NCCARF
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Local Government Association
of South Australia

Quantifying the cost of climate change impacts on local government assets

Final Report

Jacqueline Balston, Jon Kellett, Geoff Wells, Steven Li,
Adam Gray and Ivan Iankov

QUANTIFYING THE COST OF CLIMATE CHANGE IMPACTS ON LOCAL GOVERNMENT ASSETS

Development of tools that allow Local Governments to translate climate change impacts on assets into strategic and operational financial and asset management plans

Local Government Association South Australia

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The role of NCCARF is to lead the research community in a national interdisciplinary effort to generate the information needed by decision-makers in government, business and in vulnerable sectors and communities to manage the risk of climate change impacts.

Disclaimer

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ABSTRACT

Australia's 560 Councils are responsible for the management of a range of assets valued at approximately $212 billion, many of which have a life span greater than 50 years and so will be affected by climate change.

Currently, maintenance and replacement of hard infrastructure by Local Government is guided by the principles, models and tools provided in the International Infrastructure Management Manual (IIMM), developed by the Institute of Public Works Engineering Australia (IPWEA) in conjunction with Councils, engineers and manufacturers of various components and materials. Currently these tools do not allow for the incorporation of climate change impacts or calculate the likely flow-on effects to asset and financial management and so Councils are limited in their capacity to estimate these changes.

On the basis of an extensive literature review and rigorous methodology developed in collaboration with the Local Government Association (LGA) South Australia (SA), IPWEA, University of South Australia (UniSA), Bureau of Meteorology (BOM), Coast Protection Board of South Australia, Municipal Association Victoria (MAV), Western Australian LGA (WALGA), and ten collaborating Councils, this National Climate Change Adaptation Research Facility (NCCARF) Settlements and Infrastructure funded research project has developed a financial simulation model and supporting decision tools to provide a clear, comparative analysis of the financial impacts of climate change on three major asset classes of importance to Australian Local Government – sealed roads (hotmix and spray sealed) and unsealed roads.

The integrated financial modelling includes options pricing and uncertainty analysis to deal with the highly variable nature of data inputs that describe the not-static components of climate change scenarios and impacts on the useful life of roads, and economic and price fluctuations. The model will provide Local Government with the capacity to regularly update the cost analysis and outputs have been designed to interface with the existing tools developed to support the IIMM to create a simple user friendly front-end that can be used by Local Government.

EXECUTIVE SUMMARY

The International Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) (IPCC 2007) states that the warming of the climate system is now “unequivocal”. As a result, southern Australia is likely to experience changes not recorded over the past century that include continued increases in temperature, changes in rainfall, an increase in evapotranspiration, a likely increase in the number of extreme fire danger days, sea level rise and increased frequency and height of storm surge events. Currently, Australia’s 560 Local Governments are responsible for the management of a range of assets valued at approximately $212 billion, many of which have a life span greater than 50 years and so will be affected by climate change.

To date, the maintenance and replacement of hard infrastructure by Local Government has been guided by the principles, models and tools provided in the International Infrastructure Management Manual (IIMM), developed by the Institute of Public Works Engineering Australia (IPWEA) in conjunction with Councils, engineers and manufacturers of various components and materials. However, these tools do not incorporate climate change impacts or calculate the likely flow-on effects to asset and financial management and so Local Governments have been limited in their capacity to estimate these changes. This project has aimed to address this gap in understanding between climate change impacts and likely costs associated with infrastructure asset maintenance and management by developing a financial modelling tool for integration into an existing IPWEA decision support tool for use by Local Governments staff.

A detailed outline of the scope of the study is given in Appendix 1 and includes a description of the structure of this report and the methodology used. Ten collaborating Councils across South Australia, Victoria, Western Australia, and Tasmania were involved in the project from the early stages and attended stakeholder meetings, provided input to the methodology, asset and financial data and gave feedback on the tools developed. The first stage in the project involved a review of the climate changes already recorded and those that are likely for southern Australia out to the year 2100. Climate data for use in the development of a climate change asset management financial tool was identified.

The second stage of the project involved a detailed review of the literature on the value and type of asset classes of importance to Local Government in Australia and the deterioration of materials widely used in significant Local Government infrastructure construction: concrete, steel and bitumen. Climatic factors likely to increase the speed of materials deterioration were also identified. On the basis of findings from the climate and literature review, and detailed discussions with the Local Government Association South Australia (LGA SA), the Institute of Planners and Water Engineers Australia (IPWEA) staff, technical and stakeholder team members, roads were identified as the key asset of most value that will be affected by climate change. Roads represent approximately 80% of the value of Council assets and so the development of a useful decision support tool that allows Local Governments to translate climate change impacts on road assets into strategic and operational financial and asset management plans focussed on three road asset classes: sealed roads (hot-mix and spray-sealed) and unsealed roads.

To support the development of a financial model, over 20 mathematical engineering models that estimate road deterioration were reviewed and their appropriateness for application to the present study evaluated. The analyses concluded that for sprayed seal roads, climate change impacts on the deterioration of the seal surface can best be assessed by Martin’s model and the maximum service life of the spray sealed surface can be determined by Oliver's model. The maximum service life of asphalt (hot/mix) surfaces can be determined using an equation by Choi and the deterioration of the road surface and sub-base by models by Austroads and the Australian Road Research Board (ARRB). Giummarra's model was identified for calculating climate change impacts on unsealed roads. In each case temperature and rainfall parameters were required to model the impacts of climate change on each of the road assets.

