Hawkesbury-Nepean Valley flood evacuation modelling to inform flood risk management planning

Hawkesbury-Nepean Valley
Flood Risk Management Strategy

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Purpose of the Report

This technical report outlines the flood evacuation modelling work undertaken as part of Outcome 3 of the Hawkesbury-Nepean Valley Flood Risk Management Strategy (Flood Strategy). This works aligns with national strategies on disaster resilience and disaster risk reduction, and key NSW policies including the State Infrastructure Strategy, the Flood Strategy, Greater Sydney Region Plan – a Metropolis of Three Cities, the Flood Prone Land Policy, the State Emergency Management Plan and the Hawkesbury-Nepean Valley Flood Emergency Plan 2020.

The intended audience includes NSW Government agencies, local councils and other organisations with a responsibility for land use, transport and flood emergency planning in the Hawkesbury-Nepean Valley. This report may have broader interest for landholders in the valley.

This technical report outlines the methodology developed to assess the current and ongoing risk to life associated with the capacity of the road evacuation network and changes to risk to life with different road and population assumptions for major flood events.

A flood evacuation model (FEM) has been developed to simulate the NSW State Emergency Service evacuation arrangements for a range of scenarios and present the associated changes to risk to life. The FEM is a regional scale model and is not suitable for informing risk to life for individual or very small developments.

The findings in this report will be used as part of the evidence base to support strategic integrated land use, transport and emergency planning from a regional perspective across the valley. It provides risk-based information to inform planning assessments. All planning decisions are made under relevant legislation and planning frameworks.

Executive Summary

The Hawkesbury-Nepean Valley and its flood risk

The Hawkesbury-Nepean Valley (the valley) covers around 500km^2 of floodplain in Western Sydney. The valley is made up of a mix of urbanised areas – such as Penrith City Centre, Windsor, Richmond, and the newer suburbs in the North West Growth Area (NWGA) such as Marsden Park – interspersed with peri-urban and agricultural landscapes. It falls mainly within the 4 Western Sydney local government areas (LGAs) of Penrith, Hawkesbury, The Hills Shire, and Blacktown. Other LGAs with smaller footprints in the floodplain are Wollondilly, Liverpool, Central Coast and Hornsby. The valley comprises 3 main floodplains – Wallacia; Penrith/ Emu Plains; and Richmond/Windsor (including backwater flooding in South Creek and Eastern Creek).

This valley has the highest unmitigated flood risk exposure in Australia related to its unique landscape and large existing population. The Hawkesbury-Nepean floodplains are highly interconnected, with flood events occurring almost simultaneously across the floodplains in the valley. Additionally, floodwaters in the valley can be extensive and much deeper than most other floodplains in NSW and Australia, and have a significant impact on lives, livelihoods, homes and critical infrastructure.

The extent and depth of flooding is influenced by the unique 'bathtub' effect created by the geography of this valley. Most river valleys tend to widen as they approach the sea. The opposite is the case in the Hawkesbury-Nepean. Large upstream catchments flow into the Hawkesbury-Nepean River, and narrow sandstone gorges downstream between Sackville and Brooklyn create natural choke points. Floodwaters back up and rise rapidly, causing deep and widespread flooding across the floodplain. The effects are much like a bathtub with multiple taps turned on, but only 1 plug hole to let the water out.

Evacuation and risk to life

Floods pose a serious risk to safety in the Hawkesbury-Nepean Valley. Some locations in the floodplain are more vulnerable than others because they are in low-lying areas which can become surrounded by floodwaters during a flood event. As floodwaters rise, these areas become isolated when low lying roads are cut, creating flood islands. Some of these islands may then become fully submerged as the waters continue to rise, putting many lives at risk. Many of the urban centres including Windsor, Richmond, Pitt Town and McGraths Hill are located on these flood islands. Additionally, major flooding events can result in a widespread 'inland sea' many kilometres across, with the potential for waves up to 1-2m high under storm conditions. This means it is considered unsafe to stay to defend homes, livelihoods or assets from major floods in this valley. Rescue in these conditions is perilous both to the community and emergency services.

These factors combined mean that the safest option for people during a flood event is to evacuate before roads are cut by floodwater (cutting off essential services and isolating communities). Evacuating during a flood event can be challenging because the evacuation network is shared across multiple communities in the valley. Evacuation often needs to occur at short notice, meaning that large numbers of people may be trying to evacuate via the same major roads, often around the same time.

People's lives are considered at risk if they are unable to evacuate due to being either isolated by floodwaters, or if they are trapped on the evacuation network by traffic congestion, local flooding, fallen trees or powerlines. This means that for the flood evacuation modelling, the failure of flood evacuation is considered the primary driver of flood risk to life in the Hawkesbury-Nepean.

> **Risk to Life** is defined for the purpose of this report as people unable to evacuate by road due to either being trapped by floodwaters or being on the evacuation road network for more than 12 hours. People are considered to have a lower risk to life if they can evacuate to safety by road within 12 hours.

Road evacuation capacity that aligns with managed growth is therefore highly important in this floodplain because it is a key factor to risk to life during mass evacuations in major flood events. It is important to note that while significant road capacity investment is critical for evacuation, it is only one of the required outcomes of the Flood Strategy in managing the regional flood risk.

Development of the Flood Evacuation Model (FEM)

Previous versions of the NSW SES's Hawkesbury-Nepean Valley Flood Emergency Plan relied on detailed spreadsheet models to inform the complex evacuation arrangements. With growth and climate change, the nature and scale of evacuation continues to become more complex, warranting more sophisticated modelling to inform integrated regional land use, road evacuation and emergency planning.

As part of development of the Flood Strategy, a prototype flood evacuation model was developed to assess the road capacity during a flood evacuation of vehicles based on NSW SES's Flood Plan arrangements. This prototype flood evacuation model was developed by National Information and Communication Technology Australia (NICTA, now the Data61 division of CSIRO). The current flood evacuation model (FEM) was developed through a collaboration between CSIRO Data 61, Urban Research and Planning (URaP), RMIT and international developers of open source transport modelling software (MatSim).

The development of the FEM was achieved through an expert-led interagency government process driven by continuous validation, verification and responsive iteration.

The FEM simulates the NSW SES evacuation timeline and arrangements under a range of assumptions. It provides the NSW Government with a repeatable process to quantify existing and ongoing risk associated with the cumulative impact of growth and climate change on road evacuation capacity in the valley.

The purposes of the FEM are to:

- understand road network evacuation performance under a range of flood events
- identify regional road capacity constraints including when/where roads are cut due to flooding
- assess the risk to life for various locations due to the vehicular capacity of the road evacuation network
- assess how potential upgrades to improve the evacuation capacity of the road network reduce the risk to life
- inform government on the ability of the existing and future road network to accommodate emergency evacuation under various land use, flood mitigation and road network infrastructure scenarios.

The FEM is used to:

- inform integrated regional land use, road network and emergency planning
- inform assessment of flood mitigation infrastructure options

- assist NSW SES and TfNSW to manage and improve flood evacuation practices by highlighting operational complexities.

Flood evacuation modelling scenarios

An FEM scenario is the simulated evacuation of the valley based on an actual or projected population and road network under various modelled flood events. Many scenarios have been modelled and analysed to describe changes in the potential risk to life associated with different development and road options. These have been modelled over 3 points in time – December 2018, 2026 and 2041.

A suite of representative flood events has been used, from a 1 in 50 chance per year flood up to a 1 in 5000 chance per year flood. The analysis focused on 2 major flood events – 1 in 500 chance per year (worst flood on record), and 1 in 1000 chance per year (more probable with climate change and the flood event which cuts off the last major evacuation route for the flood islands).

Based on 2018 data, around 43,100 residential properties would need to be considered for evacuation within the Hawkesbury-Nepean Valley, including 36,700 dwellings, 1,900 caravans/manufactured dwellings and 4,500 isolated dwellings.[1]

Included in the scenarios are future development options with projections for 2026 and 2041, based on advice from the Department of Planning and Environment (DPE), using:

- **committed development only** (development that has been zoned under existing planning instruments)
- **committed and potential development combined** (including development that has been announced but still requires a rezoning of land to proceed).

Similar to the approach adopted for future development, the following assumptions for the road network were included in the scenarios, based on advice from Transport for NSW (TfNSW):

- for 2018, roads that were in existence
- for 2026 and 2041, the projected network as well as possible but uncommitted new roads and road upgrades that would enhance overall network capacity for day-to day performance and flood evacuation.

Other key inputs to the scenarios include evacuation road design parameters, topographical data, car ownership statistics, employment scenarios, and operational assumptions of evacuation protocols. The scenarios developed inform current and longer-term land use and road planning.

Key outputs of the model include:

- when areas and road links are cut by floodwaters
- start and end times of evacuation based on NSW SES evacuation areas (known as subsectors)
- the movement of vehicles through the road network, including the number of vehicles that enter/ exit each road link
- where vehicles evacuate to
- the general location of where vehicles are isolated
- the percentage of vehicles successfully evacuated.

[1] Isolated dwellings are those located above the level of the flood but where the property would be isolated by flooding of a public road

These outputs are then visualised to provide an indication of how an evacuation is likely to evolve and impact risk to life, across the suite of flood events.

Key findings

The key findings of the flood evacuation modelling and analysis are:

- Without any further rezonings in the valley there would still be an increase in the risk to life from committed development in existing areas.
- The addition of potential development areas of West Schofields, Riverstone Town Centre and Marsden Park North (partial) individually shows that the average annual people at risk would be similar to the risk for 2041 committed development. Combining these potential development areas would increase the average annual people at risk by almost 20% above the 2041 committed development risk.
- Potential development of 4,100 dwellings below the probable maximum flood (PMF) in Marsden Park North by 2041 more than doubles the average annual people at risk. Only around 1,700 dwellings below the PMF would have similar average annual people at risk to life levels to 2041 committed development.
- 3500 vehicles and 10,400 vehicles were modelled to test the impact of potential commercial development at Penrith Lakes using current evacuation practice. This would increase the average annual people at risk from 110% to 210% respectively across the floodplain.
- The average annual people at risk to life would increase by around 55% with potential development in Penrith City Centre Stage 2 and 3 compared to 2041 committed development.
- Potential development in the Windsor and Richmond town centres forecast under the Hawkesbury Local Housing Strategy would increase the average annual people at risk by around 75%.
- Potential road network upgrades show the average annual people at risk would only reduce under 2041 committed development. For example, raising the Richmond Road bridge over South Creek, could reduce the average annual people at risk by almost 25%. Raising the Castlereagh Connection for a 1 in 500 chance per year flood would reduce the average annual people at risk by 71%. This benefit is concentrated in the Windsor/Richmond areas and assumes no potential development takes place.
- The benefits of the road options modelled are either negligible or significantly reduced for the majority of potential development scenarios.
- The number of people unable to evacuate increases significantly if all potential development was to occur. For example, for a 1 in 500 chance per year flood (similar to the worst flood on record) the risk to life would increase from an estimated 980 people under committed development to around 23,700 people by 2041.
- The number of people unable to evacuate also increases significantly with climate change. For example, for a 1 in 500 chance per year flood the estimated 980 people at risk under committed development would increase to around 6000 people with mid-century climate change.

Conclusions

The Hawkesbury-Nepean Valley's floodplains are highly interconnected by the road network. Growth in one area can have significant consequences on risk to life for existing populations across the floodplains.

The risk to life arising from flood evacuation varies across the valley and the FEM provides a better understanding of this risk distribution for different sized flood events. It allows for a more detailed understanding of the existing risk, the impact of development options and the cumulative impact of growth and climate change on the capacity of the shared road evacuation network.

The results highlight that the evacuation issue is not straightforward (a non-linear problem) and demonstrates the importance of modelling representative scenarios to evaluate the relative contribution of development options on risk to life.

The number of people who would be unable to evacuate increases significantly with development and climate change. Potential development above committed development further increases this risk.

The realisation of the level and timing of the risk to life will depend on external factors such as the global economy, rates of growth and climate change. However, scenario and sensitivity analysis show that while the actual timing and specific numbers related to risk to life might vary, the overall trend of increasing risk remains.

Next steps for the modelling

This work is ongoing due to the dynamic nature of flood risk to life in the valley. Future modelling will continue to test new scenarios and new information as it becomes available. This includes improved flood modelling, updated census data, climate change predictions, and consideration of different behavioural responses. In addition, continuous improvement in technology will allow more efficient modelling to reflect increased complexity and higher number of scenarios. This is dependent on funding for the ongoing development of the model.

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1.1 What is flood risk?

Floods are random, naturally occurring events. Flood risk is a combination of the chance of a flood occurring and the consequences of the flood for people, homes, businesses, public and private infrastructure. This risk is influenced by a number of factors, including the natural topography of the environment, climate change, population, the challenges of evacuation, and variable levels of flood awareness and preparedness in the community.

1.2 Understanding floods

Flood size is described in terms of the chance of that flood occurring in any 1 year. Small floods occur more regularly and generally have lower economic and social impacts, compared to less common larger floods that have higher impacts. Floods occur randomly and independently of each other, meaning 1 flood event does not change the chance of a subsequent flood happening.

A 1 in 100 chance per year flood has a 1% chance of happening in any year. Such a flood could occur several years in a row, or it could be more than 100 years before a flood of that size occurs again. For example, the flood that occurred in Brisbane in 2011 was about a 1 in 100 chance per year event.

The largest flood that could occur is called the probable maximum flood (PMF). Being the largest possible flood, it has the lowest probability of all possible floods. This flood defines the extent of the floodplain.

1.3 Flood risk in the Hawkesbury-Nepean Valley

The Hawkesbury-Nepean Valley (the valley) has the highest single flood exposure in NSW, if not Australia, because of its unique landscape and large existing population.[2]

The valley covers around 500km^2 of floodplain in Western Sydney (see Figure 1.1). The floodplain falls mainly within the 4 Western Sydney local government areas (LGAs) of Penrith, Hawkesbury, The Hills Shire, and Blacktown. Other LGA's with smaller footprints in the floodplain are Wollondilly, Liverpool, Central Coast and Hornsby.

The valley comprises 3 main floodplains – Wallacia; Penrith/Emu Plains; and Richmond/Windsor (including backwater flooding in South Creek and Eastern Creek). The Hawkesbury-Nepean floodplains are highly interconnected by the road network. However, the distribution of the flood risk across the areas varies, with the highest risk being on the Penrith/Emu Plains and Richmond/Windsor floodplains.

Floodwaters in the valley can be extensive, and much deeper than most other floodplains in NSW and Australia. This can have a significant impact on people's lives, livelihoods, homes and critical infrastructure.

[2] NSW Government, 2017 "Resilient Valley, Resilient Communities Hawkesbury-Nepean Valley Flood Risk Management Strategy" https://www.infrastructure.nsw.gov.au/media/2855/infrastructure-nsw-resilient-valley-resilient-communities-2017-jan.pdf

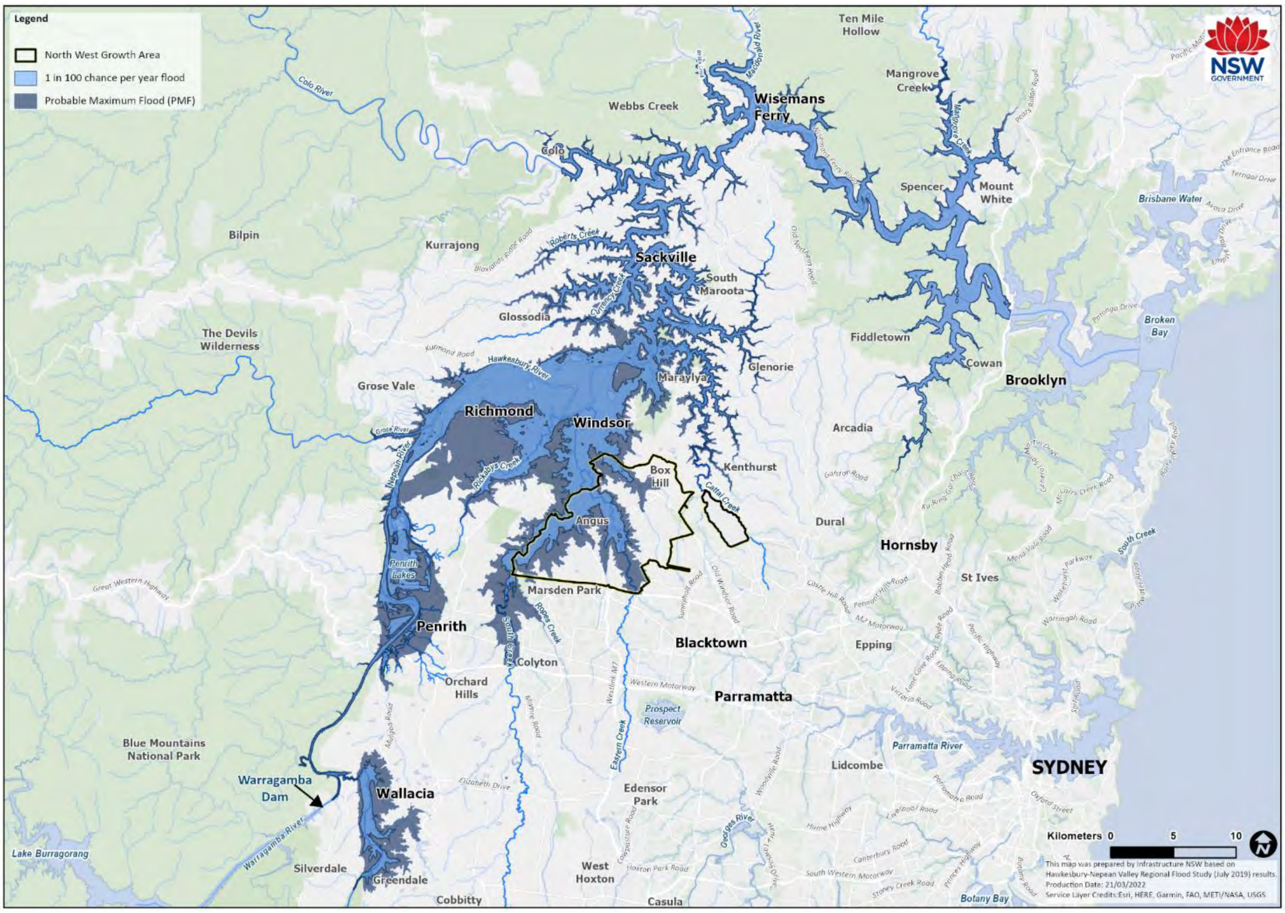

Figure 1.1: Map of Hawkesbury-Nepean Valley floodplain

The large and growing population in the valley means the exposure to flood risk is significant and increasing. More than 140,000 people currently live or work on the floodplain (based on 2018 data). Over 36,700 residential properties in the floodplain and 4.5 million square metres of commercial space are currently subject to flood risk. This is mainly due to historic development when there was no flood planning level, or it was lower than the current flood planning level adopted by councils since the mid-1990s.

Although large flood events are infrequent, they have high economic and social consequences. For example, if a 1 in 100 chance per year flood occurred (similar to the 2011 Brisbane flood) this would impact about 7,600 residential properties, require the evacuation of around 55,000 people, and cause around $3 billion in damages. If a flood similar to the 1867 flood occurred today (around a 1 in 500 chance per year event), about 15,500 residential properties would be impacted, 90,000 people would need to evacuate, and the estimated damages would cost $8 billion.

1.4 Flood depths and extents

The extent and depth of flooding is influenced by the unique ‘bathtub’ effect in this valley. Most river valleys tend to widen as they approach the sea. The opposite is the case in the Hawkesbury-Nepean. Large upstream catchments flow into the Hawkesbury-Nepean River and narrow downstream sandstone gorges between Sackville and Brooklyn create natural choke points. Floodwaters back up and rise rapidly, causing deep and widespread flooding across the floodplain. For example, the narrow Fairlight Gorge causes extreme flood depths in Wallacia while the Castlereagh Gorge causes flooding in the Penrith and Emu Plains area. The effects are much like a bathtub with multiple taps turned on, but only 1 plug hole to let the water out (see Figure 1.2).

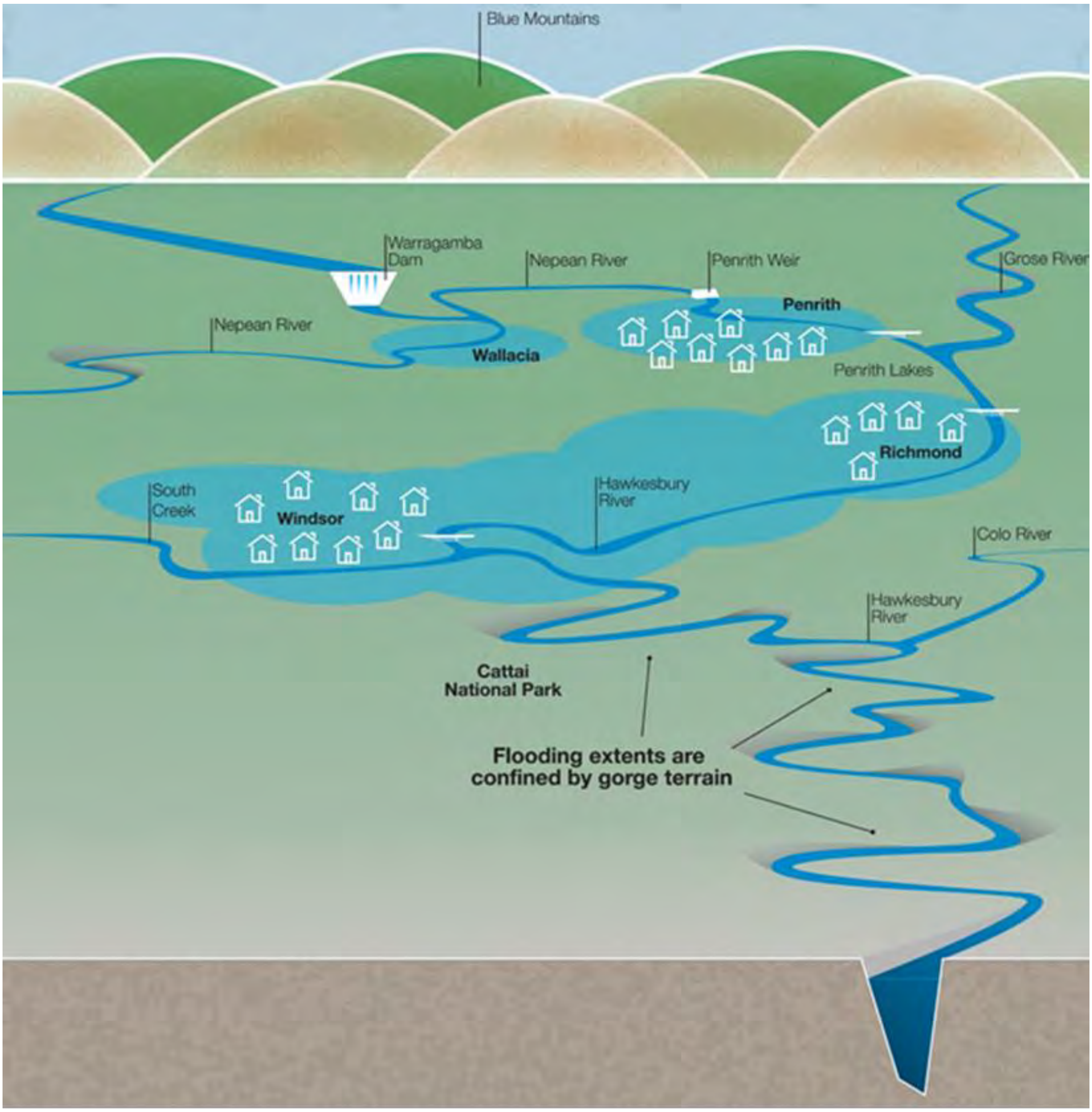

Figure 1.2: The "bathtub" effect

The February 2022 flood event in Lismore, which was close to a 1 in 1000 chance per year flood event, was just over 2 metres higher than the 1 in 100 flood level. A 1 in 1000 year flood in Windsor would be 3.3 metres above the 1 in 100 chance per year level (see Figure 1.3).

