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FINAL REPORT

Project Title: A4: Accounting for Life-cycle Costing Implications and Network Performance Risks of Rain and Flood Events (2013/14 – 2015/16)

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A4: ACCOUNTING FOR LIFE-CYCLE COSTING IMPLICATIONS AND NETWORK PERFORMANCE RISKS OF RAIN AND FLOOD EVENTS

SUMMARY

The rain and flood events across Queensland between 2010 and 2013 showed that the road network is more exposed to damage from such events than desirable, with between 23% and 62% of the state-controlled network closed or with limited access over four summers. With increasingly uncertain climatic factors and stretched infrastructure budgets, efficient optimisation and prioritisation of works is critical to the overall network condition.

Historically, works programs were focused on the highest priority treatments, which in some cases resulted in an overall deterioration in network condition over time, as measured by condition indicators such as roughness and seal age. Strategic, timely maintenance and rehabilitation programs are thought to be preferable to one-off major reconstruction programs such as the recently completed Transport Network Reconstruction Program (TNRP).

There is a need to review pavement management, maintenance and rehabilitation practices to decrease exposure to damage in a cost-effective manner. In order to prove this, the current project has analysed the life-cycle costing implications of rain and flood events in Queensland through modelling three strategic options across a series of seven case studies.

Compared to the base case (reflecting actual events), two alternative options were examined, namely:

- Option 1 which represents a fully resilient road which was modelled to increase life-cycle costs over the seven case study links by a total of $146.5 million, with very high agency costs not sufficiently offset by reduced road user costs. This approach may be best suited to the most heavily trafficked roads, where any closures and repair works typically come at an extremely high economic cost and should be avoided if at all possible.
- Option 2, whereby a more proactive, progressive rehabilitation program in a 'stitch-in-time' approach is estimated to deliver a net life-cycle cost saving of $596 million, with a small increase in agency costs being more than compensated for in reduced road user costs due to a more resilient network. The rural highway network, particularly critical inland routes, may require this small increase in funding, but this will deliver value-for-money treatments through a more progressive program of works, avoiding the 'boom-and-bust' cycle of major programs such as the TNRP.

At a discount rate of 6%, this equates to a marginal benefit-cost ratio (MBCR) of approximately 0.9, i.e. a small net loss, for the full-resilience model, and a MBCR of 6.9 for the stitch-in-time model, meaning an extra dollar of agency spending on this selection of roads returns $6.9 in road user cost savings. For a best-for-network strategy, which selects the option which maximises net benefits, the MBCR is approximately 3.7.

The analysis also highlighted two critical factors in this discussion – the uncertainty surrounding future extreme climate and weather events in the face of predicted increased climate risks to Queensland, and the importance of treating pavements within their target life before the start of accelerated deterioration.

Based on the outcomes of this project, a number of recommendations have been made:

- to review and update relative funding of various road and maintenance activities by road type and environment
- to consider options for more flexible and responsive funding models
- to develop and encourage relevant programs for accelerated funding of overdue rehabilitation works
- to explore enhanced climate and flood modelling in planning
- to drive stronger consideration of route-based investment prioritisation
- to consider sharing these findings with Queensland Treasury, other state and territory road agencies, and the Commonwealth to demonstrate a strategic approach to improving network resilience
- to consider integrating the findings of different case studies into international activities, and provide an opportunity for comparisons to be made relating to economic, social and environmental challenges (the concept of climate analoguing).

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1 INTRODUCTION

A series of three consecutive summers from 2010 to 2013 inflicted widespread flooding and natural disaster damage across Queensland, leading to significant damage to state infrastructure assets. Road pavements were heavily impacted, through extreme overland flow of floodwaters and long periods of inundation, leading to the saturation and weakening of vulnerable pavements across many regions. As a result, an unprecedented program of repair and reconstruction took place across the state, with a shared funding arrangement between the Commonwealth and state governments leading to an investment in excess of $6 billion in the road network.

The major damage incurred highlighted the high exposure of the network to floods and extreme weather events, and while a concerted effort was made to improve the overall network resilience through reconstruction works, there remains a high level of risk to further major damage should events of this nature occur in the future.

This project commenced to provide clarity to the Queensland Department of Transport and Main Roads (TMR) and government funding bodies on the life-cycle cost implications of flood and extreme weather events, and the funding levels required to enable the desirable levels of service to be achieved.

The project approaches this analysis firstly by looking at a series of seven case studies, representative of a range of typical pavements across the network, in order to calculate the life-cycle cost implications of two alternative funding scenarios, and compares these results to the best-estimate of actual network life-cycle costing.

Analyses of this nature are inherently difficult due to the high level of uncertainty surrounding many critical components. Consequently, sensitivity analyses have been undertaken to better define the possible economic risks with respect to varying event recurrence intervals, as well as looking at the effect of aging seals and accelerated deterioration on pavements that have exceeded their expected service life.

1.1 Report outline

This report presents a comprehensive background to the analysis, including:

- a summary of the scope and damage relating to rain and flood events in Queensland (Section 2), both historically and with a focus on the 2010–13 events
- a broad outline of the Transport Network Recovery Program (TNRP) undertaken in response to the widespread damage across the network (Section 3)
- the basis for the selection of case studies used to analyse the life-cycle cost implications of these events and a summary of the location and characteristics of these cases (Section 4).

The life-cycle cost analysis has been undertaken through a customised model developed by the ARRB Group in 2015, with the results presented and discussed in terms of:

- the initial analysis into the three scenarios, including the analysis approach, methodology and assumptions within the model (Section 5)
- the sensitivity analyses undertaken to evaluate the impact of key variables within the life-cycle costing framework (Section 6)
- a discussion of the key observations and lessons learnt from the project (Section 7).

A detailed exploration of the case studies, with tables documenting the impact of events, road closures, alternative routes, repair/reconstruction works and model output has been documented previously under the 2014–15 NACOE program (Peters & Beecroft 2015).

2 IMPACTS OF CLIMATE AND WEATHER ON ROAD INFRASTRUCTURE

2.1 Background

Pavements in rural areas are often designed for a life-cycle of 20–30 years, with ongoing routine maintenance and resurfacing at intervals of 8–10 years to ensure serviceability, depending on the region and pavement/surface type. The global climate is facing a period of increased uncertainty, with modelling indicating that within the coming decades, Queensland will be faced with numerous potential impacts to infrastructure.

The issues addressed in this report and the looming uncertainties presented by climate change are not able to be separated for the purposes of analysis and in terms of forward planning. While it is not generally possible to determine whether any single event has been brought about due to climate change, the underlying trends can be adopted in modelling and, subsequently, into decision making by asset owners.

Reports by the CSIRO (2015) and the Department of the Environment (Commonwealth of Australia 2015) note some of the key impacts of a changing climate as they could be expected to impact upon the Queensland road network, including:

- A high-end projected sea level rise of 1.1 metres by 2100 would place 4700 km, or $12.9 billion worth of Queensland's coastal road infrastructure at high risk of inundation and erosion.
- While remaining highly variable in frequency and intensity, the total number of cyclones may decrease, with tropical cyclones in the more intense categories (3–5) projected to increase. By 2030, there is projected to be a 60% increase in severe storm intensity, rising to a 140% increase by 2070.
- Cyclones are also likely to impact the coastline further south than has traditionally been the case, as sea temperatures rise off the coast of southern Queensland. The likely cyclone formation and decay zone could shift 100 km south during this century, increasing the probability of direct impacts with the heavily populated south-east Queensland region.
- Total rainfall across the state is projected to decrease or remain the same, however extreme rainfall intensity is projected to increase, driven by a warmer, wetter atmosphere. This could result in more regular and more extreme flooding events.

Each of these factors is projected to increase the network-wide risk to pavements, and should be taken into account when projecting future maintenance and rehabilitation funding. Conversely, in what could lead to cost savings in certain regions, a drier climate with fewer total cyclones and heavy rainfall events (even if they are more severe) may lead to less regular interventions to maintain a given level of service.

In light of modelling such as this, acknowledging the significant infrastructure risks and developing adaptation strategies for road infrastructure has been a research topic of increased prominence over recent years, advancing even since the beginning of this research project in 2013.

Transport infrastructure represents a significant, long-term investment. Modern networks are subject to extensive predictive modelling that has allowed asset owners to schedule regular maintenance and rehabilitation within a managed budget. Climate change and the associated impacts on localised weather patterns causes a disruption to these models, and introduces significant uncertainty for asset managers (OECD/ITF 2015).

In this context, work conducted by ARRB for TMR in 2008 involved the development of a Climate Change Framework (Evans et al. 2008). This project highlighted the possible impacts of climate change on road transport with specific reference to the Queensland context. It provided an overview of the impacts of climate change on the Queensland road network. In particular, the effects of climate change on operations and infrastructure due to temperature changes, changes in precipitation, rising sea levels, and increased storm activity. Additionally, the short and long-term impacts of climate change as they may affect Queensland and the implications of these for road infrastructure assets, were considered.

The project provided a framework that could assist road agencies in the formulation of a response to these changes, especially in terms of road network management. A Climate Change Framework was presented which provides a decision-making tool to consider uncertainty, incorporate probabilistic approaches to assessing risk, and is designed to assist road authorities in determining investment choices, and efficient development of adaptation responses. The Framework is divided into four phases:

- potential climate change effects – understanding the potential climate change effects (economic, social and environmental) for Queensland
- impacts on Queensland's transport infrastructure – assessment of how effects are likely to impact various regions of Queensland, modes and impacts on the wider network
- possible adaptation strategies – developing inventories of vulnerable infrastructure, assessment of adaptation options and the costs involved, determining investment priorities
- planning and project evaluation – identifying the fit of these priorities into TMR's strategic and planning and strategies.

This Framework therefore represents a holistic approach to addressing climate change adaptation from the identification of effects and impacts, through to the integration of adaptation strategies into planning, and development of strategies for addressing climate change.

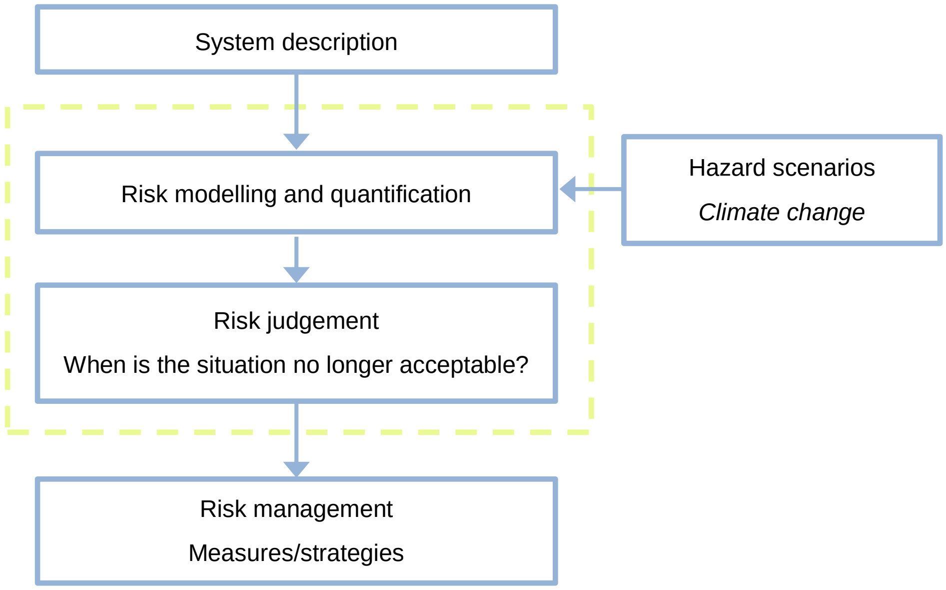
This current project is aligned to this work, in that it forms a detailed component of determining investment priorities, taking into consideration the criticality of infrastructure and adaptation measures for improved resilience and risk assessment. This issue is further discussed in Section 7.

Across the state of Queensland, asset managers have long been aware of the risk presented by extreme weather events and have (to varying degrees) balanced these risks within program budgets. For example, a region faced with a moderate-to-major flood event every 20–30 years would need to reconsider maintenance and rehabilitation treatment types and intervals when faced with the prospect of a major flood event occurring at an average 10–15 year interval.

The OECD/ITF (2015) report *Adapting Transport Infrastructure to Climate Change* highlights that there is a relationship between the expected asset life and its relative exposure to climate change impacts. Under this philosophy, a pavement with an expected life of 20–30 years would be classified as having a high risk of premature failure due to extreme weather events in a landscape of changing climatic effects.

A number of approaches have been presented which seek to incorporate the effects of a changing climate into road asset management planning. Huibregtse et al. (2016) present a risk-based methodology to quantify the effects of climate change on road infrastructure (Figure 2.1). The study looked at the resilience of road tunnels over time, in the face of traffic volumes and road user behaviour, and in an environment of increasing probability of tunnel closures due to the effects of climate change. This concept can be adapted to other forms of infrastructure.

Figure 2.1: Risk assessment approach for climate risks to infrastructure



Source: Adapted from Huibregtse et al. (2016).

The risk-based probabilistic approach meant that an urban tunnel, with a much lower tolerance for risk, was predicted to require intervention in the near future, while a regional tunnel with a higher tolerance for risk did not require intervention for the next 100+ years. This study highlighted the importance of combining a long-term analysis of potential pavement failure mechanisms (including extreme weather events) with an allocation of risk depending on the road category and traffic characteristics. According to Evans et al. (2009), it is noted that there are significant costs associated with redesigning, retrofitting, protecting and potentially relocating road infrastructure from extreme climatic weather events, so there is a need for more strategic, risk-based approaches to decision making and infrastructure design.

The issue of developing risk-based approaches is also being investigated extensively through the RIVA project initiative *Risk analysis of key transit axes of the federal main road network in the context of climate change* which is at the core of the AdSVIS[1] program initiated by the Federal Highway Research Institute (BASt) Germany. The aim of this project was to develop a methodology for identifying, analysing and assessing climate-related risks and validate these on selected routes in the German section of the Trans-European transport network. RIVA ties in with the ERA-NET ROAD project and RIMAROCC (*Risk Management for Roads in a Changing Climate*) project, and is an MS Excel-based method, using standardised measurement data (e.g. performance data of roads) and data of climate projections. It allows a first prioritisation of climate-related risks, and can be used for a comparison with other road infrastructure risks. It provides an important contribution to the development of risk management strategies as well as decision-making on necessary measures (Auerbach & Hermann 2014).

Similarly, Qiao et al. (2015) contend that in order to maintain a certain level of serviceability for road pavements, maintenance strategies need to be re-assessed and potentially altered in the face of a changing climate. This will flow through to a change in agency costs and road user costs under the new scenario. The paper advocated for a new assessment framework for such strategies, and presented a case study of three hypothetical treatments under current and predicted future climate models.

[1]In 2011, BASt Germany initiated the AsSVIS research program which is made up of 15 subprojects that together aim at analysis of climate change impacts on road infrastructure and maintenance, the conducting of vulnerability assessments for individual road infrastructure elements, and the development and testing of adaptation options and technologies.

The study concluded that climate change does have an effect on pavement maintenance strategies and life-cycle costing (in terms of agency costs and total costs), and that optimised maintenance may improve resilience against the effects of climate change, as compared to the alternative of reactive maintenance. Optimised maintenance implies triggering maintenance 8–16% earlier with a 1–2% increase in agency costs, but with this offset by a significant reduction in road user costs leading to an overall total cost saving.

In response to the major flooding across Queensland, which included extensive flooding of some areas thought to be relatively safe from such events, a state-wide flood mapping project was initiated (Queensland Reconstruction Authority 2013). The study mapped 99.3% of the state (with parts of Brisbane excluded) and incorporated validation by local councils. Flood events since the study have confirmed the findings. More specific and targeted town-based flood maps were also produced across most of the state.

Is it likely that closer collaboration between TMR, local councils, disaster relief bodies, emergency services and climate/flood modellers could assist in more accurately determining the relative vulnerability of links in the state and local road networks. This may allow future infrastructure planning with preferred road links and could better inform local residents of the likely impact of flooding on their property and access roads at various recurrence intervals.

2.2 Major rain and flood events in Queensland

With a large proportion of the state situated in tropical or subtropical climate zones, major rain and flood events have traditionally impacted Queensland every few years, with the average recurrence interval varying by location. Two major climate influences in Australia are the El Niño and La Niña cycles, collectively referred to as the El Niño-Southern Oscillation (ENSO) (Bureau of Meteorology 2016a & 2016b). El Niño typically leads to lower than average rainfall across the east of Australia, while La Niña events tend to result in higher than average rainfall across most of the year.

With much of Queensland already subject to highly seasonal rainfall, any increased precipitation over the summer months can lead to heavy flooding and saturated subgrade soils. Adding to this is the tropical storm season, which brings about heavy rain, wind and storm surges.

A commonly cited index by which ENSO is monitored is the Oceanic Niño Index (ONI), which takes a three-month running mean of the ocean surface temperature near the middle of the Pacific Ocean and compares this to a 30-year centred mean temperature (updated every 5 years) (NOAA/National Weather Service 2016a). The difference in measured temperature and the long-term mean is recorded as the ONI value, with a threshold of ± 0.5 °C from the long-term mean required to trigger an official El Niño or La Niña event. Values within 0.5 °C of the long-term mean are considered 'neutral'.

El Niño events are notoriously difficult to predict despite extensive research over recent decades, with a period of particularly high uncertainty during the southern hemisphere autumn season (L'Heureux 2015). This makes it very difficult to know with confidence whether El Niño, La Niña or neutral conditions are most likely during the upcoming summer. However, by July/August, models can predict around three-quarters of the summer fluctuations in ENSO.