The third and fourth stages of the project involved the development of the financial asset management model and tool for use by Councils. The Financial simulation Model developed was created in Excel ® and was designed to integrate with the existing IPWEA NAMS.PLUS software tools. The software provides a clear, comparative analysis of the financial impacts of climate change for each of the three road types for which there were valid mathematical models (asphalt/hotmix and spray sealed bitumen roads and unsealed roads). The model uses Monte Carlo simulations and options pricing as methods of uncertainty analysis to deal with the highly variable nature of data inputs that include the non-static components of climate change scenarios and impacts on the useful life of roads, and economic and price fluctuations.

Historical monthly temperature and rainfall data for the period from 1911 to 2010 were extracted from the Bureau of Meteorology High Quality National Real Time Monitoring (RTM) gridded data set (previously known as the Australian Water Availability Project data set (AWAP)) as an LGA area averaged, monthly data set for each of the ten collaborating Councils. This data was then used to calculate long-term climate distributions for each of the four climate variables required for the models: mean monthly precipitation; monthly mean minimum temperature; monthly mean temperature and the Thornthwaite Index. Distributions for the twenty years corresponding to the 1990 baseline years used by most Global Climate Models (GCMs) were then calculated for each LGA and each climate variable. To keep the tool simple and avoid the need to update the data with global climate model outputs either currently available or likely to be generated for the CMIP 5 runs currently underway, the model was designed to be able to alter the mean and distribution of each parameter based on user defined climate changes. This approach allows the user to test the impact of any selected climate change scenario if the projected change in annual mean rainfall or temperature compared to the 1990 baseline is known. To reduce errors associated with changing only the mean of the distribution, adjustments to rainfall data were made at the monthly scale prior to calculating annual values, to take into account the uneven distribution of rainfall throughout the year. For testing of the Model and the calculation of results for the report, the historical climate distributions were adjusted according to the CSIRO OZCLIM projected changes in mean temperature and rainfall corresponding with the IPCC Fourth Assessment Report A1FI scenario for the years 2050 and 2100. The climate change impact in terms of changes in road maintenance and repair costs is determined as the difference between the total present value of costs with and without climate change. Using an annuity formula, these costs were also transformed to the impact in terms of useful life. As the equations for the impact of climate change are different for each road asset class, they are treated separately in the model.

The fifth and final stage of the project involved testing of the software tools by eight of the collaborating Councils using their own data. It is noted that there were significant differences between Councils on data availability and accuracy, in part because of different types and stages of asset management system implementation. Key conclusions derived from the pilot modelling were: (1) Over the periods modelled the incremental impact of climate change on road infrastructure of all three types appears to be generally small and positive, with respect to both useful life and costs; and (2) Results across Councils clustered around the mean for asphalt/hotmix and spray sealed roads, but across a significantly wider range for unsealed roads. Trends evident in the 2050 scenario were amplified for the 2100 scenario.

The development and trialling of the Financial Simulation Model on selected case study Local Government areas has shown that climate change is likely to have an impact on the life of road assets, both unsealed and sealed, even though that impact is calculated to be quite small, in comparison to current life expectancy for the asset class. As the Model combines economic modelling, asset deterioration models, climate data and the option to test a range of climate projections to provide life cycle estimates as an output, it is well suited to interface with the NAMs industry standard asset management practice framework. In summary, the project has succeed in developing a rigorous model and user friendly input tool that are compatible with the current Excel ® based asset and financial management tools and that are able to calculate the cost of climate change on three asset classes (spray sealed, asphalt (hotmix) and unsealed roads) and which takes into account the uncertainty associated with financial and climate uncertainties. IPWEA are now examining the options for commercialisation of the tools at a national scale.

1 CONTEXT AND OBJECTIVES OF THE RESEARCH

1.1 The Context of Climate Change

The International Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) (IPCC 2007) states that the warming of the climate system is now "unequivocal", and is "evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice and rising global average sea level". It is also likely that despite current mitigation policies and related sustainable developments, the level of greenhouse gases in the atmosphere will continue to increase over the next few decades. As a result, the global climate system will very likely see changes that exceed those observed over the past century.

Over the coming decades, southern Australia is likely to experience continued increases in temperature, changes in rainfall (likely reductions in winter and spring), an increase in daily rainfall intensity but longer dry spells between rainfall events, an increase in evapotranspiration (the combined effects of evaporation and plant transpiration), an increase in very hot days and nights, a reduction in the frequency of frosts and snowfall events, a likely increase in the number of extreme fire danger days, sea level rise and increased frequency and height of storm surge events.

1.2 Local Government Asset Management

Within this changing climate, Australia's 560 Local Government authorities are responsible for the management of assets valued at approximately $212 billion (ALGA 2012). Many of these assets (buildings, roads, footpaths, coastal retaining walls, water infrastructure, etc.) have a life span greater than 50 years and so will be affected by long-term shifts in climate such as sea level rise as well as changes to the return periods and intensity of the extreme events including heat waves, bushfires, hail and cyclones. How these changes in the climate will impact on existing Council assets and their management has not been well understood and existing financial and asset management tools have not effectively incorporated climate change scenarios into municipal planning processes.

The challenge for Local Governments Australia wide is to adapt to the likely impacts of climate change in a timely and feasible way. To date there has been very little information and no available tools to translate these impacts into municipal financial and asset management plans. Councils have indicated that they are overwhelmed by the amount of information made available to them on climate change but do not know how to translate this information into planning processes to improve their capacity to adapt the built environment. The research undertaken in this project delivers a set of guidelines and technical modelling tools that fill this gap and provides a clear, comparative financial analysis of adaptation options to the management of Local Government assets.