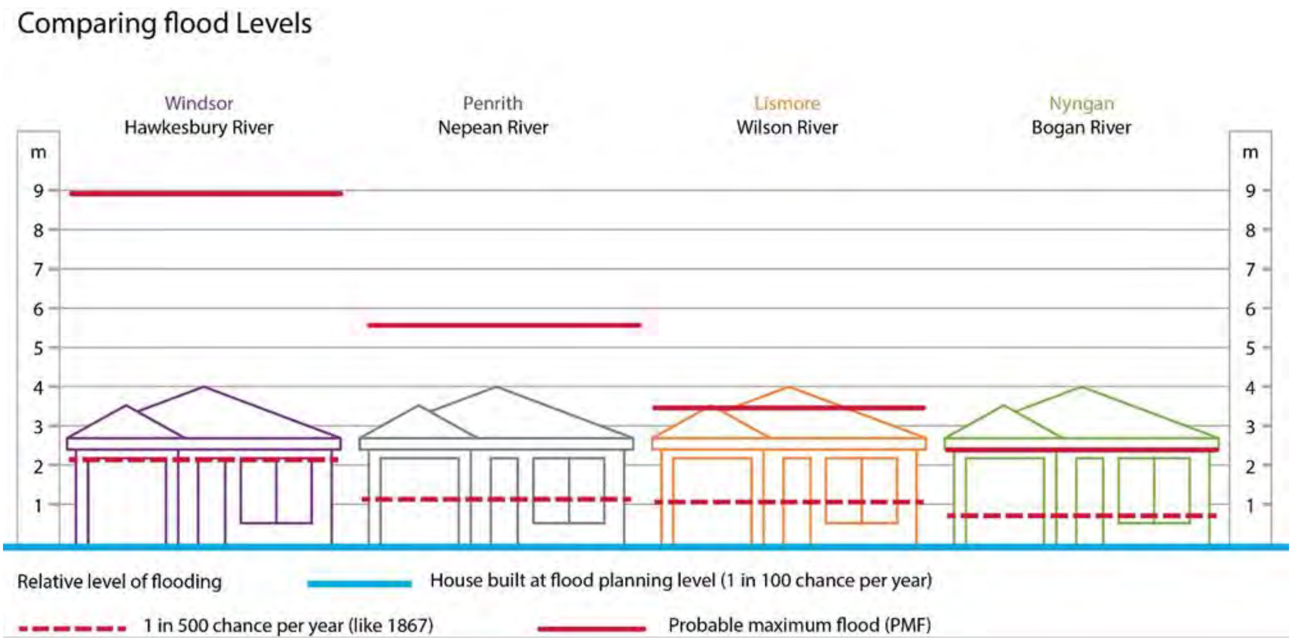

Figure 1.3: Relative depths of flooding for various NSW floodplains, Options Assessment Report [3]

Additionally, some locations in the floodplain are more vulnerable than others because they are located on flood islands. These islands form during floods due to the undulating topography in the valley. As floodwaters rise, areas can become isolated when low lying roads are cut. Some of these islands may then become fully submerged as flood waters rise. Many of the significant urban centres in the valley including Windsor, Richmond, Pitt Town and McGraths Hill are located on flood islands.

1.5 Rates of rise and fall

Every flood is different depending on the pattern and duration of rainfall, dam storage levels and conditions in the catchment. Flood levels on the Hawkesbury-Nepean floodplain can rise at a rate of half a metre an hour for several hours and can even rise at over 1m per hour for shorter periods. At these rates, a house on the lower areas of the floodplain could be submerged in 6 hours or less. For example, at North Richmond, the rate of rise can vary between 0.3 to 1.4m per hour, even if the same peak is reached (19.8m for a 1 in 500 chance per year event).

1.6 Contribution of projected climate change

Climate change also has the potential to alter the frequency and severity of extreme rainfall events and change rainfall patterns. The large flood depths in the valley make it particularly sensitive to increased flood risk with climate change. For example, research undertaken[4] for the Flood Strategy indicates a 9% climate change related increase in rainfall intensity by mid-century (~2060) would increase the 1 in 100 chance per year flood level by 1.3m at Wallacia, 0.5m at Penrith, 0.7m at North Richmond and Windsor, and 0.6m at Wisemans Ferry. Additionally, the rates of rise are predicted to increase under climate change with floods peaking earlier.

[3] NSW Government, Hawkesbury-Nepean Valley Flood Risk Management Strategy: Taskforce Options Assessment Report, 2019 https://www.insw.com/media/1976/taskforce-options-assessment-report-2019-v2.pdf

[4] WMA Water 2021, Climate Change and Flooding Effects on the Hawkesbury-Nepean https://www.infrastructure.nsw.gov.au/media/3233/climate-change-and-flooding-effects-on-the-hnv_2021.pdf

1.7 Policy and strategic context

The management of flood risk is a shared responsibility between local, state and federal governments. This means activities undertaken to manage flood risk in the valley sit within a multi-layered regulatory and policy framework. Given the fact that the flood problem in the valley spans multiple local government areas, an integrated and coordinated approach with partners working together at a regional level is required.

At the national level, the Australian Government provides guidance for flood risk management activities through:

- the National Strategy for Disaster Resilience (2011) which sets out the national standard for managing the risk of natural disasters, built upon the emergency management cycle of prevention, preparation, response and recovery (PPRR).
- the National Disaster Risk Reduction Framework (2018) which aligns with the international Sendai Framework for Disaster Risk Reduction 2015-2030 and guides national, whole-of-society efforts to proactively reduce disaster risk.

The Australian Government also provides weather predictions and flood forecasting services through The Bureau of Meteorology (the Bureau).

At a state level, flood management activities align with the following key legislation and policies:

- *The State Emergency and Rescue Management Act 1989*
- The NSW State Emergency Management Plan (EMPLAN)
- Hawkesbury-Nepean Valley Flood Emergency Plan
- The NSW State Infrastructure Strategy 2018-2038
- NSW Critical Infrastructure Resilience Strategy (2018)
- The Flood Prone Land Policy
- Floodplain Development Manual
- The Greater Sydney Region Plan: A Metropolis of Three Cities, The Western City District Plan and Central City District Plan (Greater Sydney Commission, 2018).

The NSW Government also has responsibility for strategic land use, regional roads and emergency planning while at a local level, local government has the primary responsibility for floodplain risk management. The *Environmental Planning and Assessment Act 1979* is the primary land use planning statute in NSW, which, alongside relevant State Environmental Planning Policies, Local Environment Plans and Development Control Plans, directs planning decisions and actions at a state and local government level.

To address the significant and ongoing flood risk in the valley, the NSW Government developed the comprehensive and multi-faceted Resilient Valley, Resilient Communities Hawkesbury-Nepean Valley Flood Risk Management Strategy (Flood Strategy)[5], overseen by Infrastructure NSW (INSW). This strategy has 9 key outcomes which collectively address flood risk (see Figure 1.4).

[5] NSW Government, 2017 “Resilient Valley, Resilient Communities Hawkesbury-Nepean Valley Flood Risk Management Strategy” https://www.infrastructure.nsw.gov.au/media/2855/infrastructure-nsw-resilient-valley-resilient-communities-2017-jan.pdf

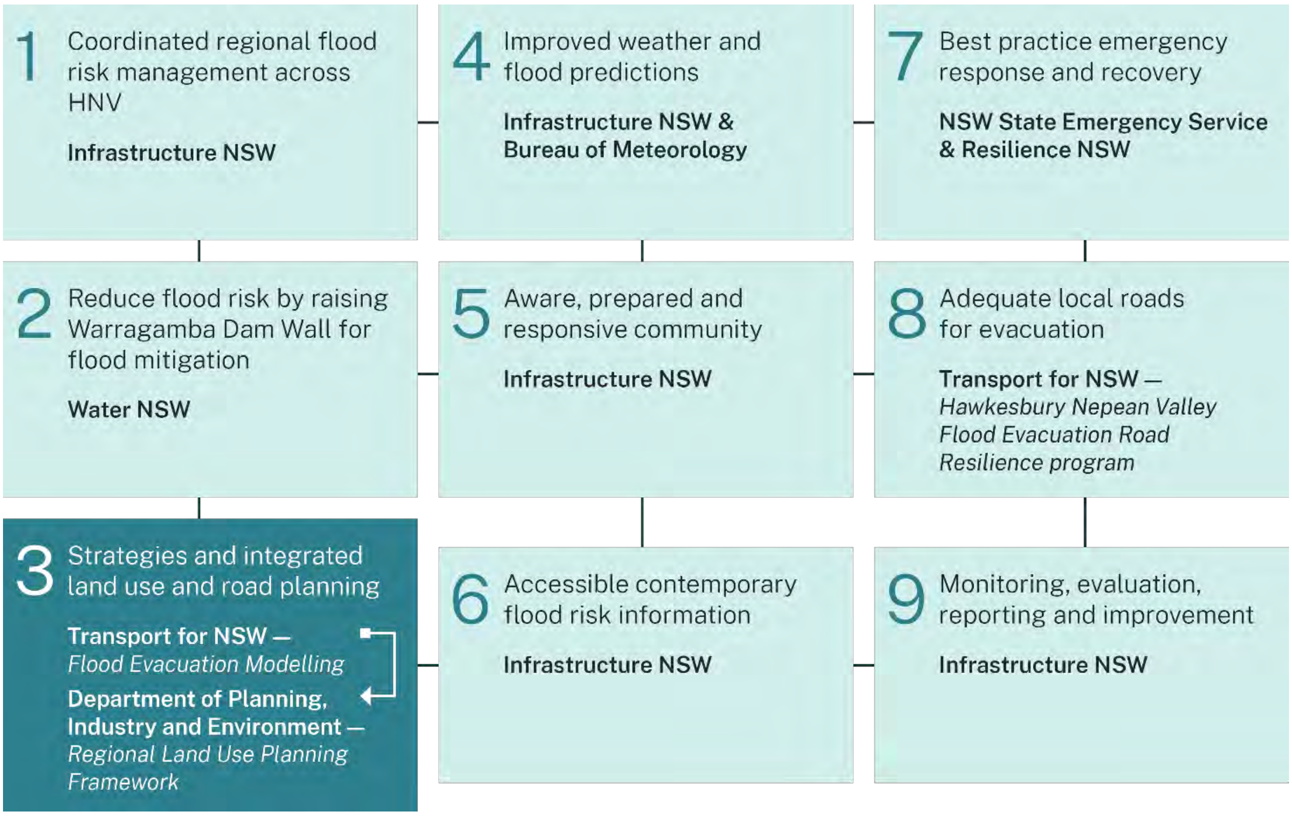

Figure 1.4: 2017 Hawkesbury-Nepean Valley Flood Risk Management Strategy's 9 key outcomes highlighting outcome 3

Under the Flood Strategy, Outcome 3 addresses flood risk with a strategic approach to integrated land use and road planning, including:

- development of the Regional Land Use Planning Framework to better consider flood risk and manage population growth in the floodplain in consideration of the cumulative impact of growth on road evacuation capacity (in progress)
- Road Transport Flood Resilience Guidelines to identify the flood resilience principles that road planners should consider when a proposed road is in the planning stage (draft guidelines being reviewed)
- the Road Resilience Program[6] of minor road upgrade improvements that will increase the capacity and efficiency of floodplain evacuation routes, for example shoulder widening, drainage and bridge structures, road raising, pipe and channel works and pinch point upgrades (progressed to Final Business Case)
- flood evacuation modelling to better understand the capacity limits of the network for integrated regional land use, road network and emergency planning (the subject of this report).

As part of best practice and continuous improvement, the Flood Strategy (Outcome 9) operates under an adaptive management framework whereby the underpinning assumptions are periodically reviewed to test their appropriateness over time.

[6] Road Resilience Program – Projects – Roads and Waterways – Transport for NSW

1.8 Hawkesbury-Nepean Valley Flood Emergency Plan 2020

As the dedicated combat agency for floods, the NSW SES has had a specific flood emergency plan in place for the Hawkesbury-Nepean for several decades. The Hawkesbury-Nepean Valley Flood Emergency Plan – 2020 (Flood Plan) is the latest iteration, approved by the NSW SES Commissioner and endorsed by the NSW State Emergency Management Committee (SEMC) in June 2020[7]. It is a Sub Plan to the State Flood Plan (2018)[8]. The Flood Plan sets out arrangements for flood emergency in the Hawkesbury-Nepean area, including:

- the potential risks and consequences of flooding to the social, built, economic, and natural environments in the Hawkesbury-Nepean Valley
- the policy and programs in place to mitigate these risks before, during and after an emergency
- the control and coordination arrangements for managing a flood impact including the evacuation timeline, evacuation routes, flood evacuation sectors and subsectors
- transition arrangements to recovery
- links to sources of information where the reader can obtain further detail
- the agencies responsible for managing specific strategies.

1.9 Flood risk to life and the importance of evacuation

Floods pose a serious risk to safety in the Hawkesbury-Nepean Valley. Flood risk to lives, homes, businesses and critical infrastructure varies with the level of exposure and associated vulnerability. For the Flood Strategy, flood risk has been considered in terms of risk to life, damages to assets and businesses, and the social and economic impacts on people and communities (see Figure 1.5).

[7] 2020, State of New South Wales – 'Hawkesbury-Nepean Valley Flood Emergency Plan' – https://www.nsw.gov.au/sites/default/files/2021-04/emergency-management-subplan-hawkesbury_nepean_valley_flood_emergency.pdf

[8] 2018, State of New South Wales – 'NSW State Emergency Management Plan' – https://www.nsw.gov.au/sites/default/files/2021-04/state-emergency-management-plan-emplan.pdf

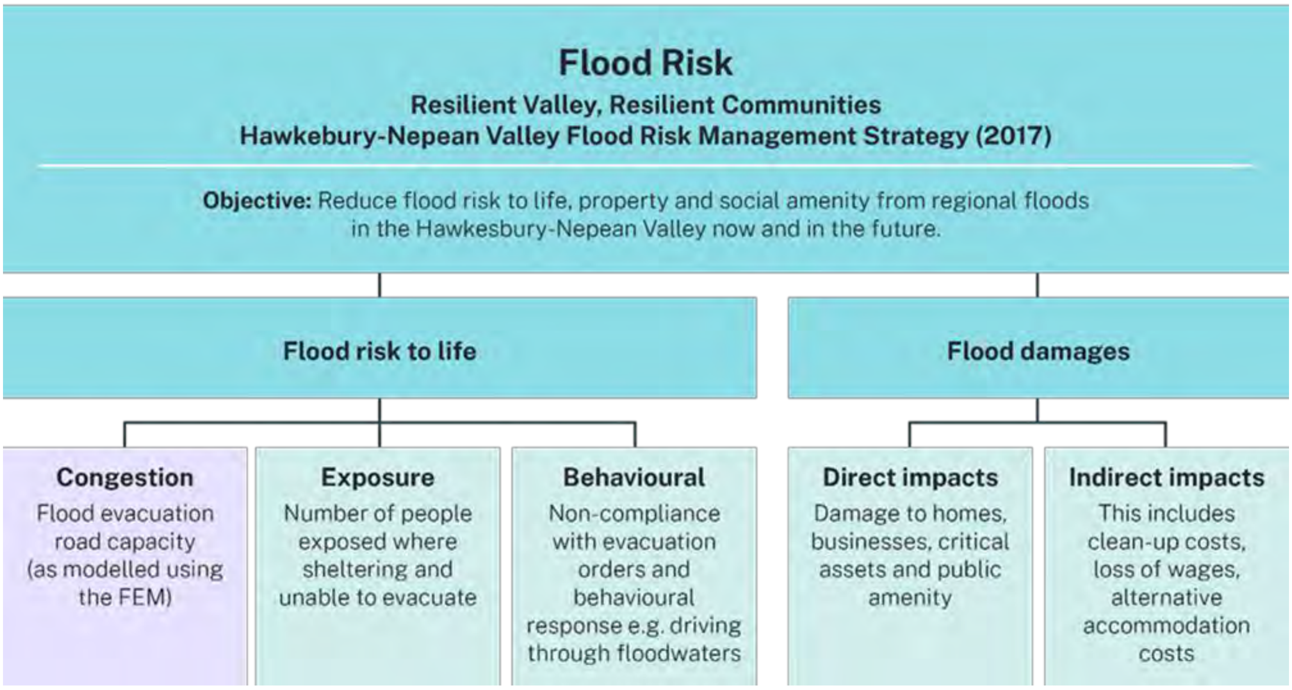

Figure 1.5: Hawkesbury-Nepean Valley flood risk: risk to life and damage categories

Risk to life from flood exposure can result in physical or trauma-related injury, or actual loss of life. This is due to:

- not being able to evacuate and becoming isolated/trapped
- non-compliance with evacuation orders or other behavioural responses, including choosing not to evacuate, delaying evacuation, and driving through floodwaters
- being trapped or unable to leave on the road evacuation network due to capacity constraints.

Some locations in the floodplain are more vulnerable than others because they are in low-lying areas which can become surrounded by floodwaters during a flood event. As floodwaters rise, these areas become isolated when low lying roads are cut, creating flood islands. Some of these islands may then become fully submerged as the waters continue to rise, putting many lives at risk. Many of the urban centres including Windsor, Richmond, Pitt Town and McGraths Hill are located on these flood islands. Additionally, major flooding events can result in a widespread 'inland sea' many kilometres across, with the potential for waves up to 1-2m high under storm conditions.

It is considered unsafe to stay to defend homes, livelihoods or assets from major regional floods in this valley. Rescue of large numbers of people who do not evacuate on time is difficult and has high risks. Rescue in these conditions is perilous both to the community and emergency services due to a number of factors including:

- the possibility of a significant number of people to be rescued
- waves generated by winds over the large inland sea
- debris and hazardous materials in the floodwaters
- high velocity of floodwaters
- weather conditions impeding the use of helicopters.

These factors combined mean that the safest option for people during a flood event is to evacuate before roads are cut by floodwater (cutting off essential services and isolating communities) so that evacuation is maximised and rescue is minimised. Additionally, the Flood Plan identifies mass self-evacuation by private motor vehicles ahead of a flood as the primary evacuation method, as other transport options are highly vulnerable to floods or have limited capacity.

Evacuating during a flood event can be challenging because the evacuation network is shared across multiple communities in the valley. Evacuation often needs to occur at short notice, meaning that large numbers of people may be trying to evacuate via the same major roads, often around the same time. Evacuation may fail due to people not evacuating on time or if there is inadequate evacuation road network capacity. Major evacuations are exceptional circumstances, and it is expected there would be significant delays on the evacuation road network due to congestion, convergence or vehicles being trapped by floodwaters.

People's lives are considered at risk if they are unable to evacuate due to being either isolated by floodwaters, or if they are trapped on the evacuation network by traffic congestion, local flooding, fallen trees or powerlines. This means that the failure of flood evacuation is considered the primary driver of flood risk to life in the Hawkesbury-Nepean.

> **Risk to Life** is defined for the purpose of this Report as people unable to evacuate due to either being trapped by floodwaters or being on the evacuation network for more than 12 hours. People are considered to have lower risk to life if they can evacuate to safety within 12 hours.

1.10 Regional flood evacuation road network

Roads are critical infrastructure for conveying large numbers of people away from flooded areas before they are cut and inundated by floodwaters. The capacity of the existing road network to service daily traffic demand also impacts mass evacuation during major flood events.

Road evacuation capacity that keeps pace with managed growth is highly important in this valley because it is a key factor to determining risk to life during mass evacuations in major flood events. However, there are limitations on the number and locations of road upgrade options that are feasible. While significant road capacity investment is critical for evacuation, it is only one of the required outcomes of the Flood Strategy in managing the regional flood risk.

The evacuation road network is a shared regional evacuation network comprising 12 major evacuation routes and 5 secondary routes. The roads that make up the network vary from single-laned rural roads to multi-laned freeways. Around 60% of the roads are under the care and responsibility of councils and 40% under the NSW Government. Figure 1.6 shows the major and secondary flood evacuation routes out of the valley.

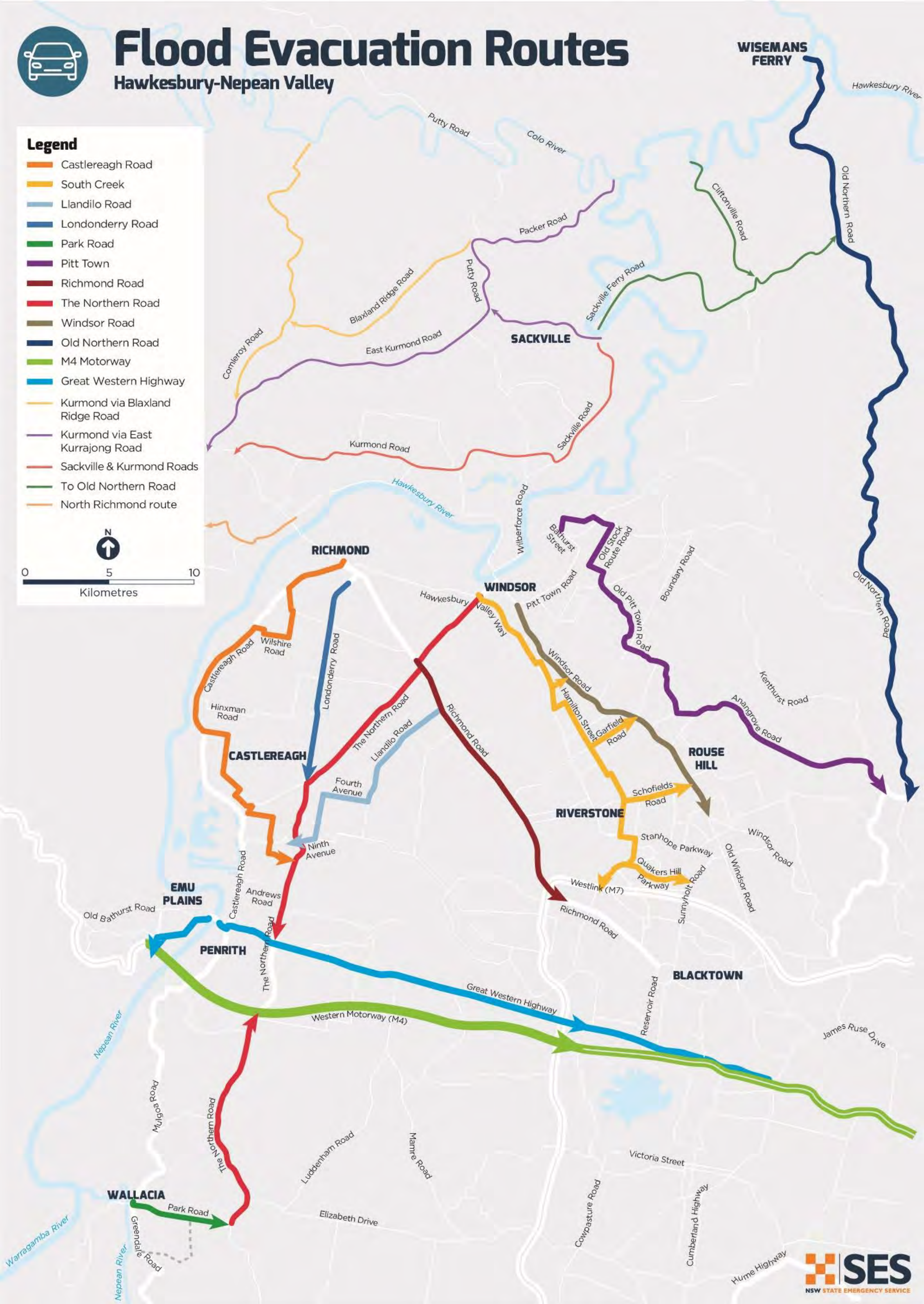

Figure 1.6: Major and secondary evacuation routes out of the Hawkesbury-Nepean Valley

The Flood Plan divides the valley into small areas, sectors and subsectors, to assist the NSW SES in progressively managing flood warnings and evacuation. The subsectors are determined by their flood classification such as low or high flood islands. Roads leading to and from these individual subsectors to the main evacuation routes are known as secondary evacuation routes. Further detail on subsectors can be found in Section 3.4.

Due to multiple tributaries and creeks making up the river system in the valley, there are many low points that can be cut due to local and main river flooding during large events. Many low points on the evacuation road network get cut well below the generally applied 1 in 100 chance per year flood planning level. This has the potential to isolate people and trap them in the floodplain.

During a flood event large numbers of vehicles are mobilised. A number of the required evacuation routes and other local routes within the area are dependent upon bridges over local and regional water courses. These bridges are subject to early flooding or have insufficient carrying capacity.

The following are key issues related to the capacity of the evacuation network:

- Many of the current flood evacuation routes can be prone to premature or temporary closure from local flooding – preventing or restricting their use during flood events. Such closures force multiple communities to use the same evacuation routes, increasing congestion and operational constraints. In particular, The Northern Road is used by numerous communities, and any disruption to this evacuation route may affect multiple communities.
- Traffic demand during a current flood evacuation period exceeds the available carrying capacity of flood evacuation routes and associated intersections. Bottlenecks and queues form as a result of insufficient capacity leading to delays in evacuation, potentially exceeding inundation warning times. Evacuation queuing times over 5 hours are likely to cause further disruptions to evacuation routes due to breakdowns, lack of fuel, and evacuee stress potentially contributing to unnecessary risk taking.
- Key elements of the evacuation network are cut by regional riverine flooding in large events. For example, the Jim Anderson Bridge over South Creek on Hawkesbury Valley Way, built as the main evacuation route from Windsor in the early 2000s, would be cut by floodwaters in a 1 in 100 chance per year event.
- Inability to predict the availability of rail resources due to the potential loss of power, and the unlikelihood of being able to count on watercraft or aerial means of evacuation except for limited rescue operations.

