INFRASTRUCTURE VICTORIA

April 2024

Methodology

Weathering the storm: adapting Victoria's infrastructure to climate change

About us

Infrastructure Victoria is an independent advisory body with 3 functions:

- preparing a 30-year infrastructure strategy for Victoria, which we review and update every 3 to 5 years
- advising the government on specific infrastructure matters
- publishing research on infrastructure-related issues.

Infrastructure Victoria also helps government departments and agencies develop sectoral infrastructure plans.

Infrastructure Victoria aims to take a long-term, evidence-based view of infrastructure planning, and we inform community discussion about infrastructure provision.

Infrastructure Victoria does not directly oversee or fund infrastructure projects.

Acknowledgement

Infrastructure Victoria acknowledges the Traditional Owners of Country in Victoria and pays respect to their Elders past and present, as well as Elders of other First Peoples' communities. We recognise that Victoria's infrastructure is built on land that has been managed by Aboriginal people for millennia.

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Summary

This report sets out the methods Infrastructure Victoria used to assess climate risks to infrastructure in Victoria. It presents evidence behind our report *Weathering the storm: adapting Victoria's infrastructure to climate change*. Victorian Government infrastructure managers can learn from, apply or modify these methods to help assess climate risks to infrastructure and identify sensible adaptation measures to reduce them.

In our report *Weathering the storm: adapting Victoria's infrastructure to climate change*, we present risks to Victoria's infrastructure, analyse barriers to adapting to them, and recommend changes for the Victorian Government to choose and deliver better adaptation responses. To do this effectively, government infrastructure managers can assess climate change risks and vulnerabilities more comprehensively and identify adaptation options. They can then select the most prudent options to prioritise.

But infrastructure managers told us that the tools they use now to manage infrastructure do not allow this type of analysis. This report documents the steps we used. It shows that infrastructure managers can use new tools, and adapt existing ones, to complete these tasks successfully.

We conducted a high-level, statewide risk assessment of certain types of Victorian infrastructure. We then selected 2 types of infrastructure for a cost-benefit analysis. We did this for a hypothetical local scenario for roads and electricity distribution networks. We show that infrastructure managers can adapt a cost-benefit analysis and use it to carefully select adaptation measures. These analyses show which adaptation measures deliver positive economic returns.

In some instances, we had to modify existing tools, or re-interpret available data, to make them useful. For example, sometimes analysts cannot directly apply past climate data, or available climate projections, to current infrastructure assessment tools. We modified data sources or made new estimates to overcome these barriers, such as by estimating probabilities based on existing data. We also added new steps that made the analysis more comprehensive than the current Victorian Government investment guidance requirements.

This report documents several methods that traditional infrastructure assessment does not include:

- We reinterpreted available hazard maps to account for future climate change. For example, we flagged infrastructure close to flood overlays as at risk of flooding, because future rainfall events might be more intense and inundate more land than is now estimated.
- We applied climate projections to estimate the probability of extreme weather events in the future. For example, we estimated the probability of a strong wind event in a particular year is 19% based on the climate projections. This is higher than historical observations.
- We assessed potential adaptation measures to check for maladaptation. For example, we identified that restoring vegetation alongside roadsides can help stabilise soil to prevent landslides. But it also increases the risk that bushfire will threaten road users in some areas.
- We examined adaptation pathways for infrastructure. For example, we looked at options to upgrade electricity distribution lines more slowly, as they reached their end of life. This might reduce the cost of upgrading them.
- We considered the cascading costs of infrastructure failure when assessing adaptation benefits. For example, we considered the costs of flow-on effects of road closures for the whole community, not only the immediate costs imposed on users of the affected roads.
- We included the cost of embodied carbon emissions when calculating the cost of an infrastructure adaptation measure.

Researchers and governments are still developing methods to assess climate risk, vulnerability and adaptations for infrastructure. Our research extends and applies these developing methods. We hope governments and other researchers can apply and further develop our methods. This can help governments to better prepare infrastructure for the impacts of climate change and select sensible adaptation actions to protect it. By doing so, governments can avoid some of the worst impacts of climate change and protect their citizens and economies from its most harmful effects.

Methodology

In August 2021, Infrastructure Victoria recommended the Victorian Government strategically review the consequences for infrastructure from a changing climate. At that time, Victoria had no current and comprehensive assessment of the climate risks to infrastructure.[1] Later that year, the Victorian Government supported the intent of that recommendation. The government said it was finalising adaptation action plans and advised that they would consider investing more in future budgets.[2]

Infrastructure Victoria started this research project to examine the effects and consequences of climate change on Victoria's infrastructure and produce more evidence that can help the government decide how to invest prudently and strategically to adapt its infrastructure. We also hope the Victorian Government can use this research when revising its adaptation action plans.

Our project objectives were to:

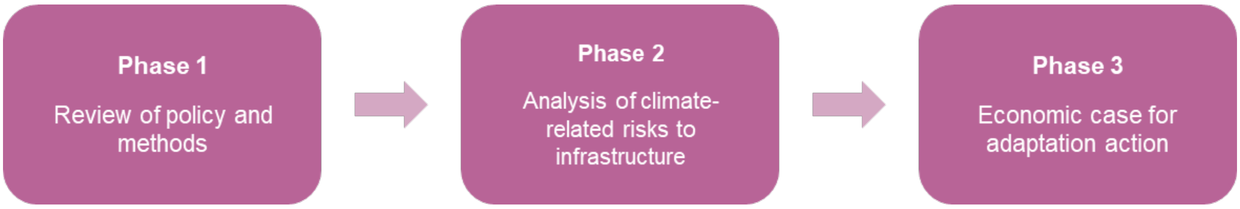
- document the state of climate change adaptation action in Victoria, including reviewing the adaptation action plans for actions relating to infrastructure
- identify some major risks that climate change poses to Victorian infrastructure
- identify a selection of adaptation actions for both direct and indirect risks
- assess the return on investment for taking adaptation action using cost-benefit analysis.

From this, we developed 2 primary research questions:

- How will a changing climate affect Victoria's infrastructure?
- What other measures can the Victorian Government implement to build on existing adaptation actions and better adapt infrastructure to a changing climate?

We designed the project in 3 phases (see Figure 1). We used different methods in each stage, including qualitative and quantitative analysis, technical advice and input from experts, practitioners and stakeholders.

Figure 1: Project phases



In the first phase, we reviewed research, policies and literature about climate adaptation, and engaged with relevant stakeholders in the Victorian Government. We decided to broadly examine infrastructure associated with transport, utilities and the built environment. This included most infrastructure the Victorian Government owns, manages, or regulates. In this phase, we identified 45 climate risks to infrastructure.

In the second phase, we used that research and consultation to choose 3 more specific climate risks to infrastructure. We conducted a more detailed risk assessment of these 3 risks. They were:

- damage to, or degradation of electricity transmission and distribution assets caused by extreme weather events
- damage to public hospital building structures caused by extreme weather events
- damage to roads and disruption of access caused by extreme weather events.

In the third phase, we conducted cost-benefit analyses on adaptation measures in 3 even more specific circumstances. We developed detailed hypothetical locations that had specific infrastructure, which was exposed to a specific climate risk. We identified a long list of possible measures that could adapt the infrastructure to help mitigate that risk. We selected the most promising adaptation measures to then assess using cost-benefit analysis. From this detailed analysis, we demonstrated the economic value of adaptation measures for the following climate risks:

- damage to, or degradation of electricity distribution assets caused by extreme wind
- damage to roads caused by flooding
- disruption of access caused by bushfires and subsequent landslide risk for roads.

We gained many insights into the challenges of assessing climate risks, vulnerability and adaptation measures. These include:

- infrastructure failure in one sector can have cascading impacts, and cause failures in other sectors
- data on climate risk, vulnerability, and impacts can be unavailable, incomplete, not collated, or not comparable
- available general guidance for assessing climate risk, vulnerability and adaptation is not compulsory and might not apply to assessing infrastructure specifically
- some adaptation measures might need cooperation between infrastructure managers to execute.

The rest of the report sets out our methods and findings in more detail.

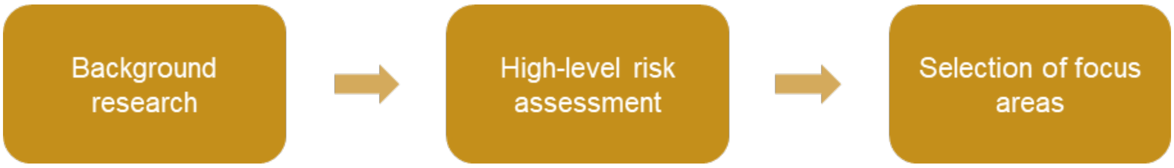
Phase 1:
Review of policy and methods

We examined Victorian Government climate adaptation policies, and collated data and research on the climate change risks to Victoria's infrastructure, to different infrastructure types and in different Victorian regions. We used this to document the climate change risks to infrastructure.

We began by reviewing relevant data and information. This helped us develop a basic, first-pass, Victoria-wide climate change risk assessment for infrastructure. This included reviewing the most recent publicly available infrastructure and climate change risk assessment for Victoria. That was published in 2007.[3]

Figure 2 summarises the methodology for phase 1. The rest of this section provides more detail on each step.

Figure 2: Phase 1 methods



Background research

We began by reviewing relevant literature. We documented new or emerging adaptation knowledge and government policy initiatives. We used this to help develop the later phases of our reports.

We examined peer-reviewed papers and research by international, national, state and local governments and businesses. We also scanned the policy literature to identify relevant policy tools for achieving infrastructure adaptation. This included the Victorian Government's 7 adaptation action plans.

High-level risk assessment

We engaged AECOM to undertake a high-level assessment of climate risks to Victorian infrastructure. We asked them to:

- assess the risk to broad infrastructure categories against climate change hazards
- identify climate change risks and asset types considered higher risk
- identify gaps in research, where relevant.

Our high-level risk assessment was a first pass assessment. It documented climate hazards affecting Victoria. It listed the broader risks to infrastructure, comprising the likelihood and consequence of climate-related events. For example, by 2030, water is likely to be less available and of lower quality because of changes in rainfall, temperature and fire conditions. This outcome becomes almost certain by 2070. That means it will have major consequences leading and warranted an extreme risk rating (see Appendix 1).

We selected appropriate climate change parameters for our analysis to complete the assessment.[4] *Victoria's Future Climate Tool* user guide offers some general information on climate model selection and climate scenarios, but does not specify what assumed degree of climate change Victorian Government infrastructure planners should use.[5] In contrast, NSW climate risk assessment guidance specifically recommends moderate to high emissions scenarios are consulted at a minimum.[6] This meant we needed to develop our own parameters.

We chose 2030 and 2070 as target dates to analyse climate risks, as Table 1 shows. We also selected our climate scenarios based on the Intergovernmental Panel on Climate Change's Representative Concentration Pathways (RCPs). These pathways correspond to different levels of global warming. We selected RCP4.5 and RCP8.5 for our analysis, as Table 2 shows. These correspond to 1.7°C and 4°C of warming, respectively.

Table 1: Timeframes

Timeframe		Reason
Near term	2030	We can expect some climate outcomes to be fixed around this time. A near-term timeframe also assists with bringing recent events into the analysis.
Long term	2070	The infrastructure we build lasts for decades and even centuries. We were particularly interested in timeframes longer than 30 years to account for infrastructure with a very long lifespans, such as ports.

Table 2: Climate scenarios

Temperature warming	2019 RCP*	Purpose
4°C (3.2°C to 5.4°C: likely 2080–2100 global average temperature above pre-industrial levels)	8.5	*High greenhouse gas emissions scenario* This scenario allows us to consider how existing infrastructure and current standards for new builds would perform under a worst-case climate scenario (assuming a global failure to achieve significant emission reductions). This could inform decision points for adaptation action if emissions reductions are not on track.
1.7°C (1.7°C to 3.2°C: likely 2080–2100 global average temperature above pre-industrial levels)	4.5	*Low emissions scenario, that projects emissions peak around 2040* This scenario allows us to think about whether existing infrastructure and current standards for new builds are vulnerable to climate change that is already locked in.

*Representative Concentration Pathway. RCPs were used by the Intergovernmental Panel on Climate Change (IPCC) to provide emissions scenarios where the different impacts of climate change can be discussed. While the IPCC has moved from using RCPs to new Shared Socioeconomic Pathways, we used RCPs to match with the Victorian Climate Projections 2019 dataset and these broadly align with temperature warming scenarios.

Risk is the product of likelihood and consequence. In other words, the risk posed by climate change is the frequency that a climate-related event might occur, multiplied by the extent of damage and harm caused by it.

In 2006, the Commonwealth Scientific and Industrial Research Organisation (CSIRO), Maunsell Australia and Phillips Fox assessed the climate risks to Victorian infrastructure.[7] We used their risk assessment for Victoria as a starting point. We updated its likelihood and consequence risk matrix. We developed new criteria to define low, medium and high likelihoods and consequences using information from the Victorian Managed Insurance Authority and CoastAdapt.[8] For example, if an event has an 10% or less chance of happening during the lifespan of a piece of infrastructure, we gave it a likelihood rating of 'rare'. Similarly, if the event has a more than 90% chance of happening during the lifespan of a piece of infrastructure, we rated it as 'almost certain'.

We rated the consequences of an event in 7 domains. The domains were financial, local growth and economy, public health, infrastructure, governance, community and lifestyle, and environment and sustainability. For example, we rated the consequences of an event as 'insignificant' if it produced a minor disruption to the service and no structural damage to the infrastructure. At the other end of the spectrum, we rated consequences as 'severe' if:

- the event destroys the asset or the asset would need large-scale engineering works to repair it
- the asset is permanently damaged or the entire state would lose the services provided by it.[9]

AECOM prepared an initial high-level risk assessment. It identified over 40 climate-related risks to Victoria's government-owned and regulated infrastructure. It assessed infrastructure used in the water, transport, buildings, facilities, energy and telecommunications sectors (see Appendix 1). Climate hazards create infrastructure risks such as:

- damage or degradation of infrastructure from extreme weather events such as storms, floods, bushfires, or extreme wind. The infrastructure included water supply and treatment equipment, roads, rail, building structures, facilities, cultural sites, electricity transmission, distribution and generation, telecommunications, and offshore, coastal and onshore gas infrastructure.
- degradation or failure of underground infrastructure or foundations from changes in soil or ground conditions such as shrink-swell caused by changes in wet-dry spells. Th infrastructure included water infrastructure, road foundations, buildings, telecommunications assets and transport tunnel structures.
- damage to infrastructure, restrictions of access or higher maintenance requirements caused by flooding. The infrastructure included telecommunication pits, electrical substations, port assets, roads and tunnels.
- damage, degradation or loss of infrastructure from more chronic climate stressors, such as damage or degradation to bridge structures or building facades caused by changes in temperature and more corrosive conditions including more CO_2 or exposure to sea spray.
- more demand on some infrastructure systems, such as water, from higher average and extreme temperatures.
- more potential for infrastructure failure from heat events, such as electricity blackouts caused by demand exceeding supply, or rail tracks buckling.

We tested these ratings with stakeholders. This included people working in government departments, academia, regulators, infrastructure operators and think tanks. AECOM's technical review panel also reviewed the ratings. We updated the ratings using this feedback. This process generated a shortlist of 13 risks, as Table 3 shows.

Table 3: High-rated climate-related risks to infrastructure

Sector	Risk description	Likelihood	Consequence	Risk rating
Water	Reduced availability and quality of water caused by changes in rainfall, temperature and fire conditions	Likely	Moderate	High
Water	Degradation or failure of water supply infrastructure caused by changes in ground conditions caused by changes from changes in rainfall, evaporation, groundwater and soil conditions	Likely	Moderate	High
Water	Capacity of stormwater and drainage system exceeded caused by more intense rainfall events, outfalls being restricted by elevated sea levels, or greater runoff volumes	Likely	Moderate	High
Water	More demand for water caused by higher average and more extreme temperatures	Likely	Moderate	High
Transport	Damage to roads and disruption of access caused by extreme weather events such as flooding, storm debris, fire, or a landslip	Almost certain	Moderate	High
Transport	Buckling of rail track caused by extreme heat	Likely	Moderate	High
Transport	Damage to rail infrastructure and disruption of services caused by extreme weather events such as heat, rainfall, fire, wind, or storm surge	Almost certain	Moderate	High
Transport	Damage to bridges caused by flooding, fire, storm debris, scour or destabilisation of embankments	Possible	Major	High
Buildings	Damage to building structures caused by extreme weather events such as flood, fire or storms	Likely	Moderate	High
Buildings	Reduction in comfort or safety of building occupants caused by extreme weather conditions such as extreme heat, fire or flood	Likely	Moderate	High
Energy	More frequent electrical blackouts caused by demand exceeding supply during extreme heat events	Almost certain	Moderate	High
Energy	Damage to, or degradation of, electrical transmission and distribution assets caused by extreme weather events such as heat, flood, fire, storms	Almost certain	Moderate	High
Energy	Damage to, or degradation of, electricity generation assets caused by extreme weather events such as heat, flood, fire, storms	Possible	Major	High

Source: AECOM, 2022.

Stakeholder observations on climate risks to infrastructure

We held 3 workshops on the high-level risk assessment. The major discussion points included:

- challenges with assessing climate risks for infrastructure from a statewide perspective, when risk rating can vary by type and location
- equity dimensions to risks, with communities with lower socioeconomic, health or education status potentially most feeling the impacts from climate change
- significant dependence on the electricity sector by other sectors, and the flow on impacts from this dependency
- scope of the built environment, including building and facility types
- impacts on infrastructure vary by hazard type and intensity, such as longer recovery periods for roads after a flooding event compared to bushfires.

Selection of focus areas

We conducted a multi-criteria analysis to interrogate these shortlisted risks and prioritised risks that:

- had fewer effective controls in place
- had more flow on impacts, including direct and indirect impacts on other sectors
- had limited adaptive capacity, such as limited redundancy, back-up solutions or where recovery would take a long time
- can add value to future infrastructure strategies or the government's adaptation action plans.

From this analysis, we selected 3 risks for more detailed analysis, being:

- damage to, or degradation of, electricity transmission and distribution assets caused by extreme weather events
- damage to roads and disruption of access caused by extreme weather events or landslips
- damage to building structures caused by extreme weather events.