Historically, maintenance and replacement of hard infrastructure in Council has been guided by the principles, models and tools provided in the International Infrastructure Management Manual, developed by the Institute of Public Works Engineering Australia (IPWEA) in conjunction with Councils, engineers and manufacturers of various components and materials. However, due to the limited information on potential impacts on infrastructure due to climate change, these tools have not allowed for the incorporation of climate change impacts and the likely flow-on effects to asset and financial management.

To address these gaps in knowledge and practical tools, the objectives of this project were to: identify key Council assets vulnerable to climate change; determine the likely impacts of climate change on Council assets; undertake a financial risk modelling exercise to quantify in monetary terms climate change asset risk; develop the necessary modifications to existing asset management and financial sustainability tools so that Councils may evaluate various climate change action scenarios at the management planning level and ultimately guide service level standards.

This project was a collaboration of the University of South Australia (UniSA), Local Government Association of South Australia (LGASA), Western Australian Local Government Association (WALGA), the Institute of Public Works Engineering Australia (IPWEA) and the Municipal Association Victoria (MAV) and has had support and input from ten case study Councils across southern Australia.

1.3 Collaborating Local Government Areas

The collaborating Local Government jurisdictions were selected from across southern Australia on the basis of a number of selection criteria and were involved in the development of the tools and provided the necessary data to support the analysis. Councils were selected on the basis of whether they were supportive of the project and willing to collaborate, had sufficient data for input to the model for testing and had undertaken a recent audit of infrastructure assets. In addition Councils representing a coastal, inland, metropolitan, rural and regional area were selected to ensure a spread of population, asset and geography (Figure 1).

The Councils that collaborated in the study were:

South Australia:	Port Adelaide Enfield (metro coastal), Campbelltown (metro inland), Barossa (regional inland), Wattle Range (regional coastal), Onkaparinga (metro coastal and hill slope) and Tumby Bay (very small regional coastal)
Victoria:	Hume City (metro inland), Bass Coast (regional coastal)
Western Australia:	Esperance (regional, coastal)
Tasmania:	Brighton (regional mixed)

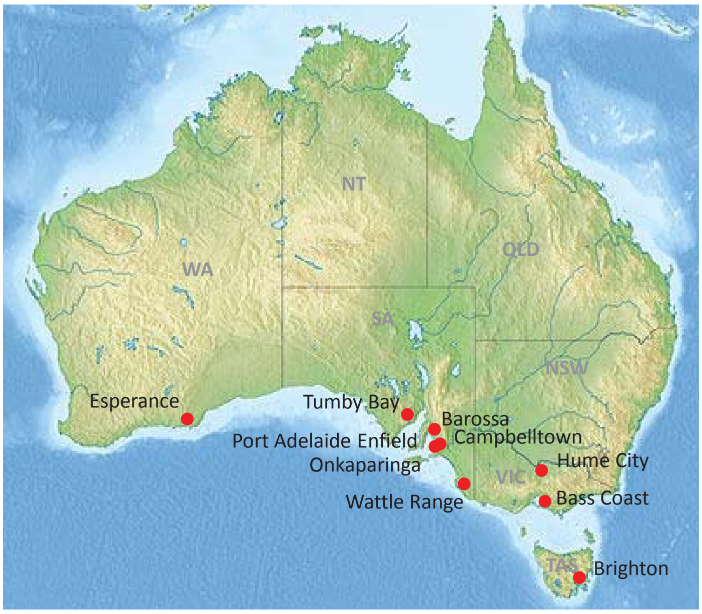


Figure 1: Map of Australia showing the location and name of collaborating Councils in the project (Adapted from http://en.wikipedia.org/wiki/Template:Location_map_Australia).

1.4 Project Methodology

The project had five key stages that align to the following chapters in this report:

- Stage 1: Climate change review and scenarios – A review of climate change across southern Australia was undertaken. The climate change SRES scenarios and projection years used for the model were then determined based on the latest climate change science and in collaboration with CSIRO and BOM researchers. Data sets describing the average climate at suitable spatial and temporal scales were identified for the ten case study Local Government areas.
- Stage 2: Determine asset vulnerability – key Local Government assets that are likely to be affected by changes to the climate were identified on the basis of an extensive literature review, data provided by IPWEA, engineering assessments of partner Local Government areas. The likely impact of the identified climate changes on those vulnerable assets was then examined and quantified where possible.
- Stage 3: Financial modelling – Existing models and tools that are used to determine the financial outcomes from highly variable economic environments such as options pricing and uncertainty analysis were modified to incorporate variables that would allow for the analysis of climate change impacts on vulnerable assets. The financial decision and risk modelling software developed included full economic, risk and uncertainty analyses in a generic framework that allows for the input of identified climate and adaptation options. The model developed provides a cost analysis of various scenarios and options and will output hard financial data that can input to other Local Government financial and asset management tools. Outputs from the financial modelling include likely changes to asset useful life and maintenance costs in response to climate changes and include the dimensions of risk and uncertainty. Although validated using data from the ten case study Local Governments across the winter rainfall dominant temperate climates of southern Australia, the outputs of the project are generic in nature and allow Local Governments anywhere in Australia to input their climate specific, site specific and infrastructure specific variables.
- Stage 4: Development of financial and asset management tools – The financial sustainability and asset management tools that are currently used by Councils were reviewed. The existing IPWEA tool NAMS.PLUS was identified as the only national asset management planning software system that is supported by a standardised methodology for use by Local Governments. The financial model developed in Stage 3 was designed to integrate into NAMS.PLUS and supporting documentation and a “How To” guide developed to assist Local Governments to undertake the analysis (Appendix 3).
- Stage 5: Council trials – The financial and asset management tool and supporting materials were trialled by each of the case study Local Governments using real data. Feedback from trials was incorporated in the final revisions of software, documentation and “How To” guide.