There is generally considered to be a more predictable relationship between strong El Niño events and a strong La Niña event in the next 1–3 summers (Table 2.1). The 2015–16 summer has been identified as the strongest El Niño event since the 1997–98 summer, with both hitting a peak ONI of 2.3 (Halpert 2016). Each major El Niño event documented here was characterised by above average temperatures over most of Australia, as well as above average incidence of bushfires. In each case, the subsequent La Niña event led to below average temperatures over much of the country, above average rainfall and increased incidence of cyclones.

Table 2.1: Previously major El Niño events and associated La Niña in succeeding years

El Niño year	El Niño maximum ONI	La Niña year(s)	La Niña minimum ONI
1972–73	2.0	1973–76 (3 years)	–1.9
1982–83	2.1	1983–85 (2 years)	–1.1
1997–98	2.3	1998–2001 (3 years)	–1.6
2015–16	2.3		

The ONI has since shifted towards a neutral position (-0.3) as of August 2016 (NOAA/National Weather Service 2016b), from a peak of 2.3 in December 2015. The ENSO Alert System sits in *La Niña Watch* mode, and notes a 55–60% chance of La Niña conditions developing by October 2016 (prediction as at 17 August 2016).

With specific reference to Australia and Western Pacific conditions, the presence of a positive Indian Ocean Dipole (IOD, a similar phenomenon to El Niño but in the Indian Ocean) in 1982, 1997 and 2015 led to a magnification of El Niño conditions. A strongly negative IOD has been present since June 2016, which when combined with La Niña conditions, has typically led to more extreme La Niña impacts (Bureau of Meteorology 2015). La Niña events have led to major infrastructure damage across the Queensland network. Table 2.2 details the stronger La Niña events since 1915.

Table 2.2: Major La Niña events and associated damage, 1900–2014

Year(s)	Southern Oscillation Index	La Niña effect on Queensland
2010–12	Strong	▪ 2010 and 2011 were 3rd and 2nd wettest years on record for Australia ▪ Almost all of the state had record or top-decile rainfall in both years ▪ Numerous flooding events across nearly every region of the state, as detailed later in this report ▪ The Category 5 tropical cyclone Yasi was the second strongest cyclone to hit Queensland
1998–01	Moderate	▪ 2000 was, at the time, the second wettest year for Australia since 1974 ▪ July–September 1998: Widespread flooding across many parts of Queensland, with some regions experiencing four separate events over this period ▪ Six major tropical cyclones between late 1998 and early 2001 led to flooding in parts of the state
1988–89	Moderate	▪ July–September 1988: Flooding across western and south-east Queensland ▪ April/May 1989: Flooding throughout central Queensland
1973–76	Moderate to strong	▪ The longest sustained period of La Niña on record, nearly three years of above average falls ▪ January 1974: Queensland’s wettest month on record, exacerbated by tropical cyclone Wanda, leading to widespread damage. Brisbane had one of its worst floods on record ▪ A number of other cyclones impacted the state and caused further flooding
1970–72	Moderate	▪ February 1971: Tropical cyclone Dora makes landfall north of Brisbane, with record February rainfall ▪ December 1971: Tropical cyclone Althea causes major damage in north, central west and south east
1954–57	Moderate	▪ Very heavy rainfall but worst effects felt across central and northern NSW
1949–51	Moderate to strong	▪ Near-record single year rainfall across Queensland ▪ March 1950: Cyclone causes flooding in Townsville region and across western part of the state
1938–39	Moderate	▪ Record falls in some parts of far north Queensland, northern WA and the Northern Territory
1916–18	Strong	▪ Late 1916: Town of Clermont ‘washed away’ and later rebuilt on higher ground ▪ Early 1918: ‘Mackay Cyclone’ dumps 1411 mm in 3 days ▪ March 1918: Major cyclone hits Innisfail, widespread damage across the region

Source: Bureau of Meteorology (2015).

Based on this data, a moderate-to-major La Niña event can be expected across most regions of Queensland roughly every 10 years (usually, but not always, following a major El Niño). This estimate does not take into account any effects of accelerating climate change, which may have an effect on the severity and regularity of El Niño and La Niña events (Commonwealth of Australia 2015).

Looking at the relative impact of recognised El Niño and La Niña events across the state (Bureau of Meteorology 2016c), rainfall totals in El Niño summers are on average 82.4% to 108.0% of the average rainfall in neutral summers, while rainfall during La Niña summers is 128.1% to 147.1% of the average rainfall in neutral summers (Table 2.3).

Table 2.3: Average summer rainfall totals (September to April) in neutral, El Nino and La Nina years (1942–2015)

City	Average rainfall in neutral summers	Average rainfall in El Nino summers		Average rainfall in La Nina summers	
		Total (mm)	Percentage of neutral	Total (mm)	Percentage of neutral
Brisbane	807.9	843.0	104.4%	1119.4	138.6%
Nambour	1214.0	1311.2	108.0%	1774.8	146.2%
Rockhampton	630.2	566.5	89.9%	848.2	134.6%
Townsville	951.3	860.2	90.4%	1398.9	147.1%
Cairns	1752.4	1443.4	82.4%	2245.3	128.1%
Barcaldine	378.6	339.0	89.5%	549.2	145.1%
Charleville	368.5	332.4	90.2%	484.2	131.4%

Source: Bureau of Meteorology (2016c).

La Niña cycles also often coincide with major cyclones, as can be seen in Table 2.2. Cyclones and tropical storms can have severe outcomes when striking an already saturated landscape. Even when compared to the serious La Niña events over the last 110 years, the extreme weather that affected Queensland from 2010 to 2013 broke records across the state, causing widespread damage.

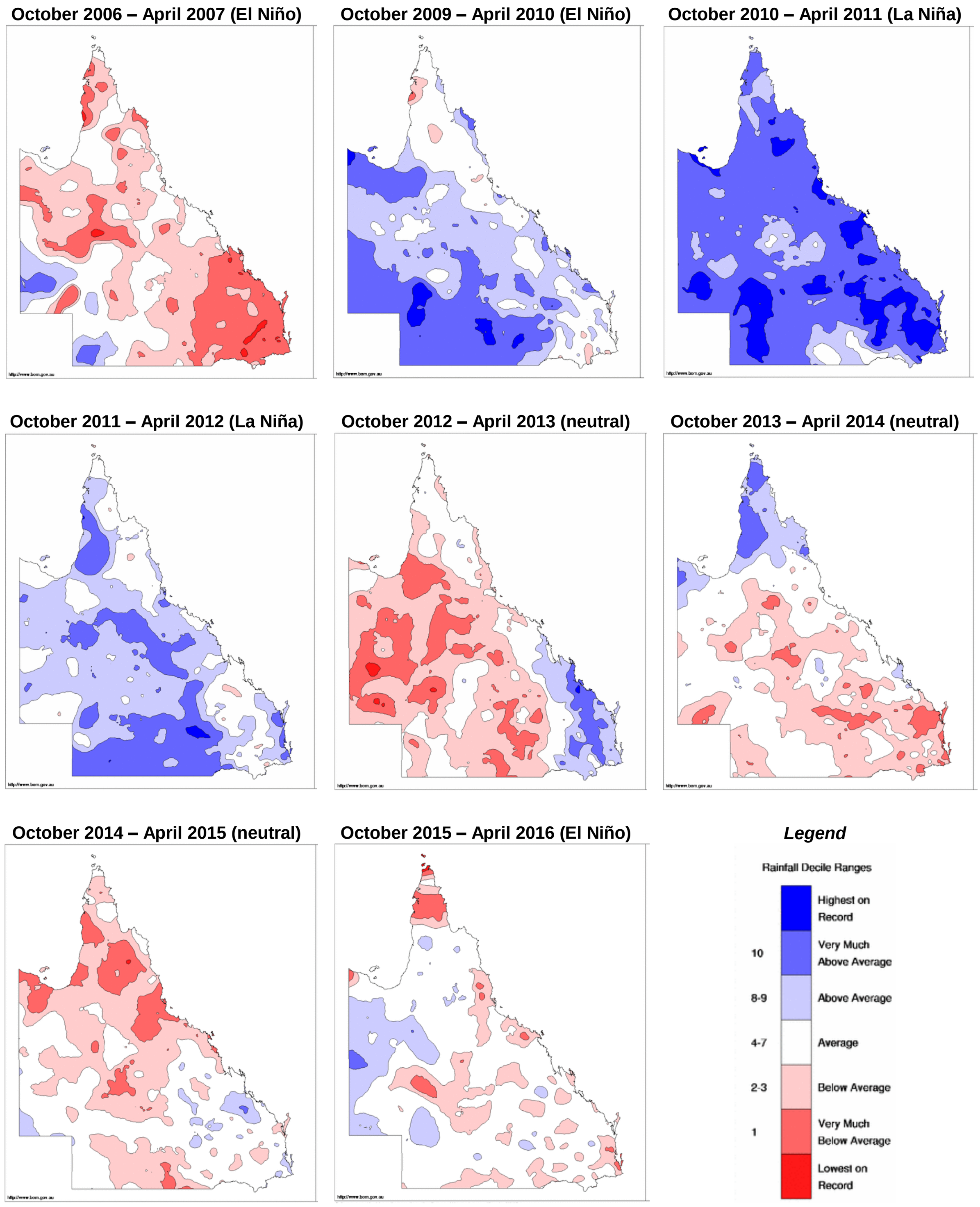
Figure 2.2 maps the annual rainfall in Queensland during the wet season from 2009 through to 2016. The 2006–07 map is also included for reference to a recent El Niño cycle. Rainfall was also very low across the state for the first 9 months of 2009, with the 2009–10 summer being notable for having relatively high rainfall across western Queensland despite prevailing El Niño conditions. The most severe drought impacts of that event were felt in Western Australia and Tasmania.

The Queensland Government recognises these climate risk factors, and in June 2016, included funding for a new *Queensland Climate Risk and Drought Resilience* program (Queensland Government 2016a). The program is targeted primarily at rural Queensland and the agricultural sector. This program will include funding for improved regional climate change forecasts and tailored adaptation strategies for the agriculture industry. Similar investment in forecasting and adaptation modelling and strategies for the infrastructure sector would likely be equally warranted.

In the coming decade, it is anticipated that predictive models and forecasting of weather and climate cycles will be an area of significant development. Some of the implications of this with respect to the asset management of road infrastructure were explored in an Austroads report on the *Impact of Climate Change on Road Infrastructure* (Austroads 2004).

In summary, it is likely that there is some capacity to optimise life-cycle costing of the network by utilising the improved knowledge of climatic patterns such as ENSO and IOD.

Figure 2.2: Rainfall deciles from October to April in select years (blue above average, red below average)



Source: Bureau of Meteorology (2016c).

2.3 Impact of the 2010–12 La Niña cycle

While La Niña events tend to only last for a single southern hemisphere summer, it is not uncommon for La Niña periods to stretch over two or even three summers (as documented in Table 2.1). The moderately strong El Niño cycle in 2009–10 had faded to neutral conditions by

April 2011, and quickly transitioned into a strong La Niña event. The sequence of events during this period is well documented in a report published by the Bureau of Meteorology (2014).

The 2010–11 summer included the following major weather events:

- three major tropical cyclones (Tasha, Yasi and Anthony)
- widespread flooding in central and southern Queensland
- severe flooding in the Brisbane River catchment and the broader south-east region
- unusually early monsoonal rains in northern Queensland
- prolonged flooding across western Queensland
- the second wettest summer on record for Queensland.

The La Niña conditions abated through mid-2011, but in September/October a second consecutive La Niña event had emerged, forecast to be a moderate event and not as severe as 2010–11. These conditions, especially considering the already-saturated landscape, gave rise to a number of further severe weather events across Queensland, including:

- two ex-tropical cyclones (Grant and Jasmine)
- further flooding across western, southern and south-east Queensland
- multiple tropical lows leading to heavy rainfall along coastal regions.

The 2012–13 season had relatively neutral conditions, although extensive damage was caused when Tropical Cyclone Oswald passed over Bundaberg in January 2013. The associated low also contributed to flooding in the northern, central southern and south-east regions of the state.

The 2010–13 flooding and natural disaster events were each given a unique identifier within the framework of the TNRP. The following events were all considered to be within the TNRP scope and all recovery/reconstruction projects specified an *Event ID* to identify the key cause of the damage (Table 2.4). It should be noted that most damage was caused by a combination of events in any particular region.

Table 2.4: Floods and weather events affecting the Queensland state network

Event year	TMR event ID	Event description
2010	7H	Qld Monsoonal Flooding & TC Olga, Neville, Ului & Paul, January–April 2010
	7J	South West Queensland Low and Associated Flooding, September 2010
	7K	South East Queensland Flooding, 9–12 October 2010
2011	7L	Queensland Flooding and Tropical Cyclone Tasha and Anthony, November 2010–February 2011
	7M	Severe Tropical Cyclone Yasi, 2 February 2011
	7N	Queensland Monsoonal Flooding, 28 February–March 2011
	7P	South West Flooding, April 2011
2012	7Q	Southern Queensland Flooding, November–December 2011
	7R	Western Queensland Tropical Low, 27 January–February 2012
	7S	South East Queensland Heavy Rainfall and Flooding, 23–26 January 2012
	7T	North Coast Storms and Flooding and East Coast Hybrid Low, 24 February 2012–7 March 2012
	7U	Tropical Low, Far Northern Queensland, 3–4 February 2012
	7V	Heavy Rainfall & Flooding Northern & Far Northern Queensland, 15 March 2012

Event year	TMR event ID	Event description
2013	13A	Tropical Cyclone Oswald and Associated Rainfall and Flooding, 21–29 January 2013
	13B	Central and Southern Queensland Low, 25 February–5 March 2013
	13C	Longreach Floods, 18 February 2013

Source: Queensland Government (2014).

2.4 Impacts of floods on infrastructure and network operations

The impacts of climate change on transport systems and infrastructure differ depending on the particular mode of transport, its geographical location, and its condition. A key challenge of climate change resilience is to determine the magnitude and direction of these changes at a local level (Evans et al. 2008).

Additionally, climate change impacts arising in the near- and longer-term can have an impact on the efficiency of transport operations and infrastructure. Climate change impacts are separated into direct (short-term) and indirect (longer-term) impacts. Often when an impact is direct, it will have immediate impact on the physical infrastructure and hence the existing transport system and network (TRB 2008b). These include impacts such as the diversion of freight routes resulting from immediate environmental events, or road closures and damage caused to the road (Evans et al. 2008).

Indirect impacts can affect the location of economic activities or levels of pollution, and as such are linked to the effects of human activity altering the demand for roads (Austroads 2004). Some examples include changes in population and demographics, long-term impacts for freight routes due to changes in production locations, changes in the ability of infrastructure to cope with increased (decreased) freight flows, and movement of people to populate new locations and activity centers. (Evans et al. 2009).

Climate-induced shifts in the distribution of agricultural production are anticipated to have implications for road usage, the building of new road infrastructure, and transport patterns/activities between emerging economic centres and urban areas (TRB 2008b). For example, climate-induced shifts in the distribution of agricultural production (i.e. due to water shortages) may lead to changes in the level and location of agricultural production. This in turn can have effects on the demand for transport, changes in freight routes, and changes in the size and location of population, e.g. through rural-urban and interstate migration to emerging economic centres (Evans et al. 2008, 2009).

In the context of Queensland, its climate is highly variable, experiencing more extreme weather events such as temperature changes, variations in rainfall (both reductions and increases), flooding, rising sea levels, storm surges, and increase in cyclone frequency and intensity. These events can vary from location to location and year to year. Their impacts can be further defined in terms of how they affect road transport infrastructure and operations in terms of short and long term implications on both infrastructure and network operations. This was a key area investigated in the Climate Change Framework (Evans et al. 2008).

For example, increases in intense precipitation events are associated with saturation of pavements and increases in scouring of roadbeds. Additionally, in terms of operations and maintenance, the increased incidence of storms can result in disruptions to network operations when roads are flooded, causing route delays, disruptions to transit services, freight and car travel, and greater need for emergency services. Appendix 1 provides an adapted table detailed in Evans et al. (2008 & 2009), and highlights these impacts on infrastructure and operations specifically for increased precipitation and floods.

2.5 Impact on the state-controlled road network

As identified in Section 2.4, there are impacts associated with floods on both the infrastructure condition and network operations. In expanding on the latter impacts, Table 2.5 details the impacts of the flood and disaster events across the state road network. Each of the four years saw very large areas of the network closed or with limited access. In a typical year, monsoonal and seasonal rainfall will lead to temporary closures (including prescribed discretionary lower (80%) load limits which may be applied during the wet season) of up to several thousand kilometres of roads across the network, however to have four consecutive years of between 23% and 62% closures or limited access is unprecedented in recent history.

The sequence of weather events between January 2010 and April 2011 contributed to the largest proportion of reconstruction costs, with around $5 billion of the total $6.9 billion allocated to roads damaged by these events.

As a result of the repeat weather events and the limited time between wet seasons, much of the reconstruction work from roads damaged in 2009–11 was not completed until 2013 or 2014.