We especially prioritised these 3 risks because they can have large cascading impacts. These types of failures can not only compromise the immediate infrastructure and disrupt its services to its direct users, but can also flow-on to other systems and services.

Damaged electricity networks can severely disrupt other essential services. They can compromise telecommunications, such as by impairing mobile phone towers, or stop power reaching water and sewerage treatment plants. They can compromise the functioning of people's homes, including by stopping people from heating or cooling their homes, or refrigerating or cooking their food. They can stop businesses from functioning by compromising lighting, refrigeration and sales equipment. Damaged electricity networks can also pose a fire risk.

Damaged roads can cut off transport routes. This can compromise access for people and freight. It might restrict access for emergency services or prevent people reaching critical care services. Damaged roads can stop people reaching their workplaces. They can impede transportation of goods and services between businesses or to consumers and can cause significant business losses. If a single road connects a community to the rest of the road network, an event that compromises that road can isolate communities during emergencies and hinder people from evacuating. Damaged roads can also restrict access for repairing and rebuilding infrastructure, such as for power lines.

Damaged buildings can disrupt the services delivered from them and inflate demand for alternative accommodation. Damaged buildings can also increase demand for health services by compromising people's health and injuring them. Buildings are a major form of infrastructure for several sectors, including, education, health and human services, justice and emergency services, and culture, sport and community. When extreme weather damages a building, agencies can have difficulty finding an alternative location to operate services from, especially as many other businesses and services might be in the same situation.

Public hospitals provide a critical service. Hospitals can experience compounding and cascading impacts during extreme weather events, such as more demand for their services due to injuries. If the hospital building was damaged in the event, it might have to limit its services, or even relocate patients to other hospitals. Some hospitals provide specialised statewide services, such as major trauma services at the Alfred Hospital. Other hospitals might be the only service in a large area, meaning alternatives are far away. These factors influenced our selection of public hospitals and extreme weather events for further analysis, alongside electricity assets and roads.

We also highly rated the risk that changes in rainfall, temperature and fire conditions could compromise water availability and quality. We further examine it because the *Central and Gippsland region sustainable water strategy*[10] and the urban water strategies were imminent and likely to consider this risk.

Phase 2: Analysis of climate-related risks to infrastructure

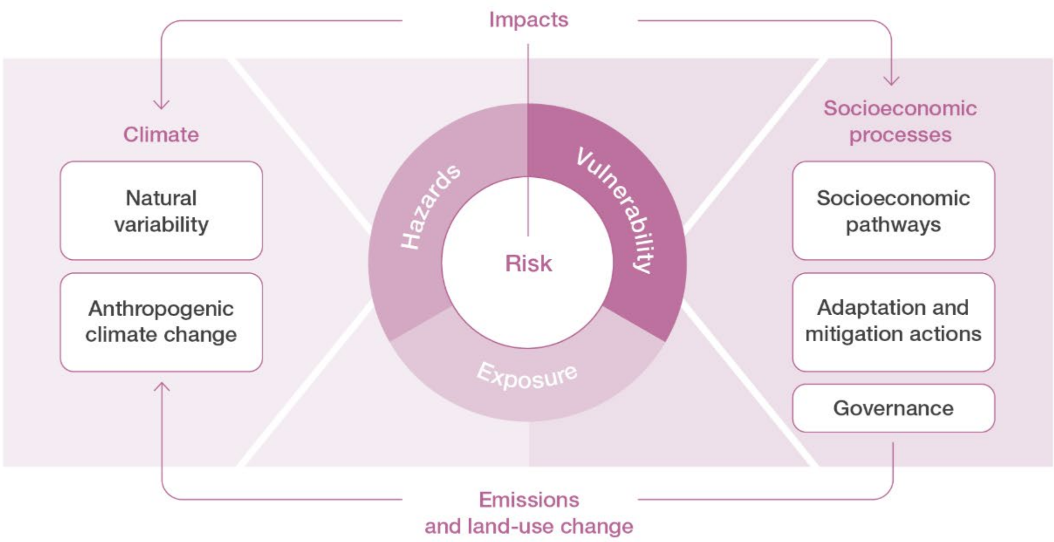
In phase 2, we more closely examined the different types of extreme weather events, exposure and high-level infrastructure vulnerabilities. We used this process to select more specific climate change risks to infrastructure, to later economically assess possible adaptation measures.

We examined in more detail the 3 risks from the high-level risk screening. They are:

- damage to, or degradation of electricity transmission and distribution assets caused by extreme weather events
- damage to roads or disruption of access caused by extreme weather events
- damage to public hospital building structures caused by extreme weather events.

In this phase, we broadened our initial risk analysis from a traditional likelihood and consequence approach. We used an approach that conceived risk similarly to the Intergovernmental Panel on Climate Change's concept of risk from climate impacts (Figure 3). That meant we considered climate hazards and the exposure and vulnerability of infrastructure to climate change. The vulnerability and exposure of infrastructure to climate impacts, such as from extreme weather events, will change over time as the climate changes.[11]

Figure 3: Risk from climate impacts



Source: IPCC, *Climate change 2014: Impacts, adaptation and vulnerability – Part A Global and sectoral aspects,* Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, 2014.

We interrogated the 3 risks by developing more specific risk statements, mapping regional exposure to climate hazards, and identifying potential sensitivity and adaptive capacity factors that can influence infrastructure's vulnerability. We also examined compounding events, cascading effects, current controls and adaptation actions. We held a second set of workshops that allowed stakeholders to provide more input. AECOM's sector specialists and technical staff also provided expertise and quality assurance.

Figure 4 summarises the phase 2 methodology. The rest of this section provides more detail on each step.

Figure 4: Phase 2 methods

Risk analysis

Risk statements

We examined our 3 selected risks in more detail to better understand the climate risks to infrastructure. We described the different assets in each infrastructure category. We also defined more specific types of extreme weather events.

For instance:

- electricity infrastructure includes transmission and distribution infrastructure, which are made up of towers, lines and substations
- public hospital infrastructure includes hospital buildings, plant and equipment attached to the buildings, car parking structures, roads, and pedestrian footpaths
- road infrastructure considers road surfaces, and access to roads.

Extreme weather events include extreme temperatures, bushfires, extreme rainfall and flooding, coastal storm surges and erosion, and storms including extreme wind and lightning.

Our risk statements put these components together to describe the climate risk to infrastructure. For example, these risk statement examples demonstrate more detail:

- Coastal storm related flooding or erosion causing damage to road surfaces
- Coastal storm related flooding obstructing roads or causing road closures, whether by inundation or landslips.

These risk statements illustrate that the same climate hazard can affect different components of a type of infrastructure in different ways and can have different consequences. The first one specifically identifies the damage flooding can inflict on road surfaces. The second statement documents that obstructed or closed roads can cause access problems.

We identified 36 detailed risks in the 3 infrastructure categories. We used a risk matrix to rate each for their likelihood and consequence. We rated them for both a low emissions scenario (RCP 4.5) and a high emissions scenario (RCP 8.5). We considered risk in the years 2030 and 2070. We documented these risks in a risk register (Appendix 2).

Regional exposure of assets to climate hazards

Each risk we shortlisted relates to many extreme weather events. Table 4 summarises the climate hazards that relate to extreme weather events for the 3 infrastructure categories.

Table 4: Climate hazards relating to extreme weather events

Climate hazard	Public hospitals	Electricity network	Road network
Extreme temperatures, including heatwaves	X	X	X
Bushfires	X	X	X
Extreme rainfall and flooding	X	X	X
Coastal storm surge and coastal erosion	X		X
Storms, including extreme wind and lightning		X	

Source: AECOM, *Climate change consequences study,* Infrastructure Victoria, 2023.

We geospatially mapped the location of infrastructure and overlaid data representing hazards. This gave us a quick visual way to examine the exposure of infrastructure to climate hazards in Victoria. Figures 5 to 10 show our exposure maps for roads, public hospitals and electricity networks. We used the following datasets in our analysis to represent climate hazards:

- the projected days with maximum temperatures over 40°C in 2070 (RCP8.5) from the Victorian Climate Projections 2019 dataset
- current bushfire management overlays
- current flood zones and overlays
- historic wind speeds from the Electricity Sector Climate Initiative.

We reinterpreted the flood zones and overlays to account for future climate change. For example, we flagged infrastructure close to flood overlays as at risk of flooding, because future rainfall events might be more intense and inundate more land than is now estimated.

The maps showed us areas and infrastructure exposed to these climate hazards. This was a 'first-pass' assessment at a whole of system level. It did not identify specific assets at risk. That would require us to more closely assess vulnerability, including knowing each assets' condition and other relevant factors.

The maps show the potential exposure of hospitals, road and electricity networks to different climate hazards. Infrastructure in different Victorian regions shows different exposure to these hazards. For example, in the Hume region, electricity networks are exposed to bushfire and extreme wind hazards, and some public hospitals are also exposed to bushfire hazards, extreme rainfall and flooding.[12]

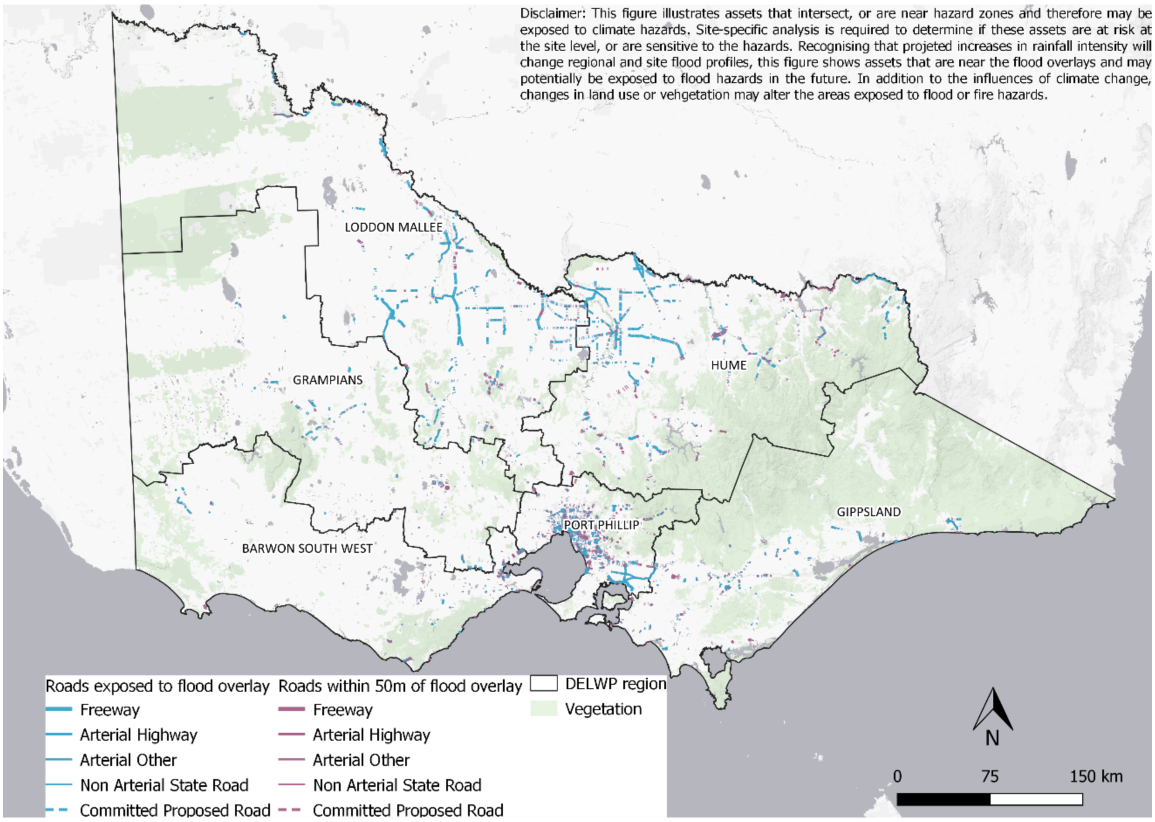
We assigned each detailed risk a regional exposure score and calculated an average regional exposure score to provide a statewide view. The highest average regional exposure scores for electricity, public hospital and road infrastructure, respectively, were for:

- the risk that bushfires or grassfires cause electricity lines to fail, to which the Gippsland and Hume regions are most exposed
- the risk that extreme temperatures (or heatwaves) cause damage to hospital plant and equipment attached to structures, such as heating, ventilation and air conditioning equipment, to which the Grampians and Loddon Mallee regions are most exposed
- the risk that bushfires or grassfires cause damage to road surfaces, to which the Barwon South West, Gippsland and Hume regions are most exposed.

The lowest average regional exposure scores for electricity, public hospital and road infrastructure, respectively, were for:

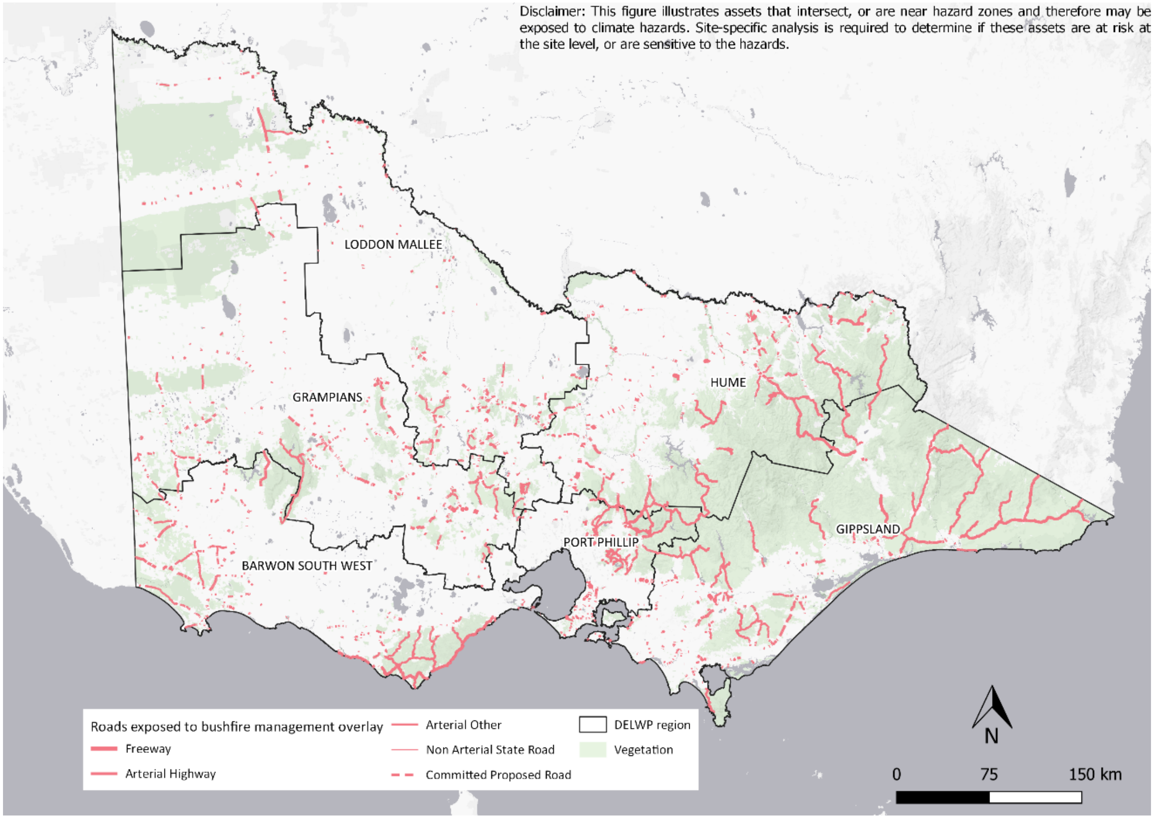
- the risk that coastal storm related flooding or erosion causes transmission substations to deteriorate or fail, to which we could not identify significant exposure in Victoria.
- the risk that coastal storm related flooding or erosion causes damage to hospital buildings, plant and equipment attached to hospital structures, such as heating, ventilation and air conditioning equipment, or multi-level carparking structures, to which Greater Melbourne is exposed.
- the risk that coastal storm-related flooding or erosion causes damage to road surfaces, inundation or landslips obstructs roads, or coastal erosion causes roads to collapse, to which Barwon South West and Gippsland are most exposed.

Figure 5: Roads exposed to flood risk



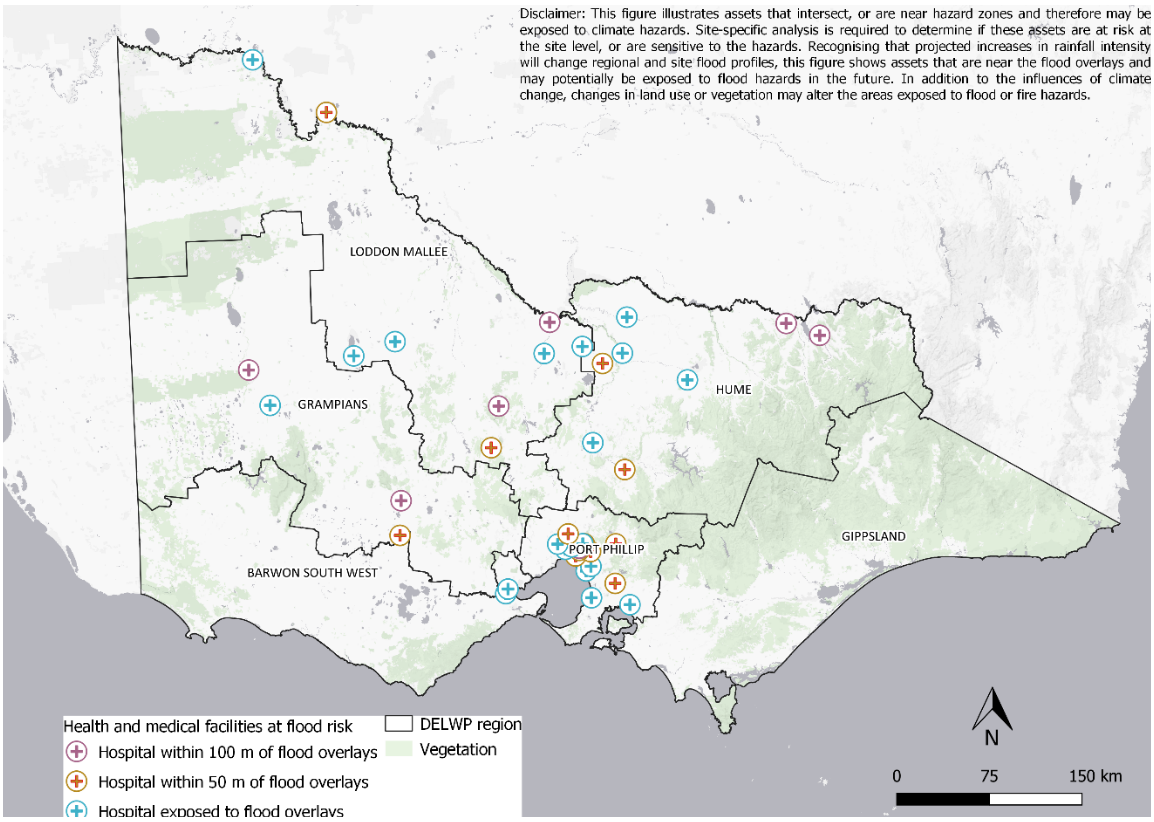
Source: AECOM, *Climate change consequences study,* Infrastructure Victoria, 2023.

