Infrastructure Victoria

Adapting Victoria's infrastructure to climate change

Phase 3: Economic analysis of adaptation for roads

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Acknowledgement of Country

Arup acknowledges the Traditional Custodians of the land on which our offices are located and pay our respects to Elders past, present, and emerging. We recognise and celebrate their continuing connection to the land and waters, and their cultures, traditions, and protocols.

Glossary

The glossary builds upon previous phases of the *Adapting Victoria's infrastructure to climate change* project.

Key term	Definition
Adaptation (to climate change)	In human systems, the process of adjustment to actual or expected climate and its effects, to moderate harm or exploit beneficial opportunities. In natural systems, the process of adjustment to actual climate and its effects; human intervention may facilitate adjustment to expected climate and its effects (IPCC, 2022). Adaptation actions may include physical changes to an asset to achieve or facilitate adaptation including changes/upgrades to technology and equipment, design standards for particular project elements, operational actions, or natural resource management actions (e.g., assisted colonisation, mixed-provenance plantings, restoration of key connectivity pathways to enable movement).
Adaptive capacity	The ability of institutions, systems, humans and other organisms to adjust to potential damage, to take advantage of opportunities, or to respond to consequences of environmental variability and change (IPCC, 2022). It includes adjustments in both behaviour and in resources and technologies (PIARC, 2015).
Adaptive planning pathways	Adaptive planning is anticipatory instead of responsive and explicitly recognizes uncertainties about the future and takes these into account in the management planning (Klijn, Kreibich, & Penning-Rowsell, 2015). It combines techniques from Dynamic Adaptive Policy Pathways approach that aim to support the development of an adaptive plan that is able to deal with conditions of deep uncertainties. Adaptive planning pathways specify actions to be taken immediately to be prepared for the near futures and actions to be taken now to keep options open to adapt if needed in the future (Hasnoot, Kwakkel, Walker, & Maat, 2013).
Annual Average Daily Traffic Volume (AADT)	Annual Average Daily Traffic (AADT) volume refers to the average number of vehicles that pass a specific point on a roadway over a year; the total number of vehicles passing in that year divided by the number of days in that year.
Annual Exceedance Probability (AEP)	The probability of a hazard event occurring in any given year. For example, 1% AEP indicates there is a 1% chance of the event occurring or being exceeded in any given year.
Arterial Road	A higher order road providing for moderate to high volumes, at relatively higher speeds. Arterial roads are typically used for inter-suburban or inter-urban journeys, often linking to freeways. Declared roads are classified under the Road Management Act 2004 as freeways, arterial roads and non-arterial state roads. Declared roads are managed by the Department of Transport and Planning (Department of Transport and Planning, 2023).
Average Annual Downtime (AAD)	Average Annual Downtime (AAD) is a metric used to quantify the expected amount of time per year that an asset or system will be unavailable or inoperable due to unplanned or planned maintenance, repairs, or other disruptions. AAD is calculated by estimating the total amount of downtime over a certain period and dividing it by the number of years in that period.
Average Annual Loss (AAL)	Average Annual Loss (AAL) is a risk management metric that quantifies the expected loss per year over the lifetime of an asset or system due to a particular risk. It is calculated by estimating the total cost of potential losses due to the risk and dividing it by the number of years in the asset's lifespan.
Average Recurrence Interval (return period)	Average number of years between exceedances of a hazard event of the same size.
Cascading impacts	Occur when a hazard generates a sequence of secondary events in natural and human systems that result in physical, natural, social or economic disruption, whereby the resulting impact is significantly larger than the initial impact (IPCC, 2022).
Climate change	A change in the state of the climate that persists for an extended period, typically decades or longer (IPCC, 2022).

Key term	Definition
	Climate change may be due to natural variability or a result of human activity.
Climate change allowance	Prediction of anticipated change for peak river flow, peak rainfall intensity, sea level rise, and offshore wind speed and extreme wave height. There are allowances for different climate scenarios over different epochs, or periods of time, over the coming century (Environment Agency UK, 2022). Climate change allowances are sourced from the Australian Rainfall Runoff Guidelines (Geoscience Australia, 2019).
Climate projections	Simulated response of the climate system (including variables such as temperature, precipitation, wind, solar radiation, sea level) to a scenario of future emissions or concentrations of greenhouse gases and changes in land use, generally derived using climate models. Climate projections depend on an emission scenario, in turn based on assumptions concerning factors such as future socioeconomic and technological developments that may or may not be realised (IPCC, 2022).
Climate variables	Factors that determine and govern the climate. Main factors include rainfall, atmospheric pressure, wind speed, wind direction, humidity, average and maximum temperature (PIARC, 2015). Changes in climate variables (such as temperature) can lead to changes in climate hazards (such as heatwaves).
Compound events	The combination of multiple drivers and/or hazards that contributes to societal and/or environmental risk (IPCC, 2022).
Consequence	Outcome of an event affecting objectives. A consequence can be certain or uncertain and can have positive or negative direct or indirect effects on objectives. Any consequence can escalate through cascading and cumulative effects (ISO, 2019).
Direct tangible risk	Quantifiable losses incurred as a result of a disaster event that have a direct market value, including damage and downtime.
El Niño Southern Oscillation (ENSO)	The term El Niño was initially used to describe a warm-water current that periodically flows along the coast of Ecuador and Peru, disrupting the local fishery. It has since become identified with warming of the tropical Pacific Ocean east of the dateline. This oceanic event is associated with a fluctuation of a global-scale tropical and subtropical surface pressure pattern called the Southern Oscillation. This coupled atmosphere–ocean phenomenon, with preferred time scales of two to about seven years, is known as the El Niño-Southern Oscillation (ENSO). It is often measured by the surface pressure anomaly difference between Tahiti and Darwin and/or the sea surface temperatures in the central and eastern equatorial Pacific. During an ENSO event, the prevailing trade winds weaken, reducing upwelling and altering ocean currents such that the sea surface temperatures warm, further weakening the trade winds. This phenomenon has a great impact on the wind, sea surface temperature and precipitation patterns in the tropical Pacific. It has climatic effects throughout the Pacific region and in many other parts of the world, through global teleconnections. The cold phase of ENSO is called La Niña.
Exposure	The presence of people, livelihoods, species or ecosystems, environmental services and resources, infrastructure, or economic, social, or cultural assets in places that could be adversely affected (IPCC, 2022).
Extreme weather event	An event that is rare at a particular place and time of year. The characteristics of what is called extreme weather may vary from place to place (IPCC, 2022).
Forest Fire Danger Index (FFDI)	FFDI is an index that combines measurements of temperature, relative humidity, wind speed, and fuel moisture content to calculate a single number that represents the potential for fire in a given area. High FFDI values indicate that the conditions are favourable for a fire to start and spread quickly, while low values indicate that the risk of fire is relatively low.
Greenhouse gases	Gaseous constituents of the atmosphere that absorb and emit radiation at specific wavelengths within the spectrum of radiation emitted by the Earth's ocean and land surface, by the atmosphere itself, and by clouds. This property causes the greenhouse effect. Water vapor, carbon dioxide, nitrous oxide, methane and ozone are the primary greenhouse gases in the Earth's atmosphere (IPCC, 2022).
Hazard (climate hazard)	The potential occurrence of a natural or human-induced physical event or trend or physical impact that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems, and environmental resources (IPCC, 2022).

Key term	Definition
Indian Ocean Dipole (IOD)	The Indian Ocean Dipole (IOD) is defined by the difference in sea surface temperature between two areas (or poles, hence a dipole) – a western pole in the Arabian Sea (western Indian Ocean) and an eastern pole in the eastern Indian Ocean south of Indonesia. The IOD affects the climate of Australia and other countries that surround the Indian Ocean Basin and is a significant contributor to rainfall variability in this region.
Indirect tangible risk	Tangible flow-on effects not directly caused by the disaster event, but arise as an external consequence, including wider economic impacts associated with infrastructure damage or downtime.
Infrastructure	The designed and built set of physical systems and corresponding institutional arrangements that mediate between people, their communities, and the broader environment to provide services that support economic growth, health, quality of life, and safety (IPCC, 2022).
Intangible risk	Direct and indirect damage that cannot easily be quantified, including cultural and heritage value.
Likelihood	The chance of something happening (ISO, 2019).
Mitigation (of climate change)	Actions taken globally, nationally and individually to reduce greenhouse gas emissions and/or increase the amounts of greenhouse gases removed from the atmosphere by greenhouse sinks (IPCC, 2022).
Representative Concentration Pathways (RCPs)	Scenarios that include time series of emissions and concentrations of greenhouse gases and aerosols and chemically active gases, as well as land use/land cover. The word representative signifies that each RCP provides only one of many possible scenarios. The term pathway emphasises the fact that not only the long-term concentration levels, but also the trajectory taken over time to reach that outcome are of interest (IPCC, 2022).
Resilience (climate resilience)	The capacity of interconnected social, economic and ecological systems to cope with a hazardous event, trend or disturbance, responding or reorganising in ways that maintain their essential function, identity and structure (IPCC, 2022).
Risk	The potential for adverse consequences for human or ecological systems, recognising the diversity of values and objectives associated with such systems. In the context of climate change, risks can arise from potential impacts of climate change as well as human responses to climate change. Climate-related risks result from dynamic interactions between climate-related hazards with the exposure and vulnerability of the affected human or ecological system to the hazards (IPCC, 2021)
Southern Annular Mode	The Southern Annular Mode, or SAM, is a climate driver that can influence rainfall and temperature in Australia. The SAM refers to the (non-seasonal) north-south movement of the strong westerly winds that blow almost continuously in the mid- to high-latitudes of the southern hemisphere. This belt of westerly winds is also associated with storms and cold fronts that move from west to east, bringing rainfall to southern Australia. The SAM has three phases: neutral, positive and negative. Each positive or negative SAM event tends to last for around one to two weeks, though longer periods may also occur. The time frame between positive and negative events is quite random, but typically in the range of a week to a few months. The effect that the SAM has on rainfall varies greatly depending on season and region.
Sub-tropical ridge	The sub-tropical ridge is a belt of high pressure that encircles the globe in the middle latitudes. It is part of the global circulation of the atmosphere. During warmer months the ridge is positioned to the south and is often associated with stable high pressures over southern Australia. During cooler months the ridge position moves towards the equator. The equatorward movement of the subtropical ridge during the cold season is due to increasing north-south temperature differences between the poles and tropics.
Vulnerability	The degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes (PIARC, 2015). Vulnerability encompasses a variety of concepts and elements, including sensitivity or susceptibility to harm and lack of capacity to cope and adapt (IPCC, 2022).

Executive summary

Climate change is causing pervasive and diverse impacts on Victorian infrastructure that will cascade through the economy and society into the future. Extreme temperatures, bushfires, floods, and sea level rise will increasingly disrupt critical systems and services, exacerbate existing vulnerabilities, and present material financial risks. Infrastructure will be grossly affected by the physical impacts of climate change but will also continue to play a pertinent role in building the resilience of communities in the face of climate-related shocks and stresses.

Economic analysis of infrastructure adaptation investments does not always consider the wider costs and benefits of climate-related impacts on society, which can result in under-investment in resilience. As such, Victoria needs a replicable, robust, and comprehensive approach to identify, quantify, and articulate common costs and benefits of adaptation to climate change that can be applied to adapting existing infrastructure and enhancing infrastructure resilience.

As part of its research program, Infrastructure Victoria is assessing the risks and opportunities of adapting Victoria's infrastructure to climate change. The project considers existing climate change adaptation actions in Victoria, identifies priority adaptation measures to improve the resilience of infrastructure in response to climate-related risks and evaluates the return on investment for adaptation actions.

Infrastructure Victoria engaged Arup to build the economic case for appropriate action and investment in climate resilient roads by asking the following question:

What is the economic return on investment for selected climate change adaptation measures in selected Victorian Government infrastructure sectors?

This study addresses the question through the following objectives:

- Build a case for further government action and investment in resilient infrastructure by identifying quantitative and qualitative upstream and downstream costs and benefits (including economic, social, and environmental impacts) of investing in climate adaptation measures for roads, and the potential costs of no or limited action when factoring in the growing risks from climate change.
- Determine return-on-investment for adaptation actions in the context of increasing climate risks over time, recognising the impact of staged implementation.
- Present a replicable, robust, and scalable methodology for measuring and valuing investment in climate adaptation for infrastructure.

This report has been written alongside a separate assessment of potential climate adaptation measures for wind hazards affecting electricity distribution infrastructure, led by ACIL Allen.

Approach and Methodology

Building the economic case for adaptation action comprises four key stages:

1. Climate risk assessment: detailed quantitative and semi-quantitative risk assessment to calculate the direct, indirect, and intangible risks of climate-related hazards for road infrastructure.
2. Adaptation measures: identification and assessment of higher and lower-cost investments, maintenance, and hazard management adaptation measures to mitigate climate-related risks for road infrastructure.
3. Comprehensive economic analysis: valuation of direct, indirect, and intangible costs and benefits (avoided losses) associated with priority adaptation measures to inform economic analysis using net present values (NPV) and benefit-cost ratios (BCR).
4. Case for investment in adaptation: holistic appraisal of economic analysis results, consideration of project-specific requirements and values, and application of adaptive planning pathway principles.

Due to the inherent uncertainty of climate change, climate risk has been considered for two climate scenarios and time horizons to ensure that proposed adaptation measures are robust under multiple plausible futures. Climate risk under current climate conditions in 2022 is compared to future climate conditions in the year 2070 based on a high emissions pathway known as Representative Concentration Pathway 8.5 (RCP8.5).

The methodology is applied to two de-identified, hypothetical road exemplars with climate-related risks that were prioritised in previous project phases:

- Damage to road surfaces caused by flooding and/ or extreme rainfall events.
- Service interruption of roads caused by bushfires and subsequent rainfall-induced landslides.

While these exemplars are grounded in real data, they do not refer to a specific location and contain asset and hazard features representative of multiple locations across Victoria. Some cost and vulnerability assumptions used in the economic analysis for the exemplars may be appropriate for use in future infrastructure projects, however ultimately every adaptation implementation project needs to be site-specific to respond to unique factors such as infrastructure age, hazard exposure, and asset criticality.

Priority adaptation measures

Eight priority adaptation measures are identified and assessed for each of the two exemplars in this report. These measures represent a range of higher-cost and lower-cost investments, maintenance, and hazard management adaptation options which could be implemented in various locations and projects across Victoria to address flood and bushfire/ landscape hazards. These are summarised below:

Adaptation measures for flooding risk
Foamed bitumen stabilisation
Optimise road grade and drainage with immunity to future 5% AEP (20-year return period with a climate change allowance)
Staged design to optimise road grade and drainage with immunity to future 5% AEP (20-year return period with a climate change allowance), and uplift to future 1% AEP (100-year return period with a climate change allowance)
Viaduct with immunity to future 0.2% AEP (500-year return period with a climate change allowance)
Water Sensitive Urban Design (WSUD) including catchment upgrades to achieve immunity to future 20% AEP (5-year return period with climate change allowance)
Increased frequency of preventative maintenance
Increased frequency of programmed rehabilitation
Hazard management including early warning system, heavy load limits, and temporary rerouting
Adaptation measures for bushfire and landslide risk
Remediate the two highest risk slopes (ALR2 pre-bushfire) with flexible barriers.
Remediate the eleven high and moderate risk slopes (ALR2 and ARL3 pre-bushfire) with flexible barriers.
Fire-resistant planting
Fire break (vegetation clearance zone)
Increased programmed drainage clearing and vegetation management
Post-fire responsive drainage clearing
Post-fire erosion protection and slope stabilisation
Risk management plan

Case for investment in adaptation

The study confirmed that there is a compelling case for investment in adaptation when direct, indirect, and intangible costs and benefits are considered holistically.

Most of the priority adaptation measures for flooding outperformed the base case (representing the scenario of taking no action) and will also yield a positive return-on-investment. Foamed bitumen stabilisation and water sensitive urban design have the highest return-on-investment under both current climate conditions in 2022 and future climate conditions in 2070 under a high emissions scenario (RCP8.5), considering multiple discount rates. Preventative maintenance and increased programmed maintenance also prove to be effective adaptation measures, consistently outperforming the base case across different climate scenarios. Their lower upfront capital expenditure makes them attractive if there are limited financial resources available.

For the bushfire exemplar, there are fewer adaptation measures that outperform the base case. Programmed drainage clearing has the highest return-on-investment for current climate conditions in 2022 and future climate conditions in 2070 under RCP8.5, using both 4% and 7 % discount rates. Lower-cost investments, maintenance measures, and hazard management demonstrate positive return-on-investment as climate conditions become more intense in the future under a high emissions scenario.

For both exemplars, there are adaptation options which demonstrate lower return-on-investment and do not appear economically viable when compared to the base case. However, it is important to recognise that these measures, including a viaduct eliminating flood risk and remediation of high-risk landslide slopes, achieve the greatest reduction in damage, downtime, and life safety risk and therefore may be appropriate for highly critical road corridors.

Limitations of holistic economic analyses

It is important to note that the results of the economic analysis are site-specific to the exemplars used in this study, including the socioeconomic, physical geographic, and functional setting, as well as the assumptions made on the costs and effectiveness of adaptation measures. Therefore, the adaptation measures with the highest return-on-investment for the exemplars in this study may not be representative of every road project in metropolitan, regional, and rural contexts in Victoria.

There is no perfect approach to capturing all intangible impacts of project, and therefore economic analysis will only form one part of decision-making. In addition to economic metrics, it is essential to consider the contribution of adaptation measures to broader strategic objectives to ensure that investment in climate adaptation measures for road infrastructure is not only economically viable but also socially and environmentally sustainable. These strategic objectives should be site-specific and may include reducing impacts on vulnerable people, protecting intangible cultural, heritage, and/or ecological value, complying with standards for critical road infrastructure service levels, road safety, avoiding maladaptation, minimising embodied carbon, and enhancing resilience to multi-climate hazards. Stakeholder engagement serves as an important tool for understanding, respecting, and incorporating local values and priorities in investment decision-making.

Embedding adaptive planning approaches

Recognising the interdependencies and potential synergies between adaptation measures will help to enhance infrastructure and community resilience. This integrated approach, known as adaptive planning pathways, allows for the strategic combination and sequencing of measures to achieve a higher level of overall resilience.

By adopting a holistic perspective in consideration of the interactions between different measures, opportunities for bundling and sequencing can be identified. Rather than implementing individual measures in isolation, they can be strategically grouped and implemented in a coordinated sequence, amplifying their effectiveness to create greater resilience outcomes.

The adaptive planning pathways approach acknowledges that the combined impact of multiple measures can be more powerful than the sum of their individual effects. It encourages a comprehensive and coordinated approach to adaptation, where measures are strategically integrated to maximise their synergistic benefits and create a more resilient and adaptive system. Adaptation measures identified in this study can be layered and sequenced based on site-specific needs to address deep uncertainty in a changing climate.

This economic analysis demonstrates a framework to quantify risk efficacy and holistic economic performance of adaptation measures that considers wider societal impacts. The presented framework of adaptation prioritisation, base case valuation, adaptation risk efficacy assessment, and economic analyses is scalable and repeatable for infrastructure and climate hazards in Victoria to support the case for investment in climate change adaptation.

1. Introduction

1.1 About this report

Infrastructure Victoria is the state's independent infrastructure advisory body. It has three main functions:

- preparing a 30-year infrastructure strategy for Victoria, and reviewing and updating the 30-year strategy every 3 to 5 years
- advising the Victorian Government on specific infrastructure matters
- publishing research on infrastructure-related issues.

As part of its research program, Infrastructure Victoria is assessing the risks and opportunities of adapting Victoria's infrastructure to climate change. The project considers existing climate change adaptation actions in Victoria, identifies priority adaptation measures to improve the resilience of infrastructure in response to climate-related risks and evaluates the return on investment for adaptation actions.

The project phases include:

1. High-level risk assessment of climate impacts across key infrastructure sectors including a literature review and workshops with government stakeholders.
2. Detailed analysis of shortlisted climate risks across Victoria and potential adaptation actions for selected asset categories (for example, roads and electricity).
3. Economic assessment of the return on investment for specific climate change adaptation measures including a quantitative and qualitative assessment of direct and indirect costs and benefits.
4. Final research report.

This report is part of Phase 3, which aims to build the economic case for appropriate action and investment in climate resilient roads and electricity networks by asking the following question:

What is the economic return on investment for selected climate change adaptation measures in selected Victorian Government infrastructure sectors?

This report focuses on the road network by exploring a cost-benefit analysis of adaptation measures relevant to selected exemplars. The outcome of this analysis will aid in identifying appropriate investments and showcase the significance of adaptation in enhancing the resilience of road infrastructure and its capacity to serve communities and the local economy. It also presents a methodology which may be used by other stakeholders to assess the return on investment in climate adaptation of infrastructure.

Due to the inherent uncertainty of climate change, climate risk has been considered for two climate scenarios and time horizons to ensure that proposed adaptation measures are robust under multiple plausible futures. Climate risk under current climate conditions in 2022 is compared to future climate conditions in the year 2070 based on a high emissions pathway known as Representative Concentration Pathway 8.5 (RCP8.5).

The methodology for climate risk assessment and economic analysis of adaptation measures is applied to two de-identified, hypothetical exemplars in this report. While these exemplars are grounded in real data, they do not refer to a specific location and contain asset and hazard features representative of multiple locations across Victoria. Some cost and vulnerability assumptions used in the economic analysis for the exemplars may be appropriate for use in future infrastructure projects, however ultimately every adaptation implementation project needs to be site-specific to respond to unique factors such as infrastructure age, hazard exposure, and asset criticality.

The exemplars are two roads with climate-related risks that were prioritised in previous project phases:

- Damage and service interruption to road surfaces caused by flooding and/ or extreme rainfall events.
- Service interruption of roads caused by bushfires and subsequent rainfall-induced landslides.

This report has been written alongside a separate assessment of potential climate adaptation measures for wind hazards affecting electricity distribution infrastructure, led by ACIL Allen.

1.2 Structure of this report

This report starts by introducing the climate context for Victoria in Section 2 to outline the drivers for investment in climate adaptation and resilience.

The methodology in Section 3 presents a repeatable and scalable framework for conducting climate risk assessments for infrastructure assets, prioritising appropriate adaptation measures, and conducting economic analysis to inform decision-making. This is intended for application to future infrastructure projects in Victoria.

The methodology is applied to two worked exemplars in this report, illustrating a flooding and bushfire scenario. The approach for establishing these exemplars is outlined in Section 4, and is followed by the flooding and bushfire exemplars in Section 5 and Section 6, respectively. For each exemplar, the full approach and findings are detailed to demonstrate how the methodology in Section 3 may be applied to future infrastructure projects in Victoria. This includes the steps involved in undertaking a risk assessment, identifying and shortlisting adaptation measures, and developing a case for investment in adaptation through holistic economic analysis.

2. Climate change in Victoria

Building upon the *Assessing risks and adapting Victoria's infrastructure to climate change – Phase 2* report, this section outlines the baseline and projected climate in Victoria including an overview of anthropogenic climate change and natural climate variability associated with climate and weather systems. Further detail is provided for the relevant hazards in the flooding and bushfire exemplar sections.

2.1 Observed changes

Driven by unabated global greenhouse gas emissions, changes in our climate are now being observed in every region of the world and across entire Earth systems (IPCC, 2021a). According to the Sixth Assessment Report (AR6) released by the Intergovernmental Panel on Climate Change (IPCC), the climate has warmed at a rate that is unprecedented in thousands of years, contributing to many observed changes in weather and climate extremes (IPCC, 2021a).

In Australia, mean temperature has increased by nearly 1.5°C during the period 1910–2019 (IPCC, 2021c) (CSIRO and Bureau of Meteorology, 2022). While Victoria's climate is strongly influenced by drivers such as the El Niño Southern Oscillation, the Indian Ocean Dipole, and the Southern Annular Mode which affect natural climate variability, long-term trends indicate increasing average temperatures, declining cool season rainfall, rising sea levels, and more frequent extreme heat events and harsh fire weather (Clarke, et al., 2019) (DELWP, 2020) (Victorian Water and Climate Initiative , 2021).

2.2 Future climate

Although climate change is now an "established fact" (IPCC, 2021a), there is still significant uncertainty around the future climate. Representative Concentration Pathways (RCPs) are a set of four greenhouse gas concentration trajectories that were developed to represent different possible future scenarios of anthropogenic emissions and their impact on climate change, shown in Figure 2-1.

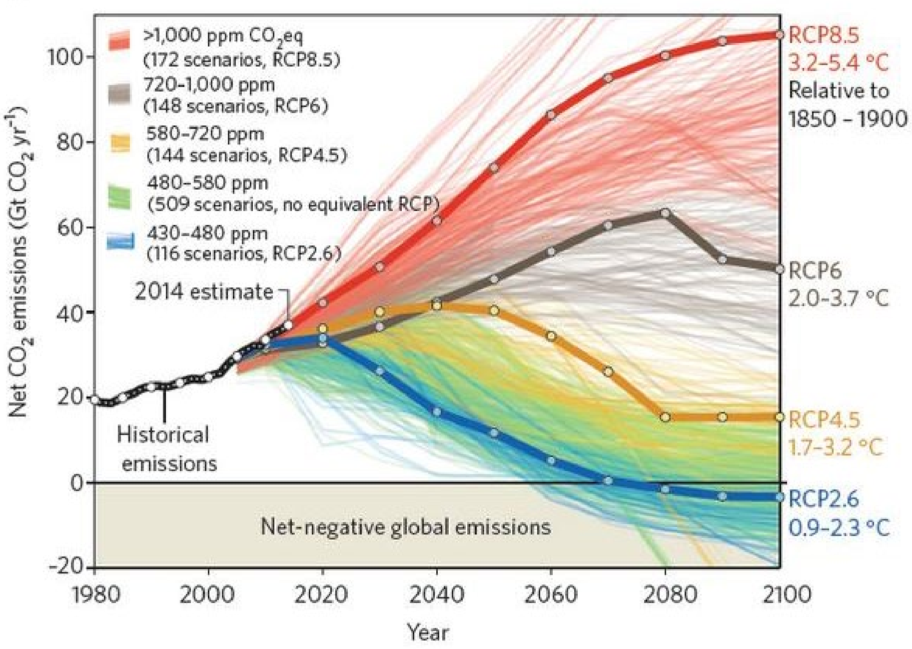


Figure 2-1: Representative Concentration Pathways from IPCC Fifth Assessment Report (Nature, 2014)

These emissions scenarios are based on the Coupled Model Intercomparison Project Phase 5 (CMIP5), released in 2011/12. RCP8.5 represents a high-emissions, or 'business-as-usual' scenario, under which greenhouse gas concentrations could exceed 1000 parts per million by the year 2100, leading to an increase in global temperature of 3.2 – 5.4ºC above pre-industrial levels.

RCP8.5 is currently the most appropriate emissions scenario for conducting assessments of climate change risk in Victoria as it represents the greatest plausible changes for key hazards (CSIRO & AEMO, 2021) and is the closest approximation of both historical emissions and anticipated outcomes of current global policies (Schwalm, Glendon, & Duffy, 2020).

RCP4.5 represents a stabilised emissions pathway under which it is more likely than not to exceed global warming of 2ºC. RCP4.5 may be used for sensitivity testing in climate risk assessments to ensure adaptation is robust under multiple plausible climate futures, although it is important to recognise that it will fall in between the current (baseline) climate conditions and the future climate conditions under RCP8.5. Therefore, climate risk assessments often consider current climate conditions and RCP8.5 as a conservative approach.

The Victoria's Climate Projections 2019 (VCP19) are climate projections for the state of Victoria that have been dynamically downscaled based on CMIP5 (CSIRO and BoM, 2020). These projections describe how the climate of Victoria may be affected by global warming under RCP8.5 until 2090. The projected changes are summarised below (DELWP, 2019):

- Victoria’s climate will continue to warm, with maximum and minimum temperatures increasing. The increase in average temperatures also translates to an increase in extreme temperatures and more frequent hot days. Extreme daily maximum temperatures could increase by as much as twice the rate of increase in the average maximum temperatures. Projected changes in temperature are higher inland compared to coastal regions.
- Victoria is likely to continue to get drier in the long term in all seasons except summer. While Victoria is projected to likely receive less overall total rainfall in the future and extended periods of drought, extreme rainfall events are projected to increase in frequency and intensity leading to increased risk of flooding.
- More frequent and severe bushfire weather will be driven by hotter and drier conditions. The number of high fire danger days in Victoria is expected to increase in the future, with a larger increase in fire days for alpine regions.
- Future rises in sea level are projected with high confidence, driving increasing frequency and intensity of extreme sea level events such as storm tides.

The IPCC AR6 released in 2021 features an updated model, CMIP6, and a different set of emissions scenarios, known as Shared Socioeconomic Pathways (SSP). These SSPs result in similar projected changes in climate variables in the year 2100 to the respective CMIP5 RCP scenarios, however, have not currently been downscaled for Victoria at the time this report was developed. Once available, these updated climate scenarios should be used to inform the risk assessment although it is not anticipated that this will significantly impact the results of this analysis.

3. Methodology

3.1 Overview

This section presents a replicable, robust, and scalable methodology for measuring and valuing investment in climate adaptation for infrastructure. This includes a detailed approach for undertaking a climate risk assessment; identifying, assessing, and prioritising adaptation measures; and conducting a holistic economic analysis of adaptation options to inform climate-sensitive investment decision-making.

3.2 Risk assessment frameworks

In Australia, two important standards for climate risk assessments are *AS5334-2013 Climate change adaptation for settlements and infrastructure – a risk based approach* and *ISO14090:2019 Adaptation to climate change – Principles, requirements and guidelines/ ISO 14091:2021 Adaptation to climate change – Guidelines on vulnerability, impacts and risk assessment*. These standards follow the International Standard, *ISO31000:2009, Risk management— Principles and guidelines* (adopted in Australia and New Zealand as AS/NZS ISO31000:2009), which provides a set of internationally endorsed principles and guidance on how organisations can integrate decisions about risks and responses into their existing management and decision-making processes.

AS5334 provides a framework for climate risk assessment and management, which includes establishing the project and climate context, assessing and evaluating risks, and implementing risk treatment (adaptation) options. Risk analysis and evaluation are conducted using qualitative assessment of likelihood and consequence of climate risks, which is in line with the definition of risk from the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (IPCC, 2007).

The ISO14090 series follows a similar pathway to risk identification and adaptation planning set out in AS5334, however the risk analysis and evaluation component involves semi-quantitative assessment of exposure and vulnerability of identified climate-hazards. This definition of risk, as a product of hazard, exposure, and vulnerability, is more in line with the most recent IPCC Assessment Reports (AR5 and AR6).

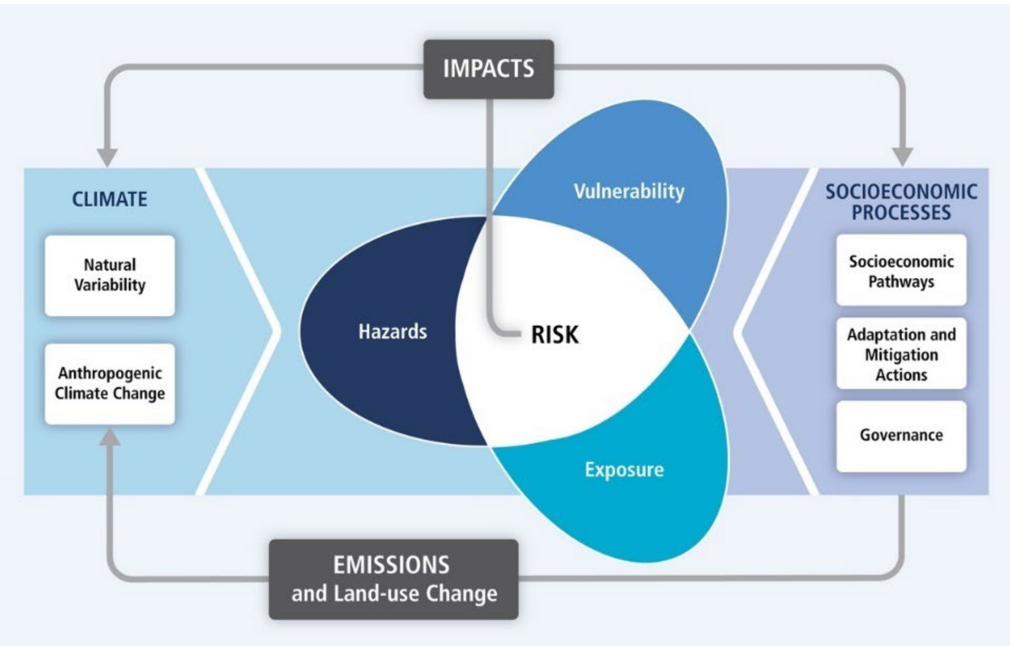


Figure 3-1: Illustration of the core concept of risk from IPCC AR6

Alongside these Australian and international standards, the World Road Association (PIARC) has published an International Climate Change Adaptation Framework for Road Infrastructure to help transportation professionals worldwide understand and address the impacts of climate change on road infrastructure (PIARC, 2015) (PIARC, 2019). The framework outlines a four-step process for adapting to climate change, consistent with the ISO14090 series (Evans & Kafalenos, 2022):

1. Identifying scope, variables, risks and data: Seeks to establish the aims and scope for an assessment, and provides guidance on how to assess the vulnerability in terms of the exposure, sensitivity and adaptive capacity. Additionally, it defines the assets, locations and climate change projection scenarios and considers stakeholder engagement in terms of establishing roles and responsibilities in the assessment process.
2. Assessing and prioritising risks: guides road decision-makers through identifying the likelihood and consequence of climate risks on road infrastructure.
3. Developing and selecting adaptation responses and strategies: Focusses on developing and selecting adaptation response to assist in identifying adaptation measures and prioritising these responses through the use of economic methodologies such as MCA, CBA, Life-cycle costing methods.
4. Integrating findings into decision-making processes: Covers the integration of findings into decision-making processes including education awareness and training, business case development and future planning and monitoring (PIARC, 2015).

The approach to risk assessment in this study draws upon these various frameworks and standards to reflect global best practice.

3.3 Climate risk assessment

In this project, climate risk is defined as the expected impact from natural hazard events today and in the future, over a defined timescale. It is communicated in this report as direct, indirect, and intangible losses. Risk is often represented as probability of occurrence of hazardous events or trends (likelihood) multiplied by the impacts (or consequences) if these events or trends occur. Risk is borne from the interaction of hazard, exposure, and vulnerability (IPCC, 2014), shown in Figure 3-2. This approach is well-established and clearly delineates the composite factors that contribute to overall risk. It builds upon the earlier definition of risk based on likelihood and consequence (IPCC, 2007). A clear understanding of each factor is useful to ultimately inform adaptation measures that can have the greatest effect on reducing risk and enhancing resilience.

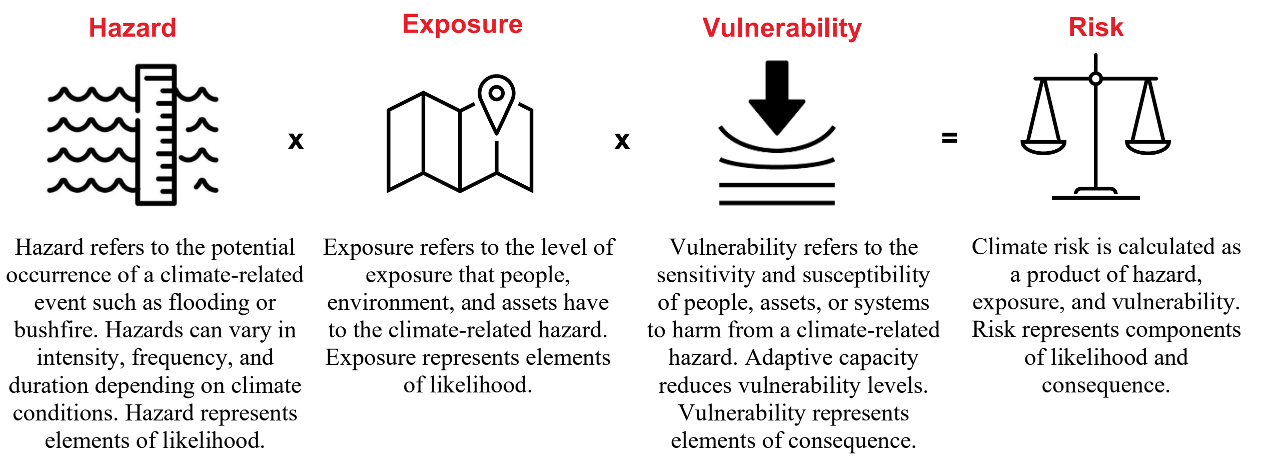


Figure 3-2: Composition of risk based on IPCC Fifth Assessment Report (2014)

3.3.1 Project baseline

Prior to commencing the risk assessment, it is necessary to understand the baseline for adaptation for the project site. This includes identifying the drivers of adaptation, assessing the availability of data (governance data, hazard data, socio-economic, environmental data), and formulation of indicators (such as the number of persons/ communities impacted, resources spent on repairs, crashes, and distance of roads affected). This baseline also considers the scale of the analysis (temporal and spatial), defining threshold and tolerance levels for risk adaptation and mitigation within the project boundary, and building an understanding of physical, functional, and/ or seasonal asset criticality (PIARC Forthcoming, PIARC International Climate Change Framework for Road Infrastructure). Although the consideration of road infrastructure is implicit, the broader function and performance levels of the road as a transport service to a community should be defined.

Once the project baseline has been established and data availability is mapped, the risk assessment can commence.

3.3.2 Risk assessment scope and climate hazards

The first stage in conducting a climate risk assessment is establishing the scope of the climate risk assessment and screening for relevant climate projections and natural hazards for the defined project boundary. The screening for relevant climate projections and natural hazards includes selection of appropriate climate scenarios and time horizons for the asset components.