Table 2.5: Natural disaster impacts 2009–13

Impact	2009–10	2010–11	2011–12	2012–13	Total
Length of state-controlled roads closed or with limited access for some time	18,370 km (55%)	20,610 km (62%)	10,890 km (33%)	7,655 km (23%)	27,304 km [(1)] (82%)
Local government areas (LGAs) disaster declared for restoration of essential public assets	67 (92%)	73 (100%)	50 (69%)	59 (81%)	73 (100%)
State-controlled roads requiring full or partial reconstruction (cumulative)	-	20% (6,709 km)	26% (8,545 km)	26% (8,732 km)	26% (8,732 km)
Reconstruction budget	$1.2 b	$3.8 b	$1 b	$0.9 b	$6.923 b
Progress made before next weather event	N/A	19%	42%	78%	N/A

1 Length of road link closed or with limited access, at least once over the four summers, due to natural disasters.

Notes:

- Data in the table should not be added for two or more summers as the data is not cumulative, with the exception of the length requiring reconstruction. Refer to the data for each summer separately, or use the total over the four summers provided above.
- Affected roads are shown on the maps at the back of the *TNRP Strategic Plan* (Queensland Government 2014) – this includes roads closed during disaster events, as well as damaged roads.
- QLD*Traffic* (13 19 40) data showing road closures/restrictions for each event is outlined in the spreadsheets attached to the SPO Questionnaire response.

3 THE TNRP/NDRRA PROGRAM

3.1 Establishment

TMR has a responsibility to reconnect Queensland communities and economies disrupted as a result of natural disasters. Owing to the widespread nature and unprecedented scale of the damage, existing recovery frameworks were not deemed suitable and the TNRP was established. The primary goal of the program was to manage the recovery and reconstruction of Queensland's integrated transport system following the extreme rainfall and flood events from 2010 to 2013. While the program covered roads, rail and marine infrastructure, by far the bulk of the effort involved work on rural pavements and road transport infrastructure (bridges, culverts etc.).

Funding was provided in accordance with the Commonwealth's Natural Disaster Recovery and Relief Arrangements (NDRRA) (Queensland Government 2013). The NDRRA is a joint federal/state program set up to provide financial assistance to community members, businesses, industry and local and state governments who have been affected by a defined and declared natural disaster in their region.

In the case of the 2010–13 flood and cyclone natural disasters across Queensland, NDRRA funding for the TNRP was predominantly applied in a joint funding arrangement, with a 75% contribution from the Commonwealth Government and the remaining 25% from the Queensland Government. A similar arrangement exists for funding recovery and reconstruction works in more 'typical' years, particularly in the tropical far north of the state which experiences major rain and flood events during most wet seasons.

The recovery and reconstruction of Queensland's transport network following damage during natural disasters in 2010, 2010–11, 2011–12 and 2012–13 led to the allocation of a budget of $6.92 billion, with funding directed towards (Queensland Government 2016b):

- 8741 km of the state road network
- 1733 structures including bridges and culverts
- 1421 locations requiring earthworks and batters
- 3335 locations needing clearing of silt and debris.

Policies regarding 'like-for-like' replacement of damaged sections meant that in many cases, further complementary funding was provided by the Queensland Government to efficiently deliver valuable additional works while reconstruction was underway.

3.2 Government oversight and control

The program was initiated following the 2010–13 natural disasters (Table 2.5), as was the States' Queensland Reconstruction Authority (QRA) which was established to overview the wider reconstruction effort in Queensland following those events.

QRA acted as the conduit between the state and Commonwealth in accordance with National Partnership Agreements, particularly with respect to the levels of funding and to certain program parameters in addition to the NDRRA guidelines, such as the eligibility criteria for works.

The Commonwealth established the Australian Government Reconstruction Inspectorate to undertake value-for-money reviews of the work. This activity has been the subject of a Commonwealth Government review (Commonwealth of Australia 2014). Part of the conclusion of the latest review states 'there have been no projects that the Inspectorate has determined do not represent value for money'.

3.3 Program management and coordination

TMR established a state-wide program office based in Brisbane to coordinate the TNRP. The TNRP Office strengthens program accountability, transparency and decision-making, and delivers consolidated reporting on the TMR state-wide recovery and reconstruction program. A key responsibility of the TNRP Office was the development, establishment and implementation of a structured, standardised operating framework based on TMR policies and processes.

Delivery of the state-wide program of works was managed by the department's regions in partnership with industry, local government and other government agencies. Input from regions, each transport mode and from a state-wide perspective across the public and private sectors was used to schedule and prioritise works, and maximise value for money and access for communities and industry at all times throughout the reconstruction activities. Regional Project Offices (RPOs) were established to support TMR Regional Offices in the planning, design and delivery of works.

The three sectors of the Queensland civil construction market, namely private, local government and RoadTek, were engaged through the TMR regions to deliver the work.

A significant feature of the TNRP was the coordination and integration for delivery of work identified within and funded by other programs. Coordination occurs where those works may have been impacted by the in-scope events and where coordination with reconstruction works would result in greater project efficiencies and better value-for-money outcomes than if the projects were undertaken separately. Coordination involved managing contracts that incorporated a component of non-TNRP work, or delivering complementary work through the same contract.

Regional Directors and other project owners were responsible for seeking approval for reconstruction and complementary works funding within the relevant guidelines and through the relevant governance mechanisms. The program of works was funded via the QRA, Queensland Transport and Roads Investment Program (QTRIP) allocations and other funding sources.

3.4 Budgets and expenditure

As of June 2015, the final works were completed on roads damaged during the natural disaster events in 2010, 2011, 2012 and 2013 activation periods. The final expenditure on the TNRP exceeded $6.9 billion. This expenditure can be broadly allocated to the event years in which the damage was incurred, although many roads did incur damage from multiple events (Table 3.1).

Table 3.1: Event expenditure summary

Event	2010 events 7H, 7J, 7K	2011 events 7L, 7M, 7N, 7P	2012 events 7Q, 7R, 7S, 7T, 7V	2013 events 13A, 13B, 13C	Total events
Approved budget ($ millions)	1239.8	3768.2	1015.3	900.0	6923.3
Expenditure to June 2015 ($ millions)	1223.9	3484.2	668.4	306.7	5683.2

4 CASE STUDY SELECTION

As highlighted in Section 2.4, there can be impacts on both the infrastructure and operations. This section addresses the first issue where the majority of network damage occurred to pavements, but also to other elements of the road structure such as unsealed shoulders, formation, floodway protection, bridge and culvert approaches, slopes and transverse/longitudinal waterways. Damage also occurred to culverts and bridges due to extreme concentrated flow of water and debris.

The selection of case studies in this project is based on a matrix approach where both the nature of the damage risk and the level of the damage risk are considered. Both are described below and case study selection has attempted to incorporate all of these so that analyses can include as many risk elements as possible. Each case chosen for analysis is representative of a class of road in a geographic part of the state such that, after completion of the case studies, some reasonable conclusions could be drawn across the broader network.

4.1 Nature of water-damage risks to roads

The rain events caused damage to the roads through concentrated water flow across or along roads and/or through inundation of lengths of the roads. The damage was broadly categorised by TMR into three overall groups:

- pavement damage – approximately 85%
- damage due to slope instability – approximately 10%
- damage to bridges, culverts and floodways – approximately 5%.

Concentrated flow occurs at or near watercourses where the water flows under, across or along the road, and damage results from a combination of the volume and the speed of flow. This damage is usually in the form of scouring of material, lifting and removal of bitumen surfaces and damage to culverts, protection devices and to the structure of the road itself. It can also, in extreme cases, cause damage to bridge/culvert foundations and the structure.

Inundation is the main cause of saturation damage to roads as the water is present adjacent to or above the road surface for extended periods, and is able to easily infiltrate pavements and shoulders that are susceptible to water. It occurs in one or a combination of prolonged rain events, where the road surface is submerged by flood waters or water lies adjacent to the road for long periods. Water infiltrates the pavement from the edges, through permeable layers, from above through inadequate surfacing or from below through natural springs or subsurface drainage that has been blocked and does not allow the free flow of water away from the pavement.

The other aspect of damage is the nature of the loading to roads. Heavy vehicles cause more stress on roads than light vehicles and, particularly when road pavements are wet, cause most of the damage. There has also been some documentation of heavy vehicles being allowed to access recently inundated roads earlier than preferable owing to the urgency for heavy vehicles to access isolated regions, or to return to the east coast following being stranded by road closures. The complexities of these issue were also noted in 2006 when Cyclone Larry in Northern Queensland caused severe damage to road infrastructure and crops, e.g. banana plantations. This had flow-on effects to the economy, where government expenditure was required to ‘get communities back on their feet’. Other impacts included the increase in price of bananas for consumers for example, and implications for the freight industry in terms of reduced freight demand due to lost production. In 2008/09 many state owned roads were limited to 80% carrying capacity in order to prevent long-term damage to the road, alternative re-routing onto unsealed roads not built to sustain heavy loads, and hence increased maintenance costs. This also had the effect of reducing the efficiency of the road transport industry by 20% (QDMR 2008; Evans et al. 2008).

4.2 Level of water-damage risk

The level of risk of damage could be related to two broad risk factors – the amount of loading (particularly from heavy vehicles) and the structure of the road itself.

Considerations when assessing water-damage risk include the extent of cracking in the seal, the level of protection provided by the shoulders (typically demonstrated by width and structure) that keeps water away from the outer wheel path, the quality and thickness of the pavement and subgrade material, and the level of maintenance to drainage structures. Drainage structures can be transverse structures such as culverts or floodways, and can also include longitudinal structures such as table drains. Risk is decreased if these drains are kept in a good condition and free of debris or other material, so that they operate efficiently and move water away from the road as quickly as possible without causing scour.

4.3 Case study selection

Case studies were selected from four regions to provide a representative set of cases to enable some broader conclusions for the whole network, based on the analysis methodology selected.

The cases chosen for the analysis are representative of a range of Queensland regions, traffic, road function and local climates (Table 4.1). The sections can be broadly categorised across their four regions, three general traffic levels of very low volume, low volume and moderate/high volume, across a range of predominant functions and with major event frequencies ranging from less than five years in the tropical north to greater than 15 years in the southwest of the state.

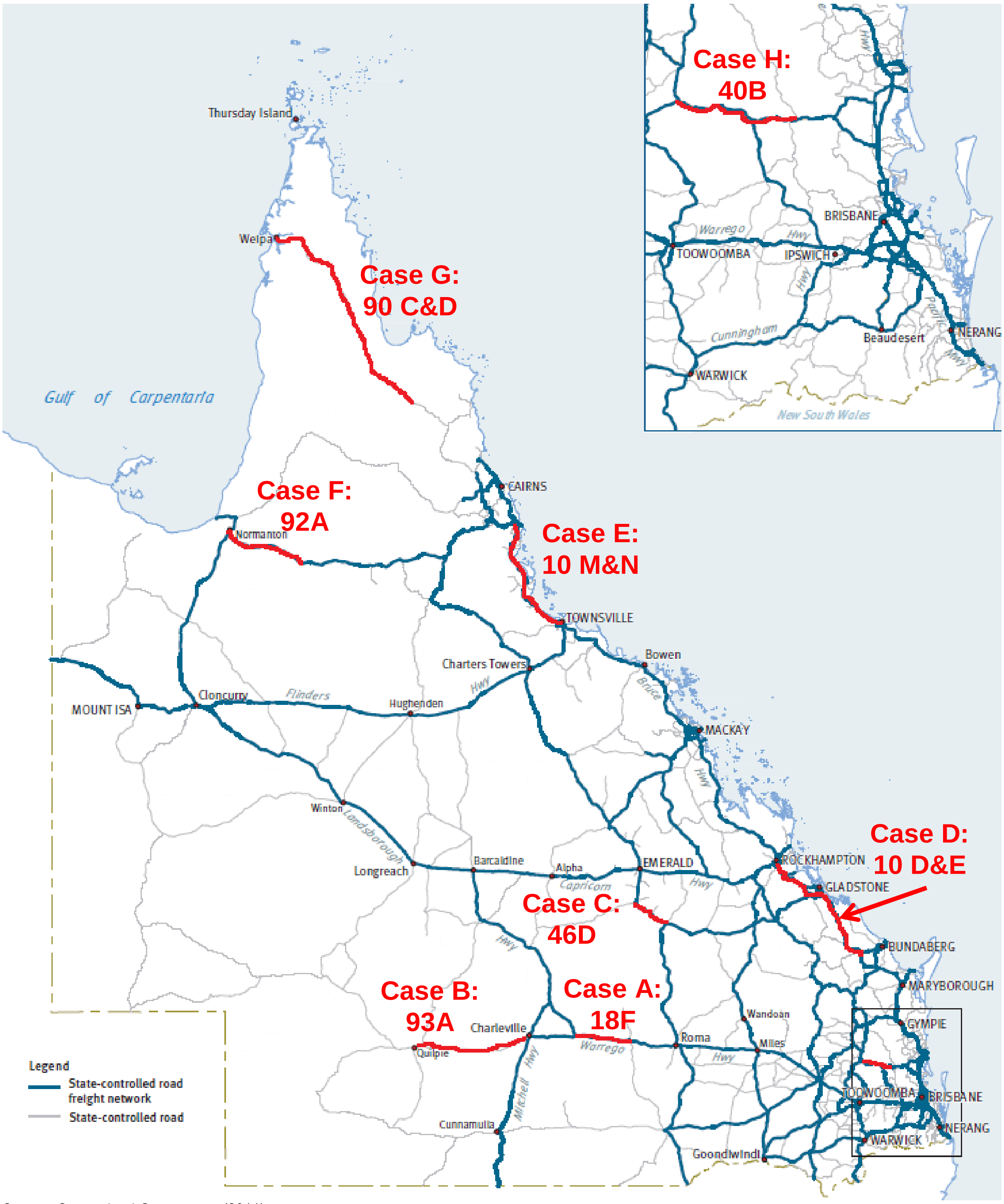
Table 4.1: Case studies analysed

	Region	Traffic volume	Function	Event frequency
Warrego Highway 18F	South West	Low (LL) (620 AADT)	Freight, agriculture	Rare (~15 years)
Diamantina Development Road 93A	South West	Very Low (VL) (120 AADT)	Remote link, agriculture, freight	Rare (~15 years)
Dawson Highway 46D	Central	Low (LL) (624 AADT)	Agriculture, mining, freight	Moderate (~10 years)
Bruce Highway 10D&E	Central	Moderate (AM) (4945 AADT)	Agriculture, freight	Moderate (~10 years)
Bruce Highway 10M&N	Far North & Northern	High (HH) (6500 AADT)	Freight, tourism	Frequent (<5 years)
Gulf Development Road 92A	Far North	Very Low (VL) (148 AADT)	Remote link, freight	Frequent (<5 years)
Peninsula Development Road 90C&D	Far North	Very Low (VL) (104 AADT)	Remote link, freight	Frequent (<5 years)

It should be noted that Case H, planned to be an analysis on the impact of major embankment failures on the D'Aguilar Highway through the Blackbutt Ranges, was removed as a case study due to difficulties in applying the same analysis methodology as the more pavement-focussed cases.

The locations are visually presented in Figure 4.1 and summarised in Table 4.2.

Figure 4.1: Map of case studies across Queensland



Source: Queensland Government (2011).

Table 4.2: Summary of case studies chosen

Region	Case study	Road	Link	Events	Event duration	Resilience (duration of impact on road link)	Alternative routes	TNRP cost ($m) (1)
South West (Roma)	A	Warrego Highway	18F Mitchell to Morven	7H	1 day	8 days	Significant delays to trip, but dependant on route	46.8
				7L	1 month	Negligible		
				7R	3 days	5-8 days		
	B	Diamantina Development Road	93A Charleville to Quilpie	7H	1 day	3 weeks	No reasonable alternative	15.6
				7L	1 month	Up to 3 weeks		
				7R	3 days	2 weeks		
Central (Fitzroy)	C	Dawson Highway	46D Rolleston to Springsure	7H	3 days	Intermittently closed over a 6 week period	Detour via Capricorn Hwy through Emerald	18.4
				7L	2 months	Intermittently closed over a 3 month period		
				7V	1 month	Intermittently closed over a 2 month period		
				13A	3 days	2 days		
	D	Bruce Highway	10D and 10E south of Rockhampton	7L	1 month	18 days	Inland highways, 1 hour or more detour	324.7
				13A	3 days	Negligible		
Northern and Far North	E	Bruce Highway	10M and 10N Townsville to Innisfail	7H	4 months	Negligible	Inland roads, major delay	108.2
				7L/M/N	3 months	Total of 8-12 days		
				7V	1 day	Negligible		
Far North (Cairns)	F	Gulf Development Road	92A Normanton to Croydon	7H	4 months	Total of 5 weeks	7+ hours delay to north or south	16.5
				7L/M/N	3 months	Total of 8 weeks		
	G	Peninsula Development Road	90C and 90D Laura to Weipa	7H	4 months	Closed for 3 months, load limits for 4 months	No reasonable alternative	76.1
				7L/M/N	3 months	Closed for 3 months, load limits for 5-6 months		
							Total:	**606.3**

1 Based on RIPA data, sourced September 2014.

5 MODELLING LIFE-CYCLE COSTS

5.1 Approach

As this project presented a range of unique requirements, it was decided that the best method of analysis was to develop a customised model, which allowed for a flexible range of inputs and variables to best model the network life-cycle cost effects of rain and flood events, as well as the modelling of a number of alternative options and to test the sensitivity of the model to changes in key inputs. This model was developed by ARRB Group, and was based on the framework developed for previous work in regions affected by major weather events (ARRB Group 2011; FCU Strategies & ARRB 2011).