Figure 6: Roads exposed to bushfire risk



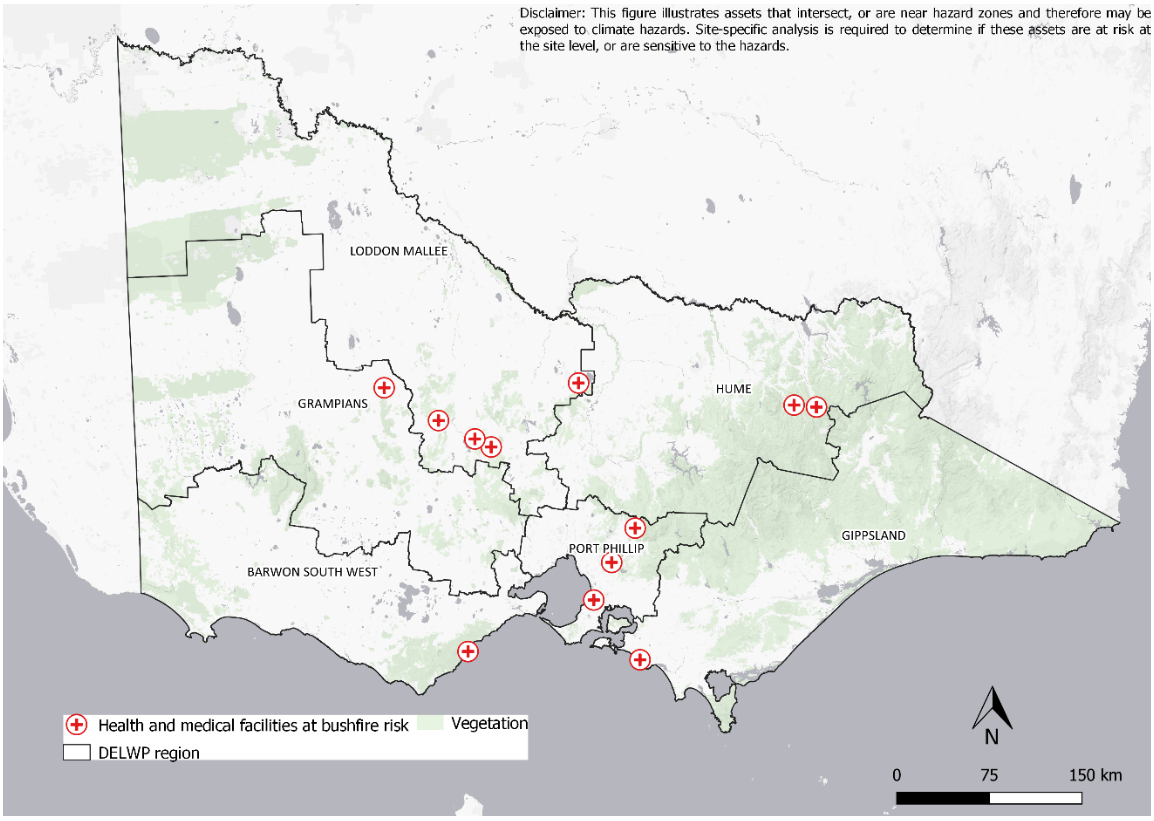
Source: AECOM, *Climate change consequences study,* Infrastructure Victoria, 2023.

Figure 7: Public hospitals exposed to flood risk



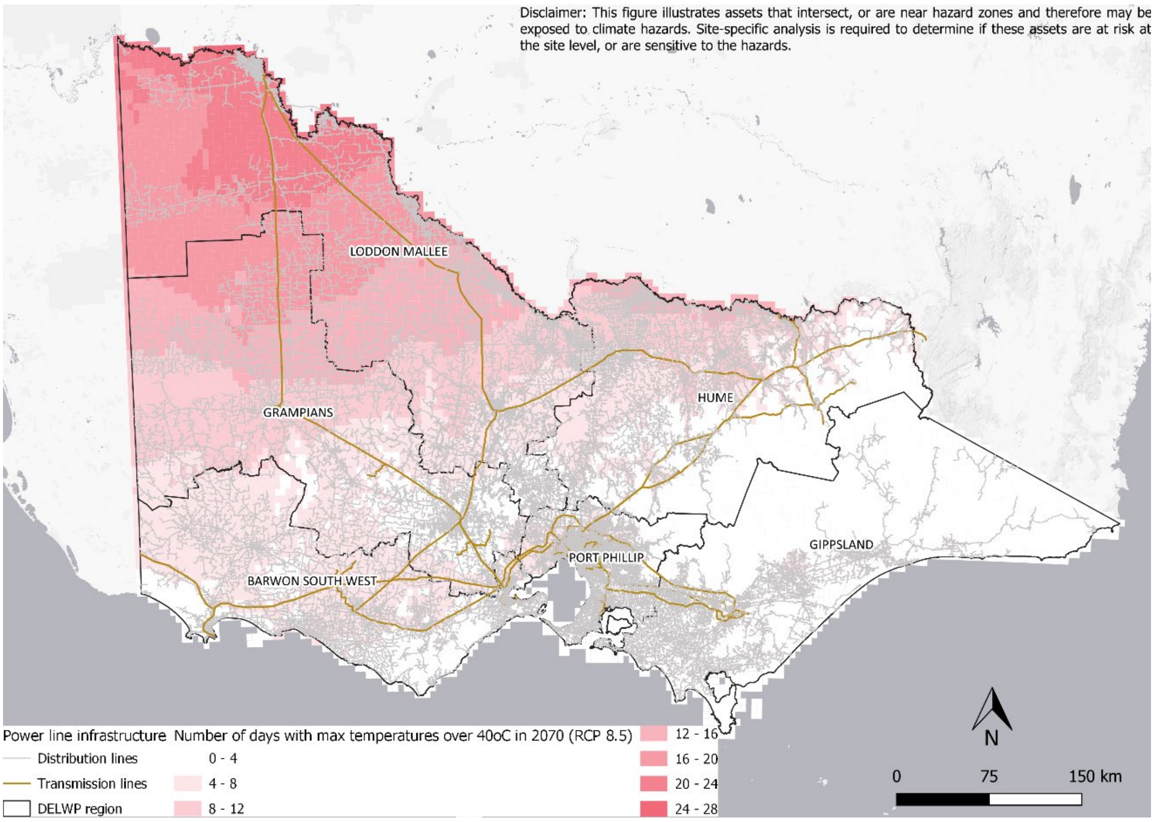
Source: AECOM, *Climate change consequences study,* Infrastructure Victoria, 2023.

Figure 8: Public hospitals exposed to bushfire risk



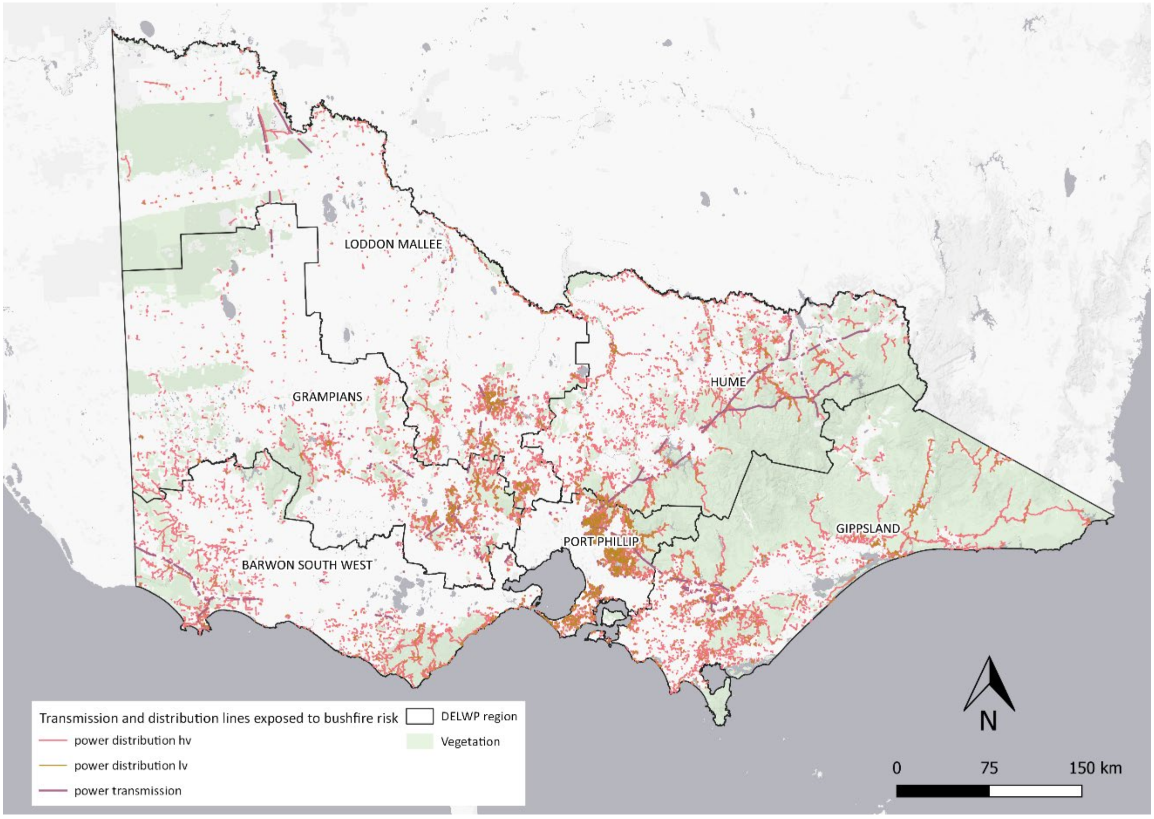
Source: AECOM, *Climate change consequences study,* Infrastructure Victoria, 2023.

Figure 9: Electricity lines exposed to extreme heat



Source: AECOM, *Climate change consequences study,* Infrastructure Victoria, 2023.

Figure 10: Electricity lines exposed to bushfire risk



Source: AECOM, *Climate change consequences study,* Infrastructure Victoria, 2023.

Infrastructure vulnerability

Exposure to climate hazards is not the only component of risk. The level of risk also depends on the vulnerability of infrastructure to that particular hazard, and the susceptibility of infrastructure to the effects of the hazard. Assessing the vulnerability of infrastructure to climate hazards requires detailed analysis at a subregional or site scale. We only conducted a state-wide analysis. We examined the exposure maps that we generated and the sensitivity and adaptive capacity factors that might influence infrastructure's vulnerability. Table 5 summarises the factors that can influence an individual asset's risk profile.

Climate sensitivity is the degree that climate change can affect infrastructure. An asset's specific characteristics affect its climate sensitivity, such as its structure, design capacity, remaining service life, maintenance intensity, and condition. For example, an asset might be exposed to a climate hazard, but if it was built to standards that incorporate climate change, then it is likely to be less sensitive than an older asset. Our high-level statewide analysis did not assess infrastructure's climate sensitivity, because that would require more detailed information on specific assets.

Adaptive capacity is the ability for infrastructure or a system to successfully adjust to, take advantage of, or respond to the consequences of climate change impacts.[13] For instance, a road has better adaptive capacity if it can quickly reopen after a disruptive event, or vehicles have an alternative route if they cannot use the road. Adaptive capacity can sometimes moderate the effects of exposure and sensitivity.

These different climate risk elements then help practitioners assess the likelihood of an impact occurring, and the consequence of hazards in a risk assessment, so they can prioritise adaptation measures. If an agency determines that certain infrastructure is exposed to a high climate-related risk and has a low adaptive capacity, then it might find a beneficial adaptation action to reduce that risk.

The project gave a statewide adaptive capacity score to each of the 36 detailed risks to assist us to understand the vulnerability of Victoria's infrastructure. Of the 36 risks, we rated 9 risks as having low adaptive capacity. Damage to public hospitals and their multi-level car parks made up 6 of those low adaptive capacity risks, covering several climate hazards.

Table 5: Factors that influence infrastructure's vulnerability to climate effects

Sensitivity factors	Adaptive capacity factors
Infrastructure design	Availability of back-up assets
Infrastructure age and condition	Ease of repair access for quick recovery
Infrastructure materials	Ease of access to alternative services
Network redundancy features	Social factors influencing resilience
Remoteness	
Criticality of the asset, service or community it serves	

Source: AECOM, *Climate change consequences study,* Infrastructure Victoria, 2023.

Compounding events and cascading impacts

We considered the potential indirect impacts of climate hazards for each of our 36 detailed risks. These impacts included compounding events and cascading impacts. Including them gives us a more holistic climate risk assessment.

Compounding events involve multiple hazards or events occurring at the same time. They can take different forms, such as a primary hazard triggering multiple downstream hazards simultaneously. For example, a storm can trigger both floods and landslides. Two independent hazards can affect the same region, and might happen at the same time. For example, an earthquake might precede an extreme cold weather event. Multiple hazards could be the combination of extreme heat and fire, or extreme rainfall following a fire which magnifies the impacts of the fire event.[14] Compounding events can create demand and supply challenges. For instance, a heatwave can intensify demand for medical services, a bushfire can compromise both roads and public transport, and both events can reduce the availability of skilled workers. This can create operational limitations such as skill or resource shortages that affect the speed of repairs.[15]

Cascading impacts are the flow on effects from the direct impact of a hazard event, when one hazard causes another hazard to occur. For example, a high wind event can destabilise trees and cause them to fall on electricity distribution lines, which can then cause fires to break out. Cascading impacts can be physical, natural, social or economic, can affect multiple sectors. For instance:

- an electricity supply interruption can affect telecommunications infrastructure, meaning people lose access to real-time information that can help them in an emergency
- an interruption to health services can cause longer hospital wait times, meaning staff might not treat patients as quickly as needed
- road authorities divert traffic away from a closed road, causing more rapid deterioration or damage to other roads that might not have been designed to tolerate that amount of traffic.[16]

In our analysis, we identified many cascading impacts for all our detailed risks. Each had cascading impacts on four or more other sectors. This shows that climate change can have system-wide effects, and that managing risks that can cause cascading impacts can have benefits beyond its immediate sector.

We also considered existing and planned controls for each of the 36 detailed risks we identified for electricity networks, public hospitals and roads. This built on our initial high-level risk assessment in phase 1. Controls are measures that maintain or modify risk.[17] We looked for controls by reviewing the government's adaptation action plans, regional adaptation strategies and other sector-specific knowledge or studies.[18] We assessed all our detailed risks as having partially effective controls in place. This means that infrastructure managers might need to keep monitoring these risks, and might need to redesign, improve or supplement the current controls. It also means they can consider more adaptation actions.

Results

Assessors can prioritise infrastructure risks for action by considering together the climate hazards, exposure to climate hazards, vulnerability factors, likelihood, and potential consequences, including cascading impacts. Appendix 2 documents our full risk register. We used this risk assessment process, and the risk register it produced, to select priority risks for further assessment.

We rate the highest risk for electricity infrastructure to be storm damage or degradation of transmission and distribution lines, including from extreme wind and lightning. Most electricity infrastructure is high above ground. In regional Victoria, it sometimes spans long distances, which makes it more susceptible to storm damage.

We rated the highest risk for public hospitals to be flooding from extreme rainfall. This causes damage to hospital structures, plant and equipment. Extreme rainfall flooding a hospital can have major consequences. The potential adaptation options to protect buildings from flooding, or to recover faster from the event, include:

- locating structures, critical plant and equipment outside of or above future flood levels
- installing onsite detection systems
- using removable fixtures and fittings
- increasing drainage capacity
- using water resistant or easy to clean materials in areas exposed to flood water.[19]

We rated high risks for roads to include extreme rainfall, flooding and bushfire. Extreme rainfall and flooding can cause damage to road surfaces, such as by creating potholes, washing out roads, flooding their surfaces, or causing landslides to obstruct them. Bushfires or grassfires can also obstruct roads, by reducing visibility with smoke, or posing a fire safety risk to motorists.

We narrowed the scope of our further assessment based on these ratings, and more investigation of available data and stakeholder consultation. We selected:

- damage to road surfaces caused by flooding or extreme storm events
- obstruction or closure of roads caused by bushfires or other climate hazards
- degradation or failure of electricity distribution assets caused by extreme storm events, such as extreme wind and lightning.

By examining more than one sector, we could test our methodology in contrasting sectors, as each sector has different ways of valuing costs and benefits. Interrogating a variety of climate change hazards also allowed us to test the hazard data needed to undertake an economic assessment for infrastructure adaptation.

Stakeholder engagement

We engaged with stakeholders throughout phase 2. We held 3 workshops to interrogate the findings of our detailed risk analysis, confirm current and planned adaptation actions, and identify more adaptation actions. We discussed gaps and barriers to adaptation with stakeholders, who gave insights about potential improvements to policy, processes and implementation.