The influence of climate models on climate hazard datasets are the primary means for understanding projected changes in future climate. For infrastructure assets, it is recommended that RCP8.5 is adopted to represent a worst-case scenario and current business-as-usual. This is consistent with the Infrastructure Sustainability Council's Infrastructure Sustainability Rating Scheme Version 1.2 and 2.1 which are widely used across Victoria and Australia (Infrastructure Sustainability Council of Australia, 2021). Scenarios based on the most recent CMIP6 models featured in IPCC AR6 have not been translated to the Victorian context to date, however it is expected that these will be adopted once available.

Time horizons should reflect the design lives of the infrastructure asset components, typically the current year or 2030 to represent the construction period and assets with shorter operating lives, and 2070 or 2090 to inform the design of 'fixed' asset components with longer operating lives.

Figure 3-3 shows the respective design lives of highways and road asset components. Assets with shorter design lives, such as road surface and pavement, and ITS will be replaced multiple times compared to bridges, tunnels, or culverts. Therefore, it may be appropriate to plan for staged adaptation to avoid overengineering in shorter-term horizons. Many roads across Victoria were constructed in the decades following the establishment of the Melbourne Transportation Plan in 1969 and consequently are approaching the end of design life for asset components.

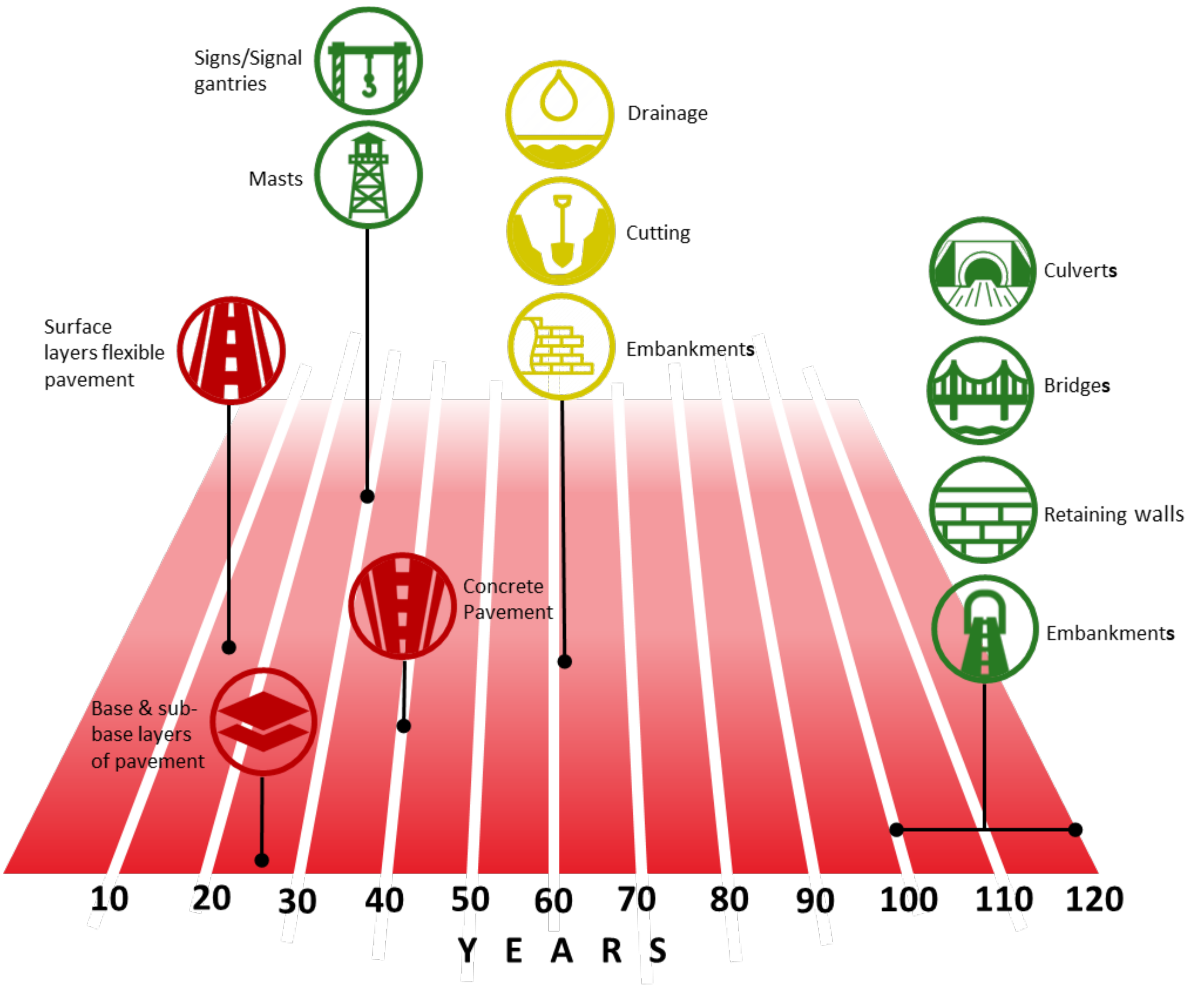


Figure 3-3: Design life of road assets. Modified by Arup from PIARC (PIARC, 2015).

It is important to recognise that climate scenarios determine the direction and magnitude of projected changes in climate variables. Changes in these variables contribute to the hazards which can impact roads (e.g., increased rainfall contributes to increased flooding, increased temperature contributes to bushfire risk).

Table 3-1 describes relevant climate variables and associated climate hazards for road infrastructure assets in Victoria. These hazards can cause the infrastructure to fail if adequate adaptation measures are not incorporated into the design and operation of assets, which in turn, will affect network operations.

Table 3-1: Climate variables and hazards for infrastructure assets in Victoria

Climate Variable	Hazard	Vulnerable asset components
Rainfall	Flood, groundwater	Bridge, culvert, drainage, pavement, road surface, embankments
Temperature	Extreme heat	ITS and electrical, road surface
Wind	Strong winds	Bridge, ITS and electrical
Drought, Rainfall, Sea level	Groundwater	Embankments, slopes, structures, pavement
Temperature, rainfall, wind	Bushfire and subsequent landslide	Embankments, slopes, road surface, structures
Rainfall	Landslide	Embankments, slopes
Sea level	Sea level inundation and erosion	Culvert, drainage structures, pavement, road surface

The selection of hazards for adaptation planning should be based on consideration of past events using historical data and consideration of future climate conditions based on available site-specific climate change projections (such as Victoria's Climate Projections 2019).

Once relevant hazards have been determined for the asset, climate hazard data can be sourced, developed, or modelled for the project location. A range of hazard scenarios expressed in annual probabilities, also referred to as return periods, should be included to capture the frequency and scale of impact events. Example hazard modelling scenarios for flood and bushfire are provided in Table 3-2.

Table 3-2: Typical Hazard modelling scenarios

Hazard	Hazard modelling scenarios
Flood	5-year (20% annual exceedance probability), 10-year, 20-year, 100-year, 200-year, 500-year return periods 5-year, 10-year, 20-year, 100-year, 200-year, 500-year return periods with climate change allowance[1]
Bushfire	Present day burn probability 3% annual probability. Annual burn probability increases proportionally to the number of fire days with Forest Fire Danger Index (FFDI) greater than 50.

3.3.3 Exposure assessment

The exposure assessment quantifies the extent to which assets and people are exposed to the hazard. Hazard exposure is characterised in terms of duration, intensity, and locality, and can be determined according to existing, predictive, and future exposure levels (PIARC, 2019). For each hazard modelling scenario, exposure levels are calculated through the integration of the geospatial footprint of the assets at-risk with multi-hazard map layers. This can be done using geographic information systems (GIS). Asset components such as culverts and bridges can be overlayed with hazard maps to assign exposure intensity, such as flood depth.

Traffic volumes based on Annual Average Daily Traffic (AADT) and population data for local communities from Census data may be used to inform the exposure of people and associated social and economic impacts. Land-use mapping can be used to identify environmental and other natural resources.

Seasonality can be considered in the exposure assessment depending on the granularity of available data. This could capture seasonal variance in both hazard exposure, as well as seasonally adjusted AADT.

3.3.4 Vulnerability assessment

The vulnerability assessment estimates the performance of an asset with respect to damage, the vulnerability of network performance with respect to downtime, and the vulnerability of people to loss of life, when exposed to a hazard. The assessment includes an evaluation of the sensitivity of the assets – the degree to which a system is affected adversely or beneficially by a hazard (PIARC, 2015). This is determined by factors such as the level of maintenance required, asset age/ remaining service life, design capacity, condition, adjacent land use, level of visual inspections, and sensitivities to communities and businesses. Additionally, vulnerability assessment is impacted by the level of adaptive capacity including redundancy and asset/ network adaptive capacity, organisational adaptive capacity, and community adaptive capacity (PIARC, 2015).

To estimate damage, vulnerability functions are used to relate a given hazard intensity measure, such as flood depth, to a level of damage for each asset (see Figure 3-4). For each damage state, there is uncertainty in the cost to repair or replace the component or asset, which is captured in a consequence function. The consequence function relates a level of damage to a cost to repair or replace the component or asset.

[1] Australian Rainfall and Runoff Guidelines 2019 provides a methodology for applying a climate change allowance to flood models.

In addition to the cost to repair or replace, the vulnerability assessment can also estimate the downtime associated with each damage state. This is captured in an additional consequence function that relates a level of damage to the amount of time that the asset will be out of service.

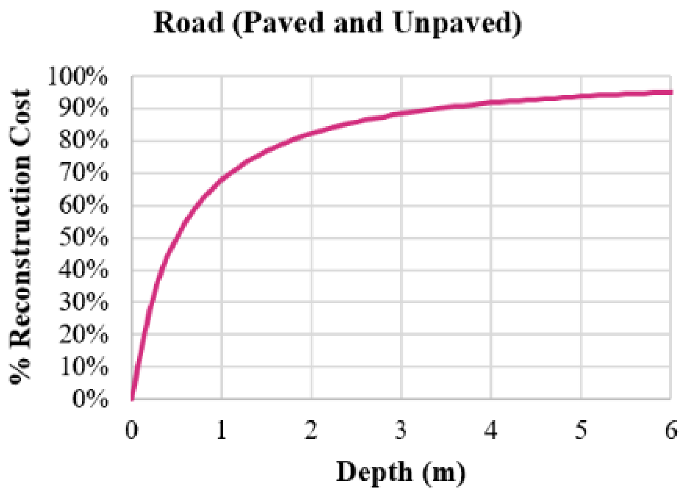


Figure 3-4: Example vulnerability function for flood hazards for roads, where the curve relates hazard intensity to damage represented as a percentage of total reconstruction cost (Arup, 2021).

3.3.5 Risk assessment

The risk assessment evaluates various types of risks, including direct tangible risks, indirect tangible risks, and intangible risks, which are expressed as losses. It aims to estimate the potential impacts and losses in the base case scenario, which represents the situation where no changes or adaptation measures are implemented. The base case considers direct tangible, indirect tangible, and intangible losses that can be reliably quantified based on available information. Additionally, qualitative assessment is conducted to evaluate other significant impacts, especially intangible losses that may not be easily quantifiable.

Risks are characterised as a product of hazard, exposure, and vulnerability in accordance with current best practice (IPCC, 2021a) (IPCC, 2014), building upon earlier definitions of risk as a product of likelihood and consequence (IPCC, 2007). Likelihood is captured in the assessment of the probability of the hazard, exposure of the asset, and vulnerability (and adaptive capacity) of the asset. Consequence is captured in the risk metrics, in terms of direct, indirect, and intangible losses.

Direct tangible losses are defined as the damage in financial loss and downtime of the asset from climate-related hazards. Indirect tangible losses are the quantifiable flow-on consequences from downtime, including economic costs of disruption to freight and the community. Intangible losses are those which cannot be easily quantified in monetary terms, such as impacts on biodiversity, nature, and health.

The assessment of direct tangible losses integrates the hazard, exposure, and vulnerability to calculate risk of multi-hazards to assets as average annual loss (AAL) from direct damage, and average annual downtime (AAD). AAL aggregates loss across multiple return periods and weights the losses by probability of occurrence to quantify a single annualised risk metric, as shown in Figure 3-5. AAD similarly weights the downtime to quantify a single annualised loss metric.

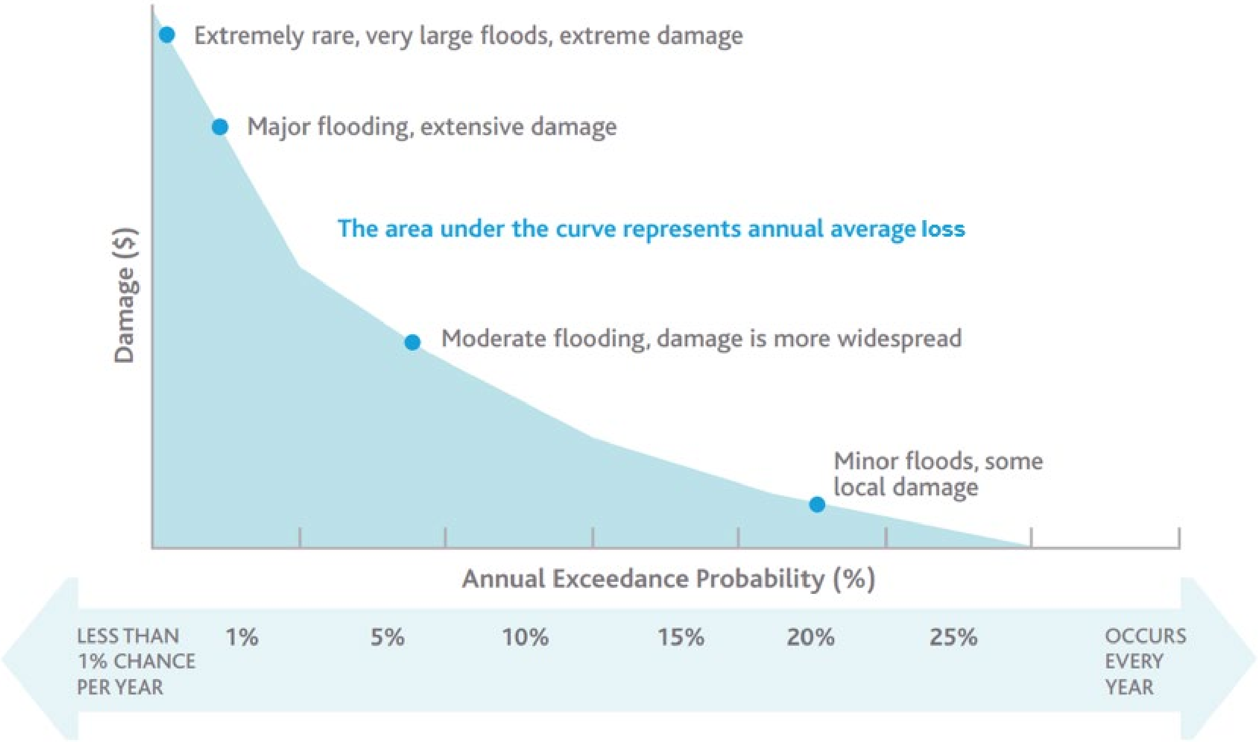


Figure 3-5: Relationship between hazard events and financial loss where the area under the curve represents average annual loss. Modified from Melbourne Water. (Melbourne Water, 2015)

Indirect tangible losses are the impacts generated from the closure (i.e., AAD) of the road in part of a broader community system. The approach to quantifying these may involve market and non-market valuation techniques:

- Market valuation – these techniques can be used to estimate the value of loss of flow-on benefits (like tourism activity and productivity) and costs of damage (like emergency, clean-up, and rehabilitation costs).
- Non-market valuation – these techniques can be used to estimate values such as recreational values, economic value for community assets and activities, and non-use values for natural assets.

Intangible losses are not direct costs to individuals or businesses but are borne by broader communities and ecosystems. Non-market valuations such as the environmental parameter values in the Australian Transport Assessment and Planning Guidelines can be employed to appropriately capture indirect and intangible impacts and externalities in economic appraisals (Australian Transport Assessment and Planning Guidelines, 2021). It is important to recognise that there is no perfect approach to capturing all intangible impacts, and therefore economic analysis will only form one part of decision-making. Stakeholder engagement serves as an important tool for understanding, respecting, and incorporating local values and priorities in investment decision-making.

3.4 Adaptation Measures

Adaptation measures refer to actions taken to increase the ability of infrastructure to maintain their service performance levels in the face of extreme climate events and climate change. The specific adaptations that can be implemented on infrastructure assets to enhance resilience vary depending on the specific objectives of the adaptation and the characteristics of the site. In the case of road assets, the objectives of the adaptation, such as achieving immunity to a certain flood level or enhancing maintenance practices drives its selection.

Once climate risk is well-understood and ideally quantified for road infrastructure, adaptation opportunities can be identified to reduce at least one component of the risk model: hazard, exposure, or vulnerability.

Four types of adaptation measures have been considered for this project based on examples from international best practice (PIARC, 2019). These are described in Table 3-3. Some measures will be mutually enhancing and therefore multiple adaptation measures can be packaged and sequenced to address climate-related risks.

Table 3-3: Adaptation types

Adaptation type	Description
Higher-cost investment	Higher-cost investment can include the use of physical structures to reduce the impacts of climate change. Investments are generally more capital-intensive capital intensive with examples including new construction, upgrades or significant reinforcement of infrastructure. This involves engineering solutions to the infrastructure under consideration or the surrounding system such as through protection measures (Sovacool, 2011).
Lower-cost investment	Lower-cost adaptation measures can be simple, and can also involve smaller investments that are modular, flexible, or scalable. Lower-cost adaptation can include measures that interact with the natural environment, such as nature-based solutions. Nature-based solutions use characteristics of natural features and processes, or mimics it through human design and engineering, providing both risk reduction and ecological benefits (U.S. Department of Transportation Federal Highway Administration 2019, 2019).
Maintenance	Maintenance adaptation refers to altering maintenance regimes so that existing infrastructure remains resilient and functional in the face of changing climate conditions. Periodic and preventative maintenance regimes can be examined. Periodic maintenance adaptation refers to altering the set schedule for inspection and repair of assets to account for changing conditions. Preventative maintenance refers to the use of predictive analysis to proactively forecast asset failure and reduce the risk of failure by scheduling maintenance ahead of time based on historical data. Maintenance initiatives can also involve various technologies used for monitoring hazards and infrastructure condition.
Hazard management	Hazard management adaptation refers to improving operational plans for managing extreme weather events and natural disasters (Technical Committee E.1 Adaptation Strategies and Resiliency, 2019). Hazard management can be quite broad and cover areas such as preparation before an extreme event, response during an event and immediate recovery (ROADAPT, 2015). This can include, and is not limited to, early warnings, user awareness and behaviour campaigns, communication of information during and after times of disruption or incidents, measures to ensure a level of service continuity, emergency repairs, removal of hazards, temporary set -up of structures and immediate actions to reduce cascading impacts.

Adaptation measures are highly site-specific, and what may work in one location may not be effective or suitable in another. For example, increasing roadside vegetation for stormwater management can be an effective adaptation measure in some areas. Vegetation can help to slow down and absorb rainwater, reducing the risk of flooding and erosion or it may mask signs of slope instability. In areas with high bushfire risk, this adaptation measure can be maladaptive. Vegetation can act as a fuel for bushfires, potentially increasing the severity and spread of the fire. It is crucial to carefully assess the site-specific conditions and potential impacts of any adaptation measure to determine whether it is appropriate and effective for a particular location.

A longlist of adaptation measures should be developed based on literature review and project examples. The longlist should be screened for measures that are appropriate for the asset type and site-specific conditions to avoid maladaptation and ensure effective risk management. An example longlist is provided in Appendix A, collated from engineering projects and the PIARC International Climate Change Adaptation Framework for Road Infrastructure (2015).

3.4.1 Prioritising adaptation opportunities

In order to evaluate a comprehensive set of adaptation measures and narrow them down to a prioritised shortlist for detailed assessment, a qualitative approach known as multi-criteria analysis (MCA) is utilised. This evaluation process considers weighted criteria across themes such as technical merit, deliverability and constructability, road service level, community impact, and environmental impact. An example list of criteria is provided in Table 3-4. The weightings can be aligned with an organisational strategy or tailored to specific projects and sites. Evaluation against these criteria must be site-specific, especially with regard to efficacy for risk reduction and avoidance of maladaptation.

Scoring of the adaptation measures against these criteria should be conducted based on the specific requirements and context of each project, and may involve stakeholder engagement. Criteria weightings can also be adjusted to reflect the project-specific adaptation objectives and the site-specific nature of the road. To ensure comprehensive evaluation, it is advised to perform the shortlisting process for each combination of hazard and adaptation type, such as higher-cost investments for flooding.

Table 3-4: Example criteria for shortlisting adaptation measures through a multi-criteria assessment process

Assessment area	#	Criterion	Description
Technical merit	1	Efficacy of measure for risk mitigation	Extent to which measure maintains accessibility and existing level of service of the road during hazard events under multiple future climate scenarios.
	2	Uncertainty in design and construction	Extent to which there is existing capacity and capability in industry including design and construction guidance/ standards to design, deliver, and maintain measure.
	3	Recovery Time Objective (RTO)	The time and effort required to implement the measure and restore the level of service of the road following disruption/ disaster, where a higher score represents a faster RTO.
Deliverability and constructability	4	Cost of construction	Cost of construction, including consideration of length of construction period, where a higher score represents lower costs.
	5	Maintenance costs and level of effort	Maintenance costs and level of effort, including duration and frequency of maintenance, where a higher score represents lower costs.
Road service level	6	Road service level impact during construction	Extent to which road service level is maintained during construction, including consideration of associated construction downtime for road-users (e.g. freight), where a higher score represents higher road service level maintained.
	7	Road service level impact during maintenance	Extent to which road service level is maintained during maintenance works, including consideration of associated downtime for road-users (e.g. freight), where a higher score represents higher road service level maintained.
Community impact	8	Community impact during construction	Extent to which community is adversely impacted or inconvenienced during construction, where a lower score represents negative impact and inconvenience
	9	Community impact during maintenance	Extent to which community is adversely impacted or inconvenienced during maintenance, where a lower score represents negative impact and inconvenience
Environmental impact	10	Maladaptation	The extent to which the measure does not exacerbate other climate-related impacts under stabilised and high emissions scenarios over the lifetime of the adaptation, where a lower score represents maladaptive outcomes.
	11	Level of net impact on the natural environment	Level of net impact on the natural environment, including impact on ecosystem services, where a higher score represents positive impact.
	12	Embodied carbon emissions impact	Embodied carbon of construction where a lower score represents a higher, negative embodied carbon impact.

3.4.2 Post-adaptation residual risk assessment

The climate risk assessment process is repeated, and post-adaptation residual risk levels are calculated for direct tangible, indirect tangible, and intangible losses based on implementation of the shortlisted adaptation measures. Residual risk levels are compared to the base case to demonstrate the performance improvement resulting from the adaptation measure. This process is conducted individually for each adaptation measure, and should be informed based on literature review, project examples, engineering judgement, and additional modelling where appropriate. The AAL and AAD of post-adaptation residual risk to the project can be determined by updating the hazard, exposure, and/ or vulnerability information to reflect the implementation of the adaptation measure.

The efficacy of the measure for risk mitigation is expressed by a reduction in exposure or vulnerability to the hazard, leading to reduced damage or downtime. The risk assessment is re-run for the road assets with the reduction in exposure or vulnerability for the adaptation. The efficacy is calculated through comparison of the post-adaptation residual risk to the base case (i.e., the 'do nothing' scenario).

3.4.3 Development of prioritised adaptation measures

Shortlisted adaptation measures are further developed within the site-specific context to refine the scoring and support prioritisation. This process may involve feasibility design levels for higher-cost investments, and consideration of land use planning, availability of technology, and local policy frameworks.

The performance of the adaptation measures against the multi-criteria analysis (MCA) criteria should be quantified where possible. This includes consideration of risk efficacy, cost of construction, cost of maintenance, and embodied carbon, for example.

3.5 Economic analysis

3.5.1 Overview of cost-benefit analysis

Cost-benefit analysis (CBA) is an economic appraisal technique used to systematically evaluate and assess the net benefit of a proposal and transparently compare alternative options. In a CBA, the benefits are weighed against the costs in monetary terms, thereby providing a consistent basis for assessment and comparison. CBAs are widely used in decision-making and business case development; particularly where multiple options are being considered.

There are several frameworks outlining the methodology involved in conducting a CBA, including Victorian Guide to Regulation Toolkit 2: Cost-benefit analysis (Department of Treasury and Finance, 2014), the Queensland Government Cost Benefit Analysis Guide (Department of State Development, Infrastructure, Local Government and Planning, 2021), Australian Government Cost-Benefit Analysis (Department of Prime Minister and Cabinet, 2020), Infrastructure Australia Guide to Economic Appraisal (Infrastructure Australia, 2021), and the Victorian Economic Evaluation for Business Cases Technical Guidelines (Department of Treasury and Finance, 2013).

These frameworks are generally similar in overall approach, which align with Figure 3-6, overleaf.

While the CBA frameworks require consideration of economic, social and environmental impacts, and to take into account both market and non-market costs and benefits, accounting for non-market (intangible) impacts is difficult and can be overlooked. This may lead to analyses that do not capture the full impact of projects and hence CBA results that do not truly reflect the merits of particular projects.

Essential CBA components of an individual proposal or outcome include:

- Identifying affected stakeholders.
- Determining the costs and benefits associated with alternative options.
- Taking consideration for the future timing of costs and benefits—and discounting these for a consistent basis of comparison. Discount rates of 4% and 7% have been adopted for this study (Department of Treasury and Finance, 2013).
- Selecting and applying appropriate decision criteria to assess options for prioritisation and implementation.

The benefits and costs are estimated across an appraisal period, which is a time horizon in which the benefits and costs are expected to accrue. For economic analysis of climate adaptation investments, the appraisal period is consistent with the adopted risk assessment time horizons for selected emissions scenarios (e.g. current year – 2070). For the purposes of comparison between options or outcomes, a consistent appraisal period is used. The costs and benefits are discounted and aggregated for each option.

A CBA is based on two decision rules that reflect a net benefit to society:

- A net present value (NPV) greater than zero where NPV is the net benefit (total discounted benefit less costs) over the appraisal period.
- A benefit-cost ratio (BCR) greater than one where the BCR is the ratio of discounted benefits over costs.

Both NPV and BCR can be used as a basis of comparison between options and outcomes in the development and analysis of asset adaptation options to mitigate climate risk.

To better understand the sensitivity of these metrics and the distribution of net benefits across affected groups of stakeholders, sensitivity testing and distributional analysis is conducted for each option.

The overall process for conducting economic analysis is presented in Figure 3-6.

Step 1: Determine the base case

- 1.1 Determine the base case in terms of risk level expressed as losses

Step 2: Identify costs and benefits for shortlisted adaptation measures

- 2.1 Identify all costs and benefits, including market impacts and non-market impacts.
- 2.2 Determine data and resources required to value the identified costs and benefits.
- 2.3 Align the evaluation period with the adopted risk assessment time horizons.

Step 3: Quantify and monetise costs and benefits

- 3.1 Quantify the costs and benefits
- 3.2 Use the valuation techniques, appropriate default values, and other guidance reccomended in this guideline.
- 3.3 Consider impacts that are difficult to monetise and apply non-maret valuation techniques.

Step 4: Discount costs and benefits back to present values

- 4.1 Adopt the appropriate discount rates (4% and 7%) (Department of Treasury and Finance, 2013).
- 4.2 Ensure only real prices are used to ensure consistency with the use of a real discount.

Step 5: Aggregate costs and benefits

- 5.1 Calculate NPV and BCR for each adaptation measure.
- 5.2 Utilise NPV and BCR to inform and rank the viable options.

Step 6: Assess risk and uncertainty

- 6.1 Identify risk and uncertainty with the options analysed using sensitivity analysis.
- 6.2 Analyse and discuss how the sensitivity analysis may affect the feasibility and ranking of the options.
- 6.3 Define triggers and tippings points for real options and develop adaptation pathways to appropriately sequence adaptation measures.

Step 7: Assess distributional impacts

- 7.1 Idenfity the impacts on different groups in society and to the environment that are likely to be affected by the different options.

Step 8: Assess results and determine a preferred option

- 8.1 Analyse overall results including the NPV and BCE, distributional impacts, scenario/sensitivity analysis.
- 8.2 Recommend the final preferred option(s) based on economic analysis
- 8.3 Incorporate broader consideration of intangible costs and benefits to inform business case.

Figure 3-6. Overview of key steps in a CBA

3.5.2 Base case valuation

The base case is used to establish the quantifiable performance of the asset and whole-of-life costs if no adaptation action or intervention is taken against the climate-related risk (Coalition for Climate Resilient Investment, 2021). It is calculated for current climate conditions in 2022 and future climate conditions in 2070 under RCP8.5. Climate conditions refer to the baseline and projected climate variables such as rainfall intensity, average daily maximum temperature, and annual severe fire danger days.

The climate risk assessment provides a quantitative understanding of damage (AAL) and downtime (AAD) today and in the future for the base case and is supplemented with evaluation of indirect tangible and intangible impacts.

3.5.3 Estimating costs and benefits of adaptation measures

Once the base case has been established, the economic impact of shortlisted adaptation measures (identified in Section 3.3) is determined by estimating the costs and benefits (including avoided losses). The economic costs of climate change adaptation are the estimated lifecycle costs of the associated measure, which includes initial capital costs, annual operating and maintenance costs, and replacement costs. Each of these costs are described below:

- **Capital costs:** These costs, also sometimes referred to as establishment costs, are incurred when the option is implemented. Costs in this category are usually very large compared to other costs; however, they are only incurred in the first year, or sometimes in the first few years. *Examples include costs of labour, materials and equipment for construction of adaptation infrastructure.*
- **Operating and maintenance costs**: These costs tend to occur in each year that the adaption option is implemented. These are the ongoing costs associated with keeping the option performing as intended. *Examples include costs for maintenance, repair, and ongoing monitoring.*
- **Replacement/refurbishment costs**: These costs are required when a component of an asset reaches the end of its design life. They are often calculated as a proportion of the capital costs. *Examples include flood mitigation infrastructure, like draining and pumps.*
- **Opportunity costs**: Some adaptation options may result in opportunity costs, which is the forgone value from alternative investments (e.g., the decision to update high-traffic roads instead of high-risk roads).

Sources of data (often called unit values, e.g., $/per kilometre per lane) can vary depending on the cost type being assessed. For example, capital costs for some items can be sourced from Bureau of Infrastructure and Transport Research Economics (BITRE) *Road construction cost dataset* (2017) and other industry datasets and standards. Alternatively, operating and maintenance costs are likely to require further information specific to the adaptation option being assessed, as well as the proposed designs.

Benefits are calculated in terms of avoided losses; this is reduction in direct and indirect tangible and intangible losses compared to the base case. Further benefits such as ecological enhancements may also be quantified.

The economic benefit of an adaptation option is primarily calculated in terms of avoided losses; this is the reduction in direct and indirect tangible and intangible losses compared to the base case (as shown in Figure 3-7). Additional upstream and downstream benefits may also arise as a result of the adaptation option, such as ecological enhancements and improved amenity. The approach to valuing such benefits depends on the benefit under consideration.

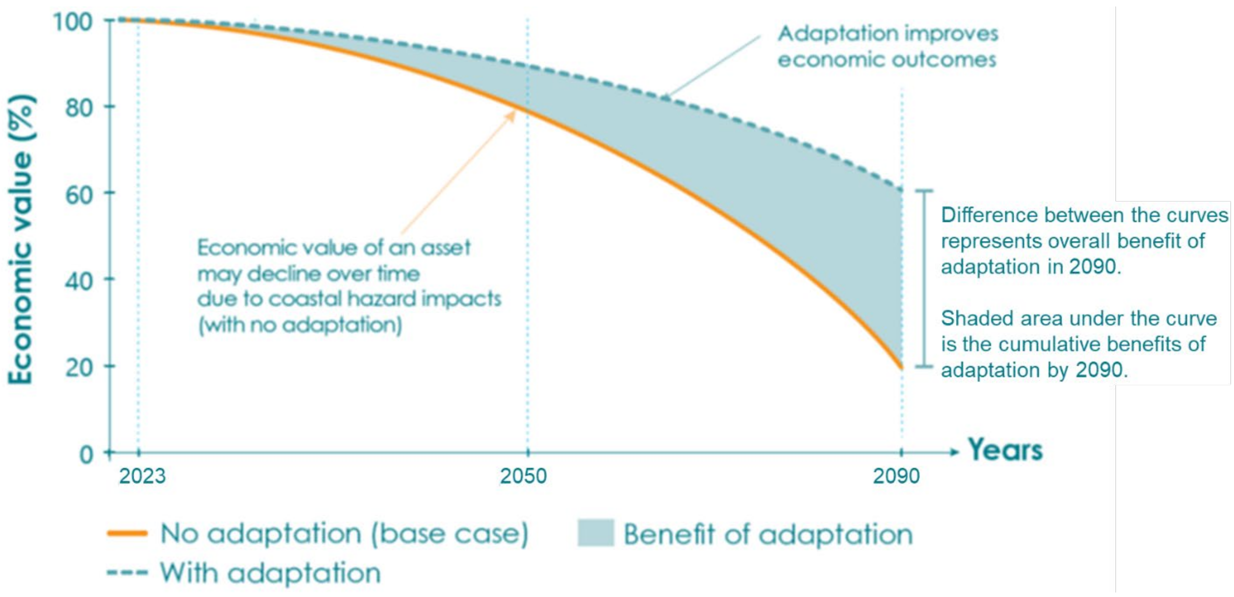


Figure 3-7: Illustrative example of how benefits from different adaptation options are estimated relative to the base case asset investment (adapted from Natural Capital Economics, 2023).

It is critical that all benefits and costs are considered in a CBA, not just those that are readily quantified or in line with the adaptation objectives. This ensures the results of the analysis reflect the outcomes for all stakeholders in the community. Costs and benefits which cannot be quantified are qualitatively evaluated. Example costs and benefits for road adaptation are summarised in Table 3-5.

Table 3-5. Example costs and benefits of adaptation for road infrastructure

Dimension	Benefits	Costs
Economic	• Avoided damage to infrastructure from lower risk exposure • Avoided loss to assets • Avoided loss from business distribution • Avoided emergency and clean-up costs • Reduced damage costs to roads • Reduced supply chain impacts due to delays with re-routing • Reduced congestion on alternative routes • Reduced downtime for road users associated with diversions • Less vulnerability to extreme weather events • Planned and considered expenditure decisions • Implementing innovative solutions • Reduced vehicle operating costs • Reduced time travel delays in the long term • Reduction in car crashes • Reduction in traffic • Decreased down time from flooding affecting road access • Reduced road closures • Improved road performance • Improved access for emergency services	• Direct costs up adapting infrastructure to risk • Administration costs • Opportunity cost of alternative investments and services • Reduced tourism, with reduced amenity value of roadside verges • Increased road congestion/ travel time in the short term • Ongoing maintenance costs

Dimension	Benefits	Costs
Social	• Minimise community social and recreational impacts associated with road diversions or closures • Avoided morbidity, stress and ongoing health consequences • Avoided loss of life • Maintain cultural significant sites • Avoided community services impact associated with road closure • Provide sense of support and security to the community • Managing impacts on communities • Improves community spaces	• Unequal distribution of impacts • Reduction in other services to pay for adaptation measures • Short term inconveniences from planned works • Potential for conflict with cultural significant sites
Environmental	• Maintained ecosystems services • Avoided loss of flora and fauna • Improved water quality with WSUD adaptation option • Opportunity to plant fire retardant flora • Provide long term habitat for fauna	• Reduced biodiversity • Reduced habitat for fauna • Disruption of soil and ecosystems • Reduced 'natural' environment

Dealing with costs and benefits that are difficult to assign a monetary value

In some instances, quantifying the costs and benefits associated with a range of options in monetary terms can be difficult. Values of this characteristic are difficult to assign a dollar amount because their magnitude or impact may be unknown or uncertain, or because they are not typically traded in a market. It is not impossible to monetise costs and benefits of this nature, but common examples include cultural and social considerations, publicity, or intangible concepts.

For instances where the costs and benefits cannot be valued, the reasons why this is the case should be made explicitly clear. The impacts should still be accounted for, but in a qualitative non-monetary process. A wide range of methodologies have been developed to help estimate the value of costs and benefits when direct market information is not available, including revealed preference techniques and stated preference techniques. See Boardman et al. (2010) or Commonwealth of Australia (2006) for more information on tools.

However, using these methods to estimate the environmental values will generally require time, money and expertise. Fortunately, many studies have been developed for non-market valuation, and it may be possible to utilise the relevant results.

3.5.4 Conducting the cost-benefit analysis

Within an economic assessment, the time value of money is expressed through a process of discounting. This process enables the direct comparison of costs and benefits that accrue in different time periods. All future benefits and costs should be discounted to present terms to enable credible comparisons of all the options over longer timeframes.

The discounted (present values) of benefits should be aggregated and compared to the discounted value of the aggregated costs. The NPV and BCR should be calculated in this step using the formula (1) and (2) below. This provides the key metrics used to assess and compare options.

1. $Net\ Present\ Value\ (NPV) = Present\ value\ of\ benefits\ (PVB) - Present\ value\ of\ cost\ (PVC)$

2. $Benefit\ Cost\ Ratio\ (BCR) = \frac{Present\ value\ of\ benefits\ (PVB)}{Present\ value\ of\ costs\ (PVC)}$

The quantified costs and benefits of each adaptation measure are inputted into a CBA model to estimate the net benefit of each individual or set of adaptation options. Results will be presented as net present values (NPV) and benefit-cost ratios (BCR).