Each of the stages was undertaken in collaboration with key advisory researchers from CSIRO, BOM, IPWEA, financial and economic modellers and climate change impact and adaptation researchers via a project stakeholder team and technical panel, as well as the collaborating Local Governments partners.

2 CLIMATE CHANGE AND SOUTHERN AUSTRALIA

To assess the likely impacts of climate change on Local Government assets, the first stage of the project as defined by the project scope (Appendix 1) was to review the likely changes in the climate across southern Australia. This chapter provides a detailed review of the current and future projections for the key climate variables of temperature, rainfall, ocean changes and extreme events for the region. Specific data requirements and scenarios for the development of the financial model are detailed in Chapter 6.

2.1 The Climate and Weather of Southern Australia

Much of southern Australia experiences a Mediterranean climate with hot, dry summers and cool wet winters. The region is affected by a number of large-scale climate systems including the latitude of the sub-tropical ridge or high pressure belt, the Indian Ocean Dipole, the El Niño / La Niña Southern Oscillation in the Pacific and the Southern Annular Mode across the south of the continent. These systems vary as a result of changes in atmospheric and oceanic temperatures and resulting large scale atmospheric and ocean circulations. Figure 2 shows the key influences that create the weather and climate across the region.

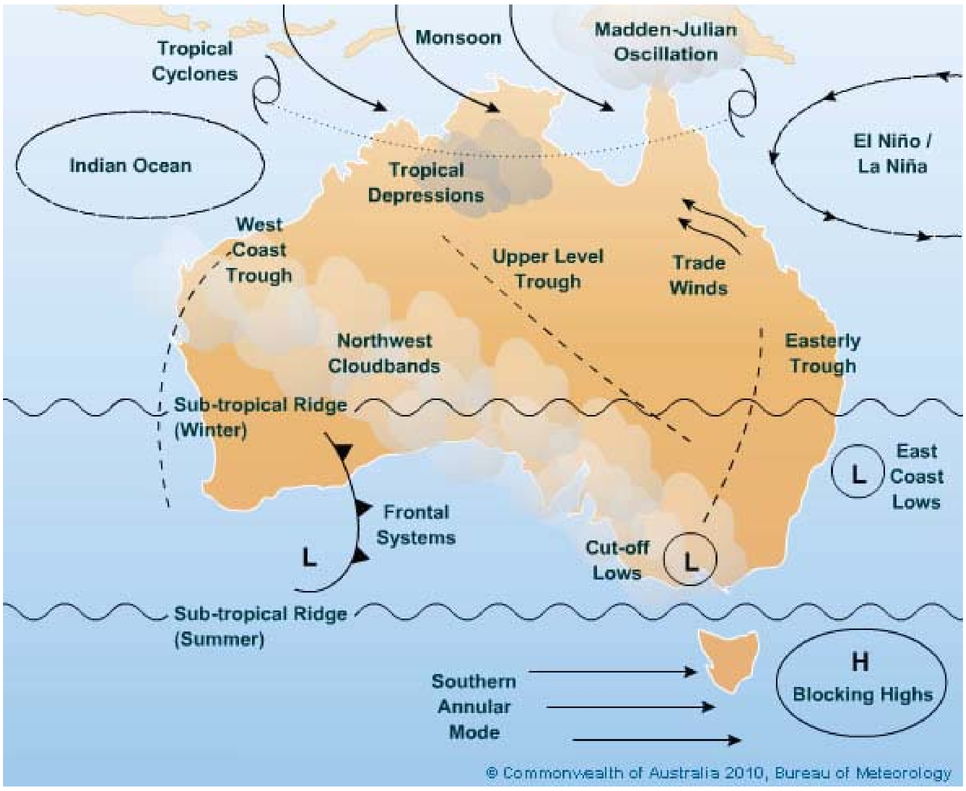


Figure 2: The main climate and weather drivers that affect Australia (Source: Bureau of Meteorology 2011).

Depending on the state of each of the large scale climate systems, southern Australia may experience above or below average incidence of particular weather conditions – drought, heatwave, bushfire risk, flood, cold events etc. The long-term seasonal variation for rainfall and temperature are shown in Figure 3 – Figure 6 (lowest on record, highest on record and full record median (50% decile) and highlight the highly variable nature of the climate across southern Australia.

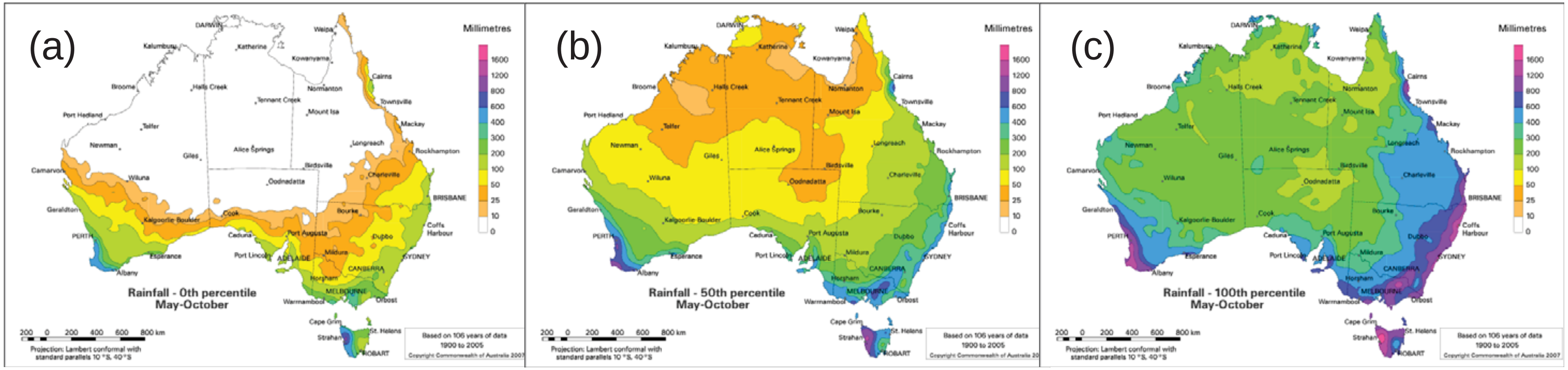


Figure 3: Historic winter (May – October) rainfall Australia for the period 1900-2005: (a) lowest on record, (b) median, and (c) highest on record (Bureau of Meteorology 2011).

