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Environmental Impact Statement – Chapter 4: Project development and alternatives

Warragamba Dam Raising

Reference No. 30012078
Prepared for WaterNSW
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4 Project development and alternatives

This chapter describes the various alternatives to the Project considered as part of the development process and explains how and why the Project was selected as the preferred option in accordance with the Secretary's Environmental Assessment Requirements (SEARs). Design refinements for elements of the Project are also addressed. The relevant SEARs are shown in Table 4-1.

The chapter is ordered chronologically in the following sections:

- Section 4.1 provides background to the development over decades of alternatives and options to provide flood mitigation in the Hawkesbury-Nepean Valley (the valley)
- Section 4.2 details the methodologies and assessment criteria used by the Hawkesbury-Nepean Valley Flood Management Taskforce (Taskforce) between 2014 and 2016 to assess and evaluate options for flood mitigation.
- Section 4.3 looks at the alternatives to reduce flood risk considered by the Taskforce
- Section 4.4 examines and compares the short-listed Warragamba Dam flood mitigation alternatives analysed by the Taskforce
- Section 4.5 summarises the Taskforce's assessment and recommendations leading to the nine outcomes of the Hawkesbury-Nepean Valley Flood Risk Management Strategy (Flood Strategy) released in 2017
- Section 4.6 details the new research, guidelines and information that has informed ongoing assessment of flood risk and management during Phase One implementation of the Flood Strategy between 2017 and 2021
- Section 4.7 examines the contemporary analysis and reassessment of flood mitigation alternatives under the Flood Strategy and that have informed this EIS
- Section 4.8 details the consolidated outcome of the reassessment and confirms the proposal to raise Warragamba Dam for flood mitigation as the preferred option.

The data and analysis contained in this chapter draws extensively on the *Hawkesbury-Nepean Valley Flood Risk Management Strategy Taskforce Options Assessment Report* (Taskforce Options Assessment Report) published by Infrastructure NSW in January 2019. Some information from the Taskforce Options Assessment Report has been updated based on more recent analysis under the Flood Strategy. This is discussed in Sections 4.6 to 4.8 and identified in other locations where appropriate.

Table 4-1. Secretary's Environmental Assessment Requirements: Project development and alternatives

Desired outcomes	Secretary's Environmental Assessment Requirements[1]	Where addressed
2. Environmental Impact Statement Desired performance outcome: The project is described in sufficient detail to enable clear understanding that the project has been developed through an iterative process of impact identification and assessment and project refinement to avoid, minimise or offset impacts so that the project, on balance, has the least adverse environmental, social and economic impact, including its cumulative impacts.	1 The EIS must include, but not necessarily be limited to, the following: (e) an analysis of any feasible alternatives to the project;	Sections 4.2 to 4.8
	(f) a description of feasible options within the project;	Sections 4.3, 4.4
	(g) a description of how alternatives to and options within the project were analysed to inform the selection of the preferred alternative / option. The description must contain sufficient detail to enable an understanding of why the preferred alternative to and options(s) within the project were selected;	Sections 4.2, 4.6 to 4.8
	(i) a demonstration of how the project design has been developed to avoid or minimise likely adverse impacts both upstream and downstream of the dam wall;	Chapters 4 and 5

1 **Note:** this chapter specifically addresses SEAR 2 in addition to those general requirements of the SEARs applicable to all chapters and as identified as such in Chapter 1 (Section 1.5, Table 1-1).

4.1 Background

4.1.1 Introduction to options development stages

As discussed in Chapter 3, the significant risk of flooding of the Hawkesbury-Nepean Valley (the valley) has been recognised by local Aboriginal people and since European settlement of the area. Over more than 25 years, alternatives and options for flood mitigation and risk reduction have been investigated by several governments through specialist committees, reviews and a taskforce. The timeline of these investigations is summarised in Figure 4-1 and discussed in further detail in the following sections.

4.1.2 Investigations up until 2004

In the late 1980s and early 1990s, local and international experts and interdepartmental committees undertook investigations and provided advice to the (then) NSW Government on potential strategies to manage flooding risk in the valley. The NSW Government's preferred option at the time was raising the crest of Warragamba Dam by 23 metres, primarily to protect the dam from overtopping and possible failure under the probable maximum flood (PMF), but also to create a flood mitigation zone (FMZ) to reduce flooding risks and impacts in the valley. The *Environmental Impact Statement for Proposed Warragamba Flood Mitigation Dam* (1995 EIS) was prepared for the dam raising.

Figure 4-1. Timeline of flood risk management investigations for the Hawkesbury-Nepean Valley

Flood risk management - analysis, assessment and implementation

1995	Proposed Warragamba Flood Mitigation Dam EIS
1997-2004	Implementation Hawkesbury-Nepean Floodplain Management Strategy
2012	State Infrastructure Strategy
2013	Hawkesbury-Nepean Valley Flood Management Review
2014-2016	Hawkesbury-Nepean Valley Flood Management Taskforce
2017-2021	Hawkesbury-Nepean Valley Flood Risk Management Strategy – Phase One implementation

Source: INSW (2021)

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

- permanent lowering of Lake Burragorang (the stored water held by Warragamba Dam) to provide air space 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 air space 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.

However, in 1997, the subsequent NSW Government decided not to proceed with the preferred option and the planning application was withdrawn.

After the proposal was withdrawn, additional further studies and investigations were undertaken into potential alternatives for flood risk management in the valley. 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 valley. The principal study area was defined as that part of the valley downstream of Warragamba Dam to Spencer, including the creek and river catchments 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:

- Hawkesbury-Nepean River Impacts of Flooding on Communities and Infrastructure (Molino Stewart 1997)
- Engineering Studies to Modify Flood Behaviour (Webb Mckeown and Associates 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.

Following adoption of the Hawkesbury-Nepean Floodplain Management Strategy, the NSW Government committed funding over five years for implementation, focusing on measures to improve flood evacuation and response. 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 (see Table 4-2).

Table 4-2. Initiatives from the 1997 Hawkesbury-Nepean Floodplain Management Strategy

Strategy initiative	Key outcomes
Improved evacuation routes	Upgraded evacuation routes for five key towns, including the Jim Anderson Bridge at Windsor.
Better flood forecasting and warning	Improved accuracy and reliability of flood forecasts
Enhanced emergency response to floods	Improvements to emergency response operations
Faster recovery for affected communities	Reduced potential for down-time of essential services; improved community support services for recovery
Increased awareness of flood risks	Implementation of regional public awareness campaign targeting communities and councils
Regional approach to flood planning	Completion of Regional Floodplain Management Study
Improved understanding of flood hazards	Release of computer-based Flood Hazard Definition Tool, together with workshops
Development of best practice land development guidelines	Release of Land Use Planning, Subdivision and Building Guidelines

Source: INSW (2019)

4.1.3 Hawkesbury-Nepean Valley Flood Management Review 2013

In 2012, extensive flooding across south-eastern Australia, including the Hawkesbury-Nepean Valley, saw Warragamba Dam spill for the first time in 14 years. This again raised awareness about the potential impacts of flooding in major urban areas.

In early 2013, the Hawkesbury-Nepean Valley Flood Management Review (2013 Review) commenced following the Government's adoption of the State Infrastructure Strategy 2012-2032 and ongoing concerns about flood risk.

Overall, the 2013 Review found that there was a significant existing and growing flood risk in the valley and concluded there was no simple solution or single infrastructure option that could address all of the flood risk.

The 2013 Review identified several priority areas for action:

- increasing flood awareness and preparedness in the community
- the enhancement of emergency planning, response and recovery
- better consideration of flood risk in land use planning
- reviewing governance for effective flood risk management
- cost benefit assessment of potential flood mitigation infrastructure options.

4.1.4 Hawkesbury-Nepean Valley Flood Management Taskforce (2014-2016)

Following the recommendations of the 2013 Review, the NSW Government established the Hawkesbury-Nepean Valley Flood Management Taskforce (the Taskforce) to develop a whole-of-government approach to flood risk management and preparedness in the valley. Through 2014-2016, the Taskforce built on the preliminary investigations of the 2013 Review, to develop a strategy under the disaster risk management framework of 'prevent, prepare, respond and recover'.

A key objective of the Taskforce was to identify, develop and assess potential alternatives and options for reducing flood impacts and risks in the valley. This included:

- reviewing previous alternatives and options from the 1997 Hawkesbury-Nepean Floodplain Management Strategy and the 2013 Review
- identifying new potential alternatives or options
- developing assessment criteria to enable the comparison of different alternatives and options
- commissioning studies and design work on feasible alternatives and options to provide suitable information to enable their assessment. This included engineering design of relevant options, flood modelling, evacuation modelling to assess risk to life, flood damages assessment, cost estimation, cost benefit analysis, and preliminary environmental impact assessment
- using the assessment criteria and information from the additional design and studies to evaluate the alternatives and options to determine which, in single or combination, were the most effective in reducing flood impacts
- developing the Hawkesbury-Nepean Valley Flood Risk Management Strategy (Flood Strategy) for Government's consideration.

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 valley. A combination of infrastructure and policy or other initiatives are required to reduce flood risk by:

- changing the probability and delaying flood events reaching critical levels
- reducing the exposure of people, property and assets to flood risk
- increasing the available time to safely evacuate areas exposed to imminent flooding
- increasing the resilience of communities, property and public assets exposed to floods.

The Taskforce Options Assessment Report (INSW 2019) provides a detailed description of the alternatives and options considered. A summary of the Taskforce alternatives and assessment process is presented in Sections 4.2 to 4.5.

4.1.5 Hawkesbury-Nepean Valley Flood Risk Management Strategy – Phase One (2017-2021)

Implementation of Phase One of the Flood Strategy (2017-2021) has included delivery against nine key outcomes across the prevent, prepare, respond and recover spectrum of disaster risk management. Outcome 2 – Reduce flood risk in the Valley by raising Warragamba Dam Wall, has key actions to complete detailed designs and an environmental impact statement for the dam raising proposal.

In delivering Outcome 2, significant further analysis has been undertaken to inform both the proposal and technically feasible alternatives to the proposal (as required by the SEARs). This further analysis is detailed in Sections 4.5 to 4.7.

4.2 Taskforce methodology and criteria for consideration of alternatives

This section describes the performance criteria and methodology developed by the Taskforce to assess the alternatives and options for flood risk mitigation. These criteria were:

- significant regional reduction of flood peak

  - reduction in downstream peak flood levels for critical flood range for damages of 1 in 50 to 1 in 1,000 chance in a year for damages and risk to life
  - extent of peak flood level reduction in the 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 impacts
- other factors.

As the assessment of alternatives has followed a progressive shortlisting approach - from the 2013 Review to the Taskforce and the Flood Strategy - only the more feasible alternatives were assessed according to the more intensive methodologies including evacuation modelling to better understand relative risk to life.

4.2.1 Taskforce assessment of significant, regional reduction of flood peak

The 2013 Review assessed how each alternative would meet the criterion to 'significantly reduce the potential economic and social impact of flooding in the Hawkesbury-Nepean Valley' (SIS 2012). Two key considerations were to:

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

To assess whether an alternative significantly reduced flood impacts, the reduction of critical peak flood levels was used as a measure. Critical floods were identified as flood events that peak between the 1 in 50 and 1 in 1,000 chance in a year under (then) current conditions and infrastructure.

Floods between the current 1 in 50 and 1 in 500 chance in a year contribute about two-thirds of calculated current average annual damages. More frequent (smaller) flood events contribute only about 12 percent of average annual damages. The 1 in 1,000 chance in a year flood was included in the definition of a critical flood because this flood event would result in Richmond being first isolated, then flooded.

Options that most effectively reduce flood levels in the critical range would be the most effective for mitigating the regional flood risk. This was assessed using hydrological and hydraulic flood modelling results (refer Appendix H1 Flooding and Hydrology and Appendix H2 Flood Risk Analysis). See Sections 4.6 and 4.7 for updated analysis.

4.2.2 Taskforce assessment of reduced risk to life

Large numbers of people live and work on the Hawkesbury-Nepean floodplain. Risk to life was assessed by:

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

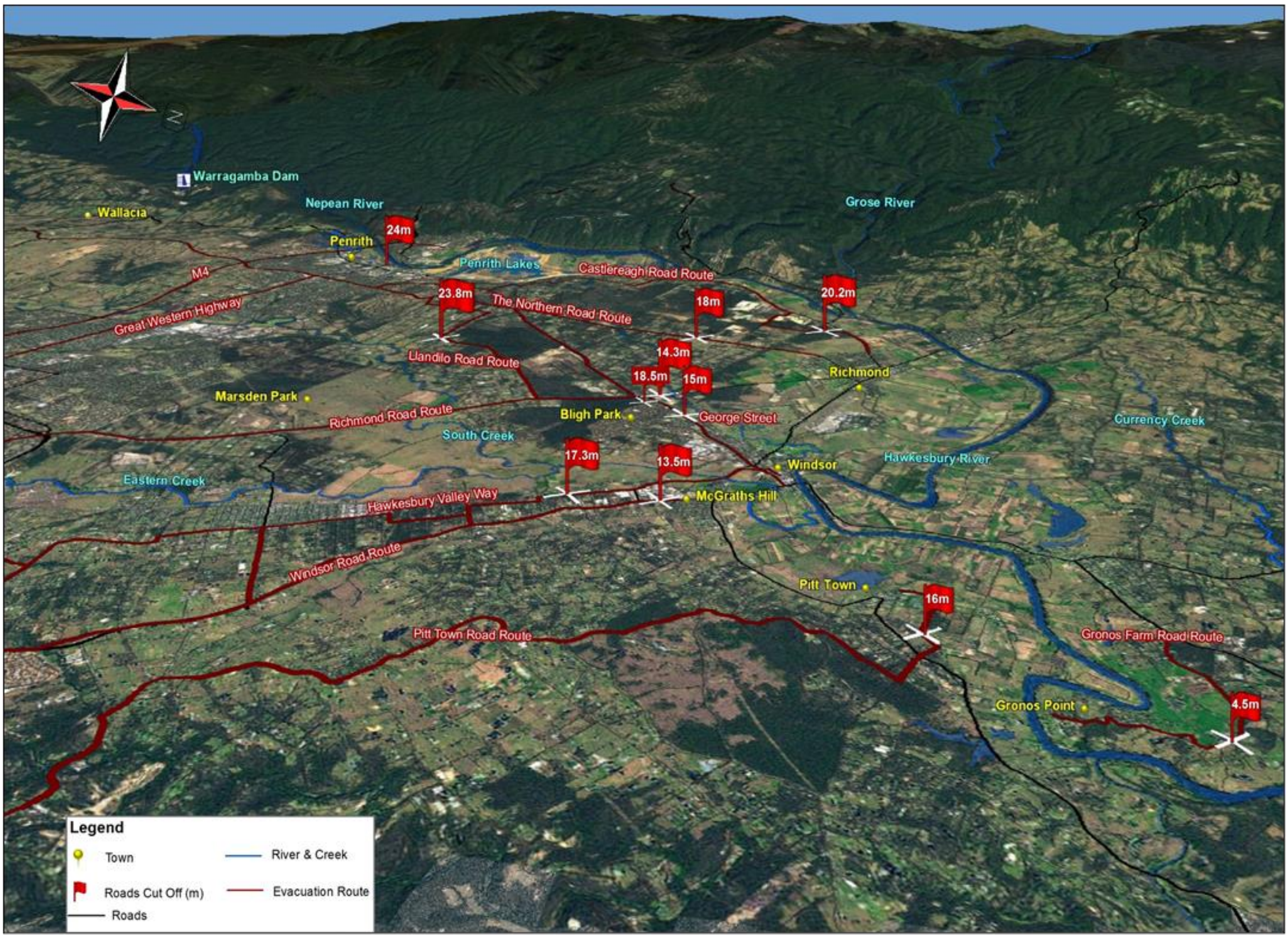
The ability to reduce risk to life was assessed for dam and evacuation road infrastructure alternatives.

Successful self-evacuation using the road network is the primary method of reducing risk to life from flooding in the valley due to limited and flood prone public transport options. Many key settlements are located on 'flood islands', which are connected to flood-free land via relatively low-level roads (Figure 4-2). These settlements on flood islands can be first isolated then inundated in large floods.

To minimise risk to life, it is essential populations on flood islands are evacuated before evacuation routes are cut. The depth and extent of flooding means sheltering in place during major floods is neither safe nor feasible in this valley.

Significant evacuations are triggered when floods are forecast to reach key levels in the floodplain. The first significant regional flood evacuation route cut is the McGraths Hill route at 13.5 mAHD. The key evacuation route for Windsor and South Windsor (Jim Anderson Bridge) is cut at around 17 mAHD. The Richmond regional flood evacuation route is flooded at 20.2 mAHD, which corresponds to between a 1 in 500 and 1 in 1,000 chance in a year flood.

Figure 4-2. Hawkesbury-Nepean Valley flood evacuation routes & flood level (mAHD) when flood routes are cut



Source: INSW (2019)

Options for targeted raising of regional evacuation routes are discussed in Section 4.3 which shows these are not effective for reducing risk to life. To minimise increased flood levels upstream of the raised roads, many kilometres would need to be raised, often as bridges, due to the relatively low gradients in the floodplain. The need to maintain access for many adjoining properties and roads from the raised evacuation routes would also be cost prohibitive.

Extreme but rare events result in floods greater than 20.2 mAHD in the Richmond/Windsor area increasing the area needing to be evacuated but with no significant additional flood island created. Most people residing above 20.2 mAHD are able to evacuate as they have rising evacuation routes. In Penrith, there are no significant flood islands, but evacuation is impacted by the high Penrith population and convergence of evacuation traffic from the Richmond/Windsor area causing local traffic congestion.

Under the Taskforce, evacuation modelling was undertaken using 2016 as an existing population, and 2041 as the time horizon. For the future scenario, 2041 was adopted as a reasonable point to represent the potential growth given existing planning permissibility under existing planning policies and with the existing Warragamba Dam.

The 2041 scenarios did 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 alternatives in relation to that flood risk.

Social research undertaken in 2014 for the Taskforce showed that around three percent of the population in the valley said they would not evacuate when instructed or ordered to evacuate, and 27 percent said they would use their own judgement in deciding to evacuate (Newgate Research 2014a, 2014b; cited in Taskforce Options Assessment Report (INSW 2019). In a 1 in 100 chance in a year flood event, even if only three percent did not evacuate, around 2,000 people that needed to evacuate would be at risk. One other key finding from the study was a high proportion of people needing assistance to evacuate, including the elderly and those with a disability.

Preferred alternatives were those that would significantly reduce the flood exposure and delay the timing of all the critical evacuation routes being cut. Therefore, the risk-to-life benefits of alternatives were assessed using the following considerations:

- **reduced exposure to floods** - Alternatives were assessed on their ability to reduce the frequency of floods where properties would be inundated and evacuation roads would be cut, as the risk to life would be directly reduced. This was assessed using the Monte Carlo suite of 19,500 possible floods.
- **flood delay providing a longer window for evacuation** - The time to evacuate some areas of the Hawkesbury-Nepean Valley exceeds the Bureau of Meteorology flood forecast target time (eight hours at Penrith to 15 hours at Richmond and Windsor), forcing the NSW SES to order evacuations based on uncertain flood level predictions. The rapid flooding characteristic of the valley requires the use of forecast rainfall rather than fallen rain or observed river level rises. If an infrastructure alternative delays the time at which the flows enter the valley, the evacuation roads are cut later in the rainfall event. This provides more certainty about the timing, making it possible to safely evacuate more people from the floodplain. Conversely, where an infrastructure alternative cuts the evacuation roads earlier in the event, risk to life is increased.
- **risk to life** - A key metric to quantify the risk-to-life benefits of reduced exposure and/or delay of peaks resulting from flood mitigation or evacuation road infrastructure alternatives is average annual vehicles or population unable to evacuate. This metric allows for comparing:
  - dam alternatives that reduce and delay downstream flood rise and peaks
  - road alternatives that increase evacuation capacity by raising, widening or expanding the evacuation road network
  - combinations of these options.

The risk to life for each alternative was compared by simulating flood evacuations and measuring the number of vehicles and people unable to evacuate. To compare alternatives, the modelling assumed a 100 percent response to the order to evacuate consistent with the aim of achieving full evacuation of people at risk. Transport services would be provided for people without vehicles as per the Hawkesbury-Nepean Flood Plan (NSW SES 2015). 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 was 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 used 46 representative modelled flood events between 1 in 50 and 1 in 5,000 chance in a year as measured at Windsor.

4.2.3 Taskforce assessment of economic costs and benefits

Another criterion was the economic costs and benefits of each alternative. The Taskforce measured the benefits in terms of reduced flood damages, based on damages to property from the peak flood level, and risk to life from the flood evacuation model results of people unable to evacuate.

The level of economic analysis was consistent with the progressive shortlisting process described in the Taskforce Options Assessment Report (INSW 2019). For some alternatives, their high cost relative to their small reduction in flood peak levels, and likely small reduction in flood damages, were sufficient reasons to eliminate them from further consideration. For more feasible alternatives, a full damages assessment was conducted to assess the benefits in terms of damages avoided. The benefits were compared to estimated costs for each alternative. This cost-benefit analysis is described further below.

4.2.3.1 Measuring benefits

The approaches taken by the Taskforce for quantifying the flood risk reduction benefits of infrastructure flood risk mitigation options are summarised in Table 4-3. A conservative approach was adopted. The Taskforce results presented are at the low end of the range of possible outcomes from the sensitivity analysis.

Table 4-3. Taskforce - measuring flood-related benefits from infrastructure flood risk mitigation options

Benefit	Measurement
Avoided loss of life	Loss of life is calculated as a subset of the number of people unable to be evacuated in reasonable time. 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/RMS. A 100 percent compliance with NSW SES orders to evacuate was assumed as flood modelling is based on enabling everyone to evacuate to safety (with a high sensitivity test of 15 percent non-compliance). Loss of life was estimated as one percent of people unable to evacuate, with low and high sensitivity tests of 0.5 percent and two percent. Recognising the difficulty of evacuating flood islands that can become fully inundated, a higher mortality function based on depth was applied in such areas. For the purposes of cost-benefit analysis, the value of statistical life used in the central case was $6.8 million 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 based on the Australian Government's Best Practice Regulation Guidance Note Value of Statistical Life (OBPR 2014).
Avoided damage to residential buildings and property	Stage damage curves developed by Geoscience Australia were used. These relate damage to flood depth for a variety of residential types. Flood modelling was used to estimate flood depths for a range of flood events for each property in the floodplain for this purpose Results were also tested using NSW Government's stage damage curves.
Avoided commercial and industrial damage	Stage damage curves developed by the Flood Hazard Research Centre at Middlesex University were used. These relate damage per square metre to flood depth for a variety of commercial/industrial types. Flood modelling was used to estimate flood depths for a range of flood events for each property in the floodplain for this purpose. It was noted that commercial and industrial damages would be highly variable across types of activity, depending on how easily plant and machinery is damaged.
Avoided indirect residential damages	Avoided indirect residential damages were assumed to be five percent of direct residential damages, with low and high sensitivity tests of zero percent and 25 percent. 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.
Avoided 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). This was measured through reference to a business survey conducted after the 2011 Queensland floods and the Centre for International Economics (the CIE) adjustments to reflect economic cost only. It was assumed to be 37.5 percent of direct commercial/industrial damages, with a high sensitivity test of 100 percent
Avoided electricity infrastructure damages	Estimates of damage at different flood levels were provided by power service providers. It was assumed that these damages are reduced in the same proportion as residential property damage.

Benefit	Measurement
Avoided road pavement damages	Avoided road pavement damages were estimated by Transport for NSW (Roads and Maritime Services), by classifying roads into condition, estimating how much road is damaged and the cost of repaving.
Avoided injury and welfare loss from evacuation	Anyone evacuating was assumed to have a welfare cost ranging from $313 per person to $641 per person. The costs per person unable to evacuate were assumed to be larger at $313 to $954. These estimates were based on previous studies of costs for those in flooded areas (based on a literature review conducted by the CIE).
Avoided other damages (caravans, agriculture, motor vehicles, telecommunications, water and sewerage)	Estimates of damage for this category were based on previous damage assessments. Based on updated information, minor adjustments were made by the CIE to reduce damages for agriculture. Estimates for damage to water and sewerage assets were cross-checked with Sydney Water and found to be sufficiently consistent with CIE's estimates. It was assumed these damages were reduced in the same proportion as residential property damage.