3.5.5 Sensitivity testing

There will always be some variability in the input data used in a CBA, and a degree of uncertainty underpinning key assumptions. It is therefore important to undertake sensitivity analysis to determine how sensitive the results are to input parameters.

Basic sensitivity analysis can be undertaken by simply changing the values of the CBA inputs to detect how it changes the outcomes of the analysis and importantly, to observe how the preferred options may change. If variation in an input has significant influence on the preferred option, a higher degree of effort should be made to ensure estimates are accurate.

Sensitivity analysis can be performed using sophisticated methods like Monte Carlo simulations.[2] This approach requires input from specialists. The resulting simulations can be used to estimate probabilistic ranges of outputs to illustrate uncertainty within the results.

Additionally, sensitivity simulations can determine which of the key input parameters are driving the uncertainty. If necessary, culpable parameters can be targeted for further refinement to reduce the error. This is consistent with a leading practice of economic analysis that underpins business cases.

Figure 3-8 provides an illustrative output from a sensitivity analysis, which indicates that, given input parameters, the NPV result will fall between approximately $2 and $7, with 90% confidence.

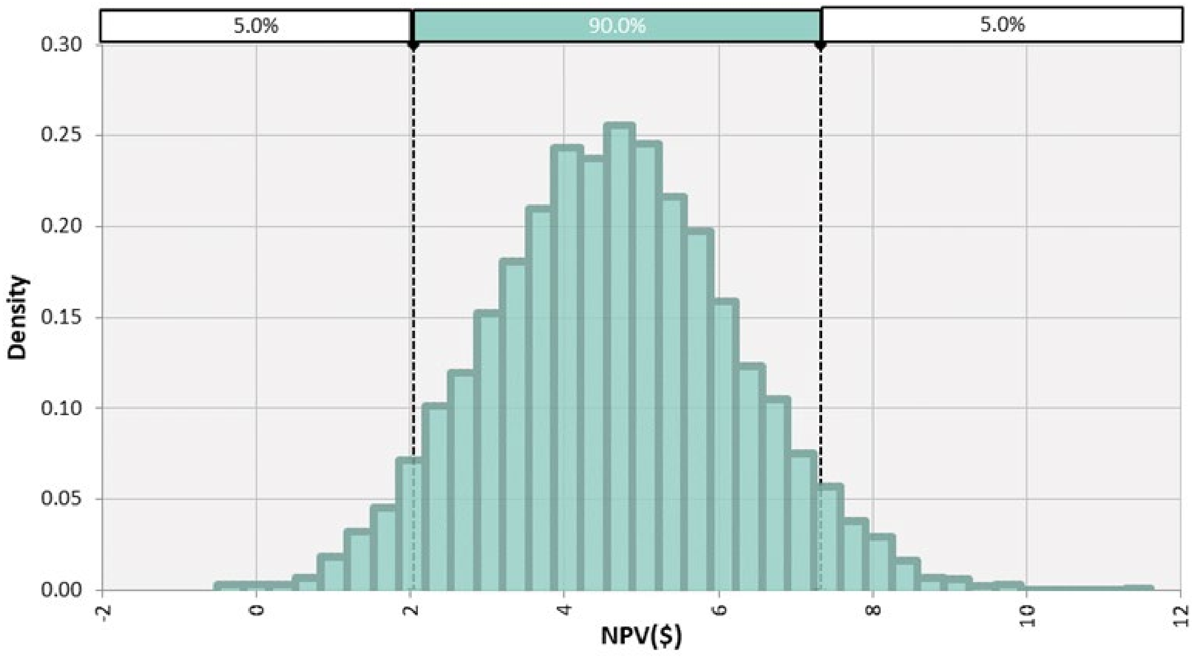


Figure 3-8: Example of probabilistic distribution of net present value from Monte Carlo simulation

3.5.6 Distributional analysis

Distributional analysis is used to investigate how the costs and benefits of each adaptation option are allocated among key stakeholder groups. This is important as although the NPV and BCR results provide insight into the net benefits to society on aggregate, it is useful for decision-makers to identify and

[2] Monte Carlo simulations are statistical techniques used to model the probability of different outcomes in a process that cannot easily be predicted due to the variability in multiple input variables used in the analysis.

understand which groups are expected to accrue benefits and costs over the appraisal period to understand the equity implications of the options under consideration.

Understanding the distributional impacts can also provide insight into the incentives of different stakeholders and whether they are likely or not to support the adaptation measures. In addition, positive distributional outcomes may provide incentive opportunities for attracting co-investment in the adaptation option.

Distributional analysis can range in complexity based on the scale of the project and expected impacts. Where the scale of impact is expected to be significant, detailed scoping and appraisal of ramifications to specific groups may be necessary (e.g., based on residents in specific regions). Where impacts are less significant, qualitative analysis can still provide useful information and context in decision-making (Office of Best Practice Regulation, 2020).

3.5.7 Interpreting CBA results

In this final step, the results are interpreted, assessed, and communicated. It should be noted that a CBA does not make the decision but is a basis to inform the decision. Identifying the option that provides the greatest net benefit is based on consideration of the NPV and BCR results. A positive NPV indicates that the total discounted benefits are greater than the total discounted costs, while a BCR greater than one indicates that the project has a positive net benefit.

The rankings provided by the NPV and BCR methods can differ for a given set of adaptation options due to various factors, including differences in scale and efficiency.

NPV measures the present value of the net cash flows generated by an investment over its lifetime. It considers the timing of cost and benefit flows and discounts them to account for the time value of money. NPV focuses on the absolute value of the expected benefits and costs, taking into account the project's scale and the magnitude of the costs and benefits.

On the other hand, BCR compares the total benefits of a project to its total costs. It provides a ratio that indicates the efficiency of generating benefits relative to the costs incurred. BCR is less influenced by the scale or size of the project and is more concerned with the relative cost-effectiveness or efficiency.

In some cases, a large-scale project may have a high NPV because of significant expected cash flows over a longer time period. This higher NPV can be attributed to the larger absolute value of the benefits and costs involved. However, the BCR may be higher for a smaller, more capital-efficient project that generates relatively higher benefits compared to its costs. The BCR considers the efficiency of generating benefits per unit of cost, which can be favourable for smaller projects that achieve a higher cost-effectiveness ratio.

The difference between scale and efficiency is a key factor in the contrasting rankings provided by NPV and BCR. A large project with substantial cash flows may have a high NPV but a lower BCR if the costs associated with its scale outweigh the efficiency of benefit generation. Conversely, a smaller project may have a higher BCR due to its efficient cost-to-benefit ratio, even if its absolute monetary value is smaller than that of the larger project.

It is important to consider both NPV and BCR, along with other relevant factors, when evaluating and ranking options or projects. These metrics provide different perspectives on financial viability and cost-effectiveness, and their combined analysis can offer a more comprehensive understanding of the overall merit and suitability of different options.

Table 3-6 illustrates how NPV and BCR can be utilised to apprise decision-making. Each option subsequently provides information on the extent of mutual exclusivity and the scope to which budgets are constrained. Generally, NPV is preferred if options are mutually exclusive except when multiple, non-exclusive projects can be funded with a limited budget.

Table 3-6. Decision rule selection matrix

		Exclusivity	
		Options mutually exclusive	Options not mutually exclusive
Budget	Limited	**NPV preferred** Choose the project with the largest NPV within the budget constraint.	**BCR preferred** Rank all projects by BCR and fund all projects in order of their BCRs (highest to lowest) until the budget constraint is reached.
	Unlimited	**NPV preferred** Choose the project with the largest NPV.	**NPV or BCR** Fund all projects with NPV greater than 0 (or BCR greater than 1).

3.6 Case for investment in adaptation

The findings from the Cost-Benefit Analysis (CBA) including the quantification of the Net Present Value (NPV) and Benefit-Cost Ratio (BCR) for all potential adaptation measures can be used to support business case and investment decision making for adaptation.

A positive NPV indicates that the benefits of the investment in an adaptation measure outweighs the costs, while a BCR greater than one suggests that the benefits are greater than the costs. These metrics offer insight into the financial feasibility of the investment and its potential return on investment.

While incorporating non-financial (environmental, social, cultural) values into NPV and BCR analyses can provide a more comprehensive picture of the true costs and benefits of a project, there are limitations to doing so.

One limitation is the difficulty in accurately quantifying and valuing environmental, social, and cultural costs. These costs are often intangible and difficult to measure, making it challenging to include them in traditional economic analyses. As a result, the estimates of these costs and benefits may be subjective or incomplete, leading to potential inaccuracies in the analysis.

Additionally, there may be different perspectives on the value of environmental, social, and cultural costs, which can lead to disagreements and uncertainties when estimating their value. For example, some stakeholders may prioritise economic benefits over environmental or social costs, while others may place a greater value on environmental or social benefits.

Despite these limitations, incorporating environmental and social costs into NPV and BCR analyses can provide valuable inputs into business cases.

The results of a CBA should form one component of a decision-making process, where costs and benefits that can only be expressed qualitatively are nonetheless considered.

4. Approach for establishing exemplars

4.1 Priority climate risk impacts

Phase 2 of this project involved a high-level, qualitative risk assessment of climate impacts across key infrastructure sectors and further analysis and shortlisting of climate risk impacts for the road network. The analysis focussed on risk impacts associated with damage to roads and disruption of access due to extreme weather events. A total of ten risk impacts were identified in 2030 and 2070 under a high emissions scenario (RCP8.5), of which the most significant are outlined below:

- Damage to road surfaces caused by flooding and/ or extreme storm events.
- Obstruction or closure of roads caused by bushfires and landslides.

Across the state, Victoria is projected to experience more extreme short-duration rainfall events and associated flooding. The impacts of more frequent and intense downpours are compounded by other climate hazards including prolonged droughts and declining soil moisture which reduce the absorptive capacity of soil and increase runoff.

Bushfire weather is also becoming more dangerous with warming temperature, rising drought factor, and greater occurrence of thunderstorms (which can ignite bushfires) (DELWP, 2019). A major potential hazard following bushfire events is the occurrence of landslides.

Both bushfire and extreme rainfall directly influence the frequency at which landslides may occur on susceptible slope areas. Landslides occur when the stability of a slope is compromised, leading to the downward movement of soil, rock, or debris. The removal of vegetation cover by the fires exposes the soil to increased erosion and reduces its stability, making it more susceptible to landslides during heavy rainfall events. The increased intensity of rainfall events can saturate the soil, reducing its shear strength and triggering slope failures. As the absorptive capacity of the soil decreases, the excess water accumulates, creating additional pressure on the slope.

The Phase 2 study confirmed that the effects of the shortlisted climate risks will not be experienced evenly across the state. Effective adaptation to these impacts requires detailed investigation of exposure and vulnerability at the site level to consider important factors such as road criticality, infrastructure age, and the local economy and communities.

4.2 Exemplars

In this phase of the project, two exemplars are used to demonstrate the process for undertaking quantitative risk assessment and economic analysis of adaptation investment opportunities. This allows for consideration of those site-specific factors including hazard exposure, asset criticality, and system interdependencies. The exemplars are de-identified and hypothetical to ensure they are robust, representative, and scalable.

De-identified: grounded in real site and project data for robustness and rigor in the risk assessment and economic analysis process.

Hypothetical: representative of multiple locations; contains a range of road asset components and hazard features for scalability; suitable for a range of adaptation measures.

For each exemplar, this study provides detailed risk assessment and economic analysis of eight adaptation measures, respectively. The suite of adaptation measures includes options from four adaptation categories to demonstrate applicability to future infrastructure projects across Victoria. The shortlisted adaptation measures were developed and assessed with input from engineering specialists across flooding, geotechnics, bushfire, pavement, and ecology.

5. Exemplar for adaptation to flooding

5.1 Overview

The first exemplar explores the impact of flooding and extreme storm events on roads. Flooding presents significant issues for road infrastructure, causing damage to various components of the road, including road surfacing and pavement, embankments and retaining walls, culverts, and transverse and longitudinal drainage systems.

The two primary damage mechanisms for roads associated with flooding are inundation and washout. These are detailed in Phase 2 of the project and are summarised in Table 5-1. Sealed and unsealed unbound granular pavements are more vulnerable to these risks than deep-strength asphalt and concrete pavements.

Table 5-1: Impacts on roads caused by flooding

Damage mechanism	Impacts on roads
Inundation causing increase moisture content and weakening of pavement, subbase layers, and subgrade	• Cracking of the surface due to weakened surface and pavement base layers • Rutting, depressions, and potholes due to trafficking following inundation • Surface stresses including delamination • Edge break of sealed surfaces and shoulder erosion
Washout of road embankments and pavements due to insufficient culvert size or high velocity flows	• Erosion of material surrounding culverts • Road collapse or washout • Blocked drainage infrastructure from debris • Softening of subgrade

As the climate changes and temperatures continue to rise, Victoria is projected to experience more frequent and intense rainfall events. Figure 5-1 illustrates road assets that presently intersect or are within close proximity to flooding overlays in Victoria. These roads will become increasingly exposed to flooding hazards in the future.

Two types of flooding a significant threat to Victorian road infrastructure assets. Fluvial flooding occurs when rivers and streams overflow their banks due to heavy rainfall or snowmelt, causing water to inundate adjacent areas. It is more prevalent in rural and regional settings where river systems are present. Pluvial flooding occurs due to surface runoff due to rain. Pluvial flooding primarily affects developed urban areas and is the focus of this exemplar.

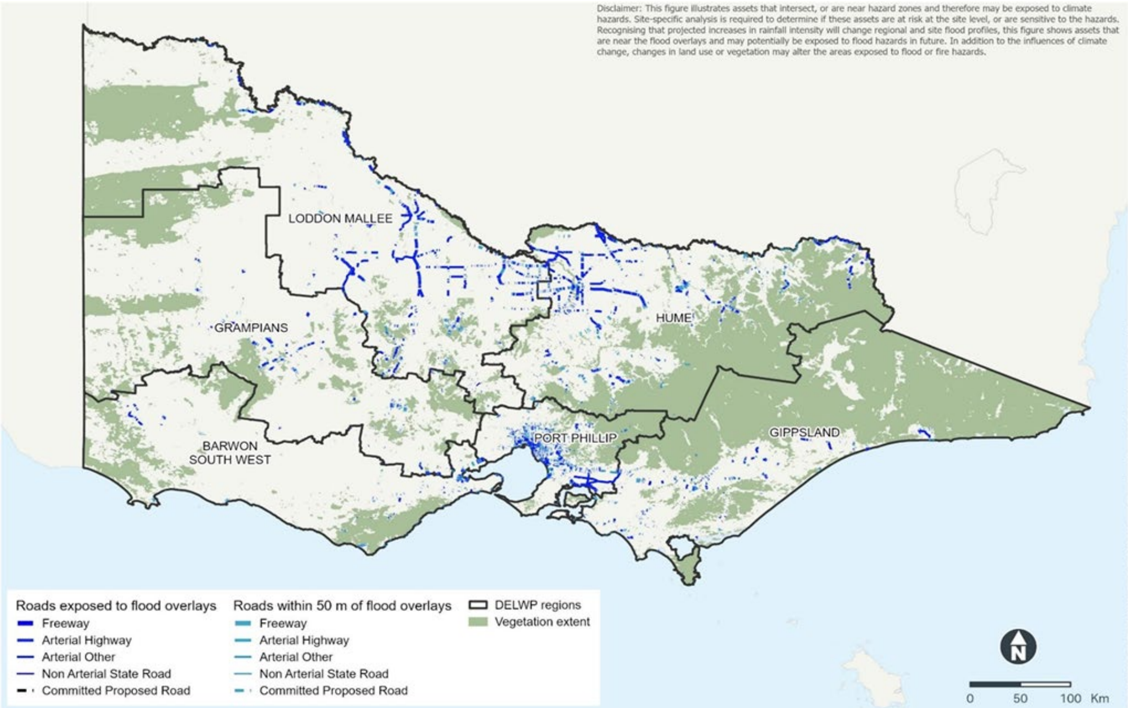


Figure 5-1: Road exposure to flood risk from Phase 2 of this project. (AECOM, 2022)

5.2 Problem definition

This flood exemplar considers the impact of increasing rainfall intensity and pluvial flooding on road infrastructure assets in metropolitan Melbourne. Due to the effects of climate change, flooding events in metropolitan Melbourne and regional Victoria are becoming more frequent and existing roads across the state are not sufficiently resilient to withstand their impacts.

As a result of flood events, inundation and partial wash-out from overtopping flows as well as debris cause major disruption to the road corridor and extended downtime while repairs are conducted. This not only increases travel time, cost, and risk of car crashes, but also places additional pressure on the surrounding road network, which may not have the capacity to accommodate the diverted traffic. This disruption often results in negative environmental externalities such as emissions, noise, and biodiversity impacts. The increasing frequency of flooding events is accelerating the rate of deterioration for the road, resulting in increasing costs for recovery and reduced reliability for road users.

Figure 5-2: Flash flooding in Melbourne suburbs (Stephens, 2016)

5.3 Site characteristics

5.3.1 Site characteristics and system interdependencies

The exemplar is a major arterial road, as defined by Victoria's Department of Transport and Planning, located in the urban fringe of metropolitan Melbourne within an Urban Floodway Zone, Floodway Overlay, and Land Subject to Inundation Overlay. The 2-lane, single carriageway 7km road corridor has Annual Average Daily Traffic Volume (AADT) of around 11,000 vehicles passing through daily, and this is predicted to rise to nearly 20,000 vehicles by 2030.

The current grade and transverse drainage infrastructure of this exemplar has been designed to protect the road corridor from a 20% annual exceedance probability (AEP) flood event equivalent to a 5-year return period flood event. However, it currently experiences overtopping (inundation), causing disruption for road users, businesses, and communities in the surrounding area. This will become worse with climate change.

The exemplar is surrounded by industrial and residential areas and is immediately adjacent to a national park with a Bushfire Prone Area (BPA) overlay. Within the exemplar area, there is a network of local roads. Around 100,000 people live in close proximity to the road corridor, and this is projected to grow to 150,000 by 2050. There is limited public transport access within 3km radius of the exemplar road, and many residents rely on private vehicles as their main mode of transport.

While not all roads in Metropolitan Melbourne have all of these characteristics, many would have a mixture of these and therefore this exemplar provides a useful representation of adaptation opportunities for road projects in Greater Melbourne.

5.3.2 Road function

The major arterial road is vital infrastructure that serves as a key linking road to the freeway and highways, providing a critical corridor for regional connectivity, major freight movements, and access to large employment, commercial, and activity centres. The road is a key route for emergency services, although is supported by a network of smaller surrounding roads.

5.3.3 Asset components

The road asset components and potential failure modes from flooding are summarised in Table 5-2 for this exemplar.

Table 5-2: Road asset components and failure modes from flooding

Road asset component	Possible failure mode from flooding
Road pavement and surface	Erosion, cracking, washout, loss of structural integrity resulting in potholes, rutting, and uneven surfaces
Culverts and drainage structures	Blockage or damages resulting in water overflowing
Embankments	Scour and erosion resulting in road obstruction or damage to adjacent structures
Intelligent Transport Systems (ITS) and electrical	Water damage, power outages and malfunction

5.4 Exposure assessment

5.4.1 Climate hazard scenarios

To estimate flooding hazard under current and future (RCP8.5) climate conditions in 2022 and 2070 respectively, existing peak water levels were estimated using a two-dimensional hydraulic model for flood events ranging from 20% AEP to 0.2% AEP events.

Peak water levels from rainfall in 2070 under RCP8.5 has been determined using a 13.85% climate change allowance to scale current (baseline) flood data. This climate change allowance is determined using the Australian Rainfall and Runoff Guidelines (Geoscience Australia, 2019).

5.4.2 Exposure assessment

To assess the exposure of the road under each flood event, a Digital Elevation Model representing the current road elevation was overlayed with the flood layers provided by the hydraulic model to determine the flood depth across the road corridor.

5.5 Vulnerability assessment

5.5.1 Vulnerability

The vulnerability of the asset is defined by a vulnerability curve which relates hazard intensity (flood depth) to damage represented as a percentage of total replacement cost. The vulnerability curve was derived from literature and engineering judgment.

The function was developed primarily using data from a U.S. Army Corps of Engineers study in 2009 (US Army Corps of Engineers, 2009). The study estimated level of damage to roads resulting from flood depths and associated costs to repair. The data showed significant damage at low flood depths (e.g., almost full repairs required at 30cm of flooding). The curve used in this study was implemented assuming that the road would not be repaired after each flood event, but it would instead need eventual replacement due to cumulative flood damage. The cost of replacement includes the damage to all road components, including pavement and embankments, to capture the multiple ways that floods damage roads.

The vulnerability curve for the base case is shown in Figure 5-4.

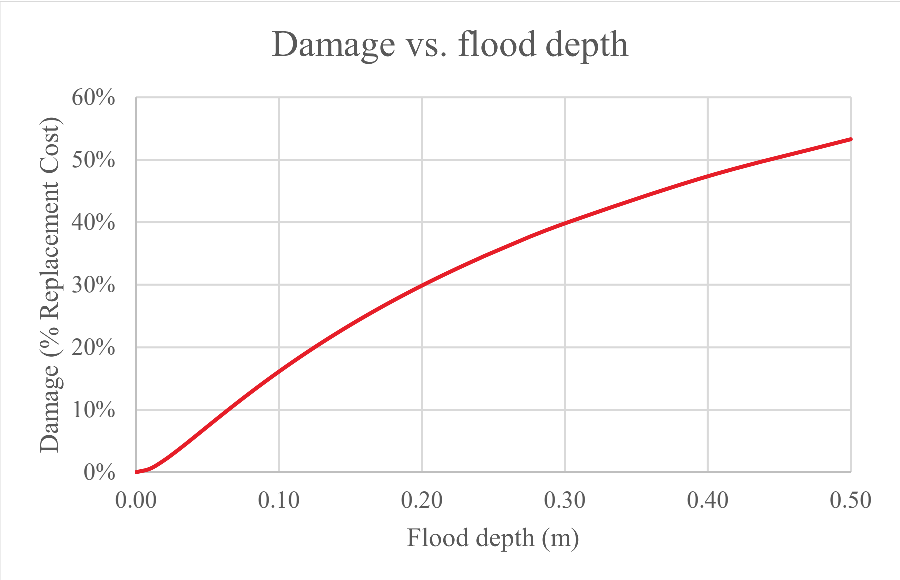


Figure 5-3: Vulnerability curve for flooding for roads

The consequences of damage were calculated in terms of financial loss and downtime. Financial loss was calculated by multiplying the percentage damage by the asset replacement cost of $12,000,000 per kilometre of road (Department of Infrastructure, Regional Development, and Cities, 2017).[3]

Downtime was calculated based on time for waters to recede and time required to inspect, prioritise, and conduct repairs. The number of days of downtime was based on model runs of critical storms, information from Australian storms and flooding, and engineering judgment. It is assumed that there is no downtime until 15cm of flood depth because cars and trucks are able to drive through low depths of floodwater. Three days of downtime was assumed at depths between 15cm and 45cm (corresponding to approximately 30-50% damage) for debris clearing, and 30 days was assumed for necessary repairs when damage reaches 50% or more. The consequence curve for percentage damage and downtime is shown in Figure 5-5.

[3] Replacement cost assumes road is a two-lane, Class 7 road under Austroads' function road classification. Replacement cost represents the median value for this road class and features and is not representative of all road types.

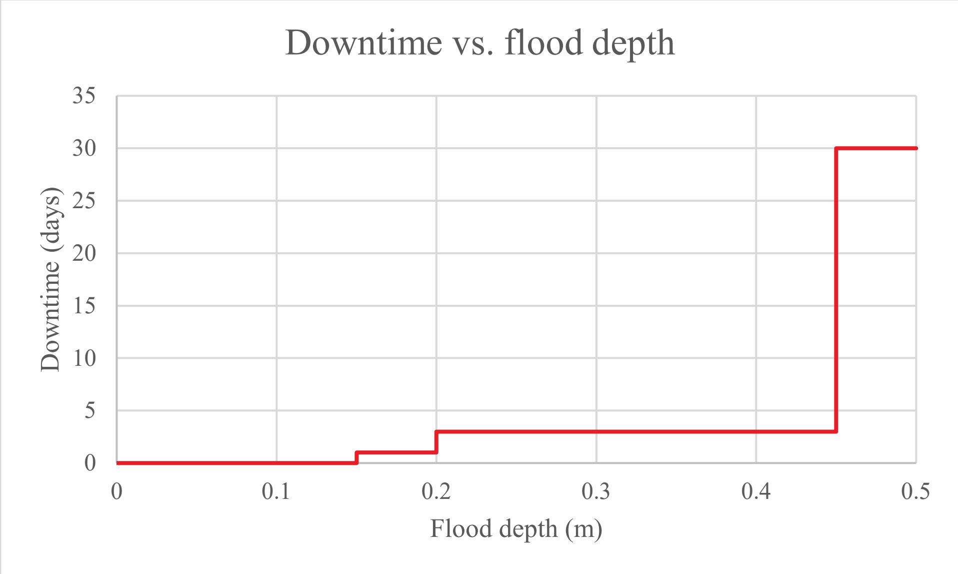


Figure 5-4: Downtime-damage consequence curve

5.6 Base case climate risk assessment

5.6.1 Risk metrics

To estimate flood-related risk for the base case, the following risk metrics were included for current climate conditions and future climate conditions under RCP8.5:

- Average Annual Loss (AAL) in $AUD
- Average Annual Downtime (AAD) in days.
- Indirect tangible losses in $AUD including emergency costs and disruption to public services and community, car crashes (fatality, injury, serious injury), disruption to freight, disruption to passenger vehicles, business and service disruption, air pollutions, emissions, and noise.
- Intangible loss in $AUD including impacts on soil and water, nature and landscape, urban effects, biodiversity, health costs, and social and recreational values.

5.6.2 Findings

Direct tangible, indirect tangible, and intangible losses were calculated for the road exemplar impacted by 20% AEP (5-year return period) to 0.2% AEP (500-year return period) events for flooding using the risk assessment model developed for the exemplar.

The damage and downtime curves for the flood exemplar under current climate conditions are shown in Figure 5-6 and Figure 5-7. These curves are tools used to estimate the potential damage and losses caused by flooding at different flood depths. The AEPs correspond with flood depths across the length of the road exemplar. The area under the curves represents the AAL and AAD, respectively. These curves were scaled to represent future climate conditions in 2070 under RCP8.5 in the assessment.

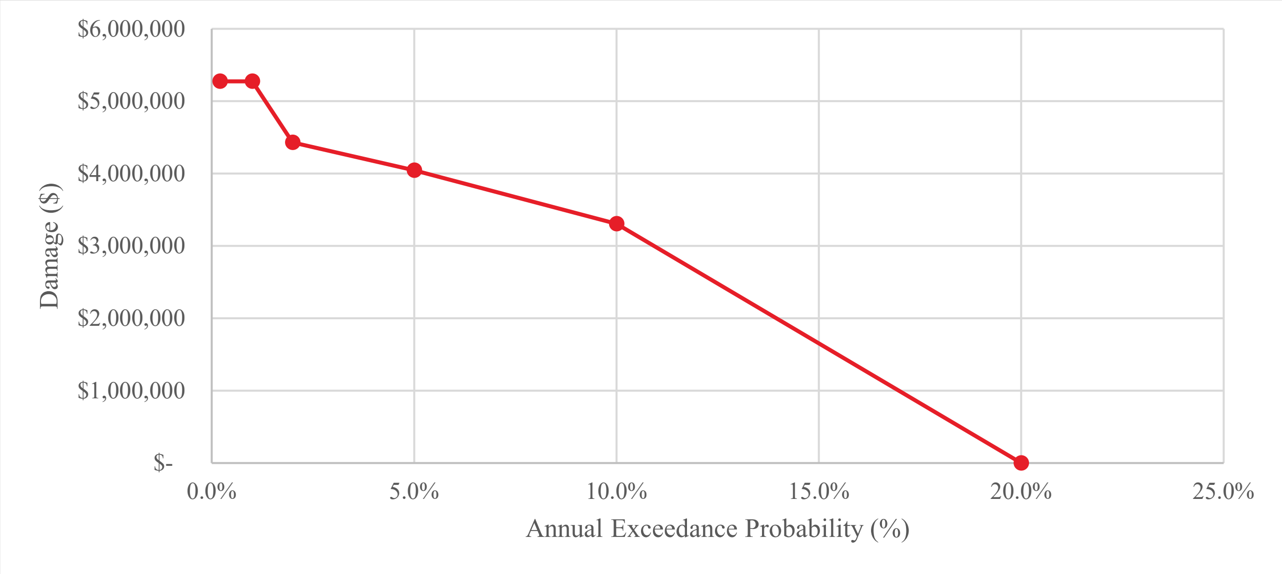


Figure 5-5: Damage curve for flood exemplar under current climate conditions.

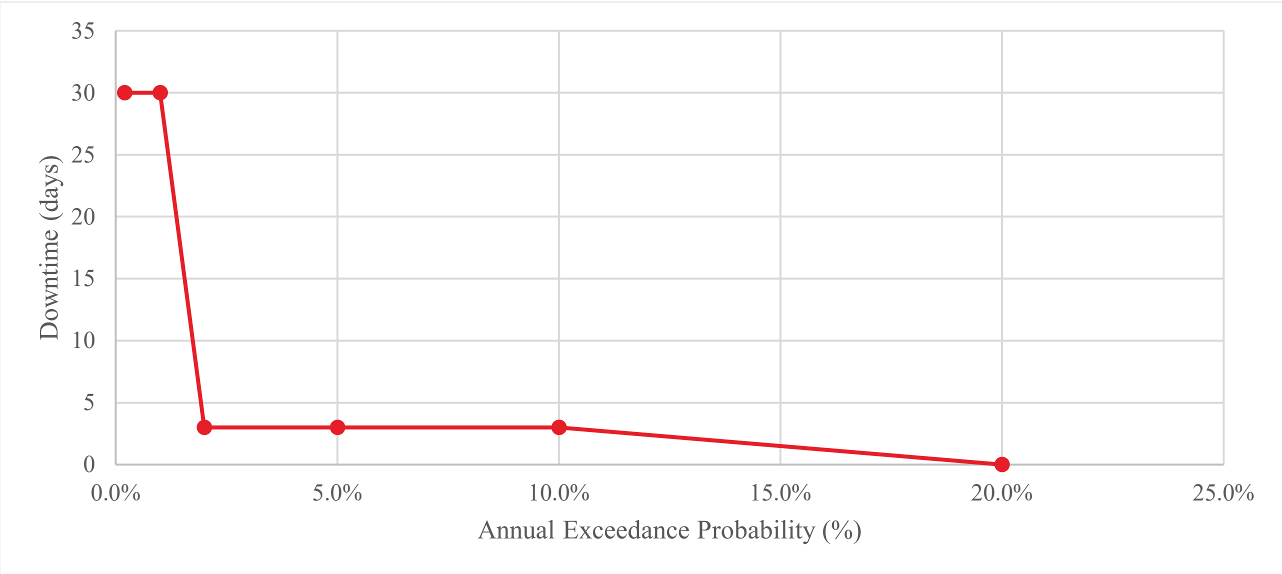


Figure 5-6: Downtime curve for flood exemplar under current climate conditions.

The quantified loss from flood risk in terms of AAL and AAD for the exemplar is presented in Table 5-3. A sample calculation is provided in Appendix C. The total loss increases from current climate conditions in 2022 to future climate conditions in 2070 under RCP8.5.

Table 5-3: Average annualised losses from flooding under current and future climate conditions

	AAL	AAD (days)	Indirect tangible and intangible losses (annualised)
Current climate in 2022	$577,679	0.86	$90,614
Future climate in 2070 (RCP8.5)	$927,439	1.45	$153,407

5.7 Adaptation measures

5.7.1 Priority adaptation measures

Eight adaptation measures are implemented for this exemplar, summarised in Table 5-4 and detailed in the subsequent sections. The MCA process for shortlisting these measures is presented in Appendix B, including respective scoring against the multi criteria. The shortlist includes measures across the four adaptation categories: higher-cost investment, lower-cost investments, maintenance, and hazard management.

Despite a low MCA score, a viaduct adaptation measure has been included for this exemplar to illustrate a measure that can achieve immunity to the future 500-year return period. This would be appropriate for future projects with a low-tolerance threshold for downtime (i.e. highly critical road corridors with emergency response functionality).

Table 5-4: Shortlisted adaptation measures for flooding exemplar

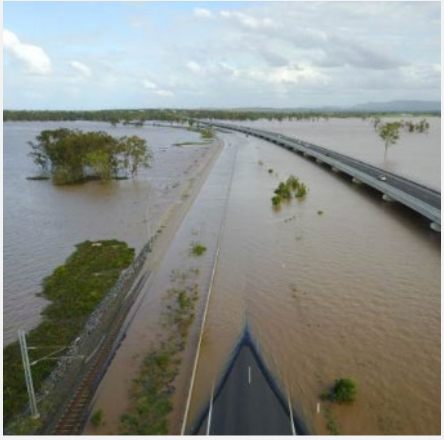
Adaptation ID	Adaptation measure	Adaptation type
F_FBS	Foamed bitumen stabilisation	Higher-cost investment
F_5%_Grade	Optimise road grade and drainage with immunity to future 5% AEP (20-year return period with a climate change allowance)	Higher-cost investment
F_5%_Staged	Staged design to optimise road grade and drainage with immunity to future 5% AEP (20-year return period with a climate change allowance), and uplift to future 1% AEP (100-year return period with a climate change allowance)	Higher-cost investment
F_Viaduct	Viaduct with immunity to future 0.2% AEP (500-year return period with a climate change allowance)	Higher-cost investment
F_WSUD	Water Sensitive Urban Design (WSUD) including catchment upgrades to achieve immunity to future 20% AEP (5-year return period with climate change allowance)	Lower-cost investment
F_Prevention	Increased frequency of preventative maintenance	Maintenance
F_Programmed	Increased frequency of programmed rehabilitation	Maintenance
F_Hazard_Mgmt	Hazard management including early warning system, heavy load limits, and temporary rerouting	Hazard management

Foamed bitumen stabilisation

Foamed bitumen stabilisation (FBS) is a pavement treatment methodology involving insitu or plant mix stabilisation of pavement materials with bitumen and lime/cement. It is used to improve the strength of granular materials while retaining a flexible pavement. The process involves generating foamed bitumen by injecting small quantities of water and air into regular road-grade bitumen under high pressure, causing the bitumen to expand up to 20 times its initial volume (Austroads, 2017). In the foamed state, bitumen is highly effective at coating finer particles of pavement material and binding the mixture and making it more resilient to shrink / swell effects.

FBS materials and pavements have been the focus of multiple national research projects, spanning more than 10 years, to validate their performance characteristics and improve design approaches. With support from Austroads, Road Agencies and contractors, this research has included full scale construction trials on major arterial roads. The FBS construction process is 25% faster than the traditional pavement construction methodology and the subgrade is exposed for less time which reduces construction risk.

There are various applications of FBS across New South Wales, Queensland, and New Zealand with proven benefits, and several pilot applications in Victoria over the last two decades. Recent projects where FSB has been applied in Victoria include the Midland Highway and Ballarat Burrumbeet Road.



Foamed bitumen stabilisation in Queensland

"Investing in research and innovation has paid big dividends for Queensland's Department of Transport and Main Roads, with millions of dollars saved in the wake of Cyclone Debbie through more resilient pavements." (Institute of Public Works Engineering Autralasia, 2017)

Foamed bitumen pavements have proven to be more resilient to flooding in Queensland. Compared to conventional asphalt/ granular pavements in similar flood conditions, FBS was found completely intact when flood waters of up to 3 metres receded. Examples include Bruce Highway near Bowen, Yeppen Floodway near Rockhampton, and Stegemann Road in Logan City Council (PIARC, 2019).

FBS may not be suitable for strengthening all types of existing pavement materials. Suitability is mainly determined by measuring the engineering properties of insitu pavement materials. As an example, in southwest Victoria, the pavements are typically in scoria and may not be suitable for FBS.

Upgrade flood immunity to future 5% AEP

The exemplar is currently designed with immunity to 20% AEP, or the 5-year return period flood event. This adaption measure will upgrade the road with immunity to the future 5% AEP (20-year return period flood event with a climate change allowance). Implementation involves several measures, including raising the road level above the projected flood level in 2070 under RCP8.5, improvements to transverse drainage systems and additional culverts installed to ensure adequate water flow and prevent waterlogging on the road surface. Other measures such as erosion control to withstand floodwater velocities are also considered for this flood immunity level.

Staged immunity to future 5% AEP and future 1% AEP

For this adaptation measure, the road is upgraded to achieve flood immunity to the future 5% AEP (20-year return period event with a climate change allowance) in accordance with the previously described adaptation measure.

However, the upgrade includes a wider embankment to allow for an uplift in immunity level to the future 1% AEP (100-year return period flood event with a climate change allowance). This uplift would be implemented at the first rehabilitation cycle, within 20 years. The staged approach allows for reassessment of the road's performance in line with the capital expenditure of the first rehabilitation cycle and defers the cost of topping up the flood immunity until there is reduced uncertainty in the future climate.

Viaduct

A viaduct is a type of elevated roadway over a floodplain or waterway. For this adaptation measure, the construction of a concrete viaduct over the floodplain achieves flood immunity to the present-day 0.5% AEP (200-year return period flood event), equivalent to the future 1% AEP with a climate change allowance. The total length of 1600m comprises 48 spans, supported by a series of columns along the length of the structure.

This approach provides a stable and safe route for critical traffic, while also minimising the impact on the surrounding landscape and protecting against potential future flood events.