Current adaptation actions

When prompted to identify current adaptation actions, workshop attendees often described flood-related activities, bushfire management, alternative energy solutions and asset management. The flood-related activities included locating or elevating critical infrastructure away from flood hazards. For roads and electricity infrastructure, they identified possible new drainage infrastructure or other flood protections, such as retarding basins.

For bushfire management activities, stakeholders mentioned reviewing bushfire risks for different types of infrastructure, fire consequence mapping, and clearing vegetation close to infrastructure.

As possible alternative energy solutions, attendees talked about onsite biomass power generation and automatic operation of emergency backup generators at hospitals. To adapt electricity infrastructure, infrastructure managers are considering using of backup generators for critical assets, building microgrids, or facilitating distributed or onsite electricity generation and storage.

For all three infrastructure categories, people considered asset management to be a current adaptation action. This included general maintenance programs and use of automated asset inspection technologies.

Planned adaptation actions

Attendees at all 3 workshops believed Victoria's infrastructure should be more resilient but found it difficult to specify exactly how. They frequently talked about rebuilding infrastructure differently following an event.

They also mentioned plans to assess and audit infrastructure to better understand their assets or risks, and the opportunities for adaptation. For instance, individuals cited site specific assessments of vegetation risk, audits on ageing infrastructure for environmental performance, and identifying opportunities to replace damaged or end-of-life public assets with alternative technologies.

Other adaptation actions

Beyond this, workshop attendees talked about improving their planning and asset management processes as another adaptation action. For instance, they suggested using detailed local area climate projections as an input to all infrastructure planning, targeting sea level rise analysis at drainage and flooding at coastal sites, embedding adaptation considerations into their organisation's strategic plans, and developing programs or tools to help use existing maintenance and renewal budgets.

They also mentioned using new infrastructure technology. Their suggestions included conducting more trials or investigations into different building materials to enhance resilience, such as fire-retardant materials or road pavement materials that drain better. They also suggested using remote sensors more often to monitor the condition of infrastructure.

Barriers to adaptation

Stakeholders discussed several barriers to adaptation. For public hospitals and roads, they talked about not having enough dedicated funding and resources. Some people suggested that one-off emergency funding or short-term funding can divert funds from preventative work, which can then compound maintenance issues for ageing assets.

Participants in all 3 workshops identified their staff's lack of expertise, experience and understanding of adaptation as a barrier. They also talked about data gaps and working with uncertainty. For instance, the historical climate record is no longer a good predictor of future climate risks. Much asset management practice is premised on the idea that 'past behaviour is the best predictor of future performance'. Climate change upends this approach, which means asset managers need new and accepted methods and baselines to make decisions in practice.

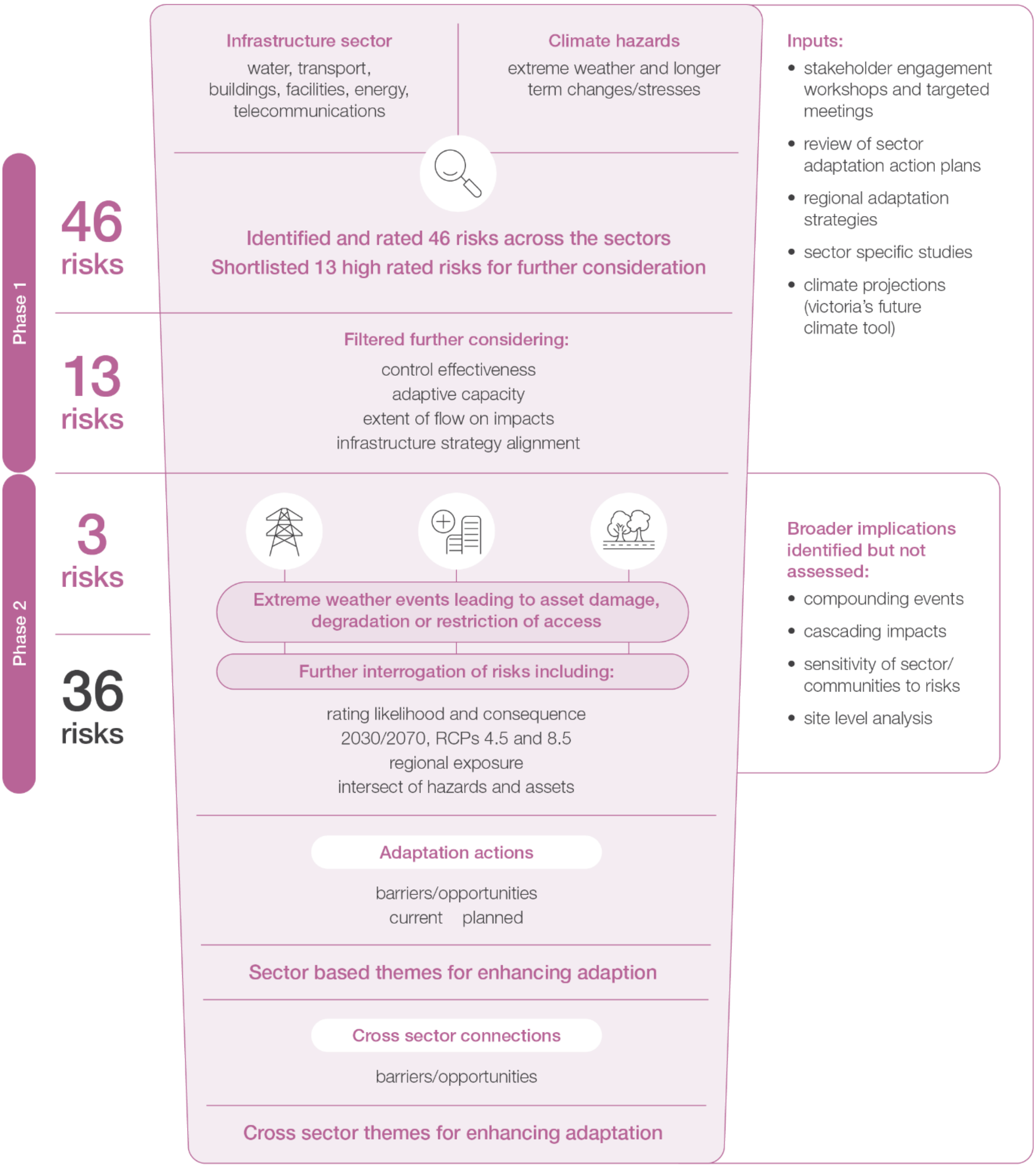
Lastly, many commented on barriers to operationalising infrastructure adaptation, including:

- not having methodologies for capturing costs and benefits relating to long-term climate impacts
- overwhelming and inconsistent guidance
- the importance of coordination and collaboration, but unclear roles and responsibilities
- using the community to help identify assets as well as responses to climate change
- adaptation considerations throughout procurement and project delivery, such as in contracts, and at design and construction stages.

Outcomes from the risk assessment process

Figure 11 summarises our high-level risk assessment process. AECOM used this risk analysis and stakeholder engagement to propose a set of priority adaptation actions to act now, for the next adaptation action plans or for further research (Table 6).

Figure 11: Summary of phase 1 and 2 analysis of climate change impacts



Source: AECOM, *Climate change consequences study,* Infrastructure Victoria, 2023.

Table 6: AECOM's proposed adaptation actions

	Act now	Act by 2026	Further research
Actions to address risk of damage to, or degradation of electricity transmission and distribution assets caused by extreme weather events			
Prioritise sections of the electricity network to undergo site specific assessment of climate risks	X		
Embed adaptation design principles into the design of new and upgraded or renewed infrastructure	X		
Include self-healing networks in the proposed adaptation design principles for new and upgraded infrastructure	X		
Develop a climate change adaptation plan at the transmission and distribution network level		X	
Enhance centralised agreement on priorities for emergency restoration and recovery	X		
Actions to address risk of damage to hospital structures caused by extreme weather events			
Prioritise hospitals for site specific assessment of climate risks and development of priority actions	X		
Supplement the Victorian Health Building Authority sustainability guidelines with tools to support decision making	X		
Consider enhancing assessment of climate risks in the Victorian Managed Insurance Authority's site risk surveys		X	
Actions to address risk of damage to roads or disruption of access caused by extreme weather events			
Prioritise sections of the road network for site specific assessment of climate risks and development of priority actions	X		
Embed adaptation principles into funding and targeting of proactive or preventative maintenance and road rehabilitation	X		
Embed adaptation principles into the design of new and upgraded or renewed infrastructure	X		
Enhance the formalised approach to slope risk management in Victoria		X	
Enhance resilience of major alternative road-based routes		X	
Actions to enhance climate adaptation in multiple sectors			
Advance the development of downscaled climate and hazard projections			X
Enhance standardised approaches to cost-benefit analysis	X		

Source: AECOM, *Climate change consequences study,* Infrastructure Victoria, 2023.

The major adaptation themes across public hospitals, electricity and road networks were:

- strengthening guidance or processes to support climate adaptation decision-making and implementation in all 3 infrastructure categories
- prioritising public hospitals and roads for detailed vulnerability investigations at a site level
- building resilience of electricity networks
- strengthening emergency response and recovery for electricity and road network infrastructure.

We used the high-level risk assessment to select three priority risks on which to undertake economic assessment of infrastructure adaptation measures. In our engagement, we confirmed infrastructure managers were hesitant or unsure how to make an economic case for adapting infrastructure, given the lack of accepted methodologies used in government agencies. We wanted to demonstrate how to include climate change in a cost-benefit analysis. Cost-benefit analysis is a major tool that agencies use to inform infrastructure decision-making and make the case for adaptation.

Our main finding from undertaking the high-level risk assessment was that infrastructure's climate vulnerability and risk vary by location and sector. This means that practitioners need to conduct site specific analysis to select the best adaptation measures.

Phase 3: Economic case for adaptation action

In phase 3, we used cost-benefit analysis to evaluate the case for investing in adaptation measures for more specific infrastructure risks. We selected adaptation measures that protect electricity and road infrastructure from extreme storm events, floods, bushfires and landslides. We also demonstrated economic methodologies for infrastructure adaptation that others can use.

Our research question for this phase was:

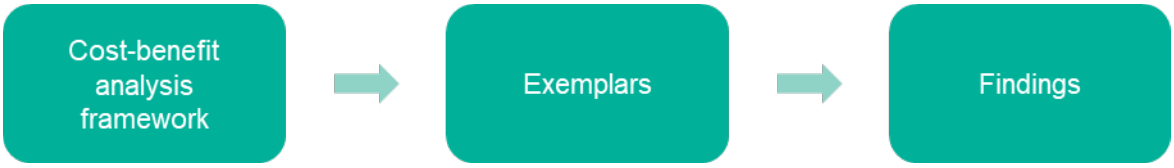
> What is the economic return on investment for selected climate change adaptation measures in the identified infrastructure sectors?

From the previous risk analysis, we identified and selected 3 priority risks for further assessment. We engaged Arup to undertake economic assessments for roads, and ACIL Allen for the electricity distribution assessment.[20] The specific objectives of this work were to:

- identify the quantitative and qualitative direct and indirect costs and benefits (including the economic, social and environmental benefits) of investing in specific climate adaptation measures for our selected infrastructure sectors, and monetise as many as practical
- assess the economic case for early investment versus 'do nothing', and incorporate the increasing climate risks over time
- assess the influence of adaptation measures against multiple variables to avoid maladaptation
- present a methodology that others can use to assess the value of climate adaptation for infrastructure.

The methodology for phase 3 is summarised in Figure 12. The rest of this section gives more detail.

Figure 12: Phase 3 methods



Cost-benefit analysis framework

Approach

Cost-benefit analysis is a rigorous and transparent method that quantifies and values the costs and benefits of projects in monetary terms. It helps governments decide between infrastructure projects based on their relative merits. It helps governments consider the different impacts of proposals, but it is not the only tool available.[21]

We used cost-benefit analysis to conduct both the roads and electricity economic assessments. We incorporated some changes to the standard Victorian Government methods. We based these changes on international practice. We reflected climate change impacts in the base case, so that we accounted for the costs of more frequent and intense events. These climate impacts represent future costs if no adaptation action is taken. We used the base case to assess the merits of different adaptation measures, including the avoided costs of climate events.

Other methodological advances included:

- using a framework for considering many adaptation measures, which included upgrading, altering or adding infrastructure, changing the environment around assets, altering maintenance regimes, or options that support managing the infrastructure better during emergencies
- valuing embodied emissions of infrastructure adaptation measures, covering the upfront carbon impact from materials extraction, manufacture, transport and installation
- considering the cascading costs of infrastructure failure when assessing the benefits of adaptation, for example, by considering the costs of flow-on effects of road closures for the whole community, and not only the immediate costs imposed by users of the affected roads
- considering the sequencing or bundling of adaptation measures over time as more information becomes available about climate change impacts
- considering maladaptation, which occurs when an adaptation measure, meant to protect the community from climate change, inadvertently increases the vulnerability of a system, sector or social group.[22]

Our high-level phase 2 risk assessment demonstrated that infrastructure's climate vulnerability and risk vary by location and sector. This means that infrastructure managers must conduct site specific analysis to select the best adaptation measures. For our analysis, we decided to apply cost-benefit analysis to de-identified hypothetical exemplars to illustrate a site-specific analysis. We grounded the exemplars in real data and used asset and hazard features that occur in many places. We de-identified the exemplars because our exercise was to demonstrate the technique, not recommend particular changes in specific local communities.

We also set some common parameters and inclusions for the quantitative analysis for all 3 exemplars to provide some methodological consistency, allowing comparisons between them, including:

- calculating direct, indirect and intangible costs and benefits, such as the downtime of infrastructure, loss of life, emergency costs and disruptions to public services and community, and wider impacts on biodiversity, health costs and environmental conditions
- using different discount rates of 4% and 7%, aligning with the Department of Treasury and Finance's guidance[23]
- using the New South Wales carbon emissions value and profile, which is based on the market price of the EU emissions trading scheme[24]
- presenting results using a benefit-cost ratio and net present value, and showing return on investment metrics in the road and electricity study
- considering distributional impacts, including the incidence of costs and benefits borne by different groups
- considering real options and adaptation pathways, which are frameworks for thinking strategically about infrastructure investments under conditions of uncertainty.

Differences between the road and electricity methodologies

The road and electricity analyses present valid methods and approaches to assessing climate change impacts and adaptation measures using a cost-benefit framework. The two methodologies have many similarities and can be used for other types of infrastructure. The main differences were in measuring the climate hazards. Because we used different data sources, we had to transform it in different ways to use it in our analysis.

For our electricity distribution exemplar, we estimated an annual probability of a wind event using historic and projected wind data to calibrate climate impacts.[25] We estimated the probability of a strong wind event in a particular year is 19% based on the climate projections, which is significantly more than historical observations. Analysis indicated faster maximum wind speeds in the Victorian Climate Projections, which supports an assumption of more weather and vegetation-induced outages. The literature did not directly support a specific value, and we assumed it could increase power outages by 20% more in the future.[26] The benefits of adaptation measures were largely based on their effectiveness in avoiding outages.

The road exemplars estimated the relationship between the intensity of the hazard event, replacement costs and the number of downtime days.[27] This is a type of vulnerability assessment. Each adaptation measure was assessed for the risk reduction it achieved. This evaluation estimated the residual risk after the adaptation measure is complete. It produced values for the average annual loss, average annual damage days, and indirect tangible and intangible losses.

Framework for physical adaptation measures

Prioritising non-build or low build solutions is a principle for developing business cases for new infrastructure or modifying existing infrastructure. During our research, we heard about challenges in making the case for physical infrastructure adaptation, with only a small amount of funding going toward this activity.

Our climate adaptation analysis categorises adaptation measures to help practitioners consider the many different options available.[28] We developed an initial framework for considering physical infrastructure adaptation measures. We included the categories of upgrading, altering or adding infrastructure, changing the environment around assets, altering maintenance regimes, or developing options that help better manage infrastructure in emergencies, as Table 7 shows. This framework can offer a starting point for infrastructure managers to think about their available options. It can also be used to help prioritise investment decisions, by applying measures in each categories to the prevention, protection, response and recovery of infrastructure.

Table 7: Initial framework for infrastructure adaptation measures

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 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 using protection measures.
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 them using human design and engineering, providing both risk reduction and ecological benefits.
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. Hazard management can be quite broad and cover areas such as preparation before an extreme event, response during an event and immediate recovery. 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 new structures and immediate responses to reduce cascading impacts.

Sources: BK Sovacool, 'Hard and soft paths for climate change adaptation', Climate Policy, 2011, 11(4):1177-1183; ROADAPT, *Roads for today, adapted for tomorrow – Guidelines*, Conference of European Directors of Roads, 2015; The World Road Association (PIARC), *Adaptation methodologies and strategies to increase the resilience of roads to climate change – Case study approach*, Technical Committee E.1 Adaptation Strategies and Resiliency, 2019; Tonkin + Taylor and Tregaskis Brown, *National resilience programme business case*, Waka Kotahi NZ Transport Agency, 2011; U.S. Department of Transportation Federal Highway Administration, *Nature-based solutions for coastal highway resilience: An implementation guide*, U.S. Government, 2019.

Exemplar 1: Adapting the road network for flooding

We examined the economic costs and benefits of investing in climate adaptation for the road network with Arup.[29] The results of the economic analysis are site-specific to the exemplars used in this study, including their socioeconomic, topographic, and functional settings, and the assumptions made on the costs and effectiveness of adaptation measures. The adaptation measures with the highest return-on-investment might not be the same for every road in every location.

We examined adaptation measures in a hypothetical suburban scenario

Our phase 1 and 2 analysis produced a high rated climate risk for the transport network and showed that extreme weather events could damage roads and disrupt road access.

In this exemplar, we examined how floods might affect a major suburban Melbourne arterial road. We compared the net benefits of different adaptation measures to a base case that had no extra adaptation interventions in place. We based our scenario on real world data. It was a 7-kilometre stretch of arterial road with 2 lanes on a single carriageway within a flood zone. The road served around 11,000 vehicles each day, and standard projections forecast this would rise to nearly 20,000 vehicles each day by 2030.[30]

This exemplar considers the risk of flooding to urban road surfaces from inundation and washout during rain events. Washout and debris on roads can disrupt traffic and cause the road surface to deteriorate. This affects recovery costs and reduces reliability for road users. This exemplar uses climate projections that forecast that rainfall intensity will become more intense.

