low trapped perimeter and certain overland access areas in the Hawkesbury-Nepean Valley pose particular problems due to:

- people being isolated in areas which are progressively submerged with significant depth of inundation (up to eight to nine metres)
- high rate of rise of floodwaters – can be 0.5 m/hr and up to 1.0 m/hr
- when buildings are completely submerged there are significant distances (up to several kilometres) to swim to safety at the edges of the floodplain.

This combination of factors leads to a high likely loss of life.

### *Review of methods*

Subsequent to the work described in this Appendix, a review of the various loss of life estimation methods and their applicability to the Australian context was published (Smith & Rahman, 2016). However, this review did not look specifically at Hawkesbury-Nepean Valley flooding. No firm conclusions can be drawn from this report in relation to likely mortality from flooding in the Hawkesbury-Nepean Valley.

Jonkman (2007) provides an overview of various methods for estimating loss of life in floods.

Many of the various estimation methods are complex and factor the effects of warning, evacuation and rescue into the calculation.

Di Mauro et al. (2012) provide a review of the following methods for loss of life estimation:

- mortality functions method as exemplified by Jonkman et al. (2008)
- Flood Risk to People (FRTP) method as developed in the UK (HR Wallingford et al., 2006)
- Life Safety Model (LSM) as developed in Canada (BC Hydro, 2004), and further developed by HR Wallingford, to estimate loss of life and damage to buildings and vehicles due to a flood.

Di Mauro et al. (2012) note that the three methods compare well given that they strongly depend on flood characteristics (though in different ways in detail). The ease of application is compared below:

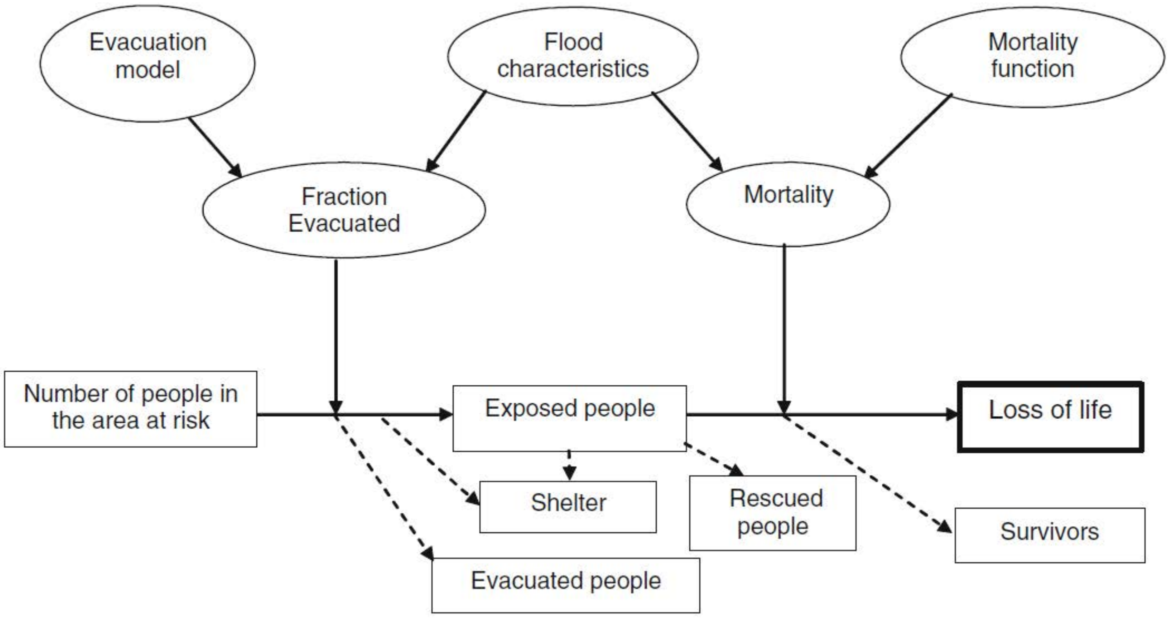
> *'The methods are not equally easy to be used. The Mortality Functions and FRTP methods are easy to apply, and their sensitivity is easy to explore to provide uncertainty boundaries. The LSM, however, requires a lot of detailed data and is therefore more difficult to set up. The sensitivity and uncertainty of the LSM is also more difficult to study since many parameters can be varied and are co-dependent.'* (p.1107)

The NSW SES found that the FRTP method requires more data inputs than the mortality function approach.

Taking these considerations into account, to provide a first order estimate of loss of life in the Hawkesbury-Nepean Valley, the general approach for estimating loss of life proposed by Jonkman (2007) is used. This general method, in contrast to many other methods, has the advantage of separating out the effect of warning, evacuation and rescue on the population at risk. The mortality functions proposed by Jonkman and colleagues, adapted to the NSW SES flood area classification scheme, are then applied to the population at risk.

### *Population at risk*

Jonkman et al. (2008) proposed the following general approach for the estimation of loss of life due to flooding:




The key feature of this approach is to define the population at risk after taking into account the effects of warning, evacuation, shelter and rescue.

### *Mortality functions*

A simple approach to estimating the loss of life is to apply a fixed proportion to the population at risk. Using data from the OFDA/CRED International Disaster Database, Jonkman (2007) and Jonkman and Vrijling (2008) found an average event mortality of about 0.5% for river floods and 3.6% for flash floods. An average event mortality of about 1% was found for ‘coastal’ floods, that is, those associated with oceanic inundation including the 1953 storm surge inundation of low-lying areas of the Netherlands and the United Kingdom, the storm surge associated with Hurricane Katrina in New Orleans in 2005, and other events from Bangladesh, India and Japan. These events are often characterised by severe flood effects (large depths and velocities) when low-lying coastal areas are flooded. In addition, they have often occurred unexpectedly without substantial warning.

Jonkman et al. (2011) applied three average event mortalities to assess risk to life from flooding behind ‘dike rings’ (levees) in the Netherlands:

- 1% mortality for coastal levees with severe flooding (large water depths, high flow velocities, unexpected)

- 0.7% mortality for levees influenced by both sea and river (some warning time but still extensive flooding)
- 0.5% mortality for levees along rivers (long warning time and to some extent expected).

Jonkman et al. (2018) found an overall mortality rate of less than 0.1% for the record floods associated with Hurricane Harvey in Texas. The authors conclude that:

> *'the flooding of Houston is expected to be less deadly than those in New Orleans during Katrina for a number of reasons: flood depths and flow velocities in most areas were lower, waters receded more quickly, and people were better warned about flooding beforehand.'* (p.1076)

Jonkman et al. (2008) sought to develop more detailed mortality functions for the Netherlands using flood characteristics. They concluded that existing methods for estimating loss of life were not fit for purpose. Instead, using empirical data for flood characteristics and mortality, Jonkman (2007) and Jonkman et al. (2008) proposed the following mortality functions, where $F_D$ = mortality, $h$ = depth of inundation and $v$ = flow velocity:

| Zone | Function | Characteristics of flood for which it applies |
|---|---|---|
| **Breach zone** | $F_D = 1$ | $hv \geq 7$ m²/s and $v \geq 2$ m/s |
| **Rapidly rising water zone** | $F_D(h) = \Phi_N\left(\frac{\ln(h) - \mu_N}{\sigma_N}\right)$ <br> $\mu_N = 1.46 \quad \sigma_N = 0.28$ | ($h \geq 2.1$ m and *rate of rise* ≥ 0.5 m/hr) <br> and <br> ($hv < 7$ m²/s or $v < 2$ m/s) |
| **Remaining zone** | $F_D(h) = \Phi_N\left(\frac{\ln(h) - \mu_N}{\sigma_N}\right)$ <br> $\mu_N = 7.60 \quad \sigma_N = 2.75$ | (*rate of rise* < 0.5m/hr or (*rate of rise* ≥ 0.5m/hr and $h < 2.1$m)) <br> and <br> ($hv < 7$ m²/s or $v < 2$m/s) |

The functions are based on historic observations from floods in the Netherlands, Japan, UK and USA and mostly for floods that occurred in the 1950s, and are designed to be applied to floods in low lying areas of the Netherlands.

These functions consider the characteristics of the flood, extent of the exposed population and mortality of those exposed. The level of warning and collapse of buildings affect mortality but are not incorporated into the functions; further investigation of these is recommended by Jonkman et al. (2008).

The function for the remaining zone has a very weak correlation with observations due to outliers with high mortality. It predicts the order of magnitude of mortality (rather than the absolute mortality). An update of this function to account for improvements in building quality since the 1950s sets the parameters $\mu_N$ = 1.68 and $\sigma_N$= 0.37 for the situation in the Netherlands.

The mortality function for rapidly rising water can also be corrected (Jonkman 2007), as a first order estimate, for improved building quality to current standards in the Netherlands with $\mu_N$ = 1.68 and $\sigma_N$ = 0.37.

### *Application to Hawkesbury-Nepean floodplains*

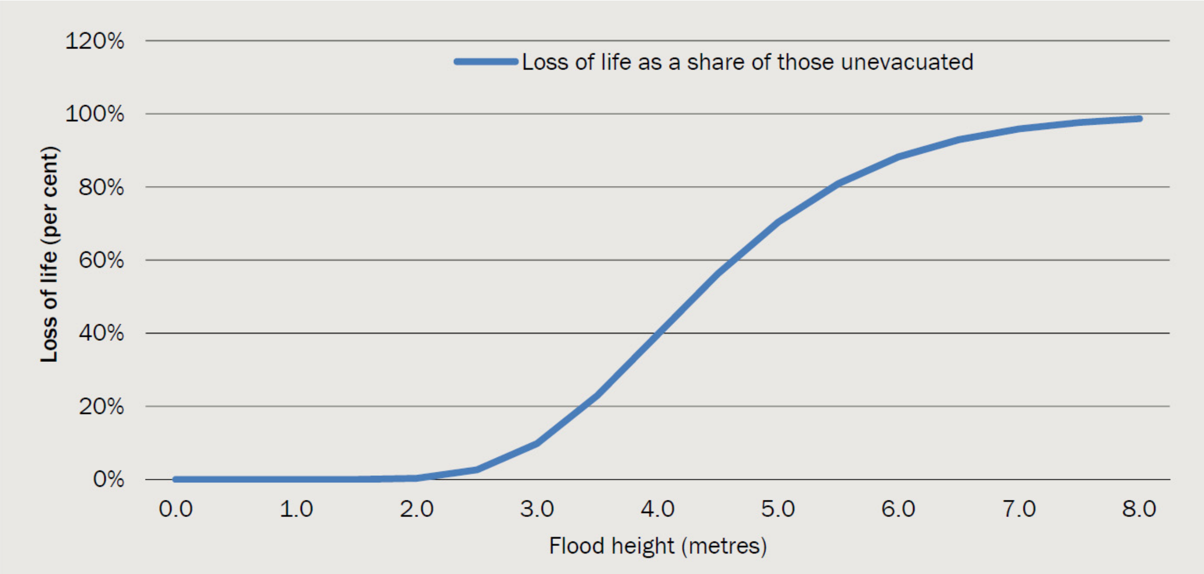
Deriving mortality functions based on depth of floodwaters is problematic in Rising Road Access (RRA) areas due to the constantly changing depth and perimeter as flood levels increase. The 1% mortality (of the population at risk) rule of thumb for coastal flooding was applied for RRA areas in the Hawkesbury-Nepean Valley. Although this is higher than the global mortality rate of 0.5% that Jonkman and Vrijling (2008) found for river floods, the potential for extremely deep, high velocity and fast-rising floods in the Hawkesbury-Nepean floodplain commend adoption of the higher rate.

A 1% mortality was also applied as a conservative estimate for populations at risk (when flooded) on High Flood Islands and High Trapped Perimeter areas. This assumption is being reassessed for the next stage of evacuation modelling.