Water Sensitive Urban Design (WSUD)

WSUD is a holistic approach to infrastructure development and involves the design and implementation of natural infrastructure and systems that capture, treat, and manage stormwater runoff from roads. For this exemplar, WSUD includes bio-retention basins, swales, and catchment improvements to reduce peak flows and increase the flood immunity from present day 20% AEP (5-year return period flood event) to future 20% AEP (5-year return period with a climate change allowance).

Preventative maintenance
As road condition worsens, the cost of repair and rehabilitation increases. This adaptation measure involves increased preventative maintenance such as surface treatments to preserve pavement condition, reduce the rate of deterioration, and extend the life of pavement (Figure 5-8). It involves regular inspections using a combination of automated inspections and machine learning to identify weaknesses and trigger preventative works. As a result, the frequency of programmed rehabilitation may be reduced and the need for substantial reconstruction significantly delayed.

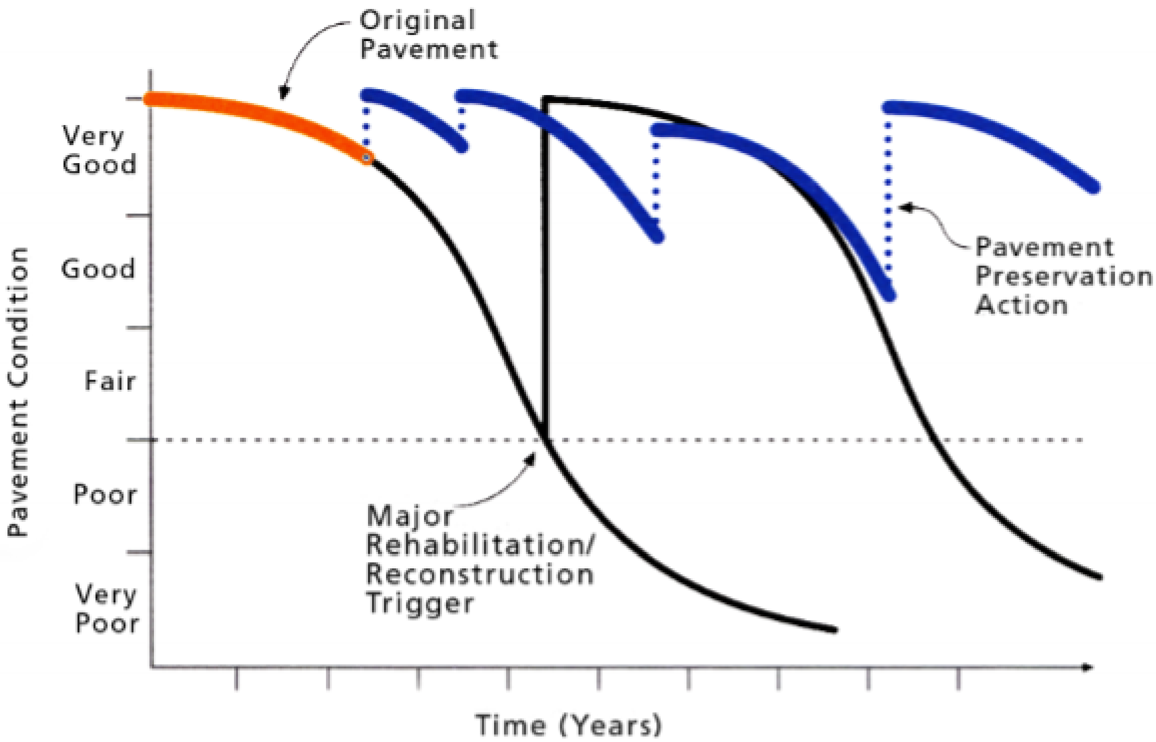


Figure 5-7: Pavement preservation curve from preventative maintenance (Lautenbach, 2022)

Programmed rehabilitation
Programmed rehabilitation of roads involves more frequent and extensive repairs and maintenance activities aimed at improving the overall condition of the road pavement (Figure 5-9). It often involves more comprehensive repairs than preventative maintenance, which may only involve minor repairs and routine maintenance activities. Programmed rehabilitation may include activities such as resurfacing or repaving the road, repairing or replacing damaged sections of the road, and improving drainage systems.

This adaptation measure is focused on increasing the minimum acceptable road condition which increases the frequency of programmed rehabilitation and reduces the need and cost of total reconstruction.

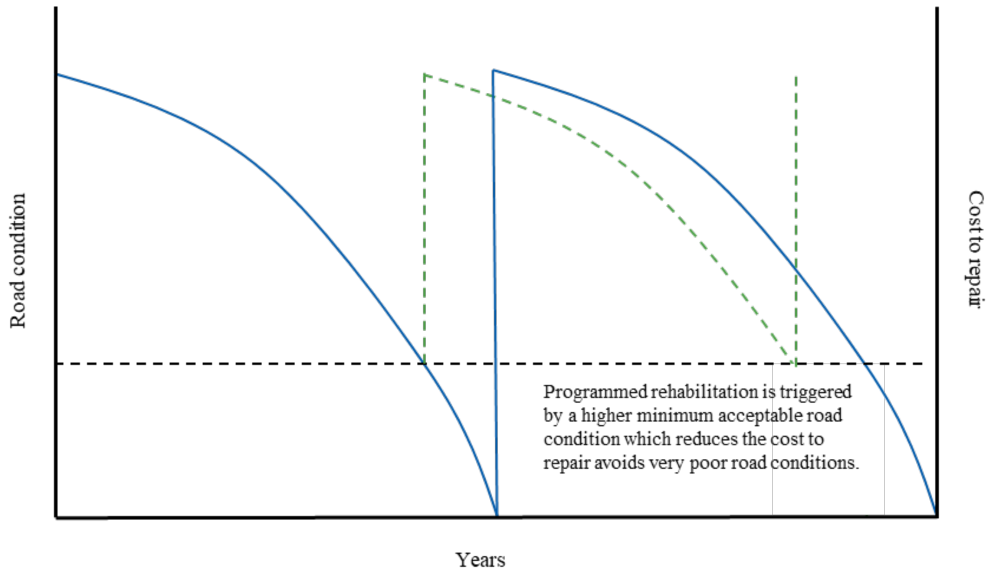


Figure 5-8: Pavement preservation curve from programmed rehabilitation. Modified by Arup from US Department of Transport (2014). The blue line represents business-as-usual deterioration of asset condition prior to programmed rehabilitation. This longer maintenance cycle results in higher total rehabilitation costs. The green line represents shorter programmed rehabilitation cycle where maintenance is triggered at a higher minimum acceptable road standard (dotted black line). This shorter cycle results in relatively lower rehabilitation costs.

Hazard management

Effective communication of hazards via ITS solutions coupled with rerouting can aid in reducing damage to infrastructure and improve the resilience of the road network (PIARC, 2019).

This adaptation measure is focussed on the prevention of further damage to roads from heavy loads after a flood event has occurred. The measure includes implementation of early warning systems to reduce the speed of traffic during and following a storm event, limiting heavy load on roads that may have been weakened by the storm, and temporarily rerouting traffic to alternative routes. It is effective up to 0.2m flood depths, after which it is assumed that road damage may result from high water velocities irrespective of traffic volume or type.

ITS solutions for early warning systems may include hazard data transfer using vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) technologies.

ITS early warning systems in Norway (PIARC, 2019)

The web portal developed by the Norwegian Public Roads Administration, Norwegian Water Resources and Energy Directorate, Bane Nor, and the Norwegian Meteorological Institute is an innovative solution to improve road operation tracking during extreme weather events. The portal captures both temporal and spatial climate data, including temperature, precipitation, wind speed, and other meteorological parameters, and uses this data to generate an alert system for climate-related hazards.

The system is designed to inform road operators, road users, and the public about potential hazards associated with extreme weather events, such as floods, landslides, and snowstorms. By providing timely and accurate information about weather conditions and potential hazards, the system can help improve the safety and efficiency of road operations, reduce the risk of car crashes, and minimise the impact of extreme weather events on road infrastructure and the environment.

The web portal provides a user-friendly interface that allows users to access real-time climate data, hazard alerts, and other information relevant to road operations. The system is also designed to be scalable, meaning that it can be easily adapted to different regions and weather conditions, and can be customized to meet the specific needs of different user groups.

5.7.2 Efficacy of adaptation measures

The performance improvements from adaptation measures for flooding are described in Table 5-5. Residual risk levels in terms of direct, indirect, and intangible losses are summarised for the base case and each adaptation measure in Table 5-6.

Table 5-5: Efficacy of adaptation measures for flooding

Adaptation ID	Adaptation measure	Efficacy
F_FBS	Foamed bitumen stabilisation	FBS can reduce vulnerability to flood damage by 99% and shorten the downtime required to restore full capacity traffic axle loading after a flood event. To calculate the post-adaptation residual risk level, the vulnerability curve and consequence curve (damage-downtime) are adjusted accordingly.
F_5%_Grade	Optimise road grade and transverse drainage with immunity to future 5% AEP (20-year return period with a climate change allowance)	Raising the road grade and designing transverse drainage to achieve immunity to future 5% AEP reduces overall exposure to flooding. The change is implemented in adjusted hazard exposure.
F_5%_Staged	Staged design to optimise road grade and drainage with immunity to future 5% AEP (20-year return period with a climate change allowance), and uplift to future 1% AEP (100-year return period with a climate change allowance)	Raising the road grade and designing drainage to achieve immunity to future 5% AEP reduces overall exposure to flooding hazard. The road is further raised to achieve future 1% AEP with the first rehabilitation cycle, within 20 years, reducing exposure to flooding hazard. The change is implemented in a staged adjustment of hazard exposure.
F_Viaduct	Viaduct with immunity to future 0.2% AEP (500-year return period with a climate change allowance)	The construction of a viaduct with immunity to the future 0.2% AEP (500-year return period with a climate change allowance) reduces overall exposure to flooding. The change is implemented in adjusted hazard exposure.

Adaptation ID	Adaptation measure	Efficacy
F_WSUD	Water Sensitive Urban Design (WSUD) including catchment upgrades to achieve immunity to future 20% AEP (5-year return period with climate change allowance)	WSUD reduces overall exposure to flooding. The change is implemented in adjusted hazard exposure.
F_Prevention	Increased frequency of preventative maintenance	Preventative maintenance slows degradation and reduces vulnerability to damage by 50%. Downtime due to debris clearing and repairs is reduced by 50% as a result of preventative maintenance. Programmed maintenance is extended from every 10 years to every 15 years, and repair cost is reduced by 25% due to improved overall road condition.
F_Programmed	Increased frequency of programmed rehabilitation	Increasing programmed maintenance from every 10 years to every 7.5 years (resurfacing) and 20 years to 15 years (major rehabilitation) reduces the vulnerability to damage by 50%. Downtime for repairs and repair cost are also reduced by 50% due to a higher minimum acceptable road condition and reduced absolute deterioration.
F_Hazard_Mgmt	Hazard management including early warning system, heavy load limits, and temporary rerouting	As a result of limiting heavy loads following flood events, the vulnerability of the road is reduced by 99% up to the 0.2m flood depth. Above 0.2m flood depth, the vulnerability curve is equal to the base case as high velocity floodwaters cause damage to the pavement. Downtime is eliminated due to temporary rerouting, so the damage-consequence curve is shifted accordingly.

Table 5-6: Annualised direct, indirect, and intangible losses associated with the base case and each adaptation measure under current 2022 climate conditions and future 2070 climate conditions under RCP8.5. Values are presented in 2022 $AUD.

Adaptation measure	Average Annual Loss (AAL)		Average Annual Damage (AAD), days		Indirect tangible and intangible losses (annualised)	
	Current climate in 2022	Future climate in 2070 (RCP8.5)	Current climate in 2022	Future climate in 2070 (RCP8.5)	Current climate in 2022	Future climate in 2070 (RCP8.5)
Base case	$577,679	$927,439	0.86	1.45	$90,614	$153,407
F_FBS	$5,777	$9,274	0.45	0.72	$47,691	$76,147
F_5%_Grade	$17,178	$30,921	0.00	0.00	$0	$0
F_5%_Staged	$11,452	$13,170	0.00	0.00	$0	$0
F_Viaduct	$0	$0	0.00	0.00	$0	$0
F_WSUD	$88,057	$145,924	0.11	0.18	$11,128	$19,077
F_Prevention	$216,630	$347,790	0.23	0.36	$31,794	$50,765
F_Programmed	$144,420	$231,860	0.34	0.54	$31,794	$50,765
F_Hazard_Mgmt	$443,069	$712,118	0.00	0.00	$0	$0

Note: indirect tangible and intangible losses are downtime dependent. Therefore, for adaptation measures which effectively eliminate downtime, there will be no indirect or intangible losses. Based on the adopted downtime-damage curve, downtime only occurs when flood depth is 15cm or greater.

5.8 Economic analysis of flooding adaptation measures

Building upon the risk assessment of the priority flooding adaptation measures, holistic economic analysis captures the tangible and intangible costs and benefits of investing in resilient roads to help inform decision-making. By comparing the base case losses to the benefits (avoided losses) and costs (installation, maintenance, carbon) of priority adaptation measures, the value of the options can be quantified.

5.8.1 Base case valuation

The base case describes the total losses arising from a hazard if no adaptation measures are implemented. These losses include the direct asset damage and downtime (quantified in Section 5.6), the indirect tangible costs for State and Local government, freight, passenger vehicles, and the wider community, and intangible social, environmental, and cultural impacts.

The average annualised base case losses for the current climate conditions and future climate under RCP8.5 are summarised in Table 5-7. These represent the expected annual loss resulting from the impact of flooding for the time horizon of 2070. As expected, the losses associated with flood risk rise as a consequence of climate change by 2070.

Table 5-7: Annualised direct tangible, indirect tangible, and intangible losses for the base case under current 2022 and future 2070 (RCP8.5) climate conditions. Values are presented in 2022 $AUD.

Base case losses					
Direct cost (AAL)		Direct cost (AAD), days		Indirect tangible and intangible losses (annualised)	
Current climate in 2022	Future climate in 2070 (RCP8.5)	Current climate in 2022	Future climate in 2070 (RCP8.5)	Current climate in 2022	Future climate in 2070 (RCP8.5)
$577,679	$927,439	0.86	1.45	$90,614	$153,407

Indirect tangible and intangible losses have been calculated based on damage and downtime dependencies using appropriate environmental and social parameters. These have been sourced from:

- Australian Transport Assessment and Planning Guidelines – PV2 Road Parameter Values (2016)
- Australian Transport Assessment and Planning Guidelines – PV5 Environmental Parameter Values (2021)
- Department of Treasury and Finance Economic Evaluation for Business Cases Technical guidelines (2013)
- Transport for NSW Road & Rail Cost Escalation Indices 2022 Update (2022)

5.8.2 Costs of adaptation

Each priority adaptation measure incurs costs related to installation, ongoing maintenance, and embodied carbon emissions. Installation and maintenance costs are summarised in Table 5-8, along with their maintenance frequency. For example, a frequency of 10 years indicates that the maintenance cost will be incurred four times in the 2070 time horizon. All adaptation installation and maintenance costs use the New South Wales average escalation rate of 3.9% per annum.[4]

[4] The New South Wales cost escalation guidance was the most up to date, publicly available information at the time of this study. While there can be differences between New South Wales and Victoria, the North East Link business case used a similar cost escalation figure with 4% for capital expenditure and lifecycle costs, and 2.5% operating and maintenance costs.

Table 5-8: Flooding adaptation installation and maintenance costs

Adaptation ID	Description	Installation cost ($AUD, 2022)	Maintenance cost ($AUD, 2022)	Maintenance frequency (years)
Base case	Base case without adaptation	0	Pavement resurfacing: $800,000	10
			Pavement replacement: $1,600,000	20
F_FBS	Foamed bitumen stabilisation	$2,160,000	Pavement resurfacing: $1,600,000	10
			Pavement replacement: $2,400,000	20
F_5%_Grade	Optimise road grade and transverse drainage with immunity to future 5% AEP (20-year return period with a climate change allowance)	$8,850,000	Pavement resurfacing: $800,000	10
			Pavement replacement: $1,600,000	20
F_5%_Staged	Staged design to optimise road grade and drainage with immunity to future 5% AEP (20-year return period with a climate change allowance), and uplift to future 1% AEP (100-year return period with a climate change allowance)	$14,200,000	Pavement resurfacing: $800,000	10
			Pavement replacement: $1,600,000	20
F_Viaduct	Viaduct with immunity to future 0.2% AEP (500-year return period with a climate change allowance)	$160,000,000	Pavement resurfacing: $800,000	10
			Pavement replacement: $1,600,000	20
F_WSUD	Water Sensitive Urban Design (WSUD) including catchment upgrades to achieve immunity to future 20% AEP (5-year return period with climate change allowance)	$735,400	Pavement resurfacing: $800,000	10
			Pavement replacement: $1,600,000	20
F_Prevention	Increased frequency of preventative maintenance	$0	Pavement resurfacing: $1,600,000	20
			Intermediate repairs: $192,000	3
F_Programmed	Increased frequency of programmed rehabilitation	$0	Pavement resurfacing: $800,000	7.5
			Pavement replacement: $1,600,000	15
F_Hazard_Mgmt	Hazard management including early warning system, heavy load limits, and temporary rerouting	$250,000 for the plan and $250,000 (incurred 10 times following assumed flood events)	Pavement resurfacing: $800,000	10
			Pavement replacement: $1,600,000	20

5.8.3 Embodied carbon analysis

As climate change continues to worsen, there is growing recognition of the importance of reducing carbon emissions. While adaptation measures can help mitigate the impacts of climate change, they also have their own carbon footprints. Embodied carbon, which refers to the carbon emissions associated with the production and transportation of materials used in construction, can be a significant cost of adaptation measures. As such, it is important to consider the embodied carbon of adaptation measures when evaluating their total costs and benefits.

The upfront embodied carbon impact for each adaptation measure is summarised in Table 5-9. These would be incurred per replacement cycle, as set out in Table 5-8. Embodied carbon emissions associated with business-as-usual maintenance activities have been excluded for the base case and all adaptation measures on the basis that they are consistent across all options. To determine embodied carbon emissions using emission factors for material volumes, a systematic approach must be followed. The initial step involves identifying activities and materials involved in the adaptation measure and ascertaining their respective volumes. Subsequently, emission factors specific to each material are determined. These factors quantify the greenhouse gas emissions associated with a given volume of the material, commonly measured in kilograms of CO_2 equivalent per unit volume. By multiplying the volume of each material by its corresponding emission factor, the emissions for each material can be calculated to find the overall embodied carbon impact.

The embodied carbon cost of each adaptation measure in Table 5-9 has been calculated using emissions factors from the IS Materials Calculator (v2.0.13) (Infrastructure Sustainability Council). Material volumes have been determined using engineering judgement and real infrastructure projects.

A carbon price of $123 has been used for this economic analysis, based on the NSW Government Guide to Cost-Benefit Analysis (NSW Treasury, 2023).

Table 5-9: Upfront embodied carbon impact of adaptation measures, calculated by Arup based on IS Materials Calculator (v2.0.13) (Infrastructure Sustainability Council).

Adaptation ID	Description	Embodied carbon
F_FBS	Foamed bitumen stabilisation	16.3 tCO_2e
F_5%_Grade	Optimise road grade and drainage with immunity to future 5% AEP (20-year return period with a climate change allowance)	276 tCO_2e
F_5%_Staged	Staged design to optimise road grade and drainage with immunity to future 5% AEP (20-year return period with a climate change allowance), and uplift to future 1% AEP (100-year return period with a climate change allowance)	227 tCO_2e
F_Viaduct	Viaduct with immunity to future 0.2% AEP (500-year return period with a climate change allowance)	5,121 tCO_2e
F_WSUD	Water Sensitive Urban Design (WSUD) including catchment upgrades to achieve immunity to future 20% AEP (5-year return period with climate change allowance)	N/A
F_Prevention	Increased frequency of preventative maintenance	770 tCO_2e
F_Programmed	Increased frequency of programmed rehabilitation	942 tCO_2e
F_Hazard_Mgmt	Hazard management including early warning system, heavy load limits, and temporary rerouting	N/A

The viaduct (F_Viaduct) has a substantially higher upfront embodied carbon impact than other priority measures. Conversely, lower-cost adaptation measures including water sensitive urban design (F_WSUD), may generate a net positive carbon outcome through carbon sequestering properties. These carbon benefits have not been included in this exemplar due to a lack of site-specific granularity on species selection, irrigation requirements, and other important factors.

5.8.4 Benefits of adaptation

Benefits associated with each of the priority adaptation measures are calculated in terms of direct, indirect, and intangible avoided losses compared to the base case. These are summarised in Table 5-10 and presented in Figure 5-10.

Table 5-10: Annualised direct, indirect, and intangible benefits of adaptation measures compared to the base case under current and future (RCP8.5) climate conditions. Values are presented in 2022 $AUD. Benefits represent that avoided losses compared to the base case, resulting from implementation of the adaptation measure.

Adaptation ID	Benefits compared to the base case			
	Direct tangible (AAL)		Indirect tangible and intangible (annualised)	
	Current climate in 2022	Future climate in 2070 (RCP8.5)	Current climate in 2022	Future climate in 2070 (RCP8.5)
F_FBS	$571,902	$918,165	$42,922	$77,260
F_5%_Grade	$560,501	$896,518	$90,614	$153,407
F_5%_Staged	$566,227	$914,269	$90,614	$153,407
F_Viaduct	$577,679	$927,439	$90,614	$153,407
F_WSUD	$489,622	$781,514	$79,486	$134,331
F_Prevention	$361,049	$579,649	$58,819	$102,642
F_Programmed	$433,259	$695,579	$58,819	$102,642
F_Hazard_Mgmt	$134,610	$215,321	$90,614	$153,407

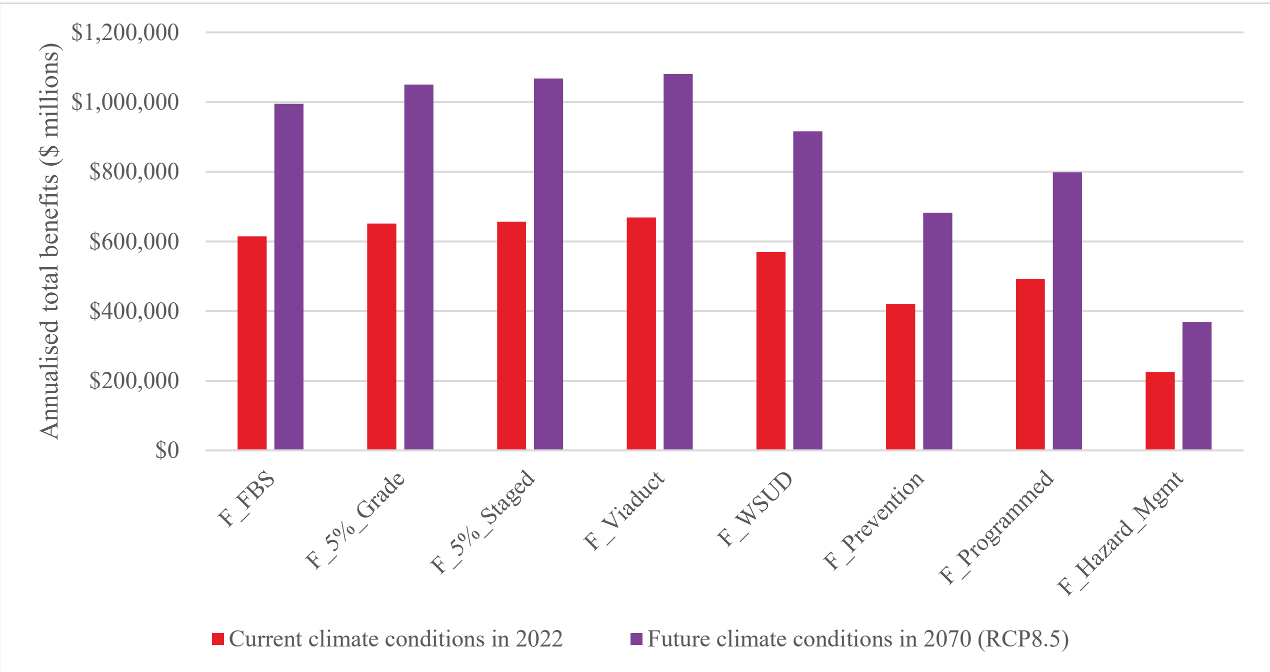


Figure 5-9: Annualised total direct, indirect, and intangible benefits (avoided losses) of flooding adaptation measures compared to the base case under current and future climate. Values are presented in 2022 $AUD.

The installation of a viaduct (F_Viaduct) yields the highest benefits in terms of mitigating losses from flooding in this specific scenario. It is followed by optimising the road grade (F_5%_Grade and F_5%_Staged) as the next most beneficial measures. Conversely, the hazard management plan (F_Hazard_Mgmt) offers the lowest overall benefits in terms of avoiding direct, indirect, and intangible losses.

Increasing the road grade to achieve a 5% Annual Exceedance Probability (AEP) immunity (F_5%_Grade) provides similar benefits to the two adaptation options that grant immunity to a 1% AEP (F_5%_Staged & F_Viaduct).

The use of foamed bitumen stabilisation (F_FBS) and water sensitive urban design techniques (F_WSUD) demonstrate that it is possible to achieve significant benefits in terms of risk reduction and resilience without relying solely on increasing road grade immunity. While the latter measures may provide a higher level of protection against flooding events in some cases, foamed bitumen stabilisation and water sensitive urban design approaches offer substantial benefits while maintaining the same risk level. This is achieved through reducing the vulnerability of the road to damage and downtime, rather than reducing exposure.

The findings suggest that a diversified approach to adaptation should be considered. Instead of solely relying on measures that require significant changes to road infrastructure, alternative strategies such as foamed bitumen stabilisation and water sensitive urban design can offer comparable benefits.

5.8.5 Cost-benefit analysis

Net present values (NPV) are used to determine whether the benefits of an adaptation measure outweigh the costs over the lifetime of the measure. NPVs are normalised to the base case to enable comparison of the relative improvements and cost-effectiveness of adaptation measures. A positive NPV indicates that the measure is economically viable, as the discounted benefits outweigh the expenses.

The degree of variability in NPV is investigated using discount rates of 4 and 7 percent (Department of Treasury and Finance, 2013).

In the NPV analysis of adaptation measures from 2022 to 2070 shown in Figure 5-11, all adaptation measures outperform the base case except for the viaduct (F_Viaduct), the hazard management plan (F_Hazard_Mgmt) under current climate conditions in 2022, and the staged road grade optimisation (F_5%_Staged) under current climate conditions in 2022 with a 7% discount rate. Adaptation measures with a positive NPV demonstrate a positive return-on-investment. Figure 5-12 excludes the viaduct which has the lowest NPV to illustrate the return-on-investment of the positive priority adaptation measures more clearly.

Foamed bitumen stabilisation (F_FBS) shows the highest return-on-investment based on NPV under all scenarios: current and future climate conditions with a 4% and 7% discount rate. This is followed by Water Sensitive Urban Design (F_WSUD).

All adaptation measures with significant capital costs appear more attractive at lower (4%) discount rates than at higher (7%) discount rates. All options that demonstrate a positive NPV under the current climate conditions become more attractive under harsher future climate conditions.

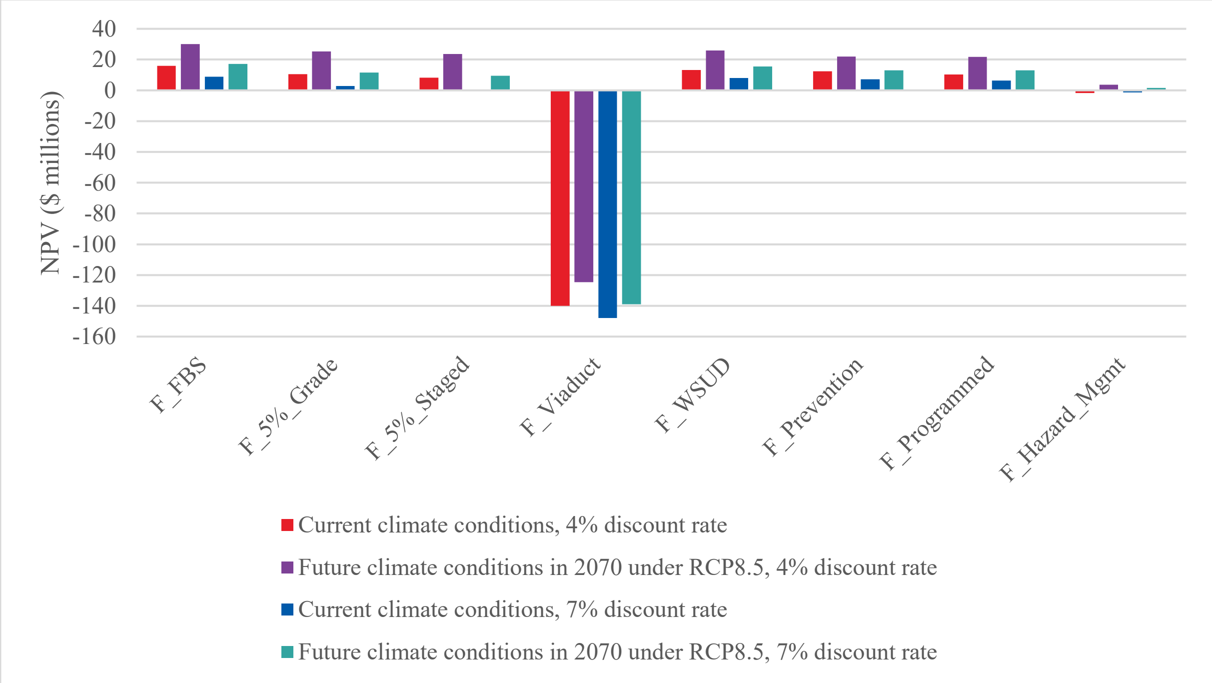


Figure 5-10: Net Present Values for priority flooding adaptation measures under current (2022) and future (RCP8.5, 2070) climate conditions based on 4% and 7% discount rates.

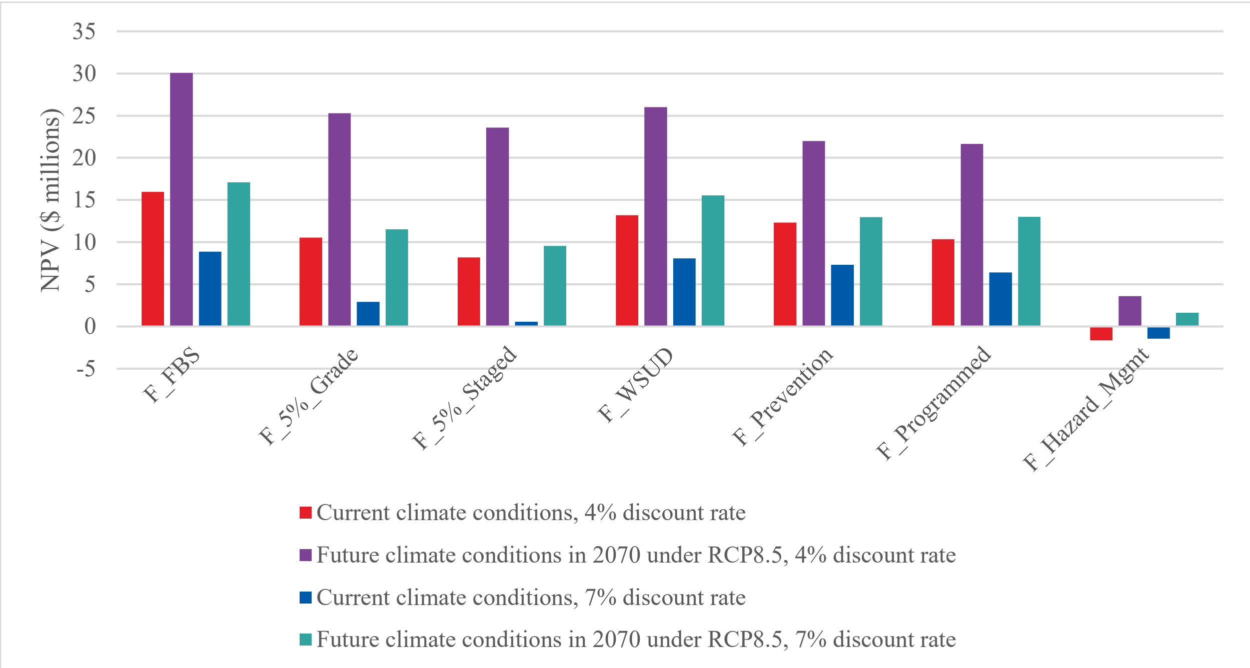


Figure 5-11: Net Present Values for priority flooding adaptation measures, excluding the viaduct, under current and future climate conditions.

The NPV results are summarised in Table 5-11. Adaptation measures ranked higher than the base case represent options with a positive return-on-investment under each of the climate condition scenarios and discount rates based on NPV results.

Table 5-11: Ranking of bushfire adaptation measures based on NPV results under current climate conditions in 2022 and future climate conditions in 2070 under RCP8.5, using 4% and 7% discount rates.

Ranking	Current climate conditions		Future climate conditions under RCP8.5	
	4% discount rate	7% discount rate	4% discount rate	7% discount rate
1	F_FBS	F_FBS	F_FBS	F_FBS
2	F_WSUD	F_WSUD	F_WSUD	F_WSUD
3	F_Prevention	F_Prevention	F_5%_Grade	F_Programmed
4	F_Programmed	F_Programmed	F_5%_Staged	F_Prevention
5	F_5%_Grade	F_5%_Grade	F_Prevention	F_5%_Grade
6	F_5%_Staged	Base case	F_Programmed	F_5%_Staged
7	Base case	F_5%_Staged	F_Hazard_Mgmt	F_Hazard_Mgmt
8	F_Hazard_Mgmt	F_Hazard_Mgmt	Base case	Base case
9	F_Viaduct	F_Viaduct	F_Viaduct	F_Viaduct

In addition to NPV, benefit cost ratios (BCR) have been calculated for each adaptation measure under current and future climate conditions. A BCR is calculated by dividing the present value of the benefits by the present value of its costs, whereby a BCR greater than 1 indicates that the project is financially viable. In other words, for every dollar spent, the adaptation measure generates more than one dollar of benefit.

The BCR values for the priority flooding adaptation measures are summarised in Table 5-12.

Table 5-12: Benefit cost ratios for flooding adaptation measures with current and future climatic conditions.

Adaptation ID	4% discount rate		7% discount rate	
	BCR under current climate conditions	BCR under future (RCP8.5) climate conditions	BCR under current climate conditions	BCR under future (RCP8.5) climate conditions
F_FBS	3.33	5.40	2.98	4.83
F_5%_Grade	1.78	2.87	1.26	2.03
F_5%_Staged	1.52	2.48	1.04	1.71
F_Viaduct	0.15	0.24	0.09	0.14
F_WSUD	2.67	4.30	2.90	4.66
F_Prevention	4.83	7.84	5.10	8.29
F_Programmed	2.31	3.75	2.51	4.06
F_Hazard_Mgmt	0.83	1.36	0.77	1.26

Under current and future climate conditions, preventative maintenance (F_Prevention) has the highest BCR compared to other adaptation measures. This is primarily due to cost savings from addressing maintenance needs promptly, extending the lifespan of infrastructure assets, improving operational efficiency, and reducing the vulnerability to climate-related risks. Preventative maintenance helps avoid costly repairs, premature replacements, and disruptions while enhancing infrastructure resilience. This is followed by foamed bitumen stabilisation (F_FSB), which generates the second highest BCR.

The viaduct (F_Viaduct) does not yield benefits that outweigh the installation costs under both current and future climate conditions. This means that the expenses associated with constructing and maintaining the viaduct outweigh the advantages it provides in terms of cost savings, risk reduction, or other measurable benefits.

In the case of the hazard management plan (F_Hazard_Mgmt) and staged optimisation of the road grade (F_5%_Staged), the benefits exceed the costs only under future climate conditions for RCP8.5. This is consistent for both discount rates.

5.8.6 Distributional analysis

Distributional analysis in cost-benefit analysis (CBA) aims to understand and assess the distributional impacts of a proposed policy or project on different individuals or groups within a society. For this exemplar, the following stakeholder groups have been considered:

- Local government
- State government
- Community
- Freight
- Passenger

The distribution of present value benefits is shown in Figure 5-13. This type of analysis can enable decision-makers to prioritise adaptation investments based on equity drivers. For this exemplar, the priority adaptation measures have a similar profile of distributed benefits across the stakeholder groups. The distributional analysis focuses on benefits across stakeholder groups given that it is assumed costs will be borne by either state or local governments.