The road exemplars examined 2 timeframes and climate scenarios:

- impacts to 2030 under existing climate conditions
- impacts to 2070 under future climate conditions, using RCP8.5.

We estimated the base case for flood-related risks for each climate scenario. The base case represented a scenario where the road would not be repaired after being degraded by each flood event but would need eventual replacement because of cumulative flood damage.

The road exemplars also assessed infrastructure vulnerability to climate hazards. For this exemplar, the vulnerability assessment estimated the relationship between the damage to roads from different flood levels, and the size of its replacement costs and the number of downtime days.[31] The results showed that the costs of floods increase as a consequence of climate change, if no adaptation measures are implemented. The current average annualised direct loss would change from $577,679 in the present, to $927,429 in the future. In other words, we estimate that climate change might nearly double the average yearly cost of repairing flood damage to this hypothetical road. We also looked at the indirect tangible and intangible losses to show the extent of impact more widely on the community with indirect tangible and intangible annualised losses increasing from $90,614 to $153,407.

We created a long list of adaptation measures. We found many adaptation measures relevant to the scenario in every category. We conducted a multicriteria analysis to create a short list of adaptation measures. We also assessed the efficacy of each measure, and the embodied carbon associated with producing and transporting the materials for each one. We developed assessment criteria for community impacts during construction and maintenance, recovery time, cost of construction, level of net impact on the environment, maladaptation risks and embodied emissions.

We used a matched pairs analysis to weight each criterion by its relative importance. This involved comparing two criteria at a time and deciding which one was more important. We repeated this process until we had ranked all the criteria against one another. This necessarily involves some subjective judgement, but it offered a way to actively consider and document each element and makes our choices transparent.

We then assigned scores against each criterion on a scale of 0 to 5 for each adaptation measure and applied the weighting. We reviewed those scores to guide our selection of 8 adaptation measures for each exemplar.[32] Details of the multi-criteria analysis can be found in the in the technical report, *Adapting Victoria's infrastructure to climate change: economic analysis of adaptation for roads*, which is available on our website.

From this analysis, we selected 8 measures to examine:

- foamed bitumen stabilisation (higher cost)
- optimising the road grade and improving drainage now to absorb 1-in-20 year flood events (higher cost)
- optimising the road grade and improving drainage now to absorb 1-in-20 year flood events, and upgrade in future to absorb 1-in-100 year flooding (higher cost)
- viaduct (higher cost)
- water sensitive urban design (bio-retention basins and catchment improvements to reduce peak flooding) (lower cost)
- increase preventative maintenance (repairs to preserve pavement condition) (maintenance)
- programmed rehabilitation of roads (more frequent extensive repairs and maintenance) (maintenance)
- hazard management (ITS solutions and rerouting to prevent further damage to roads after flooding) (hazard management).[33]

For the road exemplars, each adaptation measure was assessed for its ability to reduce the level of risk that was originally quantified by the vulnerability assessments. This evaluation estimated the residual risk after adopting the adaptation measure. It resulted in values for the average annual loss, average annual damage days, and indirect tangible and intangible losses. The road exemplar relating to bushfires and landslides also included an estimate of the annual probability of loss of life. We used specific flood modelling tools for the metropolitan road flood exemplar and bushfires and landslides for the regional road exemplar.[34]

Low cost and maintenance adaptation measures produce consistent high returns

We found adaptation measures that produced a positive return on investment in all conditions: foamed bitumen stabilisation, water sensitive urban design, preventative maintenance, programmed rehabilitation, and optimising the road grade now to withstand a 1-in-20 year flood event.[35]

Table 8 gives a summary of the adaptation measures ranked by benefit-cost ratio.

Table 8: Benefit-cost ratios for flooding adaptation measures for roads under current (2022) and future (2070, high emissions scenario) climate conditions based on a 7% discount rate

Adaptation measure	BCR current conditions (7% discount rate)	BCR future conditions (7% discount rate)
Preventative maintenance	5.10	8.29
Foamed bitumen stabilisation	2.98	4.83
Water sensitive urban design	2.90	4.66
Programmed maintenance	2.51	4.06
Upgrade road and drainage to 1-in-20 year flood events	1.26	2.03
Staged road and drainage upgrading to 1-in-20 year and 1-in-100 year flood events	1.04	1.71
Hazard management solution	0.77	1.26
New raised road viaduct	0.09	0.14

Source: Arup, *Adapting Victoria's infrastructure to climate change: economic analysis of adaptation for roads*, Infrastructure Victoria, 2023.

High-cost measures produce varied results

Preventative maintenance and foamed bitumen stabilisation produced the highest returns on investment under both current and future conditions. Preventative maintenance produced $5.10 of value for every $1 spent in current climate conditions, increasing to $8.29 under future conditions. Both estimates use a 7% discount rate. This adaptation extended the lifespan of infrastructure assets and helped to avoid costly repairs and premature replacements. Foamed bitumen stabilisation produced $2.98 in net benefits for every $1 spent in current climate conditions and $4.83 under future conditions.[36]

Building a road viaduct was the only option that made the road completely resilient to flooding. But in our exemplar it did not produce benefits that outweighed its installation costs in either current or future climate conditions. It was the only adaptation measure that did not produce positive results under any scenario.[37] But it might still be an option to consider if the exemplar road is deemed critical, such as for access for emergency services.

Planning the implementation of adaptation can produce better results

Our research explored how individual adaptation measures compared against a base case scenario. But some adaptation measures that do not produce a high return on investment by themselves might work better when coordinated with other measures or implemented using a staged approach. This is known as adaptation pathway planning. A pathway approach identifies a range of options that can be sequenced as a long-term plan and updated over time when new information is available or when thresholds are met. This approach also allows decision makers to then adjust their decisions over time to enhance infrastructure and community resilience.[38] This can help with the use of resources and maximises the benefits from the adaptation measures.

This exemplar includes an example of a sequenced adaptation measure. The adaptation measure was developing the road grade to a level that provided immunity to a 5% annual exceedance probability (AEP) flood event, then after 20 years, raising the road to achieve immunity to a 1% AEP flood.[39] This accounts for climate hazards increasing in later years, requiring a later significant upgrade to the road compared to building at a higher resilience level today. An AEP is a way of describing the chance of a flood event occurring, with a 1% AEP meaning there is a 1-in-100 chance of a flood exceeding in any given year.[40]

Other individual adaptation measures that produced lower results, such as hazard management, might work better when coordinated with other measures.[41]

The full details of this cost-benefit analysis are in *Adapting Victoria's infrastructure to climate change: economic analysis of adaptation for roads*, which is available on our website.

Exemplar 2: Adapting the road network for bushfires and bushfire-induced landslides

We examined the economic costs and benefits of investing in climate adaptation for the road network with Arup.[42] The results of the economic analysis are site-specific to the exemplars used in this study, including their socioeconomic, topographic, and functional settings, and the assumptions made on the costs and effectiveness of adaptation measures. The adaptation measures with the highest return-on-investment might not be the same for every road in every location.

We examined adaptation measures in a hypothetical regional scenario

Our phase 1 and 2 analysis produced a high rated climate risk for the transport network that bushfires and subsequent rainfall-induced landslides could cause service interrupts on roads.

This second exemplar examines the impact of a hotter and drier climate on roads. This climate can cause more dangerous fire weather and can produce more frequent and intense rainfall events that create higher landslide risks after a bushfire.

We examined how bushfires might affect a regional road, and how the costs and benefits of adaptation measures compare to the costs and benefits of "doing nothing" in a base case. Our area was based on site-specific real-world data. Our hypothetical road was a 50-kilometre undivided carriageway in a bushfire zone. The road connects 3 small towns with a total population of 600 people, and provides essential access for residents, freight, tourists and emergency services. The surrounding area has few alternative roads other than unsealed roads.[43]

This second exemplar assesses the impacts of bushfires and subsequent landslides on road infrastructure. Debris left after a bushfire can cause disruptions to road access and road closures. Subsequent rainfall events can also generate erosion and landslides, causing even larger disruptions to road services.

The road exemplars examined 2 timeframes and climate scenarios:

- impacts to 2030 under existing climate conditions
- impacts to 2070 under future climate conditions, using RCP8.5.

The road exemplars also assessed infrastructure vulnerability to climate hazards. For this exemplar, we examined the direct closure and cost to repair the asset components most at risk such as slopes, drainage, cuttings, embankments and landscaping.[44]

We assessed each adaptation measure in our road exemplars to show how much it reduced the level of risk that we originally quantified in vulnerability assessments. This evaluation estimated the residual risk left after implementing the adaptation measure. It produced values for the average annual loss, average annual damage days, and indirect tangible and intangible losses. The road exemplar for bushfires and landslides also included an estimate of the annual probability of loss of life.

We examined the extra risk of landslides occurring post-bushfire event. Bushfires rarely cause direct damage to roads, but can destabilise the surrounding landscape, which can cause erosion and debris. Bushfire-induced landslides risk causing more disruption to the road than a bushfire itself.[45] Post-bushfire events were examined to show the probability that debris will detach, and probability that these materials will cause total road closure. The results show that total losses from bushfire and landslide increase under current and future climate conditions.

The road exemplars had many different adaptation measures. To reduce the number, we shortlisted them using a multicriteria analysis process with weightings, using the same method as the previous exemplar.

We used this analysis to select 8 measures to examine:

- remediate high risk slopes (2) with flexible barriers (higher cost)
- remediate high and moderate risk slopes (11) with flexible barriers (higher cost)
- fire-resistant planting (lower cost)
- fire break (vegetation clearance zone) (lower cost)
- increased programmed drainage clearing and vegetation management (maintenance)
- post-fire responsive drainage clearing (maintenance)
- post-fire erosion protection and slope stabilisation (maintenance)
- risk management plan (hazard management).[46]

Programmed drainage produced over 5 times the return on investment

Our analysis clearly demonstrated that, in this exemplar, increasing programmed drainage would produce a large and positive return on investment. At a 7% discount rate, increasing programmed drainage under current climate conditions would return $5.88 for every $1 spent. For future climate conditions, this increases to $11.52 for every $1 spent.[47] More programmed drainage would increase flood resilience, reducing the effects of post-bushfire landslides without the need for more expensive interventions.

Higher cost does not equal the best return on investment

In this exemplar, maintenance and hazard management measures had the largest positive return on investment. The lower upfront initial expenditure makes these measures attractive when few financial resources are available.

In the bushfire exemplar, few adaptation measures outperformed the base case compared to the flood exemplar (see Table 9 below). Immediate post-bushfire erosion and drainage clearing produced positive returns on investment under future climate scenarios.[48] The results also showed that some adaptation measures can be combined, enhanced and sequenced when implemented in a certain order. For instance, improving soil erosion control and vegetation restoration before undertaking infrastructure upgrades can help stabilise slopes and minimise erosion impacts. In this exemplar, these adaptation measures might be worth investing in first and can be monitored as part of an adaptation pathway approach.

Neither of the higher cost slope remediation measures produced a positive return on investment under a 7% discount rate, although remediating the 2 high risk slopes was close under future climate conditions at a 4% discount rate.[49] The lower-cost fire-resistant planting measure also produced a positive return on investment for future climate projections at a 4% discount rate.

We calculate a low BCR for fire breaks because they had high costs associated with their establishment and maintenance in this exemplar. Fire breaks can be effective for roads, and but their cost varies in different locations depending on their environmental constraints and terrain, the scale of the treatment and the assets they protect.[50]

Table 9: Benefit-cost ratios (BCR) for bushfire and landslide adaptation measures for roads under current (2022) and future (2070, high emissions scenario) climate conditions based on a 7% discount rate

Adaptation measure	BCR current conditions (7% discount rate)	BCR future conditions (7% discount rate)
Programmed drainage clearing and vegetation management	5.88	11.52
Post-fire erosion protection and slope stabilisation	0.73	1.37
Risk management plan	0.71	1.07
Post-fire responsive drainage clearing	0.57	1.07
Fire-resistant plants	0.42	0.82
Remediate 2 high risk slopes with flexible barriers	0.19	0.58
Remediate 11 high and moderate risk slopes with flexible barriers	0.19	0.28
Fire break (vegetation clearance zone from the road)	0.17	0.32

Source: Arup, *Adapting Victoria's infrastructure to climate change: economic analysis of adaptation for roads*, Infrastructure Victoria, 2023.

We also assessed our potential adaptation measures to check for maladaptation. For example, we identified that restoring vegetation alongside roadsides can help stabilise soil and prevent landslides. But it also increases the risk that a bushfire might threaten road users.

Our findings indicate that local area analysis can identify the best adaptation options. The best options are not necessarily the most expensive one Lower cost options can sometime yield the strongest results, including options that do not require construction. The full details of this cost-benefit analysis can be found in the technical report, *Adapting Victoria's infrastructure to climate change: economic analysis of adaptation for roads*, which is available on our website.

Exemplar 3: Adapting electricity distribution infrastructure for extreme wind events

We examined the economic costs and benefits of investing in climate adaptation for electricity distribution infrastructure with ACIL Allen.[51] Electricity distribution networks transport electricity from the high voltage transmission network to homes, businesses and industrial premises. They include poles and wires, substations, transformers and switching equipment.[52]

We examined adaptation measures in a hypothetical urban scenario

Our phase 1 and 2 analysis produced a high rated climate risk that extreme storm events, such as extreme wind and lightning, could damage or degrade electrical transmission and distribution infrastructure.

We took a high-level approach to sensitivity testing by varying some major assumptions, by increasing and decreasing the parameters, based on what we could find in relevant guidance and using expert judgement. We tested our assumptions about capital costs, extreme outage severity and health costs. We also examined how much the results would change if an electricity distribution failure produced wider economic impacts. Power outages can cause widespread interruptions, that include disruptions to essential services such as transport, telecommunications, water and sewerage services.[53]

We examined how extreme winds might affect a typical metropolitan Melbourne area, and how the costs and benefits of adaptation measures compared to a "do nothing" base case that had no adaptation measures in place. Electricity lines are vulnerable when vegetation comes in contact with them. We selected an urban area for the study because an electricity distribution outage is likely to have large social and economic costs in these locations.[54] Our exemplar was based on real world data, rather than an actual location. It consisted of an electricity distribution service area which had 2,000 customers.[55]

In this exemplar, we considered the risk to electricity distribution infrastructure from increasingly severe and frequent of extreme wind events, and their subsequent impacts on customers from outages. For example, in October 2021 strong winds caused power outages for about 500,000 customers, particularly in Melbourne's eastern suburbs. Over 20,000 customers did not have power for more than 72 hours.[56]

The exemplar analysed a single overhead electricity distribution feeder in an urban area that had extensive tree coverage. The area experienced a higher than typical exposure to outages caused by wind and vegetation falling on the distribution infrastructure. It relied heavily on overhead distribution infrastructure.

The electricity distribution exemplar's analysis timeframe was 2070. ACIL Allen's analysis of wind projections estimated that maximum wind speeds in 2070 would be slightly higher using RCP4.5 climate projections compared to RCP8.5.[57] We based our analysis on RCP4.5 because this provided a higher impact stress test.

ACIL Allen used historic and projected wind data to calibrate climate impacts and estimate the annual probability of a wind event.[58]

We created a long list of adaptation measures that might reduce wind-related power outages. We categorised them into groups of higher-cost, lower-cost, maintenance and hazard management solutions. Few of these adaptation measures were highly effective for this exemplar. After considering community acceptance, financial costs and maladaptation, we selected 4 measures to examine:

- undergrounding distribution cables (higher cost)
- insulated cables (lower cost)
- tree replacement with lower growth trees (lower cost)
- grid-forming inverters (hazard management).[59]

Adaptation measures can help avoid outages from routine matters and extreme weather events. They have different degrees of protection. For example, underground electricity lines avoid all outages from extreme wind events because the lines are no longer exposed to the hazard. Insulated cables are estimated to reduce outages by about 50%, because they are still susceptible to large, falling branches.[60] We compared each measure's performance against a base case in which existing overhead infrastructure is periodically replaced as it reaches the end of its life.

Our findings from the cost-benefit analysis were mixed

We found that all 4 adaptation measures reduced electricity outages and helped to adapt distribution networks to the effects of extreme wind, but only one adaptation measure, insulated cables, delivered a positive return on investment at the 4% discount rate (Figure 13).[61]

Figure 13: Benefit-cost ratios of adaptation measures by scenario and discount rate

Source: ACIL Allen, *Economic assessment of adapting electricity distribution networks to climate change*, Infrastructure Victoria, 2023.

We also assessed the present value of embodied emissions associated with emissions from manufacturing new capital items, such as cables and construction emissions, such as from installing new insulated cables or trenching for underground cables. We found embodied carbon costs were less than 2% of the total capital cost for the base case, undergrounding and insulated cable. The embodied carbon of tree replacement was higher, at about 4% of the total capital cost of the measure.[62]

The electricity distribution network exemplar gave us an opportunity to discuss potential real options. Real options are options embedded in a plan or project to assist with managing future uncertainty. The word "real" simply refers the options relating to physical assets, as opposed to financial or commercial options – although the concept is similar. In an adaptation pathways approach, we looked at options for upgrading electricity distribution lines more slowly, as they reached their end of life, which might reduce the cost of upgrading them.

Our analysis pointed to several research gaps and complexities. These included the amenity benefits of undergrounding.

The amenity benefits of undergrounding

We analysed the costs and benefits of undergrounding power lines. Undergrounding is expensive and we found that it is not a cost-effective way to adapt electricity distribution networks to the likely future effects of extreme wind. But undergrounding can deliver major amenity benefits, including a better streetscape and more tree cover. Studies in other parts of Australia suggest that undergrounding can deliver a positive return on investment when amenity benefits are included in the analysis, but we did not consider that these estimates could be extended to Victoria.[63]

The effects of climate change on future generations

Analysts can capture future benefits and avoid maladaptation by using real options analysis and sequencing adaptation options using a pathways approach to climate resilience. But benefits that occur a long time into the future can be difficult to capture in a cost-benefit analysis. Analysts use discount rates to compare benefits that occur at different points in time. The choice of discount rate affects the value placed on future benefits. Our study used the Victorian Government's recommended approach in selecting discount rates, but other methods are available that might be more appropriate for analysis over very long periods (see recommendation 6) in *Weathering the storm: adapting Victoria's infrastructure to climate change* for further discussion on discount rates).