Low Flood Islands and Low Trapped Perimeter areas in the Hawkesbury-Nepean Valley are considered similar to Jonkman's Rapidly Rising Water Zone for the following reasons:

- The rate of rise of floodwaters in the Hawkesbury-Nepean Valley can be 0.5 m/hr to 1.0 m/hr in many flood scenarios.
- The depth of floodwaters in flood islands in the Hawkesbury area is of the order of eight to nine metres in a PMF.
- The velocity and depth products would be in the range of applicability of the Rapidly Rising Water mortality function.
- Given the varying age of buildings in various parts of the Richmond/Windsor floodplain, the tabulated parameters for rapidly rising water areas were adopted as a conservative estimate, rather than the modified parameters to take account of improvements in building quality over time.
- The resulting mortality function for Low Flood Islands and Low Trapped Perimeter areas is set out below (after Jonkman et al., 2008).

This approach was adopted for Low Flood Islands/Low Trapped Perimeter settings in the Hawkesbury floodplain as the flood surface slope is relatively flat. It was not adopted for the Nepean floodplain due to the appreciable flood surface slope around Victoria Bridge gauge, which would make the calculation quite complex. Most of the Low Flood Island population in the valley is in the Hawkesbury floodplain, so the effect of not applying the function to the Nepean flood islands is small. This provides a conservative first order estimate.




As a lower bound for estimating the number of lives lost in flood islands, Jonkman's mortality function for the Remaining Zone was applied as a sensitivity test.

As a first approximation, base ground levels were set for the Low Flood Island subsectors. These base heights approximate when floodwaters start to affect people (in streets, homes, etc) after the Low Flood Island has been isolated.

### References

BC Hydro (2004). *BC Hydro Life Safety Model - Formal Model Description*. Engineering report E299, October 2004.

Di Mauro, M., K.M. De Bruijn & M. Meloni (2012). ‘Quantitative methods for estimating flood fatalities: towards the introduction of loss-of-life estimation in the assessment of flood risk’, *Natural Hazards*, 63(2), 1083-1113.

HR Wallingford, Flood Hazard Research Centre Middlesex University & Risk and Policy Analysts Ltd (2006). *R&D Outputs: Flood Risks to People, Phase 2, FD2321/TR1*, Department for Environment, Food and Rural Affairs.

Jonkman, S.N. (2007). Loss of life estimation in flood risk assessment: theory and applications. PhD thesis, Delft University, Netherlands.

Jonkman, S.N. & J.K. Vrijling (2008). ‘Loss of life due to floods’, *Journal of Flood Risk Management*, 1, 43-56.

Jonkman, S.N., J.K. Vrijling & A.C.W.M. Vrouwenvelder (2008). ‘Methods for the estimation of loss of life due to floods: a literature review and a proposal for a new method’, *Natural Hazards*, 46(3), 353-389.

Jonkman, S.N., R. Jongejan & B. Maaskant (2011). ‘The Use of Individual and Societal Risk Criteria Within the Dutch Flood Safety Policy–Nationwide Estimates of Societal Risk and Policy Applications’, *Risk Analysis*, 31(2), 282-300.

Jonkman, S.N., M. Godfroy, A. Sebastian & B. Kolen (2018). 'Brief communication: Loss of life due to Hurricane Harvey', *Natural Hazards and Earth System Sciences*, 18, 1073-1078.

NSW SES. (2015). *Hawkesbury Nepean Flood Plan: Sub Plan of the State Emergency Management Plan* (SEMP). September 2015.

Smith, G.P. & Rahman, P.F. (2016). *Approaches for Estimating Flood Fatalities Relevant to Floodplain Management*, WRL Technical Report 2015/09, Water Research Laboratory, Manly Vale, prepared for NSW Office of Environment and Heritage.

## *Annex – flood classifications*

### *Flood islands*

These are inhabited areas of high ground within a floodplain linked to flood free areas by an access road. The access road can be cut by floodwater, closing the only evacuation route and creating an island.

After closure of the road the only access to the area is by boat or by aircraft.

Flood islands are further classified according to what can happen after the evacuation route is cut into High Flood Islands and Low Flood Islands.

#### *High flood island*

The flood island is higher than the limit of flooding (that is, above the PMF). The island is surrounded by floodwater but there is still enough land available to provide a flood free space for people remaining in the area. This flood free space may not be enough to adequately sustain the population. Properties may or may not be flooded.


The area will require resupply by boat or air if not evacuated before the road is cut. Evacuation will have to take place before isolation occurs if it will not be possible to provide adequate support during the period of isolation, if essential services won't be available, or if houses will be flooded.

#### *Low flood island*

The flood island is lower than the limit of flooding (that is, below the PMF). If floodwater continues to rise after it is isolated, the island will eventually be completely covered with all properties inundated. People left stranded on the island may drown unless rescued. Evacuation must be completed before roads are inundated.

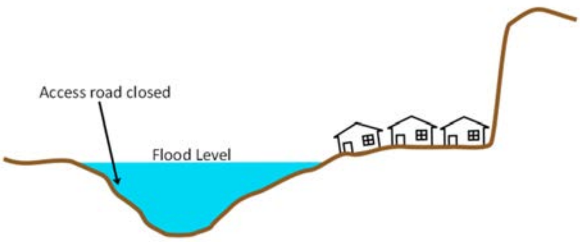
### *Trapped perimeters*

These are similar to flood islands in that they are inhabited or potentially habitable areas of higher ground. They exist at the fringe of the floodplain where the only practical road or overland access is through flood prone land and unavailable during a flood event. In some cases, normal access to the area is by boat but flood conditions may prevent usual boat access.

The ability to retreat to higher ground does not exist due to topography or impassable structures. Trapped perimeter areas are further classified according to what can happen after the evacuation route is cut as follows:

#### *High trapped perimeters*

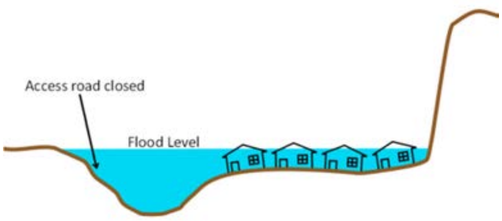
These are inhabited areas above the PMF but the only access road/s is across flood prone land. Road access may be closed during a flood.




The area will require resupply by boat or air if not evacuated before the road is cut. Evacuation will have to take place before isolation occurs if it will not be possible to provide adequate support during the period of isolation, if essential services won't be available, or if houses will be flooded.

#### *Low trapped perimeters*

The inhabited area is lower than the limit of flooding (that is, below the PMF) or does not have enough land to cope with the number of people in the area. During a flood event the area is isolated by floodwater and property may be inundated. If floodwater continues to rise after the area is isolated it will eventually be completely covered. People left stranded may drown if not rescued. Evacuation must be completed before roads are inundated.



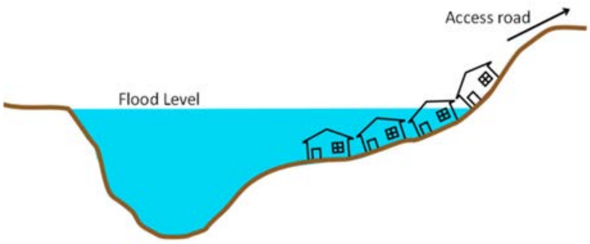

### *Areas with overland escape routes*

These are inhabited areas on flood prone ridges jutting into the floodplain or on the valley side. The access road/s cross lower lying flood prone land.


Evacuation can take place by road only until access roads are closed by floodwater. Escape from rising floodwater will be possible by walking overland to higher ground. Anyone not able to walk out must be reached by using boats and aircraft. If people cannot get out before inundation, rescue will most likely be from rooftops. Pedestrian evacuation must never be relied upon as a primary evacuation strategy. It is only ever a back-up strategy if vehicular evacuation fails.

### *Areas with rising road access*

These are inhabited areas on flood prone ridges jutting into the floodplain or on the valley side with access road/s rising steadily uphill and away from the rising floodwater. The community cannot be completely isolated before inundation reaches its maximum extent.

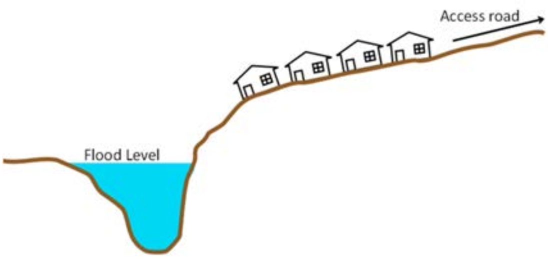



Evacuation can take place by vehicle or on foot along the road as floodwater advances. People should not be trapped unless they delay their evacuation. For example, people living in two storey homes may initially decide to stay but reconsider after water surrounds them.

These communities contain low-lying areas from which people will be progressively evacuated to higher ground as the level of inundation increases. This inundation could be caused either by direct flooding from the river system or by localised flooding from creeks.

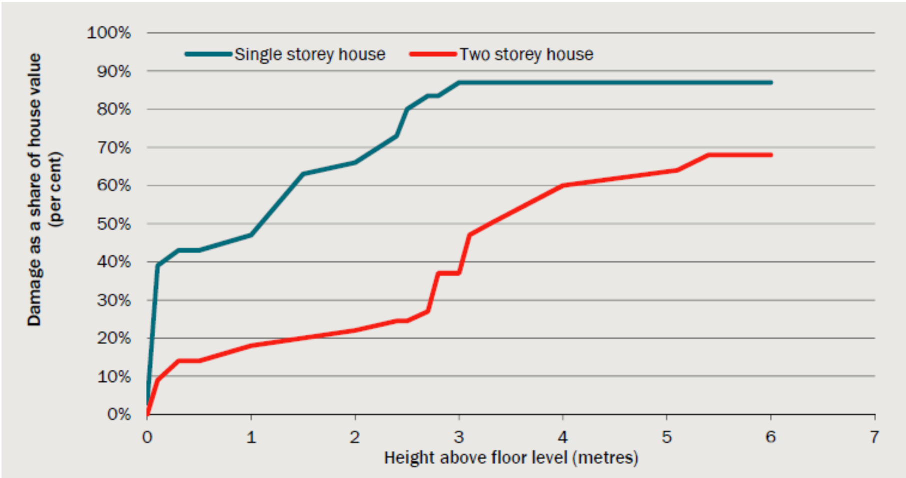
### *Indirectly affected areas*

There will be areas outside the limit of flooding which will not be inundated and will not lose road access. Nevertheless, they may be indirectly affected as a result of flood damaged infrastructure such as due to the loss of transport links, electricity supply, water supply, sewerage or telecommunications services. They may require resupply or in the worst case, evacuation.



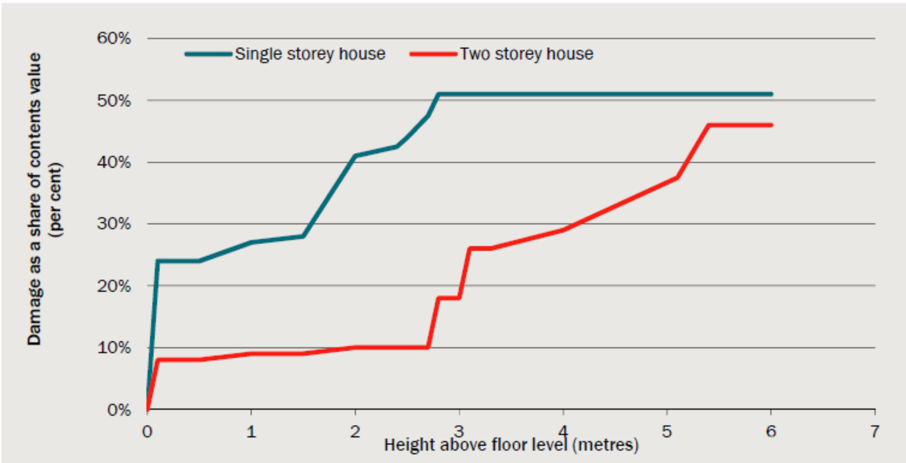
# Appendix D Damage assessment

### Adopted residential and commercial/industrial stage-damage curves



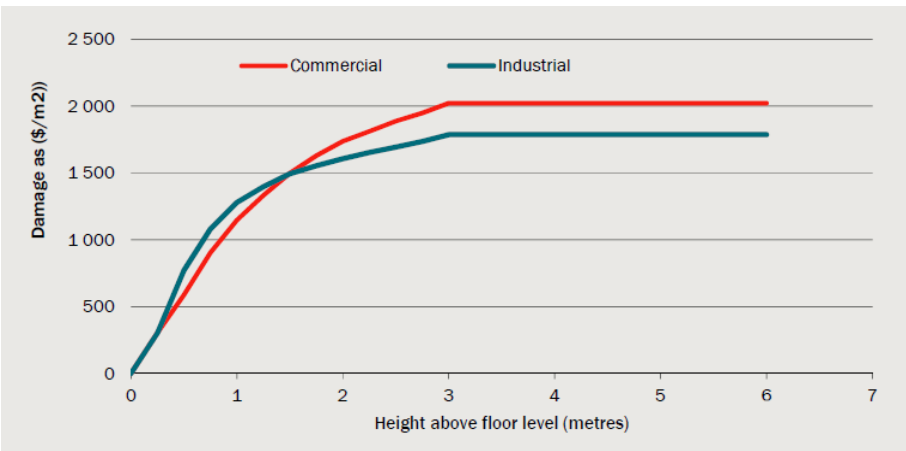

a. Residential building fabric stage-damage curves

*Source:* Geosciences Australia




b. Residential contents stage-damage curves

*Source:* Geosciences Australia




c. Commercial and industrial stage-damage curves

*Source:* Molino Stewart for the Taskforce, using 2010 FLOODSite Multi-Coloured Manual, scaled to 2013 and converted to AUD