Source: *Taskforce Options Assessment Report (INSW 2019)*

4.2.3.2 Measuring costs

The Taskforce calculated the capital and operating costs of the alternatives based upon 2015 dollars. Costs included construction costs, operational costs and for some options, costs to safeguard water security and water quality.

Options that lower the full supply level (FSL) of Warragamba Dam would have impacts on Sydney's water supply system. These impacts were measured by modelling the cost of meeting water security requirements for the different alternatives. The costs of meeting water security thresholds reflect financial and non-financial costs. These include costs of pumping water from the Shoalhaven Scheme 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 hydro-economic model used to identify optimal solutions (maximum supply, at lowest cost) for maintaining the security of Greater Sydney's water supply.

Lowering the FSL and prolonged releases of floodwaters from the FMZ could also have implications for water quality and the supply of water downstream. Potential issues are with the management of water quality in the dam, and for the Hawkesbury River where water is extracted for the North Richmond Water Filtration Plant. A reduction in water quality may require extracted water to undergo more extensive treatment (i.e. higher chemical and energy costs) and may require the water filtration plant to be upgraded. The costs of these potential impacts were provided by WaterNSW and Sydney Water.

4.2.3.3 Comparing benefits to costs

A cost benefit analysis requires assumptions about the time period for the evaluation and the discount rate, which converts future benefits and costs into their value today. The discount rate (seven percent) and time period assumptions (30 years) were in accordance with Treasury guidelines.

Assumptions were made using the best available information and expert opinion. Best practice requires an assessment of the sensitivity of the assumptions to test that an option is robust to changed assumptions. Accordingly, the cost benefit analysis applied sensitivity analysis to the 'central case' assumptions using high and low assumptions (see Table 4-3 for summary of assumptions). The 'central case' results adopted were conservative and close to the low assumptions results. Adopting the high assumption would have significantly increased the favourability of the preferred flood mitigation alternative.

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.

4.2.4 Taskforce assessment of social, environmental and cultural heritage impacts

The fourth criterion used by the Taskforce was to assess the impact of alternatives on socio-economic, environmental and cultural heritage (SECH) values. The Taskforce Options Assessment Report (INSW 2019) includes further details relating to this criterion.

Floods naturally occur 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 this, and the stage of investigation, a risk-based approach was adopted to assess the impacts of changed flood behaviour associated with infrastructure alternatives on SECH values. The risk-based impact assessment included:

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

The assessment was suitable for the Taskforce's detailed feasibility investigation and based upon known information at the time. This EIS provides additional detailed information on the impact of the preferred option and mitigation measures to reduce its impact (refer Chapters 7-12).

4.2.5 Other factors

Other factors informed the Taskforce's decisions on the feasibility of alternatives including:

- maintaining dam safety
- maintaining water supply security
- dam operations
- climate change.

4.3 Taskforce - alternatives considered

The assessed alternatives and non-infrastructure measures are detailed in the Taskforce Options Assessment Report (INSW 2019) and include:

- operational alternatives using the existing Warragamba Dam – these primarily modify how the dam is operated but may require some modification to existing infrastructure; these include:
  - opening Warragamba Dam gates more slowly to temporarily hold back inflows ('surcharge' method)
  - pre-releases from Warragamba Dam water supply to create a temporary FMZ in advance of a forecast flood
  - lowering Warragamba Dam's water supply storage to create a dedicated FMZ
  - combined operational alternatives
- new flood mitigation dams – alternatives include new dams built and operated only for flood mitigation:
  - new dams upstream of Warragamba Dam
  - new dam on Nepean River
  - new dams downstream of Warragamba Dam
- raising Warragamba Dam wall to temporarily store flood waters in a dedicated FMZ – this alternative included detailed consideration of two different heights:
  - raising by 14 metres
  - raising by 20 metres
- infrastructure upgrades to enhance drainage or protect downstream communities, including:
  - construction of diversion channels to improve the drainage of floodwaters

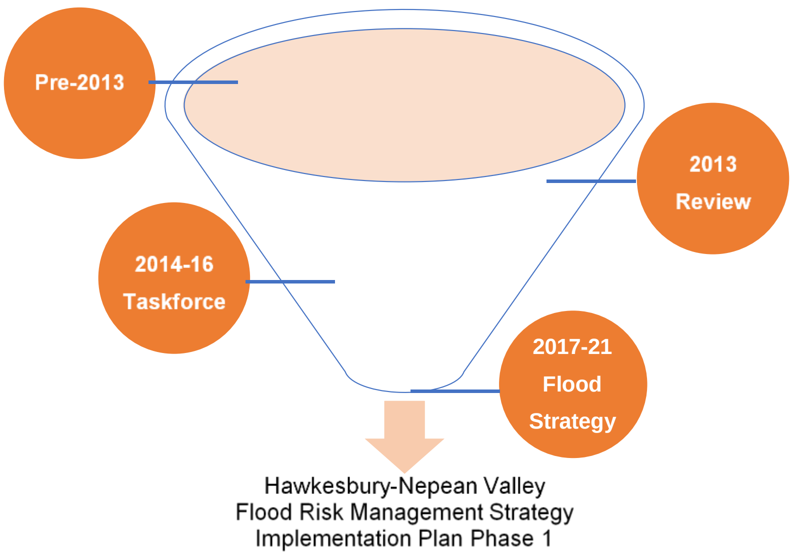
  - dredging of Hawkesbury River to improve drainage of floodwaters
  - levees to provide localised flood protection to flood prone communities
- evacuation road upgrades – involving upgrade packages to improve evacuation road network capacity. Two categories of road upgrades were considered:
  - nine evacuation road upgrade packages for major regional evacuation routes
  - local evacuation road upgrades
- non-infrastructure measures – a wide range of non-infrastructure measures was considered including changes to land use planning controls, improved flood forecasting and response, building community resilience, and better coordination between agencies. Generally, these measures do not result in any reduction in flooding extent or frequency, and so cannot be considered substitutes to flood mitigation infrastructure that would reduce significant existing risk exposure. Nonetheless, these non-infrastructure measures are critical for an integrated and sustainable approach to managing current and future flood risk in the valley.

This approach is consistent with best practice frameworks for disaster risk management across the prevent, prepare, respond and recover spectrum.

4.3.1.1 Summary of alternatives considered

As discussed previously, several regional studies were undertaken between the 1990s and 2012 to identify and evaluate alternatives and options to reduce flood risk in the Hawkesbury-Nepean Valley. The 2013 Review reconsidered many of these and put forward a list of alternatives, which were investigated as part of the Taskforce's work. In effect, a shortlisting approach was adopted, in which the most feasible alternatives were taken forward through the course of the investigations, leading to the options included in the 2017 Flood Strategy (see Figure 4-3).

Figure 4-3. Approach to shortlisting of feasible options pre-2013 to 2017



Source: INSW (2019)

Table 4-6 lists the alternatives considered as part of the progressive shortlisting process. It also shows the stage at which the evaluation of each alternative was concluded if it was judged that sufficient work had been done to exclude that alternative from further investigation. Some alternatives have been or are in process of being implemented as part of the Flood Strategy.

It is also possible to consider alternatives in combination. This is of value only where an individual alternative complements other alternatives, that is, where the outcome of undertaking both alternatives together is a higher net benefit or lower net disbenefit (cost) than the sum of the net benefits/disbenefits of undertaking each by itself. For the alternatives considered, most options were partial substitutes for most other alternatives; that is, the benefit of undertaking both alternatives together is lower than the sum of the benefits of undertaking each individually. The exceptions to this were non-infrastructure options such as land use planning and improved governance for integrated flood risk management, which complement flood mitigation measures.

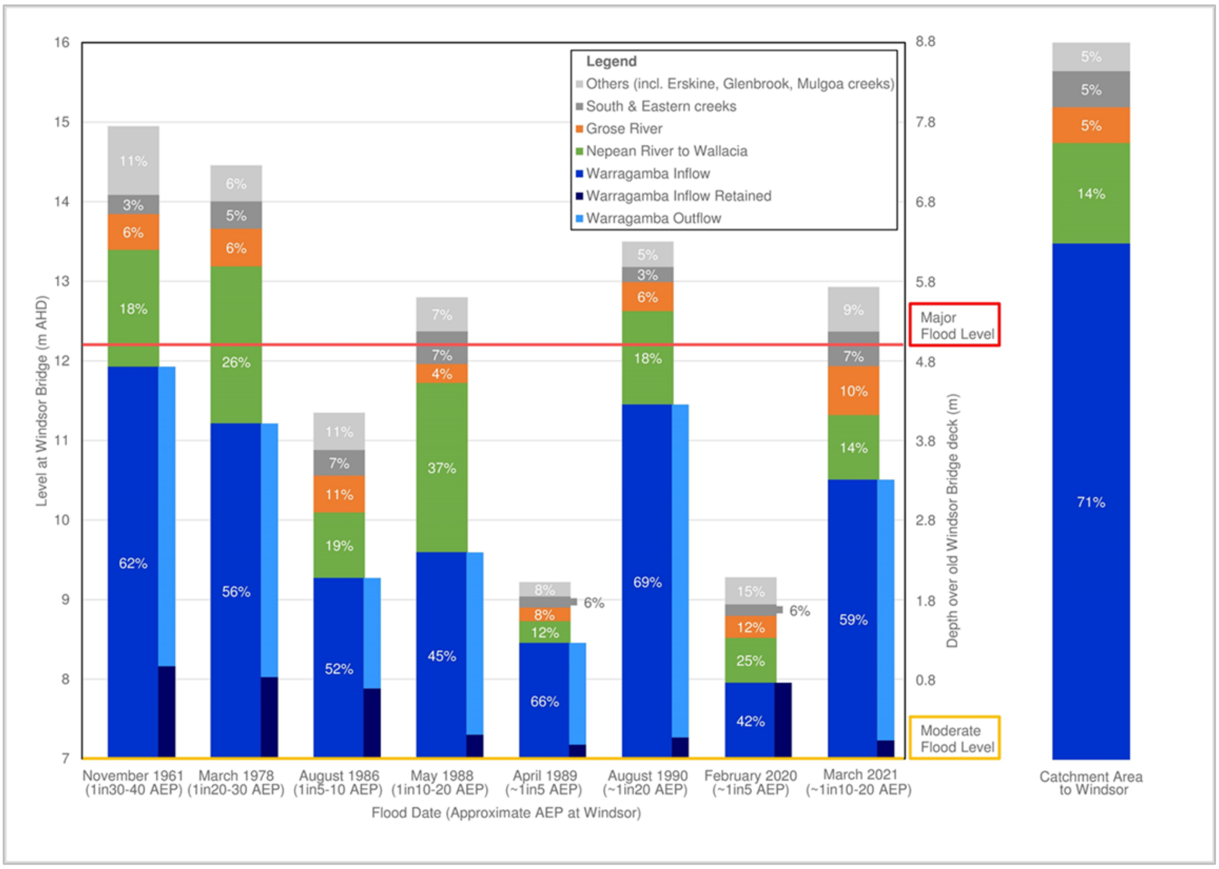
Flood modelling evolved over the process of the 2013 Review and 2014–16 Taskforce investigations, in conjunction with revisions to national guidelines and advances in practice. Options were assessed using the latest modelling outputs available at the time of their analysis.

Further refinements in climate science, flood and evacuation modelling and demographic analysis have informed the options analysis undertaken during Phase One of the Flood Strategy and to inform this EIS (see sections 4.5 to 4.7).

4.4 Taskforce - short-listed Warragamba Dam flood mitigation alternatives

The large Warragamba Dam catchment historically contributes up to 70 percent of floodwaters during flooding in the Hawkesbury-Nepean (see Figure 4-4 below). Extensive Monte Carlo modelling of around 20,000 possible floods undertaken for the Taskforce showed this contribution could be as high as 75 percent.

Figure 4-4. Relative contribution different river catchments in range of Hawkesbury-Nepean Valley floods



Source: INSW (2021(

Notes: AEP (annual exceedance probability) = chance in a year

The February 2020 event was about a 1 in 5 chance in a year flood, with Warragamba catchment modelled to contribute 42 percent of the total volume at Windsor. The dam storage level was low at the start of the event and captured all flows from the Warragamba catchment. However, had the dam been full, downstream flood levels would have been around three metres higher, or equivalent to around a 1 in 20 chance in a year event.

The Taskforce concluded that the most effective alternatives to mitigate flood risk in the Hawkesbury-Nepean Valley were those that created a dedicated FMZ at Warragamba Dam, which was large enough to significantly reduce regional flood levels downstream of the dam. The provision of a dedicated FMZ has significant benefits including:

- a reduction in the peak levels and extent of floods
- a delay in the rise of floodwaters downstream
- greater certainty in evacuation timing
- guaranteed flood mitigation capacity regardless of the accuracy of rainfall and flood forecasting.

There are three ways of creating a dedicated FMZ at Warragamba Dam:

- lower Warragamba Dam's permanent full storage level; two alternatives were considered: five or 12 metres.

- combinations of lowering the FSL and changed gate operations; and
- raise the dam wall while maintaining the current FSL.

These are described in greater detail in the following sections.

4.4.1 Lowering Warragamba Dam's permanent full supply level

4.4.1.1 Alternatives for lowering FSL of Warragamba Dam

The current FSL of Warragamba Dam is at 116.72 mAHD. This level is determined by the top of the central drum gate in the central spillway. The base of the four central radial gates at Warragamba Dam is at 104.5 mAHD, 12.2 metres below FSL. This level is the limit to which the FSL can be lowered using the existing dam gates. The proportion of Warragamba Dam's full storage capacity of 2,027 gigalitres that would be lost to the water supply system is shown in Table 4-4.

Table 4-4. Potential FMZ created from permanently lowering FSL at Warragamba Dam

Lowering of FSL	Capacity of FMZ created	Reduction in Warragamba storage	Reduction in Greater Sydney storage
-5m	360 GL	-18%	-15%
-12 m	795 GL	-39%	-31%

Source: Taskforce Options Assessment Report (INSW 2019)

4.4.1.2 Impacts on regional flood peak and duration

The effects of these options on flood behaviour were tested using the Monte Carlo model simulations of 19,500 flood events ranging from very frequent events smaller than a 1 in 2 chance in a year to extreme floods. The results below focus on the critical flood range of 1 in 50 to 1 in 1,000 chance in year events, as described in section 4.2.1.

Downstream peak flood levels

Lowering the FSL by five metres would reduce the:

- 1 in 50 chance in a year flood peak levels on average by 0.4 metres at Penrith and 0.9 metres at Windsor
- 1 in 100 chance in a year flood peak levels on average by 0.3 metres at Penrith and 0.6 metres at Windsor
- 1 in 500 chance in a year flood peak levels on average by 0.1 metres at Penrith and 0.5 metres at Windsor
- 1 in 1,000 chance in a year flood peak levels on average by 0.2 metres at Penrith and 0.4 metres at Windsor.

Lowering the FSL by 12 metres would reduce the:

- 1 in 50 chance in a year flood peak levels on average by 1.9 metres at Penrith and 2.6 metres at Windsor
- 1 in 100 chance in a year flood peak levels on average by 1.2 metres at Penrith and 1.9 metres at Windsor
- 1 in 500 chance in a year flood peak levels on average by 0.5 metres at Penrith and 1.4 metres at Windsor
- 1 in 1,000 chance in a year flood peak levels on average by 0.5 metres at Penrith and 1.3 metres at Windsor.

Downstream flood duration

Floodwater temporarily stored above the FSL in the FMZ would need to be discharged to restore its capacity to capture any potential subsequent event. The downstream flood duration is sensitive to which post-flood release strategy is employed that is, the rate at which the temporarily stored water is released.

An assessment of durations of inundation above 10 mAHD at Windsor was undertaken using the Monte Carlo suite of 19,500 possible floods and a range of release rates. This level was selected because post-flood releases are mostly contained within the riverbanks to this height (except around the Richmond Lowlands which is land primarily zoned for agricultural and recreational use). A release rate of 100 GL/d was selected to minimise downstream impacts while emptying the FMZ as quickly as possible. The results include:

- for lowering FSL by five metres:
  - about 47 percent of floods would have a shorter duration above 10 mAHD
  - about 5 percent of floods would have a longer duration above 10 mAHD
  - many floods (48 percent) would no longer reach a level of 10 mAHD at Windsor

- for lowering the FSL by 12 metres:
  - about 31 percent of floods would have a shorter duration above 10 mAHD
  - about one percent of floods would have a longer duration above 10 mAHD
  - most floods (68 percent) would no longer reach a level of 10 mAHD at Windsor.

Upstream peak flood levels and duration

Lowering the FSL will not increase the level or duration of upstream flooding. Rather, the level and duration of upstream flooding will be less than under current conditions for smaller floods.

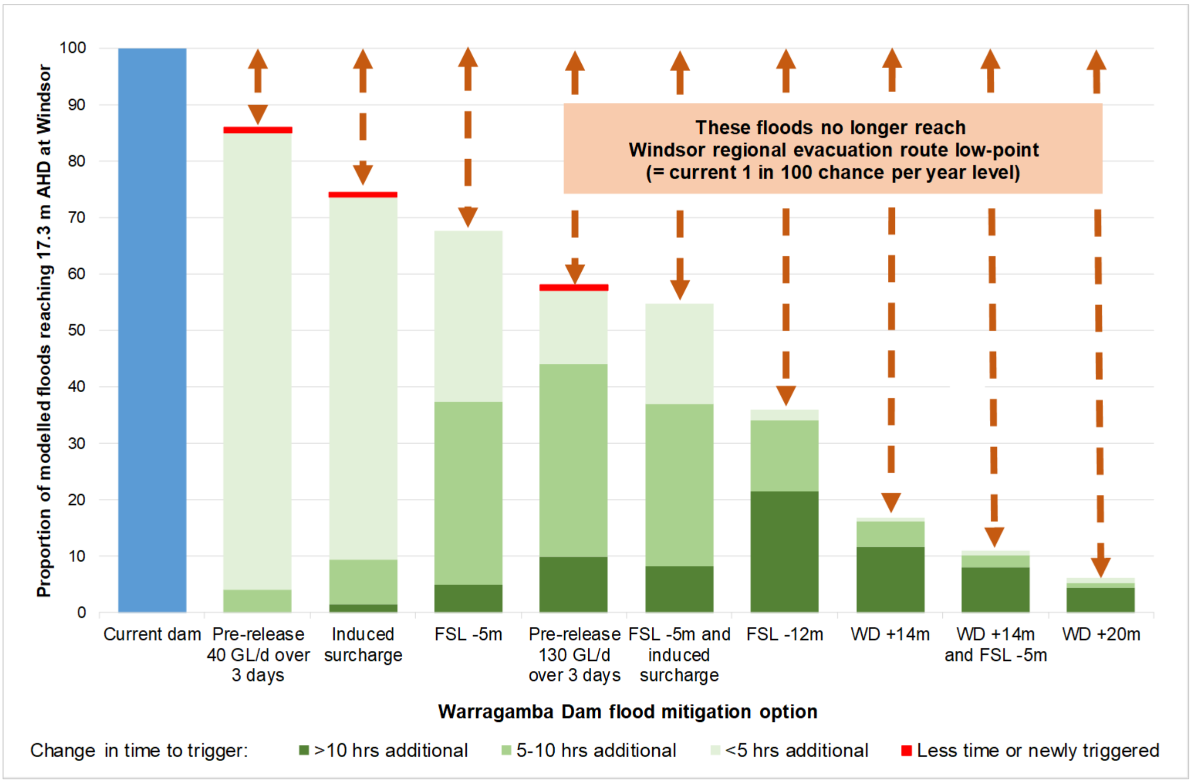
4.4.1.3 Impacts on risk to life

With a lowering of FSL by five metres, about one-third of modelled events were shown to 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.

With a lowering of the FSL by 12 metres, around 60 percent of modelled events would no longer cut evacuation routes from McGraths Hill, Pitt Town and Windsor, and the time at which the routes are cut for floods that would still reach those levels would be significantly delayed (see Figure 4-5).

These figures place in context the benefits of reduced and delayed inundation of the McGraths Hill and Windsor evacuation routes afforded by lowering FSL, showing that the risk-to-life reducing benefits are inferior to those provided by other alternatives.

Figure 4 5. Change in frequency and timing of events reaching and exceeding 17.3 mAHD level at Windsor with different Warragamba Dam infrastructure alternatives (Taskforce)



Source: Taskforce Options Assessment Report (INSW 2019)

4.4.1.4 Economic assessment

As part of the Taskforce analysis, the CIE assessed the benefits and costs of lowering the FSL by either five metres or 12 metres. The details, outlined below and in Table 4-6, are in the Taskforce Options Assessment Report (INSW 2019).

Costs

The costs of lowering FSL by 12 metres were assessed as very high, mainly due to the costs of bringing forward alternative supplies to meet Sydney's water needs, as well as costs to address water quality issues.

This cost did 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. Additionally, this cost does not account for any augmentation of the Sydney Water Corporation system that would be required.

Also, lowering the FSL by 12 metres would likely preclude environmental flows releases (e-flows) from the dam to maintain water security for Sydney. This would be an additional cost because of the predicted river health benefits foregone.

Updated analyses of the costs and benefits of the alternatives to lower FSL are detailed in Sections 4.7 and 4.8.

Benefits

The benefits assessed for the Taskforce are outlined in Table 4-5 below. 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 alternative.

Table 4-5. Benefits of two FSL lowering alternatives

Benefit	Lowering FSL by 5m ($ million 2015)	Lowering FSL by 12m ($ million 2015)
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: Taskforce Options Assessment Report (INSW 2019)
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 by the Taskforce due to the high costs that would be incurred to address impacts on water supply and quality.

Net cost/benefit

Despite its flood mitigation benefits, the Taskforce analysis showed that the alternatives to lower FSL by five metres or 12 metres had relatively high net costs respectively, largely due to the impacts on Sydney's water security (see the Taskforce Options Assessment Report (INSW 2019), and Table 4-6 for summary).

Sections 4.6 and 4.7 of this chapter have updated analysis of net costs and benefits of the dam lowering alternatives.

4.4.1.5 Social, environmental and cultural heritage impact

Lowering FSL by five metres

A report was prepared for the Taskforce to assess the socio-economic, environmental and cultural heritage impacts for the five metre FSL lowering. No high or extreme impacts were identified upstream of the dam, at the dam, or downstream of the dam.

Lowering FSL by 12 metres

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 lower 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 lowering the FSL by 12 metres, would be similar to those for dam raising. However, drawing the dam level down to -12 metre FSL after flood events could take a long time (weeks to months) 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 flood event, with potential for reduced benefits compared to the proposed dam raising.

Modifying the existing dam wall to allow for quicker recovery of the mitigation capacity for a 12-metre lowering would require a significant modification of the dam (see sections 4.6 and 4.7 for contemporary analysis).

4.4.1.6 Other factors

Water security

One of the most significant impacts of lowering FSL to create a dedicated FMZ is a loss of water supply. Lowering the FSL by 12 metres would reduce the available storage at Warragamba Dam by about 39 percent and Sydney's total storage capacity by about 31 percent.

If this alternative was adopted, greater Sydney's water supply system would incur major additional investment and operating costs to replace the lost 795 gigalitres of water supply storage.

Reducing the available storage at Warragamba will result in additional water being drawn from alternative more expensive sources (desalination and Shoalhaven pumping) and additional water sources will need to be constructed and operated (second desalination plant, recycling, etc.).

Sections 4.5 to 4.7 include updated water security matters related to the extension of inflow records to December 2019, which include the 2017-2019 drought, and updated water security modelling.

Water quality

Lowering the FSL by 12 metres would present significant risks to the quality of raw water supplies.

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
- 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.

Cyanobacteria (blue-green algae)

Investigations of historical events suggest that increased algae activity in Lake Burragorang 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.

This occurred in 2007 when nutrients that had accumulated in the catchment during the millennium drought, including from bushfires in 2006, were washed into the reservoir by heavy rainfall in June. This resulted in a major algal bloom when temperatures rose in September of that year (see Figure 4-6). There is a much greater likelihood of this situation occurring with the FSL lowered by 12 metres.

Figure 4-6. Cyanobacteria (blue-green algae) bloom at Warragamba Dam, September 2007

Image: Courtesy A White

Post flood releases

After the flood event, the water level in the storage would be higher than the -12 metres FSL. The operational procedures would then require the storage level to be brought back to FSL by controlled releases through the gates.