More research and guidance can help address these uncertainties for future analysis. The full details of this cost-benefit analysis can be found in the technical report, *Economic assessment of adapting electricity distribution networks to climate change*, which is available on our website.

Climate adaptation means adding new methods to the existing assessment toolkit

Our analysis shows that it is possible to assess the economic return on investment of adaptation to climate change by conducting a site specific analysis. Our work shows that these assessments are practicable and worthwhile to prioritise adaptation efforts.

Infrastructure managers can adapt their economic assessment methodology to determine potential co-benefits, adaptation pathways, embodied emissions and maladaptation to prioritise investment. An overview of the steps for the road exemplars is shown in Table 10.

Table 10: Overview of steps for the road exemplars

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 technical, appropriate default values, and other guidance recommended in this guideline.	3.3 Consider the impacts that are difficult to monetise and apply non-market 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 tipping points for real options and develop adaptation pathways to appropriately sequence adaptation measures.

Step 7: Assess distributional impacts

7.1 Identify 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 BCR, 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.

Source: Arup, *Adapting Victoria's infrastructure to climate change: economic analysis of adaptation for roads*, Infrastructure Victoria, 2023.

Findings from the economic assessment

Infrastructure adaptation is worth investment

Our research question for phase 3 was: "What is the economic return on investment for selected climate change adaptation measures in the identified infrastructure sectors?"

Overall, we found a compelling case for investment in some infrastructure adaptation measures. From the 20 adaptation measures we assessed in the 3 exemplars, we found 14 measures had benefit-cost ratios greater than 1 at the 4% discount rate. At the 7% discount rate, we found up to 11 measures had benefit-cost ratios greater than 1 (Table 11).

Table 11: Benefit-cost ratios for the adaptation measures at 7% discount rate

Road exemplar relating to floods (metropolitan)*	BCR	Road exemplar relating to bushfires and landslides (regional)*	BCR	Electricity distribution networks exemplar relating to extreme wind (urban)**	BCR
Increase preventative maintenance such as repairs to preserve pavement condition (maintenance)	8.29	Increased programmed drainage clearing and vegetation management (maintenance)	11.52	Tree replacement with lower growth trees (lower cost)	0.71
Foamed bitumen stabilisation which improves the ability of road surfaces to withstand flooding (higher cost)	4.83	Post-fire erosion protection and slope stabilisation (maintenance)	1.37	Insulated cables (lower cost)	0.69
Water sensitive urban design such as bio-retention basins and catchment	4.66	Post-fire responsive drainage clearing (maintenance)	1.07	Undergrounding distribution infrastructure (higher cost)	0.34

improvements to reduce peak flooding (lower cost)					
Programmed rehabilitation of roads such as more frequent, extensive repairs and maintenance (maintenance)	4.06	Risk management plan (hazard management)	1.07	Grid-forming inverters (hazard management)	0.19
Optimising the road grade and improving drainage now to absorb 1-in-20 year flood events (higher cost)	2.03	Fire-resistant planting (lower cost)	0.82		
Optimising the road grade and improving drainage now to absorb 1-in-20 year flood events, and upgrade in the future to absorb 1-in-100 year flooding (higher cost)	1.71	Remediate 2 high risk slopes with flexible barriers (higher cost)	0.58		
Hazard management such as ITS solutions and rerouting to prevent further damage to roads after flooding (hazard management)	1.26	Fire break via a vegetation clearance zone (lower cost)	0.32		
New raised road viaduct (higher cost)	0.14	Remediate 11 high and moderate risk slopes with flexible barriers (higher cost)	0.28		

Source: ACIL Allen, *Economic assessment of adapting electricity distribution networks to climate change*, Infrastructure Victoria, 2023; Arup, *Adapting Victoria's infrastructure to climate change: economic analysis of adaptation for roads*, Infrastructure Victoria, 2023.

* Under future (2070, RCP8.5) climate conditions.

**Under future (2070, RCP4.5) climate conditions.

The economic return can vary depending on the exemplar, the adaptation measures and the discount rates used. Table 12 presents a summary of benefit-cost ranges for the adaptation measures at the 4% and 7% discount rates. It also shows more explicitly that less expensive adaptation options can produce the best outcomes. From the 11 adaptation measures with positive benefit-cost ratios at a 7% discount rate, 8 were either lower cost, maintenance or hazard management adaptation measures.

Table 12: Benefit-cost ratio (BCR) ranges for adaptation measures

Exemplar	Adaptation measures		4% discount rate	7% discount rate
Electricity distribution networks exemplar relating to extreme wind (urban)*	Lowest BCR	Grid-forming inverters (hazard management)	0.24	0.19
	Highest BCR	Insulated cables (lower cost)	1.16	0.69

Road exemplar relating to floods (metropolitan)**	Lowest BCR	New raised road viaduct (higher cost)	0.24	0.14
	Highest BCR	Increase preventative maintenance such as repairs to preserve pavement condition (maintenance)	7.84	8.29
Road exemplar relating to bushfires and landslides (regional)**	Lowest BCR	Remediate 11 high and moderate risk slopes with flexible barriers (higher cost)	0.48	0.28
	Highest BCR	Increased programmed drainage clearing and vegetation management (maintenance)	10.55	11.52

Source: ACIL Allen, *Economic assessment of adapting electricity distribution networks to climate change*, Infrastructure Victoria, 2023; Arup, *Adapting Victoria's infrastructure to climate change: economic analysis of adaptation for roads*, Infrastructure Victoria, 2023.

* Under future (20270, RCP4.5) climate conditions. Return on investment break-even point for insulated cables is at 4.7% discount rate.

** Under future (2070, RCP8.5) climate conditions.

Embodied emissions

Some infrastructure adaptation measures both mitigate the impacts from climate change risks, but also contribute to it by generating greenhouse gas emissions.[64] All higher cost measures for both roads and electricity distribution networks generated emissions, because upgrading or building new structures produces emissions by extracting, manufacturing and transporting materials, and during the construction process. The road maintenance measures for flood risk also had significant embodied emissions, as did insulated electricity cables for wind risk (Table 13).

Examining lower cost measures can help protect the environment and mitigate climate risks to infrastructure. Nature-based solutions can produce multiple benefits, including biodiversity protection, carbon sequestration and making communities more resilient to climate change.[65] For example water sensitive, urban design can preserve the health of waterways and mitigate flood levels. Post-fire erosion protection and slope stabilisation can help maintain biodiversity and help avoid landslides.

We found that embodied emissions are not sufficiently large to prevent the adoption of electricity distribution measures.[66] The roads study presented more of a challenge. For instance, building a new raised road viaduct to elevate roadways over floodplain areas would grant full resilience to flooding. But the embodied emissions from this option were 5 times more than the second most carbon intensive option.

Table 13: Embodied emissions for adaptation measures

Roads		Electricity distribution	
	tCO_2e*		% total capital cost**
New raised road viaduct (higher cost)	5,121.0	Undergrounding distribution infrastructure (higher cost) and insulated cables (lower cost)	2.1%
Programmed rehabilitation of roads such as more frequent, extensive repairs and maintenance (maintenance)	942.0	Tree replacement with lower growth trees (lower cost)	4.6%

Increase preventative maintenance such as repairs to preserve pavement condition (maintenance)	770.0
Optimising the road grade and improving drainage now to absorb 1-in-20 year flood events (higher cost)	276.0
Optimising the road grade and improving drainage now to absorb 1-in-20 year flood events, and upgrade in the future to absorb 1-in-100 year flooding events (higher cost)	227.0
Remediate 11 high and moderate risk slopes with flexible barriers (higher cost)	108.0
Remediate 2 high risk slopes with flexible barriers (higher cost)	56.0
Foamed bitumen stabilisation (higher cost)	16.3

Source: ACIL Allen, *Economic assessment of adapting electricity distribution networks to climate change*, Infrastructure Victoria, 2023; Arup, *Adapting Victoria's infrastructure to climate change: economic analysis of adaptation for roads*, Infrastructure Victoria, 2023.

*Tonnes of carbon dioxide equivalent.

** At 7% discount rate.

Objectives matter alongside the numbers

Cost-benefit analysis is just one tool used in decision-making. We found some measures did not return a positive benefit-cost ratio for the road exemplars, such as a new raised road viaduct for the flood analysis (BCR of 0.14 at 7% discount rate) and remediation of 11 high and moderate risk slopes with flexible barriers the bushfire and landslide analysis (BCR of 0.28 at 7% discount rate). But both these measures presented the greatest reduction in damage, downtime and risks to safety in their respective exemplars.[67]

These measures can have a lot of merit when the objective is overall risk reduction. For instance, if the infrastructure is highly critical and any downtime or disruptions would mean significant risk to communities or to the economy. Cost-benefit analysis can bring these matters to light, and decision-makers might need to also consider the specific context, criticality and any other trade-offs to select an appropriate response.[68]

Pathways for infrastructure investment

Both studies examined options to strategically invest in adaptation. Two adaptation measures against road flooding involved raising the road surface level so that it could withstand 1-in-20 year flooding events. One of those measures included an option to upgrade the road further at a later date so it could withstand even more intense rainfall events (1-in-100 year flooding events). Both presented benefit-cost ratios greater than 1, with the upgrade option ranking lower because it had extra costs.

This presents a potential adaptation pathway for the road. The road could be elevated now to withstand 1-in-20-year flooding events. The department could monitor the conditions that affect the economic case for more investment later. The elevation project proponent might embed real options in it to allow for a future upgrade. This would create an adaptive planning pathway. 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.[69]

The electricity distribution network study assumed a base case in which the existing network was gradually replaced over time. The case for infrastructure adaptation improves if parts of the network have older infrastructure than this assumption. For example, the benefit-cost ratio for insulated cables improves from 1.2 to 2.3 using a 4% discount rate. This indicates a good case for upgrading infrastructure to be more climate-resilient at end-of-life rather than replacing it during its useful life.[70]

Methodological lessons

During our research, we heard infrastructure managers were hesitant or unsure how to make an economic case for adapting infrastructure, given the lack of accepted government methodologies. Our studies demonstrate that the cost-benefit analysis framework is compatible with assessing infrastructure adaptation when adding new methods to the existing infrastructure assessment toolkit. Infrastructure managers can adapt economic assessment methodologies to include climate change impacts, co-benefits, adaptation pathways, embodied emissions and maladaptation to help support well-informed investment decisions.

Incomplete or uncertain data can be overcome

Better data will help people make better decisions, but infrastructure managers also have options to manage incomplete or uncertain data. We found that cost-benefit analysis can incorporate climate change risk. But to do this, we needed to find suitable ways to calibrate the climate impacts. For example, in applying climate projections to the electricity distribution analysis, we estimated that the probability of a strong wind event in a particular year is 19%. This is based on examination of the future climate projection where 9 events in the next 47 years were of equal or greater intensity than events in historical projections.[71]

Infrastructure managers can use sensible analytical judgment overcome data gaps in economic assessments for infrastructure adaptation. But providing more guidance and support can help make this easier. It can reduce uncertainty when managers must make judgements about parameters that apply to many different types of infrastructure.

Discount rates

Analysts use discount rates to compare the value of future costs and benefits that occur at different points in time. The choice of discount rate affects this value. It is particularly sensitive when value is produced over long-time horizons. A higher discount rate makes large costs on future generations seem insignificant, and actions taken now to benefit future generations might not be attractive because their immediate implementation costs seem much higher.[72] This can be true for infrastructure adaptation. Our study used the Victorian Government's recommended approach in selecting discount rates, but other discount rate approaches might be more appropriate.

The choice of discount rate influenced some, but not all, results in our study. For example, none of the electricity distribution adaptation measures reached a benefit-cost ratio of 1 with a 7% discount rate, but insulated cables had a benefit-cost ratio of 1.2 with a 4% discount rate.[73] The investment case improved for 2 road adaptation measures in our study, moving from 11 adaptation measures with benefit-cost ratios greater than 1 at the 7% discount rate, to 13 adaptation measures with a 4% discount rate.[74]

There is merit in further investigating the implications of discount rates for climate change analyses. At a minimum, using sensitivity tests for discount rates will better inform decision-making. The New South Wales Treasury already recommends this.[75]

Treatment of emissions

Analysts can incorporate emissions into infrastructure assessments. Clearer guidance on carbon values would help provide consistency for practitioners undertaking infrastructure assessment and reduce search costs for appropriate values. We adopted the carbon value guidance from New South Wales Treasury.[76] We have previously recommended the Victorian Government specify climate scenarios and carbon value in assessing infrastructure (see case study next page). The Victorian Government supported the intent of this recommendation.[77]

Reducing emissions will reduce the need to adapt infrastructure. But responding to the effects of climate change involves building infrastructure that generates emissions, including embodied emissions. We understand that industry guidance is still developing in this area. Our analyses used different sources of information to estimate embodied emissions. Arup estimated material volumes and applied emissions factors from the IS Materials Calculator (v2.0.13) from the Infrastructure Sustainability Council.[78] ACIL Allen used different sources including the Environment Product Declarations, the Epic, ICM, Etool database, and expert judgement to make assumptions, alongside input from an infrastructure costing firm.[79]

Case study

Climate scenarios and carbon value in *Victoria's infrastructure strategy 2021–2051*

Recommendation 11: Specify climate scenarios and carbon value in assessing infrastructure

In the next year, update and expand practical instructions for government agencies on integrating climate-related risks into infrastructure assessments. This should include high, medium and low future climate change scenarios, transitional risks and valuing emission reductions.

Current Victorian Government infrastructure investment guidance observes the Climate Change Act 2017 requirement to consider climate risk but has not provided detailed advice on doing so and includes some outdated information.[80] At a minimum, the Victorian Government should update this guidance to explicitly determine climate scenarios for assessing infrastructure resilience, such as a future with 1.5°C of warming, and potentially more extreme scenarios. It should also explicitly advise on the appropriate method of calculating the value of avoided carbon emissions, for use in calculating emission reduction benefits. The approaches recommended should consider recognised data,[81] research,[82] systems and tools.

The infrastructure Victoria builds now will exist long afterwards and must keep performing in a changing climate. But the Victorian Government has no infrastructure performance benchmark for future climate conditions. This creates difficulties for infrastructure planners, developers and operators in assessing and responding to climate change. It also means climate risk assessments use different assumptions and methodologies in infrastructure assessments, making comparisons difficult.

Producing new, specific guidance on assessing climate risk can complement existing infrastructure investment guidelines, including on future climate scenarios, assumptions, and the value of emission reductions.

Carbon valuation is a well-established tool to measure the value of emission reductions in economic assessments of proposals. Current Victorian carbon valuation guidance was prepared in 2013, relies on the since-repealed national carbon pricing mechanism,[83] and does not consider Victoria's goal to achieve net zero emissions by 2050.[84] It does not clarify appropriate emissions to count, such as whether to include emissions embodied in materials, those generated by lifetime operation of the infrastructure, or indirect emissions from energy use or emissions enabled by the proposal. In updating guidance, the Victorian Government can draw on a growing body of national and international literature on using scenarios to assess climate-related risks,[85] and guidance on emissions measurement and carbon valuation.[86]

Specific guidance for government agencies can encourage and make it easier for strategic planners and project developers to assess their climate risks. It fosters greater consistency, improving comparability across sectors and projects and contributing to a more efficient climate response. Better assessments support better decisions, reducing the risk of stranded assets or avoidable future refurbishment and retrofit, and help agencies meet their obligations under the *Climate Change Act 2017,* including emission reduction targets.[87] For example, the *Guidelines for assessing the impact of climate change on water availability* provide a consistent approach for applying high, medium and low climate scenarios, and considers population growth and water use behaviour. [88]

Source: Infrastructure Victoria, *Victoria's infrastructure strategy 2021–2051*, 2021.

Appendix 1: High-level risk assessment

Disclaimer: The risk register presented in this appendix was developed for the purpose of this Infrastructure Victoria study, reflecting the study's individual scope and detail. This risk register does not represent an official Victorian Government risk register.