### Adopted property and contents values for Hawkesbury-Nepean floodplain

| Dwelling size | Building* | Contents | Clean-up costs/ outside costs (added where flood reaches floor level) |
|---|---|---|---|
| | $/dwelling | $/dwelling | $/dwelling |
| **Small** | 300,000 | 60,000 | 10,000 |
| **Medium** | 400,000 | 60,000 | 10,000 |
| **Large** | 450,000 | 60,000 | 10,000 |

* Calculated as the difference between house sales and land values in the Hawkesbury-Nepean area

# Appendix E Taskforce comparative flood level reductions for alternative flood mitigation infrastructure options

**Table E.1 Comparison of changes in flood levels for alternative options, Wallacia**

| **Flood event** (chance of occurrence per year) | **Base case** (m AHD) | **Option** | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **Induced surcharge** (Difference in m) | **Pre-release <40 GL/d over three days** (Difference in m) | **Pre-release <130 GL/d over three days** (Difference in m) | **Lower FSL by 5m** (Difference in m) | **Lower FSL by 5m and induced surcharge** (Difference in m) | **Lower FSL by 12m** (Difference in m) | **Raise WD by 14m** (Difference in m) | **Raise WD by 14m and lower FSL by 5m** (Difference in m) | **Raise WD by 20m** (Difference in m) | **Currency Creek diversion channel** (Difference in m) | **Sackville short bypass** (Difference in m) | **Dredging Hawkesbury River** (Difference in m) |
| *Model stage* | *2016* | *2014* | *2014* | *2014* | *2016* | *2016* | *2016* | *2016* | *2016* | *2016* | *2016* | *2013* | *2016* |
| 1 in 5 | 35.2 | 0.0 | 0.0 | 0.0 | -0.1 | -0.1 | -0.1 | -0.1 | -0.1 | -0.1 | 0.0 | Not modelled | 0.0 |
| 1 in 10 | 37.3 | -0.2 | -0.1 | -0.1 | -0.1 | -0.2 | -0.2 | -0.2 | -0.2 | -0.2 | 0.0 | | 0.0 |
| 1 in 20 | 39.5 | -0.5 | -0.3 | -0.5 | -0.5 | -0.7 | -0.7 | -0.7 | -0.7 | -0.7 | 0.0 | | 0.0 |
| 1 in 50 | 42.6 | -1.0 | -0.3 | -1.0 | -0.6 | -1.6 | -1.6 | -2.0 | -2.0 | -2.0 | 0.0 | | 0.0 |
| 1 in 100 | 44.6 | -0.4 | -0.2 | -1.0 | -0.5 | -1.6 | -1.8 | -2.7 | -2.8 | -2.9 | 0.0 | | 0.0 |
| 1 in 200 | 46.3 | +0.2 | -0.2 | -0.9 | -0.5 | -0.9 | -1.8 | -3.1 | -3.4 | -3.5 | 0.0 | | 0.0 |
| 1 in 500 | 48.7 | +0.3 | -0.1 | -0.8 | -0.5 | -0.2 | -1.7 | -3.4 | -4.2 | -4.6 | 0.0 | | 0.0 |
| 1 in 1,000 | 50.4 | +0.2 | -0.1 | -1.0 | -0.5 | -0.3 | -1.9 | -3.4 | -4.6 | -5.2 | 0.0 | | 0.0 |
| 1 in 2,000 | 54.4 | +0.1 | -0.2 | -2.5 | -1.2 | -0.3 | -3.5 | -4.9 | -6.5 | -8.2 | 0.0 | | 0.0 |
| 1 in 5,000 | 58.6 | 0.0 | -0.3 | -1.7 | -0.8 | -0.6 | -3.1 | -6.2 | -7.9 | -10.4 | 0.0 | | 0.0 |
| PMF | 62.3 | +0.1 | +0.1 | 0.0 | +0.1 | 0.2 | 0.0 | -2.0 | -2.5 | -4.2 | +0.1 | | +0.1 |

**LEGEND**

Difference in m

- > +0.1
- -0.25 to -1.0
- -1.0 to -2.0
- > -2.0

Critical range for flood risk

*Source:* WMAwater for the Taskforce

*Note:* All scenarios allow for probabilistic drawdown; base case is for H14 protocol; all FSL lowering and dam raising scenarios allow for post flood release of 100 GL/d; FSL = full water supply level; PMF = probable maximum flood

## Table E.2 Comparison of changes in flood levels for alternative options, Penrith

| Flood event (chance of occurrence per year) | Base case (m AHD) | Option | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Induced surcharge (Difference in m) | Pre-release <40 GL/d over three days (Difference in m) | Pre-release <130 GL/d over three days (Difference in m) | Lower FSL by 5m (Difference in m) | Lower FSL by 5m and induced surcharge (Difference in m) | Lower FSL by 12m (Difference in m) | Raise WD by 14m (Difference in m) | Raise WD by 14m and lower FSL by 5m (Difference in m) | Raise WD by 20m (Difference in m) | Currency Creek diversion channel (Difference in m) | Sackville short bypass (Difference in m) | Dredging Hawkesbury River (Difference in m) |
| *Model stage* | *2016* | *2014* | *2014* | *2014* | *2016* | *2016* | *2016* | *2016* | *2016* | *2016* | *2016* | *2013* | *2016* |
| 1 in 5 | 19.9 | -0.5 | -1.2 | -1.3 | -2.2 | -2.2 | -2.3 | -2.2 | -2.2 | -2.2 | 0.0 | 0.0 | 0.0 |
| 1 in 10 | 21.6 | -1.0 | -0.8 | -2.4 | -2.2 | -2.5 | -3.3 | -3.3 | -3.3 | -3.3 | 0.0 | 0.0 | 0.0 |
| 1 in 20 | 23.4 | -1.6 | -0.4 | -2.7 | -1.5 | -2.6 | -4.3 | -4.5 | -4.5 | -4.5 | 0.0 | 0.0 | 0.0 |
| 1 in 50 | 24.9 | -1.0 | -0.2 | -0.7 | -0.4 | -1.8 | -1.9 | -4.8 | -5.1 | -5.2 | 0.0 | 0.0 | 0.0 |
| 1 in 100 | 25.9 | -0.1 | -0.1 | -0.6 | -0.3 | -1.3 | -1.2 | -3.9 | -5.3 | -5.5 | 0.0 | 0.0 | 0.0 |
| 1 in 200 | 26.5 | +0.1 | -0.1 | -0.4 | -0.2 | -0.2 | -0.9 | -2.8 | -4.6 | -5.5 | 0.0 | 0.0 | 0.0 |
| 1 in 500 | 27.1 | +0.1 | 0.0 | -0.2 | -0.1 | 0.0 | -0.5 | -1.4 | -2.8 | -4.9 | 0.0 | 0.0 | 0.0 |
| 1 in 1,000 | 27.5 | +0.1 | 0.0 | -0.3 | -0.2 | -0.1 | -0.5 | -0.9 | -1.7 | -3.8 | 0.0 | 0.0 | 0.0 |
| 1 in 2,000 | 28.4 | +0.1 | 0.0 | -0.5 | -0.3 | -0.1 | -0.8 | -1.1 | -1.5 | -2.8 | 0.0 | 0.0 | 0.0 |
| 1 in 5,000 | 29.5 | 0.0 | -0.1 | -0.5 | -0.3 | -0.3 | -0.9 | -1.7 | -2.0 | -2.7 | 0.0 | 0.0 | -0.1 |
| PMF | 31.5 | 0.0 | 0.0 | -0.1 | 0.0 | 0.0 | -0.2 | -0.9 | -1.2 | -1.8 | -0.1 | 0.0 | -0.2 |

**LEGEND**

Difference in m

- > +0.10
- -0.25 to -1.0
- -1.0 to -2.0
- > -2.0

Critical range for flood risk

*Source:* WMAwater for the Taskforce

*Note:* All scenarios allow for probabilistic drawdown; base case is for H14 protocol; all FSL lowering and dam raising scenarios allow for post flood release of 100 GL/d; FSL = full water supply level; PMF = probable maximum flood

**Table E.3 Comparison of changes in flood levels for alternative options, North Richmond**

| Flood event (chance of occurrence per year) | Base case (m AHD) | Option | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Induced surcharge (Difference in m) | Pre-release <40 GL/d over three days (Difference in m) | Pre-release <130 GL/d over three days (Difference in m) | Lower FSL by 5m (Difference in m) | Lower FSL by 5m and induced surcharge (Difference in m) | Lower FSL by 12m (Difference in m) | Raise WD by 14m (Difference in m) | Raise WD by 14m and lower FSL by 5m (Difference in m) | Raise WD by 20m (Difference in m) | Currency Creek diversion channel (Difference in m) | Sackville short bypass (Difference in m) | Dredging Hawkesbury River (Difference in m) |
| *Model stage* | *2016* | *2014* | *2014* | *2014* | *2016* | *2016* | *2016* | *2016* | *2016* | *2016* | *2016* | *2013* | *2016* |
| 1 in 5 | 11.2 | -0.4 | -1.4 | -1.2 | -2.9 | -2.9 | -3.1 | -3.1 | -3.1 | -3.1 | 0.0 | 0.0 | -0.7 |
| 1 in 10 | 13.6 | -0.9 | -1.0 | -2.4 | -2.7 | -3.0 | -3.8 | -3.8 | -3.8 | -3.8 | 0.0 | 0.0 | -0.6 |
| 1 in 20 | 15.3 | -1.1 | -0.4 | -2.2 | -1.3 | -2.3 | -3.8 | -4.1 | -4.2 | -4.2 | 0.0 | 0.0 | -0.2 |
| 1 in 50 | 16.5 | -0.4 | -0.1 | -0.6 | -0.4 | -1.1 | -1.4 | -3.2 | -3.6 | -3.7 | -0.1 | 0.0 | -0.5 |
| 1 in 100 | 17.5 | -0.5 | -0.2 | -0.8 | -0.6 | -1.0 | -1.3 | -2.7 | -3.5 | -3.8 | -0.4 | -0.1 | -1.1 |
| 1 in 200 | 18.4 | -0.3 | -0.2 | -0.8 | -0.5 | -0.8 | -1.5 | -2.5 | -3.3 | -3.8 | -0.5 | -0.2 | -1.6 |
| 1 in 500 | 19.7 | -0.1 | -0.1 | -0.7 | -0.5 | -0.6 | -1.4 | -2.5 | -3.2 | -3.9 | -0.7 | -0.2 | -2.0 |
| 1 in 1,000 | 20.6 | 0.0 | -0.1 | -0.7 | -0.4 | -0.4 | -1.3 | -2.3 | -3.0 | -3.9 | -0.7 | -0.2 | -1.9 |
| 1 in 2,000 | 21.7 | 0.0 | -0.1 | -0.6 | -0.5 | -0.3 | -1.2 | -2.1 | -2.9 | -4.0 | -0.7 | -0.2 | -1.6 |
| 1 in 5,000 | 22.7 | 0.0 | -0.1 | -0.7 | -0.4 | -0.3 | -1.1 | -2.1 | -2.7 | -3.8 | -0.8 | -0.2 | -1.6 |
| PMF | 26.3 | 0.0 | 0.0 | -0.2 | -0.1 | -0.1 | -0.5 | -1.3 | -1.6 | -2.4 | -0.7 | -0.4 | -1.1 |