Any disruption during evacuation, either associated with congestion or localised flooding, increases the risk to life and property of residents, workers and others within the valley.

2 Hawkesbury-Nepean Valley Flood Evacuation Model

2.1 History of flood evacuation modelling in the valley

Previous versions of the NSW SES's Flood Plan for the valley relied on detailed spreadsheet models to inform the complex evacuation arrangements. With growth and climate change, the nature and scale of evacuation has become more complex, warranting more sophisticated modelling to inform integrated regional land use, road evacuation and emergency planning.

As part of development of the Flood Strategy, a flood evacuation model was developed to assess the road capacity during a flood evacuation of private vehicles based on NSW SES's Flood Plan arrangements. Led by the NSW Government, this prototype was developed by National Information and Communication Technology Australia (NICTA, now the Data61 division of CSIRO).

It underwent independent peer reviews by the University of NSW, with the purpose to:

- critique the reasonableness of the investigation process and modelling undertaken
- review the veracity of key assumptions used during analysis
- provide commentary on the future direction the flood evacuation assessment frameworks should take for future land releases, major road projects, and operational plans.

The independent reviews found that:

- although the pilot investigation tools of MATSim-based flood evacuation modelling have some limitations, they are acknowledged as a cutting-edge approach to the complex issues being examined, providing a sound basis for strategic-level option evaluation and a good springboard for the future development of a detailed evacuation model
- the inputs to the modelling process were considered of high quality and fit for the purposes of strategic option evaluation and quantification of benefits.

The learnings and recommendations from the peer reviews informed the next development phase, with the prototype progressing to the Flood Evacuation Model (FEM) currently used. This was led by the NSW Government, in collaboration with CSIRO Data 61, Urban Research and Planning (URaP), RMIT and international traffic modelling software (MATSim) developers.

2.2 FEM purpose and use

The purposes of the FEM are to:

- understand road network evacuation performance under a range of flood events
- identify regional road capacity constraints including when/where roads are cut due to flooding
- assess the risk to life for various locations due to the capacity of the road evacuation
- assess the impact of potential infrastructure upgrades to improve the evacuation capacity of the road network
- inform government on the ability of the road network to accommodate emergency evacuation under various scenarios.

The model has been developed for use by NSW Government agencies as a strategic decision support tool to inform integrated regional land use, road network and emergency planning. Key users of the model include:

- **TfNSW** – to assess evacuation capacity for major road upgrades

- **NSW SES** – to inform the Hawkesbury-Nepean Valley Flood Emergency Plan and to assist improve flood evacuation practices
- **DPE** – to inform the development of the Regional Land Use Planning Framework and managing growth across the floodplain
- **INSW** – to inform regional flood risk management and monitor and evaluate changes to existing and future flood risk in line with the Flood Strategy objectives and 9 outcome areas.

2.3 How does the FEM work?

The FEM is a bespoke agent-based simulation model built on the Multi-Agent Transport Simulation (MATSim) software package. MATSim simulates how agents (people or vehicles) move through a transport network and how they can dynamically react to the travel of other agents. It can include all modes of transport such as walking, cycling, public transport or by vehicle. In the modelling undertaken for this report, an agent is defined as a vehicle as this is the dominant and preferred evacuation method for the Hawkesbury-Nepean Valley. Figure 2.1 outlines the key steps in the FEM process.

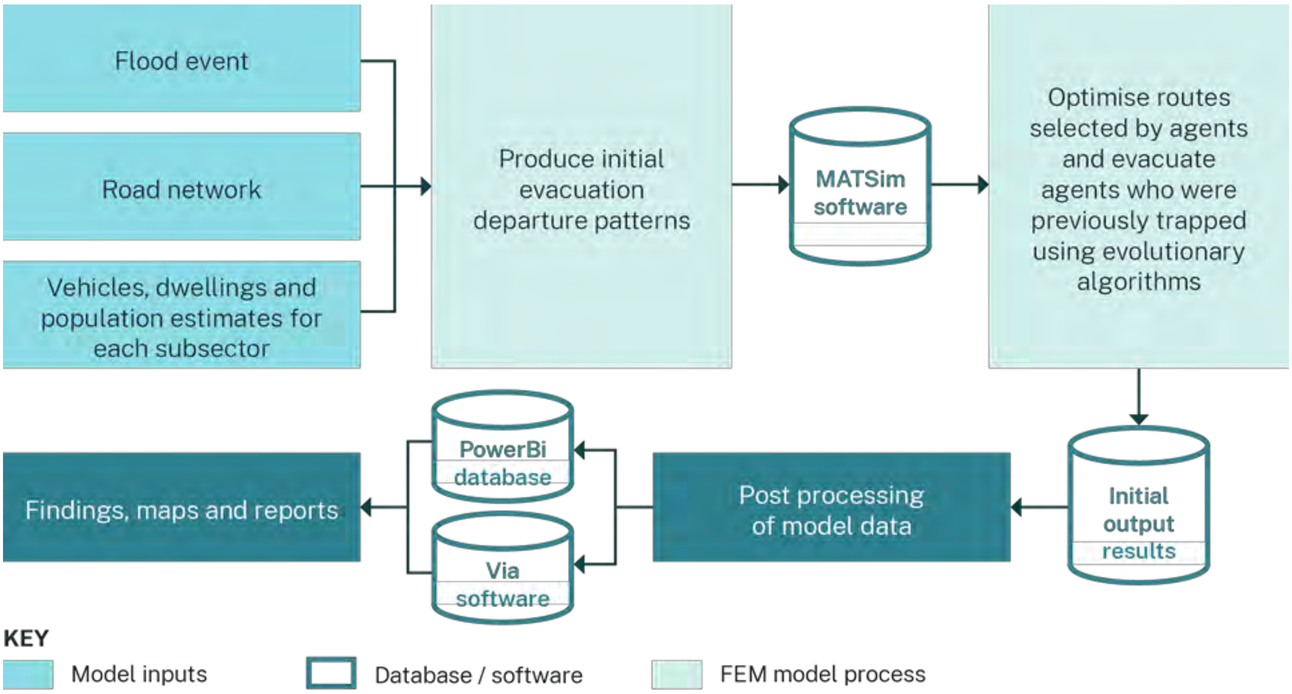

Figure 2.1: Key steps in the FEM process

The FEM prepares simulations based on various data sets (inputs) including evacuation plans (NSW SES); road network management and operations (TfNSW); storm intensity, flood profiles and population inputs (INSW and DPE). The MATSim algorithms then generate large data files (outputs) which require further analysis to determine risk to life. These outputs provide an indication on how an evacuation is likely to evolve in a flooding event and how evacuation routes perform. For example, the outputs identify how many vehicles are able to leave before evacuation routes are cut, and the number of vehicles that are trapped or isolated. These outputs are then analysed and visually presented in Microsoft Power BI.[9]

[9] Power BI is a collection of software services, apps, and connectors that work together to turn unrelated sources of data into visually insights.

In summary the key inputs and outputs of the FEM are outlined in Table 2.1 below:

Table 2.1: Inputs and outputs

Inputs	Outputs
Evacuation road design parameters Topographical data Model flood event data Population and employment data Vehicle numbers Operational assumptions of evacuation protocols Flood mitigation options under the options assessment	Progress of the flood, including when areas and road links are cut by floodwaters Start and end times of evacuation based on SES evacuation areas (known as subsectors) The flow of vehicles through the road network, including the number of vehicles that enter and exit each link Where vehicles are evacuated to The general location of where vehicles are isolated The percentage of vehicles successfully evacuated.

The FEM tests different sequences or combinations of variables to assess changes in risk to life associated with changes in growth, infrastructure options and a range of flood frequencies for current and future climate conditions. Each different combination represents a scenario. Each scenario has a designated identifier number, with specific input and output files. An FEM scenario is a combination of:

- a road network, either the current base case or assumed future network
- a development option that specifies population and dwellings to evacuate
- the flood forecast timeframes appropriate for each area in the valley, issued by the Bureau for a range of modelled representative flood events, selected from the suite of 19,500 probabilistic or Monte Carlo modelled flood events
- modelled flood hydrographs under potential flood mitigation infrastructure options, and projected climate change.

3 Assumptions for FEM input and output data

3.1 Overview of assumptions

Models are simplifications of complex real-world behaviour based on a number of assumptions.

The following table summarises the key assumptions underpinning the input data, operational rules and treatment of output data.

Table 3.1: Key flood evacuation modelling assumptions

Assumption	Description
Method of evacuation	
Evacuation by vehicle	Due to the high level of vehicle ownership as shown by census data, this is the most likely mode of evacuation and the only evacuation mode included in the modelling.
Evacuation on foot	Not included in modelling as it is a last resort.
Evacuation by rail	Not included in modelling as there is minimal opportunity due to early inundation impacts on the Richmond and Western Railway lines.
Who is evacuating and where from	
Who is triggered to evacuate (due to flooding or potential isolation)	Impacted populations evacuated from flood affected areas for each modelled flood event. The flood evacuation is triggered by areas known as sub-sectors, pre-defined by the NSW SES. See Section 3.4.
Number of residential vehicles	Average vehicles per dwelling multiplied by number of dwellings in each subsector (based on 2016 census and various transport data). Average vehicles per dwelling is not assumed to change significantly over time given the pattern of vehicle ownership in projected development.
Number of employee vehicles (including work vehicles)	Based on TfNSW's Journey to Work data (Transport, Performance and Analytics) and 2016 Census data to determine the number of employees who work in the area to be evacuated but who live outside the flood extent.
Number of visitor vehicles (shopping, recreational)	Not included in scenarios as the focus was on residential and employee vehicles.
Warnings timeframe and response	
Flood events	91 flood events were selected from the 19,500 Monte Carlo model flood events, based on peak levels and rates of rise for representative flood events between 1 in 50 chance per year to 1 in 5000 chance per year. See Section 3.9.
Climate Change	The impact of a medium climate change projection with a 9% increase in rainfall intensity on flood events was modelled, to assess implications for selected scenarios. See Section 3.10.
Flood forecast warning time	Based on current Bureau of Meteorology Service Level Specification Flood Peak Target forecast timeframes: 8 hours for Wallacia and Penrith and 15 hours for Windsor. See Section 3.7.

Order to evacuate	Assumes 100% of people evacuate in order to test evacuation capacity of the road network, not to test the behavioural response.
Shadow evacuation	Shadow evacuation occurs when people evacuate unnecessarily when they are not subject to flood risk. This can occur in areas nearby those to be evacuated. This is not modelled directly but can be inferred by looking at the effects of larger flood events which would provide an indication of the impacts of larger numbers evacuating. See Section 3.6.
On the road network	
Evacuating lane capacity	Adjacent non-flooded areas would generate background traffic which can significantly impact the regional evacuation routes. The model uses a maximum traffic flow rate of 600 vehicles per lane per hour and assumes background traffic will take up an estimated 10% of that capacity for single-laned roads and 50% for 2 to 4 laned roads. See Section 3.6.
Evacuating vehicle speed	Due to inclement weather conditions vehicle speeds are assumed to be reduced by 10- 20km/h lower than normal speed limits. See Section 3.6.
Intersection constraints	Vehicle behaviour at road intersections is not modelled in detail as it is assumed that intersections generally have a design capacity greater than the evacuation traffic capacity (any impacts would be accounted for in the above assumptions for evacuation speed and lane capacity).
Where people evacuate to	
Evacuation destinations	Research and experience have shown around 80% of people typically evacuate to family, friends and accommodation providers, and 20% typically go to evacuation centres. In the model, evacuation destinations are modelled as safe points where the road network has sufficient capacity so people can travel to their destination of choice. Major evacuation centres are located beyond the evacuation road network. See Section 3.5.
Risk to life	
Conversion of vehicles to people	As the output from the model is vehicles, this must be converted to people to assess risk to life. The outputs relating to population assume 1.32 people on average per vehicle evacuating, based on the overall demographic data across the valley. See Section 3.11.
Travel time threshold	As evacuation traffic travel times increase due to the limited road network and congestion, the risk to safety and life increases. Recognising these risks and taking a conservative approach, 12 hours has been deemed the limit of people’s tolerance to access without food and water, as well as when cars would run out of fuel.
Average annual measurement of risk	The weighted average of vehicles unable to evacuate against the annual probabilities across the full range of flood events, expressed as an annual average risk that people are exposed to each and every year. See Section 3.11.
Fatalities proportional to vehicles unable to evacuate	Based on a review of international flood events in similar areas and economies, fatalities are estimated to be 0.3% of people unable to evacuate. See Section 3.12.

3.2 Changes to risk to life over time

To understand changes in the risk to life over time, 3 points in time were modelled – 2018 (to represent the existing situation), 2026 and 2041. These time points are indicative of current, short and longer-term changes. A time profile is required to monitor and evaluate how risk to life has been trending under given assumptions, noting the dynamic nature of the systems being modelled.

External global events, economic and political drivers can affect the specific timing of growth, investment in infrastructure and rate of climate change.

3.3 Input data – dwellings, populations and vehicles

A key data input for flood evacuation modelling is a spatial distribution of the vehicles and people that live or work in the valley now, and in the future. A detailed methodology and database were developed to geolocate the population at a suitable scale to simulate the movement of vehicles during a major flood in the valley.

The estimation of vehicles for evacuation planning and hence the flood evacuation modelling comprises a combination of residential vehicles and employee vehicles. The people considered for evacuation planning is shown in Figure 3.1.[10]

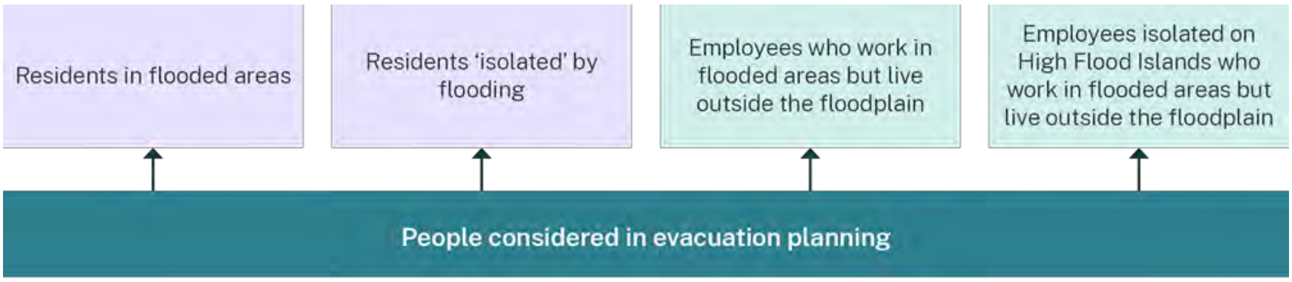

Figure 3.1: People (residents and employees) considered for evacuation planning

Vehicles from 'visitors' such as customers, students, patients and tourists are not included in the flood evacuation modelling. An exception to this is in the Penrith Lakes (Employment) area, where visitors have been included in the evacuation traffic due to the high potential numbers.

3.3.1 Existing development (2018): residential dwellings and vehicles

The spatial locations of 'existing' dwellings[11] were primarily determined using the dwelling point data available from NSW Government Spatial Services, supplemented by aerial photography (NearMap) as at the end of 2018.

[10] Note that people considered in evacuation planning is different to people needing to evacuate. People considered in evacuation planning have been estimated as an input to emergency planning and flood evacuation modelling. People needing to evacuate is estimated from outputs of the flood evacuation modelling.

[11] The definition of a dwelling has been based on the definition of a 'dwelling' from the 2016 Census Dictionary: a 'dwelling' is 'a structure that is intended to have people living in it' and includes houses, flats (individual dwellings that are part of multi-unit housing), caravans and manufactured homes. Both private and non-private dwellings are included. Occupied dwellings in caravan / residential parks or camping grounds are treated as occupied private dwellings in the 2016 Census and so have been included in the 'existing' (2018) residential database.

Based on this, 36,700 residential properties are located within the floodplain, including around 1,900 caravans/manufactured homes (see Figure 3.2). In addition, a further 4,500 isolated dwellings, located above the level of the PMF but where the property would be isolated by flooding of a public road, would need to be considered for evacuation planning.

The 2016 Census data were used to estimate the average vehicles per dwelling for existing development. The most granular information available from the 2016 Census data for vehicles is a scale of a Statistical Area 1 (SA1).[12] Based on this, there are approximately 70,000 residential vehicles located in the floodplain (not including isolated dwellings).

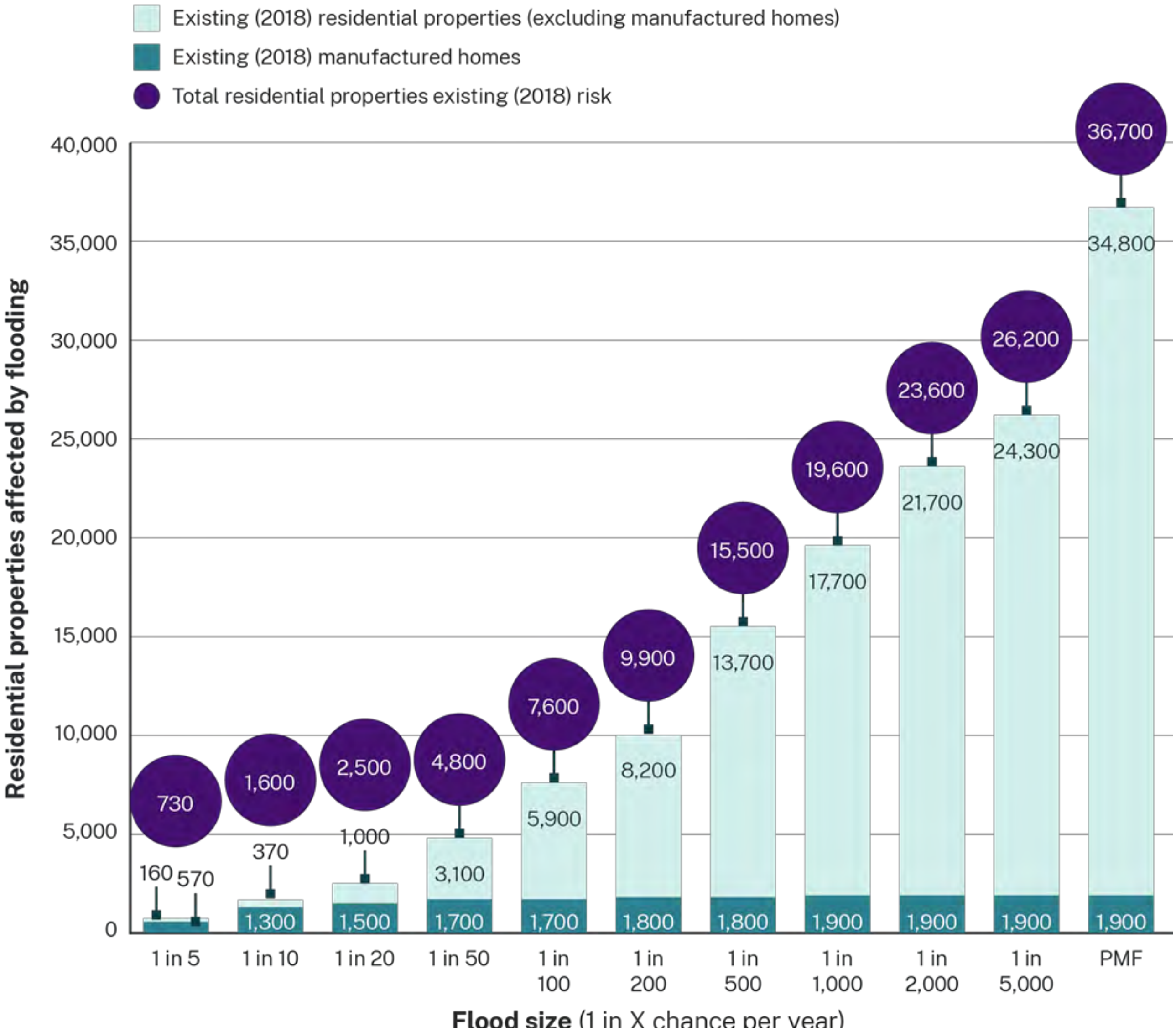

Figure 3.2: Number of residential dwellings in floodplain (as of late 2018)

[12] An SA1 is the next largest geographic area after a Mesh Block used by the Australian Bureau of Statistics (ABS) and are designed to maximise the geographic detail available for population and housing data while still maintaining confidentiality. Most SA1s have a population of between 200 to 800 people.

3.3.2 Future development residential dwellings and vehicles

All the 2026 and 2041 developments that have been considered in the flood evacuation modelling in 2017 had been publicly announced and/or publicly identified. However, not all of them have been rezoned to permit the proposed increase in residential or business-related development. These areas are defined as:

- **committed development** – this relates to those future development areas that have been rezoned, as at April 2021, permitting an increase in residential or business-related development. This land can be developed at any time and so has the highest community and landholder expectation that development can proceed. These rezonings have occurred over several decades.
- **potential development** – this relates to those future development areas that have not been rezoned for an increase in development potential, as at April 2021. As the land has not been rezoned to permit an increase in density, this potential development cannot proceed. There are two exceptions to this categorisation:
    - Windsor / Richmond – the Hawkesbury City Council Draft Local Housing Strategy (August 2020) is based on existing zonings to achieve the proposed increase in residential development
    - Penrith Lakes (Employment) – the current land zoning permits the type of non-residential development proposed.

Table 3.2 provides a summary of the modelled committed and potential future development areas included in the forecast future dwelling estimates. For each, the best available estimates of timing were used to assign the proportion of the development that would most likely be completed in the short-term (2026) and the long-term (2041).

Table 3.2: List of committed and potential future development

Committed residential development		Potential residential development	
Future Development Area	**Local Government Area**	**Future Development Area**	**Local Government Area**
North West Growth Area		**North West Growth Area**	
Box Hill and Box Hill Industrial	The Hills	Marsden Park North	Blacktown
Colebee (including Stonecutters Ridge)	Blacktown	West Schofields	Blacktown
Marsden Park	Blacktown		
Marsden Park Industrial	Blacktown		
Riverstone	Blacktown		
Riverstone West	Blacktown		
Schofields (includes Akuna Vista)	Blacktown		
Vineyard Stage 1	Hawkesbury		
Outside North West Growth Area		**Outside North West Growth Area**	
Pitt Town (Blighton, Cattai, Central Precinct, Cleary, Thornton, Thornton East)	Hawkesbury	Riverstone Town Centre	Blacktown
Jordan Springs East	Penrith	Windsor / Richmond (Windsor, South Windsor, Richmond, North Richmond and Hobartville)	Hawkesbury
Penrith City Centre Stage 1 Thornton Estate (North Penrith) – low rise residential Thornton Estate (North Penrith) – Key Site 11	Penrith	Penrith City Centre Stage 2 Stage 3	Penrith
Penrith Lakes (Residential)	Penrith	Penrith Lakes (non-residential)	Penrith
Penrith Panthers	Penrith		
South Werrington Urban Village	Penrith		

Table 3.3 summarises the residential properties in the valley (below the PMF) for future residential dwelling estimates. It also includes infill development which is defined as all the potential additional development located outside the future development areas. Infill development areas are where the land zoning already permits an increase in residential development and tends to occur in older suburbs where there are larger lot sizes.

Infill development is a small proportion of the forecast future dwelling estimate, when compared to the future development areas. Around 2,100 additional dwellings have been estimated as infill development for the Hawkesbury-Nepean floodplain by 2041, based on information supplied by DPE from the 2018 Sydney Housing Supply Forecast. Infill development does not include secondary dwellings (granny flats).

Table 3.3: Summary of the residential properties in floodplain (below PMF) for future residential dwelling estimates

Future development	Number of residential properties in the floodplain (below PMF)			
	2026		2041	
	Committed development	Committed and potential development combined	Committed development	Committed and potential development combined
Within North West Growth Area	8,300	10,300	8,500	14,700
Outside North West Growth Area	6,200	6,200	7,500	23,000
Infill development	810	810	2,100	2,100
Total additional dwellings	15,300	17,300	18,200	39,800
2018 existing dwellings	36,700	36,700	36,700	36,700
Totals	**52,000**	**54,000**	**54,900**	**76,600**

* All values rounded

To estimate the likely vehicles per dwelling for forecast future residential development the following sources of information were used:

- council car parking requirements
- current trends in vehicle ownership
- census profiling of comparative high-density residential developments outside the floodplain
- census profiling of nearby new low density, medium density and large lot areas.

3.3.3 Estimating vehicles for employment lands

The people and vehicles for the employment lands includes the following:

- the total employees who work in the floodplain
- an estimate of employees who live in the floodplain
- an estimate of employees who live outside the floodplain
- an estimate of employees who live outside the floodplain and who drive to work within the floodplain: used to estimate the number of employee vehicles (evacuation traffic) to be considered for evacuation modelling.