Risk description *Refer to Guidance for advice on developing a climate risk statement, or refer to the Example Risks tab*	Sector	Consequence category (driving the primary consequence)	Natural hazards (climate related) *e.g. map against natural hazards to help understand how many risks relate to specific natural hazards and/or*								Worst case risk rating based on 2030 RCP8.5 climate change projections *The risk if the current control strategy fails completely, based on the risk assessment criteria outlined by your*			Worst case risk rating based on RCP 8.5 2070 climate change projections *The risk if the current control strategy fails completely, based on the risk assessment criteria outlined by your*		
			Sea level rise & coastal flooding	Mean temperature	Heatwaves/extreme heat days	Relative humidity	Bushfires	Extreme rainfall and flooding	Extreme storms (incl wind & hail)	Reduced rainfall / drought conditions	Likelihood	Consequence	Risk rating	Likelihood	Consequence	Risk rating
Reduced availability and quality of water due to changes in rainfall, temperature and fire conditions	Water	Infrastructure	✓	✓	✓		✓	✓	✓	✓	Likely	Moderate	High	Almost certain	Major	Extreme
Degradation or failure of water supply infrastructure due to changes in ground conditions (e.g. shrink/swell, chemical composition) caused by changes in rainfall, evaporation, groundwater and soil conditions	Water	Infrastructure	✓					✓		✓	Likely	Moderate	High	Almost certain	Major	Extreme
Degradation or failure of water sewer infrastructure due to changes in ground conditions (e.g. shrink/swell, chemical composition) caused by changes in rainfall, evaporation, groundwater and soil conditions	Water	Infrastructure, Environment	✓					✓		✓	Possible	Moderate	Medium	Likely	Moderate	High
Increased stress on water treatment operations due to increased stormwater entering the system or changes in the licence requirements due to stressed receiving environments	Water	Infrastructure	✓					✓		✓	Likely	Minor	Medium	Likely	Minor	Medium
Degradation or failure of stormwater or drainage infrastructure due to changes in ground conditions (e.g. shrink/swell, chemical composition) caused by changes in rainfall, evaporation, groundwater and soil conditions	Water	Infrastructure, Environment	✓					✓		✓	Likely	Minor	Medium	Likely	Moderate	High
Capacity of stormwater and drainage system exceeded due to increased intensity of rainfall events combined with outfalls being restricted by elevated sea levels or greater volume of runoff	Water	Infrastructure, Social	✓					✓			Likely	Moderate	High	Almost certain	Major	Extreme
Damage to or failure of water supply and treatment equipment due to extreme weather events (e.g. extreme heat, flooding, fire, wind)	Water	Infrastructure, Environment	✓		✓		✓	✓	✓		Likely	Minor	Medium	Almost certain	Moderate	High
Increased demand for water due to increased average and extreme temperatures	Water	Infrastructure, Social		✓	✓						Likely	Moderate	High	Almost certain	Moderate	High
Degradation or loss of cultural sites due to reduction in rainfall, frequent drought conditions or bushfires	Water	Social					✓			✓	Possible	Moderate	Medium	Likely	Moderate	High
Degradation of asphalt surfaces due to increased temperatures and extreme heat	Transport - roads	Infrastructure		✓	✓						Almost certain	Insignificant	Low	Almost certain	Minor	Medium
Degradation of road foundations due to changing ground conditions caused by lower rainfall, increased evaporation, change in groundwater	Transport - roads	Infrastructure	✓	✓						✓	Likely	Minor	Medium	Likely	Minor	Medium
Damage to roads and disruption of access due to extreme weather events (e.g. flooding, storm debris, fire) or landslip	Transport - roads	Infrastructure	✓				✓	✓	✓		Almost certain	Moderate	High	Almost certain	Moderate	High
Buckling of rail track due to extreme heat	Transport - rail	Infrastructure		✓	✓						Likely	Moderate	High	Almost certain	Moderate	High
Damage to rail infrastructure and disruption of services due to extreme weather events (heat, rainfall, fire, wind storm surge)	Transport - rail	Infrastructure	✓		✓		✓	✓	✓		Almost certain	Moderate	High	Almost certain	Moderate	High

Risk description *Refer to Guidance for advice on developing a climate risk statement, or refer to the Example Risks tab*	Sector	Consequence category (driving the primary consequence)	Natural hazards (climate related) *e.g. map against natural hazards to help understand how many risks relate to specific natural hazards and/or*								Worst case risk rating based on 2030 RCP8.5 climate change projections *The risk if the current control strategy fails completely, based on the risk assessment criteria outlined by your*			Worst case risk rating based on RCP 8.5 2070 climate change projections *The risk if the current control strategy fails completely, based on the risk assessment criteria outlined by your*		
			Sea level rise & coastal flooding	Mean temperature	Heatwaves/extreme heat days	Relative humidity	Bushfires	Extreme rainfall and flooding	Extreme storms (incl wind & hail)	Reduced rainfall / drought conditions	Likelihood	Consequence	Risk rating	Likelihood	Consequence	Risk rating
Damage to bridges due to flooding, fire, storm debris, scour or destabilisation of embankments	Transport - bridges	Infrastructure	✓				✓	✓	✓		Possible	Major	High	Likely	Major	High
Degradation of bridge structures due to increased temperatures, more corrosive conditions (e.g. increased CO_2, sea spray) or changed soil conditions.	Transport - bridges	Infrastructure, Social	✓	✓	✓	✓					Possible	Insignificant	Insignificant	Likely	Minor	Medium
Damage to, or restricted access to, tunnels due to flooding	Transport - tunnels	Infrastructure, Social	✓					✓			Possible	Minor	Low	Likely	Minor	Medium
Damage to, and degradation of, tunnel structures due to changes in soil conditions (e.g. change in groundwater elevation or corrosivity)	Transport - tunnels	Infrastructure	✓	✓						✓	Possible	Minor	Low	Likely	Minor	Medium
Damage to, and degradation of, runways due to extreme heat, flooding or change in ground conditions	Transport - airports	Infrastructure, Social	✓	✓	✓			✓		✓	Possible	Minor	Low	Possible	Minor	Low
Disruption of airport operations due to extreme weather events (e.g. storm, rainfall, wind, fire)	Transport - airports	Social	✓				✓	✓	✓		Almost certain	Insignificant	Low	Almost certain	Insignificant	Low
Damage to, and degradation of, port assets due to extreme heat, flooding, sea level rise, change in ground conditions and increased exposure to salt spray	Transport - ports	Infrastructure, Social	✓	✓	✓			✓		✓	Possible	Minor	Low	Almost certain	Major	Extreme
Disruption of port operations due to extreme weather events (e.g. storm, rainfall, wind, fire)	Transport - ports	Infrastructure, Social	✓				✓	✓	✓		Likely	Minor	Medium	Almost certain	Moderate	High
Damage to building structures due to extreme weather events (flood, fire, storms)	Buildings	Infrastructure, Social	✓				✓	✓	✓		Likely	Moderate	High	Almost certain	Moderate	High
Damage to building facades due to changes in temperature, wind conditions, exposure to fire or sea spray	Buildings	Infrastructure, Social	✓	✓	✓	✓	✓				Possible	Minor	Low	Likely	Minor	Medium
Damage to, or destabilisation of, buildings due to changes in ground conditions (e.g. shrink/swell, chemical composition) caused by changes in rainfall, evaporation, groundwater and soil conditions and erosion.	Buildings	Infrastructure, Social		✓	✓					✓	Likely	Minor	Medium	Likely	Minor	Medium
Reduction in comfort or safety of building occupants due to extreme weather conditions (e.g. extreme heat, fire, flood)	Buildings	Social	✓		✓		✓	✓	✓		Likely	Moderate	High	Likely	Moderate	High
Damage to, or degradation of, facilities due to extreme weather events (flood, fire, storms)	Facilities	Infrastructure, Social	✓		✓		✓	✓	✓		Likely	Minor	Medium	Likely	Minor	Medium
Reduced amenity, or increased maintenance requirements, of public open space due to changes in temperature and rainfall, or more frequent damage from storm events.	Facilities	Infrastructure, Social	✓	✓	✓		✓	✓	✓	✓	Likely	Insignificant	Low	Likely	Minor	Medium
Mobilisation of contamination from landfills due to fire, storm, flood, erosion or change in groundwater conditions	Facilities	Infrastructure, Social, Environment	✓				✓	✓	✓		Possible	Moderate	Medium	Possible	Moderate	Medium

Risk description *Refer to Guidance for advice on developing a climate risk statement, or refer to the Example Risks tab*	Sector	Consequence category (driving the primary consequence)	Natural hazards (climate related) *e.g. map against natural hazards to help understand how many risks relate to specific natural hazards and/or*								Worst case risk rating based on 2030 RCP8.5 climate change projections *The risk if the current control strategy fails completely, based on the risk assessment criteria outlined by your*			Worst case risk rating based on RCP 8.5 2070 climate change projections *The risk if the current control strategy fails completely, based on the risk assessment criteria outlined by your*		
			Sea level rise & coastal flooding	Mean temperature	Heatwaves/extreme heat days	Relative humidity	Bushfires	Extreme rainfall and flooding	Extreme storms (incl wind & hail)	Reduced rainfall / drought conditions	Likelihood	Consequence	Risk rating	Likelihood	Consequence	Risk rating
Cancellation of outdoor events due to extreme weather conditions (e.g. heat, storm, fire) posing unacceptable health risks	Facilities	Social		✓	✓		✓	✓	✓	✓	Likely	Minor	Medium	Almost certain	Minor	Medium
Damage to, or loss of, cultural sites due to extreme weather events (flooding, fire) or coastal erosion	Facilities	Social	✓		✓		✓	✓	✓		Possible	Moderate	Medium	Likely	Moderate	High
Increased frequency of electrical blackouts due to demand exceeding supply during extreme heat events	Energy - Elec	Infrastructure, Social		✓	✓						Almost certain	Moderate	High	Almost certain	Moderate	High
Damage to, or degradation of, electrical transmission and distribution assets due to extreme weather events (heat, flood, fire, storms)	Energy - Elec	Infrastructure	✓		✓		✓	✓	✓		Almost certain	Moderate	High	Almost certain	Moderate	High
Damage to, or degradation of, electricity generation assets due to extreme weather events (heat, flood, fire, storms)	Energy - Elec	Infrastructure	✓		✓		✓	✓	✓		Possible	Major	High	Possible	Major	High
Disruption to electricity generation assets as a result of environmental conditions (e.g. extreme wind, fire weather, or lack of water availability)	Energy - Elec	Infrastructure			✓		✓		✓	✓	Possible	Moderate	Medium	Likely	Moderate	High
Arching faults on electricity transmission lines	Energy - Elec	Infrastructure		✓	✓					✓	Possible	Minor	Low	Likely	Minor	Medium
Flooding of electrical substations (and battery banks)	Energy - Elec	Infrastructure									Unlikely	Moderate	Low	Possible	Moderate	Low
Degradation, or damage to, gas distribution assets due to changes in soil conditions (e.g. change in groundwater elevation or corrosivity)	Energy - Gas	Infrastructure		✓	✓					✓	Possible	Moderate	Medium	Possible	Moderate	Medium
Damage to offshore gas infrastructure due to extreme weather and sea level rise	Energy - Gas	Infrastructure	✓						✓		Possible	Moderate	Medium	Likely	Moderate	High
Damage to coastal, onshore gas infrastructure due to extreme weather events (e.g. fire, flood, storm) or coastal erosion	Energy - Gas	Infrastructure	✓		✓		✓	✓	✓		Possible	Moderate	Medium	Possible	Moderate	Medium
Degradation, or damage to, fixed line telecommunications distribution assets due to change in soil conditions (e.g. change in groundwater elevation or corrosivity) or solar radiation.	Telco - fixed line	Infrastructure		✓	✓					✓	Likely	Minor	Medium	Likely	Minor	Medium
Increased maintenance requirements of fixed line telecommunication pits and manholes due to flooding	Telco - fixed line	Infrastructure	✓					✓			Almost certain	Minor	Medium	Almost certain	Minor	Medium
Degradation, or damage to fixed line telecommunications distribution assets due to extreme weather events (e.g. heat fire, flood, storm)	Telco - fixed line	Infrastructure	✓		✓		✓	✓	✓		Almost certain	Minor	Medium	Almost certain	Moderate	High
Damage to fixed line telecommunication exchange stations due to extreme weather events (e.g. heat, fire, flood, storm)	Telco - fixed line	Infrastructure	✓		✓		✓	✓	✓		Possible	Moderate	Medium	Possible	Moderate	Medium
Damage to mobile transmission towers due to extreme weather events (e.g. heat, wind, fire)	Telco - mobile	Infrastructure			✓		✓		✓		Possible	Moderate	Medium	Possible	Moderate	Medium

Source: AECOM, 2022

Appendix 2: Risk register for electricity networks, public hospital buildings and roads

The risk register presented in this appendix was developed for the purpose of this Infrastructure Victoria study, reflecting the study's individual scope and detail. This risk register does not represent an official Victorian Government risk register.

Category	Risk Statement	Climate hazards					Consequence category (driving the primary consequence)	2030 Low (RCP 4.5)			2030 High (RCP8.5)			2070 Low (RCP 4.5)			2070 High (RCP8.5)			2030 risk score (combination of 2030 L and 2030 H)	Regional exposure (1-Low, 2-Med, 3-High)						Adaptive Capacity (general state level comment)	Extent of Flow on Impacts	Control effectiveness Score	Average regional exposure score	Urgency rating
		Extreme temperatures (hot days)	Bushfire	Extreme rainfall and flooding	Coastal storm event (flooding / erosion)	Storms - extreme wind / hail / lightning)		L	C	Risk	L	C	Risk	L	C	Risk	L	C	Risk		Barwon South West	Gippsland	Grampians	Greater Melbourne	Hume	Loddon Mallee	Score	Score			
Utilities – Electricity	Extreme temperatures (or heatwaves) leading to derating or sagging of lines of electricity transmission lines	Y					Infrastructure	Almost Certain	Minor	Medium	Almost Certain	Moderate	High	Almost Certain	Moderate	High	Almost Certain	Moderate	High	5	1	1	3	2	2	3	2	3	2	2.0	14.0
Utilities – Electricity	Extreme temperatures (or heatwaves) leading to buckling of electricity transmission towers	Y					Infrastructure	Unlikely	Major	Medium	Unlikely	Major	Medium	Unlikely	Major	Medium	Possible	Major	High	4	1	1	3	2	2	3	2	3	2	2.0	13.0
Utilities – Electricity	Storms, including extreme wind or lightning, leading to degradation and failure of electricity transmission lines or towers					Y	Infrastructure	Possible	Major	High	Possible	Major	High	Possible	Major	High	Likely	Major	High	6	2	2	2	2	3	2	2	3	2	2.2	15.2
Utilities – Electricity	Bushfire or grassfire leading to degradation and failure of electricity transmission lines or towers		Y				Infrastructure	Unlikely	Major	Medium	Possible	Major	High	Possible	Major	High	Likely	Major	High	5	2	3	2	2	3	2	2	3	2	2.3	14.3
Utilities – Electricity	Extreme rainfall related flooding leading to damage to transmission towers (i.e. destabilisation or impact from water-borne debris)			Y			Infrastructure	Unlikely	Moderate	Low	Unlikely	Moderate	Low	Possible	Moderate	Medium	Possible	Moderate	Medium	2	1	3	2	2	2	3	2	3	2	2.2	11.2
Utilities – Electricity	Extreme temperatures (or heatwaves) leading to degradation and sagging of electricity distribution lines	Y					Infrastructure	Possible	Minor	Low	Possible	Minor	Low	Possible	Minor	Low	Likely	Minor	Medium	2	1	1	3	2	2	3	2	3	2	2.0	11.0
Utilities – Electricity	Storms, including extreme wind or lightning, leading to failure of electricity distribution lines					Y	Infrastructure	Likely	Major	High	Likely	Major	High	Likely	Major	High	Likely	Major	High	6	2	2	2	2	3	2	2	3	2	2.2	15.2
Utilities – Electricity	Bushfire or grassfire leading to failure of electricity distribution lines		Y				Infrastructure	Possible	Moderate	Medium	Possible	Moderate	Medium	Possible	Moderate	Medium	Almost Certain	Moderate	High	4	2	3	2	2	3	2	2	3	2	2.3	13.3
Utilities – Electricity	Extreme rainfall related flooding leading to damage to distribution pole (i.e. destabilisation or impact from water-borne debris)			Y			Infrastructure	Unlikely	Moderate	Low	Unlikely	Moderate	Low	Possible	Moderate	Medium	Possible	Moderate	Medium	2	1	1	1	1	3	2	2	3	2	1.5	10.5
Utilities – Electricity	Extreme temperatures (or heatwave) leading to damage and failure of transmission substations	Y					Infrastructure	Unlikely	Minor	Low	Possible	Moderate	Medium	Possible	Moderate	Medium	Likely	Moderate	High	3	1	1	3	2	2	3	2	3	2	2.0	12.0
Utilities – Electricity	Storms, including extreme wind or lightning, leading to damage and failure of transmission substations					Y	Infrastructure	Unlikely	Minor	Low	Possible	Moderate	Medium	Possible	Moderate	Medium	Likely	Moderate	High	3	2	2	2	2	3	2	2	3	2	2.2	12.2
Utilities – Electricity	Bushfire or grassfire leading to damage and failure of transmission substations		Y				Infrastructure	Possible	Major	High	Possible	Major	High	Possible	Major	High	Possible	Major	High	6	2	3	1	1	3	2	2	3	2	2.0	15.0
Utilities – Electricity	Extreme rainfall related flooding leading to damage and failure of transmission substations			Y			Infrastructure	Unlikely	Major	Medium	Unlikely	Major	Medium	Unlikely	Major	Medium	Possible	Major	High	4	0	2	0	2	0	2	2	3	2	1.0	12.0
Utilities – Electricity	Coastal storm related flooding or erosion leading to degradation, damage and failure of transmission substations				Y		Infrastructure	Rare	Major	Low	Rare	Major	Low	Rare	Major	Low	Unlikely	Major	Medium	2	0	0	0	0	0	0	2	3	2	0.0	9.0