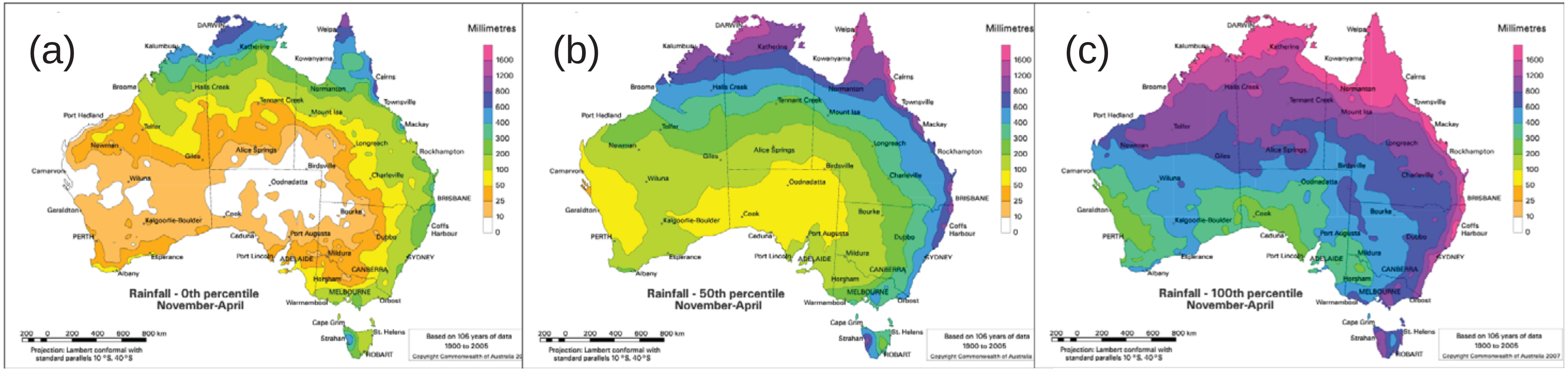


Figure 4: Historic summer (November - April) rainfall Australia for the period 1900-2005: (a) lowest on record, (b) median, and (c) highest on record (Bureau of Meteorology 2011).

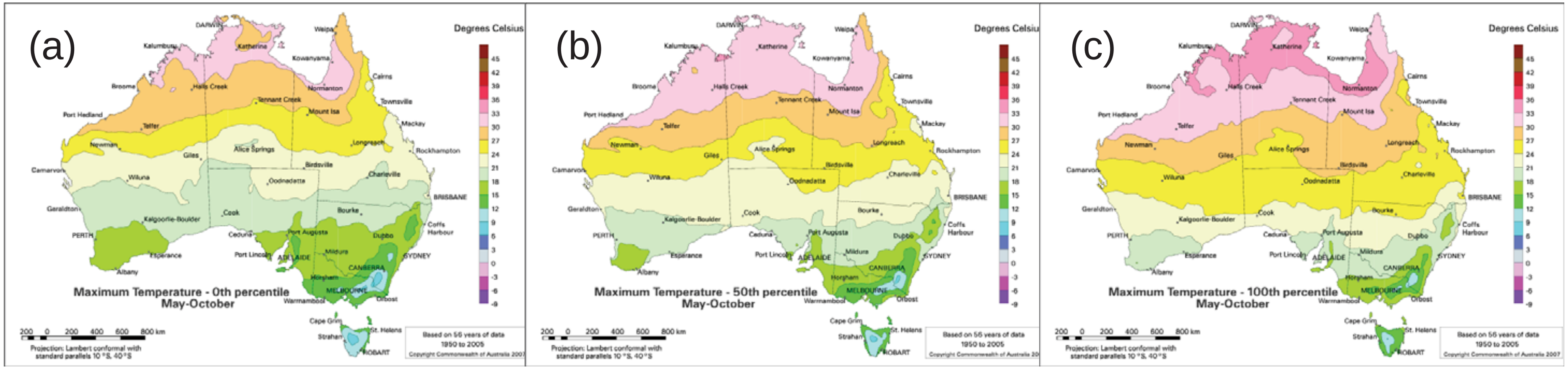


Figure 5: Historic winter (May – October) maximum temperature Australia for the period 1900-2005: (a) lowest on record, (b) median, and (c) highest on record (Bureau of Meteorology 2011).