In most spring and summer events, lowering the FSL by 12 metres would allow for the release of a significant proportion of the poorer quality water left in flood storage at the end of an overflow or interflow event (which delivers poor quality water into the upper layer of the water column).

However, because autumn and winter events are likely to be underflows which deliver the poorer quality water into the deeper zones of the lake, the upper higher quality water would be released downstream. The potential for the poorer quality water mixing 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.

Warragamba pipelines and Deep Water Pumping Station

Warragamba Dam typically supplies around 80 percent of greater Sydney's water needs. Two gravity-feed pipelines from the dam are the primary method supplying water to filtration plants at Orchard Hills and Prospect.

Lowering the FSL of Warragamba Dam by 12 metres would reduce the capacity of Warragamba pipelines by 15 percent. 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 below FSL, 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 12 metres would increase by over 20 times the likelihood of reaching the level at which the Deep Water Pumping Station would be required.

Maintenance

There is an ongoing exercise and maintenance regime for the Warragamba pipelines, gates and associated infrastructure. This regime is sensitive to the lake level at Warragamba. When the lake level is lower, specific maintenance cannot be undertaken as insufficient water can be supplied at the Warragamba Pipeline Outlet Works to meet demand requirements from Prospect Water Filtration Plant and Orchard Hills Water Filtration Plant.

Lowering the FSL would lower the average water level, with implications for the operation and maintenance of the dam assets. Lowering FSL by 12 metres would compromise the defined exercise and maintenance regime on the Warragamba pipelines and significantly and adversely impact the risk profile as these pipelines supply around 80 percent of Sydney's daily water demands.

4.4.1.7 Assessment summary

Lowering the FSL of Warragamba Dam to create a dedicated FMZ would achieve reductions in flood levels downstream of the dam. However, there are a number of issues relating to lowering the FSL including:

- *benefits limited to smaller flood events* — lowering FSL by 12 metres provides its greatest reduction in downstream peak flood levels up to the 1 in 50 chance in a year flood, and with moderate reductions for rarer events which are critical for risk to life and property in the valley:
  - for a 1 in 100 chance in a year flood peak levels would be reduced on average by 1.2 metres at Penrith and 1.9 metres at Windsor
  - for a 1 in 500 chance in a year flood peak levels would be reduced on average by 0.5 metres at Penrith and 1.4 metres at Windsor
- *loss of water supply storage* — lowering FSL would result in a permanent and substantial reduction in the water available from Sydney's water supply system. 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 of the Upper Nepean dams
  - 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 and operation of major new water supply infrastructure.
- *potential loss of water quality* — lowering the FSL by 12 metres increases the risk of poor water quality in the storage and provides less operational flexibility to release the best available water quality 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, since the costs exceed the flood mitigation benefits. The $505 million net cost ($2015) assessed by the Taskforce did not take account of the cost of modifying the existing dam wall to allow for quicker recovery of the mitigation capacity, nor the potential loss of the benefits of environmental flows.

Sections 4.6 and 4.7 contain recent analysis of the FSL lowering alternatives taking account of contemporary information and modelling.

4.4.2 Combination of lowering the FSL by five metres and gate operations

Lowering the FSL by five metres was not shown to meet the criteria of significantly reducing risk to life and damages in the critical flood range. Further investigations were undertaken to determine if the alternative was more effective when combined with operational changes at Warragamba Dam.

Two combinations of alternatives 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.

4.4.2.1 Assessment summary

A combination of lowering the FSL by five metres and 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.

For some rarer events, the reduction is greater than for lowering the FSL by five metres alternative alone. However, the combined alternatives were still lower than the significant reductions in flood levels achieved by other alternatives such as raising Warragamba Dam.

Also, the issues associated with surcharging and pre-releases are problematic, including:

- loss of evacuation time for some events
- increased risk of loss of water supply
- high complexity of dam operations
- an increased threat to the radial gates.

Accordingly, these two combined alternatives (and others as outlined in Taskforce Options Assessment Report (INSW 2019)) were not preferred because options to reduce flood levels by the way the dam is operated mostly fail to meet the objective of a significant regional reduction in flood risk.

4.4.3 Raising Warragamba Dam wall options

Completed in 1960, Warragamba Dam is a water supply dam that provides around 80 percent of Sydney's potable water 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 Dam catchment to the total catchment areas of Penrith (80 percent) and Windsor (70 percent) (refer Figure 4-4).

One way of providing a significant flood mitigation function is to raise Warragamba Dam wall while maintaining the existing FSL. The 'air space' created would be available to capture and temporarily detain high inflows to Lake Burragorang to delay and lower peak river levels downstream. Investigations into raising Warragamba Dam for flood mitigation in the Hawkesbury-Nepean Valley go back to the 1980s.

Between 2014 and 2016, the Taskforce considered a wider range of dam raising heights from 12 to 30 metres to reconfirm the lower and upper bounds of flood mitigation and to take account of contemporary construction technologies. These were evaluated against the criteria of reducing the risk to life and reducing economic damages for both the existing population and forecast future growth given the existing permissible development scenarios (projected to 2041).

This included:

- modelling flood releases from Warragamba Dam for a range of dam raising heights, spillway configurations, flood events and duration
- assessment of evacuations and rescues from flood islands for a range of dam and flood scenarios
- assessment of the economic impacts including damages associated with a range of dam and flood scenarios.

A multi-criteria analysis was applied to identify the optimal range of heights to raise the dam. Two heights, 14 metres and 20 metres, were chosen as representing the upper and lower bounds of feasible dam raising. These heights refer to the FMZ created above the FSL.

The FMZ would be created by raising the spillways while retaining the existing FSL. A FMZ of around 1,000 gigalitres would be formed by a 14-metre raising, and a 1,723 gigalitre FMZ would be formed by a 20-metre raising (subject to change depending on the adopted design of spillway levels).

The width and level of the spillways and the height of the abutments are designed to safely pass the dam design probable maximum flood (PMF) without overtopping the raised abutments, with an allowance or 'freeboard' for wave action and other factors.

Preliminary assessment of evacuation risk indicated that raising Warragamba Dam between 14 and 20 metres would allow for the evacuation of the population from flood islands in the valley for the critical flood range, using a forecast target of 15 hours across the valley. Fifteen hours is the current Bureau of Meteorology flood forecast time at Richmond and Windsor, but this is greater than the eight-hour flood forecast time at Penrith. These dam raising heights were set as the lower and upper bounds for more detailed investigation.

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, analysis was undertaken to:

- 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 dam raising locations, designs and construction methods to identify options rather than a mass concrete design (MWH)
- progress the best option (considering world best practice since the 1980s and 1990s reports) to a detailed feasibility level for the dam raisings (MWH)
- identify a preferred raising option (NSW Public Works, MWH, independent dam experts).

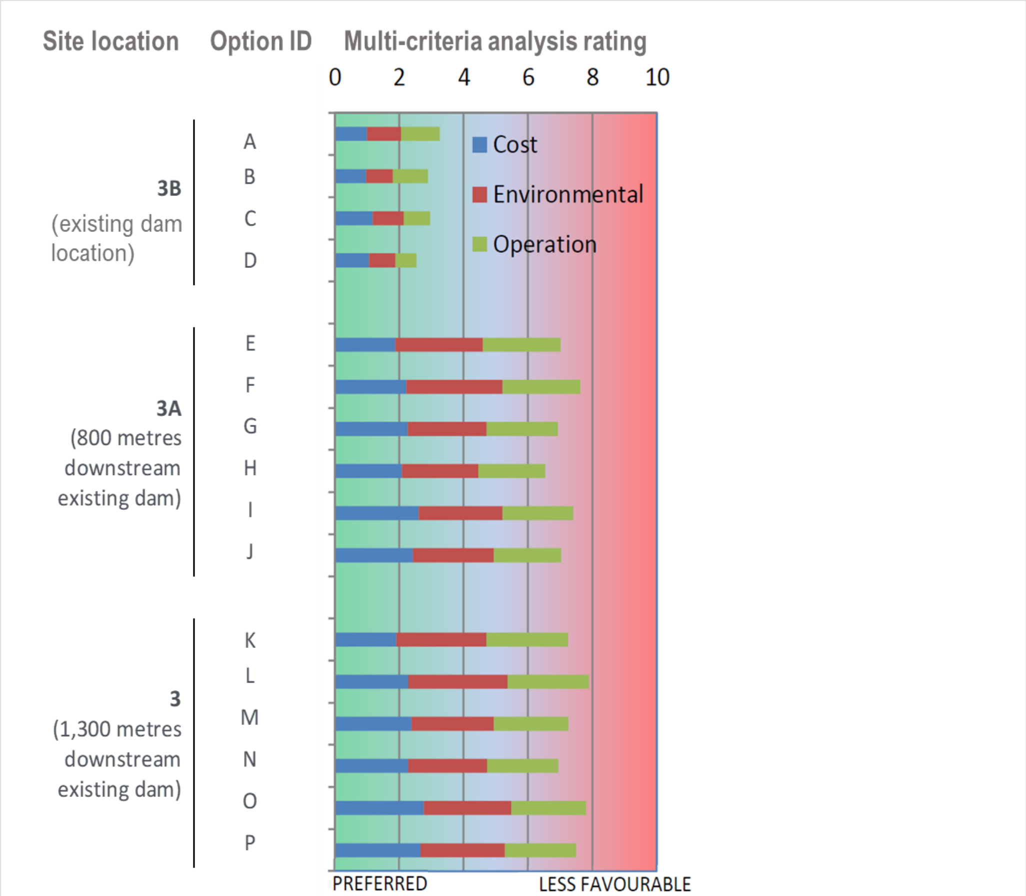
Sixteen alternatives to the mass concrete raising option recommended by the 2013 Review were considered by the Taskforce: four options involving raising of the existing dam with buttressing, and six new embankment options at each of two sites 800 metres and 1,300 metres downstream of the existing dam.

Investigated dam types for the new embankments were gravity hardfill, gravity roller compacted concrete, concrete faced rockfill and asphaltic core rockfill. The options are discussed in detail in the Taskforce Options Assessment Report (INSW 2019).

A multi-criteria analysis of the 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 against each of the options is shown in Figure 4-7.

Figure 4-7. Summary comparison of alternative dam raising options



Source: Taskforce Options Assessment Report (INSW 2019)

Dam raising options involving buttressing of the existing dam ranked more highly than new embankments downstream. The lowest scoring alternative design (best able to meet the objectives) was a hardfill buttress at the existing dam wall using a central spillway and the existing auxiliary spillway. For a 14-metre dam raising option, this was estimated to cost about $1.2 billion (2015 dollars), including a 25 percent contingency, which was significantly more expensive than the estimate for a mass concrete dam raising ($692 million, 2015 dollars).

On the basis of estimated project cost, potential environmental and social impact from construction, and technical issues involved in raising the dam, a mass concrete (concrete gravity) raising of the current dam was recommended.

Downstream Area

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 would 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 less. If the release rate is such that the FMZ is not empty when a subsequent flood event occurs, the upstream 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 and extensive sand and gravel extraction from the river and floodplain. The river is still 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 geomorphological assessment has been undertaken to better understand the impacts of altered flow on river-bank stability, refer to Appendix N2 (Geomorphology Assessment Report).

Releases from a FMZ could affect water quality (and supply), if there is increased turbidity in water drawn from the Hawkesbury River supplying the North Richmond Water Filtration Plant.

The preferred options from the Taskforce Options Assessment Report (INSW 2019) recommended construction methods for the 14 and 20-metre dam raising options which were investigated to detailed feasibility stage.

4.4.3.1 Impacts on regional flood peak

The effects of the dam raising alternatives on flood behaviour were tested using the Monte Carlo model simulations of 19,500 flood events.

Downstream peak flood levels

Raising the Warragamba Dam spillways creates air space in which floodwaters can be temporarily stored. This significantly reduces and delays the downstream peak flood levels. No other alternatives provide the same quantum of reduction in levels. The Taskforce found that:

- creating a 14-metre FMZ by raising Warragamba Dam wall would reduce the:
  - 1 in 50 chance in a year flood peak levels on average by 4.8 metres at Penrith and 3.9 metres at Windsor
  - 1 in 100 chance in a year flood peak levels on average by 3.9 metres at Penrith and 3.7 metres at Windsor
  - 1 in 500 chance in a year flood peak levels on average by 1.4 metres at Penrith and 2.6 metres at Windsor
  - 1 in 1,000 chance in a year flood peak levels on average by 0.9 metres at Penrith and 2.3 metres at Windsor.
- creating a 20-metre FMZ by raising Warragamba Dam wall would reduce the:
  - 1 in 50 chance in a year flood peak levels on average by 5.2 metres at Penrith and 4.4 metres at Windsor
  - 1 in 100 chance in a year flood peak levels on average by 5.5 metres at Penrith and 4.6 metres at Windsor
  - 1 in 500 chance in a year flood peak levels on average by 4.9 metres at Penrith and 4.3 metres at Windsor
  - 1 in 1,000 chance in a year flood peak levels on average by 3.8 metres at Penrith and 4.0 metres at Windsor.

Raising Warragamba Dam to create a 20-metre FMZ would provide more flood mitigation benefit than creating a 14-metre FMZ. This is due to its increased capacity to temporarily store flood inflows.

Raising Warragamba Dam to create a 14-metre zone changes the frequency of flooding reaching the current 1 in 100 chance in a year flood level (17.3 mAHD) to around a 1 in 600 chance in a year event at Windsor. The level of flooding experienced in the 1867 flood (approximately a 1 in 350-500 chance in a year event) would be mitigated to around a 1 in 1,500 chance in a year event at Windsor.

> If the 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 in a year flood level would continue to be subject to the same controls following the dam raising.

Downstream flood duration

Floodwater temporarily stored in the air space would need to be released to restore the flood mitigation capacity. The downstream flood duration would be influenced by the post flood release strategy implemented.

An assessment of changes to the duration of inundation above 10 mAHD (currently around a 1 in 5 chance in a year flood) at Windsor was undertaken 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 dam releases. Land below 10 metres AHD at Windsor is primarily 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/day:

- most floods (64 percent) would no longer reach a level of 10 mAHD at Windsor
- about 23 percent of floods would have a shorter duration above 10 mAHD
- about 13 percent of floods would have a longer duration above 10 mAHD.

For dam raising (either 14 or 20 metres) and a moderate release rate of 100 GL/day:

- most floods (71 percent) would no longer reach a level of 10 mAHD at Windsor
- about 28 percent of floods would have a shorter duration above 10 mAHD
- fewer than 1 percent of floods would have a longer duration above 10 mAHD.

Upstream peak levels and duration

Areas upstream of Warragamba Dam could be inundated up to 13.7 metres above FSL now during floods. The peak levels and duration of inundation upstream of a raised Warragamba Dam are a function of:

- the height of the spillway
- the size of inflows to the dam
- the rate at which the captured floodwaters in the FMZ are discharged after a rainfall event.

The Taskforce commissioned modelling of various combinations of flood frequencies, dam raisings, spillway heights and release strategies to assess the durations of upstream inundation. The depth and duration of upstream inundation is an important consideration for the tolerance of threatened ecological communities (TECs) and threatened species located within the footprint of a raised dam.

The results of the flood modelling show that even with the existing dam, inundation to the lowest observed level of Camden White Gums (120 mAHD) would be exceeded on rare occasions for a few days. Updated flood modelling for the EIS shows that this level would be exceeded more frequently for a 14-metre raised dam with durations of up to around two weeks depending on the flood event. The extent of duration would be dependent upon the final spillway design and discharge rate from the FMZ.

4.4.3.2 Impacts on risk to life

Raising Warragamba Dam to provide dedicated capacity 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, up to 84 percent of modelled events would no longer cut evacuation routes from McGraths Hill, Pitt Town and Windsor, and the time at which the routes are cut for floods that would still reach those levels would be significantly delayed (refer Taskforce Options Assessment Report (INSW 2019), Figures 4-8 and 4-9).

With a 20-metre dam raising, up to 94 percent of modelled events would no longer cut evacuation routes from McGraths Hill, Pitt Town and Windsor, and the time at which the routes are cut for floods that would still reach those levels would be significantly delayed.

The benefits of dam raising for reduced and delayed inundation of these evacuation routes is not sensitive to the rate of post flood releases. Figure 4 5 shows that dam raising performs best of all the assessed alternatives at reducing and delaying floods that cut evacuation routes.

4.4.3.3 At dam site

For a 20-metre dam raising, high risks at the dam site, even after implementation of potential mitigation measures, were identified for:

- European heritage - Warragamba Dam is heritage listed and is one of the best examples of a 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.

The residual risk rating for the 14-metre dam raise was the same as above for the at-dam impacts, with the exception of European heritage, which was rated low.

4.4.3.4 Economic assessment

The CIE assessed the benefits and costs of raising Warragamba Dam by either 14 metres or 20 metres (reported in the Taskforce Options Assessment Report (INSW 2019)).

Cost

The Taskforce progressed detailed feasibility costing for 14 and 20-metre dam wall raising alternatives, including costings for two different construction methods (mass concrete and hardfill). The costings were completed to a detailed feasibility level with contingency of 25 percent of the total cost.

The cost estimate was based on recent tenders for similar scale of works. NSW Public Works carried out detailed feasibility level costing for 14-metre and 20-metre raisings in mass concrete. This was compared to cost estimates prepared by MWH. The costing methodology was reviewed by John Holland Group, the Taskforce and its experts.

The preferred construction method of mass concrete buttressing was estimated in 2015 dollars to cost $692 million for a 14-metre raising and $865 million for a 20-metre raising.

The discounted costs assumed construction commenced in 2016 and took four to five years to complete. The CIE was not able to quantify potential environmental costs of incremental temporary inundation. Any costs identified as a result of the Environmental Impact Assessment and planning approvals will be factored into the Final Business Case.

Benefit

Raising Warragamba Dam by 20 metres would obviously create a larger FMZ so has potential to reduce peak flood levels and associated damages more than raising Warragamba Dam by 14 metres. These additional flood mitigation benefits were assessed against increased costs associated with this option as detailed in the Taskforce Options Assessment Report (INSW 2019) and discussed in the following ‘Net benefit’ section.

Confirmation of flood damages assessment

In 2015, the Insurance Council of Australia (ICA) conducted a preliminary analysis on the potential impact of dam raising alternatives on insurance premiums. The Taskforce supplied ICA with baseline and alternatives flood data. The ICA 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 (as reported in the Taskforce Options Assessment Report (INSW 2019)).

The results of the assessment were expressed as average annual damages, which is a proxy for the flood technical premium and is suitable to indicate the magnitude of potential changes to the flood technical premium 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 not the retail premium ultimately offered to a customer.

The ICA analysis found that, for a 14-metre dam raising, there would be a 76 percent reduction in average annual damages (AAD) for the region and for a 20-metre raising there would be an 87 percent reduction in AAD for the region. This result is consistent with the economic assessment conducted for the Taskforce by the CIE.

The ICA concluded that both options offer significant potential to reduce the insurance premiums for property owners who are currently exposed. ICA indicated that any reduction in flood risk at individual properties would be considered by insurers and would typically result in reduced premiums. The ICA also noted that, where effective flood mitigation has been implemented in other states, there have been significant reductions in insurance premiums.

Net benefit

For the alternative to raise Warragamba Dam for a 14-metre FMZ, comparing the benefits to the costs showed that there was a net benefit of $165 million. The net benefit was retained under low and high assumptions.

For the alternative to raise Warragamba Dam for a 20-metre FMZ, comparing the benefits to the costs shows that there is was a net benefit of $61 million. The net benefit was retained under low and high assumptions.

Based on the economic assessment, the 14-metre dam raising was preferred to the 20-metre dam raising because it had higher net benefits under the 'central case' conservative assumptions and using a discount rate of seven percent.

4.5 Taskforce - overall assessment and recommendations

The Taskforce Options Assessment Report (INSW 2019) details the assessment and outcomes of detailed investigations into options to mitigate and reduce flood risk in the valley as well as previous analysis under the 2013 Review (see Table 4-6). The results are summarised below.

4.5.1 Options not included in the Taskforce recommendations

4.5.1.1 Construction of new dams

Reviews carried out from 1987 to 1995 considered a number of site alternatives to those on the Warragamba River for new flood mitigation dams. These were rejected due to their low cost-effectiveness for flood mitigation and significant environmental impacts, with most sites located within National Parks.

As Warragamba Dam captures approximately 80 percent of the catchment upstream of Penrith, other flood mitigation dams on alternative rivers cannot be as effective. Alternative dam sites were reconsidered as part of the Taskforce work but no new information was found that would justify further consideration of new dam sites for flood mitigation.

Options to build another dam on the Warragamba River, downstream of Warragamba Dam were also assessed. However, based on the construction costs, environmental and operational impact, options that raise the existing Warragamba Dam wall were found to be more cost effective to reduce flood risk than new dams on the Warragamba River. New dam construction was up to three times more costly than raising the wall of the existing Warragamba Dam to provide similar flood mitigation benefits.

4.5.1.2 Changing operation of the existing Warragamba Dam gates (pre-release and surcharge)

The Taskforce investigated flood mitigation options for operating the current Warragamba Dam differently. The options included:

- pre-releasing water ahead of a predicted flood inflow
- changing the operation of the gates to temporarily hold back floodwater (this is called surcharging).

These options have limited effectiveness for mitigating larger floods that pose a significant risk to lives or property.

4.5.1.3 Lowering permanent water supply level of Warragamba Dam

Lowering the permanent water supply level of Warragamba Dam is another option to create air space to temporarily store floodwaters. This would reduce the volume available in Warragamba Dam for water supply. Two options for lowering the permanent water supply level of Warragamba Dam were included in the detailed cost benefit analysis, a reduction of the level by five metres and 12 metres (the maximum possible lowering of the water supply level as this would be at the base of the existing gates).

Lowering Warragamba Dam's permanent water supply level by 12 metres would be equivalent to reducing the dam water storage by nearly 40 percent, or one and a half years of water supply to Sydney. This option was not selected as it had negative net benefits. This alternative would require new sources of water supply to maintain water supply security to Sydney which would need to be built in addition to the continuous operation of the existing Sydney desalination plant. Lowering the permanent water supply level by five metres was not selected because of its limited potential benefits for managing flood sizes that cause in the greatest risk—those larger than the 1 in 100 chance in a year flood.

4.5.1.4 Dredging the Hawkesbury River and Currency Creek bypass channel

The option to dredge the Hawkesbury-Nepean River for flood mitigation would involve continuously removing sediment to reach 10 metres below the current bed level for a distance of 66 kilometres from Windsor to Wisemans Ferry. The Taskforce also completed detailed investigation of an option to cut a bypass channel to the Hawkesbury-Nepean River between Wilberforce and Currency Creek (re-joining the Hawkesbury River near the Sackville Ferry) to improve the flow of floodwaters out of the floodplain.

Dredging the Hawkesbury-Nepean River (even by 10 metres for 66 kilometres) and the Currency Creek diversion channel were not selected as they have construction costs similar to those of raising Warragamba Dam wall without the comparable regional flood risk mitigation benefits. They also have very significant environmental impacts. As shown in Table 4-6, both options would have negative net benefits.

4.5.1.5 Diversion channels other than Currency Creek

Two diversion channels in addition to Currency Creek were investigated. Sackville Gorge diversion channels were investigated as options that increase the rate at which floodwaters could drain away from the floodplain. The options assessed were:

- a diversion channel on the Hawkesbury River from Sackville to the Cumberland Reach
- a diversion channel on the Hawkesbury River from Sackville to Leets Vale.

The diversion channel from Sackville to Leets Vale was calculated by the 2013 Review to have a construction cost of more than $5 billion and would not deliver net regional flood mitigation benefits. The 2013 Review also found the Sackville to Cumberland Reach diversion channel would provide minimal flood mitigation benefits, although it would be considerably cheaper. Because Sackville Gorge is in a tidal zone and is almost at sea level, these options had limited capacity to increase the rate at which floodwaters drain away from the floodplain. As a result, these two options were not taken forward for further investigation.

4.5.1.6 Levees

Levees at McGraths Hill and Peachtree Creek were identified as cost-effective options for providing local flood protection only. As these levees provide only limited and localised benefits, they were not included in the Flood Strategy. However, Peachtree Creek levee was considered to be worthy of more detailed consideration as a local measure, potentially by local government.