Figure 3.3 shows that only 57% of employees live outside the floodplain and drive to work as a sole occupant, representing those who have been considered for flood evacuation modelling. This means that all other employees have been considered as residents for the purposes of evacuation modelling, avoiding double counting.

The results of the analysis show that there are currently around 62,000 employees in the floodplain, of which 35,000 would be driving to work as a sole occupant from outside the area. These statistics show the importance of including employees in evacuation planning in all areas of the floodplain.

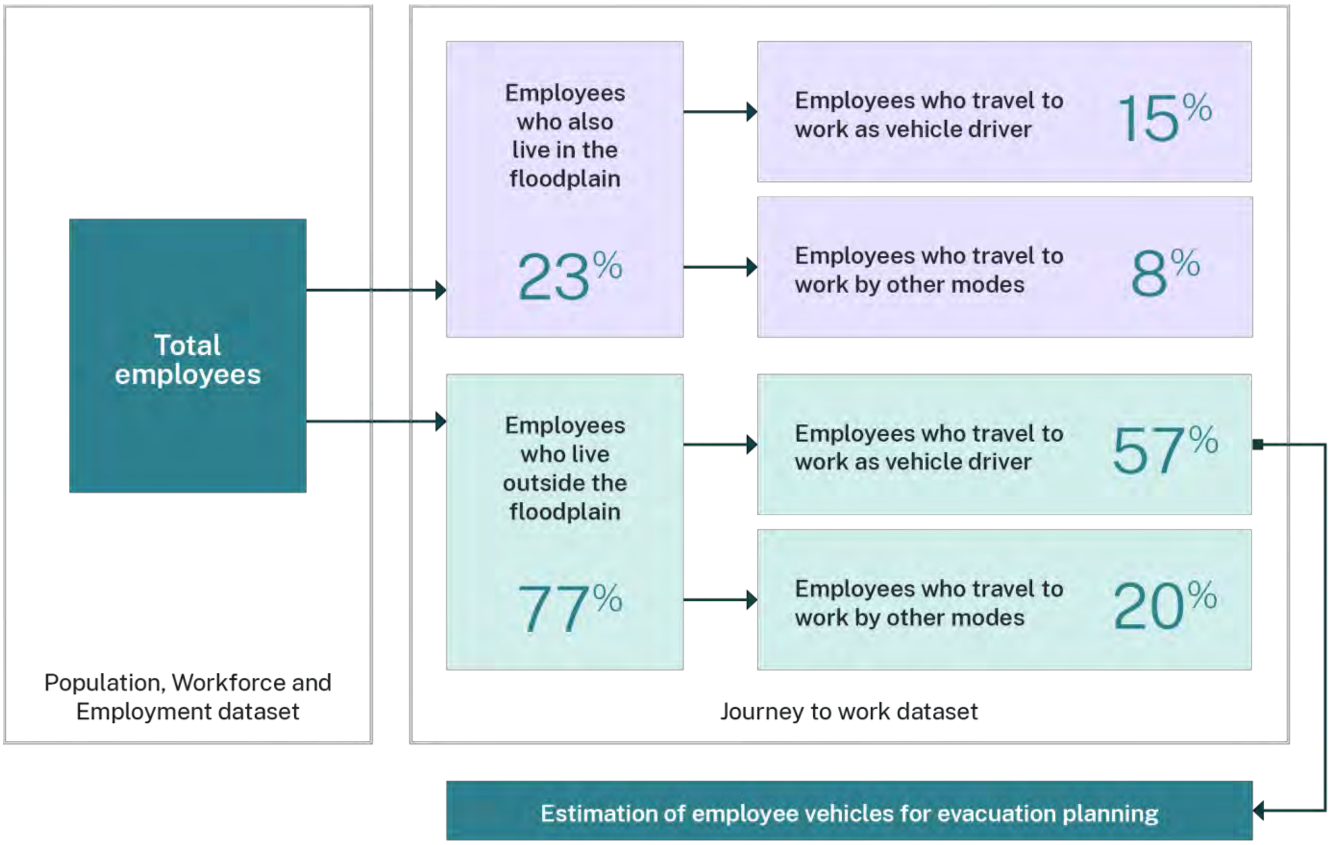

Figure 3.3: Overview of analysis of employees in the Hawkesbury-Nepean valley

3.4 NSW SES subsectors

In the FEM, areas in the valley are divided by the NSW SES into incident management sectors and 393 subsectors in accordance with the approved Hawkesbury-Nepean Flood Emergency Plan 2020. The subsectors are determined by their Flood Emergency Response Classification of Communities (FERCC).[13] Each subsector has been assigned a:

- unique evacuation area name and number
- number of vehicles – based on census and spatial data
- prioritised list of safe nodes where evacuees will seek their first safe node, but if this is blocked then they will seek their next safe node
- forecast time from the Bureau for a reasonable flood prediction (also used as a trigger for evacuation)
- water gauge level at which a sector will be impacted by a flood event to trigger evacuation and road closures.

[13] Flood Emergency Response Planning Classification Of Communities, 2007 https://www.environment.nsw.gov.au/-/media/OEH/Corporate-Site/Documents/Water/Floodplains/floodplain-risk-management-guideline-flood-emergency-response-160732.pdf?la=en&hash=07081CD0D12ABA36C56C7BDBBA4F829FA2D86738

A map of the NSW SES subsectors can be viewed in Figure 3.4.

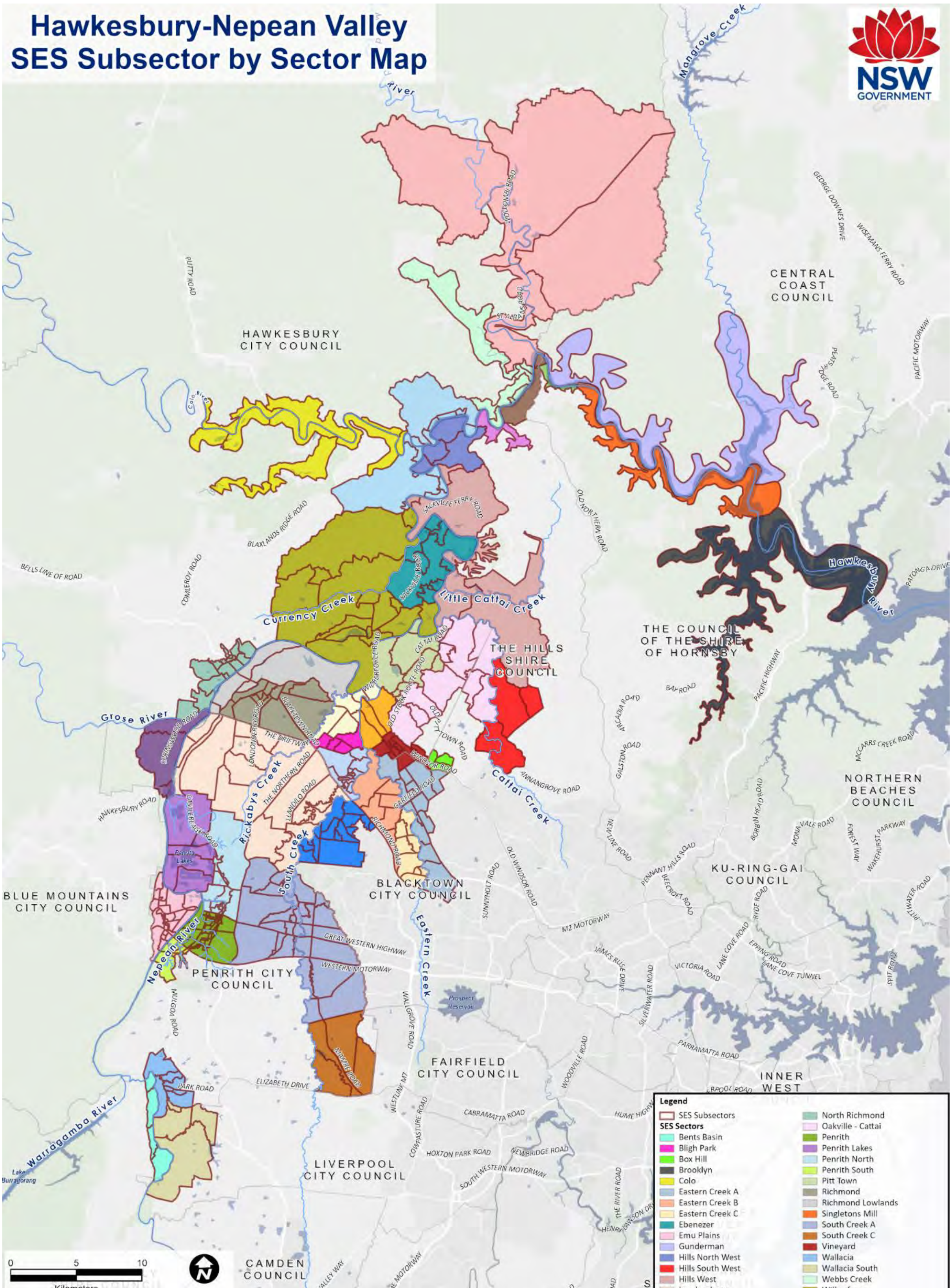

Figure 3.4: Hawkesbury-Nepean Valley NSW SES Subsector map

3.5 Road network

The road evacuation network for a scenario is derived from the May 2020 version of the TfNSW Strategic Traffic Forecast Model (STFM) – see Figure 3.5 and Figure 3.6. This was supplemented with the local road network not included in the STFM, and the evacuation routes described in the Hawkesbury Nepean Flood Plan 2020. This network includes factors such as alignments, distances, travel speeds and the height of each road link affected by flooding.

The following assumptions for the road network were included in the scenarios:

- For 2018, roads that were in existence at that time
- For 2026 (Figure 3.5) and 2041 (Figure 3.6), the assumed future road network includes potential new and major upgrades of roads that would enhance road network capacity and flood evacuation (road mitigation options).

These road network options include assumptions for some road infrastructure projects that may not be planned, developed, or currently do not have any Government commitment or funding but are projected based on potential medium and longer term strategic plans. It would be unreasonable to assume the 2018 road network would remain unchanged for a 2041 population. Flood resilience is one of many important factors considered in network planning and investment. Any commitment for future funding is subject to prioritisation by Government and subsequent business case development.

Other inclusions in modelling were:

- safe evacuation nodes (points where evacuees are no longer at risk from a flood event)
- local road networks
- roads which only open during flood evacuation events (Old Stock Route Road, Pitt Town and Thorley Street bypass, Bligh Park)
- elevation of roads especially, low points.

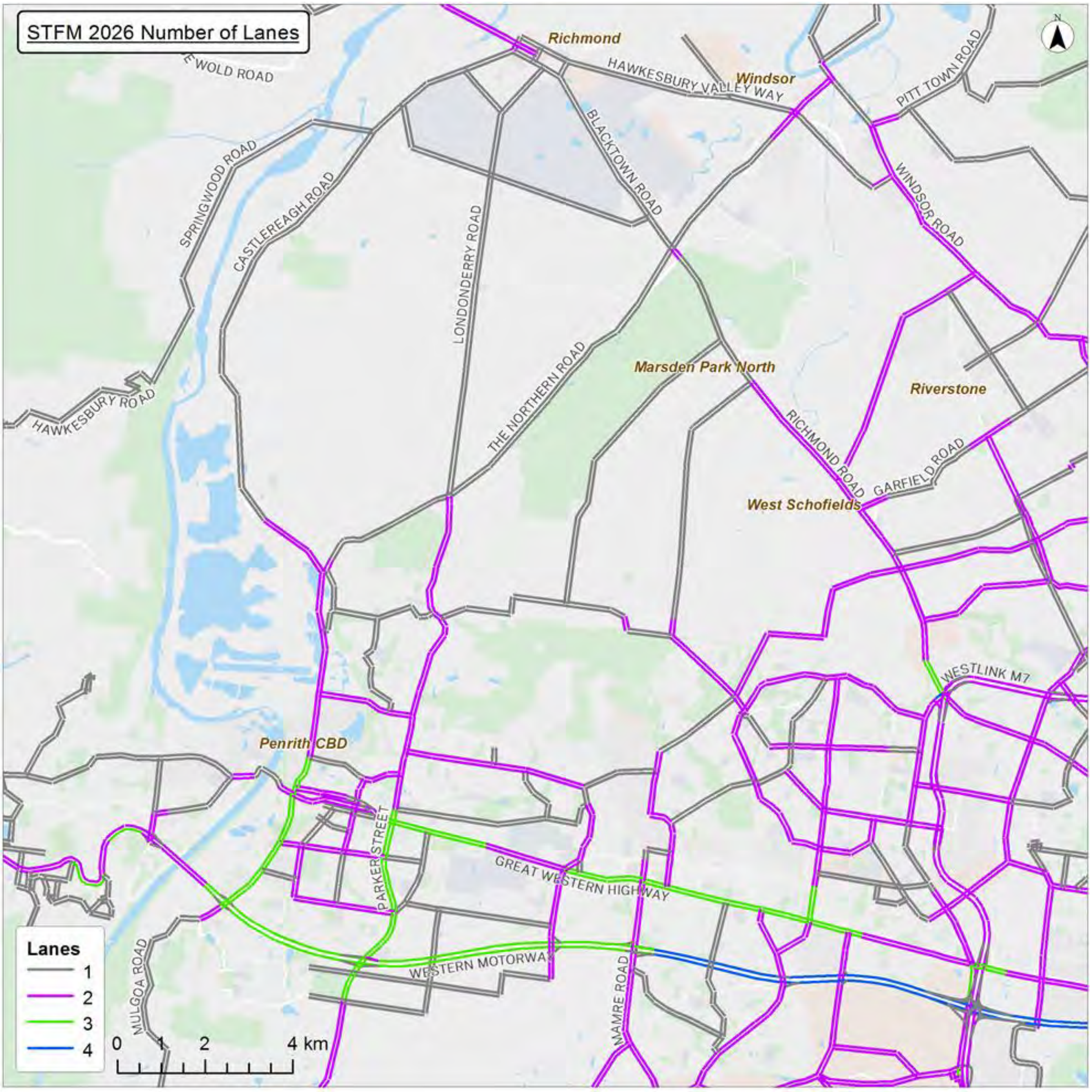

Figure 3.5: STFM 2026 number of modelled lanes

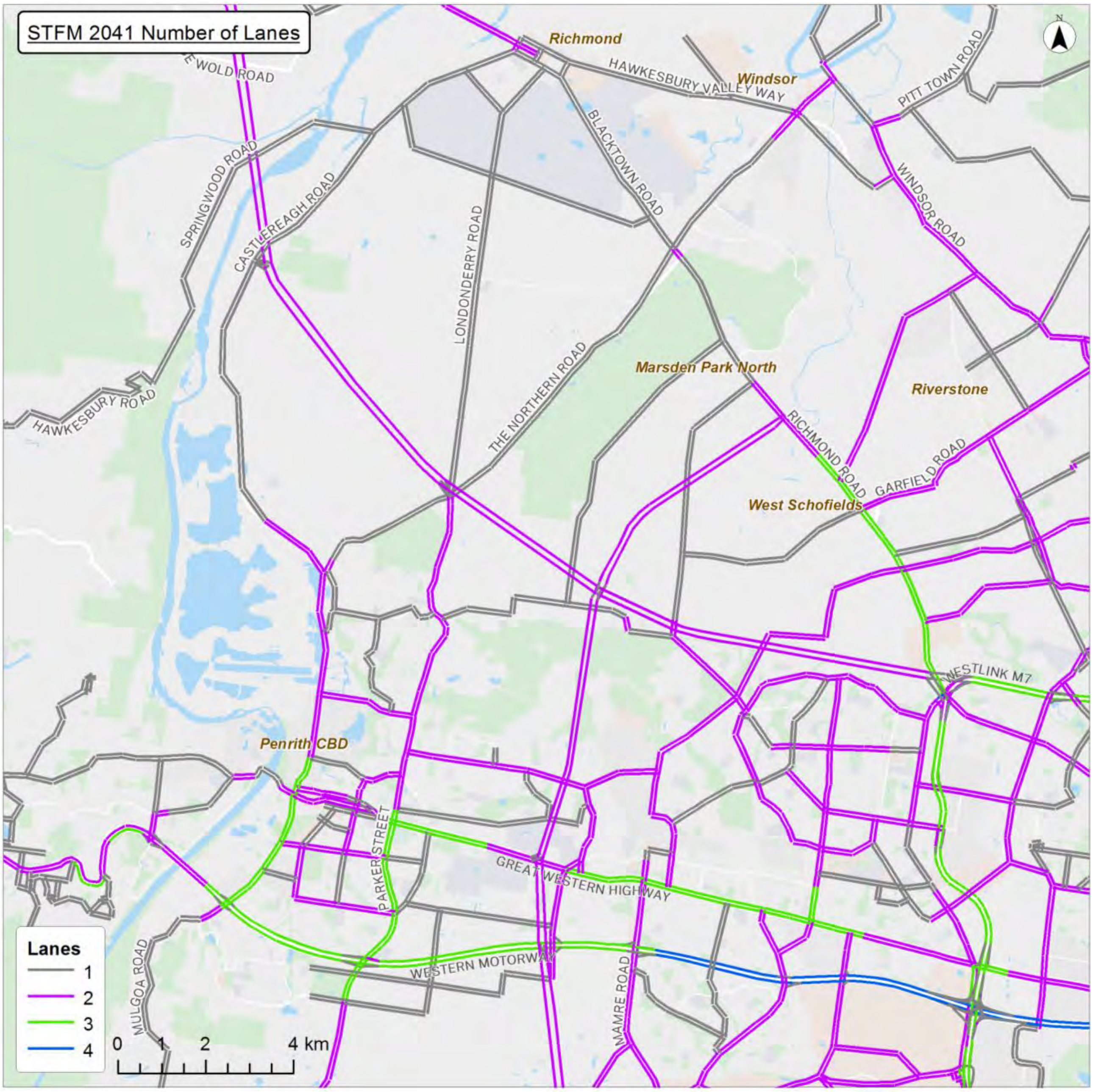

Figure 3.6: STFM 2041 number of modelled lanes

3.5.1 Assumed future road network for 2026[14]

Modifications to the road network by 2026 include projects forecast to be delivered by TfNSW's Western Sydney Infrastructure Plan around 2021, including:

- 3 traffic lanes in the southbound direction along The Northern Road from Jamison Road in Penrith to M4 Motorway and beyond
- 1-lane on-ramp onto the M4 Motorway in the eastbound direction from The Northern Road (Parker Street, Penrith)
- 2 traffic lanes in each direction along The Northern Road from Londonderry Road, Cranebrook to Vincent Street, Cranebrook.

[14] These are 2026 projections based on input data analysed in early 2019.

Any potential improvements from flood evacuation road resilience projects have been excluded as these primarily address local flood risk and not the regional flood risk that drives the mass evacuation from the valley.

3.5.2 Assumed future road network for 2041[15]

This includes 2026 network upgrades, plus:

- Castlereagh Connection, with the crossing of South Creek, built to be trafficable up to a 1 in 100 chance per year flood. The long-term Castlereagh Connection corridor is proposed to provide for an east west motorway connection between Springwood Road at Yarramundi and the junction of Richmond Road with the M7 Motorway at Colebee. The corridor is part of Future Transport 2056 as a long term corridor strategy to support growth across Western Sydney and provide an alternative route between the Sydney Motorway network and the Hawkesbury region.
- Connections between M7 Motorway and Castlereagh Road with grade separated interchanges at:
  - M7 Motorway (Dean Park) with all movements
  - Eastbound exit ramp to Richmond Road (west side) as a T-junction
  - Westbound entry ramp from Richmond Road (west side) as a T-junction
  - The Northern Road (near Fourth Avenue) with Eastbound entry ramp from The Northern Road (east side) as a T-junction and Westbound exit ramp to The Northern Road (east side) as a T-junction.

3.5.3 Potential road network upgrade options

In addition to the 2041 road network and modifications listed above, 3 road options were reassessed to test if additional flood resilience requirements would improve flood evacuation capacity. These are potential road options being considered to meet growth demand. The 3 options are:

1. Richmond Road widening upgrade (near Bells Creek) with a bridge over South Creek constructed to be trafficable for floods up to the current 1 in 200 chance per year flood
2. Castlereagh Connection, with the crossing of South Creek, built to be trafficable up to a 1 in 500 chance per year flood
3. Castlereagh Connection, with the crossing of South Creek, built to be trafficable up to a 1 in 500 chance per year flood plus Western Highway / Dunheved Road widening and intersection upgrades.

3.6 Road capacity

Mass self-evacuation ahead of a forecast flood event has different traffic characteristics than normal traffic. Road capacity is critical for evacuation and different assumptions apply compared to day to day traffic modelling. The assumptions below are based on NSW SES experience with local flood evacuation events and informed by research from interstate and overseas.

- **Lane capacity**: A maximum capacity of 600 vehicles per lane per hour were modelled as the central case assumption for evacuation. This number has been reviewed several times over

[15] These are 2041 projections based on input data analysed in early 2019.

the last 15 years and benchmarked against international examples[16]. There is no other evidence to suggest different carrying capacities would be more appropriate.

- **Vehicle speeds:** Due to inclement weather conditions vehicle speeds on the evacuation network are assumed to be reduced by 10-20km/h lower than normal speed limits. This speed reduction is often observed on roads in the Sydney metro areas during wet weather conditions and during heavy traffic conditions.
- **Background traffic:** The FEM was revised to include background traffic following a peer review recommendation. Adjacent non-flooded areas would generate background traffic which can significantly impact the regional evacuation routes. The model uses a maximum traffic flow rate of 600 vehicles per lane per hour and assumes background traffic will take up an estimated 10% of that capacity for single-laned roads and 50% for 2 to 4 laned roads. Many of the multi-lane evacuation roads move in and out of urbanised areas that may not be impacted by the flood during the event or at the time of the evacuation, so could be carrying significant day-to-day traffic (for example The Northern Road, Windsor Road, Great Western Highway and the M4). In addition, the FEM currently assumes that these traffic rates can be maintained 24 hours per day, while traffic counts during mass evacuations have shown that there is a drop off in traffic late at night and into the early hours of the morning.
- **Shadow evacuation** is when people who have not been told to evacuate decide to evacuate or evacuate ahead of the call for their area to evacuate. This extra evacuation traffic can greatly increase the flood risk to life due to impacting the capacity of the evacuation network. The FEM does not model shadow evacuation, but the subsector-based evacuation in the FEM, which is based on NSW SES evacuation plans and practices, may evacuate whole subsectors when only a portion of the subsector is flooded. This has been minimised by dividing the valley into smaller subsectors based on their flood risk. This reflects the real-world challenge of modelling the complexity versus the ability to operationalise during an event.
- **Contraflow** is not supported or undertaken for this modelling. Contraflow is the practice of creating extra outward evacuation road lanes using one or more of the incoming road lanes. This is used on several south-eastern USA interstate multi-lane highways and freeways where large populations evacuate for a high hurricane storm and flood risk. However, implementation of contraflow lane requires significant road modification and support from emergency services to enable it to operate successfully with acceptable risks. Road crossover and merging points need to be constructed, and physical separations are required to separate evacuating vehicles from incoming emergency service vehicles under inclement weather conditions. There are limited multi-lane flood evacuation roads of sufficient length in the valley where contraflow could be feasible. Contraflow is regularly put forward as an option to improve evacuation capacity. The convergence points where the evacuation capacity is constrained is often on the single lane roads and intersections before cars can access multi-lane roads and freeways. However, there is no new evidence that would warrant a change in the feasibility of contraflow in this valley for the current road network.

3.7 Flood warnings

Reliable and timely flood forecasts and warnings are critical for evacuation. Under the approved emergency planning arrangements, the NSW SES plan for and trigger evacuations based on flood forecasts from the Bureau. The Bureau aims to provide up to 8 and 15-hour flood peak predictions for flood events at Penrith and Windsor, respectively.

However, the NSW SES requires 15 hours or more to evacuate some flood islands in the valley during large flood events such as Windsor and Richmond. This means in practice that the NSW

[16] For example: 2014, Dixit and Wolshon - 'Evacuation traffic dynamics' https://www.sciencedirect.com/science/article/abs/pii/S0968090X14003167?via%3Dihub

SES can issue evacuation orders for areas requiring greater than 8 or 15 hours to evacuate based on more uncertain forecasts. This precautionary approach may mean that some areas are evacuated, which, with the benefit of hindsight, did not need to be evacuated based on subsequent flood predictions. As has been demonstrated in the valley and elsewhere, it also means that people may be reluctant to follow future evacuation orders, putting their lives at risk. However, if this precautionary approach is not taken and the flood exceeds the prediction, lives could be at risk.

For modelling purposes, the assumptions are that the flood evacuation for each individual subsector is triggered based on the current Bureau flood peak level targets (see Table 3.4). However, it is important to note that it is unlikely the Bureau could achieve these forecast flood levels early in a flood as the rainfall event is still developing.