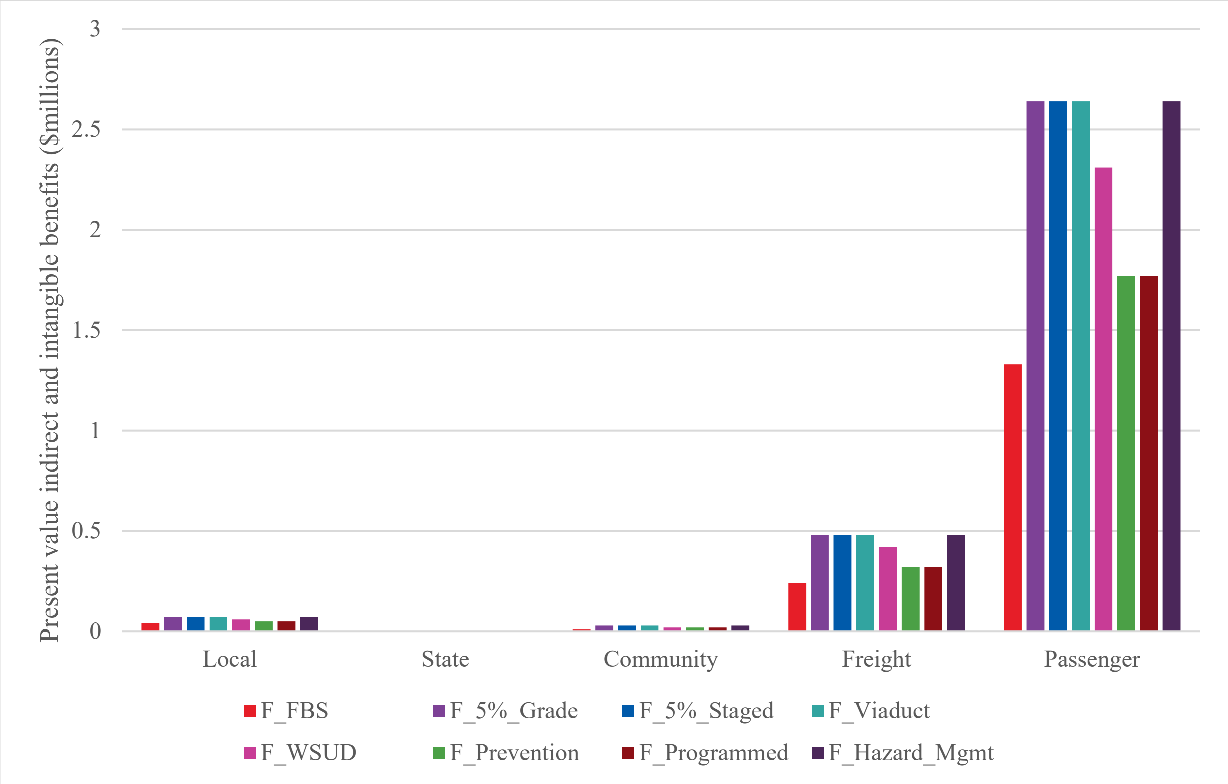


Figure 5-12: Distributional analysis of present value benefits from priority adaptation measures for flooding across stakeholder groups based on future climate conditions under RCP8.5, using 7% discount rate.

Sensitivity analysis

A sensitivity analysis has been performed to explore and measure the impact of input variables on the outcome of the CBA. The aim is to determine the primary indirect tangible and intangible factors that significantly affect the total loss. This analysis incorporates an evaluation of uncertainty in the CBA results. It considers the 90th, 50th, and 10th percentiles of the Benefit-Cost Ratio (BCR) and Net Present Value (NPV) values, using discount rates of 4% and 7%, respectively. These percentiles provide a range of potential outcomes and help account for the variability in the estimated costs and benefits of the adaptation measures. The assessment covers both present and future climate conditions.

By incorporating the uncertainties and varying discount rates, this sensitivity analysis provides a comprehensive evaluation of the CBA results for both the current and future climate conditions. It allows decision-makers to consider different scenarios and assess the robustness of the economic evaluation, providing insights into the potential range of outcomes and the relative significance of different factors in driving the total loss.

5.9 Case for investment in adaptation

5.9.1 Priority adaptation measures

The case for investment in adaptation for the flooding exemplar is based on a range of factors. The net present value (NPV) and benefit-cost ratio (BCR) are important metrics for evaluating the economic viability of adaptation measures and have been calculated to consider direct and indirect tangible costs and benefits, as well as intangible impacts as far as possible.

The adaptation measures for this exemplar have been ranked based on NPV and BCR under current climate conditions in 2022 and future climate conditions in 2070 under RCP8.5 and two discount rates in Table 5-12. These rankings are the average of the NPV and BCR rankings.

Table 5-13: Average ranking of flood adaptation measures based on NPV and BCR results for current climate conditions in 2022 and future climate conditions in 2070 under RCP8.5 for 4% and 7 % discount rates.

Ranking	Current climate conditions in 2022		Future climate conditions in 2070 under RCP8.5	
	4% discount rate	7% discount rate	4% discount rate	7% discount rate
1	F_FBS	F_FBS	F_FBS	F_FBS
2	F_Prevention	F_Prevention	F_WSUD	F_Prevention
3	F_WSUD	F_WSUD	F_Prevention	F_WSUD
4	F_5%_Grade	F_Programmed	F_5%_Grade	F_Programmed
5	F_Programmed	F_5%_Grade	F_Programmed	F_5%_Grade
6	F_5%_Staged	F_5%_Staged	F_5%_Staged	F_5%_Staged
7	F_Hazard_Mgmt	F_Hazard_Mgmt	F_Hazard_Mgmt	F_Hazard_Mgmt
8	F_Viaduct	F_Viaduct	F_Viaduct	F_Viaduct

Based on this analysis, foamed bitumen stabilisation (F_FSB) ranks the highest under both current and future climate conditions. This is consistent across both discount rates. While foamed bitumen stabilisation does not increase the flood immunity of the road from the base case level of 20% AEP, it reduces the vulnerability and associated damage and downtime. The risk reduction efficacy of foamed bitumen stabilisation equates to measures which raise the road level to increase flood immunity.

One key advantage of preventative maintenance (F_Prevention) and increased programmed maintenance (F_Programmed) is their lower upfront capital expenditure compared to other adaptation measures, which makes them more attractive if there are limited financial resources available. Water sensitive urban design (F_WSUD) also ranks highly in terms of risk efficacy and economic performance; a key benefit of this measure is its capacity to improve ecological value in the exemplar location.

While the viaduct (F_Viaduct) has the lowest economic performance compared to other measures in all scenarios, it stands out as the only option that effectively prevents all direct, indirect, and intangible losses associated with flooding in this particular exemplar. This aspect becomes particularly crucial for highly critical road corridors that cannot tolerate any downtime or disruptions. However, it is important to consider certain challenges and potential drawbacks associated with viaducts. Viaduct barriers can introduce safety concerns for road users, and there is a need to carefully design elevated roads to mitigate the potential for additional crashes caused by the barriers. Safety considerations should be addressed to ensure that the viaduct solution does not introduce new risks or hazards.

While the viaduct may offer comprehensive flood protection and uninterrupted functionality, it is essential to weigh these benefits against the associated safety concerns and potential risks. Decision-makers must carefully evaluate the specific context, criticality of the road corridor, and the trade-offs between flood protection and safety to determine the most suitable adaptation measure.

In addition to NPV and BCR, it is important to consider adaptation options for their alignment with broader resilience and sustainability objectives, including:

- Reduction in downtime and maintenance of road service level;
- Road safety
- Compliance with standards
- Preservation of cultural and heritage value;

- Avoidance of maladaptation;
- Equitable distribution of costs and benefits (based on distributional analysis);
- Multi-hazard resilience co-benefits (i.e. improved adaptation to multiple hazards).

In some instances, the economic analysis does not fully capture the broader benefits of these objectives. For example, although the viaduct adaptation does not generate benefits that exceed the installation costs, it could be mandated to minimise environmental impact to natural habitats and sensitive ecosystems. It has a strategic objective commensurate with critical infrastructure of providing disaster response service levels to increase life-safety and enhance community resilience. The adaptation could also contribute to wider urban development or safe interconnectivity to public transport infrastructure including level crossing removals. Another benefit of viaducts is their long-term durability which far exceeds the 2070 time horizon explored in this study. This demonstrates why BCR and NPV represent only one component of investment decision-making.

Threshold analyses can be employed to consider the relative contribution of two adaptation measures to these types of objectives. By comparing the difference in NPV between the measures, one can determine the threshold value of intangible costs and benefits that must be achieved for one measure to be preferred over the other. For example, if Measure A has an NPV of $100,000 and Measure B has an NPV of $120,000, the difference is $20,000. Therefore, if the intangible benefits of Measure A exceed the inferred intangible benefits of Measure B by more than $20,000, Measure A would be the preferred measure. This analysis allows decision-makers to understand the trade-offs between tangible and intangible benefits and costs and make informed decisions about which adaptation measures to prioritise.

The adaptation measures can also be re-run through the MCA, used to short-list and prioritise adaptation measures (refer to Section 3.3.1), wherein the outputs of the economic analysis are used to refine scoring and prioritisation. This approach combines both quantitative and qualitative analyses to explore intangible benefits, and benefits from stakeholder engagement to reflect and incorporate local values and priorities.

Adaptive planning pathways

In this exemplar, the evaluation of adaptation measures has primarily focused on individual measures and their associated benefits. However, it is crucial to acknowledge that certain adaptation measures can have synergistic effects and can be combined and sequenced in a coordinated manner to enhance infrastructure and community resilience even further, for example bundling a higher-cost investment like foamed bitumen stabilisation with hazard management. This approach is known as adaptive planning pathways.

One example of a sequenced adaptation measure is the staged implementation of road grading to achieve immunity 5% AEP in the first replacement cycle, then raising the grade to achieve immunity to 1% AEP after 20 years.

By considering adaptation measures holistically and examining their potential interactions, it becomes possible to identify opportunities for bundling and sequencing measures. This means that instead of implementing measures in isolation, they can be strategically combined and implemented in a specific sequence to achieve greater overall resilience.

Bundling adaptation measures of different adaptation types is a cost-effective way to improve the baseline resilience of the road and provide additional adaptive capacity during periods of extreme events. An example of this is the implementation of additional hazard management during a La Niña event when extreme rainfall is more prevalent to complement optimising the road grade to achieve immunity to 5% AEP.

The concept of adaptive planning pathways recognises that adaptation is an iterative and dynamic process. It acknowledges that different measures can have complementary effects and can build upon each other to create a more resilient system. By adopting this approach, decision-makers can optimise the use of resources and maximise the benefits derived from adaptation measures.

Furthermore, adaptive planning pathways allow for flexibility and the ability to adapt to changing circumstances and future uncertainties. As new information becomes available or as climate conditions evolve, the pathway can be adjusted and updated accordingly.

Overall, the consideration of adaptive planning pathways highlights the importance of a comprehensive and integrated approach to climate change adaptation. It encourages the exploration of synergies between different measures and emphasizes the need to view adaptation as an ongoing and adaptive process rather than a one-time solution.

6. Exemplar for adaptation to bushfire

6.1 Overview

Bushfires have devastating impacts on communities and can damage and disrupt infrastructure in different ways. While direct damage to road surface from bushfires is rare, the most significant problem comes from blocked access due to fire risk, debris, erosion, and subsequent landslide.

The immediate disruption to road corridor access and the closure of roads due to debris following a bushfire is common, however after subsequent significant rainfall, erosion and landslides can occur which cause far greater disruption to the service levels of the road. Debris needs to be removed and, in some instances, significant slope stability work is required to make the road safe following the event. This results in prolonged downtime and road network disruption.

Climate change is expected to worsen the situation, with more frequent bushfires and an increase in extreme rainfall events triggering landslides. Where vegetation above soil is observed to have undergone moderate to high severity burning the likelihood of a landslide is considered to have increased by one order of magnitude (Thompson, 2022).

The bushfire exemplar addresses the impact of bushfires and subsequent landslides on road infrastructure assets. The exemplar is focused on asset components with failure modes associated with bushfire followed by landslide hazards, namely drainage, cuttings, embankments, and landscaping. While there is limited capacity for higher-cost and lower-cost adaptation measures for roads to improve the resilience of the surrounding network and communities to bushfires, there is a significant opportunity to reduce the disruption caused by associated and subsequent hazards including landslides.

The practical implementation of the bushfire exemplar builds on the way landslide slope risk is typically managed for roads across Australia through the Transport for New South Wales (TfNSW) Slope Risk Analysis (SRA) framework modified to include bushfire considerations.

Figure 6-1 illustrates road assets that presently intersect or are within close proximity to bushfire management prone areas in Victoria and Figure 6-2 shows roads in locations with high or very high landslide susceptibility.

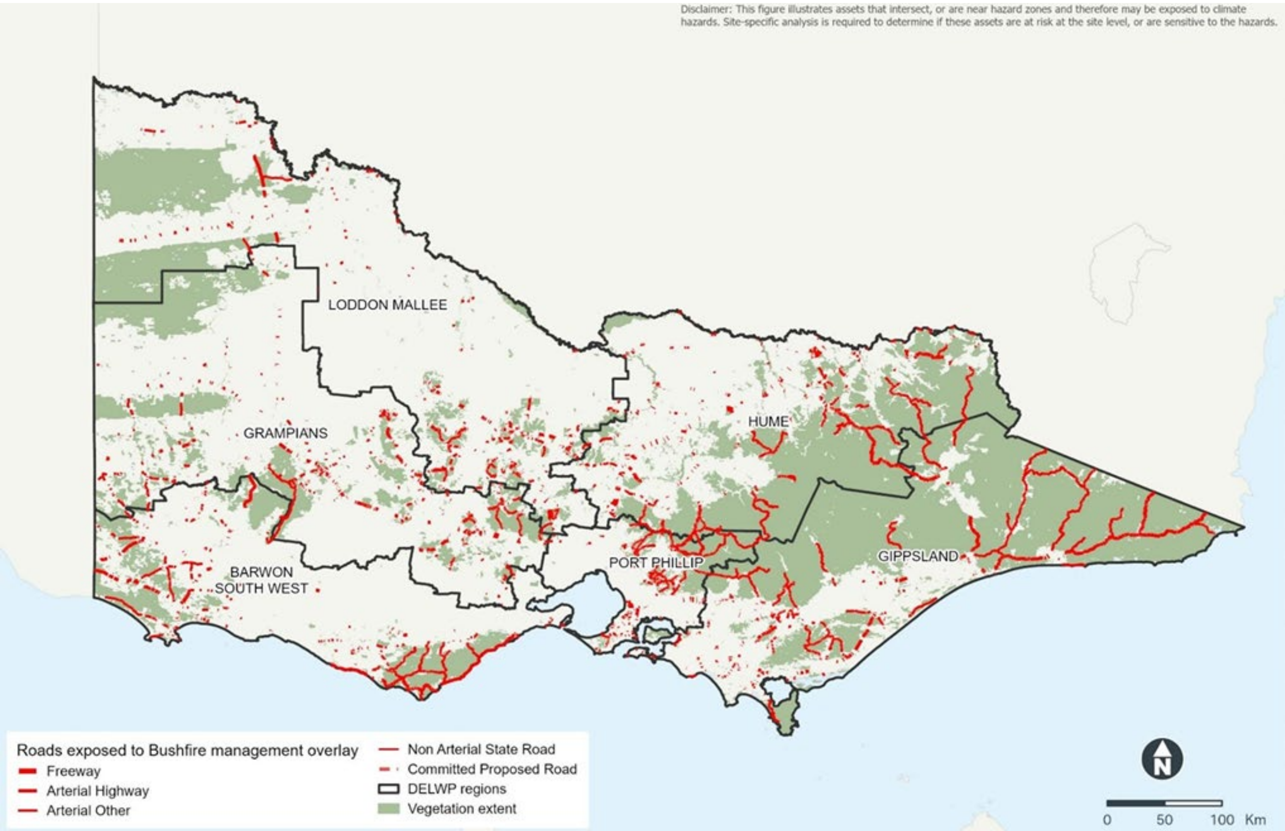


Figure 6-1: Road exposure to bushfire risk from Phase 2 of this project. (AECOM, 2022)

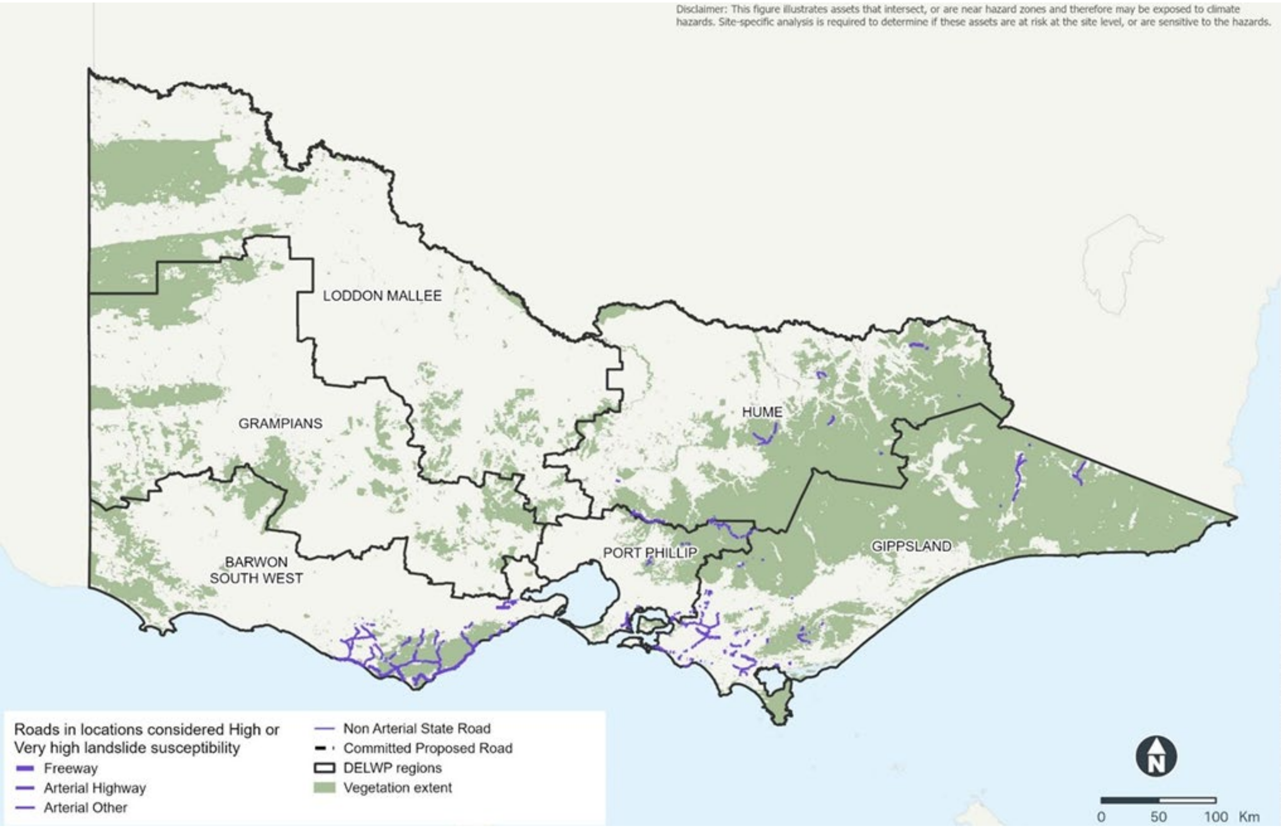


Figure 6-2: Road exposure to landslide risk from Phase 2 of this project. (AECOM, 2022)

6.2 Problem definition

This exemplar considers the impact of bushfires and associated landslides on a road infrastructure asset in regional Victoria. A hotter and drier climate coupled with more frequent and intense rainfall events will drive more dangerous fire weather and landslides in this bushfire prone area. These conditions are increasing the risk of fire-related road closure and disrupted road corridor access, and damage to drainage, cuttings, embankments, and landscaping. Existing maintenance practices do not adequately mitigate the landslide risk exacerbated by bushfire events and recovery works can last from several months to years to restore the road function to full capacity. As a result, residents, emergency services, and key industries including freight and tourism, may experience significant downtime on this critical road corridor.

6.3 Site characteristics

6.3.1 Site characteristics and system interdependencies

This exemplar assumes three small townships are connected by an undivided carriageway single road of 50 kilometres in length, providing access for residents, tourists, and emergency services. The road and towns are located within a Bushfire Prone Area (BPA) and are in close proximity to state forest and associated high bushfire risk areas. The road passes through varied topographies susceptible to landslide. Bushfire events significantly increase the likelihood of landslide, creating significant downtime disruption and damage costs.

The exemplar is surrounded by scenic forested areas and national park with rich ecosystems and biodiversity. The permanent population in the area is approximately 600 which swells in peak tourist seasons. Aside from unsealed roads, there is a limited local road network in the surrounding area. Therefore, residents, tourists, freight, and emergency services are heavily reliant on this road corridor.

6.3.2 Road function

The road serves as a key transport route for local residents and agriculture supply chains across the year, as well as for seasonal tourism which peaks in summer when bushfire risk is greatest. This is a critical road for emergency services and is subject to increasing use by heavy vehicles. Approximately 1,000 vehicles drive through this road section each day, 10% of which are trucks.

6.3.3 Road asset components

The road asset components and potential failure modes from bushfire and landslide are summarised in Table 6-1 for this exemplar. Pavement, culverts, barriers, bridges, and other structures are typically less vulnerable to bushfire.

Table 6-1: Road asset components and failure modes from bushfire and landslide events

Road asset component	Possible failure mode from bushfire and landslide
Road corridor access	Immediate closure of road due to fallen trees, debris, and other obstructions caused by bushfire. Post-fire slope failure and erosion due to destabilisation of slopes and embankments caused by removal of vegetation, resulting in road closure.
Drainage	Blocked drainage from ash and debris, increasing risk of flooding, erosion, scour, and slope destabilisation.
Cuttings, embankments, and landscaping	Loss of landscaping and vegetation from bushfire, causing slope destabilisation, increasing risk of landslide and erosion.

6.4 Risk Context

6.4.1 Risk analysis framework

The TfNSW Slope Risk Analysis (SRA) framework is commonly used by state road authorities in Australia to understand and manage slope risk to roads. The methodology is recognised as industry standard across Australia and New Zealand. State road authorities have carried out SRAs on thousands of slope assets across their respective road networks to manage slope risk maintenance and mitigation work.

The SRA methodology is based on the Australian Geomechanics Society Guidelines for Landslide Risk (2007) that was developed following the fatal Thredbo Landslide in 1997. These guidelines recommend a tolerable limit for loss of life for the person most-at-risk to be 'rare' for existing landslides; a 'rare' likelihood corresponds with a 10^{-5} approximate annual probability of loss of life. This tolerable limit is the practical risk threshold or performance level that triggers slope risk mitigation and maintenance.

The SRA methodology is a visual site-based assessment from accredited Geotechnical Engineers or Engineering Geologists. Its process is based upon logical considerations of various risk inputs to arrive at an assessment of risk as a function of hazard, exposure, and vulnerability. The inputs include:

- Slope assets definition: embankment, cuttings, retaining walls, and bridge abutments
- Hazard: size and likelihood of debris impacting the road or road foundation failing
- Exposure: number of vehicles per day
- Vulnerability: size (e.g. rockfall/debris/void volume) of the hazard paired with the speed of the vehicle
- Risk is evaluated as an Assessed Risk Level (ARL) with ARL1 (most at-risk) to ARL5 (lowest risk) for loss of life and damage to property. The risk class for property considers the class or significance of the road in the transport network.

While the SRA methodology allows for consideration of any credible slope failure mode (e.g., rainfall, earthquake, tree root jacking, animal burrows, etc.) it does not explicitly consider the increase in landslide vulnerability following a bushfire and the impacts of future climate change.

For this exemplar, the framework is modified to include a probability of bushfire and an increase in landslide susceptibility expressed as an order of magnitude increase in landslide probability following a bushfire event. The post-bushfire increase in probability is temporal and returns to pre-bushfire levels with vegetation regrowth in a few years.

To demonstrate practical implementation of adaption measures within the exemplar, ARLs are assigned relative risk levels, consequence classes, and strategic risk management actions as per Table 6-2. This follows the Queensland Department of Transport and Main Roads Natural Disaster Program (NDP) Design and Eligibility Guidelines and generally aligns with slope risk management practice across Australia.

Table 6-2: Slope Risk Level and Strategy for Mitigation

Assessed Risk Level	Relative Risk Level	Probability of Risk (loss of life)	Consequence Class for existing Slopes	Exemplar Risk Management Action
ARL1	Very High	$>10^{-3}$/annum	Generally regarded as not tolerable.	Treatment or risk management to reduce level of risk to Medium or better. Urgent mitigation or road closure.
ARL2	High	10^{-4} to 10^{-3} /annum	Maybe tolerable in short term.	Treatment or risk management to reduce level of risk to Medium or better.
ARL3	Medium	10^{-5} to 10^{-4} /annum	Tolerable in short to medium term.	Maintain risk at this level. 5-yearly annual inspection. Monitor active hazards.
ARL4	Low	10^{-6} to 10^{-5} /annum	Tolerable under most circumstances.	10-year annual Inspection
ARL5	Very Low	$<10^{-6}$ /annum	Tolerable.	Re-assess following extreme events.

6.4.2 Slope Assets

Within the 50km road, 39 slope assets are within a bushfire prone area with a credible likelihood of landslide failure. This totals 13.8km of the 50 km road, including both cuttings (upslope) and embankments (downslope).

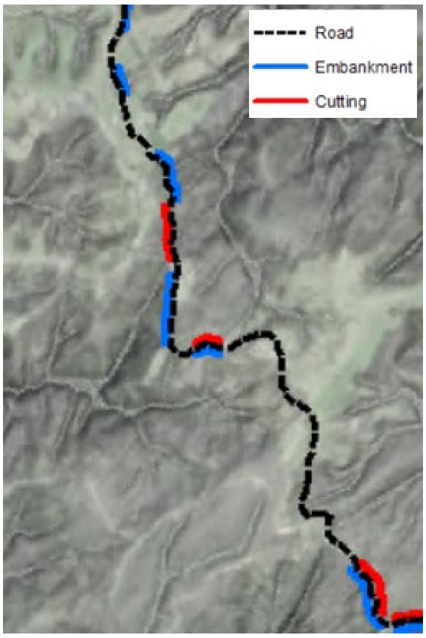


Figure 6-3 Typical section along the bushfire exemplar showing slope assets

6.5 Exposure assessment

The implementation of the bushfire exemplar assumes that, after a bushfire, the probability of landslide is increased, particularly from subsequent rainfall events. Over time, as vegetation restores itself, the probability of a landslide hazard decreases. To estimate the landslide hazard, both the probability of bushfire today under current climate conditions and in 2070 under future climate conditions (RCP8.5) are considered, in addition to the subsequent rainfall landslide triggers.

6.5.1 Bushfire

To estimate bushfire risk across the exemplar, the annual probability of bushfire is estimated.

The average area burnt each year in Victoria due to unplanned bushfires over the past five years (2018-2022) is around 350,000 hectares, equivalent to approximately 0.15% of the state's total area (Global Forest Watch, 2023). Literature review of historical records identified five significant bushfires in the region since the early 1800s.

The annual probability of bushfire in the study area is estimated to be 3% under current climate conditions in 2022. This suggests that in any given year based on current climate conditions, there is a 3% chance that bushfire will occur on the road exemplar. Given this value is a high-level estimate, it was assumed that the entire stretch of road in the exemplar would be impacted in the same event.

To estimate annual probability of bushfire under future climate conditions in 2070 based on RCP8.5, the current burn probability of 3% is scaled proportionally to the projected change in number of severe fire danger dangers from the baseline to 2070. Severe fire danger days are represented by the number of days with Forest Fire Danger Index (FFDI) greater than fifty.

The baseline average number of severe fire danger days in the exemplar region is 3.6 days, increasing to 7.1 days by 2070 under RCP8.5 (CSIRO and BoM, 2020). Therefore, it is assumed that bushfire risk will double from current bushfire risk in 2022 to future bushfire risk in 2070 under RCP8.5. Consequently, the annual probability of bushfire under future climate conditions in 2070 is projected to increase to 6%.

Table 6-3: Baseline and projected number of days of Forest Fire Danger Index categories in Victoria

Scenario	Days per year with FFDI of 25-50, "Very High"	Days per year with FFDI of 50-75, "Severe"	Days per year with FFDI of 75-100, "Extreme"	Days per year with FFDI greater than >100, "Catastrophic"
Baseline number of days (centred on 1995, representative of 2022)	43	3.6	0.24	0.05
Projected number of days in 2070 under RCP8.5	59	7.1	0.66	0.09

6.5.2 Landslide

For the bushfire exemplar, the pre-bushfire probability of landslide hazard was estimated considering geology, discrete hazard identification, general slope angle, past failures, and visual observations. The probability of landslide hazard post-bushfire event is determined by scaling the pre-bushfire probability of landslide hazard. For this exemplar, it is assumed that debris from a landslide event is significant enough to cause total road closure.

The estimate of probability of a landslide reaching the road follows the SRA guidance considers:

- The probability of detachment (Pd): the probability that material associated with a particular hazard will detach; usually estimated by order of magnitude considerations of a triggering event, for example, 0.1 for a 10-year rainfall event, 0.01 for a 100-year rainfall event.
- The probability of travel or transport to the active road corridor (Pt): the probability that, once detached or dislodged, material will travel as far as the element at risk, in this instance the road edge line. This probability is also usually estimated by order of magnitude.

The product of the two inputs (i.e., Pd * Pt) establishes a probability of debris reaching the element at risk.

The pre-bushfire landslide hazard probability is increased by an order of magnitude to define the post-bushfire landslide hazard probability.

6.6 Vulnerability assessment

6.6.1 Asset component vulnerability

The vulnerability of the road to bushfire and landslide is applied as direct closure and cost to repair the slope and road. Pavement, culverts, barriers, bridges, and other structures are typically less vulnerable to bushfire. Bushfires can also cause damage to bridges which affect access; however this was not assessed as part of this exemplar. The damage is not negligible, but, compared to cost and consequence from landslide failure, the damages from bushfire alone are less significant. As a result, the focus of the adaptation measures has been on slopes.

6.6.2 Social vulnerability – loss of life

The estimation of probability of loss of life of an individual if a road is impacted by a landslide hazard follows the SRA framework and considers the speed of the road (80 km/hr) and the size of the hazard. Following the SRA methodology, the probability of loss of life from soil and rock debris impacting a vehicle travelling at 80 km/hr is 0.01 – 0.001.

6.7 Climate risk assessment

6.7.1 Risk metrics

To estimate bushfire and landslide-related risk for the base case, the following risk metrics were included for current and future climate conditions, where future climate is explored under RCP8.5 in 2070:

- Average Annual Loss (AAL) in $AUD.

- Average Annual Downtime (AAD) in days.
- Loss of life in terms of annual likelihood of fatality.
- Indirect tangible losses in $AUD including emergency costs and disruption to public services and community, car crashes (fatality, injury, serious injury), disruption to freight, disruption to passenger vehicles, and business and service disruption.
- Intangible loss in $AUD including air pollution, emissions, noise, soil and water, nature and landscape, urban effects, biodiversity, health costs, and social and recreational values.

6.7.2 Pre-bushfire and post-bushfire slope risk

The assessed risk levels for the 39 slopes across the exemplar are summarised for pre-bushfire and post-bushfire scenarios (Table 6-4).

The assessment shows that under pre-bushfire conditions, the majority of slopes are at acceptable risk levels under the exemplar slope risk management plan. There are two slopes at tolerable risk levels, and it is assumed that the road authority is managing this tolerable risk with programmed maintenance or pending mitigation.

When considering the compound event of bushfire and landslide, the risk increases by an order of magnitude which puts two slopes at unacceptable risk levels and nine slopes at potentially tolerable limits in the short-term.

The unacceptable risk slopes are likely to fail from significant rainfall before the vegetation recovers sufficiently to stabilise the slope. The intensity of rainfall required to trigger a landslide is very site-specific. For this exemplar rainfall with a 1- to 5-year annual recurrence interval (e.g. return period), commensurate with the time it takes the vegetation to regrow, is considered a credible trigger for landslide.

Table 6-4: Assessed Risk Level for slope assets across exemplar pre- and post-bushfire.

Assessed Risk Level	Relative Risk Level	Consequence Class for existing Slopes	Pre-Bushfire Number of Slopes	Post-Bushfire (within ~5-years) Number of Slopes
ARL1	Very High	Generally regarded as not tolerable.	0	2
ARL2	High	Maybe tolerable in short term.	2	9
ARL3	Medium	Tolerable in short to medium term.	9	26
ARL4	Low	Tolerable under most circumstances.	26	2
ARL5	Very Low	Tolerable.	2	-

6.7.3 Findings

The pre-bushfire and post-bushfire landslide risk expressed in terms of financial loss ($AUD) and downtime (days) is summarised in Table 6-5. The change in AAL and AAD highlights the increase in risk of landslide following a bushfire event.

Table 6-5: Annualised direct risk in terms of average annual financial loss and downtime for pre-bushfire landslide risk and post-bushfire landslide risk under current 2022 climate conditions. Costs are presented in $AUD 2022.

Hazard under current 2022 climate conditions	AAL ($)	AAD (days)
Pre-bushfire risk (only landslide)	$3,135	0.7
Post-bushfire landslide risk (base case)	$12,581	3.6

Direct tangible, indirect tangible, and intangible losses were calculated for the bushfire exemplar with consideration of the 39 slopes. The total loss increases from current climate conditions in 2022 to future climate conditions in 2070 under RCP8.5.

Table 6-6: Average annualised losses from bushfire and landslide under current and future climate conditions

	AAL	AAD (days)	Indirect tangible and intangible losses (annualised)	Annual probability of loss of Life
Current climate in 2022	$12,581	3.6	$466,341	0.00023
Future climate in 2070 (under RCP8.5)	$21,562	6.4	$833,534	0.00034

6.8 Adaptation measures

6.8.1 Priority adaptation measures

A total of eight adaptation measure are examined for this exemplar, summarised in Table 6-7. The multi-criteria analysis (MCA) process for shortlisting these measures is presented in Appendix B, including respective scoring against the criteria.

The adaptations are applied in the context of the 39 slope assets and an understanding of the pre-bushfire risk assessed risk level as per the SRA.

Table 6-7: Shortlisted adaptation measures for bushfire exemplar

ID	Adaptation Measure	Type
B_Barrier1	Remediate the two highest risk slopes (ALR2 pre-bushfire) with flexible barriers.	Higher-cost investment
B_Barrier2	Remediate the eleven high and moderate risk slopes (ALR2 and ARL3 pre-bushfire) with flexible barriers.	Higher-cost investment
B_Planting	Fire-resistant planting	Lower-cost investment
B_FireBreak	Fire break (vegetation clearance zone)	Lower-cost investment
B_ProgDrain	Increased programmed drainage clearing and vegetation management	Maintenance
B_RespDrain	Post-fire responsive drainage clearing	Maintenance
B_Erosion	Post-fire erosion protection and slope stabilisation	Maintenance
B_RiskMgmt	Risk management plan	Hazard management

Remediate highest risk slopes (ARL2 pre-bushfire)

For this adaptation measure, flexible debris barriers are installed for two cuttings covering a total of 1.4km. This remediates the two very high-risk slopes, reducing the pre-bushfire risk from ARL2 to ARL5. While the pre-bushfire risk is a tolerable limit for loss of life, a bushfire event would increase the landslide susceptibility to an unacceptable risk level. Slopes with AL3 and AL4 are not remediated in this adaptation measure.

Flexible barriers provide protection against landslide by intercepting and containing debris flow or rockfall. They have limited environmental impact and can be installed near the base of a slope depending upon configuration. They require periodical removal of debris accumulated behind the structure, however the timing of this can be optimised to minimise disruption to road users.

Remediate high and medium risk slopes (pre-bushfire ARL2 and ARL3)

In addition to the two ARL2 slopes at the pre-bushfire tolerable limit, this adaptation measure aims to remediate nine ARL3 slopes, considered acceptable pre-bushfire. Without adaptation following a bushfire, these slopes would be considered ARL2 at tolerable risk levels and require monitoring and risk reduction as reasonably practicable. The slope remediation includes installation of flexible debris barriers for cuttings and soil nails to stabilise for embankments, covering a total of 5.1km.

Great Ocean Road rockfall protection

To protect road users along the Great Ocean Road from potential rockfalls and landslides, a passive drapery system has been installed on a 125m long high cutting near Kennett River. The cuttings comprise weathered Otway Group sandstones with a stony, gradational soil profile developed over rock (Geofabrics Australasia , 2020). The flexible drapery barriers ensure that rockfall is contained and does not impede road users.

Fire-resistant planting

Fire-resistant and fire-retardant planting, including spatial layout of vegetation, supports slope stability and reduces landslide susceptibility post-bushfire. Fire-resistant plants are those that will not burn in the face of continued flame, whereas fire-retardant plants will not burn in the first wave of a bushfire but may be susceptible once dried out. A list of fire-resistant and fire-retardant plants can be used to inform species selection with site-specific considerations in Victoria (Australian Plants Society (Victoria), n.d.). This measure would be applied across all at-risk slopes, over 13.8km of road length.

Fire break (vegetation clearance zone)

A fire break is a vegetation clearance zone from the road to reduce the rate of spread and intensity of fire. These can be classified as landscape protection breaks (LPB) or asset protection breaks (APB). This adaptation measure involves a LPB of ~10m to remove hazardous vegetation in proximity to the road. An example fire break of 2m is shown in Figure 6-4. Vegetation removal on sloping land may increase landslide risk by reducing root strength contributions, therefore it is important that geotechnical investigations are undertaken to enable site-specific considerations (Forbes & Broadhead, 2011).