4.5.1.7 House repurchase in flood risk areas

The Taskforce assessed that large urban development in the valley precludes house purchase as a flood mitigation option. For example, around 4,800 houses were assessed as being located below the 1 in 100 chance in a year flood planning level - an area that contributes significantly to existing flood risk. These houses were assessed to cost around $3.8 billion ($2017), assuming a median house price for the two key councils (Penrith and Hawkesbury) of $780,000. An updated assessment of this option is in Sections 4.6 and 4.7 of this chapter.

4.5.1.8 Major regional evacuation road options

Upgrades to increase the capacity of major regional evacuation roads would reduce exposure to flood risk by increasing the number of people that are able to evacuate, reducing risk to life. However, it should be noted that investment in road evacuation infrastructure does not change flood behaviour. It does not have an effect on the likelihood that certain flood levels in the valley will be reached and so does not decrease flood damages.

A number of major regional evacuation road options were selected for evaluation based on their ability to increase evacuation capacity. The options were developed by an expert group of Roads and Maritime Services, NSW SES and Infrastructure NSW. Nine major regional road options were considered in detail. These included combinations of:

- raising selected existing low points on roads to the current 1 in 100 and 1 in 200 chance in a year flood levels
- adjusting the use of existing roads to add lane capacity during flood emergency evacuation
- bringing forward the construction of the Castlereagh Freeway constructed to various road heights.

Major regional evacuation road options would not have positive net benefits as they have high construction costs relative to their benefits by 2041 in terms of reducing risk to life. In addition, these options do not reduce potential economic damages. Therefore, no major regional evacuation road options were selected for the Flood Strategy. However, the strategy includes actions to consider flood risk on regional road planning for growth in valley.

4.5.2 Options recommended by the Taskforce and included in the Flood Strategy

4.5.2.1 Raising Warragamba Dam for a 14-metre FMZ

The Taskforce found raising Warragamba Dam wall to create a 14-metre FMZ is the infrastructure alternative with the highest net benefit. This would significantly reduce flood risk by creating air space in the dam to temporarily hold back and control release of floodwaters coming from the large Warragamba River catchment. It would significantly reduce the risk to life downstream and reduce average annual flood damages by around 75 percent.

The Taskforce concluded that, while raising the Warragamba Dam wall would make a significant difference to flood risk in the Hawkesbury- Nepean Valley, no combination of infrastructure alternatives can eliminate the risk.

4.5.2.2 Local evacuation road upgrades

Local roads are those roads, generally managed by local council, that connect the population to major regional evacuation roads. In the Taskforce's evaluation of infrastructure options, around 40 high priority local evacuation road upgrades were identified as essential to maintain access to major regional evacuation routes. These were included in the Flood Strategy to be subject to a future business case. The upgrades were identified by a working group led by Roads and Maritime Services in consultation with local councils in the valley, the NSW SES and other stakeholders. The selected upgrades were those that would best prevent premature closure due to flash floods or provide additional capacity to allow evacuating communities to access major regional evacuation routes. Further work on the program was included in the Flood Strategy.

4.5.2.3 Non infrastructure options

A range of non-infrastructure measures was identified as essential to mitigate and manage the residual flood risk in the valley. The measures included in the Flood Strategy were developed by the Taskforce based on recommendations of the 2013 Review, the 2011 National Strategy for Disaster Resilience, and the national flood risk management framework. They broadly fit within the following categories and have been significantly progressed in Phase One:

- coordinated flood risk management
- strategic and integrated land use and road planning
- access to contemporary flood risk information
- community awareness, preparedness and response
- improved weather and flood predictions
- best practice emergency response and recovery.

Table 4-6. Summary of alternatives against assessment criteria – 2013 Review and Taskforce

LEGEND:

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

Costs and benefits:
$ $0M–$20M
$$ $21M–$100M
$$$ $101M–$500M
$$$$ $501M-$1,000M
$$$$$ >$1B

Note 1: The process of options identification and evaluation followed a shortlisting process from the **2013 Review** through the **2014-16 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.

Note 2: Social, environmental and cultural heritage impacts are drawn from assessment report prepared for the **2014-16 Taskforce.**

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 chance in year 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	2014-16 Taskforce	**0.0 to 1.0 m Penrith 0.0 to 0.7 m Windsor**	26% floods no longer reach 1 in 100 chance in a year 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	2014-16 Taskforce	**0.0 to 0.2 m Penrith 0.1 to 0.3 m Windsor**	14% floods no longer reach 1 in 100 chance in year 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	2014-16 Taskforce	**0.2 to 0.7 m Penrith 0.7 to 1.3 m Windsor**	42% floods no longer reach 1 in 100 chance in a year level at Windsor	Few floods significantly delayed & some floods reach evacuation routes faster	Not assessed	Yes	$$	Medium	Not assessed	Medium	**Increased risk of loss of water supply; impacts on water quality**
Lower FSL by 2m	2013 Review	**Negligible reduction**	Not assessed	Not assessed	Not assessed	Not assessed	Not assessed	Not assessed	Not assessed	Negligible-Low	**Does not meet primary objective, high remaining risk**
Lower FSL by 5m	2014-16 Taskforce	**0.1 to 0.4 m Penrith 0.4 to 0.9 m Windsor**	32% floods no longer reach 1 in 100 chance in year level at Windsor	Few floods significantly delayed	Provides some benefits but less effective than dam raising	Yes	$$$	$$$	$58M	Low-Medium	**Does not meet primary objective, high remaining risk**
Lower FSL by 12m	2014-16 Taskforce	0.5 to 1.9 m Penrith 1.3 to 2.6 m Windsor	64% floods no longer reach 1 in 100 chance in a year level at Windsor	Most floods that still reach 1 in 100 chance in a year level at Windsor significantly delayed	Not assessed	Yes	$$$$$	$$$$	**-$505M**	Higher than FSL -5m	**High water security costs; less flexibility to manage air space for sequential events**
New flood mitigation dams											
New dams upstream of Warragamba (combined Wollondilly and Coxs) (see note 5)	2013 Review	1.5 to 1.8 m Penrith 2.2 to 2.3 m Windsor (see note 5)	Not assessed	Not assessed	Not assessed	Yes	$$$$	Not assessed	Not assessed	**High-extreme**	**No sites on Wollondilly and Coxs Rivers as well suited as Warragamba**
New dam on Nepean River (see note 5)	2013 Review	1.1 to 1.7 m Penrith 1.5 to 1.7 m Windsor (see note 5)	Not assessed	Not assessed	Not assessed	Yes, but increased flood risk in Camden area	$$$–$$$$	Not assessed	Not assessed	**High-extreme**	**Does not mitigate predominant Warragamba Catchment floods**
New dams downstream of Warragamba (Grose or Colo) (see note 5)	2013 Review	**0.0 m Penrith 0.2 to 0.5 m Windsor** (see note 5)	Not assessed	Not assessed	Not assessed	No mitigation at Penrith	$$$–$$$$	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 chance in year 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	Progressing	**0.9 to 4.8m Penrith 2.3 to 3.9m Windsor**	83% floods no longer reach 1 in 100 chance in year level at Windsor	Most floods that still reach 1 in 100 chance in a year level at Windsor significantly delayed	Significant reductions	Yes	$$$$	$$$$	**$166M**	High	**Highest net benefit**
WD +20m	2014-16 Taskforce	3.8 to 5.5m Penrith 4.0 to 4.6m Windsor	94% floods no longer reach 1 in 100 chance in a year level at Windsor	Most floods that still reach 1 in 100 chance in a year level at Windsor significantly delayed	Best performing	Yes	$$$$	$$$$	**$52M (lower than WD +14m)**	**Higher than WD +14m**	**Emptying the FMZ within required timeframe more challenging**
DIVERSION CHANNELS OR ENHANCED WATER DRAINAGE FROM VALLEY											
Currency Creek diversion channel	2014-16 Taskforce	**0.0m Penrith 0.3 to 0.8m Windsor**	Not assessed	Not assessed	Not assessed	No mitigation at Penrith; slightly higher floods at Wisemans Ferry	$$$$	$$$	**-$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	$$$	Negligible	Negative due to low benefit	High	Limited benefits due to low reduction in flood peaks
Sackville large diversion	2013 Review	**Minor reduction given multiple hydraulic constrictions**	Not assessed	Not assessed	Not assessed	Likely limited mitigation at Penrith & higher floods at Wisemans Ferry	**$$$$$**	Not assessed	Negative due to very high costs	Likely extreme	Limited benefits due to low reduction in flood peaks
Dredging between Windsor and Wisemans Ferry	2014-16 Taskforce	0.0m Penrith 2.0 to 2.2m Windsor	Not assessed	Not assessed	Not assessed	No mitigation at Penrith; higher floods at Wisemans Ferry	$$$$	$$$	**-$254M**	**High-extreme**	Dredging must be maintained to maintain benefit
LOCAL STRUCTURAL WORKS											
Peachtree Creek levee	2014-16 Taskforce	Protection to 1 in 100 chance in a year 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	2014-16 Taskforce	Protection to 1 in 50 chance in a year 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 chance in year 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	2014-16 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 chance in year 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	$$	Not assessed	Not applicable	Risk increases with growth at and above current 1 in 100 chance in a year flood planning level (FPL); benefits of dam raising assume current 1 in 100 FPL is maintained
Flood risk-based regional road planning	Progressing	Not applicable	Not applicable	Not applicable	**Yes, if new or upgraded to provide evacuation capacity** (see note 6)	Yes	Not assessed	Not assessed	Not assessed	Not applicable	Road Evacuation Master Plan will consider flood risk when regional roads are upgraded for growth in the valley
Voluntary house purchase (VP)	2014-16 Taskforce	Not applicable	Effectiveness in reducing exposure depends on take up	Not applicable	Potentially reduces evacuation load	Yes, but requires multiple VP to effect valley-wide benefit	**$$$$$** (up to 1 in 100 chance in a year)	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**

Source: Taskforce Options Assessment Report (INSW (2019)

Notes:

GL/d = gigalitres per day

[1] To meet the evaluation criterion, an option needed to reduce the flood peak 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 chance in a year flood level at Windsor (17.3 mAHD) 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 chance in a year level at Windsor, 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 in a 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.

4.6 Flood Strategy Phase One implementation (2017-2021) – ongoing assessment of flood risk

Raising Warragamba Dam was selected by the NSW Government as the preferred flood mitigation alternative and included as a key outcome of the 2017 Flood Strategy for the Hawkesbury-Nepean. Under Phase One implementation of the strategy (2017-2021), further assessment and analysis has been undertaken based on contemporary research and guidelines, as described below.

4.6.1 Revised Australian Rainfall and Runoff guideline

The Australian Rainfall and Runoff (AR&R) guideline is the reference document for undertaking flood studies in Australia. The 1987 version of AR&R was replaced by the 2016 version, which was subsequently updated again to the 2019 version, during the course of Phase One of the Flood Strategy and the investigations into the proposed dam raising.

The most relevant change of the AR&R guideline to the project was the preference for Monte Carlo modelling over simple design flood events, in which a range of flood events are modelled and ranked rather than a single representation of events at defined probabilities like 1 in 100 chance in a year. The flood modelling for the dam raising and the assessment of the upstream and downstream impacts adopted Monte Carlo flood modelling from the beginning ahead of the changes to the AR&R guideline, as the nearly 20,000 modelled flood events facilitated more realistic assessment of impacts.

Other relevant changes to AR&R guidelines included sensitivity testing for projected impacts of climate change However, the climate change investigation undertaken by WMAwater was recognised by independent peer reviewers as exceeding industry standards.

The calculation of probable maximum flood (PMF) for dam design purposes was also changed, and these changes were considered in the dam design process.

4.6.2 Climate change research

As the dam owner and operator, WaterNSW was tasked with preparing an environmental impact statement and concept design for a raised dam at Warragamba. The exact height Warragamba Dam would be raised was to be confirmed as it was acknowledged that while a dam raising for a 14-metre FMZ appeared optimal under current climate conditions, that some additional assessment may be needed to account for climate change.

A report was commissioned to assess the impact of climate change on rainfall and flooding and to provide advice on the appropriate level for the raising of Warragamba Dam (WMA 2017). When the report was at a final draft stage, the NSW Office of Chief Scientist and Engineer organised an independent peer review by professors of the University of Adelaide and the University of NSW. The peer review found the investigation was sound and went beyond industry practice.

The impact of climate change on flood-producing rainfall is quite complex and there is still considerable uncertainty around exactly how a warming climate will influence flood behaviour. Warmer temperatures increase the moisture carrying capacity of the atmosphere and theoretically will lead to higher rainfall, but the causes of rare floods are more complex.

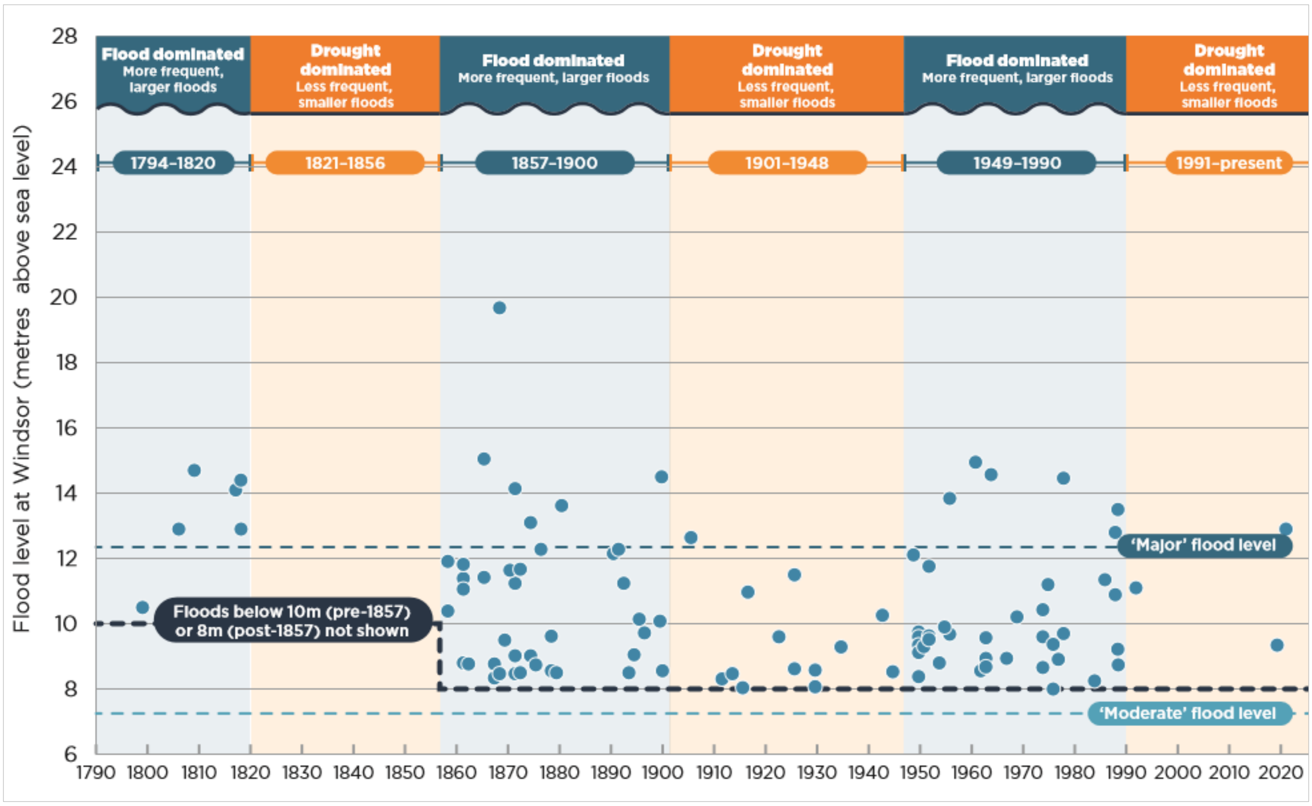
Nearly all major floods in the Hawkesbury-Nepean Valley are associated with an East Coast Low, an intense low pressure weather system off the eastern coast of Australia that can occur on average several times each year. The overall frequency of these systems and how often they impact the Hawkesbury-Nepean River catchments is also likely to change along with how dry catchments are and associated dam levels prior to a rainfall event.

It is also likely that climate change will cause proportionally higher increases in rainfall in locations where the terrain enhances rainfall. While there remains some uncertainty, the climate change report assessed the current best estimate of how climate change will affect flooding based on work by CSIRO, the Bureau of Meteorology and the NSW Government's NARCLIM project.

Current research suggests that regional scale, flood-producing rainfalls will increase proportionally with temperature. On this basis the historical rainfall and streamflow record contains some warming effects and the current flood behaviour is already significantly affected.

The flood record at Windsor dates back to 1790 and is the longest in Australia. It shows distinct wet and dry periods that last for between 30 and 50 years. Nearly all the moderate and all the major floods have occurred in the wet periods with only a hand full of isolated events in the dry periods. The most recent dry period commenced in 1991. If the limited historical record is a reliable predictor of the future, the current dry period could end in the next decade (see Figure 4-8).

Figure 4-8. Flood cycles in the Hawkesbury-Nepean Valley (based on Windsor, 1790 to present)



Source: INSW (2021)

Dam raisings of 14, 15, 16 and 17 metres were investigated under historical, current and future climate conditions. The results show that the existing flood risk is set to increase with climate change and that a 17-metre dam achieves the same benefits in 2090 as a 14-metre dam under historical conditions.

Under a medium climate change projection, the 1 in 100 chance in a year flood levels at Windsor is set to increase from 17.22 metres to 18.28 metres in 2090. A 14-metre dam raising would reduce this to 13.4 metres under historical conditions, but this increases to 15.04 metres by 2090. Table 4-7 summarises the results for existing, 14-metres and 17-metres dam under historical, 2025 conditions and 2090 conditions under a medium climate change projection.

Table 4-7. Summary of flood levels with climate change (2017 analysis)

Dam scenario	1 in 100 chance in a year flood level (mAHD)		
	Historic climate	2025 climate	2090 medium climate projection
Windsor			
Existing	17.22	17.54	18.28
14 metres	13.40	13.87	15.04
17 metres	12.77	13.11	14.08
Penrith			
Existing	25.69	25.95	26.42
14 metres	22.03	22.55	23.79
17 metres	20.52	20.91	22.14

Note: Further modelling has resulted in some refinements to these levels.
Source: INSW

4.6.3 Impacts of the 2017-2019 drought

Since the Taskforce completed its work, Greater Sydney's water supply catchments experienced a severe drought - between 2017 and early 2020. As required under its regulation, WaterNSW has recalculated Greater Sydney's water supply system yield following the conclusion of the drought, extending the historical hydrological records to December 2019.

The last independent expert review of yield calculations recommended the use of varying climatic demand factors instead of fixed seasonal demand factors to disaggregate annual demand to monthly demands.

The calculation of yield is based on the system design criteria and the characteristics of the water supply system, and is based on 1,110,000 years (10,000 replicates x 111 years) of synthetically generated inflows. Yield is expressed in gigalitres per annum, or GL/a, noting a gigalitre is a billion litres.

In 2020, WaterNSW completed the estimation of varying historical climatic demand factors, capturing the complex relationship between climate and demand, and updated the yield with the new demand factors. The re-calculated Greater Sydney's water supply system yield is between 515 and 540 GL/a, a drop of up to 20 GL/a from the previous assessment, and a reduction of up to 80 GL/a from the calculation in the early 2000s (see History of Changes to Greater Sydney's Water Supply System Yield, WaterNSW, September 2020 published on WaterNSW website).

The 2017-2019 drought demonstrated the water supply system can deplete at a faster rate than had previously been anticipated. The latest yield calculation showed that Greater Sydney's supply system is significantly exposed to water security risk, and as such, any reduction in the full supply level at Warragamba Dam would expose Sydney to greater risk from drought. This warranted an updating of assessments related to flood mitigation alternatives that would reduce the FSL of Warragamba Dam (see section 4.6).

4.7 Analysing flood mitigation alternatives

The Taskforce options assessment and 2017 Flood Strategy supported raising Warragamba Dam for flood mitigation and rejected alternative options (see Table 4-6).

As detailed in section 4.4, alternatives that, following detailed assessment, did not meet the key indicator of reducing regional flood risk - such as river dredging, river diversions and local levees - were not progressed further under Phase One of the Flood Strategy.

In line with the SEARs, the dam raising option and potential feasible alternatives have been reassessed to confirm the best option to reduce downstream flood risk, to test what has changed with new data inputs and evaluation tools, and to identify the next best performing alternative/s.

4.7.1 Alternatives reassessed

In line with the SEARs, the following alternatives have been reassessed under Phase One of the Flood Strategy:

- **Raise Warragamba Dam spillway levels** to create an FMZ of around 980 gigalitres between the existing, unchanged full water supply level (FSL) and the raised spillways. This would provide air space for the temporary capture of flood inflows and their controlled release to mitigate downstream flooding.

  Contrary to a common misconception, this proposal does not increase permanent storage and when implemented would have no impact on Sydney's water security.

- **Lower Warragamba Dam FSL by 12 metres**. This would create a flood mitigation zone of around 795 gigalitres for the temporary capture of flood inflows. A lowering of 12 metres is the maximum possible with the current gate configuration, since the sill of the base of the four central radial gates is 12.2 metres below FSL. Recent investigation has shown that for the air space to be available at the start of a subsequent flood, new conduits would need to be constructed through the existing dam wall. A 12-metre lowering would reduce Warragamba Dam's water storage by about 40 percent, requiring alternative water supply sources to be developed ahead of implementation.
- **Lower Warragamba Dam FSL by five metres**. This would create a flood mitigation zone of around 360 gigalitres for the temporary capture of flood inflows. A five-metre lowering would reduce Warragamba Dam's water storage by 18 percent, requiring alternative water supply sources ahead of implementation.
- **New or upgraded regional evacuation roads** incorporating flood resilience in the road design, for improved flood evacuation. Roads are an infrastructure measure to support mass evacuation primarily by private vehicle during flood events as shelter in place is not an option for this valley. Several options have been considered:

- increasing capacity on Dunheved and Werrington Roads to two lanes and Great Western Highway to three lanes
- The Northern Road intersection with Great Western Highway - intersection upgrade and emergency traffic management options
- Castlereagh Connection from Castlereagh Road to the M7, including bridge at South Creek to either the 1 in 100 or 1 in 1000 chance in a year flood levels
- Richmond Road Bridge at South Creek upgrade to the 1 in 200 chance in a year flood level and capacity enhancements
- The Northern Road, Londonderry Road, Llandilo Road and Castlereagh Road capacity enhancements
- Hawkesbury Valley Way and Windsor Road capacity enhancements

While roads are critical for evacuation, they do nothing to mitigate the effect of floods. As a result, roads neither reduce damages nor reduce the risk to life for those people who are exposed to flood risk and cannot or do not evacuate in time.

- **Buy back all dwellings within the 1 in 100 chance in a year flood extent**. This reduces flood risk to both life and property by removing dwellings exposed to the most frequent floods and replacing them with a more compatible land use such as recreation. Implementation would have major economic and social impacts on entire communities and would incur considerable costs.
- **Disallow all new dwellings within the 1 in 500 in a year flood extent**. This reduces future flood risk, but does not reduce the large existing flood risk. Implementation would be costly and difficult, given large areas above the 1 in 100 chance in a year floodplain have been approved and/or zoned for residential development.

4.7.2 Refined data and decision support tools

The reassessment has taken advantage of new and refined data inputs and decision support tools including:

- **Flood modelling.** Modelling is used to assess the impacts of flooding on communities, and the impacts of infrastructure options on flooding. Building on previous hydrological modelling carried out for the Flood Strategy, further analysis of this modelling was undertaken to assess the likely level of inundation upstream of Warragamba Dam over a 20-year period. This involved the extensive modelling of upstream rainfall runoff which included the full range of possible flood events and rainfall pattern variations. The 19,500 events were evaluated through the Monte Carlo methodology to generate thousands of hypothetical flood sequences including during wet periods and dry periods. This flood sequence over thousands of years was further analysed into 20-year periods to determine the peak level for each period. The likely inundation level was then determined from the average of all the peak levels and does not represent a single flood frequency. This approach has been undertaken for the existing dam and dam raising scenarios so that a comparison of inundation extents can be made.