In the FEM these forecast times have been used to trigger the progressive evacuation of subsectors, which assumes the Bureau can forecast the rising flood levels to the forecast target time with reasonable accuracy. If the flood was bigger or rises earlier than forecast, the risk to life would be higher than has been modelled in the FEM.

For evacuation capacity planning purposes, the scenarios modelled assume 100% community compliance with an order to evacuate, and that transport services would be provided for people without vehicles as per the Hawkesbury-Nepean Flood Emergency Plan 2020. While 100% response is unlikely, the FEM evacuation simulations needs to assume full compliance to test the road network's capacity to evacuate large populations within the given constraints and available flood forecast time.

Table 3.4: Bureau of Meteorology flood warning times

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

Source: Service Level Specification for Flood Forecasting and Warning Services for New South Wales and the Australian Capital Territory (BoM, 2020)

3.8 Evacuation planning and timeline

The model is based on the evacuation timeline in the endorsed Hawkesbury Nepean Valley Flood Emergency Plan 2020, where up to 393 NSW SES subsectors are progressively triggered to evacuate across the valley before either the low point on the evacuation route is cut, or houses within the subsector are impacted by the flood event. Subsectors are predetermined areas used by the NSW SES to manage flood warnings during flood events.

Flood evacuation planning simulates vehicles moving from evacuation nodes to safe nodes based on the shortest time, following an operational approach adopted by the NSW SES. The evacuation timeline for each subsector is based on a factor of the timing and severity of the flood event.

The evacuation process is based on the evacuation timeline model[17], Figure 3.7. It is based on an assessment of flood evacuations in Australia and comparable countries. It recognises the time required for the largely volunteer-based emergency services to mobilise and disseminate warnings of forecast flood events, and the time people need to accept and act on those warnings and evacuate.

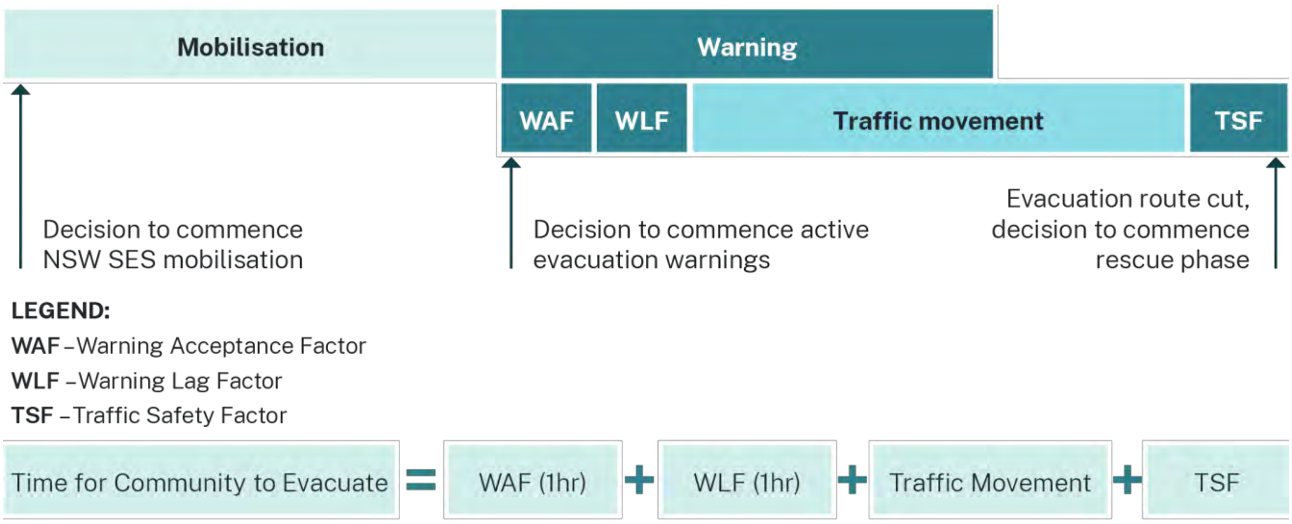

Figure 3.7: The NSW SES evacuation timeline model, Hawkesbury-Nepean Flood Plan

Evacuation orders by the NSW SES are triggered when evacuation routes are predicted to be cut and are based on flood gauge information. The trigger is initiated if all available routes out of a sector are forecast to be flooded.

3.9 Flood events

Flood events are simulated externally to the FEM using the regional flood model to estimate flooding behaviours in the valley. The outputs from the regional flood model feed into the FEM as a time series of flood height data for the representative flood gauge data points. These flood gauge data points represent key locations along the river to measure the differences in flood behaviour such as flood slope. The flood water height determines if an evacuation subsector (or road closure) is triggered.

[17] 2010, Opper, Cinque and Davies – 'Timeline modelling of flood evacuation operations' https://www.researchgate.net/publication/237902389_Timeline_modelling_of_flood_evacuation_operations

To reflect the variability in real events, the FEM uses 7 fast to slow rising modelled flood events from a 1:50 chance per year to a 1:5000 chance per year at each flood size from the suite of 19,500 probabilistic modelled flood events.

The 7 flood probabilities modelled, based on the peak levels at Penrith and Windsor, are:

- 1 in 50 chance per year
- 1 in 100 chance per year
- 1 in 200 chance per year
- 1 in 500 chance per year
- 1 in 1000 chance per year
- 1 in 2000 chance per year
- 1 in 5000 chance per year

The 7 results were then averaged to produce a single set of results for each flood probability.

This report presents the 1 in 500 chance per year and 1 in 1000 chance per year floods as examples to show the estimated numbers of people unable to evacuate within 12 hours. The 1 in 500 chance per year flood was chosen as it represents the highest flood on record, and the 1 in 1000 chance per year flood represents the flood that cuts off the last major evacuation route for the Richmond flood island. See Section 4.

It was not considered necessary at this stage to model flood evacuation under the largest possible flood event the (PMF) for several reasons:

- the PMF is an extremely unlikely theoretical flood event for the valley given the size of the upstream catchment. The Australian Rainfall and Runoff Guideline 2019, Table 8.2.2 states that "*There are no established procedures to assign an AEP* (Annual Exceedance Probability) *to the PMF*". Since the PMF event does not have a known probability, the relative impact of this event cannot be meaningfully compared with other flood events of a known likelihood.
- the PMF is a design flood level and extent created from the maximum probable rainfall event across the entire catchment with limited temporal variation. The modelled hydrographs for a PMF event have more consistent rates of rise than the more realistic variable rates of rise seen in flood events generated from Monte Carlo modelling. This could mean that the modelled flood evacuation risk from PMF event could be lower than say a 1 in 5,000 chance per year flood event, which would be misleading.
- there is limited increase in flood evacuation risk between the Monte Carlo modelled 1 in 5000 chance per year flood events and the PMF. Most of the population and critical evacuation road low points and resultant flood evacuation risk occurs below the 1 in 5000 chance per year flood level. This means that most additional evacuees between the 1 in 5000 level and the PMF would be evacuating along rising evacuation roads on the edge of the floodplain or within subsectors already triggered to evacuate.

3.10 Climate change

A peer-reviewed investigation of the impact of projected climate change on flood risk in the valley[18] determined that the most appropriate method of estimating flood risk was to base an increase of rainfall intensity on the temperature scaling approach outlined in Australian Rainfall and Runoff Guidelines[19]. A 9% increase in rainfall intensity was decided as an appropriate sensitivity test for the impact of climate on the flood risk to life. This correlates to the impact of projected climate change around 2060 under the most likely climate change scenario, but this date could change depending on global action to address greenhouse gas emissions. The catchment hydrological model was run with this 9% scenario, and the modelled flood levels were used to evaluate the flood risk to life under this climate change projection.

3.11 Vehicle evacuation metrics

The FEM can report outputs for a range of modelled flood events from 1 in 50 chance per year up to 1 in 5000 chance per year. The outputs can be summarised by subsector or floodplain, highlighting hotspot areas where vehicles or people are either trapped by floodwaters or congested on the road network.

Risk to life is about people. The FEM simulates vehicles numbers which are converted into number of people. The average number of people in evacuating vehicles is 1.32 based on census and other data such as journey to work data. Evacuation success varies with the scale and severity of a flood. Therefore, it is important to understand how flood risk varies for individual floods distributed across the floodplains and how the average risk changes over time with climate, population growth and effectiveness of flood mitigation measures. The flood risk metrics are presented as:

1. **the average annual number** of people at risk is a weighted average over all flood probabilities and represents a measure of the average risk for each and every year.

   Average annual people unable to evacuate is a comparative metric which is useful to assess relative change in risk to life over time, and the relative performance of flood mitigation options. The expected annual risk to life, therefore, represents the full range of flood probabilities and provides a more complete picture of risk to life impacts. The annualised numbers are generally much lower than the estimated risk to life for a flood event with a specific probability (see Section 4.1).

2. **the number of vehicles** distributed for specific flood events represented as:

   — **unable to evacuate**, due to either through being trapped (cut off by floodwaters) or congestion

   — **able to evacuate**, where a vehicle leaves the designated subsector and moves to beyond the peak flood extent, reaching the broader road network within the travel time threshold (see Section 4.3).

3.12 Estimation of fatalities from vehicles at risk

Many researchers have studied the correlation between flood fatalities, flood risk and exposure. Some studies have attempted to correlate flood fatalities to the number of people within inundated areas in total, or have tried to correlate fatalities to flood depth, velocity, rates of rise and other factors. However, flood fatalities can vary widely and can be influenced by:

[18] WMA Water 2021, Climate Change and Flooding Effects on the Hawkesbury-Nepean – https://www.infrastructure.nsw.gov.au/media/3233/climate-change-and-flooding-effects-on-the-hnv_2021.pdf

[19] 2019, Ball 'Australian Rainfall and Runoff Guideline' – http://www.arr-software.org/arrdocs.html

- the weather conditions associated with the flood event, such as the high winds associated with the cyclonic East Coast Lows that generate most major flood events in the valley
- incidents and accidents, including those associated with the prolonged traffic congestion from a mass evacuation
- hazards associated with flooding, such as electrocution, debris, and contaminants in the floodwaters and sediment
- behavioural factors, particularly risk taking, which can greatly impact fatalities. For example, 87% of flood fatalities in Australia from 1900 to 2015 were male[20] (Haynes, de Oliveria, Gissing, Bird, & D'Arcy, 2016).
- demographics and development – a fall in flood fatalities correlates with increased economic development status.

The literature suggests that the relative number of flood fatalities is decreasing through time, see Figure 3.8. Possible drivers of this are improved flood forecasting, better communications, improved rescue services or increased car ownership. However, this reduction in fatalities may not be realised in the Hawkesbury-Nepean given the valley's bathtub effect which may preclude finding safe refuge areas and inclement conditions.

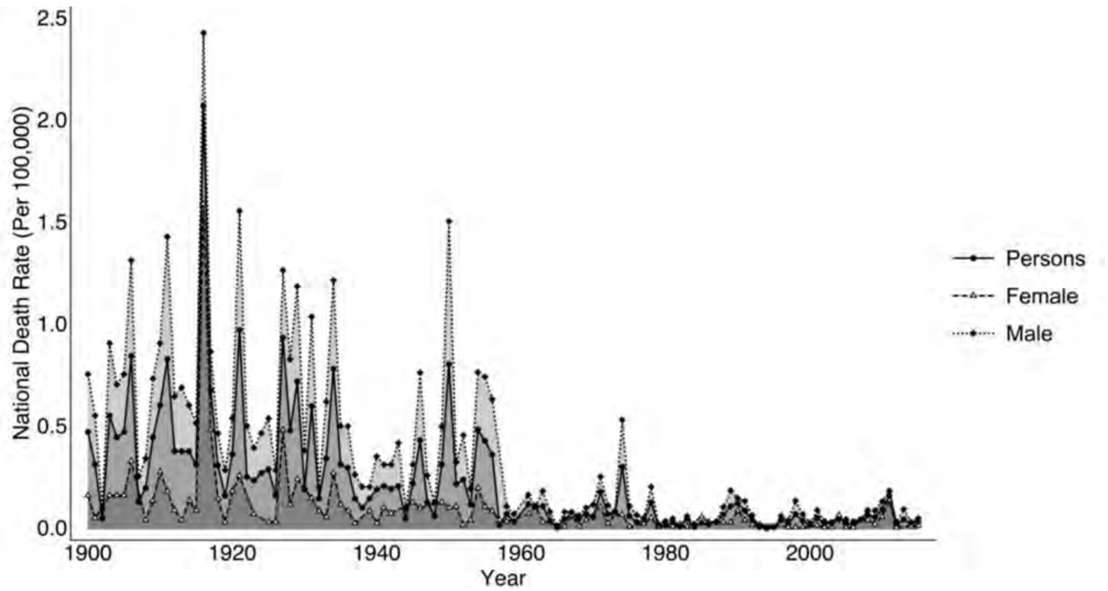

Figure 3.8: Australian death rates due to flood, 1900 to 2015 (Hayes et al, 2016)

In consideration of these factors flood fatality rates for people impacted by recent flood events were examined in areas similar to the valley. Some of these studies related flood fatalities to flood depth. It is difficult to determine the flood depth of every vehicle within the evacuation road network in the FEM, but the flood depths in the valley are greater than most floodplains. For a typical flood depth of 2.5m, a flood fatality rate of 30 per 1000 or 0.3% was assumed for potential loss of life for people in vehicles unable to evacuate.

[20] Haynes, de Oliveria, Gissing, Bird, & D'Arcy, 2016, An analysis of human fatalities from floods in Australia 1900-2015 – https://www.bnhcrc.com.au/publications/biblio/bnh-2735

4 Scenarios and key findings

The following sections presents the key findings of the flood evacuation modelling, using different metrics (as described in Chapter 3):

- Section 4.1 describes the changes in average annual people at risk.
- Section 4.2 describes the modelled risk to life for a 1 in 500 chance per year flood.
- Section 4.3 presents results using a spatial analysis for the number of people at risk for a 1 in 500 chance per year and a 1 in 1000 chance per year flood event.
- Section 4.4 describes the key findings.
- Section 4.5 provides an overall conclusion.

4.1 Average annual people at risk

Table 4.1 summarises the average annual people at risk for the modelled scenarios for development and infrastructure options for existing development (2018) and future development (2026 and 2041). The scenarios test a representative range of options to evaluate the relative changes in risk to life arising from flood evacuation. It is not feasible to model every combination due to the time required to develop and run scenarios.

The existing development for 2018 and committed development for 2026 and 2041 represents the business-as-usual conditions where there are no flood mitigation infrastructure changes, no road network upgrades specifically for flood evacuation, and no changes to the current planning rules or rezoned areas. This is what could happen if a major flood occurred in 2018, or in 2026 or 2041 with no significant intervention.

Table 4.1: Average annual people in vehicles at risk under various scenarios

	2018 (existing)	2026	2041	2041 Richmond Rd Bridge*	2041 Castlereagh Connection#	2041 Castlereagh Connection# Great Western HWY + Dunheved Rd
Committed development						
Average annual people at risk (baseline)	12	28	42			
Effectiveness of road infrastructure options on average annual people at risk in 2041				32	12	
Committed development with potential development option						
1. Marsden Park North		29	88	100	59	
2. West Schofields		29	44	46		
3. Riverstone Town Centre			44			
4. Hawkesbury Local Housing Strategy			73	60	88	
5. Penrith City Centre Stage 2			63	51	32	
6. Penrith City Centre Stages 2 and 3			65	54	40	
7. Penrith Lakes lower capped at 3500 vehicles			89			
8. Penrith Lakes upper capped at 10,400 vehicles			131	120	98	
Committed development with varying combined potential development options						
9. Riverstone Town Centre + West Schofields + Marsden Park North (partial)^			50			
10. West Schofields + Penrith City Centre Stages 2 and 3			66			
11. Riverstone Town Centre + West Schofields + Marsden Park North (partial) + Penrith City Centre Stage 2			66			
12. All potential development options (Marsden Park North + West Schofields + Penrith City Centre Stages 2 and 3 + Penrith Lakes + Riverstone Town Centre + Hawkesbury Local Housing Strategy)		109	249	253	241	229

* Richmond Road Bridge across South Creek raised to 1 in 200 level, two outbound lanes.

Castlereagh Connection from M7 to Castlereagh Road, crossing South Creek at 1 in 500 (20.5m soffit). Assumes 25% background traffic

^ Marsden Park North (partial) is up to 1,700 dwellings, inclusive of existing dwellings, below the PMF

4.1.1 Changes in average annual people at risk with committed development

Table 4.1 shows the baseline risk presented as the average annual people at risk during a flood evacuation for existing development in 2018 and committed development for 2026 and 2041. For 2018 existing development, the average number of people unable to evacuate across all floods within 12 hours each year would be around 12 people. This average annual risk increases to 28 people in 2026 (more than doubling) and to 42 people in 2041 (an increase of nearly 4 times from 2018).[21]

The primary driver in the increase in average annual people at risk is development. Without any further rezonings in the valley there will still be an increase in the average annual people at risk with committed development.

4.1.2 Changes in average annual people at risk with potential development options

Scenarios 1 – 8 in Table 4.1 present the relative changes in the average annual risk to people for individual development options, in addition to committed development.

Scenarios 9 – 12 show how various combinations change the level of risk to life across the valley.

All dwellings are modelled below the PMF.

The findings are summarised below:

- **Marsden Park North** (scenario 1) – 1700 dwellings were modelled for 2026 and would result in a minor increase to the average annual people at risk for committed development. However, a further 2400 dwellings in addition to the 1700 for 2041 would almost double the average annual people at risk from 42 to 88.
- **West Schofields** (scenario 2) – 700 dwellings for 2026 and an additional 1600 dwellings in 2041 were modelled. The additional dwellings would result in a minor change in the average annual number of people at risk.
- **Riverstone Town Centre** (scenario 3) – 3500 dwellings for 2041 were modelled and would result in only a minor change to the average annual risk to life.
- **Hawkesbury Local Housing Strategy** (scenario 4) – 3000 dwellings were modelled for 2041 and the average annual people at risk would increase from 42 to 74, a 76% increase.
- **Penrith City Centre** – above the 4050 dwellings under committed development, a further 6000 dwellings for Stage 2 (scenario 5) and 4000 dwellings for Stage 3 (scenario 6) were modelled for Penrith City Centre. The average annual people at risk would increase from 42 to 63 for Stage 2 and 65 for Stage 3, an increase of up to 55%.
- **Penrith Lakes** – 3500 vehicles (scenario 7) and 10,400 vehicles (scenario 8) were modelled to test the impact of a range of vehicles for the employment lands. An additional 3500 vehicles for 2041 would increase the average annual people at risk from 42 to 89 (around a 110% increase). The 10,400 vehicles for 2041 would increase the average annual people at risk from 42 to 131 (around a 210% increase).[22]

[21] It is noted that the average annual people at risk for 2022 is between the 2018 existing risk and 2026 committed development, i.e. between 12 and 28 people.

[22] The modelling assumed NSW SES evacuation arrangements consistent with residential areas. Further work is being undertaken by DPE to assess the feasibility of early evacuation for the precinct.

4.1.3 Changes in average annual people at risk with combinations of potential development options

The Hawkesbury-Nepean Valley road evacuation network is highly interconnected and growth in one area can have significant consequences on risk to life for existing populations across the floodplains. Modelling different combinations of development options quantifies the cumulative impact on evacuation capacity and on average annual people at risk. The following summarises the key findings for different potential development combinations:

- Committed development with **Riverstone Town Centre, West Schofields and Marsden Park North** (partial) (scenario 9) would change the average annual people at risk from 42 to 50, almost a 20% increase.
- Committed development with **West Schofields** and **Penrith City Centre (Stages 2 and 3**) (scenario 10) would change the average annual people at risk from 42 to 66, almost a 60% increase.
- Committed development with **Riverstone Town Centre, West Schofields, Marsden Park North** (partial) and **Penrith City Centre (Stage 2)** (scenario 11) would change the average annual people at risk from 42 to 66, almost a 60% increase.
- Committed development with all the combined potential developments of **Marsden Park North, West Schofields, Penrith City Centre (Stages 2 and 3), Penrith Lakes** (scenario 9), **Riverstone Town Centre** and the **Hawkesbury Local Housing Strategy** were modelled to test cumulative impact of all combined options on risk to life (scenario 12). The average annual people risk to life would increase from 28 to 109 for 2026, nearly 4 times, and from 42 to 249 for 2041, nearly 6 times.

4.1.4 Effectiveness of potential road options in reducing average annual people at risk

Selected road options were modelled to assess the effectiveness of specific major road upgrades and how they would reduce the average annual people at risk. Many road upgrade options were considered by the previous Taskforce and continue to be investigated by TfNSW as part of the strategic long-term road planning.

3 potential options for 2041[23] were reassessed in the FEM to test if additional flood resilience requirements would improve flood evacuation capacity. The key findings are summarised below:

- **Richmond Road Bridge across South Creek on Richmond Road raised to 1 in 200 chance per year flood, with 2 outbound lanes**. This bridge would be effective in reducing the average annual people at risk by 24% for 2041 committed development. While this option provides reductions for Penrith City Centre and the Hawkesbury area, it can increase the risk for developments in the NWGA. This is because evacuation traffic from the NWGA would be competing for access with people evacuating from the Windsor-Richmond area, for the flood events larger than a 1 in 200 chance per year flood. This option makes no difference for the committed and full potential development option (scenario 12).
- **The Castlereagh Connection from the M7 Motorway to Castlereagh Road, with a crossing at South Creek passable for a 1 in 500 chance per year flood event for flood resilience**. The 2041 assumed road network for committed development included the Castlereagh Connection at a 1 in 100 chance per year flood.

The Castlereagh Connection with the 1 in 500 chance per year flood was modelled at a higher level for flood resilience and was found to reduce the risk to life based on committed development only, and if no future potential development occurs. It would reduce the average annual people at risk for 2041 committed development by 71% (from 42 to 12 people).

[23] Note these are planning assumptions for the model and are not developed or committed projects

The benefits on risk to life from the Castlereagh Connection would be eroded significantly for most potential development options. For the Penrith City Centre Stage 2 and 3 scenario, there would be some risk to life benefits from the Castlereagh Connection. However, when analysed spatially, the risk to life benefits are concentrated in the Richmond/ Windsor area and not Penrith, as it provides a new evacuation route (see Figure 4.15, Figure 4.16 and Figure 4.17). Castlereagh Connection would reduce the average annual people at risk for the Penrith City Centre Stage 2 option with 2041 committed development by 24% (from 42 to 32 people). However, this assumes that no other potential development takes place in the floodplain.

- Combined options of the **raised Castlereagh Connection, Great Western Highway intersection upgrade** and **Dunheved Rd** shows that if all potential development was to occur, this option would minimally reduce the average annual people at risk by 8%, and would still be almost 5.5 times more than under 2041 committed development.

4.2 Total number of people at risk

Similar to Table 4.1, Table 4.2 shows the total modelled number of people unable to evacuate for one specific event.

It shows an averaged total across 7 different 1 in 500 chance per year floods which range from slow to fast rising.

Compared to Table 4.1, Table 4.2 shows that the expected numbers of people unable to evacuate are much higher than the weighted average annual number of people unable to evacuate across all floods – ranging from small to the largest and rarest floods. For example, for 2041 committed development around 1,000 people would be unable to evacuate for a 1 in 500 chance per year flood. However, on an average annual basis across all flood probabilities, this number is 42 which does not convey the number of people unable to evacuate for the larger flood events. As stated previously, average annual is a useful metric to compare options and the overall relative risk.

Table 4.2: Total number of people unable to evacuate for a 1 in 500 chance per year flood

	2018 (existing)	2026	2041	2041 Richmond Rd Bridge*	2041 Castlereagh Connection#	2041 Castlereagh Connection# Great Western HWY + Dunheved Rd
Committed development						
People at Risk (baseline)	12	820	980			
Effectiveness of road infrastructure options in 2041				520	460	
Committed development with potential development option						
1. Marsden Park North		900	3700	3600	2500	
2. West Schofields		640	1100	2800		
3. Riverstone Town Centre			1000			
4. Hawkesbury Local Housing Strategy			3000	1700	1000	
5. Penrith City Centre Stage 2			5200	4400	4700	
6. Penrith City Centre Stages 2 and 3			5100	4500	5000	
7. Penrith Lakes lower capped at 3500 vehicles			2700			
8. Penrith Lakes upper capped at 10,400 vehicles			7000	6200	6300	
Committed development with varying combined potential development options						
9. Riverstone Town Centre + West Schofields + Marsden Park North (partial)^			1200			
10. West Schofields + Penrith City Centre Stages 2 and 3			5200			
11. Riverstone Town Centre + West Schofields + Marsden Park North (partial) + Penrith City Centre Stage 2			5900			
12. All potential development options (Marsden Park North + West Schofields + Penrith City Centre Stages 2 and 3 + Penrith Lakes + Riverstone Town Centre + Hawkesbury Local Housing Strategy)		5700	23700	27400	21600	22500

* Richmond Road Bridge across South Creek raised to 1 in 200 level, two outbound lanes.