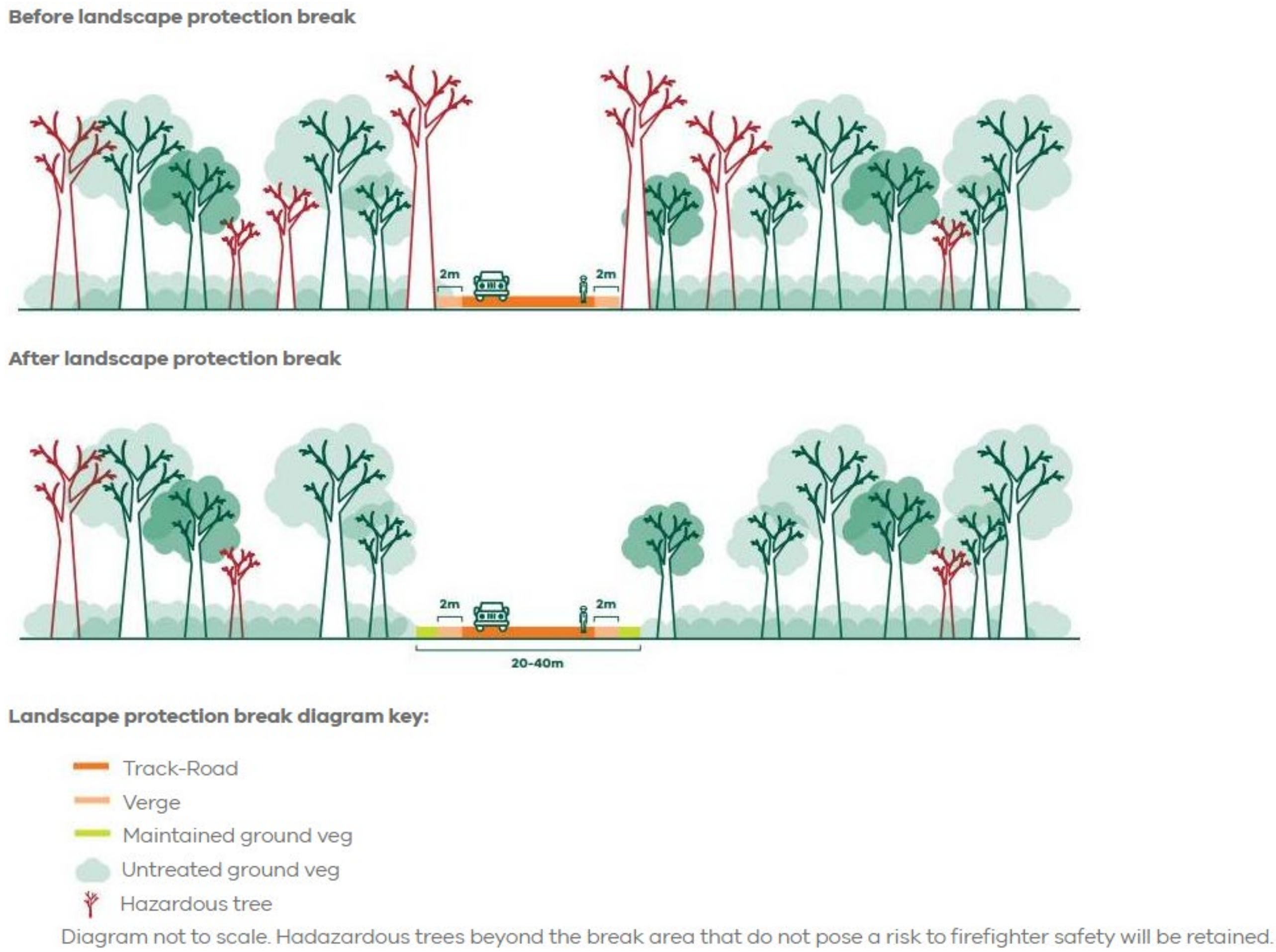


Figure 6-4: Landscape protection break (Forest Fire Management Victoria, 2021)

Increased programmatic drainage clearing and vegetation management

Excess pore water pressure is one of the prime causes of embankment slope failure after bushfire events, as a rise in pore water pressure reduces the strength of soil. Drainage and vegetation are the two main methods for managing this. Surface and sub-surface drains work to redirect water flow away from the slope. Vegetation cover on the slip area increases water absorption / reduces excess water.

This adaptation measure involves increasing programmatic drainage clearing and vegetation management to reduce the extent and frequency of landslides. This may include controlled burns. Practically this would include annual maintenance action. This also may require the cooperation of neighbouring landholders and Landcare groups to address the underlying causes of landslides beyond the immediate road boundary. This measure is planned across all 13.8km of slope assets on the exemplar.

Post-fire responsive drainage clearing

Landslide risk is substantially increased following the occurrence of bushfire as slopes are destabilised and drainage is compromised by debris blockage and loss of vegetation for water absorption. Responsive drainage clearing following bushfires significantly reduces infiltration-induced landslide activity (De Graff, 2018).

This adaptation measure involves immediate drainage clearing for embankments and cuttings along 13.8km of slopes following a bushfire event. The key for this adaptation measure is to complete the drainage clearing before the first significant rainfall.

Contingency budget, engaged contractors, and pre-defined specifications are required for the immediate response. These works often align with implementation of Disaster Response Management Plan.

Post-fire erosion protection and slope stabilisation
This adaptation measure is immediately applied following a bushfire event as a proactive disaster response. It involves erosion protection of slopes via seeding and jute matting in addition to responsive drainage clearing as per the previous adaptation measure. Installation of jute matting and seeding promote plant growth on slopes to improve water absorption and reduce landslide risk and erosion. This is applied across 5.1km of the highest risk slopes (ARL2 and ARL3).

As for drainage clearing, the key is to install the protection before the first significant rainfall. These works would align with implementation of Disaster Response Management Plan and require pre-planning on budget, planning and specification.

Site-specific risk management plan
A comprehensive risk management plan, including components of early warning systems for bushfire, slope movement, and rainfall triggers, improves safety of road users and the efficiency of response and recovery efforts following an event. This site-specific plan provides additional granularity to existing state-wide hazard management plans to consider local conditions and resource planning. The plan sets out triggers and actions including speed reduction, road closures, ITS signage alerts users of road hazards, and disaster responsive planning procedures for inspections, maintenance, and rehabilitation.

6.8.2 Efficacy of adaptation measures

The performance improvements from adaptation measures for bushfire and landslides are described in Table 6-8 which serves as a basis for estimating risk benefits in support of this report. Residual risk levels in terms of direct, indirect, and intangible losses are summarised for the base case and each adaptation measure in Table 6-9.

Table 6-8: Efficacy of adaptation measures for bushfire and landslide

ID	Adaptation measure	Efficacy
B_Barrier1	Remediate the two highest risk slopes (ALR2 pre-bushfire) with flexible barriers.	Slope remediation with flexible barriers improves the two very highest risk slopes (ARL2) to acceptable risk. This reduces landslide susceptibility and improves the immunity of the road by one order of magnitude. Practically, all slopes with a 1% annual landslide probability or greater are reduced to 0.001%.
B_ Barrier2	Remediate the eleven high and moderate risk slopes (ALR2 and ARL3 pre-bushfire) with flexible barriers.	Slope remediation with flexible barriers improves the 11 highest risk slopes (ARL2 and ARL3) to acceptable. This reduces landslide susceptibility and improves the immunity of the road by two orders of magnitude. Practically, all slopes with a 0.1% annual landslide probability or greater are reduced to 0.001%.
B_Planting	Fire-resistant planting	Fire-resistant planting reduces the susceptibility to landslides following a bushfire event, as the vegetation maintains its root network and stabilising properties. It is proposed that this planting reduces the detrimental consequences of a bushfire on slope stability by half. The vulnerability of the road to bushfire damage is reduced by 50% and there is a 25% reduction in downtime to clear burned material. The vulnerability of the road to landslide damage is reduced by 10% due to less burned debris.
B_FireBreak	Fire break (vegetation clearance zone)	As a result of a fire break, bushfires do not impact the slope stability. The pre-bushfire slope conditions remain following the bushfire event.
B_ProgDrain	Increased programmed drainage clearing and vegetation management	Increased programmed drainage clearing and vegetation management reduces the post-bushfire susceptibility to landslides by ~20%. Downtime due to bushfire is reduced by 25% as a result of more frequent vegetation management, and road vulnerability to damage from fire is also reduced by 25% as a result of less debris. The costs due to landslide are reduced by 10% due to less available debris.

ID	Adaptation measure	Efficacy
B_RespDrain	Post-fire responsive drainage clearing	Post-fire responsive drainage clearing reduces the post-bushfire susceptibility to landslides from ~70% for the embankment slope assets. The cutting assets would have little risk reduction as they are typically upslope of the drainage.
B_Erosion	Post-fire erosion protection and slope stabilisation	Post-fire erosion protection and slope stabilisation of the 11 highest risk slopes reduces the post-bushfire susceptibility to landslides by ~80%.
B_RiskMgmt	Risk management plan	This will not reduce the likelihood, downtime, or damage to the road from bushfire or landslides. Loss of life (likelihood of fatality) is reduced by one order of magnitude. Downtime from landslide events is reduced by 10% considering a faster mobilisation of recovery.

Table 6-9: Annualised direct, indirect, and intangible losses associated with the base case and each adaptation measure under current 2022 climate conditions and future 2070 climate conditions under RCP8.5. Values are presented in 2022 $AUD.

Adaptation measure	Average Annual Loss (AAL)		Average Annual Damage (AAD), days		Indirect tangible and intangible losses (annualised)		Annual probability of loss of life	
	Current climate in 2022	Future climate in 2070 (RCP8.5)	Current climate in 2022	Future climate (RCP8.5)	Current climate in 2022	Future climate in 2070 (RCP8.5)	Current climate in 2022	Future climate (RCP8.5)
Base case	$12,581	$21,562	3.6	6.4	$466,341	$833,534	0.00023	0.00034
B_Barrier1	$8,042	$14,780	2.6	4.9	$341,143	$646,410	0.00002	0.00003
B_Barrier2	$6,019	$11,755	2.2	4.3	$285,508	$563,257	0.00000	0.00000
B_Planting	$7,146	$11,284	2.6	4.5	$337,795	$583,539	0.00016	0.00021
B_FireBreak	$8,595	$14,055	2.7	4.8	$356,528	$626,685	0.0001	0.0001
B_ProgDrain	$9,507	$15,891	2.8	4.9	$368,298	$640,997	0.00019	0.00027
B_RespDrain	$11,883	$20,249	3.4	6.1	$447,196	$797,471	0.00023	0.00034
B_Erosion	$9,038	$14,889	2.8	5.0	$368,730	$649,668	0.00011	0.00013
B_RiskMgmt	$12,581	$21,562	3.4	6.1	$446,217	$803,456	0.00002	0.00003

6.9 Economic analysis of adaptation measures

Building upon the risk assessment of the priority bushfire and landslide adaptation measures, holistic economic analysis captures the tangible and intangible costs and benefits of investing in resilient roads to help inform decision-making. By comparing the base case losses to the benefits and costs (installation and maintenance) of priority adaptation measures, the options can be further evaluated.

6.9.1 Base case valuation

The base case describes the total losses arising from a hazard if no adaptation measures are implemented. These losses include the direct asset damage and downtime (quantified in Section 6.7.3), the indirect tangible losses for State and Local government, freight, passenger vehicles, and the wider community, and intangible social, environmental, and cultural impacts.

The average annualised base case losses for the current climate conditions and future climate under RCP8.5 are summarised in Table 6-10. These represent the expected annual loss resulting from the impact of bushfire and landslides for the time horizon of 2070. As expected, the losses associated with bushfire and landslide risk will rise as a consequence of climate change by 2070.

Table 6-10: Direct tangible, indirect tangible, and intangible losses for the base case. Values are presented in 2022 $AUD.

Base case losses							
Direct loss (AAL)		Direct loss (AAD)		Indirect and intangible losses (annualised)		Annual probability of loss of life	
Current climate in 2022	Future climate in 2070 (RCP8.5)	Current climate in 2022	Future climate in 2070 (RCP8.5)	Current climate in 2022	Future climate in 2070 (RCP8.5)	Current climate in 2022	Future climate in 2070 (RCP8.5)
$12,581	$21,562	3.6 days	6.4 days	$466,341	$833,534	0.00023	0.00034

Disruption to freight and road passengers caused by bushfire and landslide events represent the most significant indirect tangible losses for the pre-adaptation base case. When a major transportation route in regional Victoria becomes inaccessible, vehicles are forced to take longer and less direct alternative routes, resulting in additional fuel consumption, wear and tear on vehicles and roads, increased potential for car crashes, traffic congestion, and carbon emissions and their corresponding effects on biodiversity and climate change.

While the exemplar is in a regional setting with lower traffic volumes compared to urban areas, disruption from downtime is made worse by the limited surrounding road network. Longer diversions increase the risk of car crashes causing fatality or injuries which can diminish the ability of the individual to participate in the labour force or reduce their earning capacity. These impacts are captured as indirect tangible community losses. The indirect costs associated with car crashes including police, ambulance and public health services will increase as a result of increased downtime and more frequent car crashes. Local government will also face higher costs associated with clearing of roads and provisioning of signage to ensure safe access.

The intangible losses accrued from vehicle diversions include the broader impacts from the additional car emissions including social cost of air pollution, the indirect impact on climate change, noise emissions, soil and water degradation, and adverse nature and biodiversity effects. Moreover, the intangible community costs account for the loss of social and recreational amenity values, and community trauma associated with car crashes.

Indirect tangible and intangible losses have been calculated based on damage and downtime dependencies using appropriate environmental and social parameters. These have been sourced from:

- Australian Transport Assessment and Planning Guidelines – PV2 Road Parameter Values (2016)
- Australian Transport Assessment and Planning Guidelines – PV5 Environmental Parameter Values (2021)

- Department of Treasury and Finance Economic Evaluation for Business Cases Technical guidelines (2013)
- Transport for NSW Road & Rail Cost Escalation Indices 2022 Update (2022)

6.9.2 Costs of adaptation

Each priority adaptation measure incurs costs related to installation, ongoing maintenance, and embodied carbon emissions. Installation and maintenance costs are summarised in Table 6, along with their maintenance frequency. A frequency of 10 years indicates that the maintenance cost will be incurred four times in the 2070 time horizon. All adaptation installation and maintenance costs use the New South Wales average escalation rate of 3.9% per annum.

Table 6-11: Bushfire adaptation installation and maintenance costs

Adaptation ID	Description	Installation cost ($)	Maintenance cost ($)	Maintenance frequency (years)
B_Base_Case	Base case without adaptation	$0	$137,725	10
B_Barrier1	Remediate the two highest risk slopes (ALR2 pre-bushfire) with flexible barriers.	$7,014,241	$100,000	10
B_ Barrier2	Remediate the eleven high and moderate risk slopes (ALR2 and ARL3 pre-bushfire) with flexible barriers.	$21,009,985	$100,000	10
B_Planting	Fire-resistant planting	$6,610,780	$137,725	10
B_FireBreak	Fire break (vegetation clearance zone)	$13,722,459	$137,725	5
B_ProgDrain	Increased programmed drainage clearing and vegetation management	$0	$137,725	5
B_RespDrain	Post-fire responsive drainage clearing	$505,765 (assume implementation in 2050)	$137,725	10
B_Erosion	Post-fire erosion protection and slope stabilisation	$2,023,056 (assume implementation in 2050)	$137,725	10
B_RiskMgmt	Risk management plan	$250,000	$137,725	5

6.9.3 Embodied carbon analysis

As climate change continues to worsen, there is growing recognition of the importance of reducing carbon emissions. While adaptation measures can help mitigate the impacts of climate change, they also have their own carbon footprints. Embodied carbon, which refers to the carbon emissions associated with the production and transportation of materials used in construction, can be a significant cost of adaptation measures. As such, it is important to consider the embodied carbon of adaptation measures when evaluating their costs and benefits.

The upfront embodied carbon impact for each adaptation measure is summarised in Table 6-12 and has been calculated using emissions factors from the IS Materials Calculator (v2.0.13) (Infrastructure Sustainability Council). Material volumes have been calculated using engineering judgement and infrastructure projects. These embodied carbon emissions would be incurred per replacement cycle, as set out in Table 6-11. Embodied carbon emissions associated with business-as-usual maintenance activities have been excluded for the base case and all adaptation measures on the basis that they are consistent across all options.

A carbon price of $123 has been used for this economic analysis, based on the NSW Government Guide to Cost-Benefit Analysis (NSW Treasury, 2023).

Table 6-12: Embodied carbon impact of adaptation measures, calculated by Arup based on IS Materials Calculator (v2.0.13) (Infrastructure Sustainability Council).

Adaptation ID	Description	Embodied carbon impact
B_Barrier1	Remediate the two highest risk slopes (ALR2 pre-bushfire) with flexible barriers.	56 tCO2e
B_ Barrier2	Remediate the eleven high and moderate risk slopes (ALR2 and ARL3 pre-bushfire) with flexible barriers.	108 tCO2e
B_Planting	Fire-resistant planting	Potential avoidance of 7 kgCO2e/m² of material emissions for repairs, based on patching emission factor
B_FireBreak	Fire break (vegetation clearance zone)	Potential avoidance of 7 kgCO2e/m² of material emissions for repairs, based on patching emission factor
B_ProgDrain	Increased programmed drainage clearing and vegetation management	Potential avoidance of 7 kgCO2e/m² of material emissions for repairs, based on patching emission factor
B_RespDrain	Post-fire responsive drainage clearing	Potential avoidance of 7 kgCO2e/m² of material emissions for repairs, based on patching emission factor
B_Erosion	Post-fire erosion protection and slope stabilisation	Potential avoidance of 7 kgCO2e/m² of material emissions for repairs, based on patching emission factor
B_RiskMgmt	Risk management plan	N/A

6.9.4 Benefits of adaptation

Benefits associated with each of the priority adaptation measures are calculated in terms of direct, indirect, and intangible avoided losses compared to the base case. These are summarised in Table 6-13.

Table 6-13: Annualised direct, indirect, and intangible benefits of adaptation measures compared to the base case under current and future (RCP8.5) climate conditions. Values are presented in 2022 $AUD. Benefits represent the avoided losses compared to the base case, resulting from implementation of the adaptation measure.

Adaptation ID	Benefits compared to the base case					
	Direct tangible (AAL)		Direct tangible (AAD)		Indirect tangible and intangible (annualised)	
	Current climate in 2022	Future climate in 2070 (RCP8.5)	Current climate in 2022	Future climate in 2070 (RCP8.5)	Current climate in 2022	Future climate in 2070 (RCP8.5)
B_Barrier1	$4,539	$6,782	1.0	1.5	$125,198	$187,124
B_ Barrier2	$6,562	$9,807	1.4	2.1	$180,833	$270,277
B_Planting	$5,435	$10,278	1.0	1.9	$128,546	$249,995
B_FireBreak	$3,986	$7,507	0.9	1.6	$109,813	$206,849
B_ProgDrain	$3,074	$5,671	0.8	1.5	$98,043	$192,537
B_RespDrain	$698	$1,313	0.2	0.3	$19,145	$36,063
B_Erosion	$3,543	$6,673	0.8	1.4	$97,611	$183,866

Adaptation ID	Benefits compared to the base case					
	Direct tangible (AAL)		Direct tangible (AAD)		Indirect tangible and intangible (annualised)	
	Current climate in 2022	Future climate in 2070 (RCP8.5)	Current climate in 2022	Future climate in 2070 (RCP8.5)	Current climate in 2022	Future climate in 2070 (RCP8.5)
B_RiskMgmt	$0	$0	0.2	0.3	$20,124	$30,078

Among the evaluated adaptation measures for this exemplar, the remediation of high and moderate risk slopes with flexible barriers (B_Barrier2) stands out as the most beneficial in terms of mitigating losses from bushfire and landslide events. This measure eliminates the risk across a total of 11 slopes, resulting in significant avoided losses.

Following this, fire-resistant planting (B_Planting), remediation of the two highest risk slopes (B_Barrier_1), and implementation of a fire break (B_FireBreak) achieve the highest total benefits.

Responsive drainage clearing following bushfire events (B_RespDrain) and the risk management plan (B_RiskMgmt) yield the lowest total benefits in terms of avoiding direct, indirect, and intangible losses. Although these plays a crucial role in overall risk reduction and management, the specific benefits in terms of avoided losses are comparatively lower when compared to other adaptation measures.

6.9.5 Cost-benefit analysis

Net present values (NPV) are used to determine whether the benefits of an adaptation measure outweigh the costs over the lifetime of the measure. The degree of variability in NPV is investigated using discount rates of 4 and 7 percent (Department of Treasury and Finance, 2013). NPVs are normalised to the base case to enable comparison of the relative improvements and cost-effectiveness of adaptation measures.

Figure 6-6 illustrates the Net Present Value (NPV) analysis of adaptation measures from 2022 to 2070. Programmed drainage clearing (B_ProgDrain) emerges as the most financially favourable option, surpassing the base case in both current and future climate conditions with discount rates of 4% and 7%.

Post-fire responsive drainage clearing (B_RespDrain), post-fire erosion protection and slope stabilisation (B_Erosion), and risk management including early warning systems (B_RiskMgmt) prove to be economically viable alternatives, outperforming the base case exclusively under future climate conditions, regardless of the discount rate employed.

When considering a 4% discount rate, remediating high-risk slopes with flexible barriers (B_Barrier1) and implementing fire-resistant planting (B_Planting) exhibit positive returns on investment under future climate conditions. However, they do not surpass the base case when a higher discount rate is applied.

The NPV for remediating the eleven high and moderate risk slopes with flexible barriers (B_Barrier2) is relatively low due to the significant upfront installation costs outweighing any short-term benefits when compared to the base case. A similar situation arises for the fire break (B_FireBreak) adaptation option.

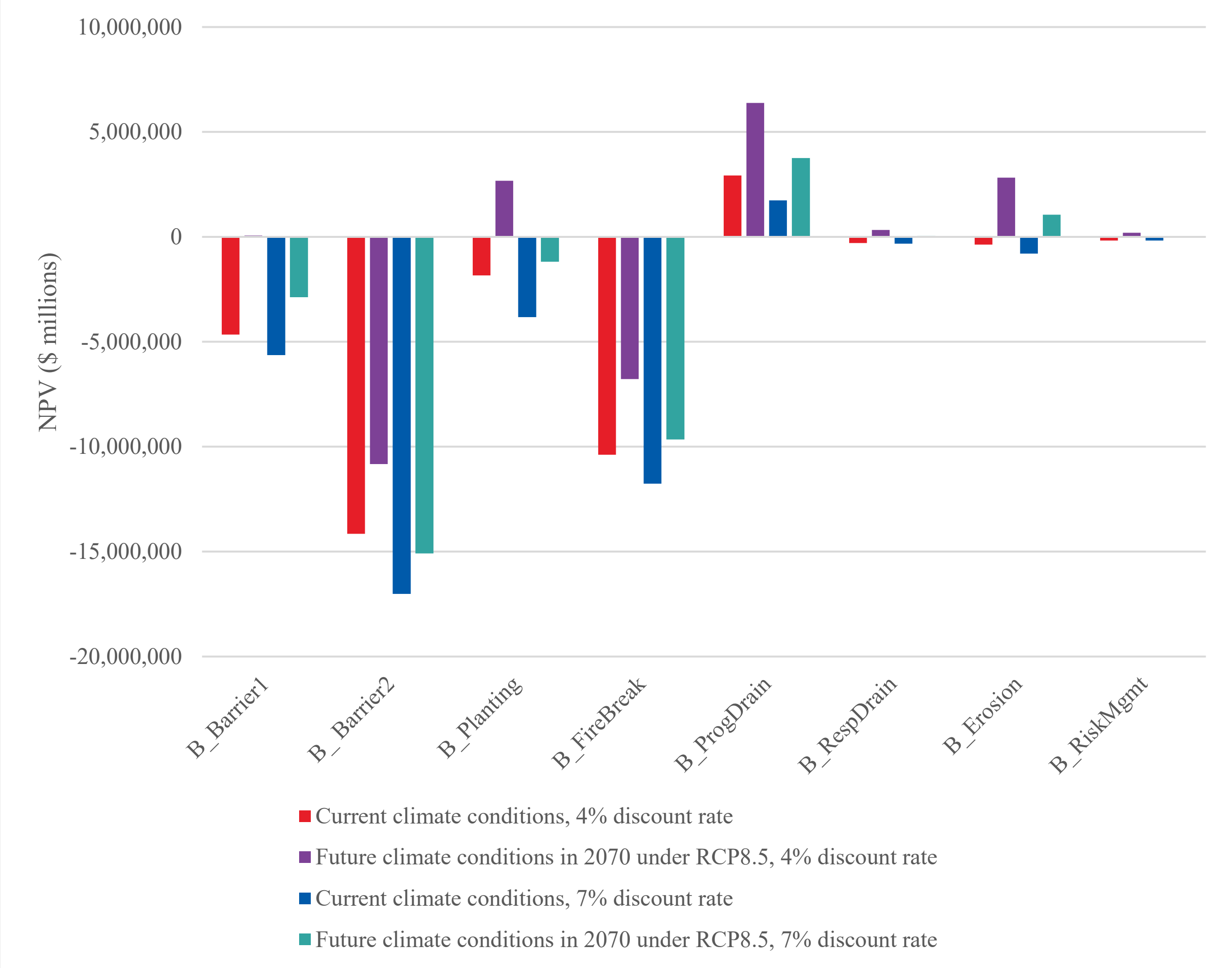


Figure 6-5: Bushfire net present value of adaptation measures compared to the base case 2022-2070

The NPV results are summarised in Table 6-14. Adaptation measures ranked higher than the base case represent options with a positive return-on-investment under each of the climate condition scenarios and discount rates based on NPV results.

Table 6-14: Ranking of bushfire adaptation measures based on NPV results under current climate conditions in 2022 and future climate conditions in 2070 under RCP8.5, using 4% and 7% discount rates.

Ranking based on NPV	Current climate conditions		Future climate conditions under RCP8.5	
	4% discount rate	7% discount rate	4% discount rate	7% discount rate
1	B_ProgDrain	B_ProgDrain	B_ProgDrain	B_ProgDrain
2	Base case	Base case	B_Erosion	B_Erosion
3	B_RiskMgmt	B_RiskMgmt	B_Planting	B_RespDrain
4	B_RespDrain	B_RespDrain	B_RespDrain	B_RiskMgmt
5	B_Erosion	B_Erosion	B_RiskMgmt	Base case
6	B_Planting	B_Planting	B_Barrier1	B_Planting
7	B_Barrier1	B_Barrier1	Base case	B_Barrier1
8	B_FireBreak	B_FireBreak	B_FireBreak	B_FireBreak
9	B_ Barrier2	B_ Barrier2	B_ Barrier2	B_ Barrier2

In addition to NPV, present and future benefit cost ratios (BCR) have been calculated for each adaptation measure. These are summarised in Table 6-15. Programmed drainage clearing (B_ProgDrain) emerges as the adaptation measure with the highest BCR across both current and future climate conditions, regardless of the discount rate applied. This indicates that the benefits derived from implementing programmed drainage clearing outweigh the costs involved, making it a financially favourable investment.

The high BCR of programmed drainage clearing can be attributed to several factors. First, by regularly clearing and maintaining drainage systems, the risk of flooding and water accumulation is significantly reduced. This leads to a decrease in potential damage to infrastructure, such as roads and buildings, resulting in cost savings associated with repairs and replacements. Secondly, effective drainage systems help mitigate the negative impacts of heavy rainfall and stormwater runoff, which are likely to increase under both current and future climate conditions. By efficiently managing water flow, programmed drainage clearing minimises the potential for erosion, soil saturation, and related issues. This contributes to the preservation of soil stability, reducing the need for costly erosion protection measures or slope stabilisations.

The second highest BCR is observed for post-fire erosion protection and slope stabilisation (B_Erosion). This adaptation measure addresses the specific risks associated with erosion and slope instability following a fire event. By implementing erosion protection and slope stabilisation measures, the potential for further damage and risks to infrastructure is reduced, resulting in considerable benefits that outweigh the associated costs.

Remediating high risk slopes with flexible barriers (B_Barrier2) and the fire break (B_FireBreak) do not generate benefits that exceed costs under any conditions in this analysis. This finding suggests that the investments made in these measures do not result in a positive return on investment, as the avoided losses or benefits are insufficient to outweigh the initial costs.

Several factors may contribute to these measures not generating favourable benefit-cost outcomes. Firstly, remediating high-risk slopes with flexible barriers may involve significant upfront costs for installation and maintenance. While these barriers are designed to enhance slope stability and mitigate potential damage, the associated benefits may not be substantial enough to offset the expenses incurred.]

Similarly, the implementation of fire breaks, which aim to prevent or control the spread of wildfires, may also have high costs associated with their establishment and maintenance. However, in this analysis, the benefits derived from avoided losses due to fire incidents are not substantial enough to justify the expenses.

Table 6-15: Benefit cost ratios for bushfire adaptation measures under current and future climate conditions, with a 4% and 7 % discount rate.

Adaptation ID	4% discount rate		7% discount rate	
	BCR under current climate conditions	BCR under future (RCP8.5) climate conditions	BCR under current climate conditions	BCR under future (RCP8.5) climate conditions
B_Barrier1	0.32	1.01	0.19	0.58
B_ Barrier2	0.32	0.48	0.19	0.28
B_Planting	0.72	1.41	0.42	0.82
B_FireBreak	0.28	0.53	0.17	0.32
B_ProgDrain	5.38	10.55	5.88	11.52
B_RespDrain	0.71	1.33	0.57	1.07
B_Erosion	0.91	1.71	0.73	1.37
B_RiskMgmt	0.81	1.21	0.71	1.07

Sensitivity analysis
A sensitivity analysis has been performed to explore and measure the impact of input variables on the outcome of a Cost Benefit Analysis (CBA). The aim is to determine the primary indirect tangible and intangible factors that significantly affect the total loss. This analysis also incorporates an evaluation of uncertainty in the CBA results. It considers the 90th, 50th, and 10th percentiles of the Benefit-Cost Ratio (BCR) and Net Present Value (NPV) values, using discount rates of 4% and 7%, respectively. The assessment covers both present and future climate conditions.

6.10 Case for investment in adaptation

6.10.1 Priority adaptation measures

The case for investment in adaptation for the bushfire exemplar is based on a range of factors. The net present value (NPV) and benefit-cost ratio (BCR) are important metrics for evaluating the economic viability of adaptation measures and have been calculated to consider direct and indirect tangible costs and benefits, as well as intangible impacts as far as possible.

The adaptation measures for this exemplar have been ranked based on NPV and BCR under current climate conditions in 2022 and future climate conditions in 2070 under RCP8.5 and two discount rates in Table 6-16. These rankings are the average of the NPV and BCR rankings.

Table 6-16: Average ranking of bushfire adaptation measures based on NPV and BCR results for current climate conditions in 2022 and future climate conditions in 2070 under RCP8.5 for 4% and 7 % discount rates.

Ranking	Current climate conditions in 2022		Future climate conditions in 2070 under RCP8.5	
	4% discount rate	7% discount rate	4% discount rate	7% discount rate
1	B_ProgDrain	B_ProgDrain	B_ProgDrain	B_ProgDrain
2	B_RiskMgmt	B_Erosion	B_RiskMgmt	B_Erosion
3	B_Barrier1	B_Planting	B_Erosion	B_RespDrain
4	B_Erosion	B_RespDrain	B_RespDrain	B_RiskMgmt
5	B_RespDrain	B_RiskMgmt	B_Planting	B_Planting
6	B_Planting	B_Barrier1	B_Barrier1	B_Barrier1
7	B_ Barrier2	B_FireBreak	B_FireBreak	B_FireBreak
8	B_FireBreak	B_ Barrier2	B_ Barrier2	B_ Barrier2

Based on the combined economic analysis rankings, programmed drainage (B_ProgDrain) performs best under current climate conditions and future climate conditions under RCP8.5, irrespective of the discount rate. The fire break (B_FireBreak) and implementation of barriers for the high and moderate risk slopes (B_Barrier2) demonstrate the worst performance based on economic analysis.

Immediate post-bushfire erosion and drainage clearing (B_RespDrain) also demonstrate relatively high economic performance. This is in line with current practice. The bushfire adaptation measures that return relatively higher benefits are dominated by preventative maintenance and hazard management activities, and make a general case for more investment in this area.

While remediating the eleven high and moderate risk slopes with flexible barriers has the worst economic performance across all scenarios and discount rates, it achieves the greatest reduction in downtime and life safety which may be an important consideration for highly critical road corridors.

It is important to note that results of the economic analysis are reflective of the site-specific exemplar developed here, including socioeconomic, physical geographic, and function setting along with the assumptions made on costs and efficacy of adaptation measures. The positive ranking of adaptation measures here does not mean they are applicable for every site.

Some adaptation measures are mutually enhancing when combined or appropriately sequenced. Some measures may be more effective when implemented in a particular order, taking into account dependencies, timeframes, and priorities. For example, implementing measures to improve soil erosion control and vegetation restoration before undertaking infrastructure upgrades can help stabilise slopes and minimise erosion impacts during construction activities.

In addition to NPV and BCR, it is important to consider adaptation options for their alignment with broader resilience and sustainability objectives, including:

- Reduction in downtime and maintenance of road service level;
- Road safety
- Compliance with standards
- Preservation of cultural and heritage value;
- Avoidance of maladaptation;
- Equitable distribution of costs and benefits (based on distributional analysis);
- Multi-hazard resilience co-benefits (i.e. improves adaptation to multiple hazards).

In some instances, the economic analysis does not fully capture the broader benefits of these objectives. For example, although the flexible barrier adaptation measure does not generate benefits that exceed the installation costs, it could be mandated after a bushfire to meet minimum life safety risk levels as per technical operational requirements of the road authority. Following the Queensland Department of Transport and Main Roads Natural Disaster Program (NDP) guidelines, these slopes would be at or above the tolerable risk levels to loss of life post-bushfire and would require mitigation and/or risk management from a road user safety perspective. This would temporarily close the road and obligate the road authority to remediate the slopes with flexible barriers to meet operational requirements. This builds the case for pre-emptive fire-resistant planting and preventative maintenance to reduce overall risk of bushfire, and by extension, reduce the risk of post-bushfire landslide.

The risk management plan (B_RiskMgmt) delivers the lowest total benefits in terms of avoided direct, indirect, and intangible losses adaptation, but will communicate information that enhances community resilience. The hard adaption measures may also provide a level of comfort and safety to the community.

Another example is the broader regional benefit that the firebreak adaptation offers in its primary purpose of reducing the spread of bushfire across a region, rather than to increase immunity of road asset performance.

Threshold analyses can be employed to consider the relative contribution of two adaptation measures to these types of objectives. By comparing the difference in NPV between the measures, one can determine the threshold value of intangible costs and benefits that must be achieved for one measure to be preferred over the other. For example, if Measure A has an NPV of $100,000 and Measure B has an NPV of $120,000, the difference is $20,000. Therefore, if the intangible benefits of Measure A exceed the inferred intangible benefits of Measure B by more than $20,000, Measure A would be the preferred measure. This analysis allows decision-makers to understand the trade-offs between tangible and intangible benefits and costs and make informed decisions about which adaptation measures to prioritise.

The adaptation measures can also be re-run through the MCA, used to short-list and prioritise adaptation measures (refer to Section 3.3.1), with the output of the economic analysis to refine prioritisation. This approach combines both quantitative and qualitative to explore intangible benefits.

Adaptive planning pathways

In this exemplar, the evaluation of adaptation measures has primarily focused on individual measures and their associated benefits. However, it is crucial to acknowledge that certain adaptation measures can have synergistic effects and can be combined and sequenced in a coordinated manner to enhance infrastructure and community resilience even further. This approach is known as adaptive planning pathways.

By considering adaptation measures holistically and examining their potential interactions, it becomes possible to identify opportunities for bundling and sequencing measures. This means that instead of implementing measures in isolation, they can be strategically combined and implemented in a specific sequence to achieve greater overall resilience.

The concept of adaptive planning pathways recognises that adaptation is an iterative and dynamic process. It acknowledges that different measures can have complementary effects and can build upon each other to create a more resilient system. By adopting this approach, decision-makers can optimise the use of resources and maximise the benefits derived from adaptation measures.

Furthermore, adaptive planning pathways allow for flexibility and the ability to adapt to changing circumstances and future uncertainties. As new information becomes available or as climate conditions evolve, the pathway can be adjusted and updated accordingly.

Overall, the consideration of adaptive planning pathways highlights the importance of a comprehensive and integrated approach to climate change adaptation. It encourages the exploration of synergies between different measures and emphasizes the need to view adaptation as an ongoing and adaptive process rather than a one-time solution.

7. Conclusion

The objective of this study was to provide a framework for undertaking a holistic economic analysis of climate adaptation measures for roads based on a detailed quantitative assessment of climate-related risks. The methodology was applied to two de-identified, hypothetical exemplar roads, one in a metropolitan area prone to flooding and the other in a regional setting susceptible to bushfires and landslides, to demonstrate the case for investing in adaptation.

For each exemplar, road adaptation measures were prioritised for site applicability considering multiple criteria including technical merit, deliverability and constructability, road service level, community impact, and environmental impact. This included consideration of risk mitigation efficacy, avoidance of maladaptation, and embodied carbon impact of adaptation. It is crucial to recognise that not all adaptation measures will be appropriate for every site-specific scenario and every project will require detailed analysis of adaptation options to determine suitable adaptation investments.

A risk assessment and economic analysis was completed that included consideration of direct tangible, indirect tangible, and intangible costs and benefits of the adapted roads to capture the wider value of resilient infrastructure for the surrounding environment, communities, and economy.

Adaptation costs and benefits (avoided losses) were investigated for the current climate in 2022 and the future climate in 2070 under a high emissions scenario (RCP8.5) to consider factors such as safety, environmental externalities, community amenity, and embodied carbon costs.

Net present values (NPV) and benefit-cost ratios (BCRs) were established for each adaptation measure in the exemplars to calculate their economic performance relative to the base case 'do-nothing' scenario.

While the economic analysis in this study primarily focused on individual measures and their associated benefits, it is crucial to acknowledge that certain adaptation measures can have synergistic effects and can be combined and sequenced in a coordinated manner to enhance infrastructure and community resilience even further. This approach is known as adaptive planning pathways and allows for flexible staging of measures and the ability to adapt to changing circumstances and future uncertainties. A common approach for implementing adaptive planning pathways is to bundle different adaptation types, such as a lower-cost investment measure with hazard management and maintenance measures.

7.1 Findings

Based on the comprehensive economic analysis conducted for the two exemplar scenarios, which consider both current and future climate conditions (based on climate in 2022 and projected climate in 2070 under RPC8.5), with discount rates of 4% and 7%, it has been determined that a greater number of adaptation measures for flooding are economically viable compared to measures addressing bushfire and landslide risks.