  The Hawkesbury-Nepean Valley Regional Flood Study[1] has been used as the base case for the area downstream of Warragamba Dam. Climate change sensitivity runs have been modelled for a range of scenarios. The climate change results reported in this chapter adopt a 9.1 percent increase in rainfall intensity projected by mid-century (~2060).

- **Property database**. Information about the distribution of properties, people and vehicles is required to assess flood risks, now and in the future, with and without flood mitigation options. The previous estimates in the study area have been updated. The base case scenario was brought forward from 2015 to 2018 and incorporates updated development data and the results of the 2016 census. The future scenario years of 2026 and 2041 were retained and updated with projections of permissible growth that could occur under existing plans and zonings (see Table 4-8 below).

  The flood levels from the latest flood modelling were applied to the updated current (December 2018) database of residential properties in the floodplain. The property data were compiled by Infrastructure NSW based on information from Australian Bureau of Statistics, Department of Planning, Industry and Environment, NSW SES, councils, aerial photography and other sources.

  The number of residential properties affected by flooding (or 'homes/dwellings in the floodplain') relates to the property ground level (2017 LiDAR or 2011 LiDAR downstream of Wisemans Ferry) at the centre of the dwelling

[1] WMAwater, July 2019

(centroid), not the centre of the lot. As some properties are in multi-storey dwellings, the number of residential properties does not relate to the constructed floor level of the dwelling.

For the assessment of flood damages these property centroid ground levels have been adjusted to provide assumed floor levels for different types of dwellings.

The 2018 residential property numbers include manufactured housing that was not included in the Hawkesbury-Nepean Valley Flood Risk Management Strategy Taskforce Options Assessment Report (INSW 2019). Manufactured housing includes relocatable, prefabricated dwellings (caravans, transportable manufactured homes, temporary dwellings, cabins) that are normally located in purpose-built estates and caravan parks. The manufactured housing is generally situated low in the floodplain.

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 scenario does not represent a growth target but provides a means to test the sensitivity of future flood risk to the potential growth given the existing planning permissibility, and to measure the effectiveness of potential flood mitigation options. It also informs planning for managing future development.

- **Flood evacuation modelling.** In the Hawkesbury-Nepean Valley, a key indicator of risk to life from flooding is people unable to evacuate within available timeframes. The ability of people to evacuate is assessed through a flood evacuation model. An enhanced model has been developed to assess evacuation capacity.

  This includes a more detailed road network to better model likely evacuation traffic movement, an increased number of subsectors to better model evacuation, and recognition that different target forecast times are available for Penrith (eight hours) and Richmond/Windsor (15 hours). The flood evacuation model assumes a 100 percent response to an evacuation order to determine the capacity of the evacuation network for the given population with the current Bureau of Meteorology forecast capacity.

- **Flood evacuation response.** Although the flood evacuation modelling is based on 100 percent response, in practice the response to evacuation orders varies from over or shadow evacuation (people evacuating when they have not been called to evacuate) to under evacuation (sheltering in place).
- In the recent large flood evacuation in Australia (Townsville, 2019) only 50 percent of people responded to a 1 in 1,000 chance in a year flood event. If there was a similar level of response to a flood of this magnitude in the valley, the potential loss of life could be catastrophic. For the cost benefit analysis, the risk to life estimates assume a 10 percent non-response.
- **Flood fatality functions.** A review of the global literature and careful consideration of the Hawkesbury-Nepean context has led to the adoption of revised flood fatality functions. New depth-fatality curves have been developed, with 0.4 percent fatality at depths of 0-2 metres rising to five percent fatality at depths greater than four metres under medium assumptions. As an interim approach, a typical depth of 2.5 metres was assumed for translating the results of the evacuation model to estimates of fatalities. The same inundation depth was assumed for those not responding.
- **Flood damages assessment.** An updated assessment has been undertaken to quantify the economic costs, benefits and net economic benefits for different flood mitigation options compared to the base case. This includes extensive sensitivity tests to check that the options are robust to a range of assumptions applied in the cost-benefit analysis.

4.7.3 Assessment against key performance indicators (KPIs)

The following sections present a reassessment of the above six options considered to offer potential to reduce the existing regional flood risk. This analysis led to a recommended package of infrastructure and complementary measures that best meet the Flood Strategy objective, assessed using the following KPIs:

- risk to life - minimise lives lost in regional floods (KPI 1)
- reduce total damages caused by regional flood events (KPI 2)
- minimise social and environmental impacts (KPI 3)
- deliver the most cost-effective outcome (KPI 4).

These KPIs are aligned to the evaluation criteria used for the options assessment by the Taskforce.

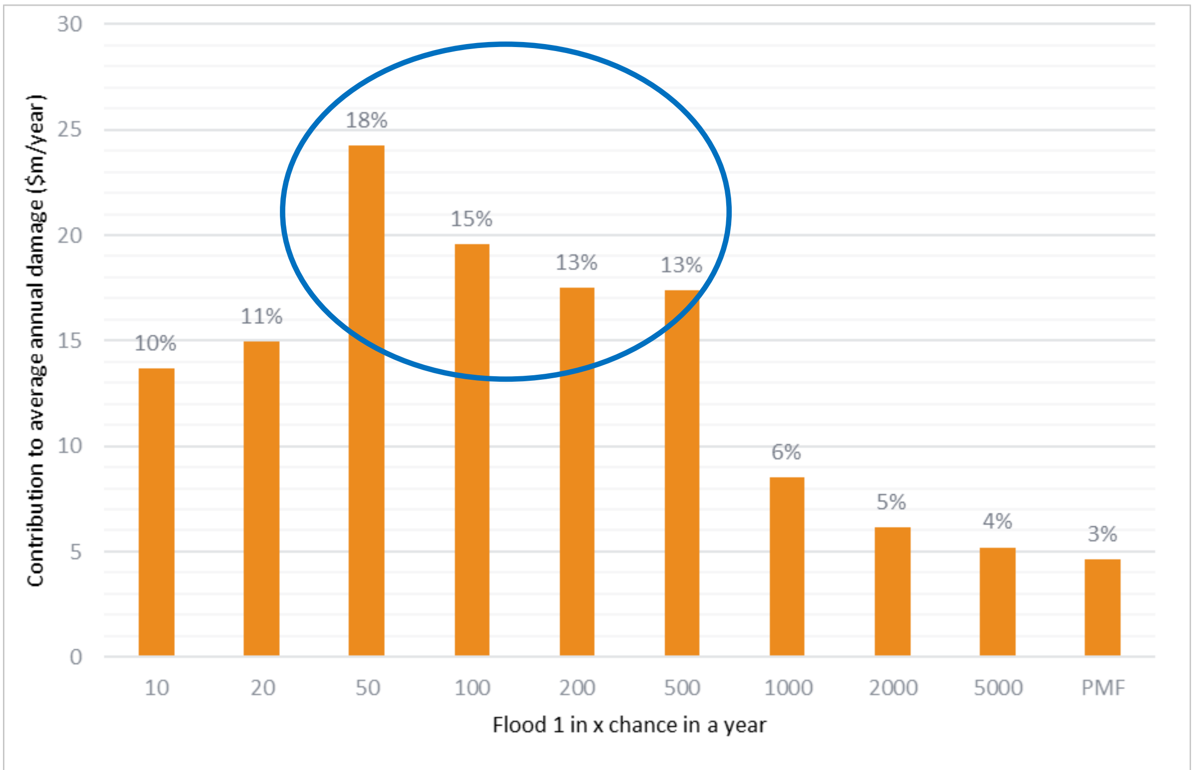
4.7.4 Significant, regional reduction in flood risk

Another evaluation criterion used by the Taskforce has also been used for this reassessment: a significant, regional reduction in flood risk. This objective has informed the staged assessment of options since the 2013 Review.

As previously discussed, to meet the objective of significantly reducing the impact of flooding, an option needs to make a substantial difference to floods in the range of 1 in 50 to 1 in 1,000 chance in a year. Average annual damage is the damage per year that would occur in a particular area from flooding averaged over a very long period of time. It represents a weighted average and provides the basis for comparing the economic effectiveness of different management measures against floods of all sizes. This is a standard method used by flood risk management specialists and actuaries for the insurance industry. As identified in Figure 4-9 below, around 60 percent of average annual damages occurs from floods between 1 in 50 and 1 in 500 chance in a year.

The defined critical range includes the 1 in 1,000 chance in a year flood because this incorporates the risk to life associated with the Richmond flood island being cut off and flooded.

Figure 4-9. Contribution of flood events to average annual flood damage in the valley, 2018 development levels



Note: Average annual damage is the average damage per year that would occur in a particular area from flooding over a very long period of time. It represents a weighted average and provides the basis for comparing the economic effectiveness of different management measures against floods of all sizes. This is a standard method used by flood risk management specialists and actuaries for the insurance industry.

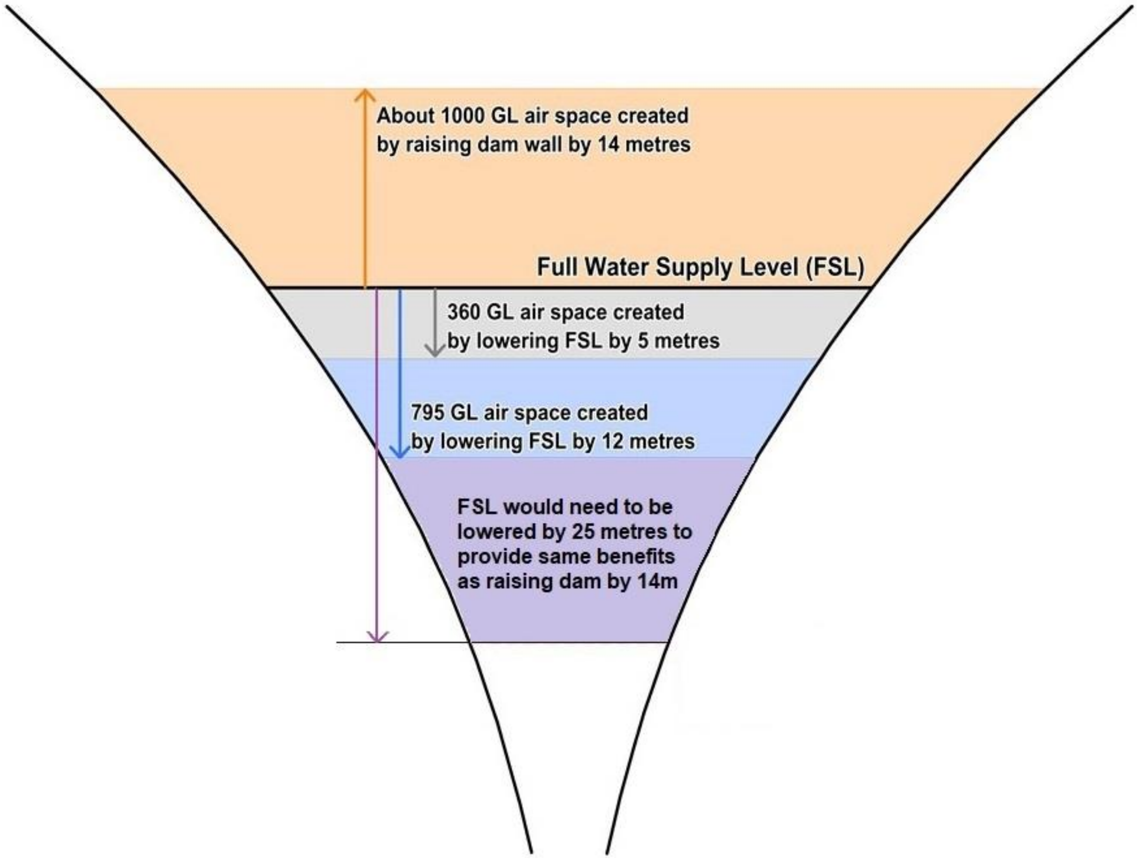
Source: INSW 2021

4.7.4.1 Creating a FMZ at Warragamba Dam

Only the three Warragamba Dam alternatives that create flood mitigation zones (of different sizes) act to reduce the extent and depth of downstream flooding. Regional road upgrades, buy-back of dwellings or disallowing new dwellings do not change flood extents.

The deep V-shaped valley behind Warragamba Dam means that the volume of air space created by raising the dam by 14 metres is significantly more than the volume created by lowering FSL by five or 12 metres, as shown in Figure 4-10.

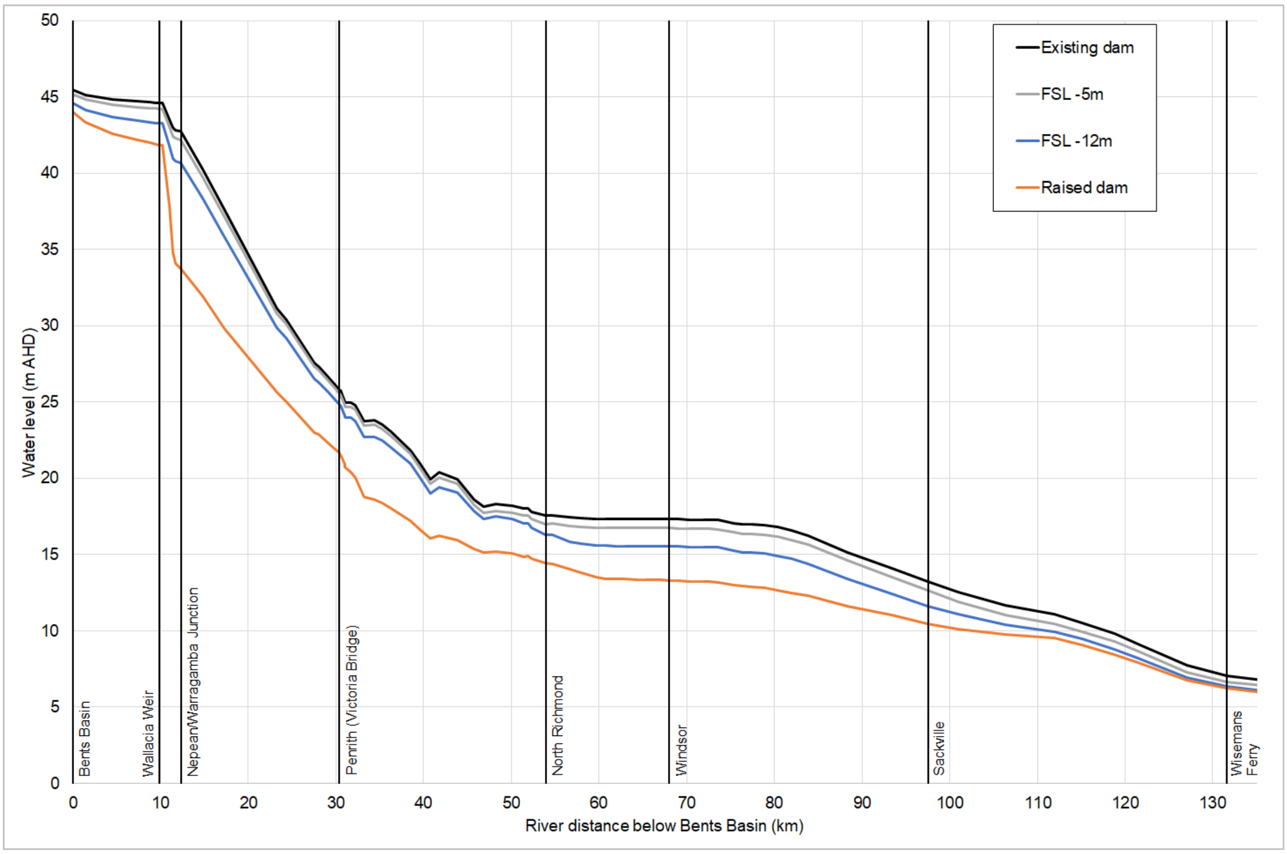
Figure 4-10. Comparison of air space with different options for creating an FMZ at Warragamba Dam



Source: INSW

Figure 4-11 shows the impact of the Warragamba Dam alternatives on the flood profile downstream in the Hawkesbury-Nepean River for a 1 in 100 chance in a year event. The figure shows flooding profiles from Bents Basin near Wallacia in the south, to Wisemans Ferry in the Lower Hawkesbury.

Figure 4-11. Hawkesbury-Nepean River profile 1 in 100 chance in a year flood – Bents Basin to Wisemans Ferry



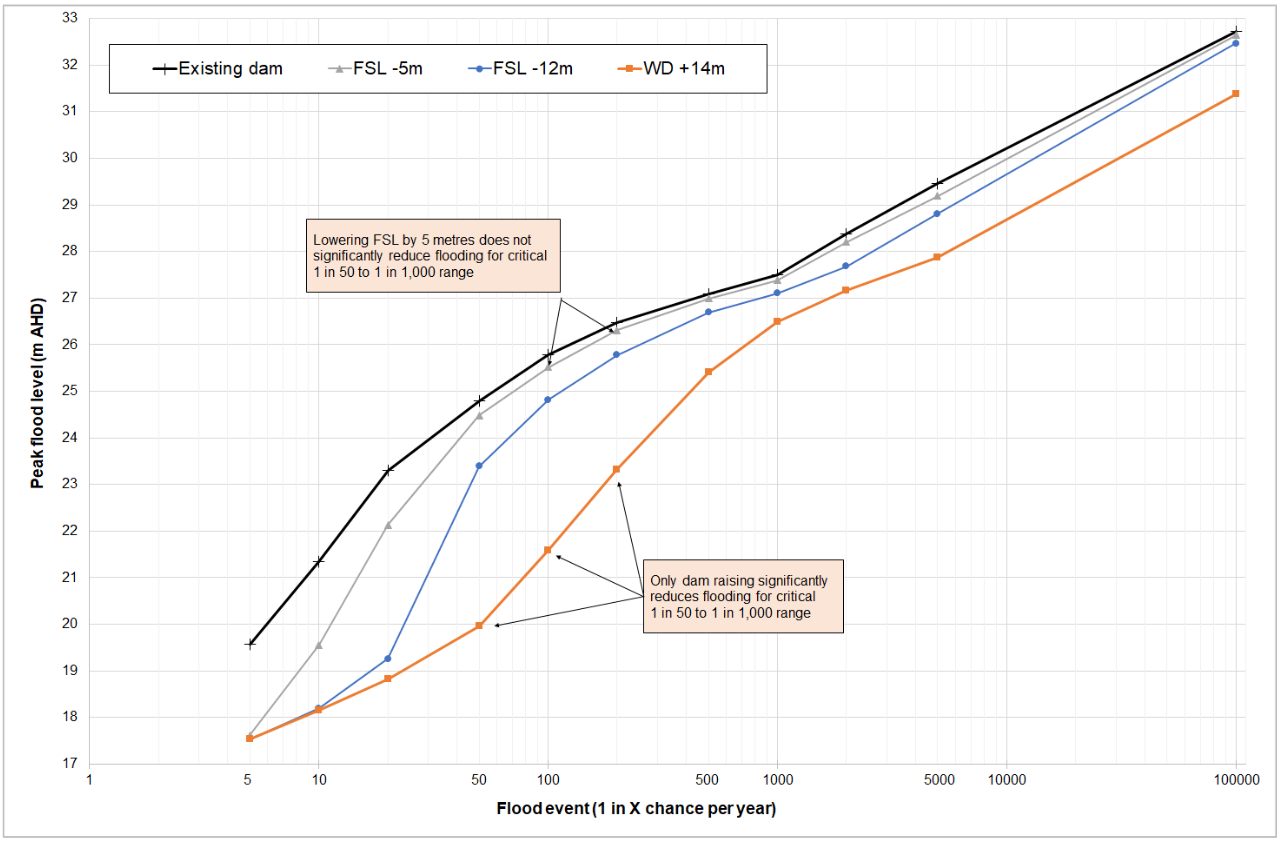
Source: INSW (2021)

Lowering full supply level by 12 metres offers moderate benefit for the 1 in 100 chance in a year flood, reducing levels by 1.0 metre at Penrith and 1.8 metres at Windsor. These benefits are subdued for a 1 in 500 chance in a year flood similar to the 1867 flood of record, with a 0.4 metre reduction at Penrith and 1.1 metre reduction at Windsor.

Recent investigation has also shown that to achieve these benefits would require four outflow conduits to be built through the existing dam wall. This is because with the existing gates, it is difficult to keep the dam level at 12 metres below current FSL, meaning for a significant portion of modelled floods, the actual starting level would be around 10 metres below current FSL, reducing the available air space.

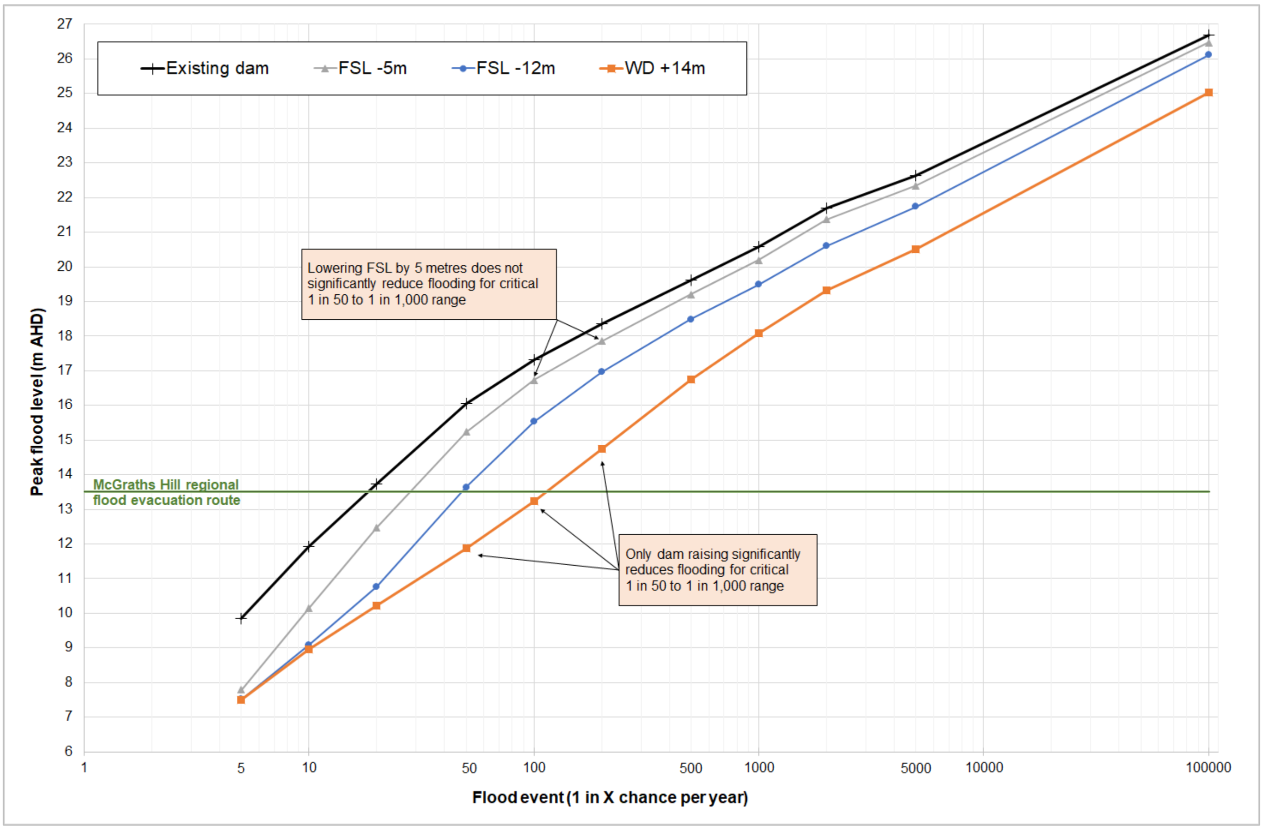
Figures 4-12 and 4-13 below show the effect of the three dam options on flood levels at Penrith and Windsor, across the full range of floods. Lowering full supply level by five metres offers little benefit in reducing flood levels for the flood range that contributes most to flood risk (1 in 50 to 1 in 1,000 chance in a year).

Figure 4-12. Effects of Warragamba Dam flood mitigation options on full range of floods, Penrith



Source: INSW (2021)

Figure 4-13. Effects of Warragamba Dam flood mitigation options on full range of floods, Windsor



Source: INSW (2021)

The option to raise Warragamba Dam for a 14-metre FMZ offers significant benefits over the option to lower FSL by 12 metres. It would reduce the 1 in 100 chance in a year flood level by 4.2m at Penrith (3.2 metres more than the 12-metre lowering) and by 4.1 metres at Windsor (2.3 metres more than the 12-metre lowering). The McGraths Hill regional evacuation route – now cut in a 1 in 20 chance in a year flood – would no longer be cut during a 1 in 100 chance in a year flood.