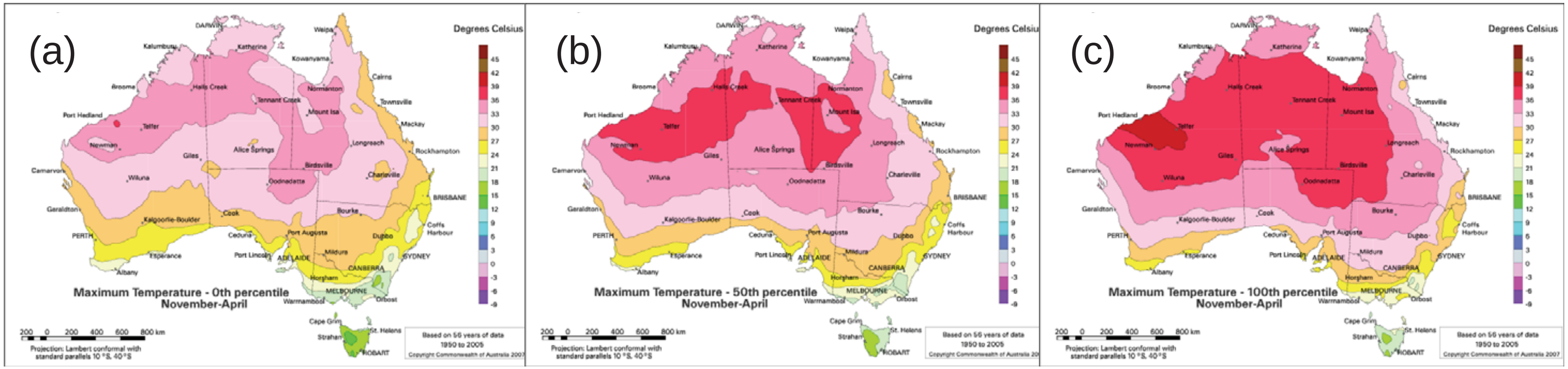


Figure 6: Historic summer (November - April) maximum temperature Australia for the period 1900-2005: (a) lowest on record, (b) median, and (c) highest on record (Bureau of Meteorology 2011).

2.2 Climate Change – Latest Trends

In 2007, the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) was released and provided a review of the latest findings from climate change science and impacts. Since then there has been further research and updated data on many of the key aspects of climate change including recent trends. This review considers those aspects of climate change that may affect Local Government owned infrastructure across southern Australia as defined in the Project Scope document (Appendix 1).

2.2.1 Greenhouse gas emissions

Between 1960 and 2009, humans released 273 billion tonnes of carbon dioxide into the atmosphere by burning fossil fuels (coal, oil, gas) (Mikaloff-Fletcher 2011). More carbon dioxide and other greenhouse gases (methane, nitrous oxide and others) have been released as part of industrial processes and land clearing. Increased concentrations of greenhouse gases in the atmosphere enhance the naturally occurring greenhouse effect and further heat the lower levels of the atmosphere because they allow short-wave radiation (sunlight) from the sun to heat the earth, but prevent long-wave thermal radiation (heat) from escaping back out into space. This process is now validated by global surface, balloon and satellite data (IPCC 2007).

In 2008, global emissions of carbon dioxide (CO_2) from the burning of fossil fuels were nearly 40% higher than those in 1990 and the level of CO_2 in the atmosphere by the end of 2010 was 387 parts per million (ppm), up from 280 ppm prior to the industrial revolution. Carbon dioxide levels are now the highest in over 800,000 years. Methane levels are now 1800 parts per billion (ppb) (Figure 7). Total greenhouse gas emissions in the atmosphere by 2010 were equivalent to 465 ppm CO_2 (Allison, Bindoff et al. 2009; Garnaut 2011). Emissions of CO_2 from fossil fuels have risen by 3.4% per year from 2000 – 2008, more than 10 times faster than natural increases at any time over the past 22,000 years and faster than the worst-case scenario expected by the IPCC (Allison, Bindoff et al. 2009). Most of these emissions came from burning fossil fuels, followed by land use changes including deforestation and conversion to crops (Garnaut 2011). In addition, the efficiency of natural carbon sinks (oceans, forests etc.), that have so far soaked up close to half of all CO_2 released, has declined by about 5% over the past 50 years (Allison, Bindoff et al. 2009).

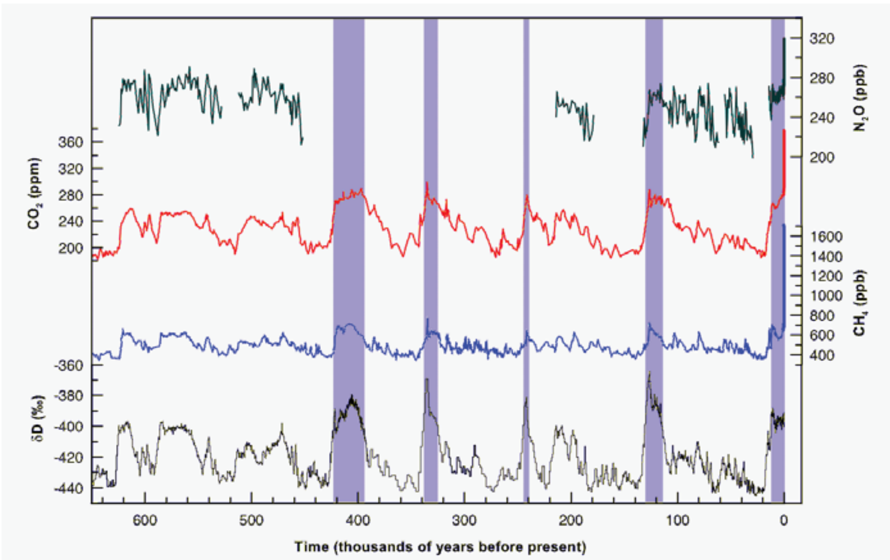


Figure 7: Observe red levels of carbon dioxide, methane and nitrous oxide emissions over the past 650,000 years as measured in ice core data (IPCC 2007).