**LEGEND**

Difference in m

- > +0.1
- -0.25 to -1.0
- -1.0 to -2.0
- > -2.0
- Critical range for flood risk

*Source:* WMAwater for the Taskforce

*Note:* All scenarios allow for probabilistic drawdown; base case is for H14 protocol; all FSL lowering and dam raising scenarios allow for post flood release of 100 GL/d; FSL = full water supply level; PMF = probable maximum flood

## Table E.4 Comparison of changes in flood levels for alternative options, Windsor

| Flood event (chance of occurrence per year) | Base case (m AHD) | Option | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Induced surcharge (Difference in m) | Pre-release <40 GL/d over three days (Difference in m) | Pre-release <130 GL/d over three days (Difference in m) | Lower FSL by 5m (Difference in m) | Lower FSL by 5m and induced surcharge (Difference in m) | Lower FSL by 12m (Difference in m) | Raise WD by 14m (Difference in m) | Raise WD by 14m and lower FSL by 5m (Difference in m) | Raise WD by 20m (Difference in m) | Currency Creek diversion channel (Difference in m) | Sackville short bypass (Difference in m) | Dredging Hawkesbury River (Difference in m) |
| *Model stage* | *2016* | *2014* | *2014* | *2014* | *2016* | *2016* | *2016* | *2016* | *2016* | *2016* | *2016* | *2013* | *2016* |
| 1 in 5 | 9.4 | -0.2 | -1.0 | -0.8 | -2.4 | -2.4 | -2.6 | -2.5 | -2.5 | -2.6 | 0.0 | 0.0 | -2.6 |
| 1 in 10 | 11.6 | -0.4 | -0.8 | -1.8 | -2.1 | -2.3 | -3.0 | -3.1 | -3.1 | -3.1 | 0.0 | 0.0 | -2.1 |
| 1 in 20 | 13.5 | -0.7 | -0.5 | -1.8 | -1.5 | -2.1 | -3.2 | -3.6 | -3.6 | -3.6 | -0.1 | 0.0 | -1.8 |
| 1 in 50 | 16.0 | -0.7 | -0.3 | -1.3 | -0.9 | -1.7 | -2.6 | -3.9 | -4.3 | -4.4 | -0.3 | -0.1 | -2.0 |
| 1 in 100 | 17.2 | -0.5 | -0.2 | -0.9 | -0.6 | -1.3 | -1.9 | -3.7 | -4.4 | -4.6 | -0.5 | -0.1 | -2.1 |
| 1 in 200 | 18.2 | -0.3 | -0.2 | -0.8 | -0.5 | -0.8 | -1.6 | -3.2 | -4.1 | -4.6 | -0.6 | -0.2 | -2.1 |
| 1 in 500 | 19.5 | -0.1 | -0.1 | -0.7 | -0.5 | -0.6 | -1.4 | -2.6 | -3.5 | -4.3 | -0.8 | -0.2 | -2.2 |
| 1 in 1,000 | 20.4 | 0.0 | -0.1 | -0.7 | -0.4 | -0.4 | -1.3 | -2.3 | -3.1 | -4.0 | -0.8 | -0.2 | -2.1 |
| 1 in 2,000 | 21.5 | 0.0 | -0.1 | -0.6 | -0.5 | -0.3 | -1.2 | -2.1 | -2.9 | -4.0 | -0.8 | -0.2 | -1.8 |
| 1 in 5,000 | 22.6 | 0.0 | -0.1 | -0.7 | -0.4 | -0.3 | -1.1 | -2.1 | -2.7 | -3.8 | -0.8 | -0.3 | -1.7 |
| PMF | 26.2 | 0.0 | 0.0 | -0.2 | -0.1 | -0.1 | -0.5 | -1.3 | -1.7 | -2.4 | -0.7 | -0.4 | -1.2 |

**LEGEND**

Difference in m

- > +0.1
- -0.25 to -1.0
- -1.0 to -2.0
- > -2.0

Critical range for flood risk

*Source:* WMAwater for the Taskforce

*Note:* All scenarios allow for probabilistic drawdown; base case is for H14 protocol; all FSL lowering and dam raising scenarios allow for post flood release of 100 GL/d; FSL = full water supply level; PMF = probable maximum flood

## Table E.5 Comparison of changes in flood levels for alternative options, Wisemans Ferry

| Flood event (chance of occurrence per year) | Base case (m AHD) | Option | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Induced surcharge (Difference in m) | Pre-release <40 GL/d over three days (Difference in m) | Pre-release <130 GL/d over three days (Difference in m) | Lower FSL by 5m (Difference in m) | Lower FSL by 5m and induced surcharge (Difference in m) | Lower FSL by 12m (Difference in m) | Raise WD by 14m (Difference in m) | Raise WD by 14m and lower FSL by 5m (Difference in m) | Raise WD by 20m (Difference in m) | Currency Creek diversion channel (Difference in m) | Sackville short bypass (Difference in m) | Dredging Hawkesbury River (Difference in m) |
| *Model stage* | *2016* | *2014* | *2014* | *2014* | *2016* | *2016* | *2016* | *2016* | *2016* | *2016* | *2016* | *2013* | *2016* |
| 1 in 5 | 1.2 | 0.0 | -0.1 | 0.0 | -0.3 | -0.3 | -0.4 | -0.4 | -0.4 | -0.4 | 0.0 | Not modelled – 1997 study suggests increases of up to 0.2 m likely | +0.4 |
| 1 in 10 | 2.4 | -0.2 | -0.2 | -0.2 | -0.4 | -0.5 | -0.6 | -0.6 | -0.6 | -0.6 | 0.0 | | +0.4 |
| 1 in 20 | 3.8 | -0.2 | -0.2 | -0.3 | -0.4 | -0.5 | -0.6 | -0.8 | -0.8 | -0.8 | +0.1 | | +0.5 |
| 1 in 50 | 5.4 | -0.1 | -0.1 | -0.3 | -0.4 | -0.5 | -0.7 | -0.8 | -0.8 | -0.8 | +0.1 | | +0.4 |
| 1 in 100 | 6.5 | -0.1 | -0.1 | -0.3 | -0.4 | -0.5 | -0.7 | -0.7 | -0.8 | -0.8 | +0.2 | | +0.3 |
| 1 in 200 | 7.5 | -0.1 | -0.1 | -0.1 | -0.4 | -0.4 | -0.5 | -0.5 | -0.6 | -0.6 | +0.1 | | +0.3 |
| 1 in 500 | 9.1 | -0.1 | -0.1 | -0.3 | -0.4 | -0.4 | -0.7 | -0.9 | -0.9 | -1.0 | +0.2 | | 0.0 |
| 1 in 1,000 | 10.2 | -0.1 | -0.1 | -0.4 | -0.4 | -0.5 | -0.7 | -0.8 | -0.8 | -0.9 | +0.2 | | -0.2 |
| 1 in 2,000 | 11.2 | -0.1 | -0.1 | -0.4 | -0.4 | -0.5 | -0.7 | -0.8 | -0.8 | -0.9 | +0.2 | | -0.2 |
| 1 in 5,000 | 12.5 | -0.2 | 0.0 | -0.4 | -0.3 | -0.4 | -0.6 | -0.7 | -0.9 | -0.9 | +0.2 | | -0.1 |
| PMF | 14.6 | 0.0 | 0.0 | -0.2 | -0.2 | -0.1 | -0.5 | -1.2 | -1.6 | -2.3 | +0.3 | | +0.4 |

**LEGEND**

Difference in m

- > +0.1
- -0.25 to -1.0
- -1.0 to -2.0
- > -2.0
- Critical range for flood risk

*Source:* WMAwater for the Taskforce

*Note:* All scenarios allow for probabilistic drawdown; base case is for H14 protocol; all FSL lowering and dam raising scenarios allow for post flood release of 100 GL/d; FSL = full water supply level; PMF = probable maximum flood

# Appendix F 2013 Review shortlisting of selected flood mitigation infrastructure options

## *F.1 Shortlisting assessment criteria*

Due to the large number of non-Warragamba Dam infrastructure flood mitigation options that had previously been investigated for the Hawkesbury-Nepean floodplain, shortlisting assessment criteria were developed as part of the 2013 Review to determine a shortlist of channel modification works (including bypass channels) and levee options that would be investigated in more detail as part of the Review. Flood mitigation dam options were also included in the shortlisting process for comparative purposes.

The criteria were developed to meet the following overall objectives:

- provide significant reduction to the risk to life or property, particularly for floods in the range of 1 in 50 to 1 in 1000 chance per year, which are critical for flood damages and risk to life
- be the best examples of other similar flood mitigation options
- have acceptable environmental and social impacts, relative to their flood risk reduction
- be feasible to build and operate using conventional engineering practices
- do not exacerbate upstream flooding, such as large levee systems that significantly block the floodway and make upstream flooding worse.

**Table F.1** presents the methodology of how each of the non-Warragamba Dam infrastructure options was evaluated against the following criteria:

- number of properties protected from flooding
- level of protection in terms of the size of flood
- capital cost
- social impact and amenity
- impact on upstream and downstream flood behaviour
- operational costs over 10 years
- technical feasibility
- environmental impacts.

In developing the methodology for the shortlisting assessment criteria, weightings were applied. The highest weighting was assigned to the criterion for the ‘number of properties protected from flooding’ as this was considered to be the key measure to indicate the relative reduction of risk to life and property. The ‘level of protection in terms of size of flood’ was also ranked highly to help distinguish those options that provide flood mitigation for larger flood sizes up to the probable maximum flood (PMF).

Changing the scoring and weighting of these criteria would impact on the absolute ranking of different types of flood mitigation infrastructure, relative to each other. However, the main aim of the shortlisting assessment was to identify the best example(s) of different types of mitigation options for further investigation, rather than to decide what the best type of option would be.

**Table F.1 Shortlisting assessment criteria for non-Warragamba Dam infrastructure options**

| Criteria | How criteria measured | | Score | | | | |
|---|---|---|---|---|---|---|---|
| | Scale | Description | 1 | 2 | 3 | 4 | 5 |
| | | | NOT FAVOURABLE | | | | FAVOURABLE |
| Number of properties benefited | Quantitative (Number of residential properties) | Estimated from previous investigations and checked using Google Earth; does not take into account infrastructure | 0 | >10 | >100 | >1,000 | All |
| Level of protection | Quantitative (size of flood) | Use to separate flood mitigation options that impact all floods from those that protect to a certain flood event (levees) | smaller than 1 in 20 chance per year flood | 1 in 50 chance per year flood | 1 in 100 chance per year flood | 1 in 200 chance per year flood | larger than 1 in 500 chance per year flood |
| Capital cost | Quantitative ($ millions) | Previous cost estimates indexed to 2013 using construction price index | more than $200 million | more than $100 million | more than $50 million | more than $20 million | more than $10 million |
| Social impact (social amenity) | Qualitative (Scale from 1 to 5) | From previous investigations and/or experience, expertise and knowledge | majority against, minimal support | more against, some support | balanced for and against | more for, some opponents | majority for, few opponents |
| Impact on flood behaviour | Qualitative (Scale from 1 to 5) | From previous investigations and/or experience, expertise and knowledge | Significant impacts on flooding or flood velocities | moderate impacts | minor impacts | some impacts | Negligible impacts or some benefits |
| Operational costs (over 10 years) | Quantitative ($ millions over ten years) | From previous investigations and/or experience, expertise and knowledge | more than $2 million | more than $1 million | more than $500,000 | more than $200,000 | negligible costs |
| Technical feasibility | Qualitative (Scale from 1 to 5) | From previous investigations and/or experience, expertise and knowledge | major issues (unproven, first/largest of its kind, high risks) | some issues | neutral | minor issues | no issues (proven, well established, no risks) |
| Environmental impacts | Qualitative (Scale from 1 to 5) | From previous investigations and/or experience, expertise and knowledge | Major irreversible impacts, including greenhouse | moderate impacts | minor impacts | some impacts | Negligible impacts or environmental benefits |

*Source:* NSW Public Works for the Taskforce

## F.2 Outcome of shortlisting assessment

Using the shortlisting assessment criteria, the results of the assessment are presented in **Table F.2**. The top four ranking flood mitigation options were found to be:

- levee at Peachtree Creek at Penrith
- levee for the suburb of McGraths Hills
- levee for the township of Pitt Town
- diversion channel at Currency Creek, between Wilberforce and Sackville.