A flood reaching the current level of the 1 in 100 chance in a year flood at Windsor, also the lowest level of the last evacuation road out of Windsor, would be much less frequent – decreasing to about a 1 in 700 chance in a year event. To offer the same quantum of downstream reductions in flood levels as the preferred option to raise Warragamba Dam wall, the full supply level at Warragamba Dam would have to be permanently lowered by around 25 metres. This would result in an estimated 1,400 gigalitres loss of water storage capacity or 67 percent loss in storage behind Warragamba Dam wall. It would also reduce the contribution from Warragamba Dam to Greater Sydney's ability to sustainably supply water to the overall system by around 150GL/annum or 30 percent.

4.7.4.2 Property buyback

The option of compulsory buying back all residential property below the current 1 in 100 chance in a year flood (around 6,000 homes) would significantly reduce the risk by removing much of the exposure (people and dwellings) from the reach of the most frequent floods. However, it would not remove commercial/industrial or infrastructure assets, and would not remove residential exposure above the current flood planning level. Given the potential depth of floodwaters above the 1 in 100 chance in a year flood (e.g. 2.4 metres in the record 1867 flood at Windsor), and the large number of dwellings located just above the current flood planning level, the risk would still be significant.

Further, with predicted climate change, the current 1 in 100 chance in a year flood level is likely to be reached more frequently to around a 1 in 65 chance in a year event by mid-century. Alternatively, around 3,000 additional homes would be impacted by a 1 in 100 chance in a year flood by that time. Practically, implementation would also be very challenging. It may be possible to implement a voluntary buyback scheme, but experience with these schemes is that they do not achieve complete acceptance, and the state and local governments and utility providers are left maintaining services to a partly settled area. In the Hawkesbury-Nepean, whole suburbs such as McGraths Hill would have to be relocated to new areas.

4.7.4.3 Preventing new development below current 1 in 500 chance in a year flood level

Disallowing any new residential development below the current 1 in 500 chance in a year flood level would provide no benefit for the existing significant existing development below that level. About 15,500 residential properties were already exposed to the 1 in 500 chance in a year event in 2018.

Such an initiative would prevent some 10,000 new dwellings from being exposed to an 1867-sized flood scenario by 2041. However, as with the buyback option above, the benefits would be eroded over time under the influence of predicted climate change, which will have the effect of making the increasing the extent of the 1 in 500 chance in a year flood and increasing the number of residences within this flood footprint.

4.7.5 Risk to life (KPI 1)

4.7.5.1 Exposure of properties

Changes in the exposure of residential properties to flooding with the three Warragamba Dam flood mitigation options, are presented in Figure 4.11 for current development (2018).

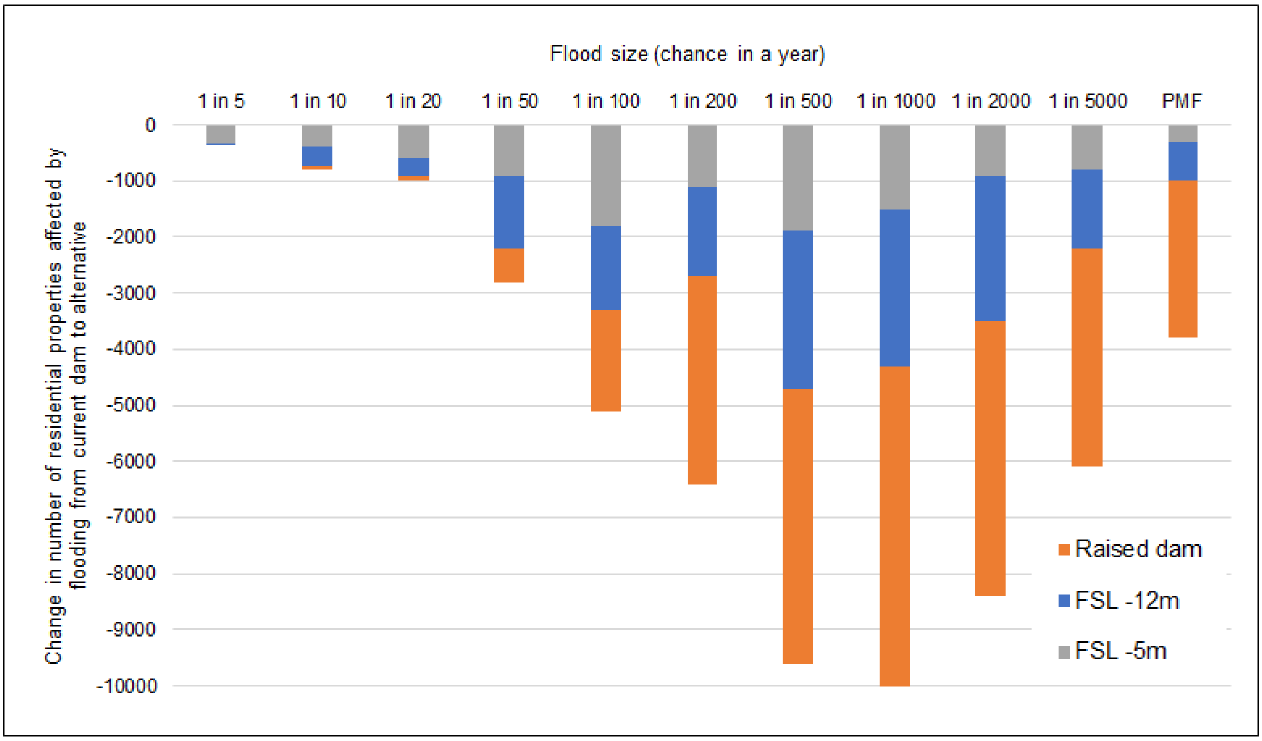
Of the dam options, lowering FSL by five metres makes the least reduction in the number of residential properties exposed to flooding across the flood range. Lowering FSL by 12 metres offers greater benefits, while the dam raising option would provide distinctly greater benefits than the other mitigation options, reducing the number of residential properties impacted by the larger floods (see Tables 4-11, 4-12 and 4-13).

Climate change will increase the height of floods in the critical flood range and so expose more residential properties to flooding of the same average frequency. Changes in the exposure of residential properties to two flood sizes, with the three Warragamba Dam flood mitigation options, are presented in Figure 4-14 for 'current' (2018) development. Figure 4-15 illustrates potential development of residential properties that could occur to 2041 under existing plans and zoning, and with projected impacts of climate change.

Lowering FSL by five metres reduces the number of residential properties currently exposed to flooding by 24 percent and 12 percent in the 1 in 100 and 1 in 500 chance in a year floods, respectively. Lowering FSL by 12 metres offers greater benefit, reducing the numbers by 43 percent and 30 percent, respectively. Raising Warragamba Dam for a

14 metre FMZ affords the greatest reductions, by 68 percent in the 1 in 100 chance in a year flood, and by 62 percent in the 1 in 500 chance in a year flood.

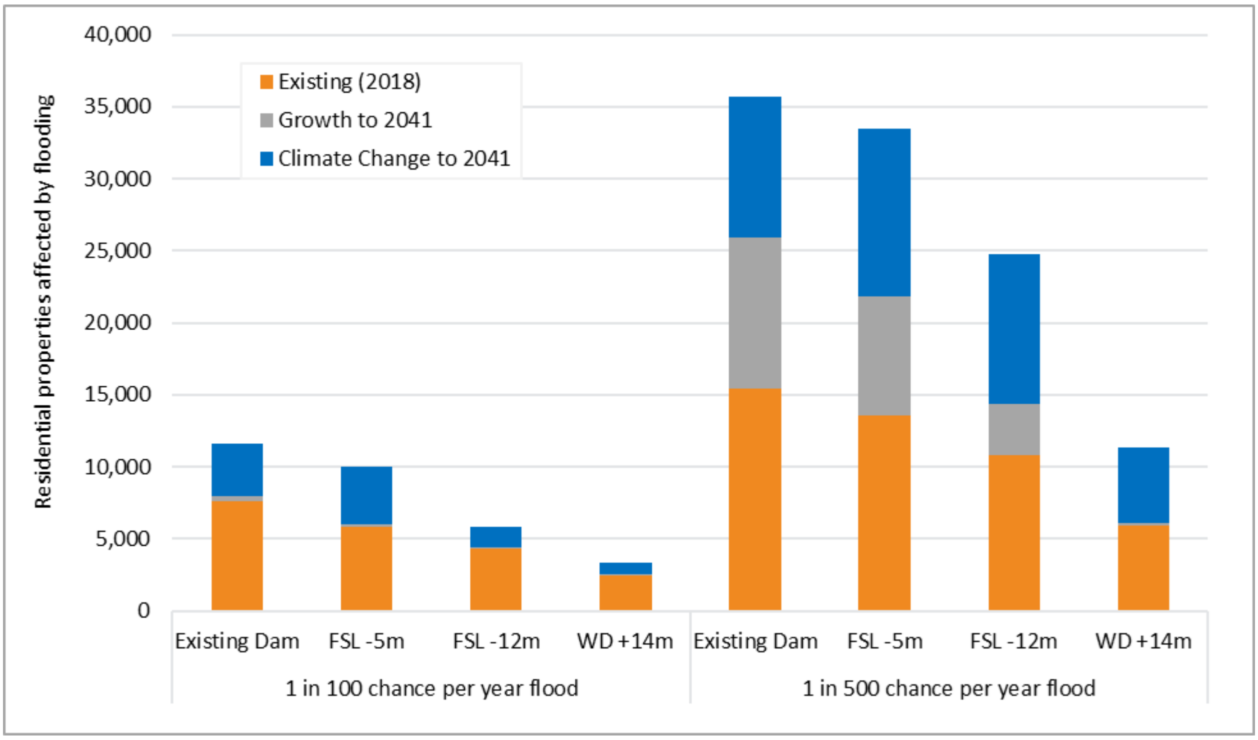
Figure 4-14. Change residential properties impacted 1 in 5 chance in a year flood to PMF (2018 development)



Note: Stacked columns are cumulative top to bottom, eg, for a 1 in 1,000 chance per year flood, the reduction for the raised dam is 10,000.

Source: INSW (2021)

Figure 4-15. Potential change residential properties impacted 1 in 100 and 1 in 500 chance in a year floods with growth, climate change and Warragamba Dam infrastructure options



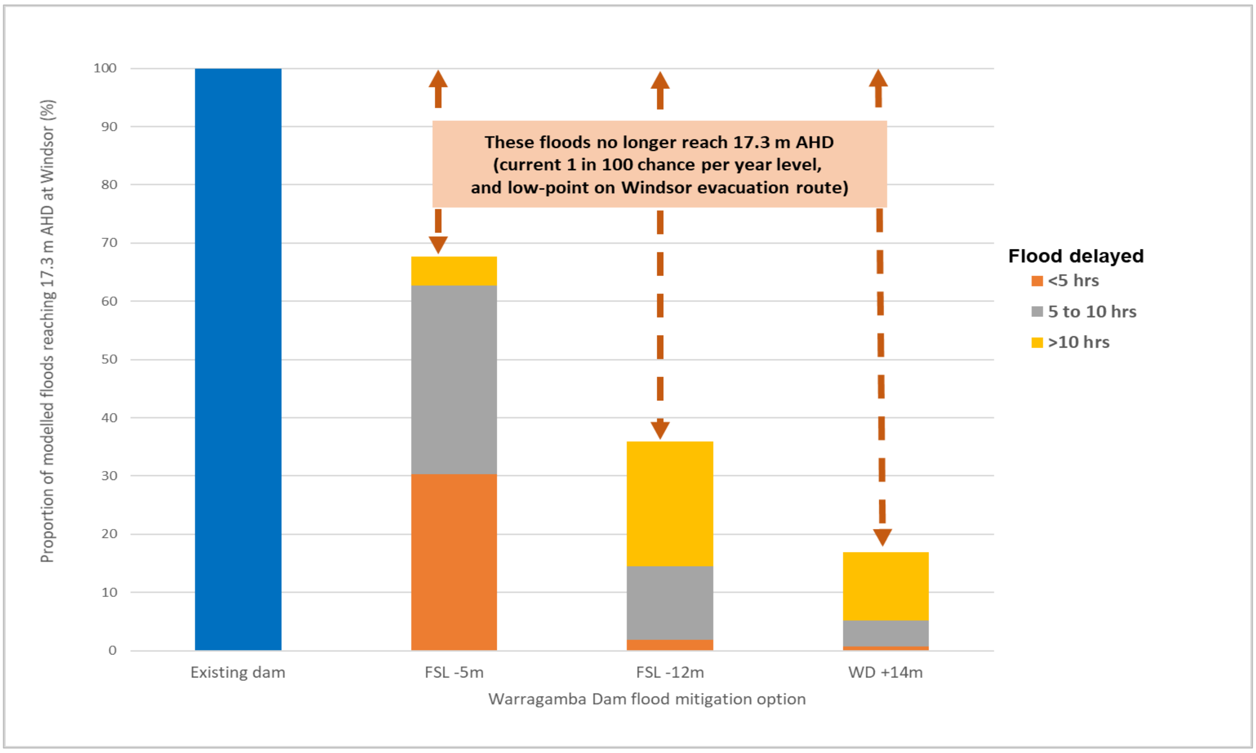
Source: INSW (2021)

4.7.5.2 Exposure of evacuation roads and lead times before they are cut

Changes in both the probability of a key regional evacuation road being cut, and in the probability of greater lead time prior to the road being cut, are shown for the three Warragamba Dam flood mitigation options in Figure 4-16. This shows that dam raising outperforms lowering FSL by 12 or five metres.

Raising the dam for a 14-metre FMZ would prevent 83 percent of events that currently reach or exceed the Windsor evacuation route from reaching that level. Of the floods that would still reach that level, 70 percent would be delayed by more than 10 hours, providing more opportunity for safe evacuation from the Windsor flood island.

Figure 4-16. Change in the frequency and timing of events reaching and exceeding 17.3 mAHD at Windsor with different Warragamba Dam infrastructure options



Source: Adapted from Taskforce Options Assessment Report (INSW 2019)

4.7.5.3 People unable to evacuate

A reassessment of the average annual vehicles and people at risk was undertaken using the latest flood evacuation model. Consistent with the Taskforce modelling, it was necessary to assume a 100 percent community response to an evacuation order to measure 'no fault' risk to life. 'People at risk' is defined to include both those trapped by floodwater or queued on the evacuation road network for more than 12 hours.

Every flood is different. It is difficult to assess actual numbers of fatalities as it involves people responding to life threatening situations where flood depths can be extreme and there is limited access to places of safe shelter with the large inland sea created by the bathtub effect in this valley. Loss of life or fatalities have been calculated on those vehicles trapped by floodwaters on the evacuation network. This approach is used to assess the ultimate capacity of the flood evacuation road network.

There are several noteworthy features of the assessment.

- The critical areas for this flood risk are Bligh Park, Richmond and Emu Plains. The areas with prolonged evacuation times include Penrith Lakes and Emu Plains and the established areas of Londonderry, Clarendon, Bligh Park and Windsor Downs.
- The dam raising option performs much better than even the best road option (the Castlereagh Connection set at the 1 in 1000 chance in a year level). This is a critical finding: regional road upgrades cannot substitute for the dam raising. It is not feasible or cost effective to build enough roads to significantly reduce the risk to current levels, with or without the dam.
- However, in combination with the dam raising, the best road options can provide additional, complementary risk-to-life-reducing benefits to partly offset the effects of growth and climate change.

- The dam raising option performs significantly better than options to lower FSL by 12 metres or to buy back all residential properties below the 1 in 100 chance in a year flood. The 14-metre dam raising option performs best because it provides the greatest reduction in flood levels across the floodplain, reducing the scale of evacuation and reducing and delaying flooding of evacuation roads. Also, even though the 14-metre dam raising delays most floods by eight to 15 hours, this delay has not been added to the forecast time, making the risk to life reductions from the dam raising the conservative worst case.
- Disallowing new residential development below the current 1 in 500 chance in a year flood level has limited benefits for reducing risk to life. This is because the numerous flood islands in the valley trigger evacuations above the 1 in 500 chance in a year level before they become isolated.

Average annual people at risk is a useful metric to compare the relative effectiveness of the options but underplays the actual people at risk for the larger events that pose the greatest risk to life.

The relative reductions in people unable to evacuate and risk to life in 1 in 100 and 1 in 500 chance in a year floods are summarised in Tables 4-11 and 4-12.

4.7.6 Risk to property (KPI 2)

A substantial component of flood damages and the greatest social impact result from inundation impacts on residential properties. Drawing on the updated database, the impacts on these properties of flooding related to climate change under the existing dam, and two of the most effective mitigation alternatives, are discussed below.

There are significant numbers of dwellings that occur from the level of around the 1 in 50 chance in a year flood. This is because the flood planning levels (1 in 100 chance in a year flood) change over time as a result of better information, changes to the catchment and to policy. For example, the current 1 in 100 chance in a year level of 17.3 metres at Windsor was increased from around 16 metres in the 1999. As a result of these changes over time, and the history of land use in the floodplain, there is a substantial number of residential properties below the current 1 in 100 chance in a year flood planning level.

4.7.6.1 Impacted properties with current climate

In the critical 1 in 50 to 1 in 1,000 chance in a year flood range, a 14-metre dam raising would reduce the number of residential properties (December 2018) currently impacted by between 50 percent and 67 percent. Figure 4-17 shows that in this flood range the reduction in the number of residential dwellings currently affected with a raised dam is higher than lowering FSL by 12 metres.

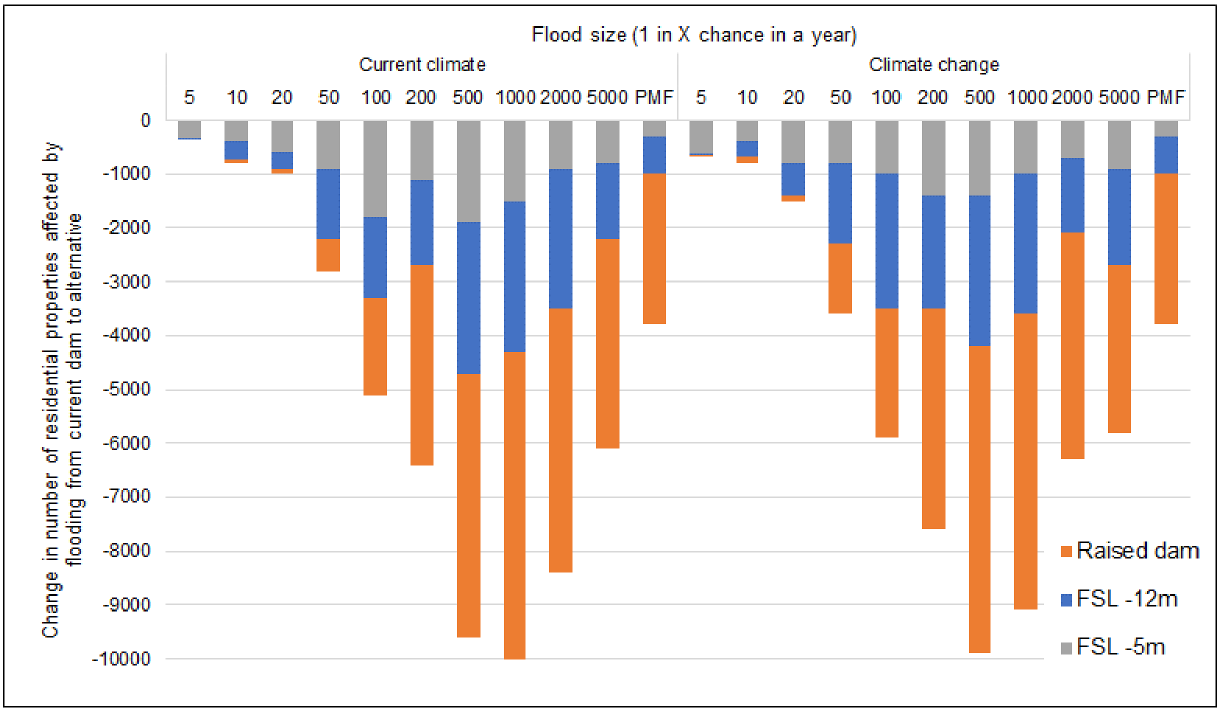
The difference between the mitigation alternatives continues with larger floods up to the PMF. For example, in a 1 in 5,000 chance in a year flood a raised dam would still reduce the number of residential properties affected by 6,100, compared to 2,200 for lowering the FSL by 12 metres.

4.7.6.2 Impacted properties with climate change

Modelling the impacts of a medium climate change scenario shows the benefits of flood mitigation alternatives would increase, but that the difference between the 14-metre raised dam and a 12-metre lowering of FSL remains constant. Figure 4-1717 shows the number of residential properties affected under a medium climate change projection compared to the current climate, across the full range of floods, with the existing dam and the most feasible mitigation alternatives.

A comparison between a 14-metre raised dam and lowering FSL by 12 metres under climate change shows the difference between them would increase in the flood range up to 1 in 500 chance in a year and decrease for events above the 1 in 1000 chance in a year. For these floods, the reduction in the number of residential properties inundated with a 14-metre dam raising would still be more than double the reduction achieved by lowering the FSL by 12 metres.

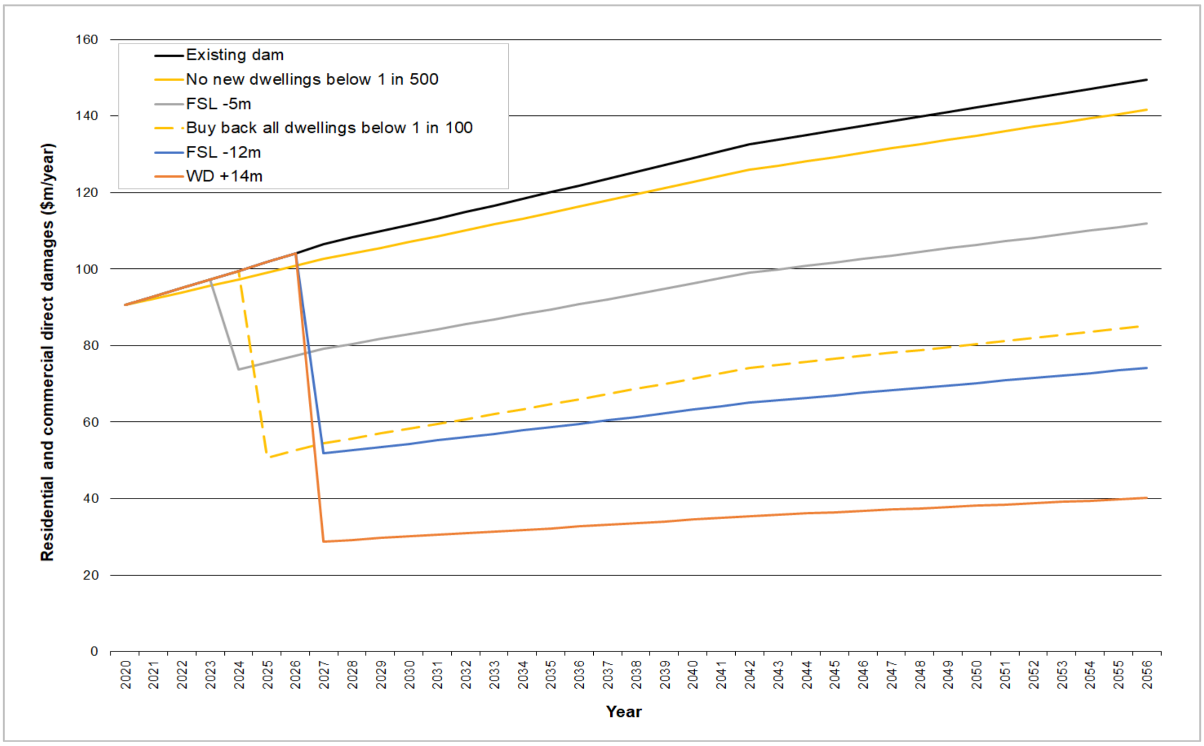
Figure 4-17. Reduction in properties affected by flooding compared with existing dam - with current climate and, with climate change - 5-metre lowering, 12-metre lowering and 14-metre raising (current development)



Note: Stacked columns are cumulative top to bottom.
Source: INSW (2021)

Figure 4-18 shows the impact of the options being reassessed on the annualised costs of flooding from 2020 to 2056. Without intervention, the chart shows increasing flood damages over time due to permissible growth and climate change. The 14-metre dam raising has by far the most noticeable and persistent impact on the costs of flooding. Reducing FSL by five metres would have a short-lived benefit, with the costs back to current levels by around 2036. Major road upgrades are not included on the chart because they do not reduce damages to property.