2.2.2 Temperature

Between 1850 and 2007 the global surface temperature had increased by approximately 0.76°C (IPCC 2007). The eight warmest years have all occurred since 1998, and the 14 warmest years have all occurred since 1990 (Scientific Committee on Antarctic Research 2009). The World Meteorological Organization recently concluded that "the year 2010 ranked as the warmest year on record, together with 1998 and 2005" and that the decade ending 2010 was the warmest on record. Temperatures over land have increased at roughly twice the rate of ocean surface temperatures and the poles have warmed faster than the equatorial regions (Figure 8).

Both maximum and minimum temperatures have increased equally. The rate of warming over the last 50 years is almost double that for the last 100 years (IPCC 2007). Short-term changes (less than 10 years) in the temperature trend show natural variation and do not change the long-term observed global warming trend. There is now no credible explanation (e.g. solar activity, volcanos) for the level of observed warming except as a result of the released greenhouse gases from human activity (Allison, Bindoff et al. 2009).

Aerosols such as dust, smoke and haze both absorb and reflect heat in the atmosphere. The net effect to date has been to cool the earth and so they have masked some of the warming from the greenhouse gases (Garnaut 2011). It is likely that over the coming years the concentration of aerosols in the atmosphere will be decreased by measures to reduce the associated health risks, and so the cooling effect will be reduced. In addition, an increase in clouds and water vapour in a warmer world (because of increased evaporation and humidity) are now known to create "positive feedbacks" that will warm the planet further. The increased humidity is also likely to lead to a significant rise in heat stress and make tropical areas less liveable (Sherwood 2011).

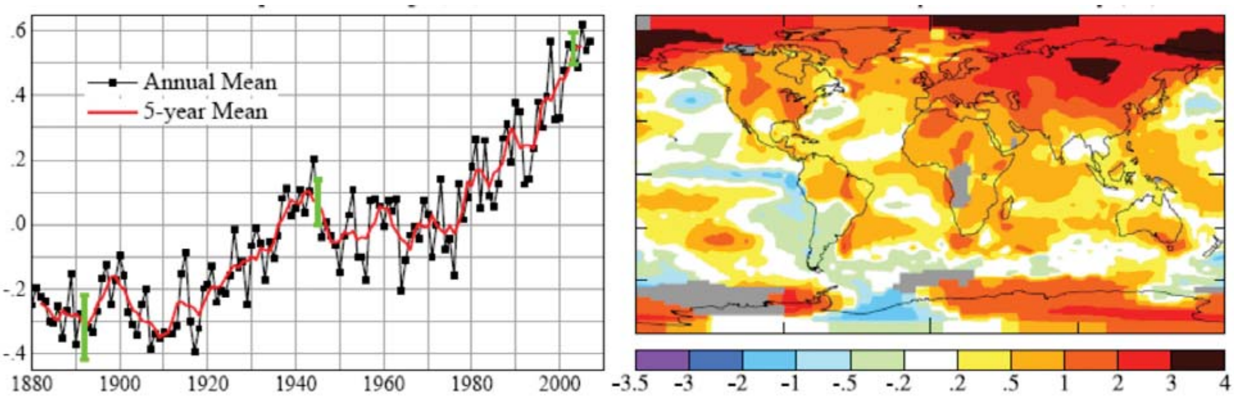


Figure 8: Global temperature change (°C) 1880 – 2007 (left) and the 2007 surface temperature anomaly (°C) relative to the average 1951 – 1980 temperature (right) (Scientific Committee on Antarctic Research 2009).

From 1950 to 2007, the average temperature of Australia increased by 0.9°C. The frequency of hot nights had increased and cold nights decreased (CSIRO and BoM 2007) (Figure 9).

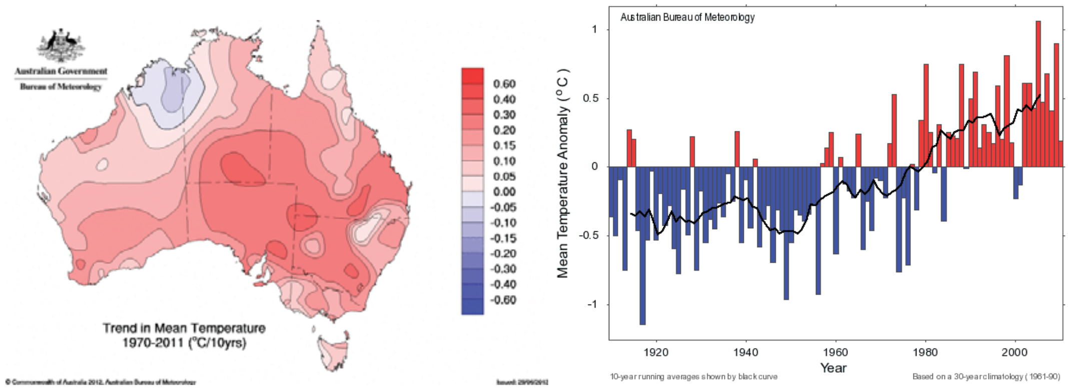


Figure 9: Increase in Australian mean (average) temperature (left) in °C/decade and (right) the long term annual mean temperature change from 1961-1990 average (Source: Bureau of Meteorology 2011).

2.2.3 Rainfall

At a global scale, increased temperatures lead to an increase in evaporation and hence atmospheric water vapour, cloud and rainfall. As a result of an enhanced hydrological cycle, atmospheric water vapour has increased several percent per decade, and cloud cover by some 2% (IPCC 2001) since 1900. However, there are large differences in rainfall from one region of the globe to another. The tropics are expected to get wetter and the mid-latitudes drier but with an increase in the chance of intense precipitation and flooding (Steffen 2009; Garnaut 2011).