The analysis has focussed on typical sections of roads in Queensland (case studies), which would allow some general conclusions to be drawn regarding the whole network. The risk factors chosen were related to the nature of the risk and to the level of risk of road damage from rain and flood events. The methodology included the damage itself, its immediate recovery time and cost, its eventual reconstruction and the cost of repairs, community and industry delays and associated costs. The analysis methodology considered the life-cycle costs of ‘what actually happened’ (the base case) and two possible alternative approaches, namely ‘full-resilience’ and ‘stitch-in-time’ over a 30-year period.

5.2 Methodology

5.2.1 Assumptions in the model

The following are the key assumptions built into the life-cycle costing model:

(a) The model was run over a 30-year analysis period. The period extended from 2006 through to 2035. It was selected so that a period of several years before the major events could be incorporated, as well as a significant length of time afterwards to allow for reasonable assumptions to be made regarding future event recurrence intervals.

(b) The model input broke down the road into nine categories, with different characteristics for each category based on ARMIS data and other data supplied by TMR.

(c) Each section was allocated into one of three sub-categories for both ‘condition’ and ‘vulnerability’, giving a total of nine categories. Condition was determined based on the measured pre-event level of rutting and roughness, while vulnerability was determined based on a combination of seal width, seal age, pavement age and soil properties (primarily the reactivity of the soil). Table 5.1 details some of the metrics which determine the allocation of 1 km sections into categories. The descriptions were considered typical, although they may not accurately describe each individual section.

Table 5.1: Matrix of sub-category characteristics

		Vulnerability		
		High	**Medium**	**Low**
Condition	**Poor**	Reactive subgrades, narrow seal width, aging seal and/or pavement with high roughness and high rut depths	Usually a non-reactive subgrade, adequate seal width, average seal and pavement age with high roughness and rutting	Non-reactive subgrades, wide seals, recently sealed but with high roughness and rutting
	Fair	Reactive subgrades, narrow seal width, aging seal and/or pavement with moderate roughness and rutting	Non-reactive subgrade, adequate seal width, average seal and pavement age with moderate roughness and rutting	Non-reactive subgrades, wide seals, recently sealed but with moderate roughness and/or rutting
	Good	Reactive subgrades, narrow seal width, aging seal and/or pavement but low roughness and minimal rutting	Non-reactive subgrade, adequate seal width, average seal and pavement age but low roughness and minimal rutting	Non-reactive subgrades, wide seals, recently sealed and/or rehabilitated with low roughness and minimal rutting

(d) The above nine representative sections of road were assigned values for roughness, seal age and pavement age based on the average from the data on the most recent survey of those sections. These values changed as the model moved through the years due to deterioration and reconstruction/resealing. Threshold points were set that trigger resealing or rehabilitation works, after which these parameters were adjusted to a 'reset' value. The mechanisms and standards used to set these levels are outlined in Section 5.2.2.

(e) Once major rehabilitation or reconstruction works were completed on a segment, the road was recognised to be in a better condition, not just through resetting the roughness level, but by reallocating the section to an appropriate lower level of vulnerability. This had an effect on the roughness progression going forward resulting in lower maintenance spending for less vulnerable roads.

(f) Cost variables were required to be estimated, and were based on historical data obtained through TMR records (annual maintenance spending, typical rehabilitation costs etc.).

(g) A generic heavy vehicle composition was calculated, which could be altered if specific data on the breakdown by vehicle type existed.

(h) The model incorporated a diversion option, based on actual diversion routes that were taken during flood events. This was utilised in calculating delay costs. Interestingly, in most cases accelerated deterioration took place on diversion routes, this being a consequence of lower class roads being used for this purpose. This contributed to higher whole-of-life road agency costs, and as an increase in costs to road users through inferior pavement quality. Utilising a diversion route came at an overall cost to road users (otherwise it would have been the primary route), particularly in the case of heavy vehicles, but it was still often seen as preferable to waiting for roads to re-open or shifting travel modes.

(i) A road user cost model was used which assigned a proportion of affected users across four responses to a closed road, for both commercial and private vehicles as outlined in Table 5.2 (values shown are for the Warrego Highway 18F). Each of these decisions had consequences in the modelling, with varying levels of additional costs being incurred to reflect the characteristics of an affected road link.

Table 5.2: Road user response model allocation

Vehicle type	Delay travel	Take alternative route	Use alternative mode	Cancel trip
Private	25%	25%	25%	25%
Commercial	20%	60%	10%	10%

(j) When a road was subjected to reconstruction works, three parameters were specified:

— the proportion of the affected link that is subject to speed restrictions

— the reduced speed limit for the section

— the average time per trip when traffic is stopped completely.

(k) Road closures over any portion of a route were assumed to close the entire route to through traffic. Any minor traffic flows within the route were ignored, as were minor flows of closure-exempt vehicles such as emergency services, essential goods and roadwork crews.

(l) Depending on the region of Queensland, assumptions were made on the likely recurrence interval of major events. The climate and weather patterns in Queensland have a long history of major weather events, and there is some evidence suggesting that the severity of events is rising due to the changing climate. Additional events during the analysis period were also important to accurately reflect the benefits of modified maintenance and rehabilitation programs.

(m) Reconstruction costs were taken directly from completed works forms filed through the TNRP.

5.2.2 Summary of options

The model considered three cases, and compared the outputs of each, as follows:

- The base case (or 'with project' case) uses actual data from the road closure database, the TNRP job completion reports and a range of ARMIS data to attempt to quantify the life-cycle cost impact of rain and flood events on the network. Funding under this scenario was limited, and as a consequence, a significant proportion of major works only occurred after event-incurred damage.
- Option 1 represents a 'full-resilience' scenario, where the road was engineered to be significantly immune to the effects of any major weather event, while recognising that in some areas complete immunity would be prohibitively expensive and socially disruptive to adjacent communities. This generally involved raising the pavement height significantly in vulnerable areas, increased sub-surface drainage, widening shoulders, importing high-quality granular materials (bitumen or cement modified), adding some sections of concrete pavement where inundation is likely, as well as rehabilitating and re-sealing the road at regular intervals. This was intended to help maintain low pavement and seal ages. The network would require increased drainage maintenance funding and ongoing high levels of funding.
- Option 2 represents a 'stitch-in-time' approach, involving periodic major work on the road targeted at both strategically valuable links and high vulnerability sections. This option requires increased spending on programmed rehabilitation, and lower (condition or age-based) trigger points for remedial works. The goal was to make the network more immune to the immediate effects of major rain and flood events, and more resilient such that the repair programs after events are a fraction of the current magnitude. Under this scenario, it is factored in that major events will still cause some road closures and delays, but that the damage will be greatly reduced and allow rapid emergency works to re-open sections.

The model required the setting of the roughness threshold and reset levels for each option to determine when to initiate rehabilitation programs. The model calculated the roughness over time (which is dependent on traffic levels, traffic composition and current vulnerability) and triggered rehabilitation in the following year in cases where the threshold level was reached. The reset level represents the average roughness for a section immediately after any rehabilitation was completed. The threshold levels were derived from the AusLink Ride Quality Indicator table (Table 5.3), with the thresholds set depending on the scenario (Table 5.4).

Table 5.3: Illustration of AusLink Ride Quality Indicator

Example QDMR AUSLINK		Traffic range (vehicles per day)					
Roughness range (IRI)	Roughness range (NRM)	0-500	501-1500	1501-3000	3001-5000	5001-10000	>10000
		VL	LL	BM	AM	HH	VH
0-2.8	0-75	Good	Good	Good	Good	Good	Good
2.8-3.2	75-85	Good	Good	Good	Good	Good	Mediocre
3.2-3.6	85-95	Good	Good	Mediocre	Mediocre	Mediocre	Mediocre
3.6-4.0	95-105	Good	Mediocre	Mediocre	Mediocre	Mediocre	Poor
4.0-4.6	105-120	Mediocre	Mediocre	Poor	Poor	Poor	Poor
4.6-5.2	120-135	Mediocre	Poor	Poor	Poor	Poor	Very poor
5.2-5.7	135-150	Poor	Poor	Very poor	Very poor	Very poor	Very poor
5.7-6.3	150-165	Poor	Very poor	Very poor	Very poor	Very poor	Very poor
>6.3	>165	Very poor	Very poor	Very poor	Very poor	Very poor	Very poor
Average speed limit		105	102	101	97	94	96

Source: Austroads (2009).

Table 5.4: Comparison of the three cases

	Base *As it happened*	**Option 1** *Full resilience*	**Option 2** *Stitch-in-time*
Description	What actually happened	Full resilience	Stitch-in time
Direct impact of event	As it happened	No load limits or speed restrictions, full closures assumed to be 20% of normal duration	Closure days, load limit days and speed limited days cut by *one third*
Impact on reconstruction	As it happened	No reconstruction required	Reconstruction still required after major events, but reduced by 50%
Network condition	Current practices Maintenance dependent on vulnerability	Network in very good condition at all times Maintenance dependent on vulnerability	Condition maintained at a high level Maintenance dependent on vulnerability
Rehabilitation works	Rehabilitation works triggered by condition	Regular and extensive rehabilitation work	Stitch-in-time rehabilitation works, targets vulnerable sections to similar standard as TNRP style works but with lower costs for a number of reasons
Rehabilitation threshold	AusLink Ride Quality Index Table, at crossover from Poor to Very Poor at the appropriate traffic level	AusLink Ride Quality Index Table, at crossover from Good to Mediocre at the appropriate traffic level	AusLink Ride Quality Index Table, at crossover from Mediocre to Poor at the appropriate traffic level
Rehabilitation reset	Reset to a level reflecting the average post-TNRP roughness on treated sections	Reset to a level significantly below the average post-TNRP roughness on treated sections	Reset to a level below the average post-TNRP roughness on treated sections

Detailed data behind each case study and assumptions made to reach those outcomes has been documented previously under the 2014–15 NACOE program (Beecroft & Peters 2015).

5.2.3 Discount rates in analysis

Confidence margins are calculated based on a default discount rate of 6%. This rate was chosen with reference to the *National Public Private Partnership Guideline – Volume 5: Discount Rate Methodology Guidance* (Commonwealth of Australia 2016). This guidance suggested use of the *Risk Free Rate* for projects where the predominant risk is borne by the public sector. This is equivalent to the long-term public sector bond rate at the start of the analysis period.

In the case of Queensland Treasury Corporation bond rates in 2006 (the first year in the life-cycle analysis), the longest listed maturity of 15 years had a current bond rate of 6.02% (Queensland Treasury Corporation 2006). This was considered a reasonable value with which to begin the analysis.

Since 2006, the global economic climate has undergone a period of recession and return on bonds has subsequently dropped significantly, sitting as low as 3.2% for a 17 year bond issued in 2016. An additional discount rate of 4% was therefore added for the initial analysis of results to account for the generally lower rates in the period 2012–16.

Similarly, there is some uncertainty over the higher end of risk, as the risk of major failure to a large percentage of the network across Queensland is relatively high compared to many other infrastructure investments. Subsequently, a discount rate of 8% was considered, equivalent to a typical long-term discount rate of 6% plus an additional risk factor of 2%.

5.3 Results

The life-cycle costs of the seven case studies were analysed over 30 years under both Option 1 and Option 2, with the respective results compared to the Base Case. The road sections were entered into the life-cycle costing model and the model assumptions were calibrated for each option.

Separate, extended sensitivity analyses to account for the various inherent uncertainties involved in this style of modelling are detailed in Section 6.

The results break down the savings in discounted economic present value terms into three categories:

- **Agency cost savings:** this represents the savings made due to spending on pavement maintenance, repair, rehabilitation and resealing. This is represented as a negative value where the agency costs rise under the option case.
- **Accident cost savings:** models calculating accident costs factor in the traffic volume and the average accident rate and cost. Presently, this does not fluctuate considerably due to the relatively short proportion of the network life that is subject to closure and/or changed conditions.
- **Other cost savings:** referring to a combination of costs incurred during flood and rain events, comprising elevated road user costs due to prematurely rough pavements, additional time costs due to diversions, lower running speeds and temporary speed limits, freight costs due to extended/delayed trips during events and the value of cancelled trips due to closed roads.

The marginal BCR (MBCR) under these scenarios was calculated using the method described in the *National Guidelines for Transport System Management in Australia* (Australian Transport Council 2006) (Equation 1). The change in total social generalised cost (TSGC, effectively road user costs plus agency costs) is divided by the change in road asset costs (RAC) to produce a figure representing the return for each additional dollar spent on the asset.

$$Marginal\ BCR = 1 - \frac{TSGC_2 - TSGC_1}{RAC_2 - RAC_1} \qquad 1$$

Source: Australian Transport Council (2006).

The aggregated results for all case studies are shown in Table 5.5, and illustrated in Figure 5.1 and Figure 5.2 for discount rates of 4%, 6% and 8%, and tabulated in Table 5.6

Table 5.5: Aggregate change in cost by category – Option 1 and Option 2

Change compared to base case for:	Option 1: Full resilience ($ millions)	Option 2: Stitch-in-time ($ millions)
Increase in agency costs	1722	128.9
Reduction in accident costs	87.2	39.7
Reduction in vehicle operating costs	251.8	161.4
Savings from reduced travel time	208.4	94
Freight delay savings	37.8	17.1
Savings from fewer trip cancellations and alternative mode trips	991.4	412.8
Overall change to net present value	**–146**	**596**

Figure 5.1: Aggregate life-cycle costs

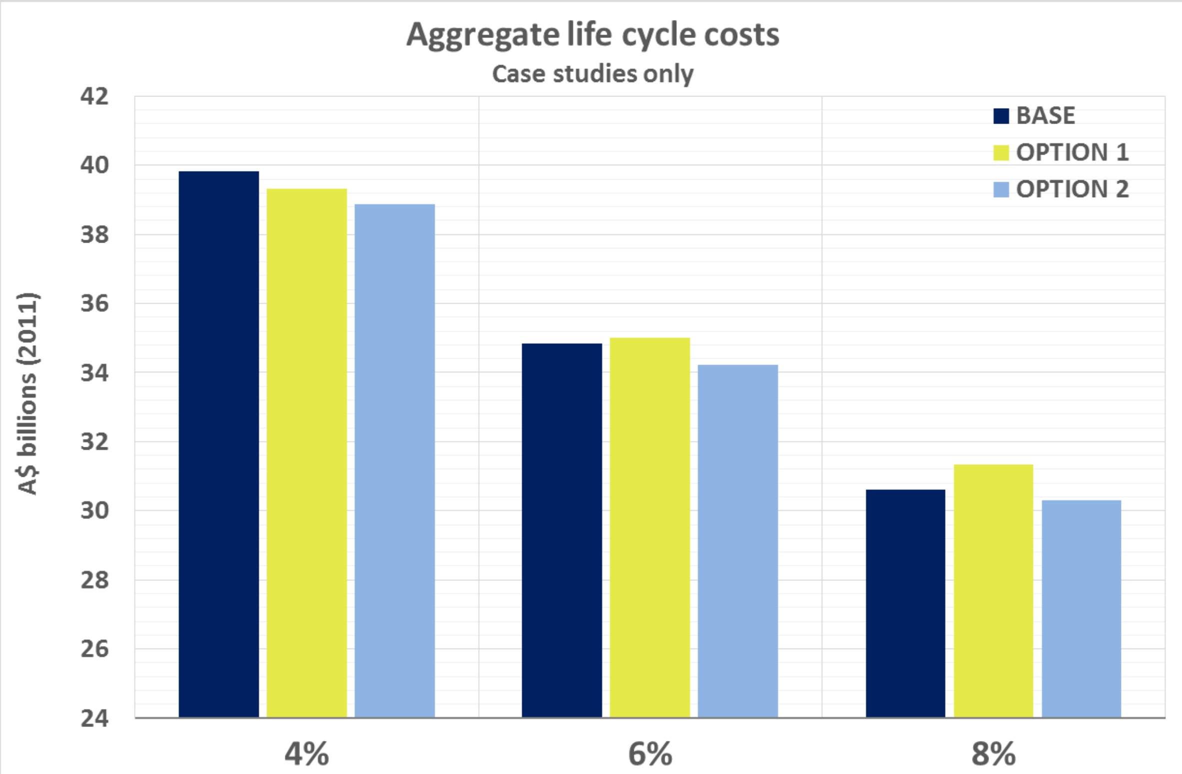


Figure 5.2: Aggregate life-cycle cost savings – change compared to base

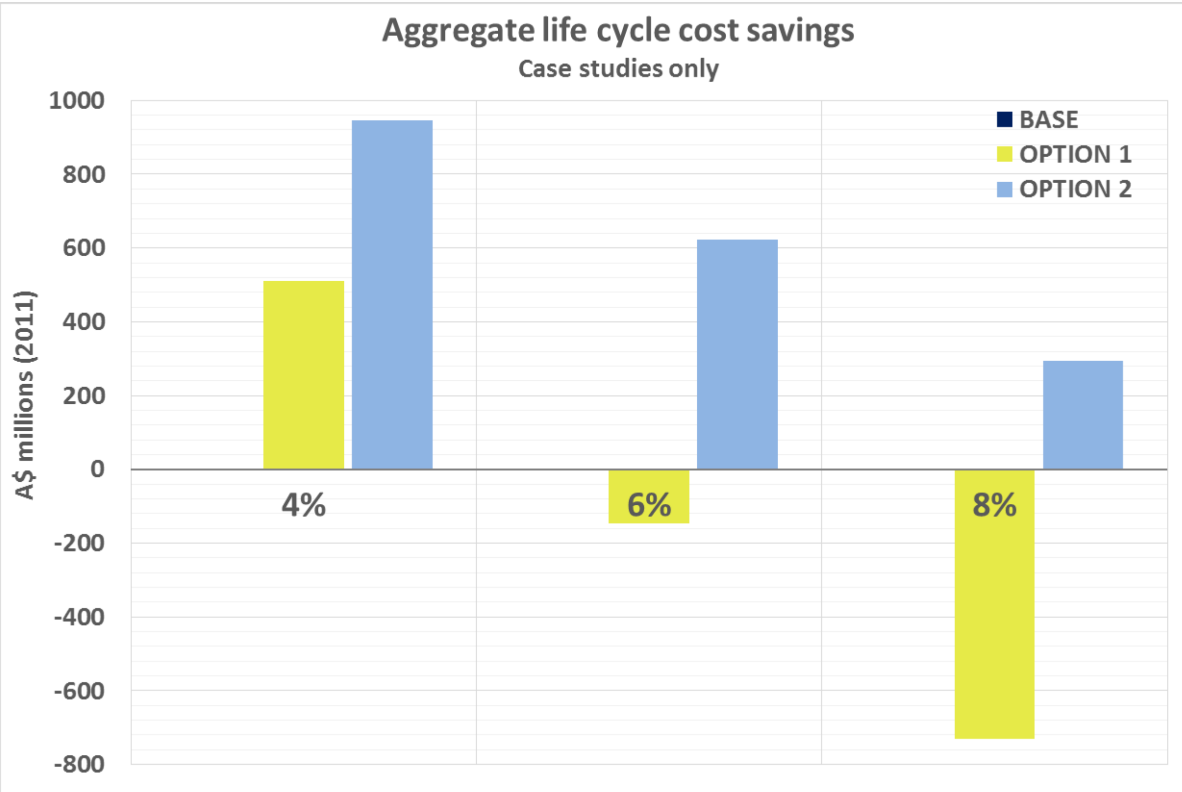


Table 5.6: Marginal BCRs for option cases

Option case	Discount rate	Marginal BCR
Option 1	4%	1.41
	6%	0.92
	8%	0.66
Option 2	4%	-6.44(1)
	6%	6.87
	8%	1.81

1 A negative MBCR can be described as a net saving arising from a reduction in agency costs. This means that a more technically efficient option has been found relative to the base case (usually the lowest cost option). In such circumstances the recommended formulation of the MBCR calculation is inappropriate, and the best option should be chosen based solely on NPV. The determination of MBCR under such circumstances is addressed by Harvey (2016).