Figure 4-18. Residential and commercial direct damages by option over time (average annual damages)



Source: INSW (2021)

Importantly, if the dam was raised by creating a 14-metre FMZ, the 17.3 mAHD minimum planning level would be retained, and the reduction in peak flood height would mean this level would only be reached by around a 1 in 700 chance in a year flood (under current climate). By comparison, lowering the dam by 12 metres would reduce flood peak such that this level would be reached by around a 1 in 230 chance in a year event.

4.7.7 Minimising social and environmental impacts (KPI 3)

In March 2016, the Australian Business Roundtable for Disaster Resilience and Safer Communities released 'The Economic Cost of The Social Impact of Natural Disasters'[2]. The report looked at the costs and long-term social impacts of natural disasters in Australia and found the social costs of natural disasters in 2015 were at least equal to the physical costs.

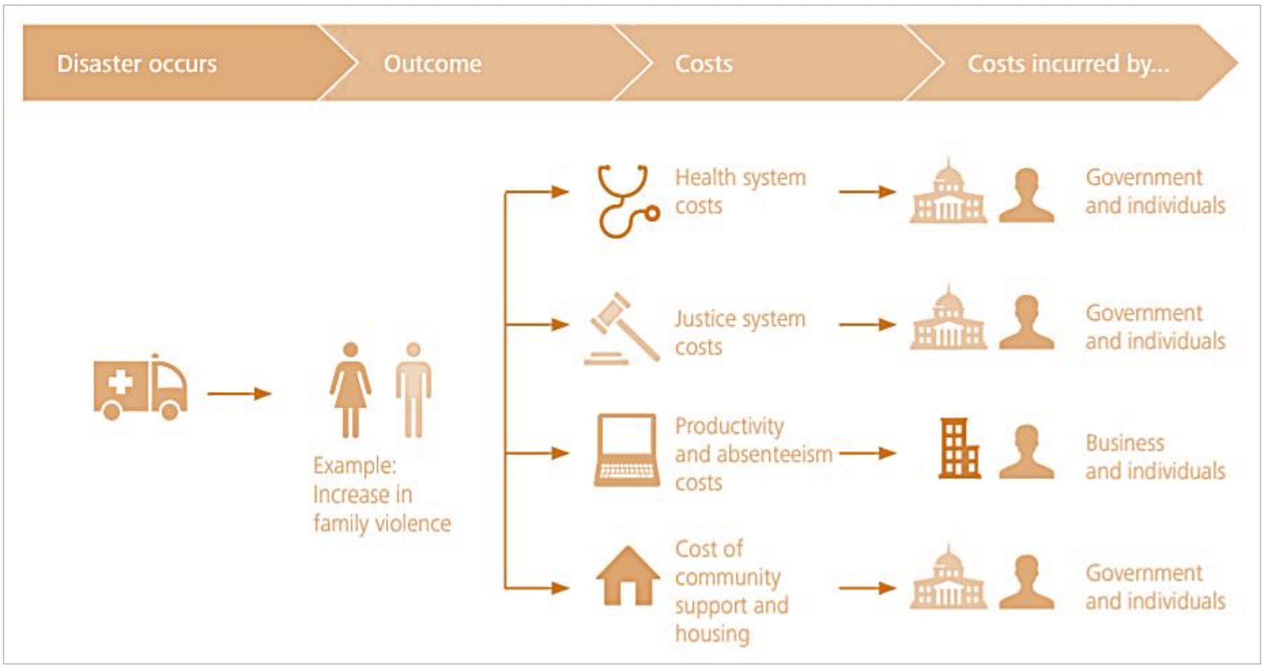
The 2010-11 floods in South East Queensland were one of the case studies in the report undertaken by Deloitte Access Economics. It found that lifetime mental health costs alone, at an estimated $5.9 billion, were approaching the cost of direct impacts on infrastructure of $7.4 billion.

The report found intangible costs arising from floods related to a range of issues impacting on individuals including:

- injuries and death
- mental health problems
- risky or high-risk alcohol consumption
- family violence
- chronic and non-communicable diseases
- short-term unemployment.

The Deloitte Access Economics report shows how outcomes from natural disasters map to costs incurred by individuals, businesses and the government (see Figure 4-19).

Figure 4-19. Example of how disaster-related outcomes map to costs



Source: Deloitte Access Economics, The *Economic Cost of The Social Impact of Natural Disasters* (2016)

Deloitte is undertaking similar analysis of the 2019 North Queensland floods for the Queensland Reconstruction Authority.[3] That flood had around a likelihood of around a 1 in 1000 chance in a year and resulted in widespread damages across urban and regional areas.

[2] The *Economic Cost of the Social Impact of Natural Disasters*, Deloitte Access Economics, 2016

[3] The social and economic cost of the North and Far North Queensland Monsoon Trough (2019), Deloitte Access Economics

At the time of writing, Deloitte noted that many of the impacts would take months to years to recover from, and that:

> *There is also anticipation of a high and lasting social cost, with some consequences for people's health and wellbeing expected to persist for the rest of their lives. These include intangible impacts on physical and mental health, family and community cohesion. By the end of March 2019, more than 60,000 people had accessed psychological first aid and more than 100,000 people had applied for personal hardship assistance grants. The human and community impact of this event is already substantial.*

An assessment of socio-economic, environmental and cultural heritage impacts of alternative flood mitigation infrastructure options was undertaken and summarised in the Taskforce Assessment Options Report (INSW 2019) and reconsidered during Phase One of the Flood Strategy. They can be summarised as follows:

- Options to lower the full supply level entail the loss of a large proportion of Sydney's water supply security and would bring forward new sources of water (likely, additional desalination plants), which would have associated environmental impacts such as high energy usage and associated greenhouse gas emissions. The building and operation of additional desalination capacity would have significant costs, which would impact negatively on water bills for residents of Greater Sydney. Lowering the dam storage would also have potential impacts on water quality, particularly when storages are low during drought.
- Compulsory buyback of all residential properties within the 1 in 100 chance in a year flood extent would have enormous social and economic consequences with the dislocation of families arising from acquisition of around 6,000 homes (including the suburb of McGraths Hill) and the need to establish new housing to accommodate them. There would also be substantial social and economic impacts for affected local councils and communities.
- Preventing further development below the 1 in 500 chance flood extent would do nothing for the tens of thousands of homes and families currently living below that level, and who are exposed to an ongoing and increasing flood risk. As outlined in Chapter 21, there are many vulnerable sectors of the community currently living within that zone.
- Major road upgrade options, while helping to reduce risk to life during a flood evacuation, do nothing to reduce the flood impacts on people's homes, businesses and communities which, as outlined above, could be catastrophic during major events and lead to significant ongoing costs to individuals, their communities and government.

Floodplain residents are already reporting challenges with the affordability of flood insurance. The projected impacts of climate change will exacerbate the issue, with more of the floodplain potentially subject to unaffordable premiums or potentially becoming uninsurable. This will have significant implications for short and long-term recovery from major floods.

The environmental and social impacts and benefits of the proposal to raise Warragamba Dam to create a 14-metre FMZ are discussed in Chapters 7 to 27 inclusive.

> The dam raising detailed concept design has been developed in parallel with the draft EIS. It has optimised the spillway arrangements to minimise the impacts both upstream and downstream of the dam. This has resulted in a reduced extent and duration of upstream inundation and improved downstream flow characteristics, compared with early-stage designs.

4.7.8 Cost effectiveness (KPI 4)

In a cost benefit analysis net present value (NPV) is the value of all future costs and benefits over the entire life of an option discounted to the present time. It assumes the value of benefits and costs reduce over time. The further into the future a benefit is obtained, or cost expended, the lower the value. It enables comparison of options that accrue benefits and/or require cash to be expended over differing time periods. This cost benefit analysis is based on projected annual cash flows of costs and benefits over 30 years with a seven percent discount rate in accordance with standard NSW Treasury practice.

A benefit-cost ratio (BCR) is an indicator showing the relationship between the relative costs and benefits of a proposed project, expressed in monetary or qualitative terms. If a project has a BCR greater than 1.0, it is expected to deliver a positive NPV on the investment.

The costs and benefits for the options are summarised in Table 4-8. This shows that raising the dam has the highest and only net benefit of these options (with all alternatives having a significant net cost).

Table 4-8. Summary of cost benefit analysis - Warragamba Dam and land use alternatives

	14m dam raising	12m FSL reduction	5m FSL reduction	Buy out properties within 1 in 100	No new development within 1 in 500
	$m, NPV	$m, NPV	$m, NPV	$m, NPV	$m, NPV
Total costs	1,075	2,035	884	3,124	392
Total benefits	1,126	778	464	662	74
Net benefits	51	-1,257	-420	-2,462	-318
BCR	1.05	0.38	0.52	0.21	0.19

Source: INSW (2021)
Note: Using a 7% discount rate and a 30-year time period post construction

The conclusions of the economic evaluation are summarised below.

- A 12-metre reduction in the FSL has a BCR of 0.38. It has lower benefits than raising the dam wall by 14 metres and would be more than double the cost. It requires modifications to the dam wall at significant cost to achieve the modelled level of benefits and the water security costs to offset the 39 percent loss in water from Warragamba Dam storage would require the equivalent of a 250 megalitre/day new desalination plant running at capacity.
- A five-metre reduction in the FSL has a BCR of 0.52. It has substantially lower benefits than the 12-metre FSL reduction, offering significantly less flood risk reduction in the critical flood range. While it has lower costs than the 12-metre reduction, it would also have a significant impact on water security. The water security impact has increased significantly since the Taskforce assessment taking into account the revised modelling of long-term water availability. This is reflected in a revised BCR which has reduced from 1.2 to 0.52.
- Compulsorily buying out all residential properties below the current 1 in 100 chance in a year flood level has a significant benefit, but does not reduce non-residential damages and does not have as large a benefit in total as the 14-metre dam wall raising or lowering the FSL by 12 metres. Its cost is also very high, comprising the cost of purchase of land and buildings and other consequential costs related to relocation of residents and stranding of assets. The land may have some value in an alternative use, although this would be inconsequential relative to the cost. Also, this analysis does not take account of the prohibitive social impact of relocating whole communities.
- Restricting new development has small benefits, because most of the flooding costs relate to development has already occurred. The cost of this option reflects not being able to use land for a higher value use based on current market prices. The cost of this approach could only be reduced if there were a readily available or infinite supply of land to accommodate future residents, which is not the case in Greater Sydney.

4.7.9 Testing alternative packages of options

As discussed above, the 14-metre dam raising option performs the best against the KPIs. New or major road upgrades for growth and land use planning management measures should be considered as complementary measures to manage the ongoing risk – once the significant existing risk is reduced.

A number of combinations of dam options were discussed in Section 4 and summarised in Table 4.6, focusing on performance against the risk to life metric. Taking this analysis a step further, other combinations of measures have been assessed to try to approach a similar level of benefits as the dam raising option.

Several different packages were assembled to test if combinations could achieve similar benefits in reducing risk to life and flood damages. The packages comprised combinations of the better performing options – Castlereagh Connection as the best regional road option, lowering the permanent water supply by five or 12 metres, and buying back all homes below the current 1 in 100 chance in a year flood planning level.

None of the combination packages were able to achieve similar benefits to raising Warragamba Dam wall. All were cost prohibitive, and none mitigate climate change impacts beyond mid-century. Therefore, these alternative packages were not considered suitable for further consideration.

4.7.10 Upgrades to regional evacuation roads

As described in Section 4.4, new and major upgrades to regional evacuation roads are not an effective solution on their own to significantly reduce flood risk. This is primarily because:

- major road upgrades have significantly less impact on reducing risk to life than dam raising, and also rely on local roads being uncongested and unimpacted by flooding, providing access to major evacuation roads
- road upgrades offer no benefit in reducing damage to existing properties and assets
- generally, roads are demand driven resulting in population uplift and increased densities, which can exacerbate the risk to life issue if the growth is not managed appropriately.

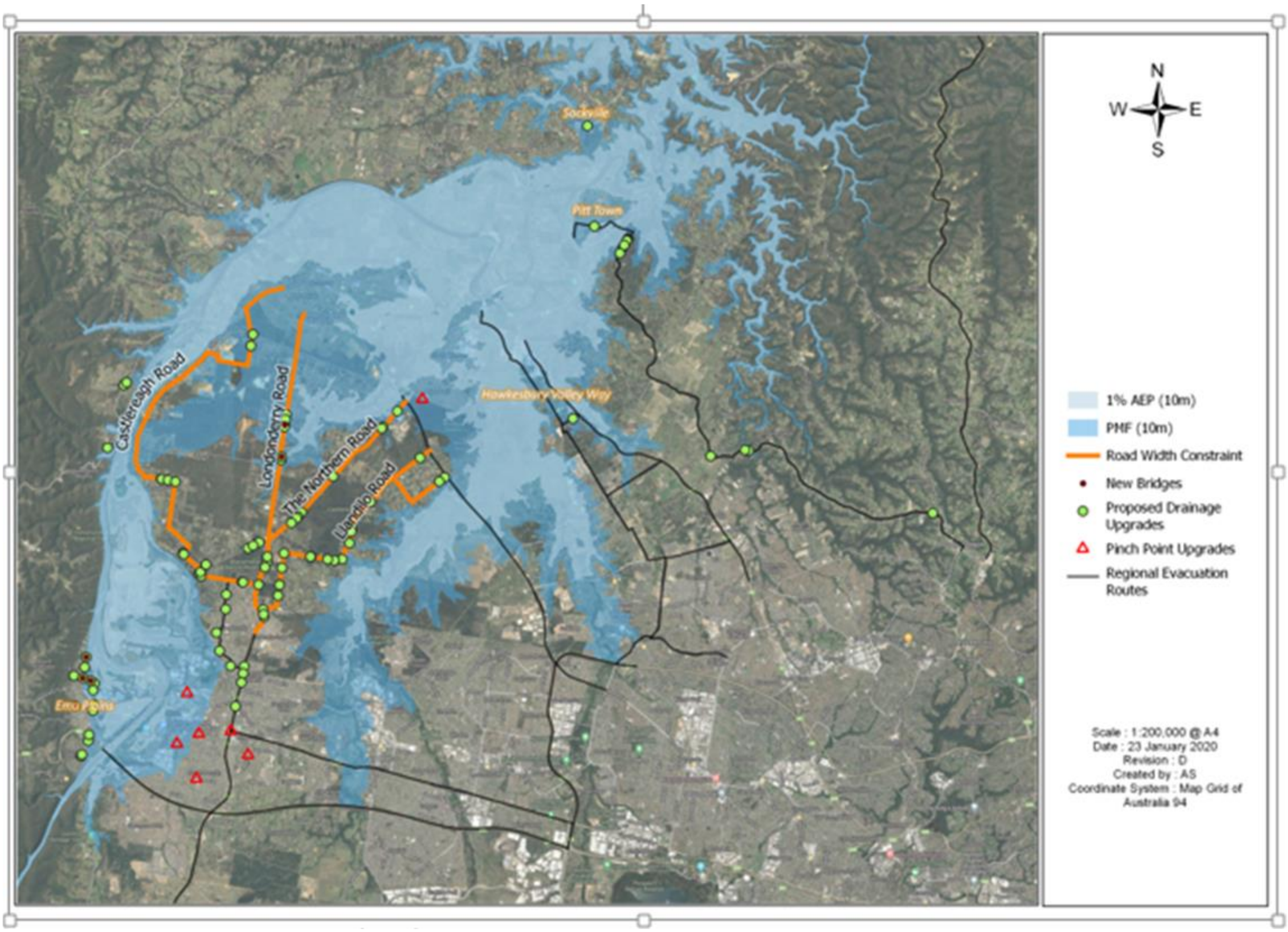
However, it was confirmed there is merit in increasing the resilience of existing evacuation roads in accordance with Phase One of the Flood Strategy. This required development of business cases to progress upgrades of priority local evacuation roads identified by the Taskforce.

These upgrades were aimed at addressing existing constraints - minimising the risk that evacuation routes would be cut by local catchment flooding during a regional flood event, removing local pinch points, and adding additional outbound lanes.

Further detailed surveying and investigations undertaken in Phase One of the Flood Strategy identified that a systemic ‘corridor’ approach is required rather than spot fixing the low points and constraints as previously identified.

The risk to life for this program has been assessed separately as part of developing the strategic business case for the program. Figure 4.20 below shows the indicative location and nature of the prioritised upgrade program.

Figure 4-20. Indicative evacuation road upgrade program – subject to business case development



Source: Transport for NSW

4.7.11 Review of complementary measures

A comprehensive review and evaluation have been completed of the program and governance of Phase One of the Flood Strategy. This has informed the recommended forward program for the complementary measures, now considered and delivered as core functions of government. They include:

- coordinated flood risk management across the valley
- strategic integrated land use and road planning
- accessible contemporary flood risk information
- building an aware, prepared and responsive community
- improved weather and flood predictions
- best practice emergency response and recovery.

Information on the implementation of Phase One of the Flood Strategy is available on the Infrastructure NSW website.

4.8 Consolidated outcome of the reassessment of options

As outlined earlier in this chapter, the Taskforce undertook analysis of all shortlisted options, including the preferred option to raise Warragamba Dam for a 14-metre FMZ for flood mitigation. Subsequent reassessment of the most feasible alternatives during Phase One of the Flood Strategy has informed this EIS.

4.8.1 Summary of Taskforce costings of options

The 2015 costs estimate developed by the Taskforce for the Warragamba Dam raising for a 14-metre FMZ were based on the scope of the project at that time which was at the detailed feasibility stage. The costs estimates have been updated based on subsequent investigations, along with new and updated data and analysis to develop the detailed concept plans and project EIS. Table 4-9 summarises the elements that have contributed to the increase, and the updated cost estimate as at December 2020.

Table 4 9. Warragamba Dam Raising: Changes in cost estimate since 2015

Description	Base estimate $ million
2015 cost estimate Base estimate cost appropriate to the scope of a detailed feasibility investigation ($2015)	**692**
December $2020 cost estimate Increased cost estimate, due to: 1. Escalation from $2015 to $2020 and application to base costs 2. Increased scope taking account of: • allowing for future climate change - overall 3m height increase for abutments and roadway from 14-17m - increased quantities for thicker buttress and auxiliary spillway floor • additional underfloor drainage at auxiliary spillway • new downstream cut-off wall for erosion protection. 3. Additional time and associated preliminaries due to the above scope increase 4. Increases to design and professional service fees 5. Adjusted contingency/risk allowances against increased base costs	**1,608**
Escalation and additional contingency/risk to 2027/28	**250-350**

Source: WaterNSW (2021)

The discounted NPV cost estimates are shown in Table 4-10. The discounted costs of options, used in the cost benefit analysis, take account of the timing of those costs and include:

- costs related to the flood mitigation activity, such as construction costs and operating costs for a higher dam wall and 12-metre reduction
- costs related to addressing other impacts from the option, including:
  - costs for environmental offsets

- costs for restoring water security for options where water yield (long-term water availability) has been reduced
- costs related to purchasing private property
- costs related to restricting the future use of private property
- provision for upgrade costs that would otherwise be required on the dam wall that are assumed in the base case.

Table 4-10. Cost of options (over 30 years)

	14m dam raising	12m reduction in FSL	5m reduction in FSL	Buy out homes below 1 in 100	No new homes below 1 in 500
Costs discounted ($M, NPV)					
Capital and operating costs (includes water security costs for 12m and 5m FSL reduction options)	1,075	2,035	884	3,124	0
Cost of development restrictions	0	0	0	0	392
Total costs	1,075	2,035	884	3,124	392

Source: INSW (2021)

The NPV ($2020) cost of the dam raising for a 14-metre FMZ is $1.075 billion and is based on several inputs:

- $1.61 billion of capital costs (P50 $2020), including costs for: design and construction, owner's project management, project insurances, environmental controls, stakeholder engagement, legal and regulatory requirements, project risk and contingency. As the dam wall raising would be delivered over several years, expected to be through to 2027/28, the final outturn cost would also incorporate additional escalation and contingency allowances of $250 to $350 million, **plus**
- a provisional allowance for environmental offset costs taking into account consultations with regulatory agencies, **plus**
- an annual additional operating cost, **less**
- a provision for works that would otherwise be required on the dam wall

For the FSL lowering options, cost estimates for works required to modify the existing dam wall are high-level estimates based on early feasibility designs. These feasibility designs would also impose a higher risk to the existing dam on the practicalities of the lowering option working due to the spillway modifications compared to the wall raising option. The designs have not been reviewed against Dams Safety NSW guidelines:

- the NPV cost estimate developed by the Taskforce to allow for a 12-metre permanent reduction in the FSL, based on a project definition level of around 15% design (feasibility), is $2.035 billion ($2020). . These works are for modifications to the central and auxiliary spillways and flow discharge system to enable the timely emptying of the FMZ to maintain the FMZ capacity post flood event. Along with these infrastructure costs, the estimated cost of water security replacement has been included.
- the NPV cost estimate developed by the Taskforce to allow for the five-metre permanent reduction in the FSL is $884 million ($2020). Note that under this option the necessary works on the existing dam would be required but have not been included for the purposes of the cost benefit analysis, but the estimated cost of water security replacement has been included (see below).
- The costs for water security replacement for the FSL lowering options have been estimated by measuring (by modelling) the long-term loss of water from the water supply system multiplied by the long run marginal cost of water from IPART's water pricing determinations.
- a 12-metre permanent reduction in FSL would reduce the storage in Warragamba Dam by 39 percent and result in around an 80 GL/a reduction in water supply system yield (long-term sustainable water availability).
- a five-metre permanent reduction in FSL would reduce the storage in Warragamba Dam by 18 percent and result in around a 35 GL/a reduction in water supply system yield.

The Greater Sydney Water Strategy team provided advice on water supply options that could 'make up' the water shortfall from lowering Warragamba Dam FSL, drawing on work underway reviewing Sydney's water supply system. Several options with varying costs could be adopted depending on water supply considerations. This is why the estimates focus on a more strategic view using the long run marginal cost approach. The specific options considered indicate the cost estimate for water security in the cost benefit analysis is conservative.

The following tables summarise the key costs and benefits for the reassessment of the preferred options and alternatives against key parameters. All costs are in 2020 dollars. It should be noted that, while the costs may change subject to escalation over time, the relative rankings of the options will not.

The assessed benefits (average annual reduction) in risk to life and damages of the 14-metre dam raising and alternatives are summarised in Table 4-11.

Table 4-11. Summary reduction annual average risk to life and damages – in all floods

		Existing dam - Business as usual (BAU)	5m reduction in FSL	12m reduction in FSL	14m dam raising	Buyout homes below 1:100 (current)	No new homes below 1:500 from 2018	Castlereagh Connection Stage 1 *
Sydney water supply % storage volume loss		0%	18%	39%	0%	0%	0%	0%
				Benefits (average annual)				
Flood damages ($M) incl. lives & % reduction from BAU	**2018**	$141M	$101M -28%	$67M -52%	$42M -70%	n/a	n/a	n/a
	2041	$176M	$129M -27%	$84M -52%	$50M -72%	$108M -39%	$144M -18%	$172M -2%
Risk to life – loss of life (trapped & non-response) & % reduction from BAU	**2018**	2.0	1.5 -28%	1.1 -48%	0.7 -65%	n/a	n/a	n/a
	2041	5.2	4.0 -24%	2.7 -49%	1.3 -75%	1.9 -64%	4.7 -10%	2.5 -52%
Homes impacted by flooding & % reduction from BAU	**2018**	430	330 -23%	253 -41%	198 -54%	n/a	n/a	n/a
	2041	462	356 -23%	267 -42%	204 -56%	75 -64%	437 -5%	462 0%

*assumes Castlereagh Connection will not increase floodplain development

Source: **INSW (2021)**

Tables 4-12 and 4-13 compare the risk to life and flood damages from 1 in 100 and 1 in 500 chance in a year flood events for the existing Warragamba Dam and alternatives.