Castlereagh Connection from M7 to Castlereagh Road, crossing South Creek at 1 in 500 (20.5m soffit). Assumes 25% background traffic

^ Marsden Park North (partial) is up to 1,700 dwellings, inclusive of existing dwellings, below the PMF

4.3 Spatial distribution of risk to life

Flood risk to life is not evenly distributed across the valley. The floodplain topography within the valley is highly variable. Areas on the edge of the floodplain are more likely to have short rising evacuation routes, reducing the risk that they will be trapped by floodwaters or subject to congestion. The higher risk areas are those in the middle of the floodplains, or on flood islands that need to evacuate before the low-lying evacuation roads are cut and they become isolated. The areas at risk also vary with the rates of rise of the floodwaters and peak flood level, and there is considerable uncertainty with the peak flood level early in the flood event when the evacuations commence. Because of these issues, the spatial distribution or location of the people at risk varies considerably.

The previous section (4.1) focused on the average annual people at risk, a useful comparative metric however can mask the larger number of people at risk for larger flood events. The following section provides an understanding of the spatial distribution of risk for people unable to evacuate for:

- 2 flood frequencies – 1 in 500 chance per year (worst historic flood) and the 1 in 1000 chance per year flood (cuts last major evacuation route) for existing development (late 2018), committed development and committed plus potential development (numbers 1-10). See Table 4.2.
- number of additional people at risk for different flood events for potential development options (number 11).
- The Castlereagh Connection, as an example of how additional road capacity could change the risk to life for different flood events across the floodplain (number 12).

1 | Existing development (2018) for a 1 in 500 chance per year flood

Figure 4.1 shows that for existing development there would be no subsector in the valley where more than 10 people are unable to evacuate within 12 hours for 1 in 500 chance per year flood event.

Figure 4.1: People unable to evacuate by subsector: 2018 (existing) risk for a 1 in 500 chance per year flood

2 | Existing development (2018) for a 1 in 1000 chance per year flood

Figure 4.2 shows that for existing development for a 1 in 1000 chance per year flood event, around 800 people would be unable to evacuate within 12 hours, concentrated in the Richmond/Windsor floodplain.

Figure 4.2: People unable to evacuate by subsector: 2018 (existing) risk for a 1 in 1000 chance per year flood

3 | 2026 committed development for a 1 in 500 chance per year flood

Figure 4.3 shows for 2026 committed development that the most affected subsector is Penrith (~90%) followed by South Windsor. Modelling indicates that around 820 people would be unable to evacuate within 12 hours.

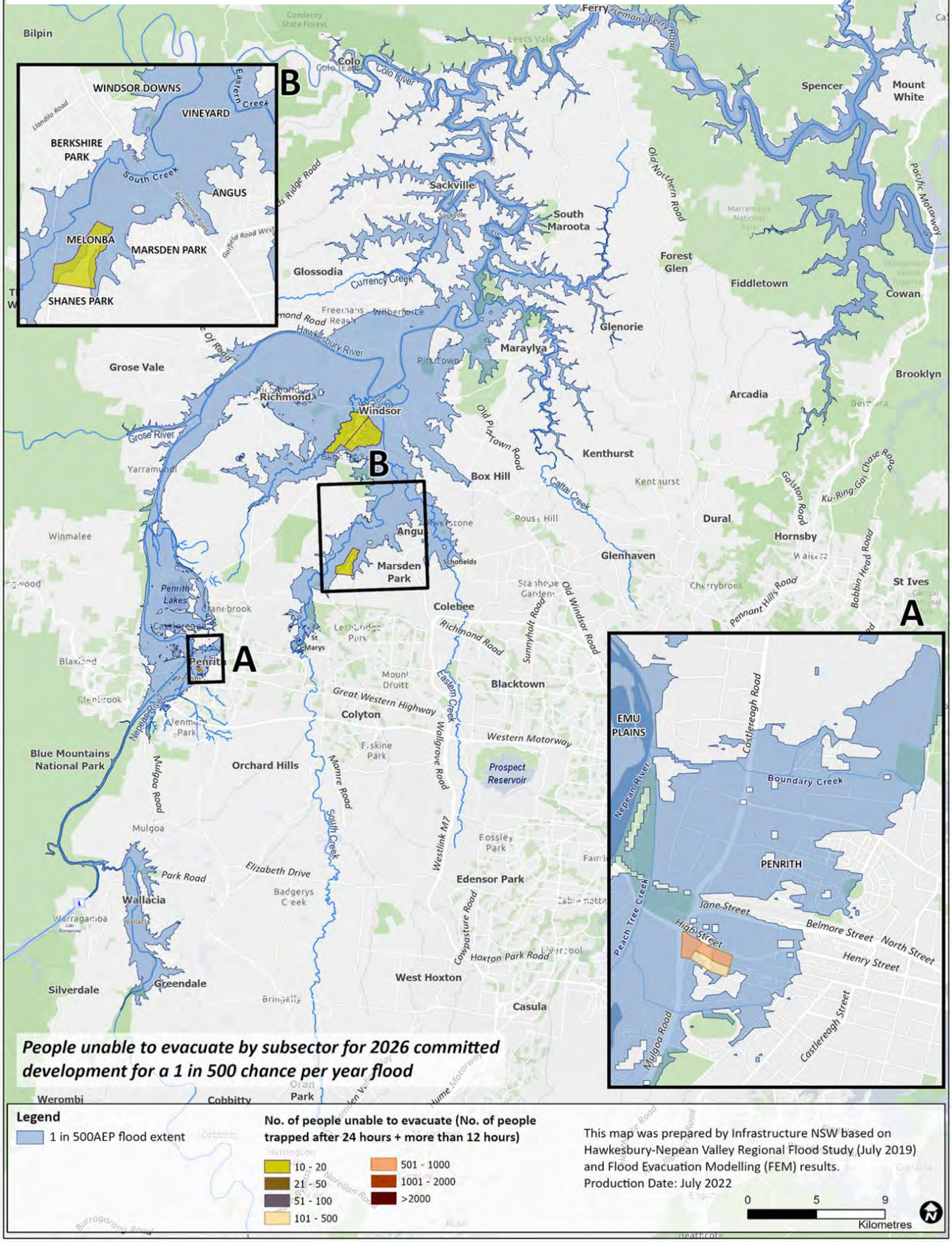

Figure 4.3: People unable to evacuate by subsector for 2026 committed development for a 1 in 500 chance per year flood

4 | 2026 committed development for a 1 in 1000 chance per year flood

Figure 4.4 shows for 2026 committed development that subsectors in the Penrith and Richmond/Windsor floodplains would have a significant increase in the numbers of people unable to evacuate within 12 hours. The modelling indicates that around 2870 people would be unable to evacuate for this size flood and level of development.

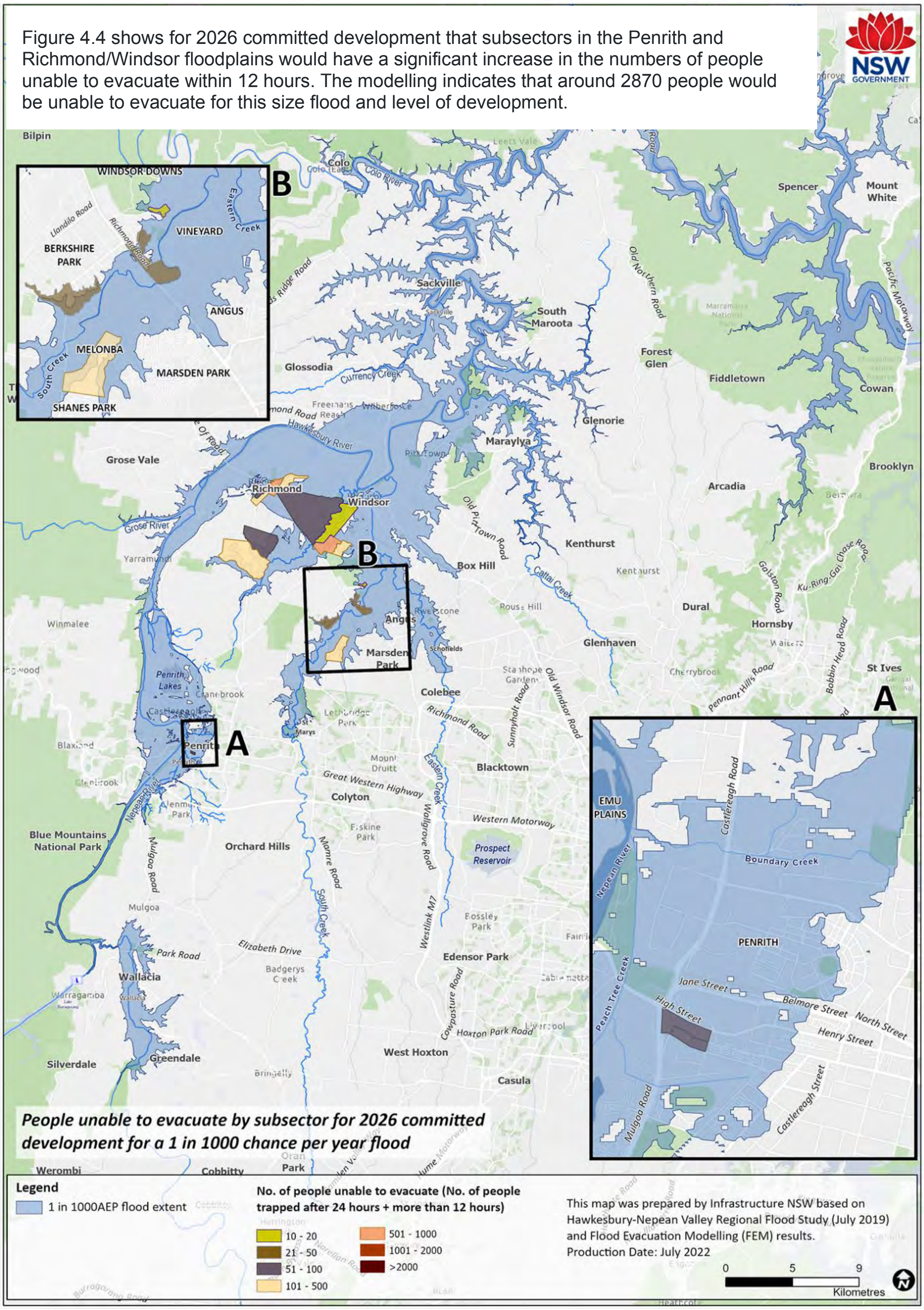

Figure 4.4: People unable to evacuate by subsector for 2026 committed development for a 1 in 1000 chance per year flood

5 | 2041 committed development for a 1 in 500 chance per year flood

Figure 4.5 shows that under 2041 committed development, Penrith (~60%) and Windsor (~40%) subsectors would have increasing numbers of people unable to evacuate within 12 hours, at around 980 people.

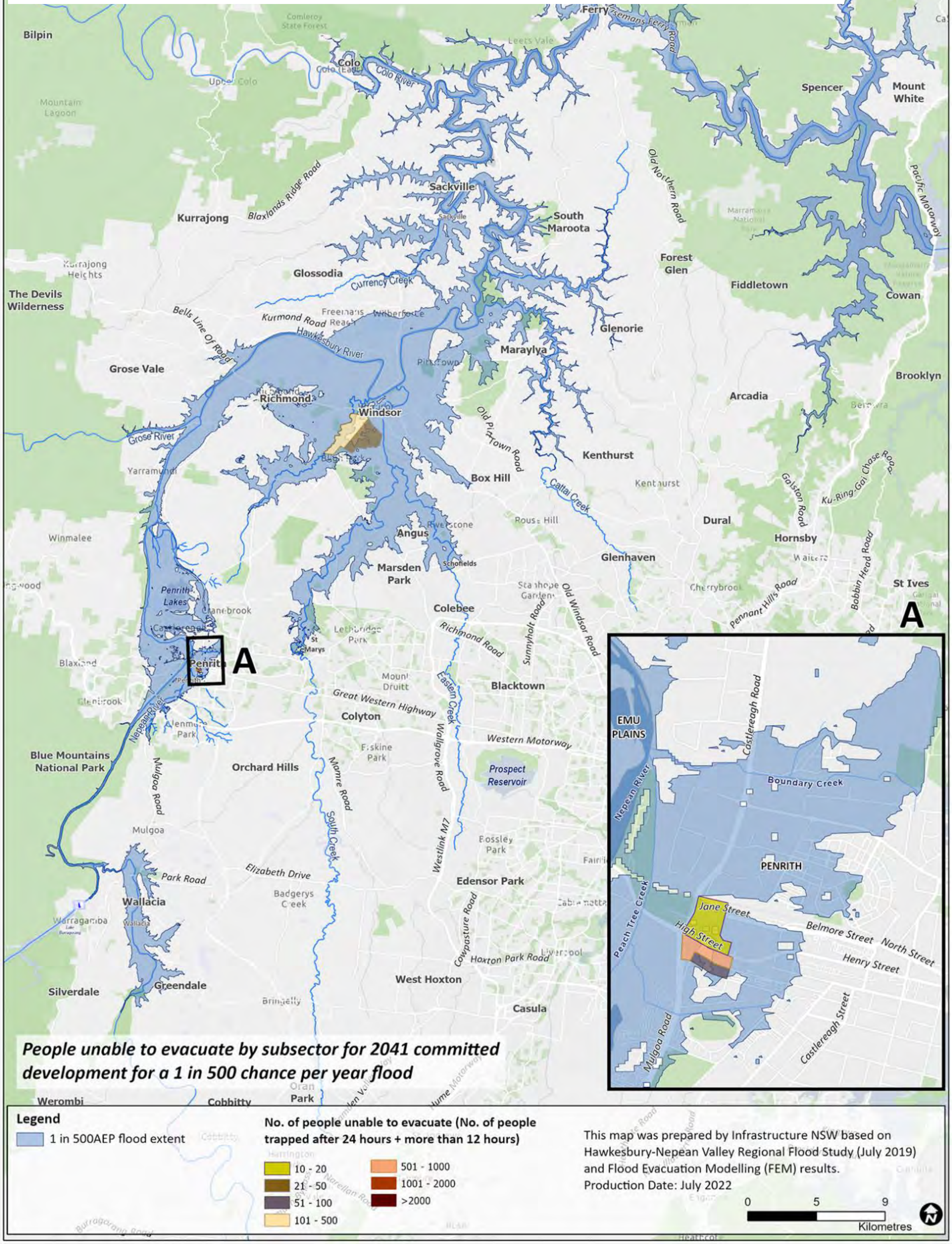

Figure 4.5: People unable to evacuate by subsector for 2041 committed development for a 1 in 500 chance per year flood

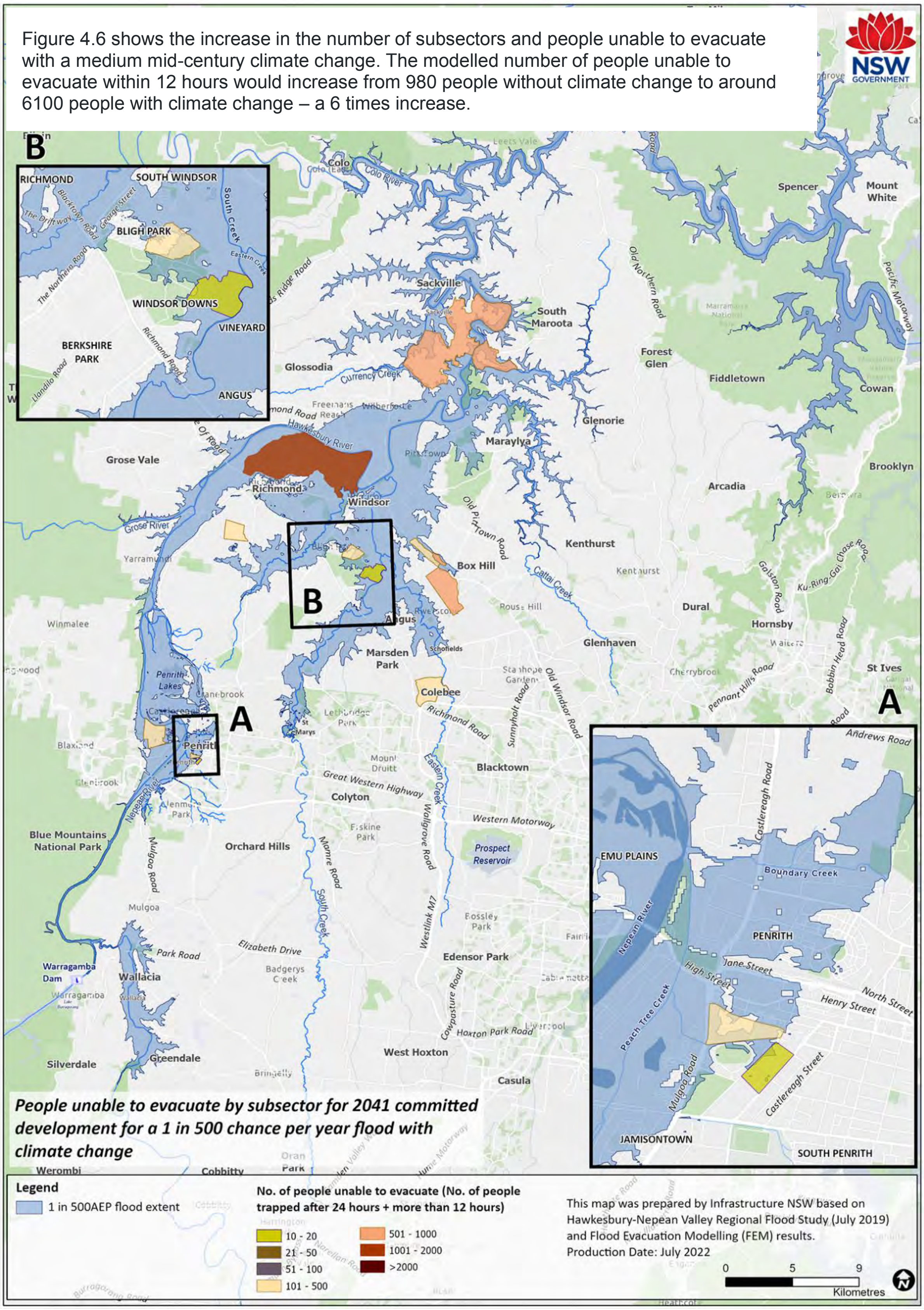

Figure 4.6: People unable to evacuate by subsector for 2041 committed development for a 1 in 500 chance per year flood with climate change

6 | 2041 committed development for a 1 in 1000 chance per year flood

Figure 4.7 shows for 2041 committed development that multiple subsectors in the Penrith and Richmond/Windsor floodplains would have a significant increase in numbers of people unable to evacuate within 12 hours. The modelled total number of people unable to evacuate within 12 hours is around 10,400.

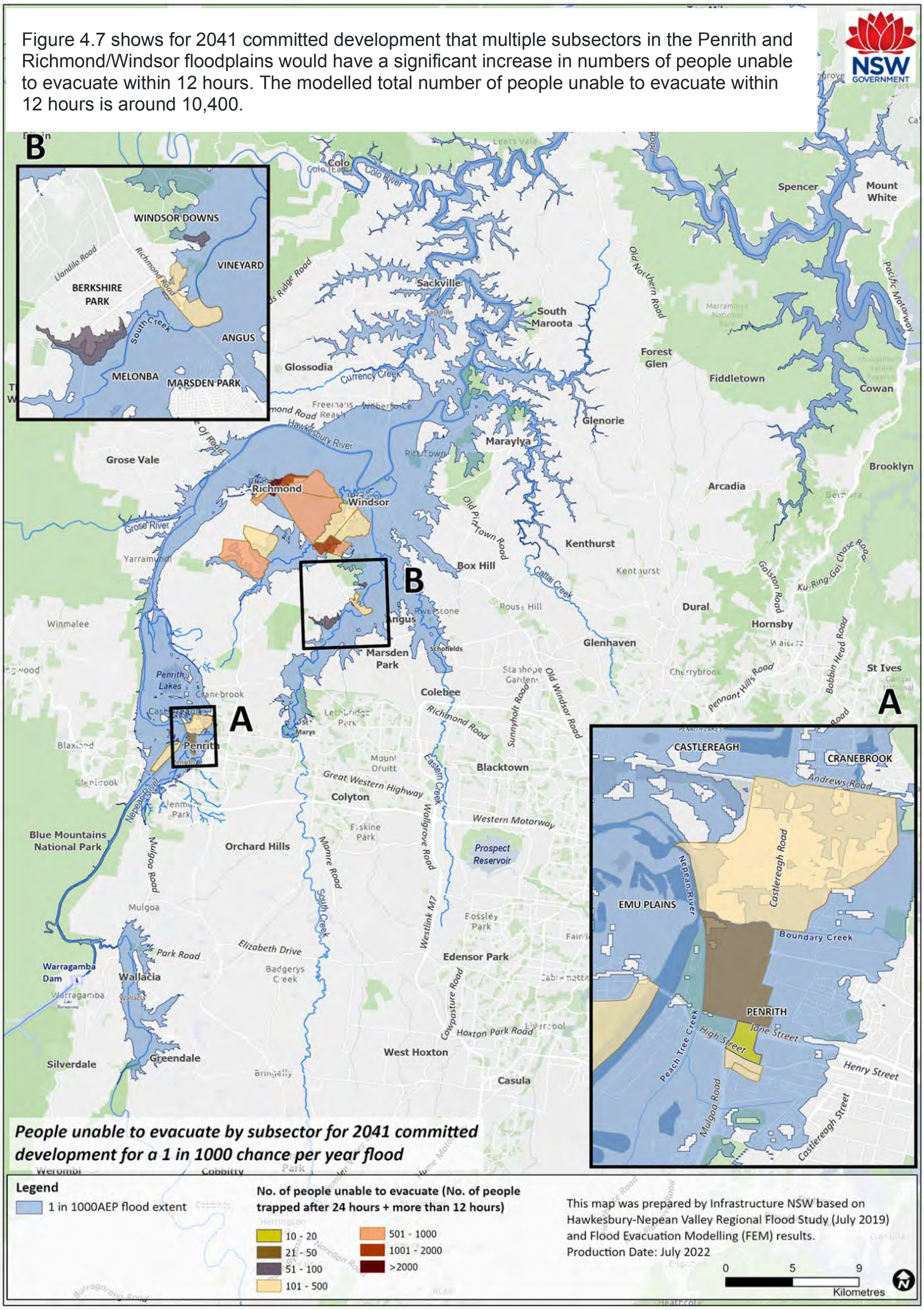

Figure 4.7: People unable to evacuate by subsector for 2041 committed development for a 1 in 1000 chance per year flood

Figure 4.8 shows the increase in the number of subsectors and people unable to evacuate under a medium mid-century climate change. The total number of people unable to evacuate within 12 hours would be around 23,200 compared to 10,400 without climate change, more than a doubling.