At a 6% discount rate, the aggregate change in net present value (NPV) across the seven case studies for the Option 1 full-resilience case was -$146.5 million (i.e. a higher life-cycle cost), comprised of an increase in agency costs of $1.7 billion, offset by significantly reduced vehicle operating costs, travel time savings and a greatly reduced impact of road closures. At a discount rate of 6%, this equates to marginal BCR of 0.92, for the full-resilience model, i.e. a modest net loss, indicating that an additional dollar of agency spending would only return 92 cents.

Option 2, the stitch-in-time approach delivers a net saving represented by an NPV of $622 million, representing decreased life-cycle costs over the 30-year analysis period. This is made up of a small increase in agency costs, which is more than compensated for in the reduced vehicle operating and travel time costs, as well as a large reduction in costs incurred through trip cancellations and alternative-mode trips during road closures. The marginal benefit in this case is calculated at 6.87, meaning an extra dollar of spending on this selection of roads returns $6.87 in life-cycle user cost savings, i.e. a very significant saving.

Table 5.7 summarises the present value (PV) of the total transport cost (TTC) broken down by case study and option at a discount rate of 6%, and the percentage change in present value, i.e. of the NPV, calculated with reference to the base case.

Table 5.7: Summary of results – change in present values (discount rate of 6%)

Case	Road name	Metric	**Base:** *As it happened*	**Option 1** *Full resilience*	**Option 2** *Stitch-in-time*
CASE A	Warrego Highway 18F	PV of TTC	$820,064,655	$931,744,238	$788,015,189
		% change in NPV	–	13.6% higher	3.9% lower
CASE B	Diamantina Development Road 93A	PV of TTC	$422,937,223	$533,120,598	$419,520,557
		% change in NPV	–	26.1% higher	0.8% lower
CASE C	Dawson Highway 46D	PV of TTC	$978,922,020	$1,074,604,620	$964,519,483
		% change in NPV		9.8% higher	1.5% lower
CASE D	Bruce Highway 10D&E	PV of TTC	$14,495,304,436	$14,346,928,747	$14,423,146,589
		% change in NPV	–	1.0% lower	1.5% lower
CASE E	Bruce Highway 10M&N	PV of TTC	$16,002,124,449	$16,324,798,008	$15,935,219,221
		% change in NPV	-	2.0% higher	0.4% lower
CASE F	Gulf Development Road 92A	PV of TTC	$455,169,639	$490,209,532	$457,386,182
		% change in NPV	-	7.7% higher	0.5% higher
CASE G	Peninsula Development Road 90C&D	PV of TTC	$1,280,735,226	$896,577,403	$1,029,760,789
		% change in NPV	-	30.0% lower	19.6% lower

The resultant effect on pavements is not easy to measure, but by looking at some of the key metrics, we can compare the relative quality of the network as a result of implementing each case (Table 5.8).

Table 5.8: Key network quality indicators over analysis period under each scenario

	Base *As it happened*	**Option 1** *Full resilience*	**Option 2** *Stitch-in-time*
Average pavement age (years)	36.7	21.1	31.7
Average seal age (years)	6.8	4.3	4.8
Average roughness (IRI)	3.1	2.4	2.8
Event impact (km.days)	16,608	3,322	11,076
Rehabilitation impact (km.days)	6,240	5,175	6,421

Across the three scenarios, Option 1 delivers the lowest average pavement age, seal age and roughness values, by large margins in most cases. Option 2 reduces the average seal age on each link, however it has a mixed and relatively minor effect on pavement age. This is due to the tendency under this case to undertake more progressive rehabilitation, compared to Option 1 which required extensive reconstruction in the first decade of the analysis period.

The other key indicator that fluctuates under the three scenarios is the average length of time that the road is closed or affected by road works. Both alternative options were assumed to lead to large reductions in the average time the roads are closed in major weather events, although the time closed for road works is difficult to calculate.

One positive aspect of the alternative approaches is that the progressive works taking place around the network are unlikely to result in ‘major’ delays as were seen during the TNRP. Local communities will be affected by work on roads in their area, but the freight, agricultural and tourism industries will not notice any major disruption. Having road works spread across the network allows for alternative routes to be utilised, and any single trip is unlikely to encounter multiple adjoining major projects on a single journey.

A number of important observations can be drawn from these results, including:

(a) as a result of the shift to Option 1 or Option 2, there are significant savings in both accident costs and road user costs, owing primarily to

— savings from fewer trip cancellations and fewer required trips by alternative travel modes

— savings in vehicle operating costs with superior pavement conditions (lower roughness)

— travel time savings from fewer speed-limited sections and shorter reconstruction time

— freight delay savings as slower alternative routes for heavy vehicles are no longer required

— reduced accident costs (higher-quality pavements)

(b) agency costs are much higher in Option 1 as the work required to bring the network up to a fully resilient standard is extensive and costly

— during the TNRP, many damaged sections did not qualify for rehabilitation or reconstruction due to funding constraints, while under Option 1 all these sections would need to be brought up to a higher standard

(c) the agency cost changes under Option 2 were varied, with several case studies showing higher agency costs and others reflecting broadly similar costs overall

— in general, the anticipated savings from progressive network-wide rehabilitation initiatives mostly offsets the increased volume of work required to improve resilience

(d) the results differed by road type and traffic volume

— in low traffic areas, regular intervention will result in very high spending and the benefits may not be realised over the pavement life. It is generally difficult to economically justify major spending on a road with roughly 100 vehicles per day, but in many situations, work will be justified based on other criteria (community or developmental reasons). When major events strike, investment may be required to bring these roads back to a reasonable standard to meet these goals

— in moderate-traffic regions, a stitch-in-time approach (Option 2) leads to overall lower spending in agency costs due to the efficient spacing out of rehabilitation works. The more regular treatments lead to a better quality pavement on average, and costs incurred during events are reduced. This represents a case where reduced, but timely spending may actually lead to increased benefits

— on higher-traffic highways, Options 1 and 2 both require increased agency spending to maintain a more resilient network. One theory behind this is that despite the enormous spending during TNRP, many sections of road that suffered minor damage and are now moderately or highly vulnerable, have not been treated and would require major work under either a full resilience or stitch-in-time approach. This would necessitate a large increase in rehabilitation spending.

5.4 Network-wide considerations

While the seven case studies provide valuable information regarding the potential overall impact of the three options, it is important to view these case study results in the context of the entire Queensland state-controlled network.

The TMR ARMIS database has 1 km records of the network, which includes a value for the predominant environment type over that kilometre. The value for this entry consists of two parts – the subgrade soil reactivity (reactive or non-reactive) and the rainfall category (wet or dry). The environmental type for each section was one of the factors that determined the vulnerability of sections in the life-cycle costing model (Section 5.2).

The state-controlled road network is situated over reactive subgrades for just under 30% of its total length (Table 5.9). The roads selected as a part of the case study analysis contain only 104 km of reactive subgrades, comprising around 7% of the total sample.

Table 5.9: Comparison between case studies and overall network by environment type

Environmental zone	Case studies		Network-wide	
	Length (km)	Percentage	Length (km)	Percentage
Dry non-reactive (DNR)	444	29.08	13,387	40.12
Dry reactive (DR)	77	5.08	8897	26.67
Wet non-reactive (WNR)	977	64.07	10,140	30.39
Wet reactive (WR)	27	1.77	940	2.82
Total length	**1525**	(4.57% of total network)	**33,364**	100%

When viewed as a percentage of the five broad traffic ranges, the case studies prove to be a roughly proportional representation of the network, with the notable variations being on very low and very-high-traffic roads which both made up higher percentages of the case studies than their share of the overall network (Table 5.10).

These two classes returned results on the extremes, with the lowest trafficked roads suggesting prohibitive costs of rehabilitation, while major highways returned results pointing towards justification for heavy investment to prevent any event-related closures.

Table 5.10: Comparison between case studies and overall network by traffic volume

Class	Range (AADT)	Case studies		Network-wide	
		Length (km)	Percentage	Length (km)	Percentage
G1	<150	553	36.22	10,023	30.04
G2	150–500	250	16.40	8214	24.62
G3	500–1500	184	12.09	6280	18.82
G4	1500–5000	211	13.81	4974	14.91
G5	>5000	328	21.48	3873	11.61
Total length		**1525**	(4.57% of total)	**33,364**	**100%**

When further broken down into environment type and traffic volume (Table 5.11), the case studies appear to be reasonably representative of the state network, despite the inherent difficulty in choosing a representative sample from only seven cases making up approximately 4.6% of the network.

Table 5.11: Comparison between case studies and overall network by environment type and traffic volume

Traffic class	Road length (km)	Environmental zone	Case studies		Network-wide	
			Length (km)	Percentage	Length (km)	Percentage
G1	10,023	DNR	328	21.51	5217	15.64
		DR	5	0.32	3713	11.13
		WNR	216	14.15	1022	3.06
		WR	4	0.25	71	0.21
G2	8214	DNR	0	0	3814	11.43
		DR	4	0.24	2384	7.15
		WNR	245	16.08	1836	5.50
		WR	1	0.08	179	0.54
G3	6280	DNR	116	7.57	2516	7.54
		DR	69	4.52	1862	5.58
		WNR	0	0	1797	5.39
		WR	0	0	105	0.31
G4	4974	DNR	0	0	1578	4.73
		DR	0	0	687	2.06
		WNR	211	13.81	2425	7.27
		WR	0	0	283	0.85
G5	3873	DNR	0	0	261	0.78
		DR	0	0	251	0.75
		WNR	306	20.03	3060	9.17
		WR	22	1.45	302	0.91

However, a major road category missing is low-traffic roads in dry regions of the state. This could be partially explained by the choice not to include a case study in the Central West and North West districts, which primarily comprised of roads in the G1 and G2 classes with a mix of dry reactive and dry non-reactive environments. While they did not escape the 2010–13 events unscathed, these regions did not experience the same degree of major pavement failures as the coastal and south west regions.

Extrapolating life-cycle benefits for the network based on a sample of 1500 km is a difficult process, and error margins in this process would necessarily have to be wide. For this reason, the observed costs and benefits for a best-for-network set of solutions has been determined by firstly calculating the road agency costs for the set of solutions which maximise NPV, i.e. the option with the lowest total transport costs has been chosen from each case study and its NPV determined in comparison with the business-as-usual, or base option.

Table 5.12 summarises the potential life-cycle cost implications stemming from adopting a best for network policy, with the full network costs and benefits determined on a simple length based pro-rata basis. The marginal benefit in this case is calculated at approximately 3.7, meaning an extra dollar of spending on this selection of roads returns $3.7 in life-cycle user cost savings, i.e. a very significant saving. This lies between the MBCR determined for Option 1 and Option 2 respectively, because the solution which maximises net benefits is a combination of all options.

Table 5.12: Exploring network-wide implications

	Case studies	Total network
Length (km)	1525	33,364
Business-as-usual strategy – life-cycle agency costs ($m)[1]	3275	71,650
Best-for-network strategy – life-cycle agency costs ($m)[1]	3546	77,579
Best-for-network strategy – life-cycle benefit ($m)[1]	736	16,102

1 All values expressed at a discount rate of 6%.

6 EXTENDED SENSITIVITY AND SCENARIO ANALYSIS

The initial results present a picture of the potential change in present value, and therefore economic savings that could accompany a shift towards one of the options. However, it was noted that the analysis relied on a series of critical assumptions which, while being formulated based on real data and observations, still impart a large degree of uncertainty over the results as presented.

Two critical factors were therefore selected for further scenario analysis to evaluate the impact that these uncertainties may have on the final results namely an analysis of the impact of varying the recurrence interval of major weather events (Section 6.1), and assuming accelerated deterioration on aged seals to simulate the 'performance drop-off' that regions have experienced after a critical surface life has been exceeded (Section 6.2).

6.1 Recurrence intervals of major future events

As outlined in Section 2, the degree of uncertainty surrounding future climate effects on the road network make analyses of life-cycle costs inherently difficult. Any assumptions regarding event recurrence intervals will therefore have a large bearing on the subsequent results generated from the life-cycle costing analysis.

It was therefore considered necessary to model the results of the analysis from three perspectives:

1. **Longer recurrence interval**, whereby the 2010–13 events are considered to be 'once-in-a-lifetime' events and the analysis reverts back to periodic 'minor' rain and flood events affecting the network. However, the betterment that took place across many regions, and the overall improvement in resilience brought about by many TNRP projects, reflects an understanding that the 2010–13 events were not a once-in-a-lifetime event, although examples can be drawn that show that many damaged roads were rebuilt to the previous standard.
2. **Normal recurrence interval**, which anticipates an additional major event in the 30-year analysis period. This scenario reflects the assumptions built into the case study analysis (Section 5.3).
3. **Shorter recurrence interval**, with multiple severe rain and flood events akin to the 2010–13 events, reflecting a hypothetical 'new normal' for Queensland consisting of regular cycles of extreme dry periods and extreme wet periods. This outlook is more in line with predicted climate scenarios (i.e. little emphasis on reduced global emissions), and reflects the potential risks to the network in a world of severe and accelerating climate change.

Table 6.1 documents the assumptions made when entering this data into the models. The major event from 2010–13 is replicated as the 'major event' for future years, while a 'minor' event is represented by halving the impact of the 2010–13 event in order to get a realistic estimate for road closures, vehicle impacts and reconstruction costs. It should be noted that the 2010–13 events are counted as one major event and included in the table, which effectively means that under the longer recurrence interval scenario, there are no additional major events anticipated.

Table 6.1: Assumptions governing analysis of recurrence intervals

Scenario	Western and Central Queensland	North and Far North Queensland
	18F, 93A, 46D, 10DE	90CD, 92A, 10MN
Longer recurrence interval	1 major event, 1 minor event	1 major event, 4 minor events
Normal recurrence interval	2 major events	2 major events, 4 minor events
Shorter recurrence interval	4 major events	4 major events, 2 minor events

6.1.1 Results

Each of the seven case studies was analysed under the three recurrence intervals, with the results of each aggregated to produce an estimate of the respective life-cycle cost impact of the two options against the base case. The results of this analysis are presented in Figure 6.1 and Figure 6.2.