The four flood mitigation options above were selected for more detailed assessment as part of the 2013 Review.

The outcome of the shortlisting assessment ranked 10 out of the top 11 flood mitigation options as levees. The three top ranking levee options (listed above) were considered to be the most viable of the levee options and representative of other similar levees types. The Currency Creek diversion channel also scored highly in the shortlisting assessment.

Large scale levees were not considered further as they scored relatively lower than small scale levees due to their impact on flood behaviour, that is, backwater flooding upstream and increased flood velocity around these levees. Similarly, deflection levees or walls reduce hydraulic impact by deflecting flood flow into the main channel and as such, also scored relatively lower than small scale levees as they do not significantly decrease inundation and can lead to other issues such as increased bank erosion.

As part of the 2013 Review, the following options were selected for more detailed assessment due to support from some members of the local community, despite ranking lower in the shortlisting assessment:

- diversion of the Hawkesbury River in the vicinity of Sackville:
    - cut-off channel at Sackville gorge
    - large diversion channel at Sackville gorge
- dredging of Hawkesbury River between Windsor and Wisemans Ferry.

## Table F.2 Shortlisting assessment of non-Warragamba Dam infrastructure options

| Option/Criteria | Capital Cost | Comment | No. Proper-ties Benefited | Comment | Social Impact (amenity) | Comment | Technical Feasibility | Comment | Level of Protection | Comment | Environmental Impacts | Comment | Impact on flood behaviour | Comment | Operational costs (over 10 years) | Comment | Rank |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Levee for Peachtree Creek (Penrith)** | 5 | Around 30,000 $m^3$ of fill required and flap gates | 3 | 100 commercial properties protected | 2 | 2.5m levee and flap gates. | 3 | Construction on floodplain and Creek means some more care should be taken for otherwise straight-forward job. | 3 | 1 in 100 chance per year flood protection | 3 | Flap gates on Peachtree Ck, however would only need fixing to existing structure on Great Western Hwy crossing. | 4 | Only minor localised changes to any flooding behaviour | 4 | General levee maintenance relatively easy | 1 |
| **Levee for McGrath Hill** | 5 | $7.2 million | 3 | 576 properties to 1 in 50 year flood protection | 2 | Levee up to 10m. | 3 | Relatively straight forward with works carried out of higher level of floodplain. | 2 | 1 in 50 chance per year flood protection | 4 | Small scale changes on developed land. | 4 | Only minor localised changes to any flooding behaviour | 4 | General levee maintenance relatively easy | 2 |
| **Levee for Pitt Town** | 5 | Around 50,000 $m^3$ of fill required | 3 | 177 properties to 1 in 50 year flood protection | 2 | Up to 3.5m levee | 3 | Relatively straight forward with works carried out of higher level of floodplain. | 2 | 1 in 50 chance per year flood protection | 4 | Small scale changes on developed land. | 4 | Only minor localised changes to any flooding behaviour | 4 | General levee maintenance relatively easy | 2 |
| **Currency Creek Diversion** | 1 | $250 - $300 million | 4 | 0.8 water level decrease at Windsor for 1 in 100 year | 2 | Land acquisition and changes to floodplain. | 2 | Huge earthwork requirements and work on floodplain. | 5 | Mitigation effect will be designed beyond 1 in 1,000 chance per year | 2 | Increase downstream erosion of Currency Creek and changes to the floodplain. | 2 | Discharges into creek rather than Hawkes-bury river therefore large potential damage due to increased velocities | 4 | Channels need very little maintenance | 2 |
| **Levee for Bligh Park** | 5 | Around 23,000 $m^3$ of fill required | 2 | 50 properties to > 1 in 100 year | 2 | 2-3m levee | 3 | Relatively straight forward with works carried out of higher level of floodplain. | 3 | 1 in 100 chance per year flood protection | 4 | Small scale changes on developed land. | 4 | Only minor localised changes to any flooding behaviour | 4 | General levee maintenance relatively easy | 5 |
| **Levee for Mulgrave** | 5 | Around 65,000 $m^3$ of fill required | 2 | Unspecified | 2 | Up to 4m levee | 3 | Relatively straight forward with works carried out of higher level of floodplain. | 3 | Flood protection unsure. Guessed 1 in 100 chance per year. | 4 | Small scale changes on developed land. | 4 | Only minor localised changes to any flooding behaviour | 4 | General levee maintenance relatively easy | 5 |
| **Levee for Wilberforce** | 5 | Around 45,000 $m^3$ of fill required | 2 | 60 properties to 1 in 100 year flood protection | 2 | Up to 5m levee | 3 | Relatively straight forward with works carried out of higher level of floodplain. | 3 | 1 in 100 chance per year flood protection | 4 | Small scale changes on developed land. | 4 | Only minor localised changes to any flooding behaviour | 4 | General levee maintenance relatively easy | 5 |
| **Levee for Riverstone** | 5 | Not specified | 2 | Unspecified | 2 | Seems unviable and not an option worth putting forward. | 3 | Relatively straight forward with works carried out of higher level of floodplain. | 3 | Assumed design to 1 in 100 chance per year level | 4 | Small scale changes on developed land. | 4 | Only minor localised changes to any flooding behaviour | 4 | General levee maintenance relatively easy | 5 |

| Option/Criteria | Capital Cost | Comment | No. Proper-ties Benefited | Comment | Social Impact (amenity) | Comment | Technical Feasibility | Comment | Level of Protection | Comment | Environmental Impacts | Comment | Impact on flood behaviour | Comment | Operational costs (over 10 years) | Comment | Rank |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Levee for Regentville (Penrith)** | 5 | Around 25,000 $m^3$ of fill required and flap gates | 2 | Estimate 40 properties to 1 in 100 year flood protection | 2 | 2.5m levee | 2 | Construction on floodplain and Creek means some more care should be taken for otherwise straightforward job. | 3 | 1 in 100 chance per year flood protection | 4 | Small scale changes on developed land. | 4 | Only minor localised changes to any flooding behaviour | 4 | General levee maintenance relatively easy | 9 |
| **Levee for Windsor (16m option as 19m deemed unfeasible)** | 4 | Around 400,000 $m^3$ of fill required | 3 | 700-800 properties to 1 in 50 year | 1 | Up to 6m in parts | 3 | Relatively straight forward with works carried out of higher level of floodplain. | 2 | 1 in 50 chance per year flood protection | 4 | Small scale changes on developed land. | 4 | Only minor localised changes to any flooding behaviour | 4 | General levee maintenance relatively easy | 9 |
| **Macro Levee (Richmond to Windsor)** | 3 | 3,700,000 $m^3$ plus a flap gate | 4 | 1867 flood plus freeboard | 1 | 15km of levee up to 10m | 2 | Construction on floodplain and major Creek works means care should be taken. | 3 | Assumed design to 1 in 100 chance per year level | 2 | Large levee with some impact. Also changes to creek system. | 2 | Large levee system with some expected changes | 4 | General levee maintenance relatively easy | 9 |
| **Clearing and Widening Downstream channel from Penrith Weir** | 3 | No information | 3 | 0.4 decrease in water level for 100 year flood with diminishing return for higher flood | 3 | Large channel changes | 2 | Large scale in channel works | 5 | Mitigation effect designed beyond 1 in 1,000 chance per year | 1 | Large scale changes to the channel | 1 | May increase in channel velocities | 3 | | 12 |
| **Levee at Emu Plains** | 3 | Includes raising roads, flap gates and concrete line channel | 3 | 1 in 200 year flood protection | 2 | 1m high levee from Regentville Bridge to Victoria Bridge | 2 | Construction on floodplain and Creek means some more care should be taken for otherwise straight-forward job. | 4 | 1 in 200 chance per year flood protection | 2 | Flap gates to Lapstone and Knapsack Creek. | 2 | Increase flooding in Penrith (0.4m in 1 in 500 chance per year flood) | 4 | Levee and road costs | 12 |
| **Levee for North Richmond** | 5 | Not specified | 2 | A few properties to 1 in 100 year | 1 | Levee up to 8m. | 3 | Relatively straight forward with works carried out on higher floodplain. | 3 | Assumed design to 1 in 100 chance per year level | 4 | Small scale changes on developed land. | 4 | Only minor localised changes to any flooding behaviour | 4 | General levee maintenance relatively easy | 12 |
| **Upstream dams (Wollondilly and Coxs)** | 1 | > $500 million | 4 | 1.8m water level decrease at Penrith and 2.3m at Windsor for 1 in 100 year | 2 | Impact on recreational users. | 2 | Major instream works. Care taken. | 5 | Mitigation effect will be designed beyond 1 in 1,000 chance per year | 1 | National Park | 2 | Large changes to upstream flood conditions. Remote-ness makes less impact. | 2 | More detailed maintenance for dams | 12 |
| **Victoria Bridge** | 4 | Replacement of piers on superstructure | 1 | 0.06 decrease in water level for 100 year flood levels at Penrith. Estimated benefits. | 4 | Major disruptions to critical road infrastructure | 2 | In-channel works with large vehicle disruption | 4 | Mitigation effect will be relevant until structure is drowned. | 4 | No major impact | 4 | No impact | 4 | | 12 |

| Option/Criteria | Capital Cost | Comment | No. Proper-ties Benefited | Comment | Social Impact (amenity) | Comment | Technical Feasibility | Comment | Level of Protection | Comment | Environmental Impacts | Comment | Impact on flood behaviour | Comment | Operational costs (over 10 years) | Comment | Rank |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Macro Levee (Richmond to McGraths Hill)** | 2 | 3,700,000 m³ plus a flap gate and gates on South Creek | 4 | 1868 flood plus freeboard | 1 | 15km of levee up to 10m | 2 | Construction on floodplain and major Creek works means care should be taken. | 3 | Assumed design to 1 in 100 chance per year level | 2 | Large levee with some impact. Big changes to South Creek | 2 | Large levee system with some expected changes | 4 | General levee maintenance relatively easy | 17 |
| **Deflection Wall at Jamison and Captains Roads (Penrith)** | 5 | No information | 1 | No information | 3 | Visual impact | 4 | Floodplain work but installation time should be speedy. | 3 | Assumed design to 1 in 100 chance per year level | 4 | No major impact | 3 | Potential turbulence | 5 | | 17 |
| **Deflection Wall (Spencer)** | 5 | No information | 1 | No information | 3 | Visual impact | 4 | Floodplain work but installation time should be speedy. | 3 | Assumed design to 1 in 100 chance per year level | 4 | No major impact | 3 | Potential turbulence | 5 | | 17 |
| **Levees around critical infrastructure-Assumes five key infrastructure points requiring 5m high and 500m long** | 5 | Estimated around 40,000 m³ fill | 1 | Potential large benefit gained by maintaining services to residents | 4 | Offers protection to the community | 4 | Proximity to services | 3 | Assumed design to 1 in 100 chance per year level | 4 | No major impact | 3 | Only minor localised changes to any flooding behaviour | 4 | | 17 |
| **Dredging of river channel** | 1 | Dredging 300 million m³ of sediment. Bewsher report gives 1992 estimate of $440 million for 20-30 million m³ | 4 | 0.5m water level decrease at Windsor | 1 | Impacts on recreational users | 2 | Massive instream dredging operation. | 5 | Mitigation effect will be designed beyond 1 in 1,000 chance per year | 1 | Major changes to the aquatic ecosystems in terms of salinity gradients and water quality. Many expected effects. | 3 | | 1 | Siltation | 21 |
| **Raising of access road at Wallacia** | 5 | No cost associated. Assumed to be minimal due to size of the works. | 1 | Only access improvements to 100 year. | 3 | Minor changes to road corridor only, but 8m high. | 2 | Relatively straight forward with road works. | 3 | 1 in 100 chance per year escape access only so scored less | 3 | Changes only to existing roadway corridor | 4 | No additional flooding impacts | 4 | Only some maintenance of roadway | 22 |
| **Sackville Cut-off** | 1 | $300 million | 2 | 0.2-0.3m water level decrease at Windsor | 2 | Land acquisition and changes to floodplain. | 2 | Huge earthwork requirements and work on floodplain. | 5 | Mitigation effect will be designed beyond 1 in 1,000 chance per year | 3 | Increased potential for downstream erosion and changes to the floodplain | 3 | Downstream increased velocities | 4 | Channels need very little maintenance | 22 |
| **Levee at Wallacia** | 4 | Expensive with over 320,000 m³ of fill required | 2 | 1 in 100 year protection and flood evacuation security | 1 | Large levee with poor visual amenity | 1 | 50m footprint makes it impractical | 3 | 1 in 100 chance per year flood protection | 3 | Changes only in roadway corridors and residential areas | 4 | No additional flooding impacts | 4 | Levee and road costs for 1.3 km of levee works | 24 |
| **Upstream dams (Wollondilly)** | 1 | > $300 million | 4 | 0.7m water level decrease at Penrith, 0.6m water level decrease at Windsor | 2 | Impact on recreational users. | 2 | Major instream works. Care taken. | 3 | Mitigation effect will be designed beyond 1 in 1,000 chance per year | 1 | National Park. | 2 | Large changes to upstream flood conditions. Remote-ness makes less impact. | 2 | More detailed maintenance for dams | 25 |