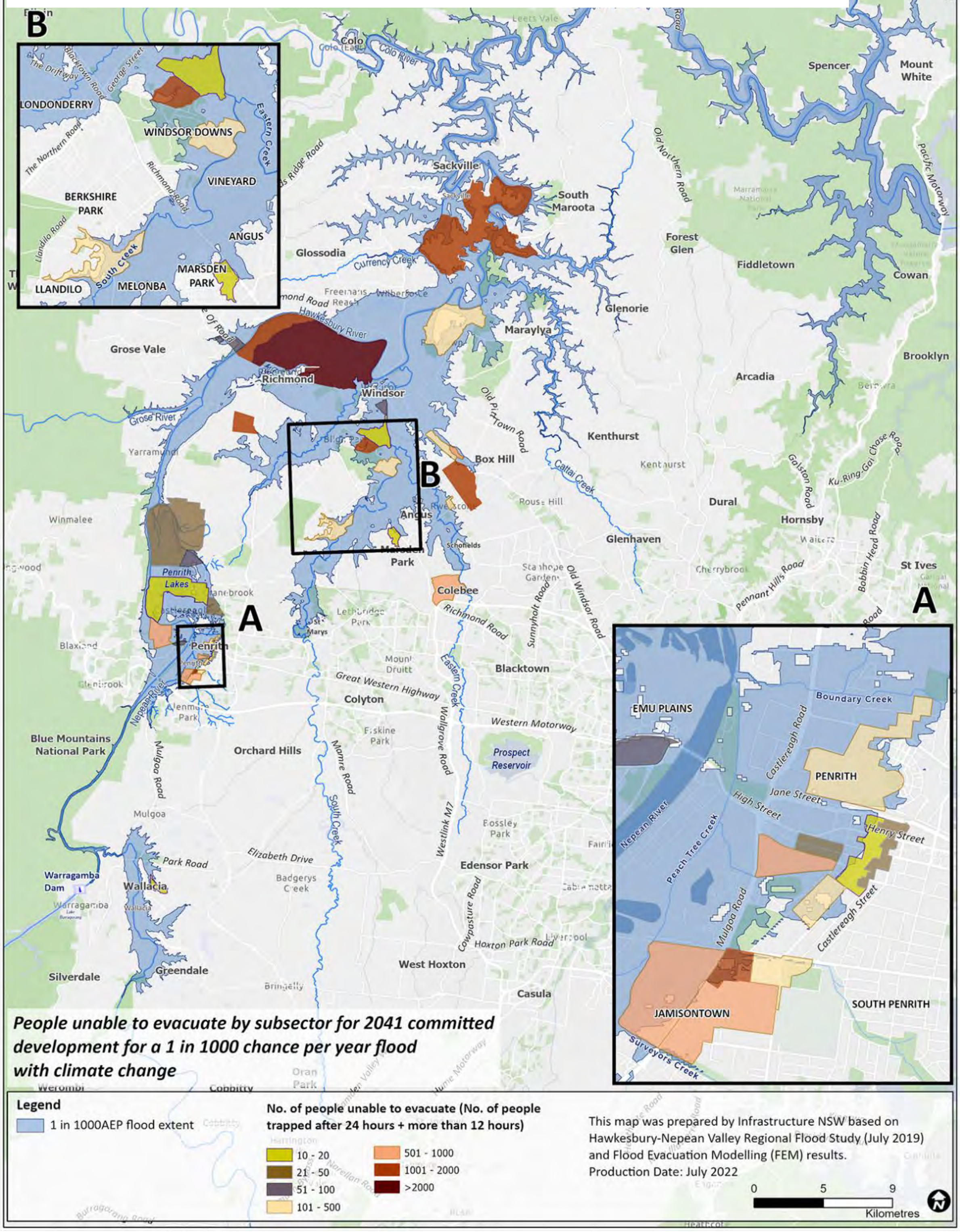

Figure 4.8: People unable to evacuate by subsector for 2041 committed development for a 1 in 1000 chance per year flood with climate change

7 | 2026 committed and potential development for a 1 in 500 chance per year flood

Figure 4.9 shows an increase in the number of subsectors and number of people unable to evacuate within 12 hours with potential development particularly for North Penrith and Penrith Lakes. Lower numbers are showing for Windsor and Marsden Park North. The total number of people unable to evacuate within 12 hours would be around 5600 compared to 820 for 2026 committed development only (Figure 4.3), nearly a 7 time increase.

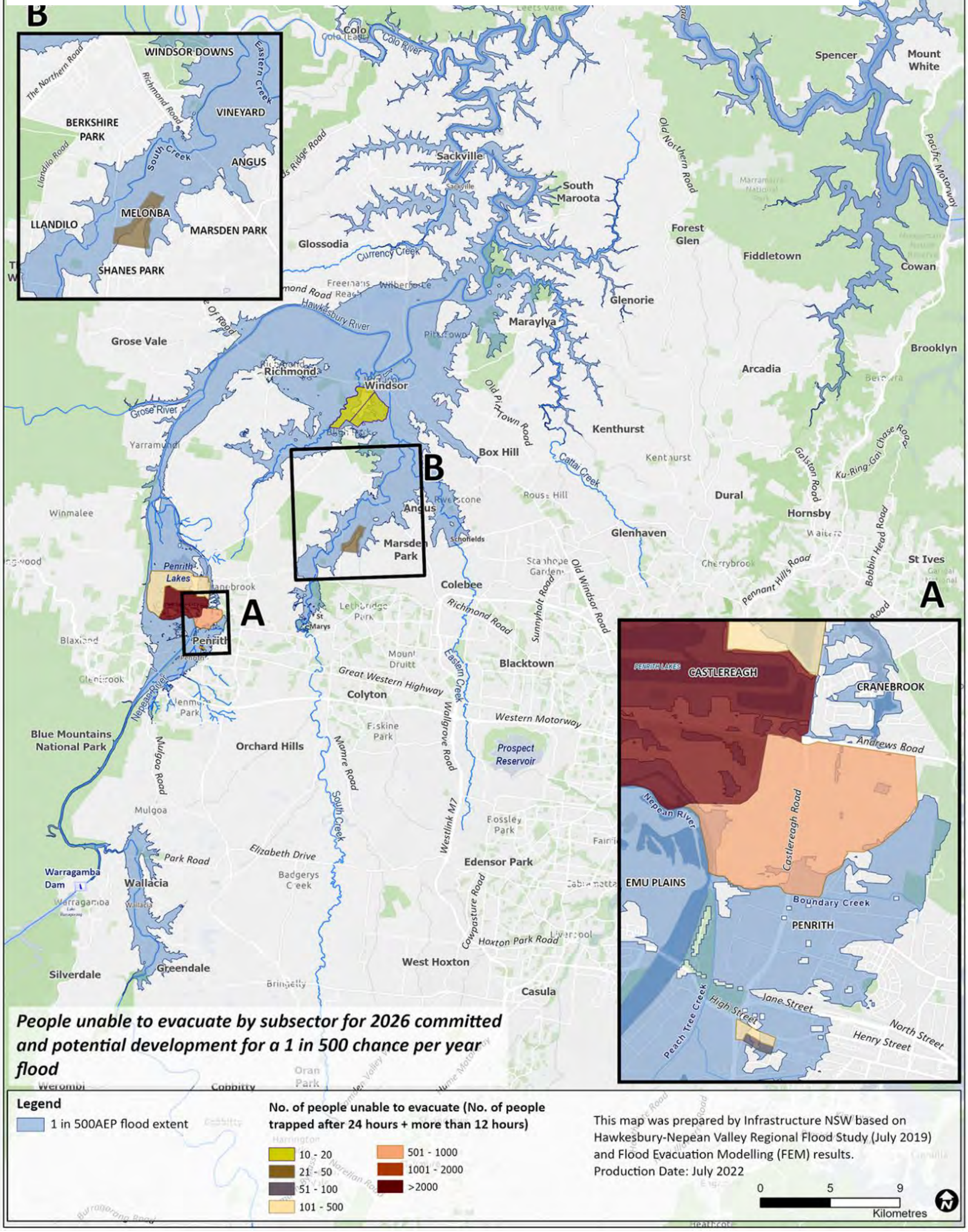

Figure 4.9: People unable to evacuate by subsector for 2026 committed and potential development for a 1 in 500 chance per year flood

8 | 2026 committed and potential development for a 1 in 1000 chance per year flood

Figure 4.10 shows an increase in the number of subsectors where significant people are unable to evacuate compared to Figure 4.4. Penrith, Penrith Lakes, Hawkesbury area and the NWGA show significant numbers of people unable to evacuate within 12 hours. The total number of people unable to evacuate for this scenario is around 13,700 compared to 2,900 for 2026 committed development for a 1 in 1000 chance per year flood – nearly a 5 times increase.

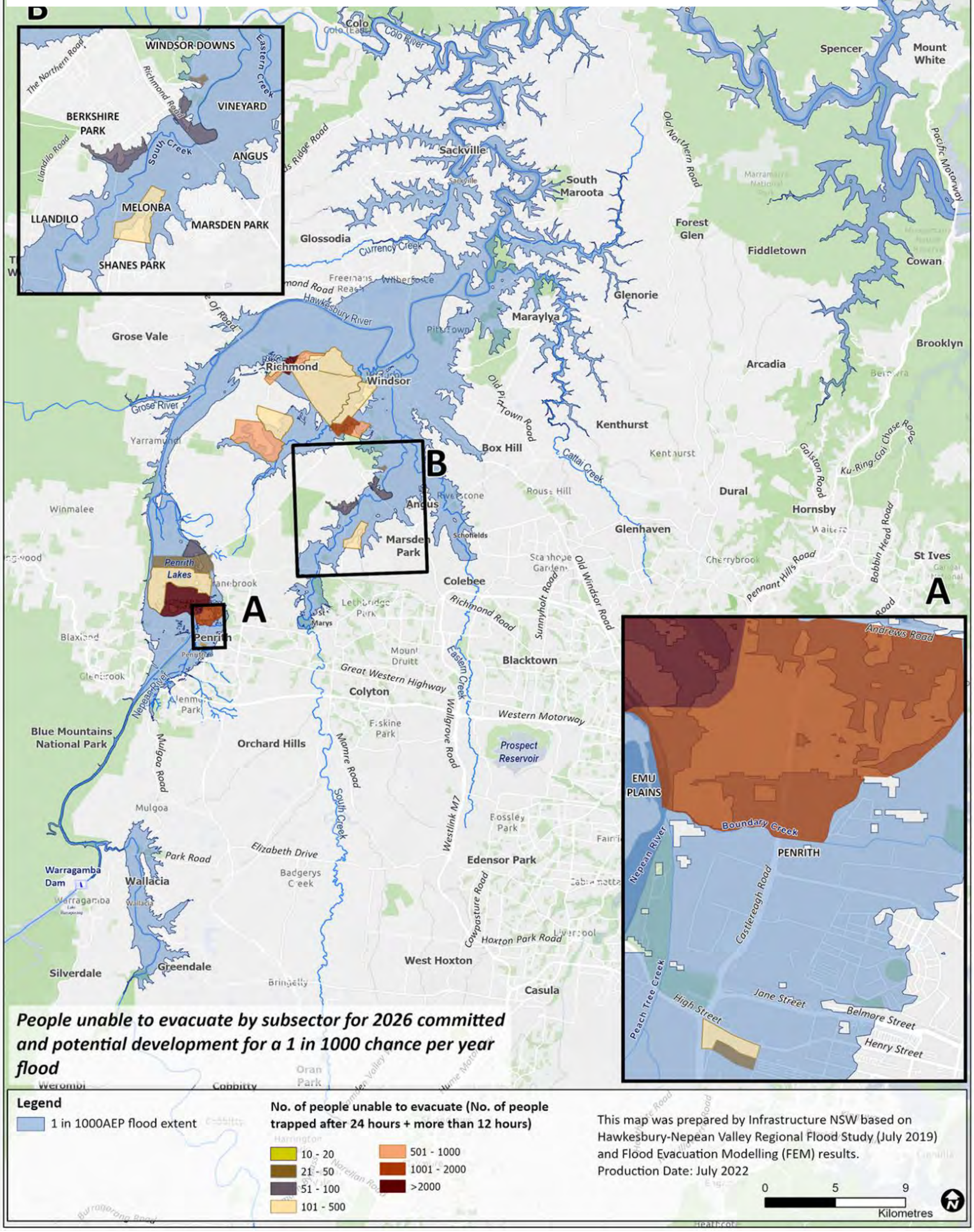

Figure 4.10: People unable to evacuate by subsector for 2026 committed and potential development for a 1 in 1000 chance per year flood

9 | 2041 committed and potential development for a 1 in 500 chance per year flood

Figure 4.11 shows that the addition of potential development increases the number of subsectors with people unable to evacuate within 12 hours, compared to Figure 4.6. The number of people unable to evacuate for this scenario is around 23,700 compared to 980 with 2041 committed development for this flood event, a 24 times increase.

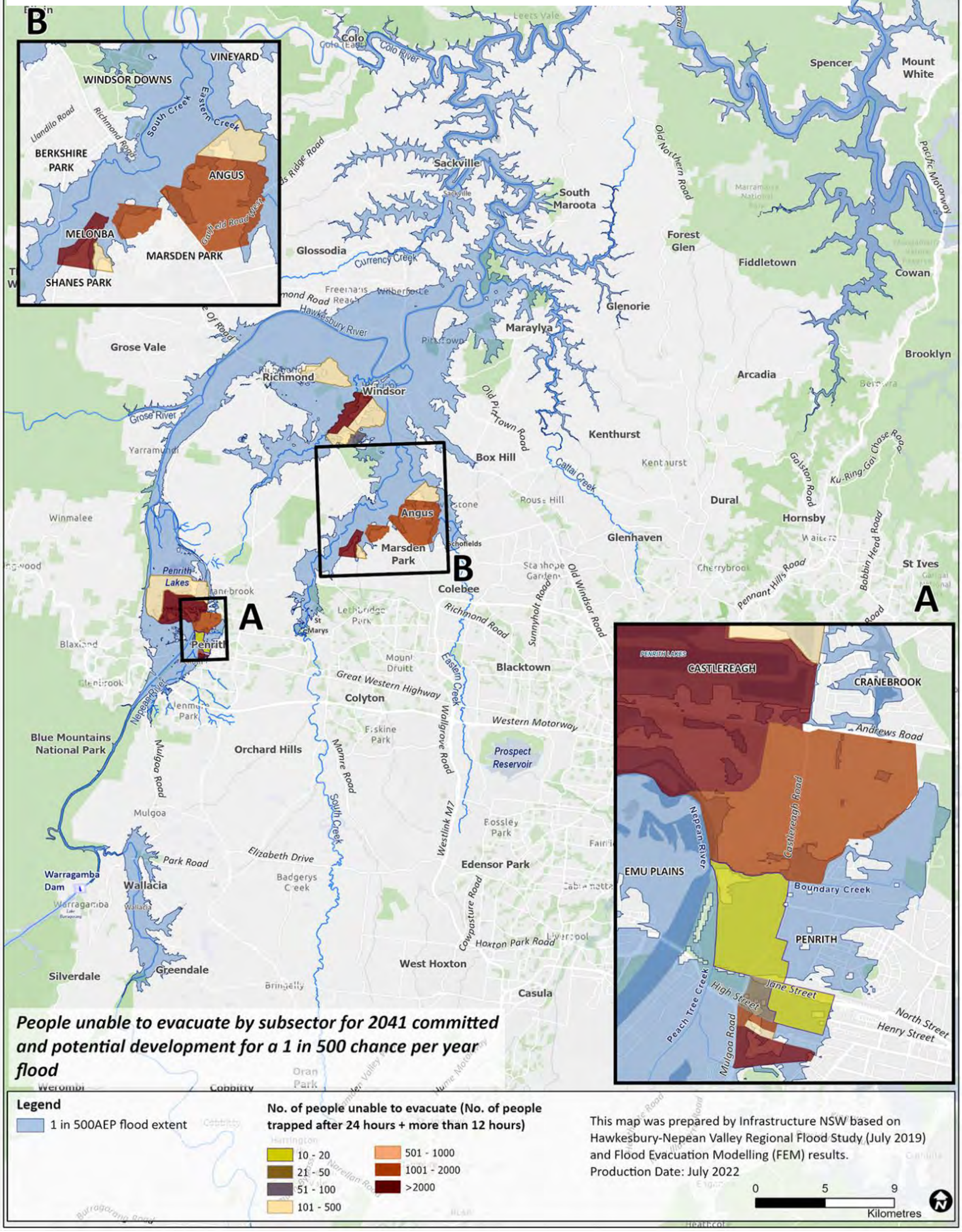

Figure 4.11: People unable to evacuate by subsector for 2041 committed and potential development for a 1 in 500 chance per year flood

10 | 2041 committed and potential development for a 1 in 1000 chance per year flood

Figure 4.12 shows that the addition of potential development increases the number of subsectors with people unable to evacuate compared to Figure 4.7. The number of people unable to evacuate for this scenario is around 45,900 compared to 10,400 with 2041 committed development for this flood event, around a 4.5 times increase.

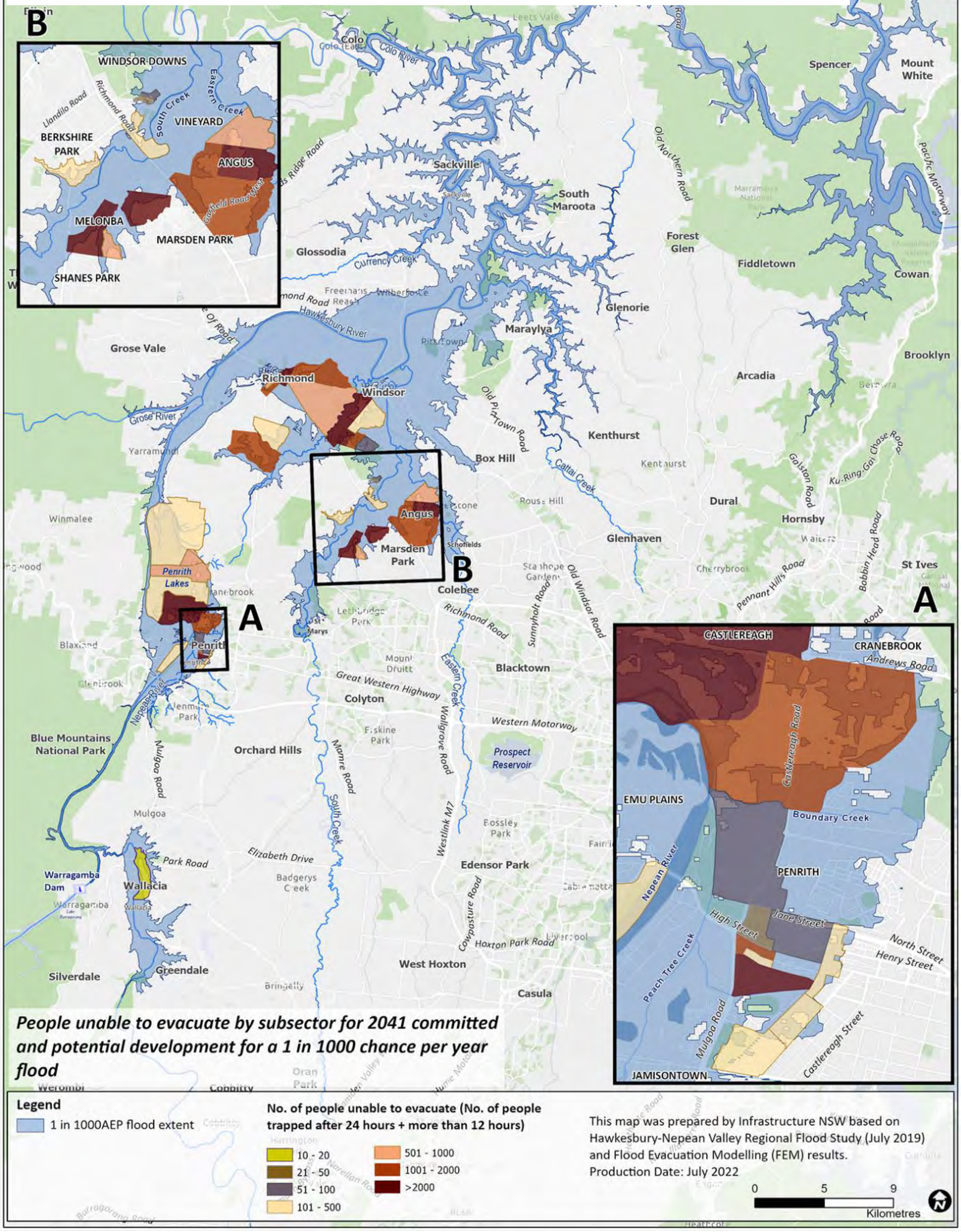

Figure 4.12: People unable to evacuate by subsector for 2041 committed and potential development for a 1 in 1000 chance per year flood

11 | Number of people at risk across the floodplain with potential development

Figure 4.13 shows that the larger the flood, the greater the number of people at risk. It also shows the spatial distribution of the flood risk across the valley for committed with potential development options for 2041.

In summary:

- for full development (4100 dwellings below PMF) at Marsden Park North (MPN) numbers of people unable to evacuate emerge at the 1 in 100 chance per year flood with a significant increase around the 1 in 200 chance per year flood
- West Schofields (2300 dwellings below PMF) and Riverstone Town Centre (3500 dwellings below PMF) show a similar impact with people unable to evacuate for floods with a 1 in 1000 chance per year flood or greater
- Hawkesbury Local Housing Strategy (3000 additional dwellings for 2041) shows that the additional 3000 dwellings have people unable to evacuate with a 1 in 80 chance per year flood and significantly increasing for larger floods
- Penrith City Centre Stage 2 (Pen 2 – 4050 dwellings) and Stage 3 (Pen 2 & 3 – further 6000 dwellings) shows that significant numbers of people would be unable to evacuate within 12 hours for floods for a 1 in 500 chance per year or greater. They show similar results up to the 1 in 2000 chance per year flood. The effect of Stage 3 shows an increase in the number of people unable to evacuate for floods at the 1 in 2000 chance per year or greater.
- For Penrith Lakes vehicles for the commercial and employment lands were modelled under a range to test the impact on people unable to evacuate across the floodplain. Under the lower range of 3500 vehicles (PL1) and the upper range of 10,400 vehicles (PL2), impacts emerge starting with floods at a 1 in 80 chance per year, with significantly higher number of people unable to evacuate at the upper range (PL2).[24]
- The variation in flood events shows the risk can vary based on factors such as the rate of rise and the sequence at which evacuation roads are cut. Therefore, the risk is not always directly related to the eventual flood peak, as seen by some results where the 1:2000 chance per year have a higher risk than the 1:5000 chance per year.

[24] Note that for Penrith Lakes no residential dwellings were modelled. The number of people were derived from vehicles related to commercial and employment lands.

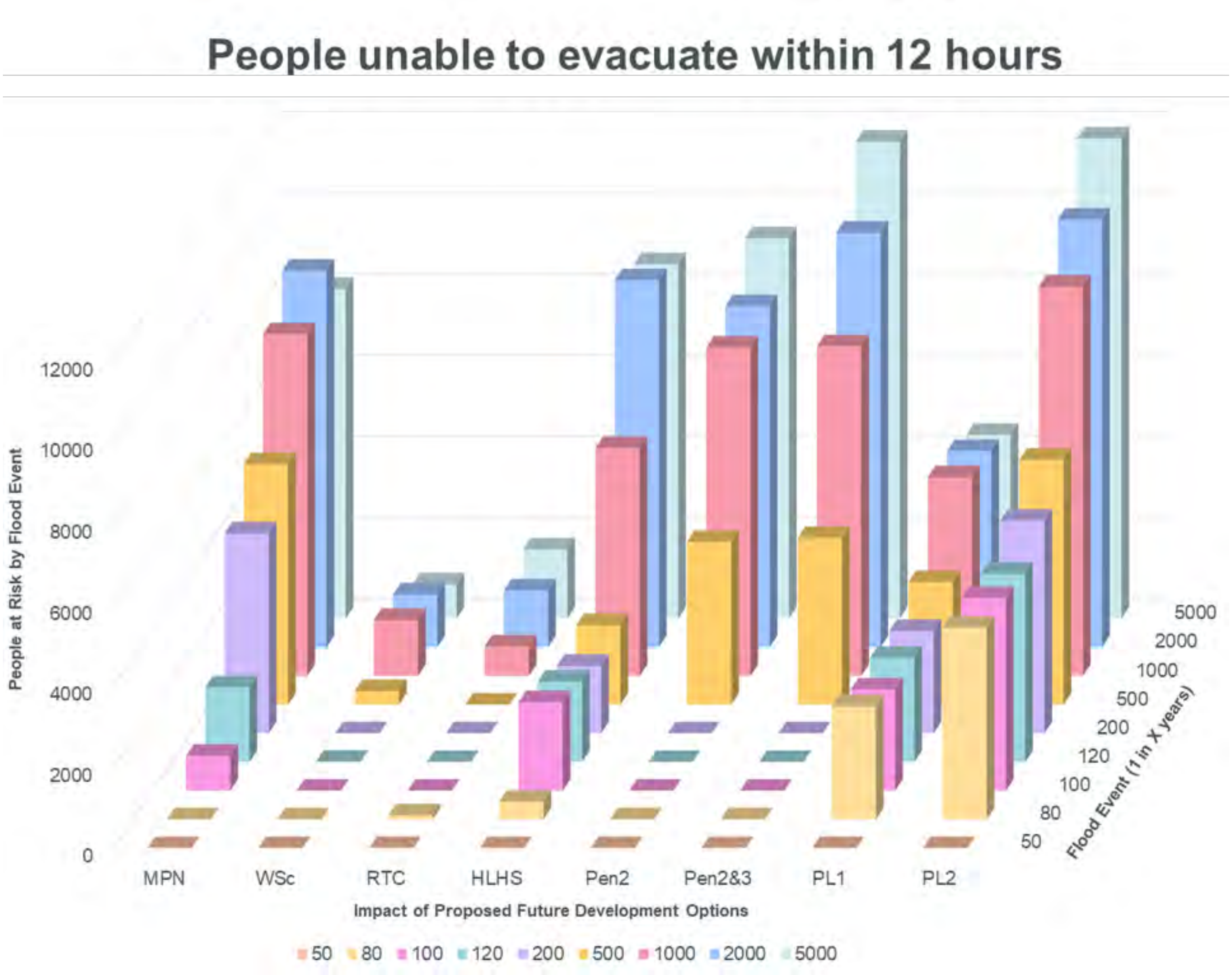

Figure 4.13: Number of additional people at risk for different flood events for 2041 potential development options

Key:

MPN – Marsden Park North	WSc – West Schofields	RTC – Riverstone Town Centre
HLHS – Hawkesbury Local Housing Strategy	Pen2 – Penrith Stage 2	Pen2&3 - Penrith Stage 2 and 3
PL1 – Penrith Lakes lower	PL2 – Penrith Lakes upper	

* This is based on current full supply level, operating rules and climate conditions.