Figure 6.1: Aggregate life-cycle costs under three event recurrence scenarios

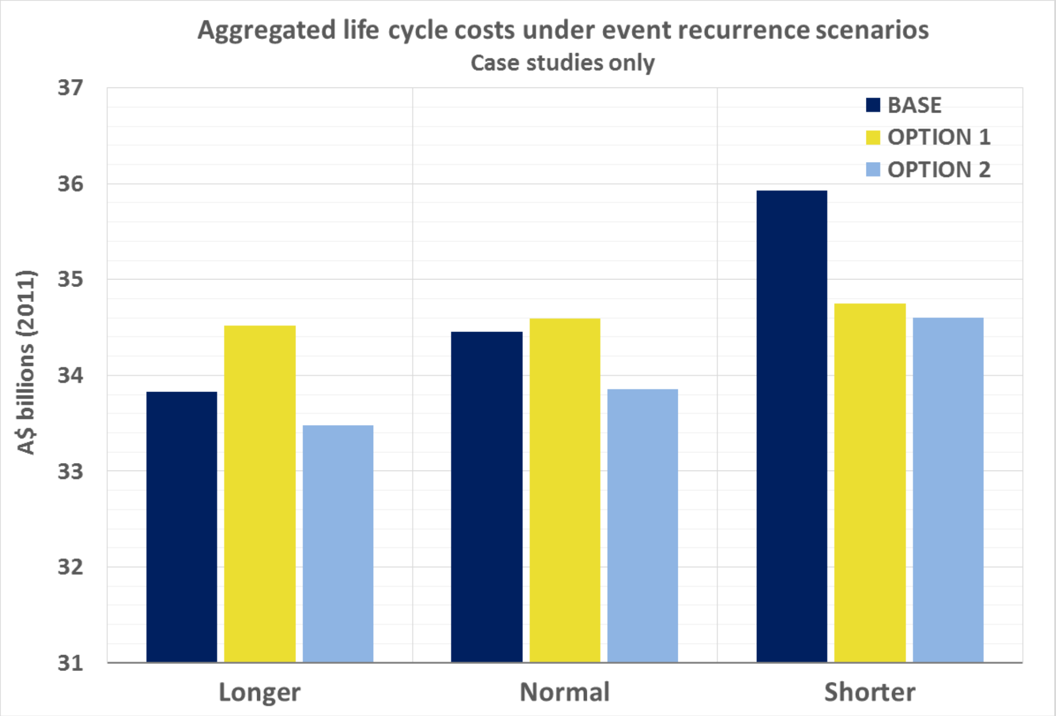
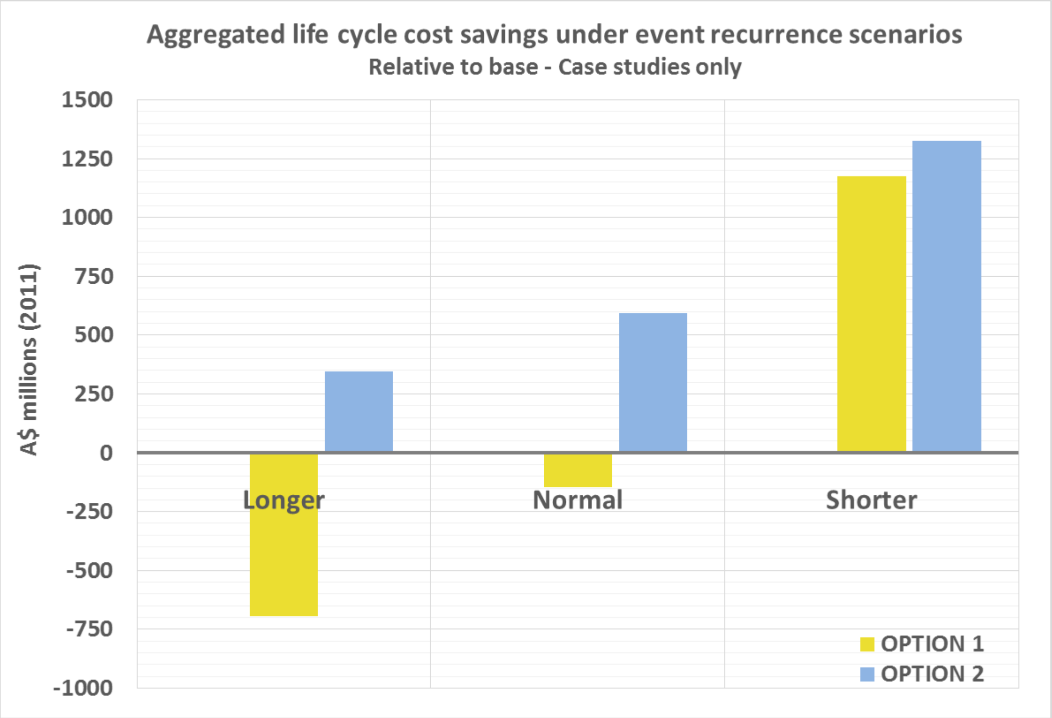


Figure 6.2: Aggregate life-cycle cost savings under three event recurrence scenarios



The impact of shortening the event recurrence interval is most acutely felt on the base case, where shifting from the 'normal' interval to modelling under a severely climate-sensitive future would lead to an increased life-cycle cost of $1.48 billion, equivalent to a 4.3% increase in life-cycle costs.

Under the Option 2 stitch-in-time case, the impact is greatly lessened, with a $740 million (2.2%) increase in life-cycle costs. This is attributable to relatively small cost increases in both agency and road user costs. The marginal BCR under this scenario of extreme climate risk is comparable to the marginal BCR under the normal event recurrence interval, at 5.43 as compared to 6.87.

Building a fully resilient network in Option 1 insulates the network against the risk of increased events. The shift from normal to shortened intervals leads to a $156 million increase in costs, equivalent to just 0.5% of the total life-cycle cost. The marginal BCR for shorter recurrence intervals compares favourably when considering the full-resilience case, with an extra dollar of spending returning $2.13 of benefits.

The clear message from this analysis is that should TMR determine that there is a high probability of transitioning towards more regular and more severe major weather events, there is a major benefit in shifting network investment decisions closer to the assumptions built into the two options.

Working under an assumption that the 2010–13 events were once-in-a-lifetime (equivalent to the 'longer' scenario in this analysis), there are still benefits in shifting towards a stitch-in-time model, owing largely to the benefit of spacing out rehabilitation across many years rather than focusing major works into a narrow post-event period.

Table 6.2: Marginal BCRs for option cases under varied recurrence interval scenario

Option case	Discount rate	Marginal BCR
Option 1	4%	0.64
	6%	0.92
	8%	2.13
Option 2	4%	2.32
	6%	5.43
	8%	-2.52

6.2 Accelerated road deterioration on aged seals

Previous Austroads studies (Martin et al 2004 & Austroads 2010) involving accelerated loading trials have shown that surface condition can deteriorate rapidly after a seal has exceeded its target age. Seals past their target age are a factor in determining the vulnerability of a pavement, as aged seals are more likely to exhibit cracks and edge breaks, which can weaken the pavement through ingress of water and lead to premature structural failure.

This concept of a 'performance cliff' means that more accurate estimates of current and future surface condition may be possible by applying an accelerated deterioration factor to the roughness progression calculation in the life-cycle cost model.

The model draws from several input variables to determine the change in roughness over a year, and should this new roughness figure exceed the rehabilitation threshold value, the model will instigate works on the pavement. The model has been modified to include an additional accelerated deterioration factor, of 1.96 times the 'uncracked' rate (Martin et al 2004), and takes effect after the seal reaches nine years of age (the notional target seal age) (Table 6.3).

Table 6.3: Assumptions governing analysis of reseal intervals (years)

	Base	Option 1 *Full resilience*	Option 2 *Stitch-in-time*
Shorten reseal interval by 3 years	9	6	6
Maintain current reseal interval	12	9	9
Extend reseal interval by 3 years	15	12	12

6.2.1 Results

The results of this analysis are presented in Figure 6.3 and Figure 6.4. While the results varied across the different case studies, the overall impact of accelerated deterioration of seals was not greatly significant for the base case, with shortening the reseal interval by three years across the case studies leading to a life-cycle cost saving of $86.6 million (0.26%).

For each of the options, shortening the reseal interval to avoid any impact of accelerated deterioration only had the effect of increasing the agency cost without delivering additional benefits. This is largely due to the fact that these scenarios often had already triggered rehabilitation before the seals reached their target age.

The largest cost saving in comparison to the base case was achieved using Option 2 with extended reseal intervals, with a life-cycle cost saving of $664.7 million (1.98%). This reflects a scenario where cost pressures push out the reseal interval to well above the target age. The stitch-in-time modelling would trigger early rehabilitation in many cases, increasing resilience across the network and contributing to smoother roads (lower road user costs).

Figure 6.3: Cumulative life-cycle costs with accelerated roughness progression for aged seals

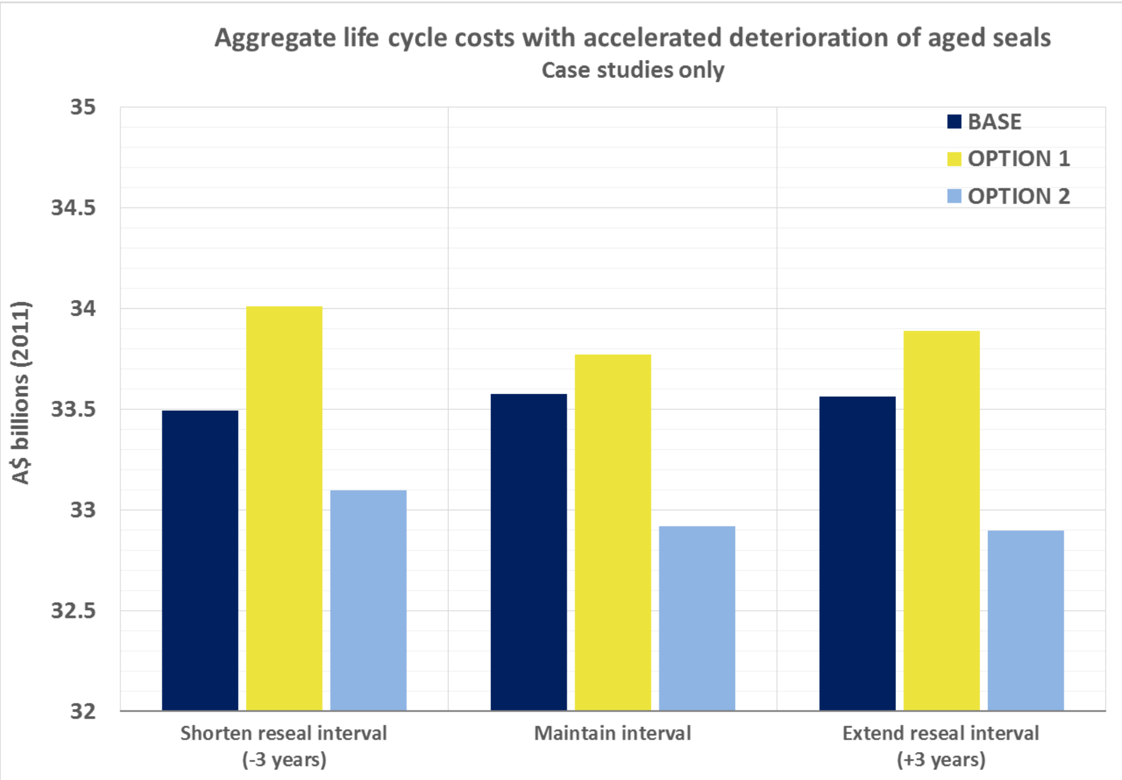
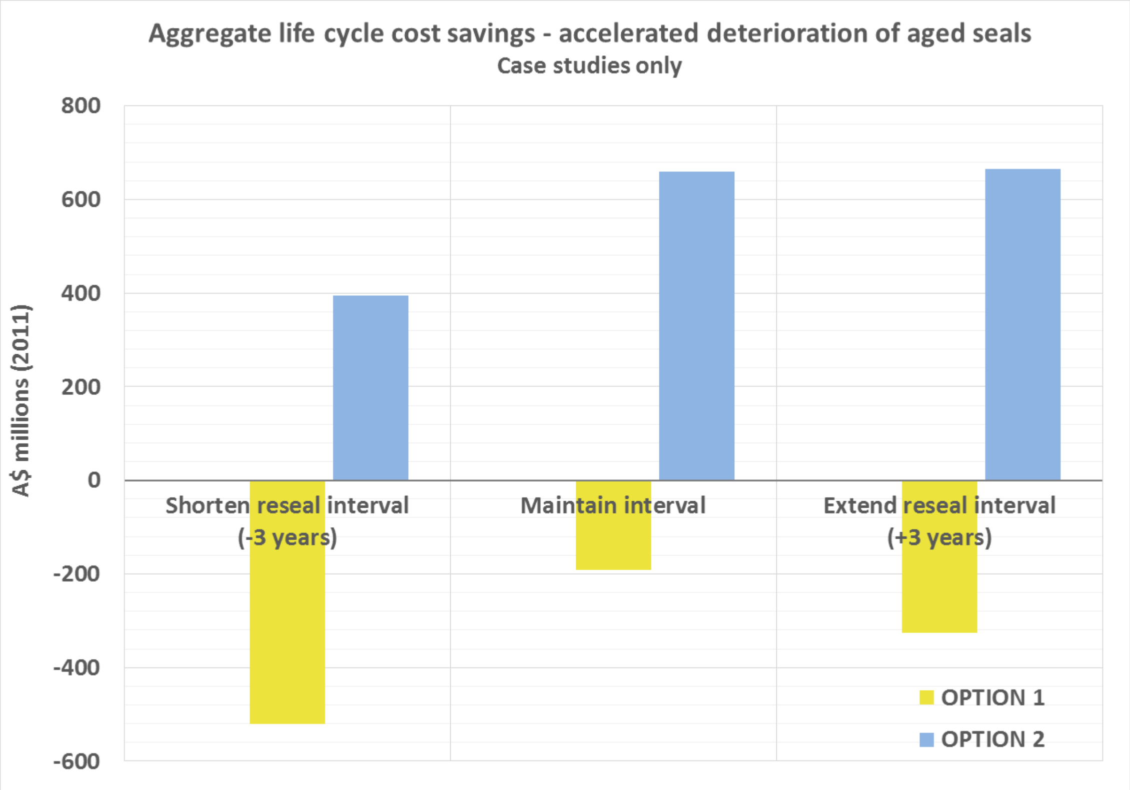


Figure 6.4: Cumulative life-cycle cost savings with accelerated roughness progression for aged seals



6.2.2 *Other observations – seal age analysis*

The data gathered to inform this analysis can also be utilised to generate some other statistics on the network before and after TNRP works. One such comparison is looking at the seal ages on treated and untreated sections to ascertain if this may have played a factor in the damage caused by the flood and rain events. If a significant difference exists, this may be evidence of damage due to poor seal condition. The model used for the life-cycle costing analysis does factor in seal age when determining the initial vulnerability of sections.

Table 6.4 lists the seal age for sections treated under TNRP and sections not treated on the Warrego Highway (18F). The average seal age was 2.4 years greater on the section that required work compared to the sections that survived the flood event without requiring rehabilitation. The average roughness before the flood events was also higher on the sections that required treatment, perhaps reflecting the average seal age. This could be some indication of seal ages having an effect on pavement vulnerability. The average pavement age did not seem to show the same trend.

Table 6.4: Seal age vs TNRP reconstruction

TNRP work	km in category	Average pavement age	Average seal age	Average roughness (2009)	Average roughness (2014)
Yes	48	23.36	5.49	3.55	2.26
Yes (reseal only)	4	15.45	5.48	4.02	2.22
No	41	38.42	3.09	3.04	3.18

7 DISCUSSION

Through the course of this project, a number of important issues have been uncovered and this section endeavours to explore a selection of these in more detail. Section 8 seeks to refine these outcomes into a series of recommendations for TMR.

7.1 Results across road categories

As explored in Section 5.4, the case studies represented a range of roads from different road categories across the state.

The overall traffic volume on each section was the most fundamental factor in determining the appropriate response to the results of the analysis. Three broad categories of roads were defined, with each kilometre of the network fitting within one of these three categories. Other factors important to the subsequent recommendations included the environment type, the region and the surfacing type (sealed or unsealed).

7.1.1 Major routes

Two sections, the Bruce Highway between Townsville and Innisfail and also the Bruce Highway south of Rockhampton, are categorised as ‘major routes’, having traffic of several thousand vehicles per day. These sections form part of the primary tourist and freight route between south-east Queensland and the tropical far north. Outside of the more populated south east of the state, this is one of the few roads that would fit within the major route category.

Along major routes, the results suggest that increased investment to the point of full resilience can return significant benefits to the economy through preventing even short periods of road closure and subsequent reconstruction. The traffic volumes are so high that maintaining accessibility and passability in the aftermath of major events should be prioritised, even in the face of high upfront costs. While there are alternative north-south routes, which are discussed in Section 7.1.2 and Section 7.5, they generally are at present of an inferior standard and would incur accelerated damage in the event of diversions.

The Bruce Highway is, in sections, a high-standard road, although much of it is still relatively poorly rated in terms of safety and stands quite vulnerable to extreme weather relative to its importance. Some large investments have been made over the last several years, and the ten-year *Bruce Highway Upgrade Program*, which commenced in 2013–14, is committed to $8.5 billion of infrastructure works (Department of Infrastructure and Regional Development 2016). This underlines the strategic value of this road, but also highlights the high cost involved in any major works on this road.

The largest proportion of this investment in the early years has focussed on realignment and widening the southernmost sections of the highway and targeted safety improvements along the entire length, with most of the more significant pavement works on the northern sections scheduled from 2019 onwards. There has also been a major improvement to one of the most vulnerable links on the Bruce Highway, the Yeppen floodplain (Queensland Government 2015). A new 1.6 km bridge now extends across the length of the floodplain, raising the old highway by 3 metres and sitting approximately 1 metre above the record flood level.

Without detailed design and plans behind these works, it is unclear as to whether these works would fit within the general philosophy of either of the options in this analysis. It is clear, however, that any works should be planned with connectivity of the entire route in mind. Upgrading a small section while leaving adjacent sections in a vulnerable condition may achieve little net benefit for road users.

There is a wide distribution of vulnerable bridge crossings and low-lying sections of pavement across the rural highway network, making any attempt at prioritisation a very difficult exercise. Should TMR invest in the most vulnerable areas, they risk fixing only small parts of a link and leaving neighbouring sections vulnerable. A 'big picture' view will allow TMR to determine the routes of highest significance, and progressively improve the standard of these routes in a long-term program of investment in resilience.