Economically viable measures are those which outperform the base case (representing the scenario of taking no action) in terms of net present values and also yield a positive return-on-investment. These are summarised in Table 7-1 and Table 7-2.

Table 7-1: Ranking of flooding adaptation measures in terms of NPV results under current and future climate conditions with a 4% and 7% discount rate.

NPV ranking	Current climate conditions in 2022		Future climate conditions in 2070 under RCP8.5	
	4% discount rate	7% discount rate	4% discount rate	7% discount rate
1	F_FBS	F_FBS	F_FBS	F_FBS
2	F_WSUD	F_WSUD	F_WSUD	F_WSUD
3	F_Prevention	F_Prevention	F_5%_Grade	F_Programmed
4	F_Programmed	F_Programmed	F_5%_Staged	F_Prevention

NPV ranking	Current climate conditions in 2022		Future climate conditions in 2070 under RCP8.5	
	4% discount rate	7% discount rate	4% discount rate	7% discount rate
5	F_5%_Grade	F_5%_Grade	F_Prevention	F_5%_Grade
6	F_5%_Staged	Base case	F_Programmed	F_5%_Staged
7	Base case	F_5%_Staged	F_Hazard_Mgmt	F_Hazard_Mgmt
8	F_Hazard_Mgmt	F_Hazard_Mgmt	Base case	Base case
9	F_Viaduct	F_Viaduct	F_Viaduct	F_Viaduct

Table 7-2: Ranking of bushfire adaptation measures in terms of NPV results under current and future climate conditions with a 4% and 7% discount rate.

Ranking based on NPV	Current climate conditions		Future climate conditions under RCP8.5	
	4% discount rate	7% discount rate	4% discount rate	7% discount rate
1	B_ProgDrain	B_ProgDrain	B_ProgDrain	B_ProgDrain
2	Base case	Base case	B_Erosion	B_Erosion
3	B_RiskMgmt	B_RiskMgmt	B_Planting	B_RespDrain
4	B_RespDrain	B_RespDrain	B_RespDrain	B_RiskMgmt
5	B_Erosion	B_Erosion	B_RiskMgmt	Base case
6	B_Planting	B_Planting	B_Barrier1	B_Planting
7	B_Barrier1	B_Barrier1	Base case	B_Barrier1
8	B_FireBreak	B_FireBreak	B_FireBreak	B_FireBreak
9	B_ Barrier2	B_ Barrier2	B_ Barrier2	B_ Barrier2

For the flood exemplar, foamed bitumen stabilisation (F_FSB) and water sensitive urban design (F_WSUD) have the highest return-on-investment under both current and future climate conditions. These adaptation measures do not increase the flood immunity of the road by raising its grade, but rather return value through decreased damage and negating future climate increase in flooding, respectively. The efficacies of both adaption measures are equivalent to the raising the road level.

Preventative maintenance (F_Prevention) and increased programmed maintenance (F_Programmed) also prove to be effective adaptation measures, consistently outperforming the base case across different climate scenarios. Their lower upfront capital expenditure makes them attractive if there are limited financial resources available.

The viaduct (F_Viaduct) presents a unique solution that effectively prevents all direct, indirect, and intangible losses associated with flooding. This makes it highly valuable for critical road corridors that require uninterrupted functionality. However, the viaduct option comes with safety concerns that need to be carefully addressed.

For the bushfire exemplar, there are fewer adaptation measures that outperform the base case across the four scenarios of climate conditions and discount rates. Programmed drainage clearing has the highest return on investment for current climate conditions and future climate conditions under RCP8.5 by 2070 using both the 4% and 7 % discount rate. The bushfire adaptation measures that return positive benefits are mainly maintenance and hazard management activities, either programmed or in response to a bushfire, and make a case for more investment in this area.

While remediating the eleven high and moderate risk slopes with flexible barriers has the worst economic performance across all scenarios and discount rates, it achieves the greatest reduction in downtime and life safety which may be an important consideration for highly critical road corridors. This emphasises the importance of a place-based approach to prioritising investments in infrastructure resilience.

In addition to NPV, a combined ranking of NPV and BCR values has been determined for each adaptation measure for the two exemplars. These are summarised in Table 7-3and Table 7-4.

Table 7-3: Average ranking of flood adaptation measures based on NPV and BCR results for current climate conditions in 2022 and future climate conditions in 2070 under RCP8.5 for 4% and 7 % discount rates.

Ranking	Current climate conditions in 2022		Future climate conditions in 2070 under RCP8.5	
	4% discount rate	7% discount rate	4% discount rate	7% discount rate
1	F_FBS	F_FBS	F_FBS	F_FBS
2	F_Prevention	F_Prevention	F_WSUD	F_Prevention
3	F_WSUD	F_WSUD	F_Prevention	F_WSUD
4	F_5%_Grade	F_Programmed	F_5%_Grade	F_Programmed
5	F_Programmed	F_5%_Grade	F_Programmed	F_5%_Grade
6	F_5%_Staged	F_5%_Staged	F_5%_Staged	F_5%_Staged
7	F_Hazard_Mgmt	F_Hazard_Mgmt	F_Hazard_Mgmt	F_Hazard_Mgmt
8	F_Viaduct	F_Viaduct	F_Viaduct	F_Viaduct

Table 7-4: Average ranking of bushfire adaptation measures based on NPV and BCR results for current climate conditions in 2022 and future climate conditions in 2070 under RCP8.5 for 4% and 7 % discount rates.

Ranking	Current climate conditions in 2022		Future climate conditions in 2070 under RCP8.5	
	4% discount rate	7% discount rate	4% discount rate	7% discount rate
1	B_ProgDrain	B_ProgDrain	B_ProgDrain	B_ProgDrain
2	B_RiskMgmt	B_Erosion	B_RiskMgmt	B_Erosion
3	B_Barrier1	B_Planting	B_Erosion	B_RespDrain
4	B_Erosion	B_RespDrain	B_RespDrain	B_RiskMgmt
5	B_RespDrain	B_RiskMgmt	B_Planting	B_Planting
6	B_Planting	B_Barrier1	B_Barrier1	B_Barrier1
7	B_ Barrier2	B_FireBreak	B_FireBreak	B_FireBreak
8	B_FireBreak	B_ Barrier2	B_ Barrier2	B_ Barrier2

It is important to note that the results of the economic analysis are site-specific to the exemplars used in this study, including the socioeconomic, physical geographic, and functional setting, as well as the assumptions made on the costs and effectiveness of adaptation measures. Therefore, the adaptation measures with the highest return-on-investment for the exemplars in this study may not be representative of every road project in urban, regional, and rural areas.

In addition to economic metrics, it is essential to consider the contribution of adaptation measures to broader strategic objectives to ensure that investment in climate adaptation measures for road infrastructure is not only economically viable but also socially and environmentally sustainable. These strategic objectives should be site-specific and may include reducing impacts on vulnerable people, protecting intangible cultural, heritage, and/or ecological value, complying with standards for critical road infrastructure service levels, road safety, avoiding maladaptation, and enhancing resilience to multi-climate hazards.

For the flooding exemplar, while the viaduct option does not return economic benefit, it has a strategic objective commensurate with critical infrastructure of providing disaster response service levels to increase life-safety and enhance community resilience.

For the bushfire exemplar, the risk to road users post-bushfire will exceed the tolerable risk limit for life without any adaptation. The unacceptable risk will obligate the road authority to temporary close or remediate the slopes with higher-investment flexible barriers to meet operational safety requirements. This builds the case for fire resistant planting and increased maintenance pre-bushfire which decrease overall risk of bushfire and therefore reduce post-bushfire risk of landslide.

Measuring alignment to broader strategic objectives will require inclusive stakeholder engagement. In the context of climate adaptation measures for road infrastructure, this ensures that the investments in resilience are prioritised according to the needs and priorities of the people who use and rely on the road infrastructure. It can also help to build awareness of climate-related risks for road users, owners, and operators, to improve overall system resilience.

This economic analysis demonstrates a framework to quantify risk efficacy and holistic economic performance of adaptation measures that considers wider societal impacts. The presented framework of adaptation prioritisation, base case valuation, adaptation risk efficacy assessment, and economic analyses is scalable and repeatable for infrastructure and climate hazards in Victoria to support the case for investment in climate change adaptation.

References

ABC Rural. (2015, December 28). Floodwaters close Victoria Highway in Top End, stranding travellers (Image supplied by Becky Myers). *ABC Rural*. ABC. Retrieved from https://www.abc.net.au/news/rural/2015-12-28/victoria-highway-closed-flood-waters/7056564

ABC Rural. (2022, November 23). Road collapse caused by flood cuts Gooramadda Road in half in north-east Victoria (Image supplied by Melanie Coid). *ABC Rural*. ABC. Retrieved from https://www.abc.net.au/news/rural/2022-11-24/excess-water-causes-goorramadda-road-collapse-victoria-floods/101688478

Agriculture Victoria. (2022, May). *Understanding weather, climate and forecasting*. Retrieved September 20, 2022, from https://agriculture.vic.gov.au/climate-and-weather/understanding-weather-climate-and-forecasting

Australian Plants Society (Victoria). (n.d.). *Fire resistant and retardant plants*. Retrieved from https://apsvic.org.au/fire-resistant-and-retardant-plants/

(2021). *Australian Transport Assessment and Planning Guidelines.* Commonwealth of Australia .

Austroads. (2017, October 25). *New foamed bitumen stabilisation test methods*. Retrieved from https://austroads.com.au/latest-news/new-foamed-bitumen-stabilisation-test-methods

Boardman, E., Greenberg, D., Vining, A., & Weimer, D. (2010). *Cost–benefit analysis: concepts and practice.* New Jersey: Pearson Prentice Hall.

Bureau of Meteorology. (2008, October). *The Sub-tropical Ridge*. Retrieved September 20, 2022, from Australian Cliamte Influences: http://www.bom.gov.au/watl/about-weather-and-climate/australian-climate-influences.shtml?bookmark=stridge

Bureau of Meteorology. (2016, August). *La Niña and impact on Australia?* Retrieved March 10, 2023, from http://www.bom.gov.au/climate/updates/articles/a020.shtml

Clarke, J. M., Grose, M., Thatcher, M., Hernaman, V. H., Round, V., Rafter, T., . . . Wilson, L. (2019). Victoria's changing climate. In V. C. Report. Melbourne: CSIRO.

Coalition for Climate Resilient Investment. (2021). *Physical Climate Risk Assessment Methodology.* Retrieved from https://resilientinvestment.org/pcram/

Commonwealth of Australia. (2006). *Handbook of cost–benefit analysis.* Canberra : Financial management Reference Material No. 6.

CSIRO and BoM. (2020, December 24). *VCP19 Publications*. Retrieved from Climate Change in Australia: https://www.climatechangeinaustralia.gov.au/en/projects/victorian-climate-projections-2019/vcp19-publications/

CSIRO and Bureau of Meteorology. (2022). *State of the climate 2020.* Commonweath of Australia.

De Graff, J. (2018, May 25). A rationale for effective post-fire debris flow mitigation within forested terrain. *Geoenvironmental Disasters, 5*(7). doi:https://doi.org/10.1186/s40677-018-0099-z

DELWP. (2019). *Victoria's Climate Science Report 2019.* The State of Victoria Department of Environment, Land, Water and Planning.

DELWP. (2020). *Guidelines for Assessing the Impact of Climate Change on Water Availability in Victoria.* The State of Victoria Department of Environment, Land, Water and Planning.

Department of Energy, Environment, and Climate Action . (2022, February 15). *Adapting now creates economic opportunities and stronger communities*. Retrieved from Building Victoria's Climate Resilience: https://www.climatechange.vic.gov.au/building-victorias-climate-resilience/our-commitment-to-adapt-to-climate-change/adapting-creates-economic-opportunities-and-stronger-communities

Department of Infrastructure, Regional Development, and Cities. (2017). *Road construction cost and infrastructure procurement benchmarking.* Australian Government. Retrieved from https://www.bitre.gov.au/sites/default/files/rr148.pdf

Department of Prime Minister and Cabinet. (2020). *Cost-Benefit Analysis.* Australian Government. Retrieved from https://oia.pmc.gov.au/resources/guidance-assessing-impacts/cost-benefit-analysis

Department of State Development, Infrastructure, Local Government and Planning. (2021). *Cost Benefit Analysis Guide.* State of Queensland. Retrieved from https://www.statedevelopment.qld.gov.au/__data/assets/pdf_file/0013/55030/further-guidance-04-cost-benefit-analysis-guide.pdf

Department of Transport and Planning. (2023). Retrieved from Planning process glossary: https://dtp.vic.gov.au/about/statutory-planning/planning-process-glossary

Department of Treasury and Finance. (2013). Economic evaluation for business cases: technical guidelines., (p. Table 7).

Evans, C., & Kafalenos, R. (2022). Roundtable on Resilience: Cross-cutting issues. *PIARC XVI World Winter Service and Road Resilience Congress.* Calgary: PIARC. Retrieved from https://proceedings-calgary2022.piarc.org/en/documents/1778

Forbes, K., & Broadhead, J. (2011). *Forests and landslides: The role of trees and forests in the prevention of landslides and rehabilitation of landslide-affected areas in Asia.* Bangkok: Food and Agriculture Organization of the United Nations .

Forest Fire Management Victoria. (2021, December 7). *Strategic Fuel Breaks Program*. (DEECA) Retrieved from Planned Burns: https://www.ffm.vic.gov.au/bushfire-fuel-and-risk-management/strategic-fuel-breaks-program

Geofabrics Australasia . (2020, February 11). *Case studies: Great Ocean Road rockfall protection* . Retrieved from https://www.rockfall.co/news/great-ocean-road-rockfall-protection

Global Forest Watch. (2023). *Monthly MODIS Burned Area Product (MCD64A1 v006).* Retrieved from Fires in Victoria, Australia: www.globalforestwatch.org

Grose, M., Timbal, B., Wilson, L., Bathols, J., & Kent, D. (2015). The subtropical ridge in CMIP5 models, and implications for projections of rainfall in southeast Australia. *Australian Meteorological and Oceanographic Journal, 65*(1), 90-106.

Hope, P., Timbal, B., Hendon, H., Ekström, M., & Potter, N. (2017). *A synthesis of findings from the Victorian Climate Initiative (VicCI).* Australia: Bureau of Meteorology.

Hydro Tasmania. (2018, November 14). *Meet our climate drivers* . Retrieved from The Spill: https://www.hydro.com.au/the-spill/the-spill/2018/11/14/meet-our-climate-drivers

Infrastructure Australia. (2021). *Guide to economic appraisal.* Retrieved from https://www.infrastructureaustralia.gov.au/sites/default/files/2021-07/Assessment%20Framework%202021%20Guide%20to%20economic%20appraisal.pdf

Infrastructure Sustainability Council. (n.d.). *IS Materials Calculator (v2.0.13).*

Infrastructure Sustainability Council of Australia. (2021). *Infrastruture Sustainability Rating Scheme Technical Manual Design & As-Built Version 2.1.* Sydney: Infrastructure Sustainability Council of Australia Pty Ltd.

Institute of Public Works Engineering Autralasia. (2017, November 13). *Foamed bitumen pavements thwart Cyclone Debbie*. Retrieved from https://www.ipwea.org/blogs/intouch/2017/11/12/foamed-bitumen-pavements-thwart-cyclone-debbie

IPCC. (2007). *Fourth Assessment Report: Climate Change 2007.* IPCC.

IPCC. (2014). *Fifth Assessment Report: Summary for Policymakers.* Intergovernmental Panel on Climate Change.

IPCC. (2021). *The concept of risk in the IPCC Sixth Assessment Report: a summary of crossWorking Group discussions.* Retrieved from https://www.ipcc.ch/event/guidance-note-concept-of-risk-in-the-6ar-cross-wg-discussions/

IPCC. (2021a). *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

IPCC. (2021c). Atlas [Gutiérrez, J.M., R.G. Jones, G.T. Narisma, L.M. Alves, M. Amjad, I.V. Gorodetskaya, M. Grose, N.A.B. Klutse, S. Krakovska, J. Li, D. Martínez-Castro, L.O. Mearns, S.H. Mernild, T. Ngo-Duc, B. van den Hurk, and J.-H. Yoon]. In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 1927–2058). Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press. doi:10.1017/9781009157896.021.

IPCC. (2022). Glossary. Retrieved from https://apps.ipcc.ch/glossary/

Lautenbach, D. (2022, May 10). *Benefits of Preventive Asphalt Maintenance*. Retrieved from EVStudio : https://evstudio.com/benefits-of-preventive-asphalt-maintenance/

Melbourne Water. (2015). *Flood Management Strategy: Port Phillip and Westernport.* Docklands: Melbourne Water Corporation .

Nature. (2014, September 21). *Betting on negative emissions*. Retrieved from Nature Climate Change: https://www.nature.com/articles/nclimate2392

NSW Treasury. (2023, February 27). *Technical note to NSW Government Guide to Cost-Benefit Analysis TPG23-08*. Retrieved from https://www.treasury.nsw.gov.au/sites/default/files/2023-03/20230302-technical-note-to-tpg23-08_carbon-value-to-use-for-cost-benefit-analysis.pdf

Pepler, A., Ashcroft, L., & Trewin, B. (2018). The relationship between the subtropical ridge and Australian temperatures. *Journal of Southern Hemisphere Earth Systems Science*(68). doi:10.22499/3.6801.011

PIARC. (2015). *International Climate Change Adaptation Framework for Road Infrastructure.*

PIARC. (2019). *Adaptation methodologies and strategies to increase the resilience of roads to climate change - case study approach* . World Road Association.

PIARC. (2019). *Refinement of PIARC's International Climate Change Adaptation Framework for Road Infrastructure.*

ROADAPT. (2015). *Roads for today, adapted for tomorrow - guidelines* . Prepared for the Conference of European Directors of Roads Transnational Road Research Program. Retrieved from https://www.cedr.eu/download/other_public_files/research_programme/call_2012/climate_change/roadapt/ROADAPT_integrating_main_guidelines.pdf

Sovacool, B. (2011). Hard and soft paths for climate change adaptation. *Climate Policy, 11*, 1178. Retrieved from https://www.adaptation-undp.org/sites/default/files/downloads/sovacool-cp-hardsoft.pdf.

Stephens, P. (2016, 30 December). Savage thunderstorms leave widespread damage across Melbourne suburbs. *The Age*. Retrieved from https://www.theage.com.au/national/victoria/savage-thunderstorms-leave-widespread-damage-across-melbourne-suburbs-20161229-gtjl5m.html

Technical Committee E.1 Adaptation Strategies and Resiliensy. (2019). *Adaptation methodologies and strategies to increase the resilience of roads to climate change - case study approach.* The World Roads Association (PIARC). Retrieved from https://www.piarc.org/en/order-library/31335-en-Adaptation%20Methodologies%20and%20Strategies%20to%20Increase%20the%20Resilience%20of%20Roads%20to%20Climate%20Change%20%E2%80%93%20Case%20Study%20Approach

Thompson, T. (2022). The Influence of wildfires on soil and rock slope risk. In Rahman, & Jaksa (Ed.), *Proceedings of the 20th International Conference on Soil Mechanics and Geotechnical Engineering* (pp. 4869-4874). Sydney: Australian Geomechanics Society. doi:978-0-9946261-4-1

Thongkham, N. (2020, August 12). *ALF complete major multi-year study*. (Australian Road Research Board) Retrieved from Australian Road Research Board: https://www.arrb.com.au/latest-research/alf-completes-major-multi-year-study

U.S. Department of Transportation. (2014). *Airport Pavement Management Program.* Retrieved from https://www.faa.gov/documentlibrary/media/advisory_circular/150-5380-7b.pdf

U.S. Department of Transportation Federal Highway Administration 2019. (2019). *Nature-based solutions for coastal highway resilience: An implementation guide.* Retrieved from https://www.fhwa.dot.gov/environment/sustainability/resilience/ongoing_and_current_research/green_infrastructure/implementation_guide/fhwahep19042.pdf

US Army Corps of Engineers. (2009). *Louisiana Coastal Protection and Restoration Final Technical Report.* Retrieved from https://www.mvn.usace.army.mil/Portals/56/docs/environmental/LaCPR/Economics.pdf

VicRoads. (n.d.) Crash Statistics. Department of Transport. Retrieved April 25, 2023 from: Crash statistics : VicRoads

Victorian Water and Climate Initiative . (2021). *Victoria's water in a changing climate.* State of Victoria Department of Environment, Land, Water and Planning .

Wigginton, S. K., & Meyerson, L. A. (2018). Passive Roadside Restoration Reduces Management Costs and Fosters Native Habitat. Ecological Restoration 36(1), 41-51. Retrieved from: https://www.muse.jhu.edu/article/687721.

Yong, C., Ward, M., Watson, J. E. M., Reside, A. E., van Leeuwen, S., Legge, S., Geary, W. L., Lintermans, M., Kennard, M. J., Stuart, S., & Carwardine, J. (2023). The costs of managing key threats to Australia's biodiversity. Journal of Applied Ecology, 00, 1– 13. Retrieved from: https://doi.org/10.1111/1365-2664.14377

Zelasky, S. E., & Buonocore, J. J. (2021). The social cost of health – and climate related on-road vehicle emissions in the continental United States from 2008 to 2017. Environ. Res. Lett. Retrieved from: The social costs of health- and climate-related on-road vehicle emissions in the continental United States from 2008 to 2017 (iop.org)

Appendix A

Example longlist of adaptation measures

A.1 Catalogue of adaptation measures for roads

Adaptation type	Hazard	Adaptation measure	Enabling conditions
Hard	Flood	Stabilising existing granular pavement with mix of cement to create durable and water-resistant road surface	Pavement design required. • Assessment of traffic load, • sufficient depth and quality gravel/crushed rock. • Availability of stabiliser, distance from quarry and materials.
Hard	Flood	Foamed stabilised bitumen (FSB)	• Pavement design required. • May also consider plant mix option if distance to suitable quarry. • Needs to be cost effective.
Hard	Flood	Improved drainage systems including table drains, culverts, longitudinal and transverse drainage designed with climate change considerations	• Excavation works to deepen drain, may be difficult depending on distance to outlets. • Select appropriate return period event (i.e. 1% AEP and include climate change allowance. • Design and construct larger culverts, without impacting upstream flows, to account for additional surface flow
Hard	Flood	Raising road level to adjust for local flooding risk	• Afflux to be considered when raising road levels. • Select appropriate return period event (i.e. 1% AEP and include climate change allowance.
Hard	Flood	Construction of flood barriers and levees along the road for protection from floodwaters	
Hard	Fires Flood	Locate critical infrastructure outside of known low areas and/or risk areas to reduce operational disruption.	
Hard	Flood Fires	Locate intelligent transportation system (ITS) cabinets in locations outside of vulnerable areas and away from vegetation to reduce operational disruption.	
Hard	Flood	Revise road geometry to shorten flow paths and reduce risk of motorway inundation	• Select appropriate return period event (i.e. 1% AEP and include climate change allowance.
Hard	Flood	Construction of a viaduct over floodplain	• Select appropriate return period event (i.e. 1% AEP and include climate change allowance.
Hard	Fires Flood	Installation of modular bridges for easy replacement following damage	
Hard	Flood	In the case that flood velocities are determined to increase significantly, additional scour protection may be deemed necessary.	• Scour protection to be assessed with reference to flood modelling climate change sensitivity testing, for the design condition case, to determine impact of increased rainfall intensities on water velocity.
Hard	Flood	Pavement design can be modified in future to allow for flood edge treatments in the event typical verge/landscaping treatments become ineffective.	• Bound /concrete edge treatments to protect batters and flood ways
Hard	Fires	Different asphalt mixes that consider projected temperatures to reduce rutting potential.	• Not a large effect on rural roads with thin asphalt surfacing.
Hard	Fires	Design noise walls and fencing to reduce the probability of damage from bushfire risk (e.g., low carbon concrete noise walls).	
Hard	Flood	Embankment design to either reduce or accommodate water infiltration, considering selection of embankment materials that reduce flood water infiltration, allow flood water to permeate through embankments and provision of subsurface drainage systems to permit water that has entered to drain away after the flooding has receded	

Adaptation type	Hazard	Adaptation measure	Enabling conditions
Hard	Fires	Pavement cover thickness based on durability modelling that account for changes in the rate of carbonation due to increased atmospheric CO2 and smoke.	
Soft	Flood	Water Sensitive Urban Design (WSUD) including catchment improvements, swales, bioretention basins	
Soft	Flood	Slope stabilisation and scour prevention through vegetation	
Soft	Fires	Fire-resistant planting (species selection and spatial layout)	
Soft	Flood Fires	Geomorphological modification through earthworks/material re-use for slope stabilisation	
Soft	Fires	Fire break (vegetation clearance zone)	
Soft	Fire Flood	Consider climate resilient and self-regenerative systems. Select plant species that is resilient to environmental risks and impacts of climate change such as flooding, extreme heat and drought.	
Maintenance	Flood	Increased inspection frequency for early intervention and preventative maintenance to reduce rate of road deterioration	• Asphalt surfacing in lieu of sprayed seals for high shear areas • Ruts and grooves occur in areas where heavy vehicles are moving slowly (i.e., uphill)
Maintenance	Flood	Increased routine maintenance to reduce overall road deterioration	•
Maintenance	Fires Flood	Low maintenance options with reinstatement considerations	
Maintenance	Flood Fires	Automated conditions assessments using machine learning to optimise maintenance frequency	
Maintenance	Flood Fire	Preventative maintenance of vulnerable roads by varying reseal intervals	• Use patrol and routine maintenance. • Monitor rate of deterioration, rate of reseals over time to determine road deterioration model
Maintenance	Fires	Increased vegetation management to reduce fire risk and landslide susceptibility	
Maintenance	Fires Flood	Low maintenance options with reinstatement considerations	
Hazard Management	Fires Flood	Early warning systems for appropriate traffic management responses i.e. rerouting, reduced speeds	• Limit heavy loads to granular pavements immediately after heavy rainfall events
Hazard Management	Flood Fires	Road decommissioning and permanent rerouting	
Hazard Management	Flood Fire	Allow for new technologies through dynamic adaptive planning	
Hazard Management	Flood Fire	Adequate access for inspection and maintenance to allow easy and safe access for inspection of the structures following any major storm events.	
Hazard Management	Flood Fire	Improve notifications and information provided to motorists using variable message signs and sources.	
Hazard Management	Flood Fire	Local provision of concrete causeways to increase trafficability, road availability and access for emergency vehicles and evacuation during and after extreme events	
Hazard management	Fire Flood	Install real time flood level and fire spread monitors	

A.2 Additional exemplar adaptation measures by hazard type from PIARC

The following list of adaptation measures for roads has been sourced from the PIARC International Climate change adaptation framework for road infrastructure (PIARC, 2015).

Sea level rise and storm surges – adaptation responses:

- Using appropriate structural materials and providing lateral protections
- Raising road and pavement levels
- Constructing levy banks with drainage/seawalls
- Road realignment
- Including additional longitudinal and transverse drainage systems
- Construction of seawalls, jetties, offshore breakwaters, groins, ripraps to protect shorelines from coastal erosion and submersion
- Protecting levy bank with suitable mangroves
- Planting artificial reefs
- Replacing metal culverts with reinforced concrete
- Development or strengthening of flood risk management plans
- Re-siting of critical infrastructure from areas that are forecast to be most at risk from rising sea-levels
- Development of a Coastal Strategy which identifies the most appropriate shoreline management plan and whether coastal defences are required/ need managing/need implementing etc.

Reduction in rainfall and increased drought – adaptation responses:

- Using flexible pavement structures
- Increasing water retention capacity and slowing infiltration through environmental measures and bio retention systems to recharge aquifers and reduce surface flow runoff
- Re-vegetating with drought tolerant species
- Using matting/erosion control blankets
- Applying granular protection
- Ensuring the selection of materials with high resistance to dry conditions
- Implement a reactive landscape and maintenance regime which accommodates for reduced rainfall
- Maintenance of soil moisture and nutrient levels

Increase in precipitation – adaptation responses:

- Applying a safety factor to design assumptions
- Reducing the gradient of slopes
- Increasing size and number of engineering structures (hydraulic structures, high river crossings)
- Increasing water retention capacity and slow infiltration through natural or bioengineered systems
- Raising pavements and adding additional drainage capacity
- Using water capture and storage systems
- Realigning natural water courses
- Enclosing materials to protect from flood water (impermeable linings)
- Using materials that are less affected by water
- Allowing for alternative routes in the event of a road closure
- Highway drainage plan
- Gully and pumping station renovation
- Mapping of flood hotspots
- Updated design standards for drainage systems
- Production of a Surface Water Management Plans, Local Flood Risk Management Plans etc.
- Pollution prevention control methods due to increased volumes of diffuse pollution resulting from increased runoff
- Implementation/ broadening of emergency warning systems in the instance of flooding
- Improved communication methods for network users in the event of an emergency
- Improved coverage of street lighting due to reduced visibility
- Slope stability studies in an attempt to minimise landslides as a result of increased precipitation
- Measures to enhance slope stability and prevent landslides and rock fall
- Soil moisture removal techniques to prevent the deterioration of the structural integrity of roads, bridges and tunnels

Increased wind strength – adaptation responses:

- Modifying the design of supports and anchorages
- Installing protection systems such as windbreaks
- Planting coastal forest and mangroves
- Increased frequency of gully maintenance activities
- Improved communication systems and warnings for network users
- Structural assessment of suspension bridges, signs and tall structures

Increased temperatures – adaptation responses:

- Using more resilient materials and processes which have heat-resistant properties
- Relocation of street traffic control equipment
- Development and implementation of emergency and resilience plans and changes to working practices and policies
- Improved conditions for vegetative growth may require an increased level of management
- Increased use of heat and fire resistant materials
- Improved coverage of fire-fighting equipment
- Enhanced cooling and ventilation of electrical equipment
- Use of anti-corrosion paint due to increase in surface salt levels in some locations
- Maintenance of soil moisture and nutrient levels

Changes to snowfall, permafrost and ice coverage – adaptation responses:

- Soil stability studies
- Production of a Surface Water Management Plans, Local Flood Risk Management Plans etc.
- Development and implementation of emergency and resilience plans and changes to working practices and policies
- Heat extraction using air convection in embankments on permafrost (this involves cooling embankments in an effort to maintain or cool frozen ground conditions)
- Use of heat drain to facilitate heat extraction from the embankment during winter
- Insulating the permafrost to mitigate thawing
- Soil stabilisation techniques used to reduce frost action in subgrade soils
- Use of a pavement surface having a high albedo (surface solar reflectivity) in order to minimise heat transfer to the underlying subgrade
- Structural assessment of road and structure integrity as a result of subsidence and weakening as a result of permafrost thaw

Appendix B

Multi-criteria analysis for adaptation measures

IV Economic analysis of adaptation for roads

Criteria selection: criteria are developed to reflect organisational or project-specific priorities and objectives

Assessment criteria	#	Criterion	Description
Technical merit	1	Efficacy of measure for risk mitigation	Extent to which measure maintains accessibility and existing level of service of the road during hazard events under multiple future climate scenarios.
	2	Uncertainty in design and construction	Extent to which there is existing capacity and capability in industry including design and construction guidance/ standards to design, deliver, and maintain measure.
	3	Recovery Time Objective (RTO)	The time and effort required to implement the measure and restore the level of service of the road following disruption/ disaster, where a higher score represents a faster RTO.
Deliverability and constructability	4	Cost of construction	Cost of construction, including consideration of length of construction period, where a higher score represents lower costs.
	5	Maintenance costs and level of effort	Maintenance costs and level of effort, including duration and frequency of maintenance, where a higher score represents lower costs.
Road service level	6	Road service level impact during construction	Extent to which road service level is maintained during construction, including consideration of associated construction downtime for road-users (e.g. freight), where a higher score represents higher road service level maintained.
	7	Road service level impact during maintenance	Extent to which road service level is maintained during maintenance works, including consideration of associated downtime for road-users (e.g. freight), where a higher score represents higher road service level maintained.
Community impact	8	Community impact during construction	Extent to which community is adversely impacted or inconvenienced during construction, where a lower score represents negative impact and inconvenience
	9	Community impact during maintenance	Extent to which community is adversely impacted or inconvenienced during maintenance, where a lower score represents negative impact and inconvenience
Environmental impact	10	Maladaptation	The extent to which the measure does not exacerbate other climate-related impacts under stabilised and high emissions scenarios over the lifetime of the adaptation, where a lower score represents maladaptative outcomes.
	11	Level of net impact on the natural environment	Level of net impact on the natural environment, including impact on ecosystem services, where a higher score represents positive impact.
	12	Embodied carbon emissions impact	Embodied carbon of construction where a lower score represents a higher, negative embodied carbon impact.

IV Economic analysis of adaptation for roads

Criteria weighting: Matched pairs analysis is used to determine the relative importance and weighting of each selected criterion

Criteria you are comparing the performance of	Relative importance (Less, Same, More)	Criteria you are comparing against	Relative importance score
Scoring Criterion 12			
Embodied carbon emissions impact	Less	Efficacy of measure for risk mitigation	0
Embodied carbon emissions impact	More	Uncertainty in design and construction	2
Embodied carbon emissions impact	Same	Recovery Time Objective (RTO)	1
Embodied carbon emissions impact	More	Cost of construction	2
Embodied carbon emissions impact	More	Maintenance costs and level of effort	2
Embodied carbon emissions impact	Same	Road service level impact during construction	1
Embodied carbon emissions impact	Same	Road service level impact during maintenance	1
Embodied carbon emissions impact	More	Community impact during construction	2
Embodied carbon emissions impact	More	Community impact during maintenance	2
Embodied carbon emissions impact	Less	Maladaptation	0
Embodied carbon emissions impact	Same	Level of net impact on the natural environment	1
Scoring Criterion 11			
Level of net impact on the natural environment	Less	Efficacy of measure for risk mitigation	0
Level of net impact on the natural environment	More	Uncertainty in design and construction	2
Level of net impact on the natural environment	Same	Recovery Time Objective (RTO)	1
Level of net impact on the natural environment	Less	Cost of construction	0
Level of net impact on the natural environment	Less	Maintenance costs and level of effort	0
Level of net impact on the natural environment	More	Road service level impact during construction	2
Level of net impact on the natural environment	More	Road service level impact during maintenance	2
Level of net impact on the natural environment	More	Community impact during construction	2
Level of net impact on the natural environment	More	Community impact during maintenance	2
Level of net impact on the natural environment	Less	Maladaptation	0
Scoring Criterion 10			
Maladaptation	Same	Efficacy of measure for risk mitigation	1
Maladaptation	More	Uncertainty in design and construction	2
Maladaptation	More	Recovery Time Objective (RTO)	2
Maladaptation	More	Cost of construction	2
Maladaptation	More	Maintenance costs and level of effort	2
Maladaptation	More	Road service level impact during construction	2
Maladaptation	More	Road service level impact during maintenance	2
Maladaptation	More	Community impact during construction	2
Maladaptation	More	Community impact during maintenance	2
Scoring Criterion 9			
Community impact during maintenance	Less	Efficacy of measure for risk mitigation	0
Community impact during maintenance	More	Uncertainty in design and construction	2
Community impact during maintenance	Same	Recovery Time Objective (RTO)	1
Community impact during maintenance	More	Cost of construction	2
Community impact during maintenance	Same	Maintenance costs and level of effort	1
Community impact during maintenance	Same	Road service level impact during construction	1
Community impact during maintenance	Less	Road service level impact during maintenance	0
Community impact during maintenance	Less	Community impact during construction	0
Scoring Criterion 8			
Community impact during construction	Less	Efficacy of measure for risk mitigation	0
Community impact during construction	More	Uncertainty in design and construction	2
Community impact during construction	Less	Recovery Time Objective (RTO)	0
Community impact during construction	More	Cost of construction	2
Community impact during construction	Same	Maintenance costs and level of effort	1
Community impact during construction	Less	Road service level impact during construction	0
Community impact during construction	Less	Road service level impact during maintenance	0
Scoring Criterion 7			
Road service level impact during maintenance	Less	Efficacy of measure for risk mitigation	0
Road service level impact during maintenance	Less	Uncertainty in design and construction	0
Road service level impact during maintenance	More	Recovery Time Objective (RTO)	2
Road service level impact during maintenance	Same	Cost of construction	1
Road service level impact during maintenance	Same	Maintenance costs and level of effort	1
Road service level impact during maintenance	More	Road service level impact during construction	2
Scoring Criterion 6			
Road service level impact during construction	Less	Efficacy of measure for risk mitigation	0
Road service level impact during construction	More	Uncertainty in design and construction	2
Road service level impact during construction	Less	Recovery Time Objective (RTO)	0
Road service level impact during construction	Same	Cost of construction	1
Road service level impact during construction	Less	Maintenance costs and level of effort	0
Scoring Criterion 5			
Maintenance costs and level of effort	Less	Efficacy of measure for risk mitigation	0
Maintenance costs and level of effort	More	Uncertainty in design and construction	2
Maintenance costs and level of effort	Same	Recovery Time Objective (RTO)	1
Maintenance costs and level of effort	Same	Cost of construction	1
Scoring Criterion 4			
Cost of construction	Less	Efficacy of measure for risk mitigation	0
Cost of construction	More	Uncertainty in design and construction	2
Cost of construction	Same	Recovery Time Objective (RTO)	1
Scoring Criterion 3			
Recovery Time Objective (RTO)	Less	Efficacy of measure for risk mitigation	0
Recovery Time Objective (RTO)	More	Uncertainty in design and construction	2
Scoring Criterion 2			
Uncertainty in design and construction	Less	Efficacy of measure for risk mitigation	0

Matched Pairs Analysis

	Efficacy of measure for risk mitigation	Uncertainty in design and construction	Recovery Time Objective (RTO)	Cost of construction	Maintenance costs and level of effort	Road service level impact during construction	Road service level impact during maintenance	Community impact during construction	Community impact during maintenance	Maladaptation	Level of net impact on the natural environment	Embodied carbon emissions impact	WEIGHTING
Efficacy of measure for risk mitigation	1	0	0	0	0	0	0	0	0	0	0	0	16%
Uncertainty in design and construction		1	2	2	2	2	0	2	2	2	2	2	2%
Recovery Time Objective (RTO)			1	1	1	0	2	0	1	1	1	1	9%
Cost of construction				1	1	1	1	2	2	0	0	2	8%
Maintenance costs and level of effort					1	0	1	1	1	0	0	2	10%
Road service level impact during construction						1	2	0	1	2	2	1	6%
Road service level impact during maintenance							1	0	0	2	2	1	8%
Community impact during construction								1	0	2	2	2	6%
Community impact during maintenance									1	2	2	2	6%
Maladaptation										1	0	0	11%
Level of net impact on the natural environment											1	1	9%
Embodied carbon emissions impact												1	10%
	23	**3**	**13**	**11**	**14**	**8**	**12**	**8**	**8**	**16**	**13**	**15**	**100%**

MCA results for shortlisted adaptation measures for flooding

Summary of shortlisted adaptation measures for flooding

MCA Criteria	*Hazard*	Flooding						
	Adaptation type	Hard			Soft (nature-based)	Maintenance		Hazard management
	MCA Weighting	Optimise road grade and drainage to improved level of immunity (5% AEP)	Foamed bitumen stabilisation	Staged implementation of road grade and drainage improvements to increase level of immunity over asset life	Water Sensitive Urban Design	Increased inspection frequency for early intervention and preventative maintenance	Increased programmed rehabilitation	Risk management including early warning system, heavy load limits, and temporary rerouting
Efficacy of measure for risk mitigation	16%	4	5	5	4	4	4	4
Uncertainty in design and construction	2%	5	4	5	3	5	5	5
Recovery Time Objective (RTO)	9%	3	5	3	2	5	4	2
Cost of construction	8%	4	4	2	4	4	3	4
Maintenance costs and level of effort	10%	4	5	4	2	4	2	2
Road service level impact during construction	6%	3	4	3	3	4	4	3
Road service level impact during maintenance	8%	3	4	3	3	4	4	2
Community impact during construction	6%	3	3	2	3	3	3	3
Community impact during maintenance	6%	3	3	3	4	4	4	4
Maladaptation	11%	3	4	3	5	4	4	4
Level of net impact on the natural environment	9%	2	3	2	5	3	3	3
Embodied carbon emissions impact	10%	2	4	2	5	4	4	3
TOTAL	Total / 5	3.2	4.1	3.1	3.7	4.0	3.6	3.2
	%	64%	83%	63%	74%	79%	72%	63%

MCA Rating	Colour	Score	Description
Strong positive		5	High positive support for meeting the criteria, performs better than the base case
Moderate positive		4	Medium positive support for meeting the criteria, performs better than the base case
No significant impact		3	Low positive support for meeting the criteria, performs the same, or similar to like the base case
Moderate, negative impact		2	No support for meeting the criteria, performs worse than the base case
Strong, negative impact		1	Low High negative support for meeting the criteria, performs significantly worse than the base case
Does not apply		0	Criteria/measure does not apply to this option - ideally all criteria apply to all options.