12 | The Castlereagh Connection option

The Castlereagh Connection option is presented as an example of the effect of increased road evacuation capacity on the number of people unable to evacuate. This road option was modelled to test whether raising the crossing at South Creek from a 1 in 100 chance per year flood to a 1 in 500 chance per year flood event reduces the number of people unable to evacuate for different floods across the floodplain (Figure 4.14), and subsectors (Figure 4.15 to Figure 4.17).

Figure 4.14 shows that the Castlereagh Connection is most effective for committed development with most of the benefits to the Windsor/Richmond floodplain. For the 2041 committed and potential development scenario, the Castlereagh Connection provides limited benefits, mostly for the Windsor/Richmond floodplain. Figure 4.15 to Figure 4.17 show that most of the subsectors where there are still high numbers of people unable to evacuate are located in both the Penrith/Emu Plains and Windsor/Richmond floodplains for events greater than a 1 in 500 chance per year flood. This would significantly increase with the addition of potential development.

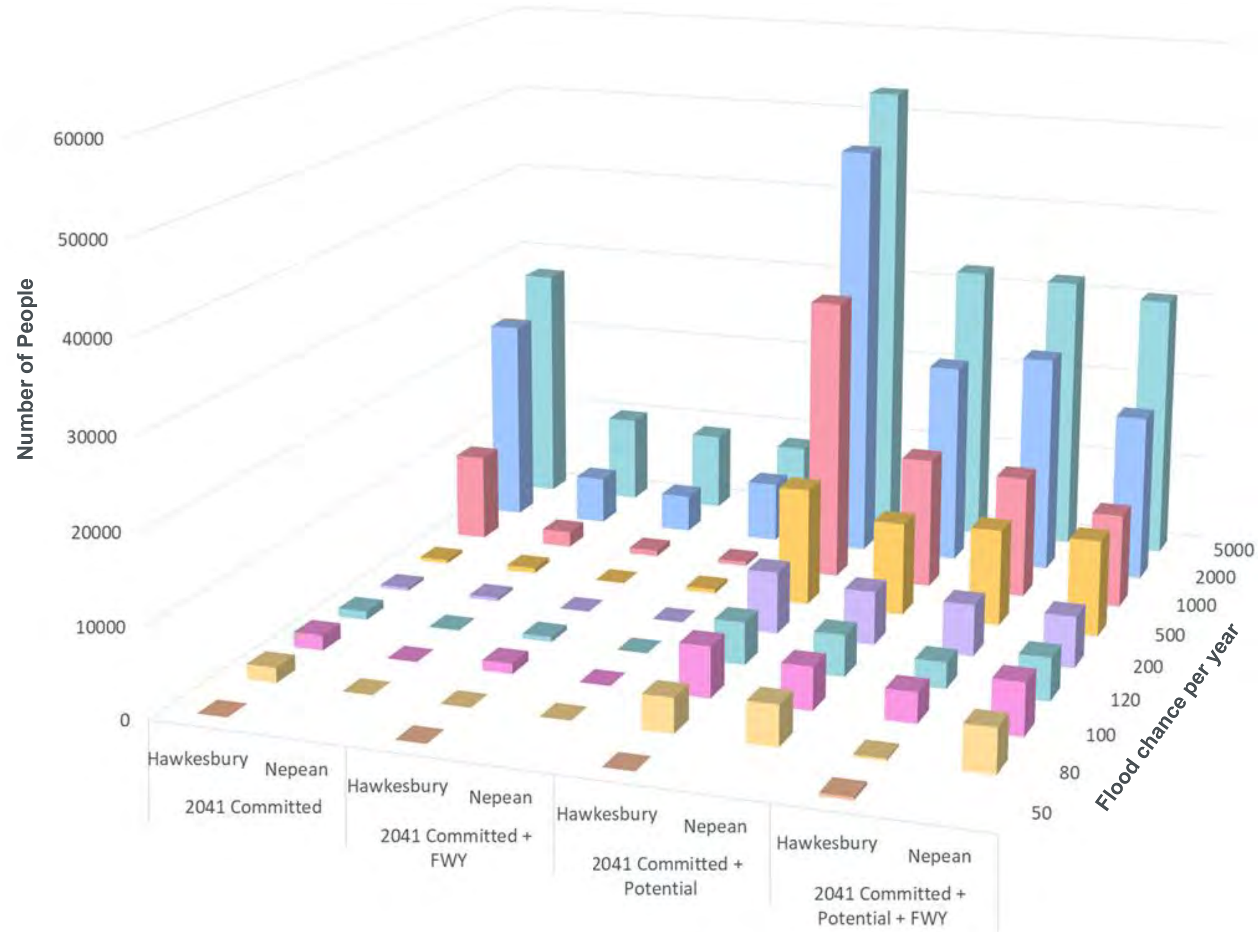

Figure 4.14: Number of people at risk for different flood events with and without Castlereagh Connection for the Hawkesbury (Richmond/Windsor) floodplains and Nepean (Penrith/Emu Plains) floodplains.

Comparing Figure 4.5 with Figure 4.15 shows that with 2041 committed development and a raised Castlereagh Connection, the benefits are primarily distributed to the Windsor-Richmond floodplain for a 1 in 500 chance per year flood. Subsectors in Penrith would still have people unable to evacuate within 12 hours.

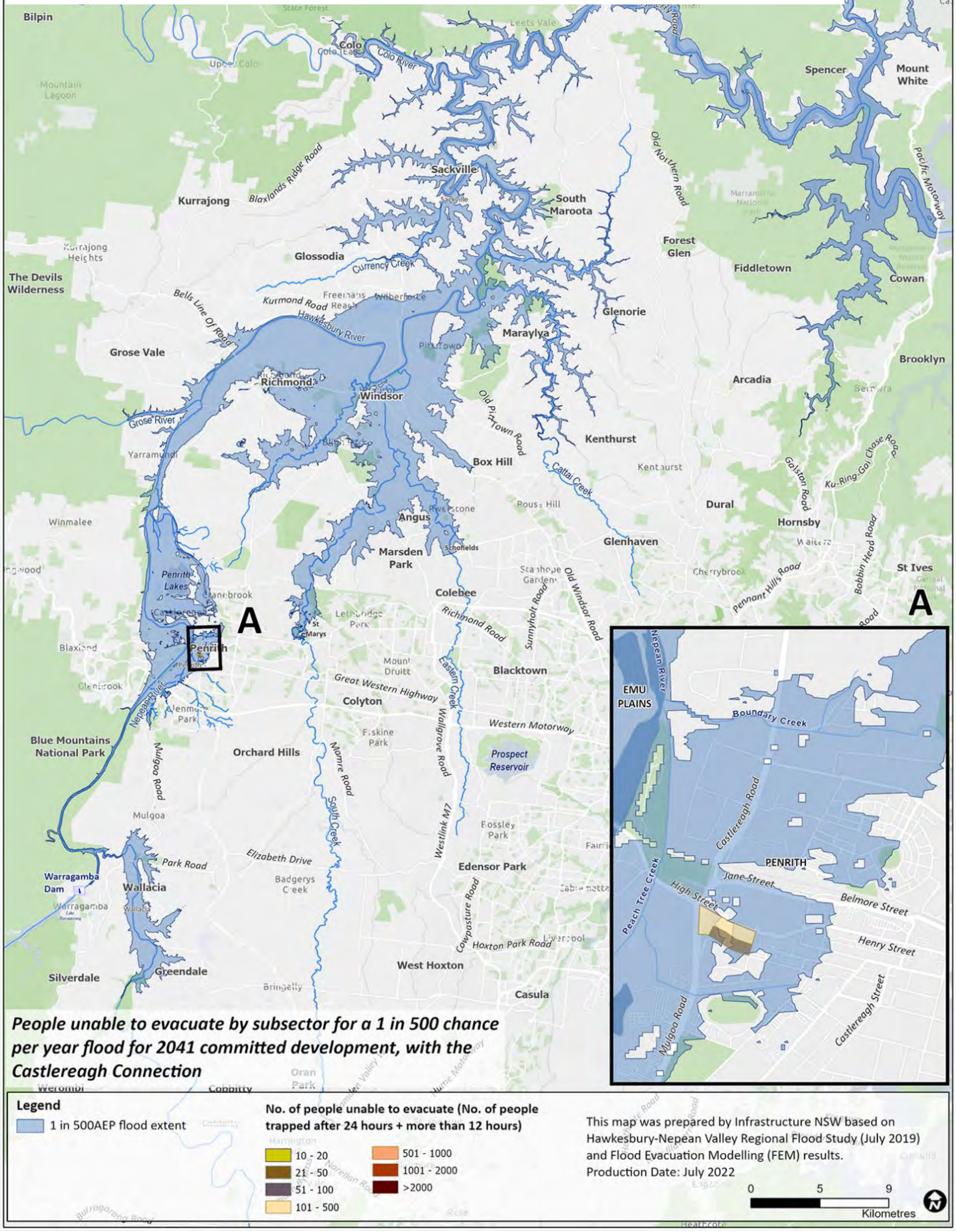

Figure 4.15: Subsectors where people are unable to evacuate for a 1 in 500 chance per year flood for 2041 committed development with the Castlereagh Connection

Comparing Figure 4.7 with Figure 4.16 shows that with 2041 committed development and a raised Castlereagh Connection, the number of people unable to evacuate within 12 hours would be reduced in both the Penrith/Emu Plains and Windsor/ Richmond floodplains for a 1 in 1000 chance per year flood. However, it would not eliminate the risk particularly with a 1 in 1000 chance per year flood.

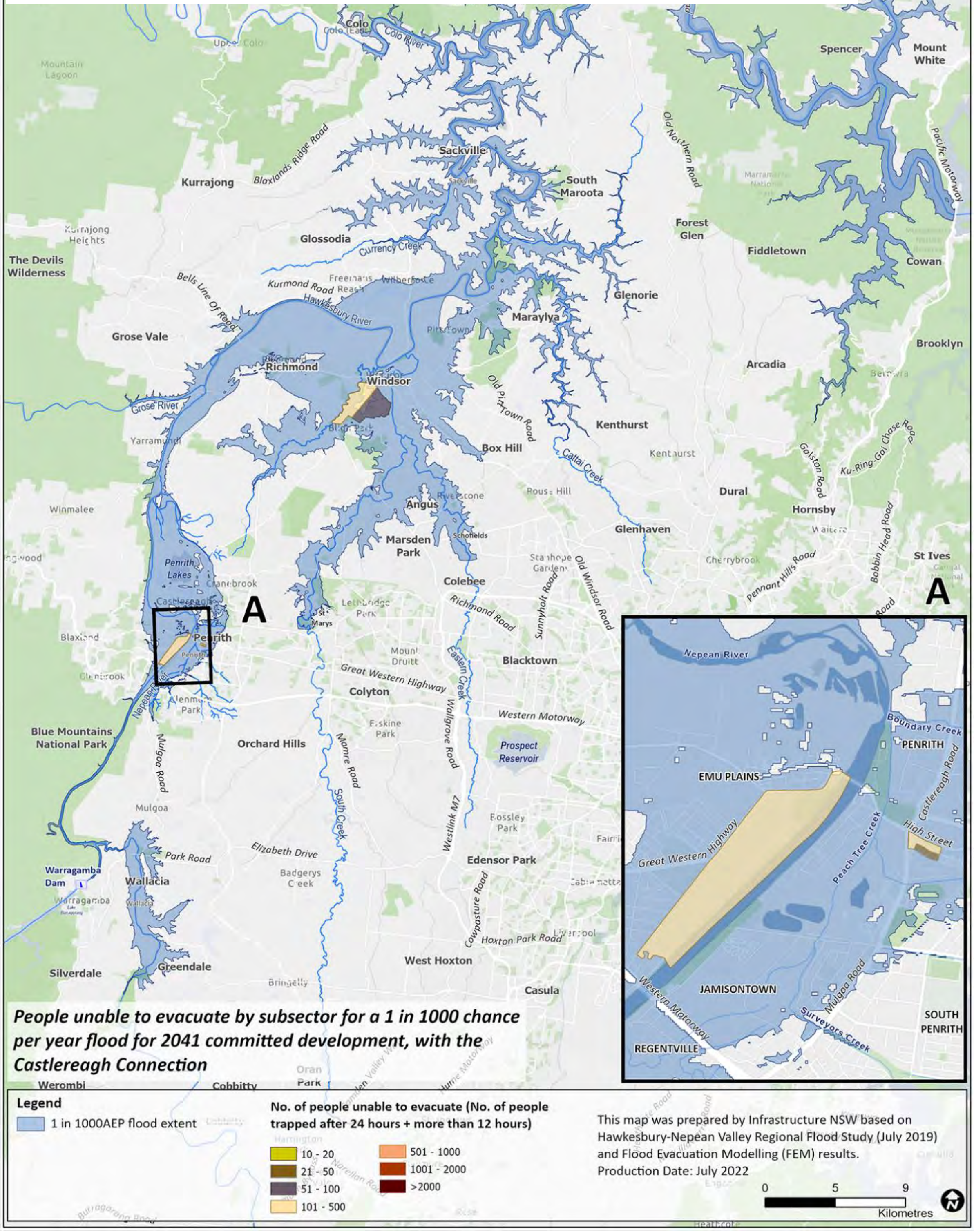

Figure 4.16: Subsectors where people are unable to evacuate for a 1 in 1000 chance per year flood for 2041 committed development with the Castlereagh Connection

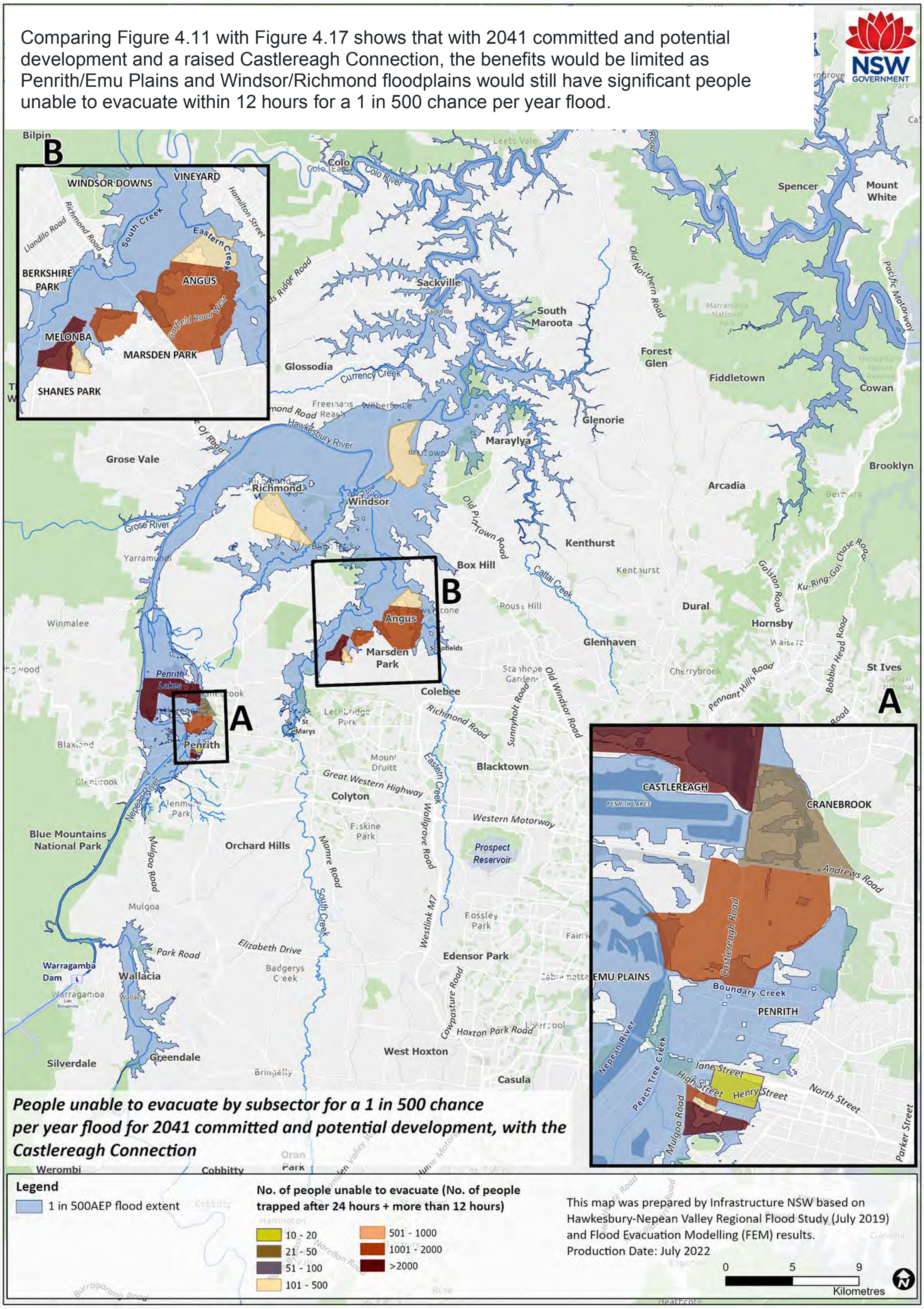

Figure 4.17: Subsectors where people are unable to evacuate for a 1 in 500 chance per year flood for 2041 committed and potential development with the Castlereagh Connection

4.4 Key findings

The key findings of the flood evacuation modelling and analysis are:

- Without any further rezonings in the valley there would still be an increase in the risk to life from committed development in existing areas.
- The addition of potential development areas of West Schofields, Riverstone Town Centre and Marsden Park North (partial) individually shows that the average annual people at risk would be similar to the risk for 2041 committed development. Combining these potential development areas would increase the average annual people at risk by almost 20% above the committed development risk for 2041.
- Potential development of 4,100 dwellings below the PMF in Marsden Park North by 2041 more than doubles the average annual people at risk. Only around 1,700 dwellings below the PMF would have similar average annual people at risk to life levels to the committed development.
- 3,500 vehicles and 10,400 vehicles were modelled to test the impact of potential commercial development at Penrith Lakes using current evacuation practice. This would increase the average annual people at risk from around 110% to 210% respectively across the floodplain.
- The average annual people at risk to life would increase by around 55% with potential development in Penrith City Centre Stage 2 and 3.
- Potential development in the Windsor and Richmond town centres forecast under the Hawkesbury Local Housing Strategy would increase the average annual people at risk by around 75%.
- Potential road network upgrades show the average annual people at risk would only reduce under 2041 committed development. For example, raising the Richmond Road bridge over South Creek, could reduce the average annual people at risk by almost 25%. Raising the Castlereagh Connection for a 1 in 500 chance per year flood would reduce the average annual people at risk by 71%. This benefit is concentrated in the Windsor/Richmond areas and assumes no potential development takes place.
- The benefits of the road options modelled are either negligible or significantly reduced for the majority of potential development scenarios.
- The number of people unable to evacuate increases significantly if all potential development was to occur. For example, for a 1 in 500 chance per year flood (similar to the worst flood on record) the risk to life would increase from an estimated 980 people under committed development to around 23,700 people by 2041.
- The number of people unable to evacuate also increases significantly with climate change. For example, for a 1 in 500 chance per year flood the estimated 980 people at risk under committed development would increase to around 6000 people with mid-century climate change.

4.5 Conclusion

The Hawkesbury-Nepean Valley's floodplains are highly interconnected by the road network. Growth in one area can have significant consequences on risk to life for existing populations across the floodplains.

The risk to life arising from flood evacuation varies across the valley and the FEM provides a better understanding of this risk distribution for different sized flood events. It allows for a more detailed understanding of the existing risk, the impact of development options and the cumulative impact of growth and climate change on the capacity of the shared road evacuation network.

The results highlight that the evacuation issue is not straightforward (a non-linear problem) and demonstrates the importance of modelling representative scenarios to evaluate the relative contribution of development options on risk to life.

The number of people who would be unable to evacuate increases significantly with development and climate change. Potential development above committed development further increases this risk.

The realisation of the level and timing of the risk to life will depend on external factors such as the global economy, rates of growth and climate change. However, scenario and sensitivity analysis show that while the actual timing and specific numbers related to risk to life might vary, the overall trend of increasing risk remains.

5 Next steps

Under Outcome 9 of the Flood Strategy and as part of best practice it is critical to monitor and evaluate the effectiveness of the management actions in light of new information. This work is ongoing due to the dynamic nature of flood risk in the valley. Future modelling will continue to test new scenarios and new information as it becomes available, dependent on funding for this project. This includes improved flood modelling, updated census data, climate change predictions, and if a flood occurs, consideration of different behavioural responses. In addition, continuous improvement in technology will allow more efficient modelling to reflect increased complexity and a higher number of scenarios.

5.1 Regional Land Use Planning Framework

Key findings from the FEM will inform the development options as part of the DPE's Regional Land Use Planning Framework for the Hawkesbury-Nepean.

Developing a Regional Land Use Planning Framework to respond to flood risk in such a diverse social, economic and environmentally sensitive area requires a collaborative approach. A one size fits all approach will not work given the diversity of the issues, risks and flood conditions.

Actions need to be identified and considered using a regional approach, integrating flood risk and land use potential. These actions will guide a future settlement pattern for the valley. The development of the Framework will be drawn from 3 key elements:

- Flood behaviour – how the flood waters move through the catchment
- The population at risk – utilising the latest housing data from DPE and councils
- Risk to life – the ability of the population to safely evacuate the valley, where current constraints lie, and where any dwelling increases could impact that evacuation ability. The framework will help improve the resilience of the valley to floods, including managing the impact of cumulative growth on road evacuation capacity and risk to life.

5.2 Continuous improvement of data and methods

Planned improvements to input data include:

2022 Hawkesbury-Nepean River Flood Study incorporating climate change

The FEM is based on 91 flood events selected from the 19,500 1D RUBICON flood model results. The quasi 2-dimensional flood model allows for a large number of flood models to be run as it is a simplified representation of complex hydraulics of the floodplain.

Under the Flood Strategy, INSW is developing a 2-dimensional (2D) Hawkesbury-Nepean River Flood model for the valley, with results expected in mid-2023. FEM modelling will be revised within the next 12 months to reflect any significant changes. The quasi 2-dimensional model will still be required for a large number of flood events using a Monte Carlo approach.

As part of continuous improvement, updated climate change information will be incorporated into the ongoing flood modelling work.

Updating property, population and vehicle data

Central to the estimation of flood risk is the spatial analysis of current and projected development in the valley. The "current" development is based on the end of 2018 data and will be revised to account for recent development and the latest census data. Throughout 2022 the Australian Bureau of Statistics will release the results of the August 2021 census. This, together with collection of data from DPE and local councils and analysis of aerial photography, provides the opportunity to update the 2018 scenario. The 2026 and 2041 data sets may also need to be revised and updated to reflect new information. This will be done in the next 18 months.

Improvements to flood forecasting and warning

Over the next 2 years, the Bureau will be working with its key partners to operationalise the improved flood forecasting product developed for the Hawkesbury-Nepean. This flood forecasting product will assist operational planning by showing the range of flood levels that occur out to 36 hours. However, as there can still be a wide range of potential flood levels predicted early in a flood, these probabilistic forecasts would not be used to trigger evacuations but to assist resource and operational planning. This new methodology will require training, testing and validation.

Flood fatality modelling

The fatality rates depend on a range of factors including the flood depth and velocity, housing structure, vehicle types, and behavioural responses. The flood evacuation modelling estimates flood risk to life based on failure of the mass self-evacuation of the valley assuming 100% response to the order to evacuate. This is because we plan for giving everyone the capacity to evacuate from the full range of flood events. However, in a flood emergency people display a range of responses. Some people are unable to or choose not to evacuate and shelter in place instead. Others evacuate late and are impacted in vehicles by floods over roads.

An alternative method of estimating the number and cause of flood fatalities is to use a flood fatality model. This simulates people being impacted within vehicles, in dwellings, and on foot using behavioural factors, building and vehicle types, subject to flood depth and velocity throughout the model flood event.

To assess the potential type and distribution of fatalities from flood events, flood fatality modelling would be required to better understand the range of flood risk to life. However, this requires more detailed 2-dimensional (2D) modelling of flood dynamics. A flood fatality model will be explored to test the flood fatality method as part of ongoing work, following completion of the 2-dimensional flood study modelling.

Taking the FEM forward

The FEM is a critical decision support tool which will inform a range of government planning and investment decisions for high risk flood areas. The NSW Government will develop protocols and guides for its ongoing development and use over the longer term to inform integrated land use, road and emergency planning for flooding. This is dependent on future funding.

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