In order to assist in this, it is possible to develop an asset inventory and prioritise the assets based on importance of these in terms of kilometres travelled, freight tonnage, evacuation routes and community priorities. This gives rise to identification of assets that are coming to the end of their design life, whether to add adaptive measures to those being replaced, and identifying assets susceptible to previous events/or future events.

7.1.2 Rural highway network

The primary inland rural highway network connects local communities with regional hubs, and much of the agricultural, mining and long-distance freight uses some combination of rural highways to access south-east Queensland or coastal ports. The secondary north-south routes connecting northern Queensland to the rest of southern Australia encompass some combination of this network. The Warrego Highway between Mitchell and Morven, and the Dawson Highway between Rolleston and Springsure form two such links, and were chosen as case studies through this project.

These routes are generally spray sealed, undivided with a single lane in each direction, often with narrow shoulders and basic drainage infrastructure. These routes were often designed for moving cattle and other goods, but in recent decades have been subjected to increasingly heavy loads through the growth in the mining and freight industries. While these routes generally only carry a fraction of the traffic compared to the Bruce Highway or highways in the south-east, they carry a relatively high proportion of heavy vehicles. These vehicles contribute a large proportion of the road user costs when links in the network are closed, and heavy vehicles are also less able to divert to minor roads in the case of closure.

For these reasons, the stitch-in-time approach appears to provide a relative advantage in overall life-cycle costs over the 30-year analysis period. Shifting to a more proactive rehabilitation policy across rural highways would save money in the long-term by minimising the need for major reconstruction programs, and would allow for critical routes to remain passable in all but the most extreme events. Imparting full resilience, as defined in this study, would potentially lead to a prohibitively large agency cost increase that may not be recouped in the rare event of a particularly extreme event.

7.1.3 Development roads and remote links

There are several thousand kilometres of remote roads in the far west and far north of the state, which serve local industry and small towns of up to several hundred people, including a number of remote indigenous communities. With traffic of less than 200 vehicles per day, the high cost of imparting increased resilience does not achieve a net benefit unless the road is likely to be closed for very long periods in extreme events. This was indeed the case when the Peninsula Development Road was analysed. The unsealed portions of the road are sometimes impassable for the entire wet season, although extensive preparations are undertaken each year to minimise the impact on communities cut off by road.

On the majority of these development roads, the relatively high cost of treatments that tangibly improve the resilience of the network would be prohibitively high, leading to a negative impact on life-cycle costs. There are potentially adjustments that could be made to existing budget allocations, particularly on unsealed roads. Unsealed roads in the far north require extensive works after nearly every wet season, which is creating issues in terms of material and resource availability, as well as the environmental impact of the loss of materials and continual quarrying of replacement materials. Specific unsealed roads that form freight routes should be looked at to progressively seal (with such programs of works already underway or planned in north and far north Queensland). This would also provide some improvement to remote communities, which is a separate issue not addressed in this study.

However, it should be acknowledged that while these development roads may not justify a large influx in spending, there is a certain minimum level of connectivity that should be expected by remote communities which is difficult to model and take account of in forming recommendations.

Recently, Austroads released a report titled *Identification of a Risk Indicator to Support 'Life Line' Freight Routes* (Austroads 2016). The study aimed to provide a more comprehensive framework for assessing the priority of road infrastructure upgrades on freight routes in remote regions, particularly in cases where a road section does not deliver positive outcomes based on traditional benefit-cost analysis. Rather than relying on traffic volume as the primary factor in determining benefits, the study found that a multitude of other factors are important in assessing the value of funding 'life line' routes. A 'risk indicator' was proposed, including input from characteristics including:

- the size and needs of the communities and establishments they service
- availability of alternative routes which could be used if the route in question is unavailable
- length and convenience of alternative routes, including distance, time and classes of vehicles that can use the route
- the likelihood that the alternative routes are also closed
- historic incidence and duration of events that close or restrict operations on the route
- assessment of responses to previous events, including cost and impacts in the regions serviced.

Many of these metrics were used in the assessment of the case studies through this project. For development roads and remote links, it would be advantageous to adopt more holistic methodologies such as this in response to funding prioritisation of this portion of the network.

7.2 Balancing the maintenance budget elements

TMR allocates maintenance budgets to the regions in three distinct categories, namely ordinary maintenance, resurfacing, and rehabilitation. One of the initial goals of this project was to identify opportunities for better balancing TMR maintenance spending between these 'funding buckets'. Additionally, it may be necessary to address whether the problem simply comes back to an insufficient level of total funding to service the ongoing maintenance needs of the network.

Through the course of this project, a number of anecdotal observations were made with respect to spending under one or more of these maintenance allocations, including:

- ordinary maintenance looks to have been neglected in many cases, particularly in anticipation of major weather events (i.e. approaching the wetter summer months)
  - — maintenance budgets have not been adjusted to allow sufficient drainage works to offset some of the impacts of flood events
- reseal intervals were already beyond optimal levels in some regions, and it was noted that the gap between average seal age and target seal age was either staying constant or growing
  - — reseals can be postponed if roughness is steady (or lower than expected) but consideration should be given to the environmental conditions experienced

  - some evidence exists that reseals had been pushed back in response to relatively steady roughness progression, but this was potentially due to dry weather giving a false reading of the overall condition of the pavement
  - for regions unsure about security of funding if they choose to postpone works, there will be no incentive to strategise if the money is constantly reduced
  - there was some historical inconsistency in approach across regional boundaries as to the use of polymer-modified binders
- drainage issues were a recurring theme through the course of the project, and it is clear that whatever the balance of spending being allocated towards drainage, it is insufficient in light of the risks presented by insufficient or poorly maintained drainage
  - further research would be recommended into the drainage treatments that have been successful in tropical regions of the state, and these may be worthwhile adopting in drier parts of the state where flood events are rare but can be severe
  - the additional cost of slightly improved drainage may significantly shorten the period during which a road is inundated and/or saturated, and may greatly reduce the eventual damage incurred by that pavement
- there are differences in optimal budget allocation depending on road type, region, event recurrence interval, traffic etc. (some differences were explored previously in Section 7.1).

The funding arrangement under the NDRRA allowed Queensland to repair infrastructure across the network for roughly a quarter of the total cost, with the bulk of the funding from the Commonwealth Government. There would naturally be an expectation that given this large injection of funds, the network would be in an improved overall condition and also possess increased resilience against future rain and flood events.

The criteria for receiving funding was strict in the early stages of the TNRP, and only became stricter as the program progressed. The burden of proof was shifted towards regional offices to show that damage was clearly caused by the events and not typical progression of damage, and it was difficult to secure funding for ‘betterment’ projects, where a damaged pavement was replaced with a superior treatment.

Should another series of catastrophic events hit Queensland within the next decade, the relatively short interval between major reconstruction programs may further raise barriers to Commonwealth funding and leave the state with an even greater net budget shortfall.

Therefore sourcing future NDRRA funding, or indeed direct state funding, could be significantly easier if a strategic approach to improved resilience on the network can be demonstrated, including an appropriate level and mix of maintenance funding. The recommendations in this report might assist in developing that strategic approach.

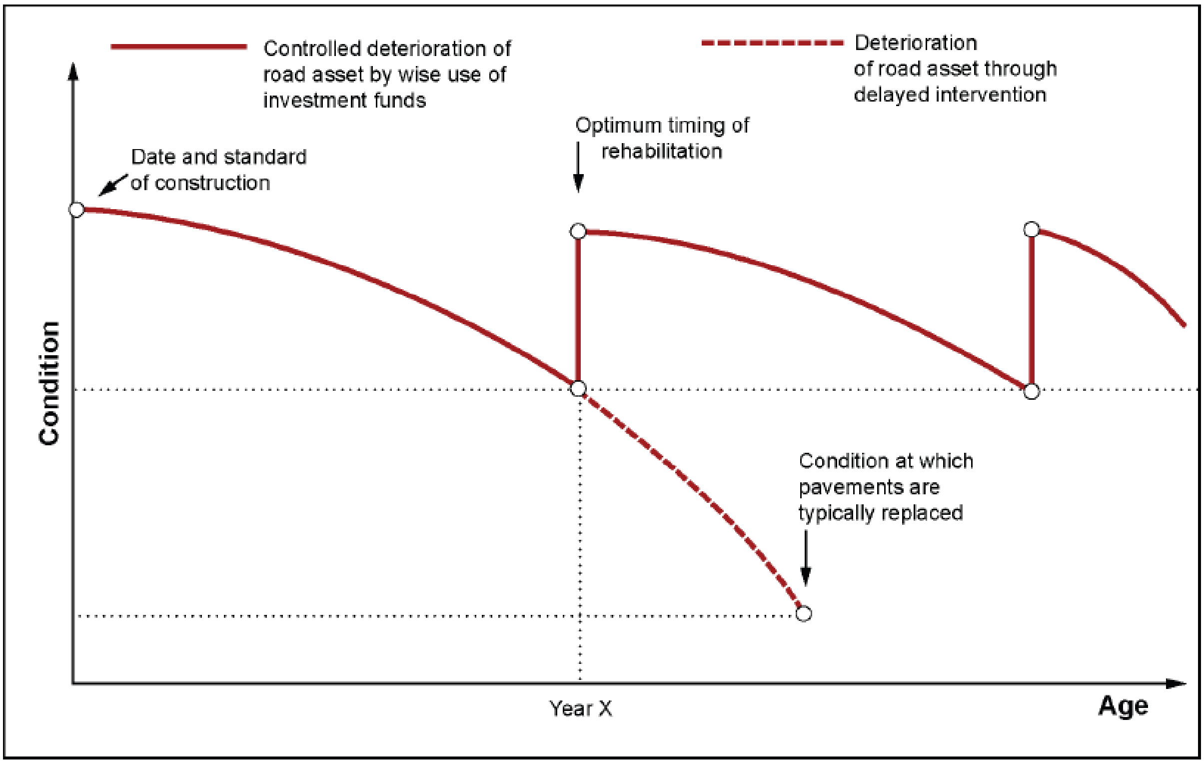
7.3 Alternative funding models

7.3.1 Accelerated Road Rehabilitation Program (ARRP) approach

The ARRB Group has previously conducted research for TMR into a concept known as the Accelerated Road Rehabilitation Program (ARRP). This concept advocates a shift from traditional asset management practices, whereby annual budgets and a prioritised list of projects governs rehabilitation spending. This has typically meant that there is a perpetual shortfall in funding, with rehabilitation delayed past the optimum time, leading to an overall increase in whole-of-life asset and road user costs. The ARRP model advocates bringing forward rehabilitation of assets, such that the benefits are also captured earlier.

This concept is illustrated in Figure 7.1, where optimum timing of rehabilitation leads to a better overall asset condition and longer intervals before a more substantial rehabilitation or complete replacement is necessary. Parallels can be drawn between this approach and the stitch-in-time model adopted as one of the option cases for this project.

Figure 7.1: Relationship between pavement life and condition



Source: Naude et al. (2008).

At least two analyses have been conducted to ascertain the estimated network benefits from shifting to the ARRP funding model in Queensland. Naude et al. (2008) found that ARRP had a significantly higher net present value than the traditional approach, as it had brought forward benefits accruing from higher-quality infrastructure, and had led to lower overall infrastructure costs. Net benefits under this study were estimated at between $15.2 and $67.5 million, depending on the traffic scenario, and comprised reduced road user costs, travel time savings, crash cost savings and reduced agency costs. These savings were derived from a section of the Dawson Highway between Banana and Calliope, and were accrued over a 30-year analysis period.

Many major infrastructure investments were made between 2006 and 2011, including an upgrade of 71 km of the Dawson Highway and the replacement of 31 timber bridges across the Wide Bay/Burnett and Darling Downs regions (Naude & Toole 2012). The overall investment of $190 million was made possible through a Department of Treasury loan of $88 million, reflecting a strong commitment to the principles of bringing forward investment for a long-term improvement in whole-of-life asset costs. Significant cost savings also accrued due to the 'bulking' of works, i.e. increased scale of works in a concentrated time-frame led to cost reductions.

An ex-post study found that the ARRP concept represented a potential alternative approach to more traditional delivery methods, and the analysis highlighted the importance of treatment selection and optimal prioritisation of works. The Dawson Highway initiatives were estimated to save $23 million over the 30-year analysis period (mainly consisting of reduced road user costs), while the bridge replacements were estimated to save $7.3 million over this same period (mainly consisting of agency cost savings).

Overall, the study concluded that some shifts in policy and funding mechanisms could bring about significant benefits (Naude & Toole 2012), including:

- accelerated asset rehabilitation needs to be closely integrated into strategic planning, particularly concerning network bottlenecks and constraints around the resilience of road links
- alternative approaches should not be leveraged to attract a disproportionate share of funds, rather they are to be used as a mechanism for shifting existing funds in time
- support and encouragement should be provided for comprehensive data collection and compilation in order to more readily evaluate competing funding models such as ARRP.

Many parallels can be drawn between the conclusions reached through the ARRP case studies and those reached through the analysis of the stitch-in-time model as defined through this NACOE project.

It is recommended that further consideration is given to expanding programs such as ARRP to include pavements that are considered vulnerable to extreme weather events. Some key features of this approach may include:

- targeted additional funding for rural highways that form critical links, particularly those servicing the agriculture and mining industries, and those routes serving as an alternative north-south route
- specific focus on stream crossings, floodplains, bridges, culverts and other areas vulnerable to concentrated flow in extreme weather
  - reduce the number of roads closed due to one or more isolated failures
  - be careful to consider the impact of opening roads to heavy vehicles too soon after major weather events when there may be underlying pavement weakness
- regions successfully employing such strategies to be rewarded with reinstatement of some or all of those future funds brought forward, as the strategic investment has cut life-cycle costs
  - potential to link flexible funding arrangements to road asset management contracts (RAMC), whereby operators are given an incentive to reduce life-cycle costs through strong up-front investment in the network
- giving due consideration to treatment selection and prioritisation of works when deciding where to target investment
- could be linked to predictive climate measures to ascertain relative risk in an upcoming summer and respond accordingly.

7.3.2 Climate-responsive funding

As noted in Section 2, recent studies by Australian and international scientific organisations have projected several notable changes to the earth's climate over the next few decades (PIARC 2015), including:

- that the earth will become warmer
- some regions with receive more rainfall, while others will receive less rainfall
- sea levels, and subsequently storm surge levels, will rise,
- the frequency and severity of extreme weather events (including cyclones and prolonged heavy rainfall) will increase in many regions.

These impacts will undoubtedly expose our road networks to increased risk of premature failure, and will require reconsideration of design, construction, maintenance and asset management practices across the network. The economic damage as a result of these climate impacts could be very significant, both in terms of agency cost increases and consequences for road user costs due to road closures and reduced access. When assessing the specific impact on the Queensland network, two major factors stand out:

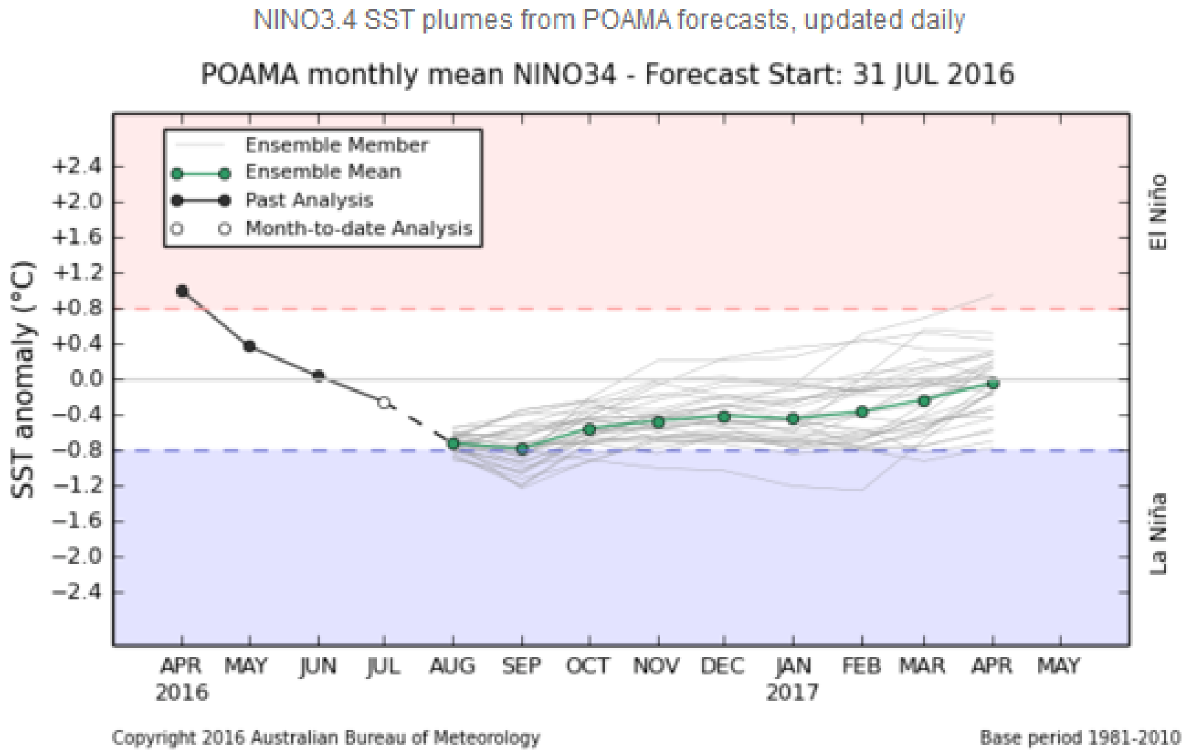
1. periodic prolonged heavy rainfall in southern and western Queensland leading to failure of saturated pavements and specific locations suffering major damage due to concentrated flow
2. more frequent and higher category cyclones along the coast, potentially impacting further south as ocean temperatures rise, and exacerbated by rising sea levels.