MCA scoring

Hard adaptation for flooding

MCA Criteria	Optimise road grade and drainage to improved level of immunity (5% AEP)	Foamed bitumen stabilisation	Staged implementation of road grade and drainage improvements to increase level of immunity over asset life	Stabilising existing granular pavement with mix of cement to create durable and water-resistant road surface	Locate intelligent transportation system cabinets in locations outside of vulnerable areas and away from vegetation	Construction of flood barriers and levees along the road for protection from floodwaters	Soil stabilisation to improve resiliency of subgrade	Construction of viaduct through floodway
Efficacy of measure for risk mitigation	4	5	5	4	1	2	3	5
Uncertainty in design and construction	5	4	5	4	4	3	3	4
Recovery Time Objective (RTO)	3	5	3	3	3	2	2	2
Cost of construction	4	4	2	2	3	2	2	1
Maintenance costs and level of effort	4	5	4	4	3	2	4	4
Road service level impact during construction	3	4	3	3	4	2	3	1
Road service level impact during maintenance	3	4	3	3	3	2	4	3
Community impact during construction	3	3	2	3	3	2	3	1
Community impact during maintenance	3	3	3	3	3	2	3	2
Maladaptation	3	4	3	3	4	1	4	3
Level of net impact on the natural environment	2	3	2	2	2	1	3	2
Embodied carbon emissions impact	2	4	2	2	3	2	2	1

Assessment

MCA Rating	Colour	Score	Description
Strong positive		5	High positive support for meeting the criteria, performs better than the base case
Moderate positive		4	Medium positive support for meeting the criteria, performs better than the base case
No significant impact		3	Low positive support for meeting the criteria, performs the same, or similar to like the base case
Moderate, negative impact		2	No support for meeting the criteria, performs worse than the base case
Strong, negative impact		1	Low High negative support for meeting the criteria, performs significantly worse than the base case
Does not apply		0	Criteria/measure does not apply to this option - ideally all criteria apply to all options.

MCA ranking

Hard adaptation for flooding

MCA Criteria	MCA Weighting	Optimise road grade and drainage to improved level of immunity (5% AEP)	Foamed bitumen stabilisation	Staged implementation of road grade and drainage improvements to increase level of immunity over asset life	Stabilising existing granular pavement with mix of cement to create durable and water-resistant road surface	Locate intelligent transportation system cabinets in locations outside of vulnerable areas and away from vegetation	Construction of flood barriers and levees along the road for protection from floodwaters	Soil stabilisation to improve resiliency of subgrade	Construction of viaduct through floodway
Efficacy of measure for risk mitigation	16%	4	5	5	4	1	2	3	5
Uncertainty in design and construction	2%	5	4	5	4	4	3	3	4
Recovery Time Objective (RTO)	9%	3	5	3	3	3	2	2	2
Cost of construction	8%	4	4	2	2	3	2	2	1
Maintenance costs and level of effort	10%	4	5	4	4	3	2	4	4
Road service level impact during construction	6%	3	4	3	3	4	2	3	1
Road service level impact during maintenance	8%	3	4	3	3	3	2	4	3
Community impact during construction	6%	3	3	2	3	3	2	3	1
Community impact during maintenance	6%	3	3	3	3	3	2	3	2
Maladaptation	11%	3	4	3	3	4	1	4	3
Level of net impact on the natural environment	9%	2	3	2	2	2	1	3	2
Embodied carbon emissions impact	10%	2	4	2	2	3	2	2	1
TOTAL	**Total / 5**	**3.2**	**4.1**	**3.1**	**3.0**	**2.8**	**1.8**	**3.0**	**2.6**
	%	**64%**	**83%**	**63%**	**60%**	**56%**	**36%**	**60%**	**52%**

Assessment

MCA Rating	Colour	Score	Description
Strong positive		5	High positive support for meeting the criteria, performs better than the base case
Moderate positive		4	Medium positive support for meeting the criteria, performs better than the base case
No significant impact		3	Low positive support for meeting the criteria, performs the same, or similar to like the base case
Moderate, negative impact		2	No support for meeting the criteria, performs worse than the base case
Strong, negative impact		1	Low High negative support for meeting the criteria, performs significantly worse than the base case
Does not apply		0	Criteria/measure does not apply to this option - ideally all criteria apply to all options.

MCA scoring

Soft adaptation for flooding

MCA Criteria	Water Sensitive Urban Design	Slope stabilisation through vegetation	Geomorphological modification through earthworks/ material re-use.
Efficacy of measure for risk mitigation	4	1	2
Uncertainty in design and construction	3	3	2
Recovery Time Objective (RTO)	2	2	2
Cost of construction	4	3	2
Maintenance costs and level of effort	2	2	3
Road service level impact during construction	3	3	2
Road service level impact during maintenance	3	3	3
Community impact during construction	3	3	2
Community impact during maintenance	4	4	3
Maladaptation	5	4	3
Level of net impact on the natural environment	5	4	2
Embodied carbon emissions impact	5	5	2

Assessment

MCA Rating	Colour	Score	Description
Strong positive		5	High positive support for meeting the criteria, performs better than the base case
Moderate positive		4	Medium positive support for meeting the criteria, performs better than the base case
No significant impact		3	Low positive support for meeting the criteria, performs the same, or similar to like the base case
Moderate, negative impact		2	No support for meeting the criteria, performs worse than the base case
Strong, negative impact		1	Low High negative support for meeting the criteria, performs significantly worse than the base case
Does not apply		0	Criteria/measure does not apply to this option - ideally all criteria apply to all options.

MCA ranking

Soft adaptation for flooding

MCA Criteria	MCA Weighting	Water Sensitive Urban Design	Slope stabilisation through vegetation	Geomorphological modification through earthworks/material re-use.
Efficacy of measure for risk mitigation	16%	4	1	2
Uncertainty in design and construction	2%	3	3	2
Recovery Time Objective (RTO)	9%	2	2	2
Cost of construction	8%	4	3	2
Maintenance costs and level of effort	10%	2	2	3
Road service level impact during construction	6%	3	3	2
Road service level impact during maintenance	8%	3	3	3
Community impact during construction	6%	3	3	2
Community impact during maintenance	6%	4	4	3
Maladaptation	11%	5	4	3
Level of net impact on the natural environment	9%	5	4	2
Embodied carbon emissions impact	10%	5	5	2
TOTAL	**Total / 5**	**3.7**	**3.0**	**2.3**
	%	**74%**	**59%**	**47%**

Assessment

MCA Rating	Colour	Score	Description
Strong positive		5	High positive support for meeting the criteria, performs better than the base case
Moderate positive		4	Medium positive support for meeting the criteria, performs better than the base case
No significant impact		3	Low positive support for meeting the criteria, performs the same, or similar to like the base case
Moderate, negative impact		2	No support for meeting the criteria, performs worse than the base case
Strong, negative impact		1	Low High negative support for meeting the criteria, performs significantly worse than the base case
Does not apply		0	Criteria/measure does not apply to this option - ideally all criteria apply to all options.

MCA scoring

Maintenance adaptation for flooding

MCA Criteria	**Increased inspection frequency for early intervention and preventative maintenance**	**Increased programmed rehabilitation**	**Automated condition assessments using machine learning**	**Develop a system to track weather-related trends and costs over time, such as through designated "weather-related" charge codes**
Efficacy of measure for risk mitigation	4	4	1	1
Uncertainty in design and construction	5	5	2	2
Recovery Time Objective (RTO)	5	4	3	3
Cost of construction	4	3	3	3
Maintenance costs and level of effort	4	2	2	2
Road service level impact during construction	4	4	3	3
Road service level impact during maintenance	4	4	4	3
Community impact during construction	3	3	3	3
Community impact during maintenance	4	4	4	3
Maladaptation	4	4	4	3
Level of net impact on the natural environment	3	3	2	3
Embodied carbon emissions impact	4	4	3	3

Assessment

MCA Rating	**Colour**	**Score**	**Description**
Strong positive		5	High positive support for meeting the criteria, performs better than the base case
Moderate positive		4	Medium positive support for meeting the criteria, performs better than the base case
No significant impact		3	Low positive support for meeting the criteria, performs the same, or similar to like the base case
Moderate, negative impact		2	No support for meeting the criteria, performs worse than the base case
Strong, negative impact		1	Low High negative support for meeting the criteria, performs significantly worse than the base case
Does not apply		0	Criteria/measure does not apply to this option - ideally all criteria apply to all options.

MCA ranking

Maintenance adaptation for flooding

MCA Criteria	MCA Weighting	Increased inspection frequency for early intervention and preventative maintenance	Increased programmed rehabilitation	Automated condition assessments using machine learning	Develop a system to track weather-related trends and costs over time, such as through designated "weather-related" charge codes
Efficacy of measure for risk mitigation	16%	4	4	1	1
Uncertainty in design and construction	2%	5	5	2	2
Recovery Time Objective (RTO)	9%	5	4	3	3
Cost of construction	8%	4	3	3	3
Maintenance costs and level of effort	10%	4	2	2	2
Road service level impact during construction	6%	4	4	3	3
Road service level impact during maintenance	8%	4	4	4	3
Community impact during construction	6%	3	3	3	3
Community impact during maintenance	6%	4	4	4	3
Maladaptation	11%	4	4	4	3
Level of net impact on the natural environment	9%	3	3	2	3
Embodied carbon emissions impact	10%	4	4	3	3
TOTAL	Total / 5	4.0	3.6	2.7	2.6
	%	79%	72%	54%	51%

Assessment

MCA Rating	Colour	Score	Description
Strong positive		5	High positive support for meeting the criteria, performs better than the base case
Moderate positive		4	Medium positive support for meeting the criteria, performs better than the base case
No significant impact		3	Low positive support for meeting the criteria, performs the same, or similar to like the base case
Moderate, negative impact		2	No support for meeting the criteria, performs worse than the base case
Strong, negative impact		1	Low High negative support for meeting the criteria, performs significantly worse than the base case
Does not apply		0	Criteria/measure does not apply to this option - ideally all criteria apply to all options.

MCA scoring

Hazard management adaptation for flooding

MCA Criteria	Risk management including early warning system, heavy load limits, and temporary rerouting	Road decommissioning and permanent rerouting	Local provision of concrete causeways to increase trafficability, road availability and access for emergency vehicles and evacuation during and after extreme events
Efficacy of measure for risk mitigation	4	4	2
Uncertainty in design and construction	5	2	2
Recovery Time Objective (RTO)	2	2	2
Cost of construction	4	1	1
Maintenance costs and level of effort	2	3	2
Road service level impact during construction	3	2	2
Road service level impact during maintenance	2	3	2
Community impact during construction	3	1	2
Community impact during maintenance	4	3	2
Maladaptation	4	1	1
Level of net impact on the natural environment	3	2	2
Embodied carbon emissions impact	3	2	1

Assessment

MCA Rating	Colour	Score	Description
Strong positive		5	High positive support for meeting the criteria, performs better than the base case
Moderate positive		4	Medium positive support for meeting the criteria, performs better than the base case
No significant impact		3	Low positive support for meeting the criteria, performs the same, or similar to like the base case
Moderate, negative impact		2	No support for meeting the criteria, performs worse than the base case
Strong, negative impact		1	Low High negative support for meeting the criteria, performs significantly worse than the base case
Does not apply		0	Criteria/measure does not apply to this option - ideally all criteria apply to all options.

MCA ranking

Hazard management adaptation for flooding

MCA Criteria	MCA Weighting	Risk management including early warning system, heavy load limits, and temporary rerouting	Road decommissioning and permanent rerouting	Local provision of concrete causeways to increase trafficability, road availability and access for emergency vehicles and evacuation during and after extreme events
Efficacy of measure for risk mitigation	16%	4	4	2
Uncertainty in design and construction	2%	5	2	2
Recovery Time Objective (RTO)	9%	2	2	2
Cost of construction	8%	4	1	1
Maintenance costs and level of effort	10%	2	3	2
Road service level impact during construction	6%	3	2	2
Road service level impact during maintenance	8%	2	3	2
Community impact during construction	6%	3	1	2
Community impact during maintenance	6%	4	3	2
Maladaptation	11%	4	1	1
Level of net impact on the natural environment	9%	3	2	2
Embodied carbon emissions impact	10%	3	2	1
TOTAL	**Total / 5**	**3.2**	**2.3**	**1.7**
	%	**63%**	**46%**	**34%**

Assessment

MCA Rating	Colour	Score	Description
Strong positive		5	High positive support for meeting the criteria, performs better than the base case
Moderate positive		4	Medium positive support for meeting the criteria, performs better than the base case
No significant impact		3	Low positive support for meeting the criteria, performs the same, or similar to like the base case
Moderate, negative impact		2	No support for meeting the criteria, performs worse than the base case
Strong, negative impact		1	Low High negative support for meeting the criteria, performs significantly worse than the base case
Does not apply		0	Criteria/measure does not apply to this option - ideally all criteria apply to all options.

MCA results for shortlisted adaptation measures for bushfire

Summary of shortlisted adaptation measures for bushfire and landslides

MCA Criteria	*Hazard*	Bushfire (and landslide)						
	Adaptation type	Hard	Soft (nature-based)		Maintenance			Hazard management
	MCA Weighting	Slope remediation (flexible barriers) of high and very high risk slopes	Fire-resistant planting including species selection and spatial layout	Fire break (vegetation clearance zone)	Post-fire responsive drainage clearing	Increased programmed drainage clearing and vegetation management	Post-fire disaster response - erosion protection and slope stabilisation	Early warning systems
Efficacy of measure for risk mitigation	16%	5	4	4	4	4	4	3
Uncertainty in design and construction	2%	4	4	4	5	4	4	4
Recovery Time Objective (RTO)	9%	5	3	4	4	3	4	4
Cost of construction	8%	2	4	3	4	2	4	4
Maintenance costs and level of effort	10%	2	2	2	3	2	3	3
Road service level impact during construction	6%	2	4	2	4	3	4	3
Road service level impact during maintenance	8%	5	3	2	3	4	3	3
Community impact during construction	6%	2	4	2	3	3	3	5
Community impact during maintenance	6%	4	3	3	3	3	3	5
Maladaptation	11%	4	4	2	4	4	3	5
Level of net impact on the natural environment	9%	3	4	2	3	3	3	3
Embodied carbon emissions impact	10%	2	4	3	3	2	3	3
TOTAL	**Total / 5**	**3.5**	**3.6**	**2.8**	**3.5**	**3.1**	**3.4**	**3.6**
	%	**69%**	**72%**	**56%**	**71%**	**62%**	**68%**	**73%**

MCA Rating	Colour	Score	Description
Strong positive		5	High positive support for meeting the criteria, performs better than the base case
Moderate positive		4	Medium positive support for meeting the criteria, performs better than the base case
No significant impact		3	Low positive support for meeting the criteria, performs the same, or similar to like the base
Moderate, negative impact		2	No support for meeting the criteria, performs worse than the base case
Strong, negative impact		1	Low High negative support for meeting the criteria, performs significantly worse than the
Does not apply		0	Criteria/measure does not apply to this option - ideally all criteria apply to all options.

MCA scoring

Hard adaptation for bushfire and landslide

MCA Criteria	**Slope remediation (flexible barriers) of high and very high risk slopes**	**Locate critical infrastructure outside of known low areas and/or risk areas**	**Design fire-resistance elements including guardrails and fencing**
Efficacy of measure for risk mitigation	5	1	2
Uncertainty in design and construction	4	4	4
Recovery Time Objective (RTO)	5	3	4
Cost of construction	2	3	3
Maintenance costs and level of effort	2	3	3
Road service level impact during construction	2	3	3
Road service level impact during maintenance	5	4	4
Community impact during construction	2	3	3
Community impact during maintenance	4	3	3
Maladaptation	4	3	3
Level of net impact on the natural environment	3	3	3
Embodied carbon emissions impact	2	3	3

Assessment

MCA Rating	**Colour**	**Score**	**Description**
Strong positive		5	High positive support for meeting the criteria, performs better than the base case
Moderate positive		4	Medium positive support for meeting the criteria, performs better than the base case
No significant impact		3	Low positive support for meeting the criteria, performs the same, or similar to like the base case
Moderate, negative impact		2	No support for meeting the criteria, performs worse than the base case
Strong, negative impact		1	Low High negative support for meeting the criteria, performs significantly worse than the base
Does not apply		0	Criteria/measure does not apply to this option - ideally all criteria apply to all options.

MCA ranking

Hard adaptation for bushfire and landslide

MCA Criteria	MCA Weighting	Slope remediation (flexible barriers) of high and very high risk slopes	Locate critical infrastructure outside of known low areas and/or risk areas	Design fire-resistance elements including guardrails and fencing
Efficacy of measure for risk mitigation	16%	5	1	2
Uncertainty in design and construction	2%	4	4	4
Recovery Time Objective (RTO)	9%	5	3	4
Cost of construction	8%	2	3	3
Maintenance costs and level of effort	10%	2	3	3
Road service level impact during construction	6%	2	3	3
Road service level impact during maintenance	8%	5	4	4
Community impact during construction	6%	2	3	3
Community impact during maintenance	6%	4	3	3
Maladaptation	11%	4	3	3
Level of net impact on the natural environment	9%	3	3	3
Embodied carbon emissions impact	10%	2	3	3
TOTAL	**Total / 5**	**3.5**	**2.8**	**3.0**
	%	**69%**	**56%**	**61%**

Assessment

MCA Rating	Colour	Score	Description
Strong positive		5	High positive support for meeting the criteria, performs better than the base case
Moderate positive		4	Medium positive support for meeting the criteria, performs better than the base case
No significant impact		3	Low positive support for meeting the criteria, performs the same, or similar to like the base case
Moderate, negative impact		2	No support for meeting the criteria, performs worse than the base case
Strong, negative impact		1	Low High negative support for meeting the criteria, performs significantly worse than the base
Does not apply		0	Criteria/measure does not apply to this option - ideally all criteria apply to all options.

MCA scoring

Soft adaptation for bushfire and landslide

MCA Criteria	Fire-resistant planting including species selection and spatial layout	Fire break (vegetation clearance zone)	Geomorphological modification through earthworks/material re-use.
Efficacy of measure for risk mitigation	4	4	2
Uncertainty in design and construction	4	4	3
Recovery Time Objective (RTO)	3	4	2
Cost of construction	4	3	1
Maintenance costs and level of effort	2	2	3
Road service level impact during construction	4	2	2
Road service level impact during maintenance	3	2	2
Community impact during construction	4	2	2
Community impact during maintenance	3	3	2
Maladaptation	4	2	2
Level of net impact on the natural environment	4	2	2
Embodied carbon emissions impact	4	3	1

Assessment

MCA Rating	Colour	Score	Description
Strong positive		5	High positive support for meeting the criteria, performs better than the base case
Moderate positive		4	Medium positive support for meeting the criteria, performs better than the base case
No significant impact		3	Low positive support for meeting the criteria, performs the same, or similar to like the base case
Moderate, negative impact		2	No support for meeting the criteria, performs worse than the base case
Strong, negative impact		1	Low High negative support for meeting the criteria, performs significantly worse than the base case
Does not apply		0	Criteria/measure does not apply to this option - ideally all criteria apply to all options.

MCA ranking

Soft adaptation for bushfire and landslide

MCA Criteria	MCA Weighting	Fire-resistant planting including species selection and spatial layout	Fire break (vegetation clearance zone)	Geomorphological modification through earthworks/material re-use.
Efficacy of measure for risk mitigation	16%	4	4	2
Uncertainty in design and construction	2%	4	4	3
Recovery Time Objective (RTO)	9%	3	4	2
Cost of construction	8%	4	3	1
Maintenance costs and level of effort	10%	2	2	3
Road service level impact during construction	6%	4	2	2
Road service level impact during maintenance	8%	3	2	2
Community impact during construction	6%	4	2	2
Community impact during maintenance	6%	3	3	2
Maladaptation	11%	4	2	2
Level of net impact on the natural environment	9%	4	2	2
Embodied carbon emissions impact	10%	4	3	1
TOTAL	**Total / 5**	**3.6**	**2.8**	**1.9**
	%	**72%**	**56%**	**39%**

Assessment

MCA Rating	Colour	Score	Description
Strong positive		5	High positive support for meeting the criteria, performs better than the base case
Moderate positive		4	Medium positive support for meeting the criteria, performs better than the base case
No significant impact		3	Low positive support for meeting the criteria, performs the same, or similar to like the base case
Moderate, negative impact		2	No support for meeting the criteria, performs worse than the base case
Strong, negative impact		1	Low High negative support for meeting the criteria, performs significantly worse than the base case
Does not apply		0	Criteria/measure does not apply to this option - ideally all criteria apply to all options.

MCA scoring

Maintenance adaptation for bushfire and landslide

MCA Criteria	Post-fire responsive drainage clearing	Increased programmed drainage clearing and vegetation management	Post-fire disaster response - erosion protection and slope stabilisation	Automated conditions assessments using machine learning	Preventative maintenance of vulnerable roads by varying reseal intervals
Efficacy of measure for risk mitigation	4	4	4	2	1
Uncertainty in design and construction	5	4	4	3	4
Recovery Time Objective (RTO)	4	3	4	3	3
Cost of construction	4	2	4	3	2
Maintenance costs and level of effort	3	2	3	2	2
Road service level impact during construction	4	3	4	3	3
Road service level impact during maintenance	3	4	3	4	3
Community impact during construction	3	3	3	3	3
Community impact during maintenance	3	3	3	4	2
Maladaptation	4	4	3	4	3
Level of net impact on the natural environment	3	3	3	3	3
Embodied carbon emissions impact	3	2	3	3	2

Assessment

MCA Rating	Colour	Score	Description
Strong positive		5	High positive support for meeting the criteria, performs better than the base case
Moderate positive		4	Medium positive support for meeting the criteria, performs better than the base case
No significant impact		3	Low positive support for meeting the criteria, performs the same, or similar to like the base case
Moderate, negative impact		2	No support for meeting the criteria, performs worse than the base case
Strong, negative impact		1	Low High negative support for meeting the criteria, performs significantly worse than the base case
Does not apply		0	Criteria/measure does not apply to this option - ideally all criteria apply to all options.

MCA ranking

Maintenance adaptation for bushfire and landslide

MCA Criteria	MCA Weighting	Post-fire responsive drainage clearing	Increased programmed drainage clearing and vegetation management	Post-fire disaster response - erosion protection and slope stabilisation	Automated conditions assessments using machine learning	Preventative maintenance of vulnerable roads by varying reseal intervals
Efficacy of measure for risk mitigation	16%	4	4	4	1	1
Uncertainty in design and construction	2%	5	4	4	3	4
Recovery Time Objective (RTO)	9%	4	3	4	3	3
Cost of construction	8%	4	2	4	3	2
Maintenance costs and level of effort	10%	3	2	3	2	2
Road service level impact during construction	6%	4	3	4	3	3
Road service level impact during maintenance	8%	3	4	3	4	3
Community impact during construction	6%	3	3	3	3	3
Community impact during maintenance	6%	3	3	3	4	2
Maladaptation	11%	4	4	3	4	3
Level of net impact on the natural environment	9%	3	3	3	3	3
Embodied carbon emissions impact	10%	3	2	3	3	2
TOTAL	**Total / 5**	**3.5**	**3.1**	**3.4**	**2.8**	**2.4**
	%	**71%**	**62%**	**68%**	**57%**	**47%**

Assessment

MCA Rating	Colour	Score	Description
Strong positive		5	High positive support for meeting the criteria, performs better than the base case
Moderate positive		4	Medium positive support for meeting the criteria, performs better than the base case
No significant impact		3	Low positive support for meeting the criteria, performs the same, or similar to like the base case
Moderate, negative impact		2	No support for meeting the criteria, performs worse than the base case
Strong, negative impact		1	Low High negative support for meeting the criteria, performs significantly worse than the base case
Does not apply		0	Criteria/measure does not apply to this option - ideally all criteria apply to all options.

MCA scoring

Hazard management adaptation for bushfire and landslide

MCA Criteria	Risk management plan	Managed retreat/ temporary road closure	Provision of alternative routes
Efficacy of measure for risk mitigation	3	5	4
Uncertainty in design and construction	4	2	2
Recovery Time Objective (RTO)	4	2	1
Cost of construction	4	2	1
Maintenance costs and level of effort	3	2	2
Road service level impact during construction	3	1	1
Road service level impact during maintenance	3	1	2
Community impact during construction	5	1	1
Community impact during maintenance	5	1	2
Maladaptation	5	4	4
Level of net impact on the natural environment	3	3	2
Embodied carbon emissions impact	3	3	1

Assessment

MCA Rating	Colour	Score	Description
Strong positive		5	High positive support for meeting the criteria, performs better than the base case
Moderate positive		4	Medium positive support for meeting the criteria, performs better than the base case
No significant impact		3	Low positive support for meeting the criteria, performs the same, or similar to like the base case
Moderate, negative impact		2	No support for meeting the criteria, performs worse than the base case
Strong, negative impact		1	Low High negative support for meeting the criteria, performs significantly worse than the base case
Does not apply		0	Criteria/measure does not apply to this option - ideally all criteria apply to all options.

MCA ranking

Hazard management adaptation for bushfire and landslide

MCA Criteria	MCA Weighting	Risk management plan	Managed retreat/ temporary road closure	Provision of alternative routes
Efficacy of measure for risk mitigation	16%	3	5	4
Uncertainty in design and construction	2%	4	2	2
Recovery Time Objective (RTO)	9%	4	2	1
Cost of construction	8%	4	2	1
Maintenance costs and level of effort	10%	3	2	2
Road service level impact during construction	6%	3	1	1
Road service level impact during maintenance	8%	3	1	2
Community impact during construction	6%	5	1	1
Community impact during maintenance	6%	5	1	2
Maladaptation	11%	5	4	4
Level of net impact on the natural environment	9%	3	3	2
Embodied carbon emissions impact	10%	3	3	1
TOTAL	**Total / 5**	**3.6**	**2.6**	**2.2**
	%	**73%**	**53%**	**43%**

Assessment

MCA Rating	Colour	Score	Description
Strong positive		5	High positive support for meeting the criteria, performs better than the base case
Moderate positive		4	Medium positive support for meeting the criteria, performs better than the base case
No significant impact		3	Low positive support for meeting the criteria, performs the same, or similar to like the base case
Moderate, negative impact		2	No support for meeting the criteria, performs worse than the base case
Strong, negative impact		1	Low High negative support for meeting the criteria, performs significantly worse than the base case
Does not apply		0	Criteria/measure does not apply to this option - ideally all criteria apply to all options.

C.1 Risk assessment sample calculation

C.1.1.1 Direct risks

Direct risk is calculated in terms of average annual loss (AAL) and average annual downtime (AAD), where risk is a product of hazard, exposure, and vulnerability.

A sample calculation of direct risks in terms of AAL and AAD is presented in Table 7-5 for a flood hazard on a 500m stretch of road. This sample calculation is indicative only, and is based on the following assumptions:

- The assumed repair cost for the road is $10,000 per meter in length.
- The assumed vulnerability curve is based on the sample data provided in Table 7-6.
- The assumed downtime curve is based on the sample data provided in Table 7-7.

Table 7-5: Sample calculation of AAL and AAD

Hazard (AEP)	Exposure		Vulnerability	Consequence			Average annual contribution				AAL ($)	AAD (days)
	Depth (m)	Length (m)	Damage (%)	Cost ($)		Downtime (days)	AAL contribution ($)		AAD contribution (days)			
			Based on vulnerability curve at depth level	% damage multiplied by length, multiplied by repair cost per meter		Based on downtime curve at % damage level	Difference in likelihood of occurrence (AEP) multiplied by average costs of consecutive flood events		Difference in likelihood of occurrence (AEP) multiplied by average downtime for consecutive flood events		Sum of AAL contributions	Sum of AAD contributions
20%	0.00	100	0	0% * 100m * $10,000	0	0	(0+20,000) / 2 * (20%-10%)	1000	(0+0) / 2 * (20%-10%)	0	12025	0.2725
10%	0.01	200	1	1% * 200m * $10,000	20000	0	(20,000+150,000)/2 * (10%-1%)	7650	(0+1) / 2 * (10%-1%)	0.045		
1%	0.10	100	15	15% * 100m * $10,000	150000	1	(150,000+400,000) / 2 * (1%-0.5%)	1375	(1+30) / 2 * (1%-0.5%)	0.0775		
0.5%	0.30	100	40	40% * 100m * $10,000	400000	30	(400,000) * (0.5%)	2000	(30) * (0.5%)	0.15		

Table 7-6: Vulnerability curve for sample calculation

Vulnerability curve	
Depth	**% Damage**
0.00	0
0.01	1
0.05	5
0.10	15
0.30	40
0.50	50

Table 7-7: Downtime curve for sample calculation

Downtime	
% or greater Damage	**Downtime (days)**
0	0
10	1
30	3
50	30

C.1.1.2 Indirect and intangible risks

The process listed below can be applied to the base case and the adaptation options. For the base case the indirect and intangible costs utilise the vulnerability and downtime curves to estimate bushfire and flood cost effects. Adaptation options cause the vulnerability and downtime curve to shift, altering the indirect and intangible costs incurred.

Road trauma costs

The first step is to calculate the cost of injuries and fatalities associated with road use in the region. This study used VicRoads(2016) and AusRoads (2019) road trauma data for metropolitan Melbourne and regional Victoria[5]. The statistical probability of an injury, serious injury or fatality should be obtained from road trauma data from the region. Let δ be the probability of an incident per kilometre, with a sample of potential probabilities provided in Table 7-8.

Table 7-8: Sample road trauma probabilities

Daily road trauma probability per vehicle kilometre travelled in rural Victoria	
Example	Daily probability of an incidents per kilometre (%) (δ)
Road trauma injury	0.000000008
Road trauma serious injury	0.000000107
Road fatality	0.000000171

Source: VicRoads (2016), AusRoads (2019)

The probability of a daily road trauma incidents per vehicle kilometre travelled (example in Table 7-8) should be used to vary the cost of a fatality, injury or serious injury with an example of the costs in Table 7-9 below.

Table 7-9: Sample road trauma cost

Daily road trauma probability cost per incident travelled in rural Victoria	
Example	Cost per incident ($) (Λ)
Road trauma injury	2,783,128
Road trauma serious injury	627,601
Road fatality	24,547

Source: VicRoads (2016), AusRoads (2019)

Let $\boldsymbol{\lambda}$ be vector of trauma costs per incident. Combining Tables 7-6 and 7-7 the cost of a road trauma per vehicle kilometre, RT_1, where there are n different road traumas being evaluated. The individual cost per road trauma type can be calculated.

$$RT_1 = \delta\boldsymbol{\lambda}$$
$$RT = \sum RT_1^n$$

[5] Aust Roads (2019). Guide to Road Safety Part 5: Road Safety for Regional and Remote Areas. Available at: https://austroads.com.au/publications/road-safety/agrs05-19/media/AGRS05-19_Guide_to_Road_Safety_Part_5_Road_Safety_for_Regional_and_Remote_Areas.pdf

Vic Roads (2016). Victorian Road Trauma Analysis of Fatalities and Serious Injuries. Available at: https://www.vicroads.vic.gov.au/-/media/files/documents/safety-and-road-rules/victorianroadsafetytrauma2015.ashx

Calculating indirect and intangible costs per kilometre travelled

The road trauma costs need to be incorporated into the wider pool of indirect and intangible costs associated with a flooding or bushfire event. Once all indirect and intangible costs have been identified, (See ATAP, 2016 and ATAP, 2021) the net costs need to be calculated. Costs are estimated on a per kilometre basis. A range of costs are incurred based on the road closure and the duration of the diversion, to calculate the total costs each individual cost needs to be estimated before the costs are combined. Costs based on the diversion's distance include vehicle wear and tear, biodiversity, vehicle emissions and climate impacts, see Table 7-10 for a sample of potential costs.

Table 7-10: Indirect and intangible example costs per kilometre for sample calculation

Daily indirect and intangible cost per kilometre examples for a medium passenger vehicle (2023 AUD)	
Example	**Cost ($/km) (x)**
Air pollution	9.73
Climate change	14.62
WTT emissions	3.72
Noise	7.63
Soil and water	3.28
Nature and Landscapes	1.73
Urban effects	5.76
Biodiversity	0.79

Source: ATAP, 2021

The additional travel distance for a single vehicle needs to be determined to calculate the costs. Let $\boldsymbol{x} \in \boldsymbol{X} \subset \mathbb{R}_+^{\boldsymbol{n_y}}$ vector of road indirect and intangible costs (Table 7-8) per kilometre that are incurred for each additional kilometre travelled because of a road closure due to flooding or bushfire impacts. Let $\boldsymbol{km_1}$ be the original distance travelled along the road before its closure and $\boldsymbol{km_2}$ represent the distance travelled with the diversion due to a road closure. Let $\boldsymbol{zc}$ be the additional cost per kilometre. The individual cost incurred due to a diversion is:

$$\boldsymbol{zc} = \boldsymbol{x} \cdot (km_2 - km_1)$$

This process should be repeated for all identified costs and then summed using the days downtime (denoted below using *dd)* to calculate the costs over the entire period the road is closed using the number of days from Table 7-8. The total indirect and intangible costs associated with a flood or bushfire road closure is:

$$Z = \sum_{i=1}^{y} (zc \times dd)$$

One of the costs incurred with the diversion is the additional time it takes to travel along the diversionary route. This cost is not included in the cost equation above. To calculate the travel time the distance, average speed limit and average hourly wage is required. The time cost of the vehicle occupant travelling the diversion is calculated using the average speed limit of the roads the diversionary route uses in km/h (e.g. 100 km/h, 60 km/h). Let π be the average speed limit in km/h on the diversionary route and l be the wage cost per hour[6]. Simplifying assumptions made are that there are no traffic flow impediments, all vehicles travel at the speed limit, and take the same time to complete the journey, regardless of vehicle type. The cost for a single vehicle travelling along the diversion (β) is:

$$\beta = \frac{(km_2 - km_1)}{\pi} \cdot l$$

Using the average number of vehicles that travels along the road daily, μ, the time cost for road users being diverted can be added together and calculated, where L is the total time cost for all vehicles travelling on the road daily.

$$L = dd(\mu\beta)$$

The total indirect and intangible costs to road users and the wider community of a flood or bushfire event is calculated by combining the additional travel time cost (L), the total diversion costs (Z).

$$Total\ indirect\ and\ intangible\ cost = L + Z$$

[6] Wage costs can be sourced from the relevant wages data for your jurisdiction, for example the Australian Bureau of Statistics Average Weekly Earnings, (2022). Available at: https://www.abs.gov.au/statistics/labour/earnings-and-working-conditions/average-weekly-earnings-australia/nov-2022