Category	Risk Statement	Climate hazards: Extreme temperatures (hot days)	Climate hazards: Bushfire	Climate hazards: Extreme rainfall and flooding	Climate hazards: Coastal storm event (flooding / erosion)	Climate hazards: Storms - extreme wind / hail / lightning)	Consequence category (driving the primary consequence)	2030 Low (RCP 4.5) L	2030 Low (RCP 4.5) C	2030 Low (RCP 4.5) Risk	2030 High (RCP8.5) L	2030 High (RCP8.5) C	2030 High (RCP8.5) Risk	2070 Low (RCP 4.5) L	2070 Low (RCP 4.5) C	2070 Low (RCP 4.5) Risk	2070 High (RCP8.5) L	2070 High (RCP8.5) C	2070 High (RCP8.5) Risk	2030 risk score (combination of 2030 L and 2030 H)	Regional exposure (1-Low, 2-Med, 3-High): Barwon South West	Gippsland	Grampians	Greater Melbourne	Hume	Loddon Mallee	Adaptive Capacity (general state level comment) Score	Extent of Flow on Impacts Score	Control effectiveness Score	Average regional exposure score	Urgency rating
Built Environment – Buildings	Bushfire events leading to damage to hospital structures		Y				Infrastructure	Rare	Major	Low	Rare	Major	Low	Rare	Major	Low	Unlikely	Major	Medium	2	1	1	1	2	2	2	3	3	2	1.5	11.5
Built Environment – Buildings	Extreme rainfall related flooding leading to damage to hospital structures			Y			Infrastructure	Possible	Major	High	Possible	Major	High	Possible	Major	High	Likely	Major	High	6	1	0	1	3	3	3	3	3	2	1.8	15.8
Built Environment – Buildings	Coastal storm related flooding or erosion leading to damage to hospital structures				Y		Infrastructure	Rare	Major	Low	Rare	Major	Low	Rare	Major	Low	Rare	Major	Low	2	0	0	0	1	0	0	3	3	2	0.2	10.2
Built Environment – Buildings	Extreme rainfall related flooding leading to damage to hospital plant and equipment attached to structures (e.g. HVAC)			Y			Infrastructure	Possible	Major	High	Possible	Major	High	Possible	Major	High	Likely	Major	High	6	1	0	1	3	3	3	2	3	2	1.8	14.8
Built Environment – Buildings	Bushfire events leading to damage to hospital plant and equipment attached to structures (e.g. HVAC)		Y				Infrastructure	Rare	Major	Low	Rare	Major	Low	Rare	Major	Low	Unlikely	Major	Medium	2	1	1	1	2	2	2	2	3	2	1.5	10.5
Built Environment – Buildings	Extreme temperatures (or heatwaves) leading to damage to hospital plant and equipment attached to structures (e.g. HVAC)	Y					Infrastructure	Possible	Moderate	Medium	Possible	Moderate	Medium	Possible	Moderate	Medium	Likely	Moderate	High	4	1	1	3	2	2	3	2	3	2	2.0	13.0
Built Environment – Buildings	Coastal storm related flooding or erosion leading to damage to hospital plant and equipment attached to structures (e.g. HVAC)				Y		Infrastructure	Rare	Major	Low	Rare	Major	Low	Rare	Major	Low	Rare	Major	Low	2	0	0	0	1	0	0	2	3	2	0.2	9.2
Built Environment – Buildings	Extreme rainfall related flooding leading to damage to hospital multi-level carparking structures			Y			Infrastructure	Unlikely	Moderate	Low	Unlikely	Moderate	Low	Possible	Moderate	Medium	Likely	Moderate	High	2	1	0	1	3	3	3	3	3	2	1.8	11.8
Built Environment – Buildings	Bushfire events leading to damage to hospital multi-level car parking structures		Y				Infrastructure	Rare	Moderate	Insignificant	Rare	Moderate	Insignificant	Rare	Moderate	Insignificant	Possible	Moderate	Medium	0	1	1	1	2	2	2	3	3	2	1.5	9.5
Built Environment – Buildings	Coastal storm related flooding or erosion leading to damage to hospital multi-level carparking structures				Y		Infrastructure	Rare	Moderate	Insignificant	Rare	Moderate	Insignificant	Rare	Moderate	Insignificant	Rare	Moderate	Insignificant	0	0	0	0	1	0	0	3	3	2	0.2	8.2
Built Environment – Buildings	Extreme rainfall related flooding leading to obstruction of, or damage to, onsite car parks, roads and pedestrian access			Y			Infrastructure	Possible	Moderate	Medium	Possible	Moderate	Medium	Possible	Moderate	Medium	Likely	Moderate	High	4	1	0	1	3	3	3	2	2	2	1.8	11.8
Built Environment – Buildings	Coastal storm related flooding or erosion leading to obstruction of, or damage to, onsite carparks, roads or pedestrian access				Y		Infrastructure	Rare	Moderate	Insignificant	Rare	Moderate	Insignificant	Rare	Moderate	Insignificant	Rare	Moderate	Insignificant	0	0	0	0	1	0	0	3	3	2	0.2	8.2

Category	Risk Statement	Climate hazards: Extreme temperatures (hot days)	Bushfire	Extreme rainfall and flooding	Coastal storm event (flooding / erosion)	Storms - extreme wind / hail / lightning)	Consequence category (driving the primary consequence)	2030 Low (RCP 4.5) L	C	Risk	2030 High (RCP8.5) L	C	Risk	2070 Low (RCP 4.5) L	C	Risk	2070 High (RCP8.5) L	C	Risk	2030 risk score (combination of 2030 L and 2030 H)	Regional exposure (1-Low, 2-Med, 3-High) Barwon South West	Gippsland	Grampians	Greater Melbourne	Hume	Loddon Mallee	Adaptive Capacity (general state level comment) Score	Extent of Flow on Impacts Score	Control effectiveness Score	Average regional exposure score	Urgency rating
Transport - Roads	Extreme temperatures (or heatwave) leading to damage to road surfaces	Y					Infrastructure	Likely	Minor	Medium	Likely	Minor	Medium	Likely	Minor	Medium	Almost Certain	Minor	Medium	4	1	1	3	2	2	3	2	3	2	2.0	13.0
Transport - Roads	Extreme rainfall related flooding leading to damage to road surfaces			Y			Infrastructure	Likely	Moderate	High	Likely	Moderate	High	Likely	Moderate	High	Almost Certain	Moderate	High	6	1	1	1	1	3	3	2	3	2	1.7	14.7
Transport - Roads	Bushfire or grassfire leading to damage to road surfaces		Y				Infrastructure	Possible	Minor	Low	Possible	Minor	Low	Possible	Minor	Low	Likely	Minor	Medium	2	3	3	2	2	3	2	2	3	2	2.5	11.5
Transport - Roads	Coastal storm related flooding or erosion leading to damage to road surfaces				Y		Infrastructure	Likely	Moderate	High	Likely	Moderate	High	Likely	Moderate	High	Almost Certain	Moderate	High	6	2	2	0	1	0	0	2	3	2	0.8	13.8
Transport - Roads	Extreme rainfall related flooding leading to damage to obstruction or closure of roads caused by inundation or landslip			Y			Infrastructure	Likely	Moderate	High	Likely	Moderate	High	Likely	Moderate	High	Almost Certain	Moderate	High	6	1	2	1	1	2	0	2	3	2	1.2	14.2
Transport - Roads	Coastal storm related flooding leading to obstruction or closure of roads caused by inundation or landslip				Y		Infrastructure	Possible	Moderate	Medium	Possible	Moderate	Medium	Possible	Moderate	Medium	Possible	Moderate	Medium	4	2	2	0	1	0	0	2	3	2	0.8	11.8
Transport - Roads	Bushfire or grassfire leading to obstruction or closure of roads caused by smoke or fire safety risk		Y				Infrastructure	Likely	Moderate	High	Likely	Moderate	High	Likely	Moderate	High	Almost Certain	Moderate	High	6	2	3	2	2	3	2	2	3	2	2.3	15.3
Transport - Roads	Storms, including extreme wind, leading to obstruction or closure of roads caused by fallen trees					Y	Infrastructure	Likely	Minor	Medium	Likely	Minor	Medium	Likely	Minor	Medium	Almost Certain	Moderate	High	4	2	3	2	2	3	2	2	3	2	2.3	13.3
Transport - Roads	Extreme rainfall leading to washout or collapse of roads			Y			Infrastructure	Possible	Major	High	Possible	Major	High	Possible	Major	High	Likely	Major	High	6	1	1	1	1	3	3	3	3	2	1.7	15.7
Transport - Roads	Coastal storm related erosion leading to collapse of roads				Y		Infrastructure	Unlikely	Major	Medium	Unlikely	Major	Medium	Unlikely	Major	Medium	Unlikely	Major	Medium	4	2	2	0	1	0	0	3	3	2	0.8	12.8

Likelihood definitions

Rating	Description
Almost certain	Has a greater than 90% chance of occurring in the assets' lifespan if the risk is not mitigated
Likely	Has a 60<90% chance of occurring in the assets' lifespan if the risk is not mitigated
Possible	Has a 30<60% chance of occurring in the assets' lifespan if the risk is not mitigated
Unlikely	Has a 10<30% chance of occurring in the assets' lifespan if the risk is not mitigated
Rare	Has a <10% chance of occurring in the assets' lifespan if the risk is not mitigated

*(Victorian Managed Insurance Authority, 2022) and (Coast Adapt, 2017)

Consequence definitions

Consequence and success criteria	Financial	Local growth and economy	Public health	Infrastructure	Governance	Community and lifestyle	Environment and sustainability
Severe	Direct loss or opportunity cost of more than $200M.	Full service or business performance disruption >1 weeks, partial disruption (months).	Severe adverse human health effects – leading to multiple events of total disability or fatalities.	Asset(s) completely damaged and/or large scale engineering works required for reinstating. Permanent damage and/or loss of infrastructure service across state. Retreat of infrastructure support and translocation of residential and commercial development.	Major policy shifts. Change to legislative requirements. Full change of management control.	The region would be seen as very unattractive, moribund and unable to support its community. Widespread and permanent loss of objects of cultural / heritage significance.	Major widespread loss of environmental amenity and progressive irrecoverable environmental damage
Major	Direct loss or opportunity cost of between $50M-$200M.	Full service or business performance disruption 2–7 days, sustained partial disruption (weeks).	Permanent physical injuries and fatalities may occur from an individual event.	Extensive structural damage to the asset(s) requiring extensive repair and significant engineering stabilisation work. Major disruption in the service of the asset – such as permanent loss of regional infrastructure services.	Notices issued by regulators for corrective actions. Changes required in management. Senior management responsibility questionable.	Severe and widespread decline in services and quality of life within the community. Widespread damage or localised permanent loss of objects of identified cultural / heritage significance.	Severe loss of environmental amenity and a danger of continuing environmental damage
Moderate	Direct loss or opportunity between $10 - $50M.	Full service or business performance disruption <2 days, consistent partial disruption (weeks).	Adverse human health effects, including mental health impacts.	Widespread (state) infrastructure damage and loss of service. Partial loss of local infrastructure. Moderate damage to some part of the structure of the asset(s) - damage recoverable by maintenance, repair and engineering stabilisation work. Moderate disruption in the service of the asset.	Investigation by regulators. Changes to management actions required.	General appreciable decline in quality of life. Localised damage to objects of cultural / heritage significance.	Isolated but significant instances of environmental damage that might be reversed with intensive efforts
Minor	Direct loss or opportunity between $2 - $10 M. Additional operational costs.	Part service or business performance disruption 1 day, limited partial disruption (days).	Slight adverse human health effects or general amenity issues. Minor mental health impacts.	Limited damage to some part of the asset(s) and require some small scale stabilisation work resulting in minor/localised service disruption. Some minor restoration work required. Need for new/modified ancillary equipment	General concern raised by regulators requiring response action.	Isolated but noticeable examples of decline in quality of life. Minor damage to objects of cultural / heritage significance.	Minor instances of environmental damage that could be reversed
Insignificant	Direct loss or opportunity cost of less than $1M.	Intermittent part service or business performance disruption, isolated partial disruption (days/hours).	No adverse human health effects or complaint.	Little disruption in service but no structural damage to the asset(s).	No changes to management required.	There would be minor areas in which the region was unable to maintain its current quality of life. Minor repairable damage to objects of cultural / heritage significance.	No environmental damage

(Victorian Managed Insurance Authority, 2022), (CSIRO, Maunsell & Phillips Fox, 2007) and (Australian Greenhouse Office 2006)

Risk matrix

		Consequence				
		Insignificant	*Minor*	*Moderate*	*Major*	*Severe*
Likelihood	*Almost certain*	Low	Medium	High	Extreme	Extreme
	Likely	Low	Medium	High	High	Extreme
	Possible	Insignificant	Low	Medium	High	High
	Unlikely	Insignificant	Low	Low	Medium	Medium
	Rare	Insignificant	isignifica	Insignificant	Low	Low

*(Victorian Managed Insurance Authority, 2022)

Rating criteria for urgency scoring

Risk Rating	*Score*	*Comment / Description*
High	3	Refer to the risk framework
Medium	2	
Low	1	
Insignificant	0	

Effectiveness of controls	*Score*	*Comment / Description*
Substantially effective	1	Existing controls address risk, are in operation and are applied consistently. Management is confident that the controls are effective and reliable. Ongoing monitoring is required.
Partially effective	2	Controls are only partially effective, require ongoing monitoring and may need to be redesigned, improved or supplemented.
Largely ineffective	3	Management cannot be confident that any degree of risk modification is being achieved. Controls need to be redesigned.

Extent of flow on impacts	*Score*	*Comment / Description*
High	3	Direct flow-on impacts to four or more sectors
Medium	2	Direct flow on impacts to up to three sectors
Low	1	Direct flow on impacts limited to two sectors

Adaptive Capacity	*Score*	*Comment / Description*
High	1	Service can be returned relatively quickly (hours), or alternative solutions such as redundancies are readily available
Medium	2	Service return within days, or some alternative redundancy solutions are available
Low	3	Return of asset service significantly delayed, no alternative redundancy solutions are readily available.

Source: AECOM, *Climate change consequences study,* Infrastructure Victoria, 2023.

Glossary

Term	Definition
adaptation	Adaptation is adjustment within natural or human systems in response to actual or projected stimuli or their effects, which aims to moderate harm or exploit beneficial opportunities.
adaptation action plans	Victoria has 7 system-based adaptation action plans. The plans guide Victorian Government adaptation efforts in each sector. The 7 sectors are the built environment, education and training, health and human services, natural environment, primary production, transport, and water cycle systems.
adaptation measure	A specific action implemented to reduce the impacts of climate change.
adaptive capacity	The ability for infrastructure or a system to successfully adjust to, or take advantage of or response to, the consequences from climate change impacts.
adaptive pathway approach	Sequences of interlinked and flexible adaptive actions and decision points, which can be implemented progressively over time depending on future dynamics and changes to climate change risks.
benefit-cost ratio	An indicator used to estimate the overall value-for-money of a project or proposal. A BCR greater (or less) than one means the net present value of all benefits exceed (or is smaller than) the net present value of costs
business case	A business case is a document that establishes an investment need, defines its benefits, explores interventions, estimates costs and confirms a preferred solution is deliverable.
carbon	A naturally occurring gas, also a by-product of burning fossil fuels from fossil carbon deposits, such as oil, gas, and coal, of burning biomass, of land use changes, and of industrial processes (e.g., cement production). It is the principal anthropogenic greenhouse gas that affects the Earth's radiative balance.
critical asset	Critical assets (physical, data/information, intellectual, process, technology) are those that are essential for supporting the social and business needs of both the local and national economy.
cascading impacts	Occur when an extreme 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.
compounding impacts	The combination of multiple drivers and/or hazards that contributes to societal and/or environmental risk.
climate change	A change in the state of the climate that persists for an extended period, typically decades or longer. Human-induced climate change is the result of a growing concentration of carbon and other greenhouse gases in the atmosphere
climate hazard	A phenomenon or human activity that may cause loss of life, injury or other health impacts, property damage, social and economic disruption or environmental degradation.

Term	Definition
climate projections	A 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.
climate model	Simulation of current and future climate change projections using modelling techniques.
cost-benefit analysis	A structured method that quantifies in monetary terms as many of the costs and benefits of a proposal as far as possible, including items for which the market does not provide a satisfactory measure of economic value.
disaster	Situation where widespread human, material, economic or environmental losses have occurred which exceeded the ability of the affected organisation, community or society to respond and recover using its own resources.
discount rate	A percentage rate used to convert future costs and benefits into present values to allow costs and benefits occurring at different points of time to be compared.
direct costs	Quantifiable losses incurred as a result of an event that have a direct market value, including damage and downtime of the asset from climate related hazards.
embodied emissions	The type of greenhouse gas emissions associated with materials used in construction, maintenance and disposal of infrastructure. This includes the emissions from the extraction, manufacturing, transportation, installation, maintenance, renovation and disposal of the materials used in these processes.
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 by a hazard.
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.
geospatial analysis	Visualisation and mapping of the exposure of vulnerable assets and operations in areas based on proximity to climate hazards.
greenhouse gas emissions	The production of gaseous constituents of the atmosphere, both natural and human-made, that absorb and emit radiation at specific wavelengths on the spectrum of terrestrial radiation emitted by the Earth’s surface, the atmosphere itself, and clouds. This property causes the greenhouse effect.
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.
indirect costs	Quantified flow-on consequences from downtime, including economic costs of disruption to freight and the community.

Term	Definition
infrastructure lifecycle	The process from the beginning of design until the end of the asset's life, including planning, development, construction, use, and decommissioning.
intangible	Direct and indirect damage that cannot be easily quantified in monetary terms, such as impacts on biodiversity, nature and health.
maladaptation	Actions that may lead to increased risk of adverse climate-related outcomes, including generating more greenhouse gas emissions, increased or shifted vulnerability to climate change, more inequitable outcomes, or diminished welfare, now or in the future. Most often, maladaptation is an unintended consequence.
mitigation	Actions taken to reduce greenhouse gas emissions or increase the amounts of greenhouse gases removed from the atmosphere.
net zero emissions	A state where the amount of greenhouse gas emissions produced by human activities equals the emissions removed from the atmosphere.
overlays	An overlay is a planning instrument/tool that applies to land with special features such as flood or bushfire risk.
preventative measures	The use of predictive analysis to forecast asset failure and reduce the risk of failure by scheduling maintenance ahead of time based on historical data.
programmed drainage clearing	Clearing of surface and sub-surface drainage to reduce the extent and frequency of climate impacts.
recovery	The coordinated efforts and processes used to bring about the immediate, medium-term, and long-term holistic regeneration and enhancement of a community following an emergency.
resilience	The ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events. This involves the capacity of a system to continue providing services, when exposed to hazards or if a disruptive event occurs, in a timely and efficient manner, including by preserving and restoring its essential basic structures and functions.
retrofit	Addition of new technologies or features to old assets.
return on investment	A measure of the efficiency of an investment, expressed as a percentage or ratio by subtracting the cost of the investment from the gain from the investment and then dividing this amount by the cost of the investment.
risk	Effect of uncertainty on objectives or system operation. Risk is often characterised by reference to the likelihood of potential events, consequences, or a combination of these and how they can affect the achievement of objectives or system operation. Risk is often expressed in terms of a combination of the consequences of an event or a change in circumstances, and the associated likelihood of occurrence.
risk assessment	Process of comparing the results of risk analysis against risk criteria to determine whether the level of risk is acceptable or tolerable. Process to comprehend the nature of risk and to determine the level of risk. Risk analysis provides the basis for risk evaluation and decisions about risk treatment.

Term	Definition
robust	The strength or ability of elements, systems and other units of analysis to withstand a given level of stress or demand without suffering degradation or loss of function.
sensitivity	The degree to which a system is adversely or beneficially affected by hazard-related stimuli.
site-specific analysis	Analysis of local conditions and resource planning specific to an asset and its location.
vulnerability	The degree to which a system is susceptible to, or unable to cope with, adverse effects of hazards, including climate change, variability and extremes.

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