Studies into the predictability and return frequency of these events are likely to be of foremost concern to Government, as climate change adaptation begins to take on a more prominent role in infrastructure policy.

There has been a growth in the number, accuracy and responsiveness of models looking into sea surface temperature (SST) anomalies in the Pacific Ocean, which are used in seasonal forecasting of El Niño and La Niña conditions. These phenomena typically peak during the Australian summer, with neutral conditions prevailing during the middle months of most years. The predictability of ENSO values is notably poorer during the southern hemisphere autumn, with improved performance of models during the winter months (L'Heureux 2015).

The Australian Bureau of Meteorology utilises eight models to predict SST anomalies for the upcoming nine-month period, and there is generally broad agreement between the model predictions (particularly after autumn). For example, a recent forecast, captured at the end of July 2016, shows a prediction of either persistent neutral conditions or a weak La Niña for late-2016 and early-2017 (Figure 7.2).

Figure 7.2: SST anomaly predictions from the Bureau of Meteorology



Source: Bureau of Meteorology (2016d).

There may be scope to utilise this modelling in the allocation and timing of funding for pavement maintenance, rehabilitation and other infrastructure investment. By the middle of each year, there is a high level of confidence in the predictions of El Niño, La Niña or neutral conditions. This can be related to the relative likelihood of events and infrastructure risk in each region based on trends and historical records, and linked to an associated asset management strategy. Some of the important factors in reaching a viable model include:

- having a system of funding, procurement and construction that is capable of responding to impending extreme climatic conditions at short notice (up to six months)
- collaboration and regular communication with other government departments including the CSIRO and the Bureau of Meteorology
- infrastructure vulnerability mapping taking into account relative regional risk, overland flow mapping, water height simulations at critical crossings, town flood mapping and other climate variables
- an understanding of the degree of certainty in predictions, so that there is awareness of the variability in outcomes for a given prediction (i.e. high predicted damage of an impending strong La Niña would necessarily have a high degree of uncertainty, but this should not undermine confidence in the model itself).

7.4 Treatment catalogues and pre-approved suppliers

A major limiting factor in the alternative funding models as proposed in Section 7.3 is the difficulty in transitioning from approved works to beginning construction to completed treatments. During the TNRP, there was often a considerable time lag between approval of the scope of works by the program office and the beginning of construction. It many cases, works on badly damaged pavements did not commence until more than a year after the damage was first incurred. In some cases, this fortuitously allowed for reconstruction of multiple years of damage.

Over the course of the TNRP, there were some efficiencies when delivering identical or very similar treatments across one or more regions. For example, one of the most common treatments across south west and western Queensland was typically 1.5% cement modified base with a polymer-modified bitumen seal. This type of treatment may indeed be relevant to a sizable percentage of the network, and could become one of a small range of ‘standard’ rehabilitation treatments.

There may also be advantages in building a stronger relationship between contractors and the quarry network, with longer-term works programs allowing quarries to continue sustainable operations and moving away from ‘boom and bust’ cycles of work. Materials with well-established properties and a strong performance record could be stockpiled and pre-approved for works, thereby reducing the delays caused by sourcing, testing and modifying suitable materials for each project.

Benefits to this approach may include:

- experienced and proficient practitioners delivering projects that they are highly familiar with
- building knowledge of local materials in a familiar application
- faster progression from tender to delivery as scope of works and materials are pre-approved
- efficiencies in delivery and the scale of work may lead to lower overall costs, as happened with the ARRP.

However, there could also be limitations to this approach, including the fact that subgrade conditions, traffic, environment and materials vary by region and by road, making it a challenge to define a small set of standard treatments that fit a wide range of applications.

Should a more responsive and accelerated works program be considered a priority, there would need to be some trade-offs in terms of the flexibility of treatment options, but balanced in such a way that there remains a net benefit to pursuing an expedited delivery model.

7.5 Queensland inland highway

Throughout the course of this study, numerous references to the concept of an alternative inland highway have been encountered. The 2010–13 events highlighted the heavy reliance on the Bruce Highway as the primary north-south route in the state, and that building redundancy into the system would have considerable benefits across a broad range of areas.

While this study has not investigated potential options in detail, for vehicles travelling between Townsville and Sydney or Melbourne, upgrading parts of some inland highways would allow for heavier vehicles and greater freight volumes to utilise this corridor instead of the coastal route via Mackay and Brisbane (Figure 7.3).

Upgrading this or alternative north-south routes as a priority (i.e. focusing on full resilience and flood immunity upgrades on critical routes) is likely to reduce the dependence on the Bruce Highway, which is vulnerable to closures and damage due to heavy rain, cyclones and storm surge from the ocean. It is possible that especially severe events on the coast will also reach far enough inland that an alternative route is also effected, however this is not likely to be the case for the majority of weather events.

Figure 7.3: Potential inland route from Townsville to Hebel

Source: Drive Australia (2016).

Another alternative north-south route even further west, through Charleville and Barcaldine and eventually to Cairns, has recently been strengthened through additional funding to seal parts of the Hann Highway, and is a strong focus of the Inland Queensland Roads Action Plan (IQ-RAP) which represents local governments, road and transport groups and RACQ (Regional Development Australia 2016). This group has proposed works for around 3000 km and 300 bridges across the inland Queensland road network over the next 18 years, at an estimated total cost of $5 billion.

The benefits from reduced travel time and lower operating costs would likely dwarf any potential savings during major weather events (Queensland Transport and Logistics Council 2015). Resilience upgrades should be prioritised based on the strategic location of the road within the network, taking into account the importance of the entire route rather than just each individual section.

7.6 Integration of findings with international developments

Section 2 notes that there are a number of initiatives being undertaken both within Australia and internationally. These provide opportunities to incorporate key findings into TMR responses. For example, in 2012, ARRB Group participated in Climate Change Resilient Road Transport US Scanning Tour (FEHRL, 2012), coordinated by the Forum of European National Highway Research Laboratories (FEHRL). One of the observations was that some of the more recent extreme weather events experienced in the USA have served as tipping points to increase the focus on climate change adaptation. There is recognition that there are extreme weather events that need to be planned and designed for in terms of the trade-offs between the costs of investments to make the infrastructure more robust and the likelihood (probability) and costs of major disruptions to the system due to climate change events. Additionally, there was a large focus on identifying vulnerable infrastructure, and establishing ways to accommodate sustained climate change impacts over a long duration, and for infrastructure to be planned and designed for more than one-off events. A range of vulnerability studies, inventories, adaptation measures, frameworks, and risk management responses as a result of major events such as Hurricane Katrina in 2005, were assessed throughout the Tour, and provide a useful connection to this current project.

Similarly, climate change adaptation frameworks can be used to provide a whole of process assessment in determining appropriate investment priorities, and to enable efficient development of climate change mitigation and adaptation responses for transport decision makers. Section 2, details the development of a Climate Change Framework for TMR (Evans et al. 2008), and at the international level, PIARC's *International climate change adaptation framework for road infrastructure* articulates an approach that covers infrastructure vulnerability and prioritising risk, and integration of findings into decision-making processes in detail.

It is noted that the work of this current NACOE project forms an integral part of informing specific steps of these frameworks. In particular, the areas of infrastructure investment, and better determining the trade-off between the costs of investment to make infrastructure more resilient, the probability of events in the future, and potential costs of infrastructure failure and/or major disruptions to the system. There is therefore, an opportunity to integrate the findings of this project into wider national and international frameworks currently being developed. This could also be achieved through consideration of further updates to the Climate Change Framework for TMR to take account of these life-cycle costing developments.

Due to the broad range of different impacts shown via the case studies assessed in this project, this work also provides a good template to inform other countries on the life-cycle implications of flood and extreme events, and the funding levels required to enable the desirable levels of service to be achieved. Similar to the concept of climate analogues[2], there is potential for these case studies to be applied to other parts of the world where conditions are similar. As a result of the diverse conditions in Queensland, this work forms a significant contribution to informing other projects not only within Australia, but also internationally.

[2] Climate change analogues involve the identification of areas that experience similar climatic conditions, but which may be separated in space or time (i.e. with past or future climates) as a reference point for considering different adaptation strategies to a changing climate. Locating areas where the current climate is similar to the projected future climate of a place of interest is a method for visualising and communicating the impact of projected changes. These tools match the proposed future climate of a region of interest with the current climate experienced in another region (http://www.climatechangeinaustralia.gov.au/en/climate-projections/climate-analogues/about-analogues/).

8 CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

1. From 2010 to 2013, a series of widespread, catastrophic weather events caused extensive damage to the state's road infrastructure, with long periods of inundation and extreme overland flow causing severe pavement damage. Repair and reconstruction works totalling in excess of $6 billion through the TNRP have restored the network to a strong condition, but in light of the damage caused, there was concern that the overall network was more vulnerable than originally thought. Should events of this nature occur again in the future, it will be critical that the network is better placed to be more resilient in the face of these flood and rain event impacts.

2. Evidence across the network indicated that many failures were attributed to, or worsened by, insufficient funding for the provision and maintenance of drainage. It is clear that the current allocation of funds towards drainage maintenance is presently insufficient in light of the risks presented by poorly maintained drainage. Even minor improvements to drainage structures may significantly shorten the periods of inundation and/or saturation, and may greatly reduce the eventual damage incurred.

3. This project has approached this question from the perspective of analysing the life-cycle costing impacts of rain and flood events on the network. The analysis included modelling the 30-year life-cycle cost implications across seven case studies, with these selected from a representative set of roads and modelling the outcomes of the base case against two options, namely a full-resilience option and a stitch-in-time option.

4. Heavily trafficked highways (such as the Bruce Highway) may require significant additional investment (building full-resilience) in order to reach a standard that will allow for minimal disruption in future major weather events. This has the potential to deliver benefits exceeding this investment, primarily in terms of reduced road user costs, and benefits to the freight industry in terms of reduced delays and trip cancellations.

5. Adopting a stitch-in-time approach across the rural highway network may require a small increase in funding, but will deliver value-for-money treatments and a more progressive program of works, providing stability for industry rather than the boom-and-bust cycle of major programs such as the TNRP. The stitch-in-time approach delivered lower average pavement and seal ages, with greater resilience assumed, significantly reducing (although not eliminating) delays to road users.

6. The analysis highlighted two critical factors in this discussion. Uncertainty surrounding future climate and weather events, in the face of predicted increased climate risks to Queensland, needs to be considered when designing pavements for 20–30-year design lives. Under a scenario of accelerating climate change, with shorter intervals between severe cyclones and more extreme heavy rainfall events, the full-resilience model becomes relatively more attractive to asset managers, while the stitch-in-time approach serves to deliver reduced life-cycle costs under all event recurrence intervals.

7. The analysis also considered the importance of treating pavements within their target life, before the start of accelerated deterioration. Shortening the reseal interval led to reduced life-cycle costs under the base case, indicating that accelerated reseal and rehabilitation programs may have some benefit. The two options cases did not show any benefit to shortening reseal intervals, largely due to the fact that intervals had already been shortened, and that significant benefits had already been realised through more extensive works early in the 30-year analysis period.

8.2 Recommendations

A range of measures have been discussed which could help to optimise the condition of the network in terms of resilience against major events, and reduce the impact to road users when roads become inundated. Increased collaboration with climate and weather modelling, as well as integrating advanced flood and overland flow modelling into network planning and pavement design, can provide asset managers with stronger tools on which to base investment decisions. Table 8.1 details a series of recommendations stemming from this research project.

Table 8.1: Recommendations for management of TMR road assets

Recommendation	Detail
1. Review and update relative funding of various road and maintenance funding allocations by road type and environment	▪ Different traffic levels and road function dictate the balance between maintenance elements at both the individual road level and at the network level, from an economic viewpoint. ▪ Evidence suggests that a stitch-in-time approach was beneficial in most cases and that problems resulted from delayed programmed maintenance. Shifting to a more proactive response across rural highways would save money in the long-term by minimising the necessary scope of major reconstruction programs. ▪ Drainage improvements are seen as essential, and are deserving of proactive attention in terms of assessment and improvement in both tropical and typically dry regions. Above all else, it is apparent that an increase in funding of drainage infrastructure and drainage maintenance is likely to return significant benefits under any climate scenario. Further research is warranted into drainage treatments that have been successful in tropical regions of the state, with the vision of potentially adopting these in drier parts of the state where flood events are less common yet still present a significant risk to infrastructure. ▪ A high-level approach to screening candidate sections for more or less treatment (e.g. shorter or longer seal age) should be taken and accounted for in forward planning. ▪ Very-low-volume development roads need a broader range of factors to be incorporated in evaluating the relative priority of resilience improvements (such as those discussed in Austroads 2016).
2. Consider options for flexible and responsive funding of maintenance and rehabilitation	▪ Develop guidelines for moving money rapidly into areas of need. Make available 'off-the-shelf' treatment options to allow for a shorter time to delivery, perhaps through review/update of relevant 'engineering notes'.
3. Develop and encourage relevant programs for accelerated funding of overdue rehabilitation works	▪ The Accelerated Road Rehabilitation Project funding model, which included a Treasury loan against future Road Investment Program (RIP) allocations is ideally suited for addressing the backlog of needs identified through this project, and evident from the resulting TNRP. ▪ Regions shown to have invested this accelerated funding strategically and in such a way that minimises total life-cycle costs, may be rewarded with partial forgiveness of loans.
4. Explore enhanced use of climate and flood modelling in planning	▪ Advanced climate and flood modelling, which can provide an indication of forthcoming and future network risk, should be included as an integrated part of maintenance and rehabilitation practices. ▪ When developed, aspects of this modelling may be incorporated into TMR asset management systems.
5. Drive stronger consideration of route-based investment prioritisation	▪ Investment has to be prioritised not just on vulnerability, but by taking into account typical freight, mining and agriculture routes and progressively build highly resilient routes throughout the state, rather than apply a 'patchwork' approach of focusing on the most vulnerable sections. ▪ There is recognition of the need for alternative north-south routes that have no highly vulnerable links. Continuity of freight movements is a major contributor to optimising life-cycle costs.

Recommendation	Detail
6. Consider sharing these findings with Queensland Treasury, the Commonwealth and other state and territory road agencies to demonstrate a strategic approach to improving network resilience	▪ Innovative strategic proposals towards ensuring greater resilience could assist in seeking NDRRA funding in future when similar rain and flood events again cause disruption and damage the road network.
7. Consider integrating the findings of different case studies into international activities, and provide an opportunity for comparisons to be made relating to economic, social and environmental challenges (the concept of climate analoguing)	▪ Seek opportunities to integrate the findings of this project into international frameworks and developments. ▪ Consider the updating of broader adaptation frameworks, such as the Climate Change Framework.

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APPENDIX 1

Table A.1 provides a summary of the potential climate change events in Queensland that cause environmental conditions to extend outside the range for which the current system is designed. This table has been developed in Evans et al. (2009) and has also been adjusted using information from TRB (2008a; 2008b). Whilst it is recognised that there are also impacts due to decreased precipitation and increases in temperature, for the purpose of this project, the weather impacts specifically related to flooding have been highlighted.

Table A.1 Climate change impacts on land transport operations and infrastructure

	Impacts on Land Transport: Roads, Rail and Pipelines	
Potential climate change	**Operations and interruptions**	**Infrastructure**
Precipitation: Increase in intense precipitation events	Infrastructure deterioration e.g. concrete deterioration, impacts on water quality, loss of property, increased hazardous cargo accidents Increases in weather-related delays e.g. traffic disruptions, increased flooding of evacuation routes Disruption of construction activities e.g. changes in rain and seasonal flooding that impact safety and maintenance operations	Overloading of drainage systems, causing backups and street flooding Increases in road washout, damages to rail-bed support structures, landslides and mudslides that damage roadways and tracks, and increases in scouring of pipeline roadbeds and damage to pipelines Impacts on soil moisture levels, affecting structural integrity of roads, bridges, and tunnels
Precipitation: Changes in seasonal precipitation and river flow patterns	Increased interruptions in travel and transport demand if rainfall patterns intensify, depending on terrain	Increased risk of floods from runoff, landslides, slope failures, and damage to roads if rainfall increases
Sea level rise, added to storm surge: Increased risk of inundation of coastal infrastructure	More frequent interruptions in travel on coastal and low-lying roadways and rail service due to storm surges and road closures More severe storm surges, requiring evacuation and increased search and rescue operations	Inundation of roads and rail lines in coastal areas, and more frequent or severe flooding of underground tunnels and low-lying infrastructure Erosion of road base and bridge supports, bridge scour, reduced clearance under bridges Loss of coastal wetlands and barrier shoreline, and land subsidence
Storms: More frequent strong cyclones	More debris on roads and rail lines, reduced visibility, interrupting travel and shipping Increased frequency of road accidents, route delays, disruption to transit services/closures, freight and standard motorists More frequent and potentially more extensive emergency evacuations	Increased road flooding Greater probability of infrastructure failures e.g. increased damage to signs, lighting, bridges, signs, overhead cables, railroad signals, tall structures Decreased expected lifetime of highways exposed to storm surge

Source: Evans et al. (2009); adapted from TRB (2008a; 2008b).