| Option/Criteria | Capital Cost | Comment | No. Proper-ties Benefited | Comment | Social Impact (amenity) | Comment | Technical Feasibility | Comment | Level of Protection | Comment | Environmental Impacts | Comment | Impact on flood behaviour | Comment | Operational costs (over 10 years) | Comment | Rank |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Downstream dams (Nepean)** | 1 | > $290 million | 4 | 1.7 water level decrease at Penrith, 1.5m water level decrease at Windsor | 1 | Land acquisition and massive changes to Camden | 2 | Major instream works. Care taken. | 5 | Mitigation effect will be designed beyond 1 in 1,000 chance per year | 1 | Large effected area with direct impact on land use and landholders. | 1 | Large changes to upstream flood conditions. | 1 | More detailed maintenance for dams | 25 |
| **Gronos Point Diversion Channel** | 4 | $5-15 million | 1 | 0.1m water level decrease at Windsor | 2 | Land acquisition and changes to floodplain. | 2 | Huge earthwork requirements and work on floodplain. | 5 | Mitigation effect will be designed beyond 1 in 1,000 chance per year | 3 | Increased potential for downstream erosion and changes to the floodplain | 2 | Down-stream increased velocities | 4 | Channels need very little maintenance | 25 |
| **Micro Levees (Port Errignhi, Spencer)** | 5 | No information | 1 | No information | 1 | Long, obtrusive levee | 3 | Relatively straight forward with works carried out of higher level of floodplain. | 3 | Assumed design to 1 in 100 chance per year level | 4 | Small scale changes on developed land. | 4 | Only minor localised changes to any flooding behaviour | 3 | General levee maintenance relatively easy | 28 |
| **Micro Levee (Wisemans Ferry)** | 5 | No information | 1 | No information | 1 | Long, obtrusive levee | 3 | Relatively straight forward with works carried out of higher level of floodplain. | 3 | Assumed design to 1 in 100 chance per year level | 4 | Small scale changes on developed land. | 4 | Only minor localised changes to any flooding behaviour | 3 | General levee maintenance relatively easy | 28 |
| **The Breakaway Cut-off Channel** | 3 | $40 million | 1 | Nil | 2 | Land acquisition and changes to floodplain. | 2 | Huge earthwork requirements and work on floodplain. | 5 | Mitigation effect will be designed beyond 1 in 1,000 chance per year | 3 | Increased potential for downstream erosion and changes to the floodplain | 2 | Down-stream increased velocities | 4 | Channels need very little maintenance | 28 |
| **Large Detention Basin (Richmond Lowlands)** | 4 | No information | 1 | Only impacts on small floods | 3 | Can be benefited from potential dual use of detention basins. | 3 | Relatively straight forward with works carried out of higher level of floodplain. | 1 | Mitigation effect will be limited in large floods | 4 | No major impact | 4 | Minor localised changes to flooding enraptured in basin. | 4 | | 31 |
| **Downstream dams (Colo)** | 1 | > $290 million | 2 | 0.2m water level decrease at Windsor | 2 | Impact on recreational users. | 2 | Major instream works. Care taken. | 5 | Mitigation effect will be designed beyond 1 in 1,000 chance per year | 1 | National Park | 2 | Large changes to upstream flood conditions. Remote-ness makes less impact. | 2 | More detailed maintenance for dams | 32 |
| **Downstream dams (Grose)** | 1 | > $290 million | 2 | 0.2m water level decrease at Windsor | 2 | Impact on recreational users. | 1 | Inaccessible terrain and major instream works. | 5 | Mitigation effect will be designed beyond 1 in 1,000 chance per year | 1 | National Park | 2 | Large changes to upstream flood conditions. Remote-ness makes less impact. | 2 | More detailed maintenance for dams | 33 |

# Appendix G Evacuation route upgrade options

This Appendix contains material prepared by RMS and URaP for the Taskforce in February 2016.

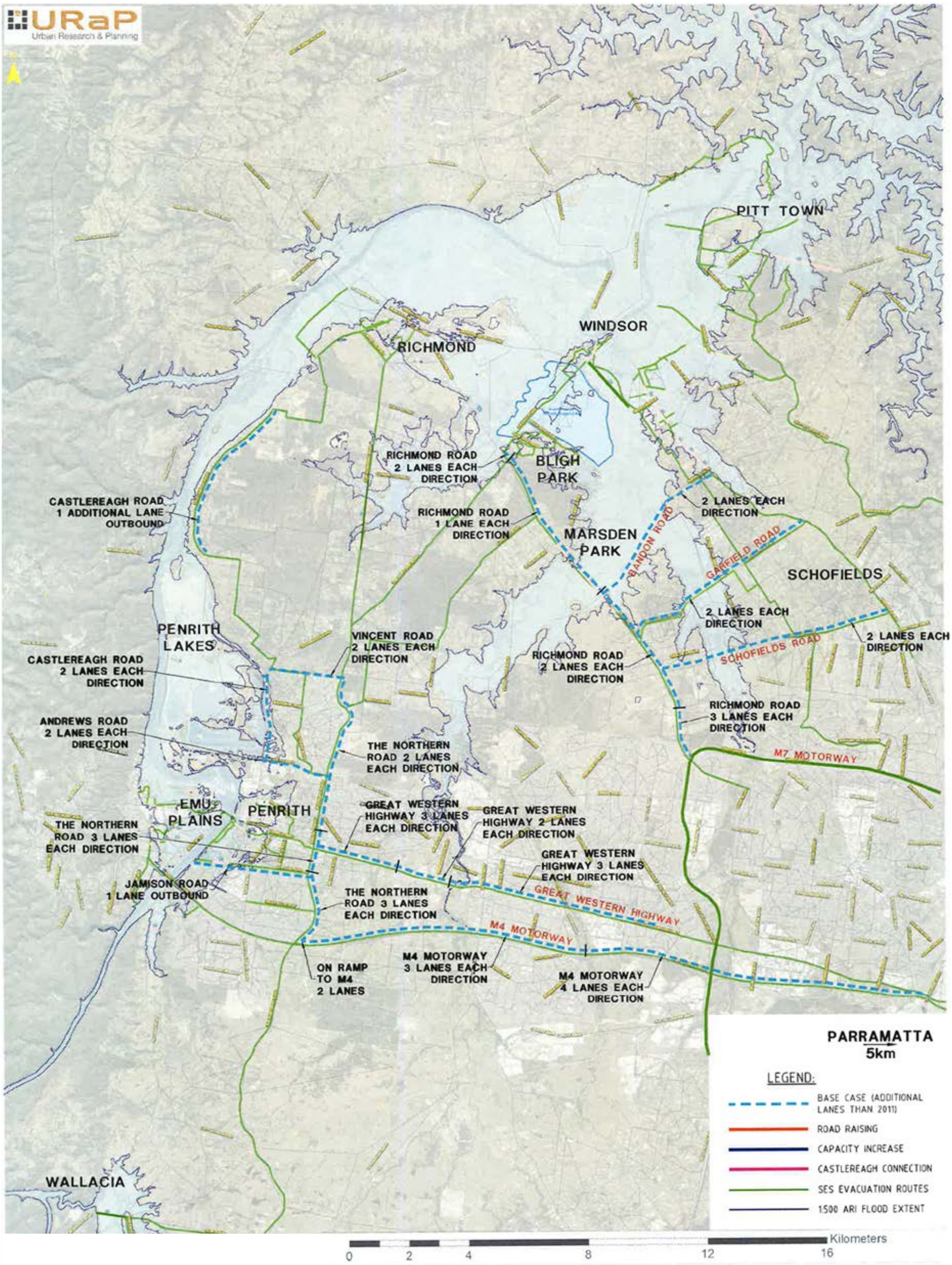
**Assumed Future (Year 2041) Evacuation Road Network**

The Assumed Future Evacuation Road Network is made up of projects that are anticipated to be delivered, largely through RMS from various sources of funding by the year 2041. These are listed below and were added to the 2011 road network to form the 2041 base case.

Principal sources of information were the RMS Strategic EMME model assumptions for 2014 and 2036, which are made up of short term committed and longer-term conjectured projects. Some lower-risk local flood evacuation upgrades were also included.

Key components of the 2041 Assumed Future Evacuation Road Network:

- M4 between Roper Road and The Northern Road, 3 lanes in each direction
- M4 between Roper Road and M7, 4 lanes in each direction
- The Northern Road
  - from Vincent Road to Copeland Street, 2 lanes in each direction
  - from Copeland Street to Jamison Road, 3 lanes in each direction
  - from Jamison Road to M4, 3 lanes in each direction
  - on-ramp to M4, 2 lanes
- Richmond Road
  - from George Street to The Northern Road, 2 lanes in each direction
  - from The Northern Road to Bandon Road, 1 lane in each direction at minimum height of 18.2m (current height 15.0m, increase to 1:100 AEP height 17.2m + 1.0m freeboard)
  - from Bandon Road to Townson Road, 2 lanes in each direction
  - from Townson Road to M7, 3 lanes in each direction
- Garfield Road East, 2 lanes in each direction, at RL 26.3m
- Garfield Road West, 2 lanes in each direction, at RL 12.6m (Note 1:100 AEP height is 17.2m)
- Schofields Road, 2 lanes in each direction, ranging from RL 22.7m (Bell Creek) to RL 18.2m (Eastern Creek Bridge) (Note 1:100 AEP height 17.2m)
- Bandon Road, 2 lanes in each direction, lowest point to be built at RL 17.3m (Note 1:100 AEP height is 17.2m)
- Castlereagh Road from The Driftway to Hinxman Road, 2 lanes outbound direction
- Andrews Road from Castlereagh Road to The Northern Road, 2 lanes outbound
- Vincent Road from Cranebrook Road to The Northern Road, 2 lanes out bound.