Table 4-12. Risk to life and flood damages (direct and indirect costs) for 1 in 100 chance in a year flood

		Existing dam - Business as usual (BAU)	5m reduction in FSL	12m reduction in FSL	14m dam raising	Buyout homes below 1:100 (current)	No new homes below 1:500 from 2018	Castlereagh Connection Stage 1
Reduction in 1 in 100 level at Windsor (m)		0m	0.6m	1.8m	4.1m	0m	0m	0m
Benefits for a 1 in 100 chance in a year flood								
Flood damages incl. lives ($M) & % reduction from BAU	**2018**	$2,877M	$1,921M -33%	$995 -65%	$453M -84%	n/a	n/a	n/a
	2041	$3,271M	$2,158M -34%	$1,099M -66%	$452M -86%	$1,768M -46%	$2,890 -12%	$3,239 -1%
Risk to life – loss of life (trapped & non-response) & % reduction from BAU	**2018**	36	28 -22%	19 -47%	12 -67%	n/a	n/a	n/a
	2041	55	31 -44%	19 -66%	12 -78%	12 -78%	36 -35%	42 -24%
Homes impacted by flooding* & % reduction from BAU	**2018**	7,600	5,800 -24%	4,300 -44%	2,500 -68%	n/a	n/a	n/a
	2041	7,900	6,000 -25%	4,400 -44%	2,500 -68%	0 -100%	7,600 -4%	7,900 0%
People for evacuation & % reduction from BAU	**2018**	55,000	44,800 -18%	31,900 -42%	14,200 -74%	35,200 -36%	55,000 0%	n/a
	2041	62,600	51,600 -18%	37,100 -41%	16,200 -74%	42,000 -33%	61,700 -1%	62,600 0%

* Includes manufactured homes
Note: all costs are in 2020 dollars
Source: INSW (2021)

Table 4-13. Risk to life and damages (direct and indirect costs) for 1 in 500 chance in a year flood

		Existing dam - Business as usual (BAU)	5m reduction in FSL	12m reduction in FSL	14m dam raising	Buyout homes below 1:100 (current)	No new homes below 1:500 from 2018	Major Road Castlereagh Stage 1
Reduction 1 in 500 level Windsor (m)		0m	0.4m	1.4m	2.9m	0m	0m	0m
Benefits for a 1 in 500 chance in a year flood								
Flood damages incl. lives ($M) & % reduction from BAU	**2018**	$7,689M	$6,734M -12%	$5,128M -35%	$2,102M -73%	n/a	n/a	n/a
	2041	$12,105M	$10,166M -16%	$6,623M -35%	$2,336M -81%	$8,201 -32%	$6,731M -3%	$11,623M -4%
Risk to life – loss of life (trapped & non-response) & % reduction from BAU	**2018**	83	73 -11%	58 -25%	32 -61%	n/a	n/a	n/a
	2041	581	483 -25%	173 -70%	33 -94%	168 -71%	437 -25%	552 -5%
Homes impacted by flooding & % reduction from BAU	**2018**	15,500	13,600 -12%	10,800 -30%	5,900 -62%	7,800 -49%	n/a	n/a
	2041	26,000	21,800 -16%	14,400 -45%	6,100 -76%	18,000 -31%	15,500 -40%	26,000 0%
People for evacuation & % reduction from BAU	**2018**	87,800	82,300 -6%	66,200 -25%	44,800 -49%	68,000 -23%	n/a	n/a
	2041	135,000	126,000 -7%	88,000 -35%	52,900 -61%	115,000 -15%	112,000 -17%	135,000 0%

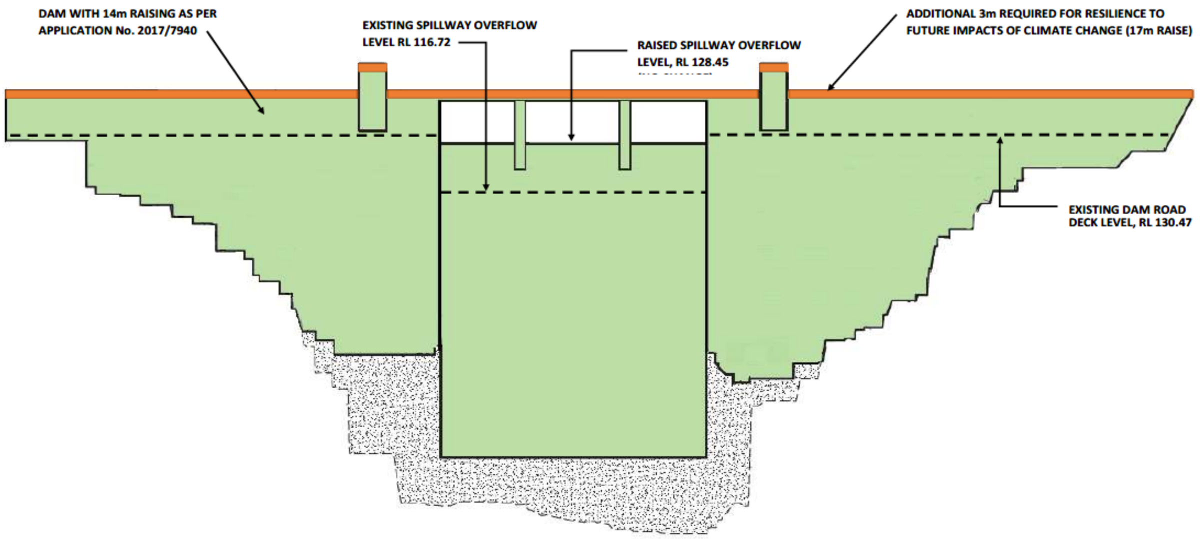
Note: All costs are in 2020 dollars. People for evacuation includes people who live or work in the floodplain.
Source: INSW

4.8.2 Impacts of AR&R guidelines and climate change research on Warragamba Dam raising design

As described in Section 4.6.2, new rainfall and runoff (AR&R) guidelines and climate change research have informed the design work on the dam raising proposal. The climate change research shows that the existing flood risk is set to increase with climate change and that a 17-metre dam raising achieves the same benefits in 2090 as a 14-metre dam raising under historical conditions.

Raising the dam in the future by an additional three metres to maintain flood mitigation capacity may not be feasible, both in terms of engineering constraints and cost. It is the spillway crest heights that determine the capacity of the FMZ. To enable the Project to accommodate potential climate change impacts and minimise future costs, the dam abutments would need to be raised by up to 17 metres, rather than 14 metres as originally proposed (Figure 4-21).

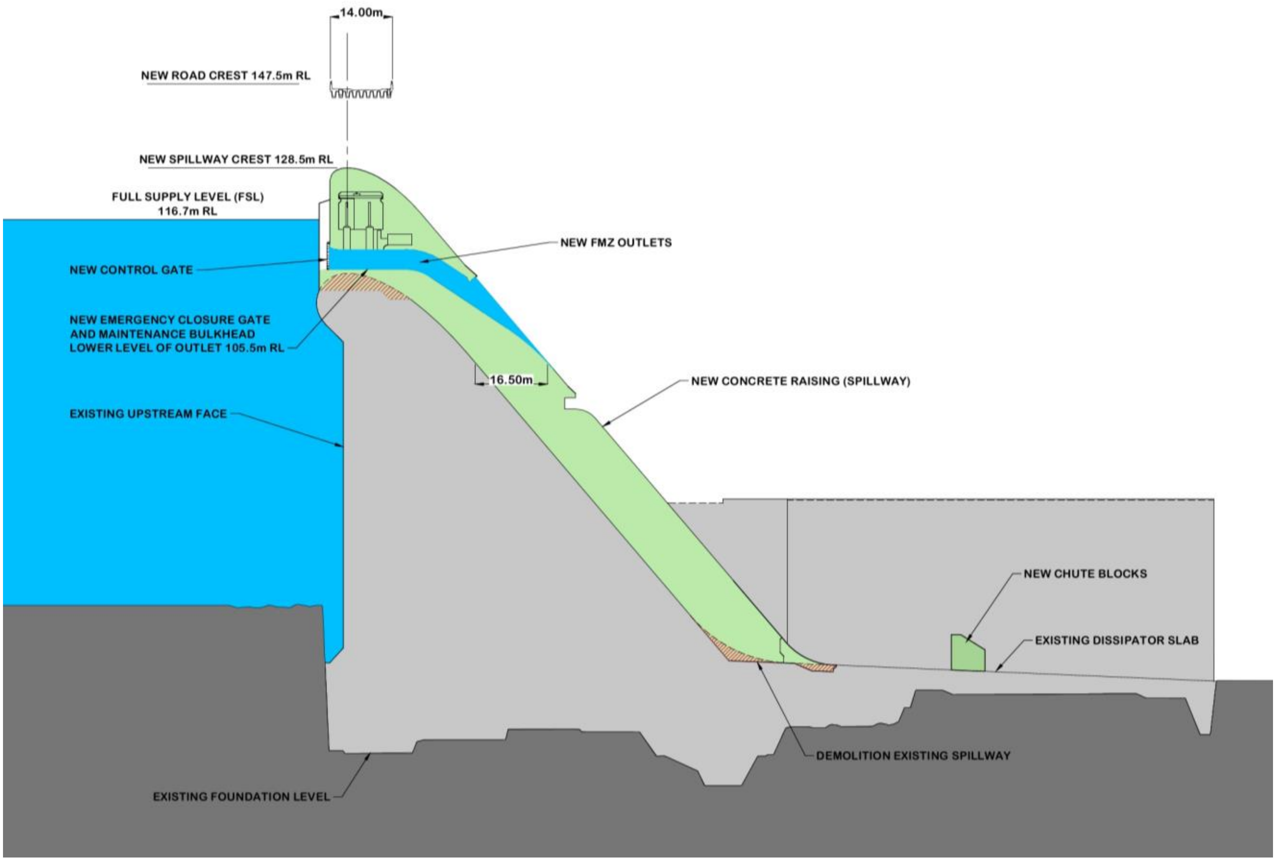
Figure 4-21. Indicative illustration of Warragamba Dam raising proposal with additional three metre to abutments for resilience to future impacts of climate change



Source: WaterNSW

This proposal does not seek or provide for any increase the level of the spillways above 14 metres. It allows for the spillway crest heights to be constructed at the levels that would create an FMZ of 14 metres. This FMZ has been applied to the assessment of upstream temporary inundation impacts and the downstream flood mitigation benefits as previously discussed in this section (see Figure 4-22). If required in the future, the spillway crest heights could be raised to accommodate climate change impacts without having to raise the abutments. Any future proposal to increase in the spillway heights would be subject to a separate design as well as approval from the relevant regulatory authorities.

Figure 4-22. Cross section of raised Warragamba Dam showing buttressed spillway



Source: WaterNSW

4.8.3 Summary of analyses – the preferred option

As shown above and in the charts below, lowering Warragamba Dam FSL by five metres does not meet the core objective of significantly reducing flood risk - reducing peak flood levels in the critical range at Windsor by up to 0.6 metres in a 1 in 100 chance in a year flood, and 0.4 metres in a 1 in 500 chance in a year event. It does not provide sufficient air space, and it does not provide the same quantum of benefits in terms of reduced exposure of houses, reduced and delayed inundation of evacuation routes as achieved through dam raising. It would have a relatively short-lived benefit in reducing damages (overtaken by growth and climate change by mid-century) and would do little to reduce risk to life.

Compared to the dam raising option, even the best-performing major road upgrade (Castlereagh Connection) was found to be much less effective at reducing risk to life, and significantly more expensive. Also, road upgrades do nothing to reduce flood damages to exposed homes, businesses and infrastructure.

While they are not comparable substitutes for the proposed dam raising, the best road options can provide modest additional, complementary benefits in reducing risk to life which partly offset the effects of growth and climate change. Flood resilience needs to be incorporated into these major road upgrades when everyday traffic from growth triggers their construction.

The option of compulsorily buying back residential property within the 1 in 100 chance in a year flood extent reduces risk by removing dwellings exposed to the most frequent floods. Its damage and risk-to-life-reducing benefits are comparable to those afforded by lowering FSL by 12 metres. It would have a high cost, overall significant net cost, and low benefit-cost ratio. It would also be very challenging to implement, with significant social dislocation associated with compulsorily relocating thousands of people from around 6,000 homes.

The option of disallowing new residential development below the 1 in 500 chance in a year flood extent would have small benefits from reduced damages and risk to life, failing to match the costs.

Both the benefits and costs for the two best performing mitigation alternatives - to raise the dam by 14 metres or lower the FSL by 12 metres - have increased since 2015. Benefits have increased as a result of more detailed assessments of the impacts on critical infrastructure and using the latest census and planning updated information for properties and assets in the floodplain.

The projected costs for Warragamba Dam Raising have increased as outlined in Table 4-10. The final costs of the proposed dam raising are still to be determined subject to any conditions of approval and dam design details being finalised.

The major cost of the alternative of lowering the FSL by 12 metres also includes for water replacement sources of manufactured water, such as desalination plants, to replace water lost from lowering the full supply level. Work is underway for long-term water planning for greater Sydney – the Greater Sydney Water Strategy - has informed the revised cost estimates for water supply options.

While lowering FSL by 12 metres would provide moderate mitigation of downstream flood peaks, evacuation modelling indicates that by 2041, benefits for reducing risk to life would be about three times less than for the dam raising project. The reduction in damages would also be substantially less. The costs to make up for the lost water supply security would be very significant, which results in a significant net cost and a BCR of 0.38.

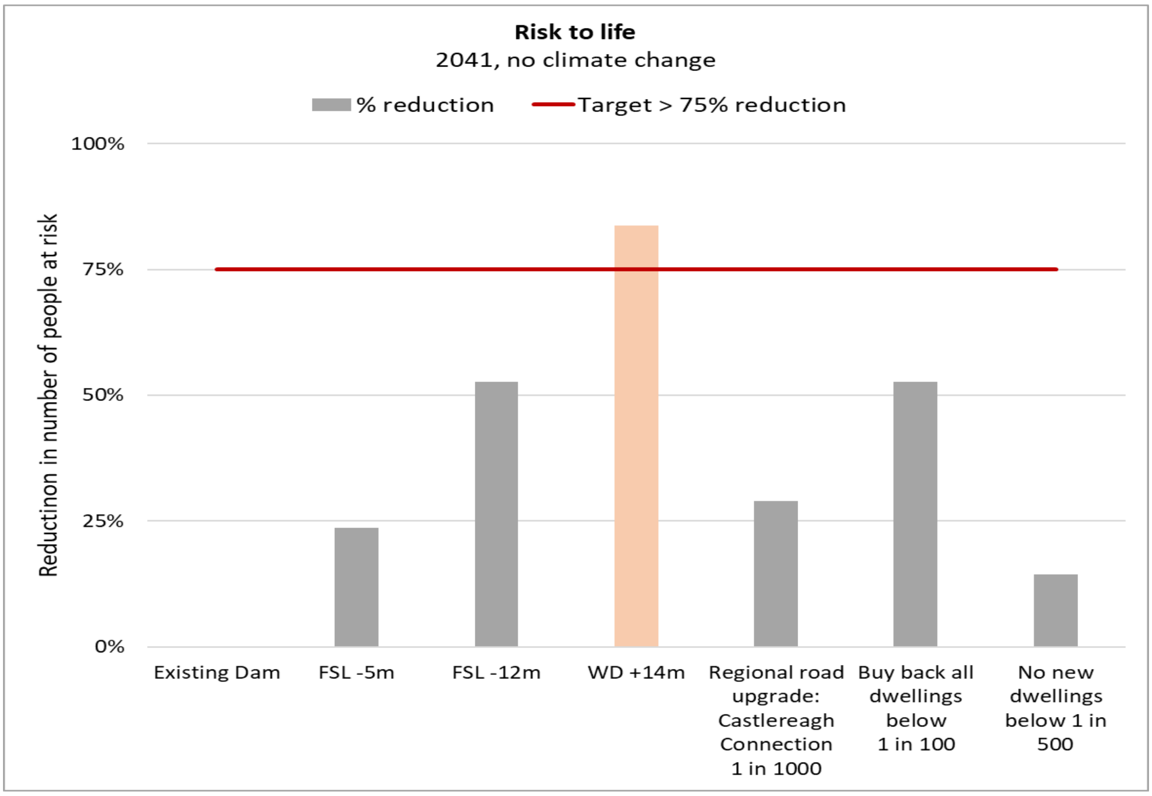
The comparison of options against three of the four KPIs is summarised in Figures 4-23, 4-24 and 4-25. As shown by the orange columns in each of the charts, raising the Warragamba Dam up to 14 metres for flood mitigation is the best performing option meeting the KPIs for reducing risk to life and property damages as well as for cost-effectiveness.

The fourth KPI – minimise social and environmental impacts - is discussed extensively in Chapters 7 to 27 inclusive.

This reassessment of the preferred option and alternatives confirms that, of all the risk-reducing options considered, the proposal to raise Warragamba Dam to create air space for a 14m FMZ for the infrequent, temporary capture of flood inflows offers the most benefit towards meeting the Flood Strategy's risk reduction objectives and KPIs.

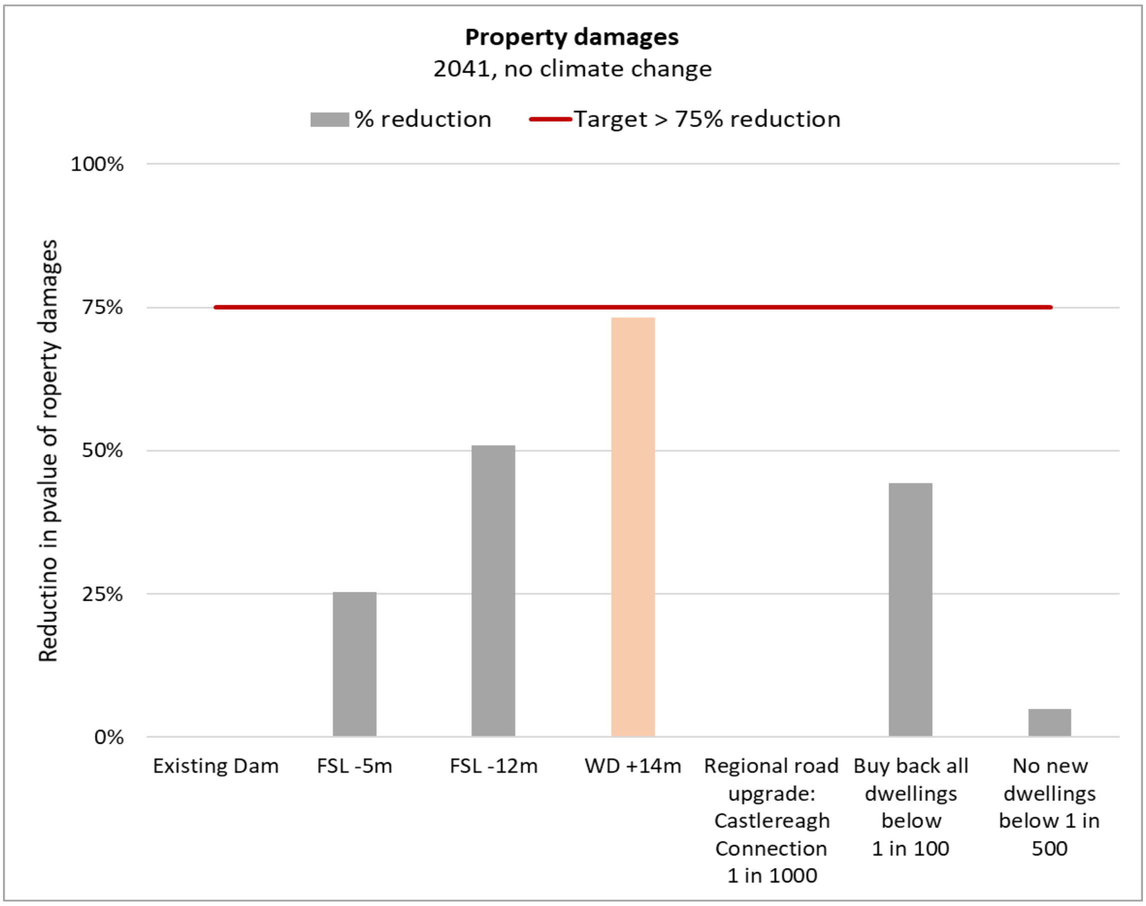
This EIS provides detailed information to consider the balance between the environmental impacts from infrequent and temporary holding of floodwater behind a raised dam wall, compared with the social and economic benefits that major flooding would have on downstream communities, businesses and public infrastructure.

Figure 4-23. Performance of short-listed options against KPI 1 - minimise lives lost in regional floods



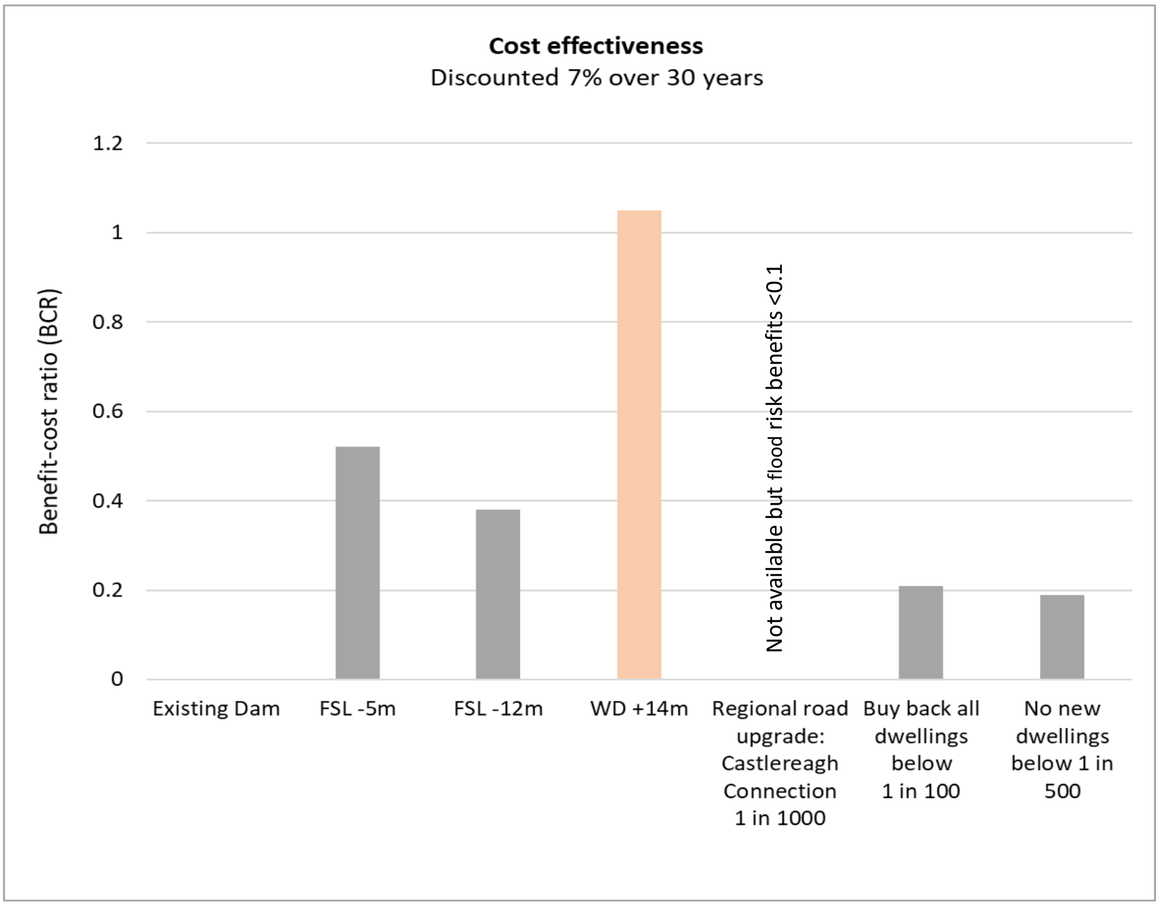
Source: INSW (2021)

Figure 4-24. Performance of short-listed options against KPI 2 - reduce total damage from regional floods



Source: INSW (2021)

Figure 4-25. Performance of short-listed options against KPI 4 – deliver the most cost-effective outcome



Source: INSW (2021)

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