Assumed future (year 2041) evacuation road network

*Source:* URaP for the Taskforce

### Evacuation Road Infrastructure Options

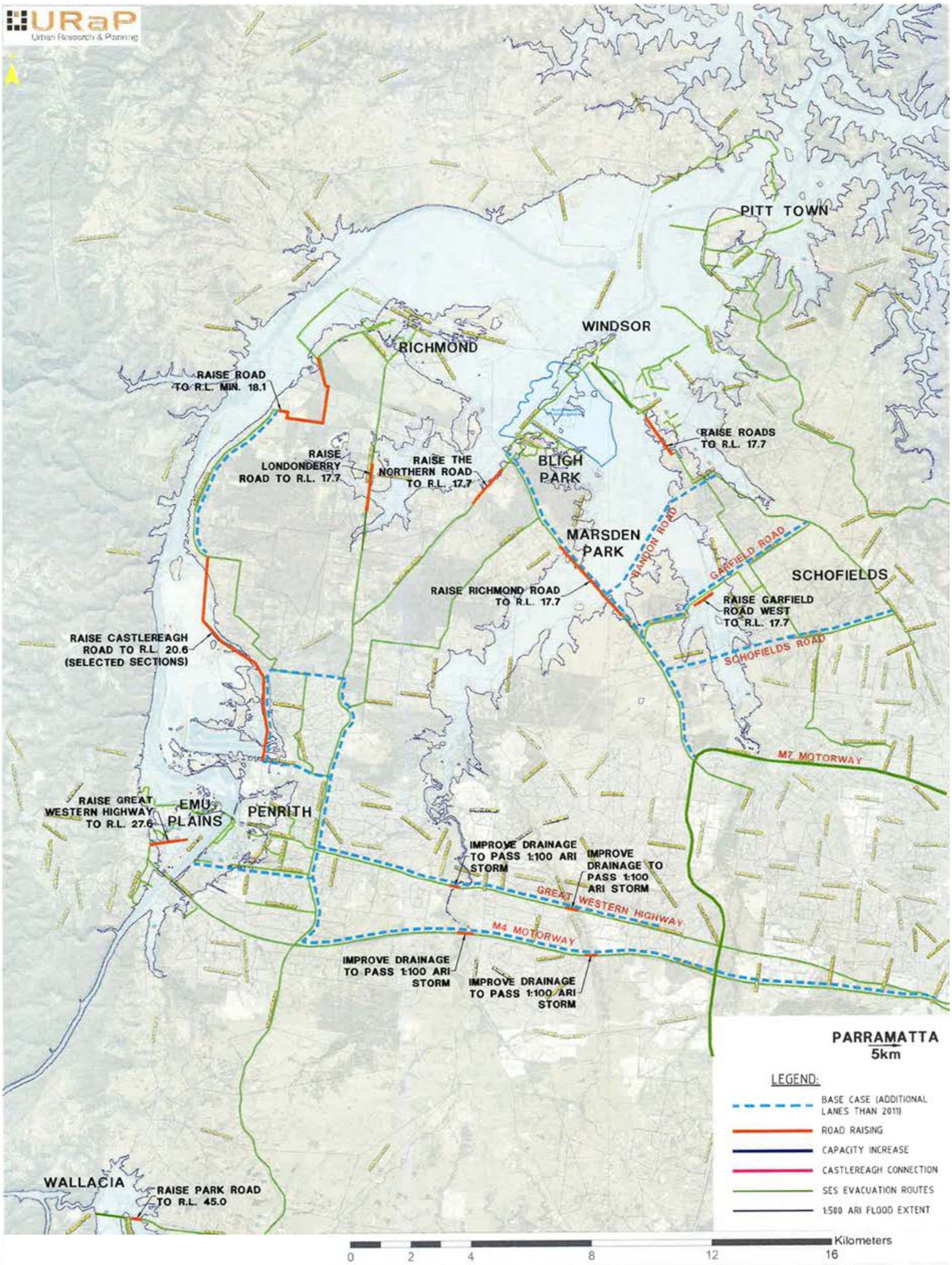
The following infrastructure options were developed in response to the preliminary simulations carried out by Data61 and URaP utilising flood evacuation and road capacity modelling. The potential improvements include both increasing the elevation of road levels to keep roads operating in evacuation mode longer, and increasing the capacity of lanes and intersections on selected evacuation routes to address bottlenecks.

Note that projects listed are considered technically feasible based on a visual assessment of the current road alignment and level. These projects will need to be refined in more detail as concept planning proceeds.

### Option 1: 2041 Base Case + 100 AEP Elevations

These are improvements to evacuation routes to eliminate backwater flooding (and some local flooding) to withstand 1 in 100 year AEP events plus approximately 200mm freeboard. Projects include:

| Location | Current or proposed level (BAU) | Proposed evacuation road improvement |
|---|---|---|
| **Garfield Road West** | RL 12.6m | min RL 17.3m |
| **Londonderry Road** | RL 17.1m | RL 17.4m plus cross drainage upgrade |
| **The Northern Road** | RL 17.0m | RL 17.4m plus cross drainage upgrade |
| **The Driftway** | RL 17.0m | RL 17.4m plus cross drainage upgrade |
| **Castlereagh Road (three sections between Hinxman Road and Andrews Road)** | RL 17.5m | RL 20.6m |
| **Great Western Highway, Emu Plains** | RL 24.5m | RL 27.8m (1:100 AEP is RL 27.6m) |
| **Park Road, Wallacia (low-point)** | RL 42.3m | RL 44.7m (1:100 AEP is RL 44.5m) |
| **Park Road to Wallace Road, Vineyard** | n/a | new road to be min 1:100 AEP level |
| **Great Western Highway and M4 at South Creek and Ropes Creek** | n/a | proposed upgrade of drainage or road levels to pass 1:100 AEP storm |



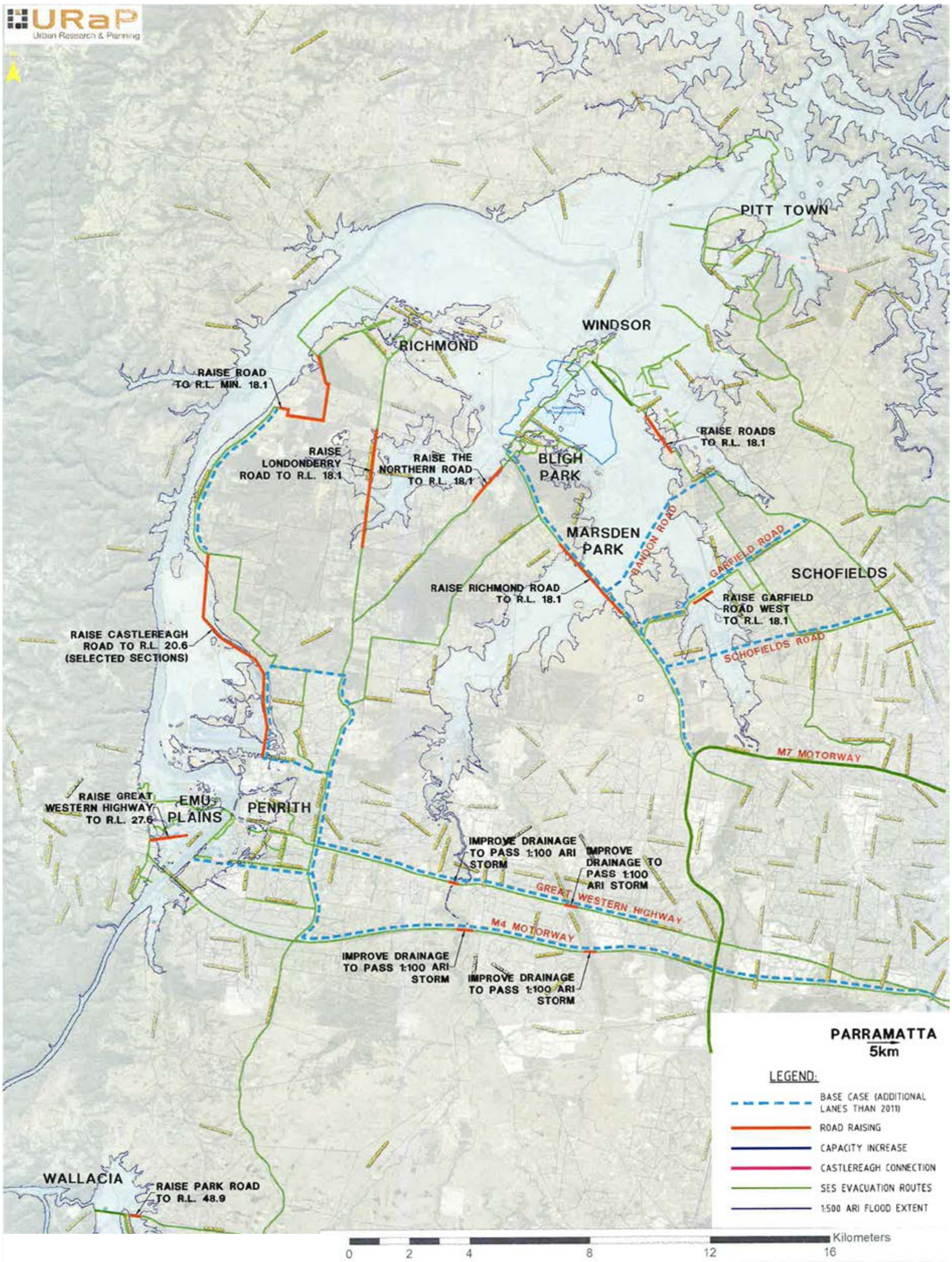

Option 1: 2041 base case + 1 in 100 AEP elevations

*Source:* URaP for the Taskforce

**Option 2: 2041 Base Case + 200 AEP Elevations**

These are improvements to evacuation routes to eliminate backwater flooding (and some local flooding) to withstand 1 in 200 year AEP events plus approximately 200mm freeboard. Projects include:

| Location | Current or proposed level (BAU) | Proposed evacuation road improvement |
|---|---|---|
| **Richmond Road, from Bandon Road to George Street** | RL 18.1m | RL 18.1m |
| **Garfield Road West** | RL 12.6m | min RL 18.1m (from current end of works to George Street) |
| **Londonderry Road** | RL 17.1m | RL 18.1m plus cross drainage upgrade |
| **The Northern Road** | RL 17.0m | RL 18.1m plus cross drainage upgrade |
| **The Driftway** | RL 17.0m | RL 18.1m plus cross drainage upgrade |
| **Castlereagh Road** | RL 17.5m | RL 20.6m for one section between Hinxman Road and Church Lane |
| **Great Western Highway, Emu Plains** | RL 24.5m | RL 27.8m (1:100 AEP is RL 27.6m) |
| **Park Road, Wallacia (low-point)** | RL 42.3m | RL 48.9m (1:200 AEP is RL 48.9m) |
| **Park Road to Wallace Road, Vineyard** | n/a | new road to be min 1:200 AEP level |
| **Great Western Highway and M4 at South Creek and Ropes Creek** | n/a | proposed upgrade of drainage or road levels to pass 1:100 AEP storm |



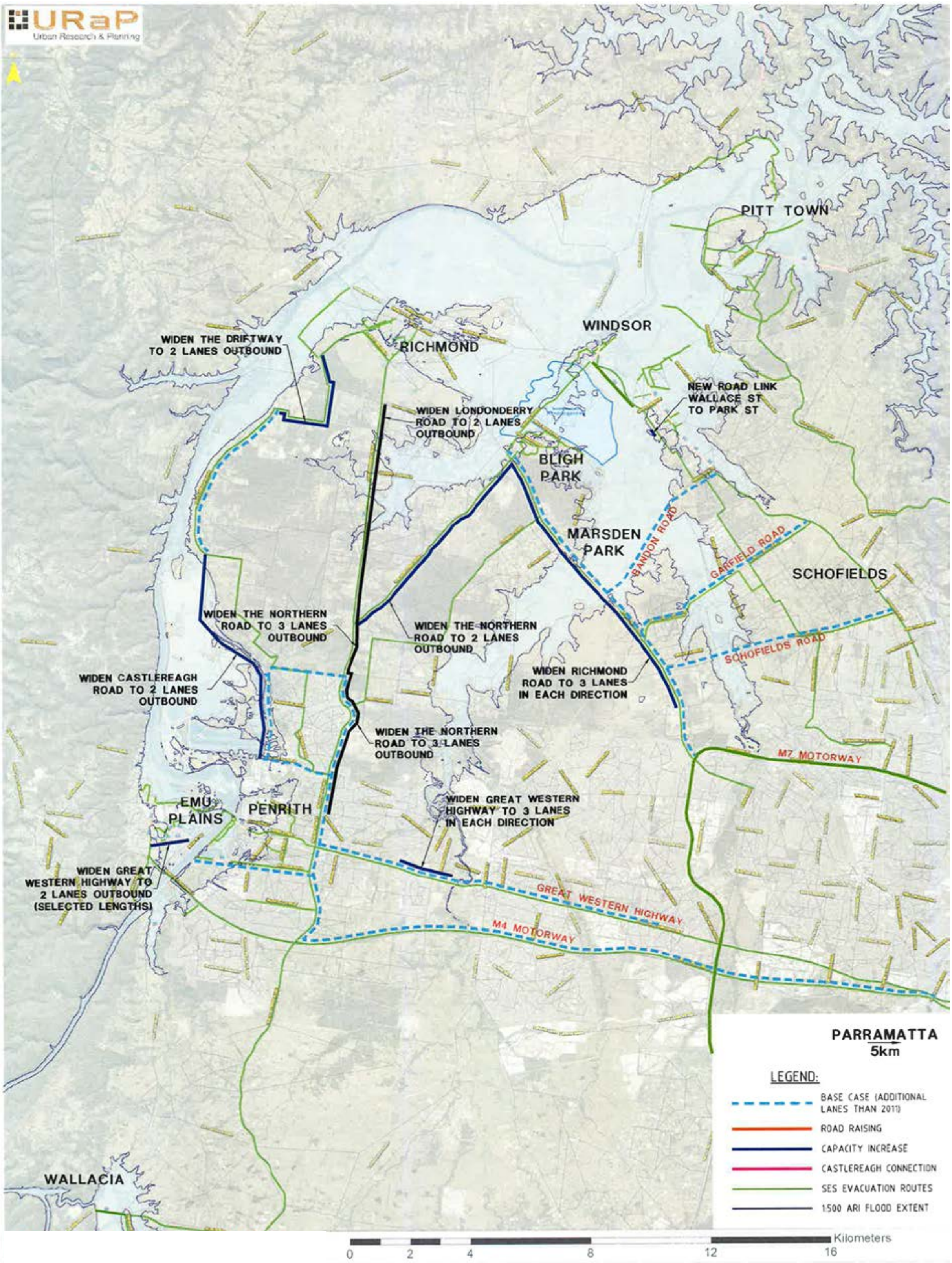

Option 2: 2041 base case + 1 in 200 AEP elevations

*Source:* URaP for the Taskforce

### Option 3: 2041 Base Case + Capacity Increases

These are improvements to eliminate capacity bottlenecks in the evacuation routes as a result of backwater flooding. Projects include:

| Location | Evacuation road improvement |
|---|---|
| **The Northern Road from M4 to Jamison Road** | widen to 3 lanes in each direction |
| **The Northern Road from Victoria Street to Vincent Street** | widen to 3 lanes in each direction |
| **The Northern Road from Vincent Street to Londonderry Road roundabout** | widen to 3 lanes in each direction |
| **The Northern Road from Londonderry Road roundabout to Richmond Road** | widen to 2 lanes in each direction |
| **Londonderry Road from Lennox Street to The Northern Road** | 1 additional lane south bound |
| **The Driftway, Jockbet Road and Wilshire Road** | 1 additional lane south bound |
| **Castlereagh Road from Southee Road to Hinxman Road (except section through Agnes Banks)** | 1 additional outbound lane |
| **Great Western Highway, Penrith from Nepean River to Russell Street** | 1 additional outbound lane |
| **Richmond Road from George Street to Townson Road** | widen to 3 lanes in each direction |
| **Park Road to Wallace Road, Vineyard** | new road link |

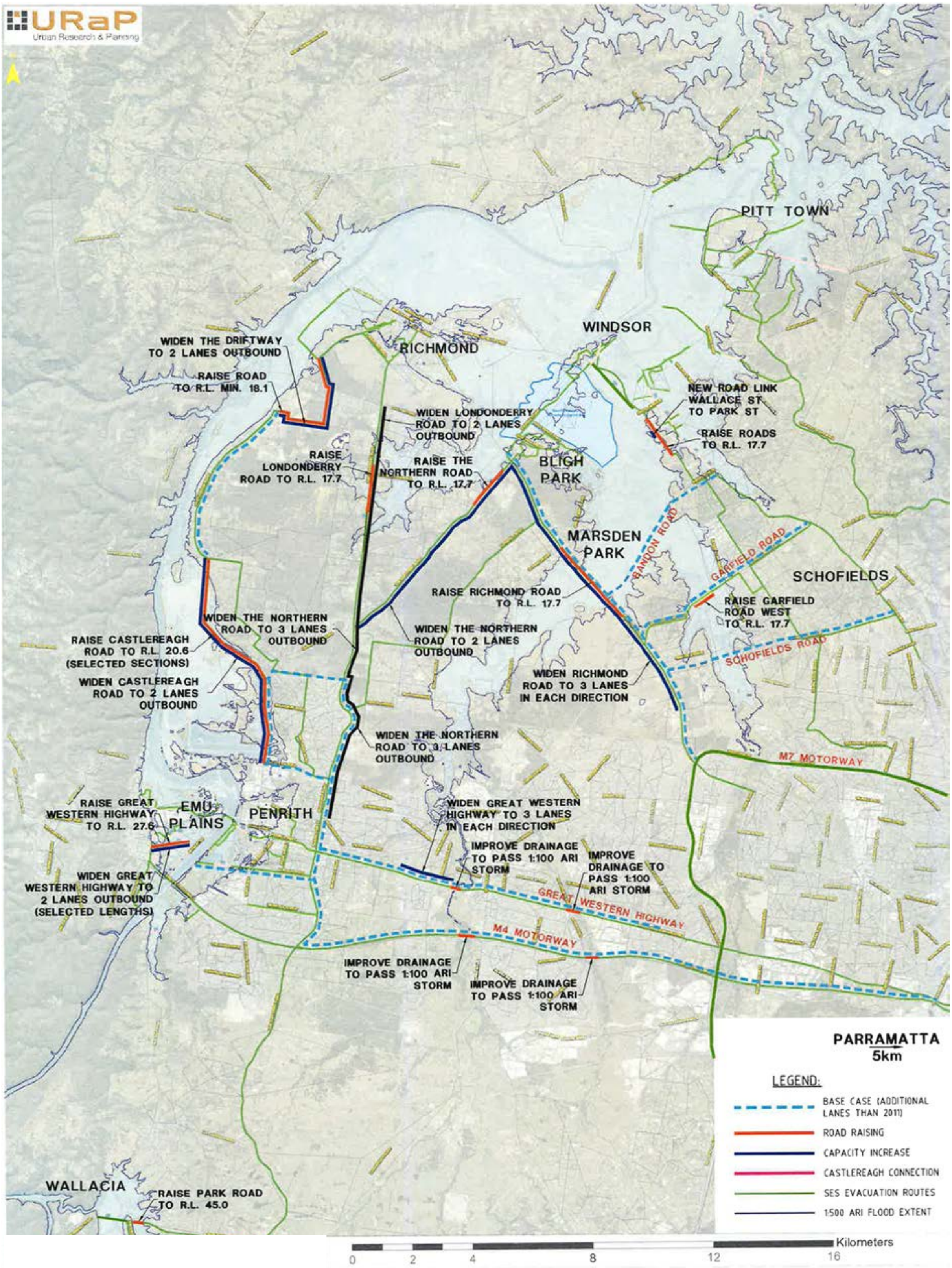



Option 3: 2041 base case + capacity increases

*Source:* URaP for the Taskforce

**Option 4: 2041 Base Case + 100 AEP Elevations + Increased Capacity**

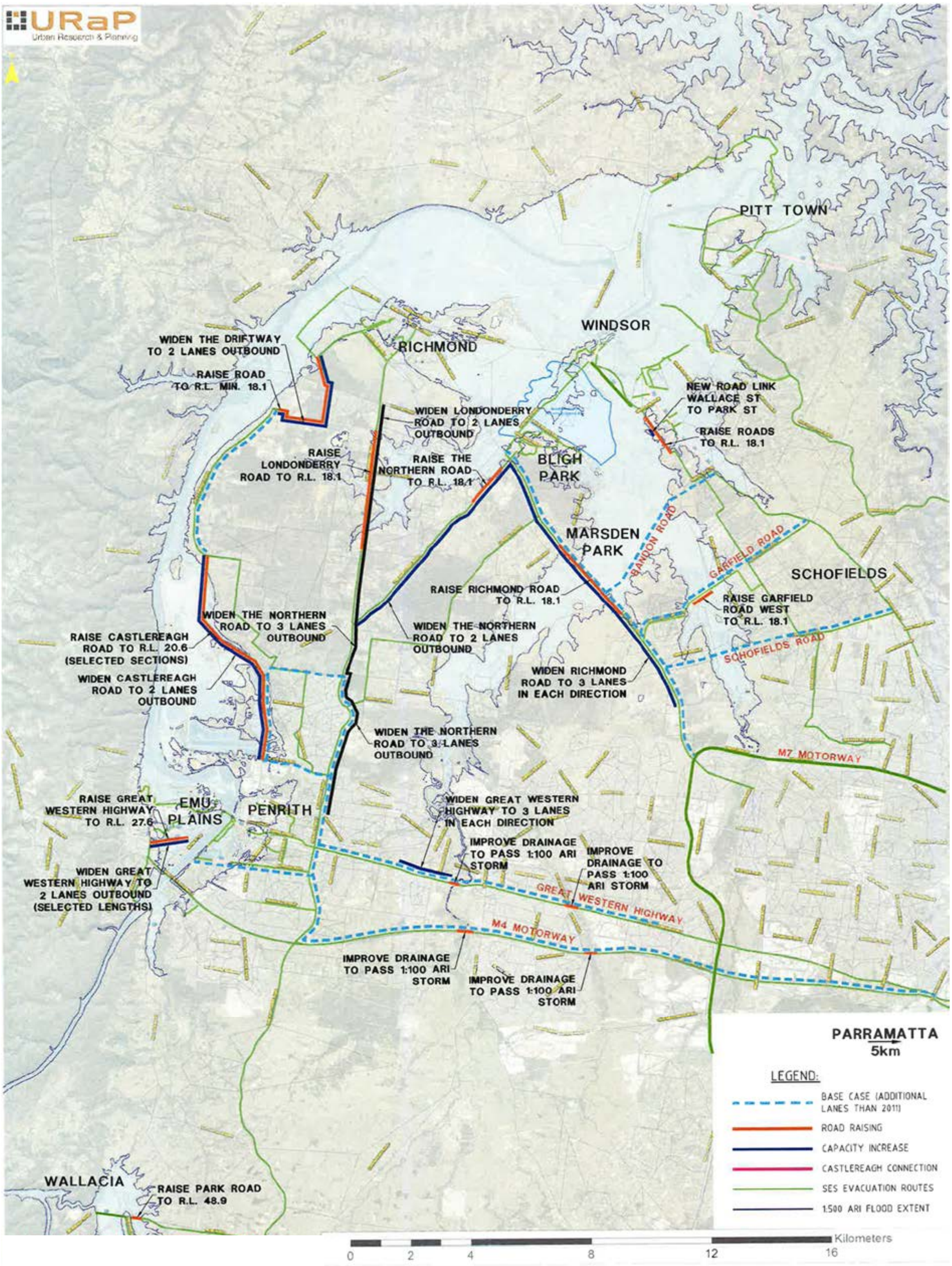
- Combination of Option 1 and 3




*Source:* URaP for the Taskforce

**Option 5: 2041 Base Case + 200 AEP Elevations + Increased Capacity**

- Combination of Option 2 and 3




Source: URaP for the Taskforce

**Option 6: 2041 Base Case + Castlereagh Freeway at RL 17.3m**

- 2041 base case, and
- Castlereagh Freeway between M7 and Castlereagh Road with full interchange at The Northern Road, 2 lanes in each direction with min RL 17.3m.

**Option 7: 2041 Base Case + 100 AEP Elevations + Castlereagh Freeway at RL 17.3m**

- Option 4 plus
- Castlereagh Freeway between M7 and Castlereagh Road with full interchange at The Northern Road, 2 lanes in each direction with min RL 17.3m.

**Option 8: 2041 Base Case + 200 AEP Elevations + Castlereagh Freeway at RL 18.5m**

- Option 5 plus
- Castlereagh Freeway between M7 and Castlereagh Road with full interchange at The Northern Road, 2 lanes in each direction with min RL 18.5m.

**Option 9: 2041 Base Case + 200 AEP Elevations + Castlereagh Freeway at RL 20.2m**

- Option 5 plus
- Castlereagh Freeway between M7 and Castlereagh Road with full interchange at The Northern Road, 2 lanes in each direction with min RL 20.2m.