Rainfall across Australia has increased slightly, although, on a continent wide basis the trend is not statistically significant due to the high inter-annual variability (Smith 2004). For regions where precipitation has increased (north-west Australia) there has been more rain in summer than winter, probably as a result of increases in heavy rainfall events and the number of rain days, and influences from atmospheric aerosol pollution from south-east Asia. Since 1976 the frequency and intensity of El Niño events has increased and resulted in a rainfall decrease along the east coast of the continent, mostly in summer and autumn (Hughes 2003; Steffen 2009) (Figure 10).

The drying trend across southern Australia since the early 1990s is most likely the result of an intensification of the sub-tropical ridge (or high pressure belt) (Post 2011) and changes to the Southern Annular Mode that have resulted in a pole-ward shift in winter storms and may explain up to 70% of the observed rainfall declines across southern Australia (Nicholls 2009). Each of these changes is consistent with a warming planet and so the drying trend is likely to continue (Steffen 2009; Garnaut 2011). Recent research on the alternating patterns of warm and cool sea surface temperatures across the Indian Ocean, now known as the Indian Ocean Dipole, suggests that the pattern may be linked to significant droughts across our region (Steffen 2009).

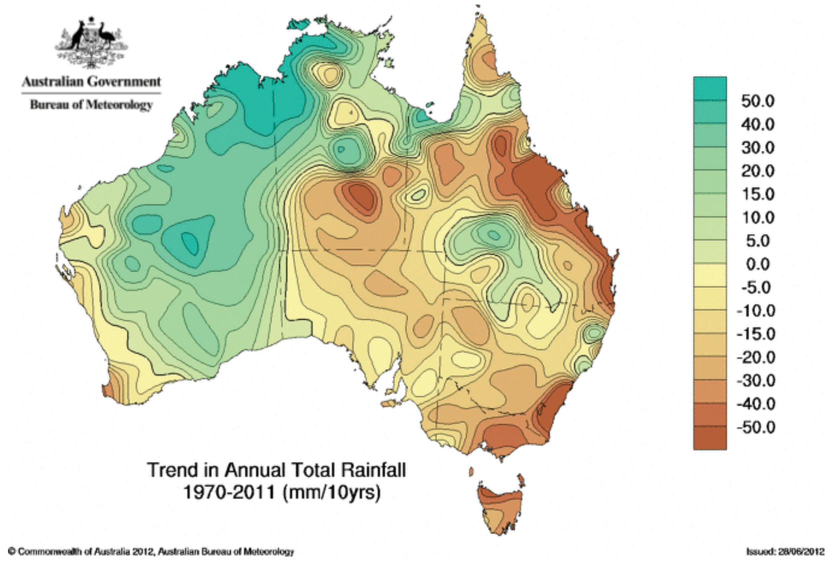


Figure 10: Annual rainfall trends across Australia 1970 – 2010 (mm/10 years) (Source: Bureau of Meteorology 2011).

The recent 13 year drought in south-eastern Australia including the Murray Darling Basin, was the worst on record and different from other droughts because (a) there were no wet years over the whole period, (b) it was confined to southern Australia and did not extend across the continent and (c) the main decrease in rainfall was in autumn rather than winter or spring. In addition, temperatures have been steadily rising across the region. These factors together indicate that the event has been partly driven by changes in the large-scale climate patterns that bring rain to the region as a result of global warming and is not just part of a naturally occurring cycle (CSIRO 2010).

2.2.4 Evaporation

As the earth warms, the atmosphere will hold more water vapour and so humidity will increase in some areas depending on atmospheric circulations (Allison, Bindoff et al. 2009). Early reductions in pan evaporation for parts of Australia have been attributed to changes in instrument exposure and since 1990, evaporation has increased as would be expected in a warming environment (Gifford, Farquhar et al. 2004; Wild 2004).

2.2.5 Ocean changes

The oceans have warmed approximately 0.7°C since 1870, mostly in the top 1000 m (Roemmich and Gilson 2011). Analysis by many groups around the world now confirms that the oceans have so far absorbed more than 90% of the increased heat associated with global warming (Church 2011). Sea surface temperatures around Australia are also rising and most of the warmer water appears to be pooling around the south / south-east of the continent because of the way ocean currents flow (Karl Braganza, National Climate Centre *pers. comm*. June 2010). During 2010, the sea surface temperatures in the Australian region were 0.54°C above the 1961 to 1990 average - the highest on record (Garnaut 2011).

Tidal gauges and satellite altimeter data show an increase in global sea levels since 1970 of about 1.7 mm per year or 17 cm in the past century (Church 2011). The most rapid increase (3.1 mm/year) has occurred since 1993 and is the result of both thermal expansion (about 45%) and land-based ice contributions (about 40%) (Steffen 2006; Church 2011). As a result, sea level rise is currently tracking at or near the upper limit of the IPCC worst-case projections (Figure 11). Global changes in ocean salinity and currents now confirm what would be expected as a result of altered rainfall and increased ice melt in Arctic and Antarctic regions (Garnaut 2011; Rintoul, Sallee et al. 2011).

The average rate of sea level rise around Australia was about 1.2 mm/year over the period 1920 – 2000 (Church, Hunter et al. 2004). As with most large coastlines, the measured increases in sea level along the coast vary as a result of tectonic movement, climatic influences including the El Niño Southern Oscillation, and anthropogenic changes such as subsidence due to the draining of wetlands and other modifications. Data from the early 1990s to June 2009 show increases in sea level around Australia of between 1.5 – 8.6 mm/year (National Tidal Centre 2009). All measurements are adjusted for tectonic movement, seasonal climate variations and anthropogenic land changes (National Tidal Centre 2009).

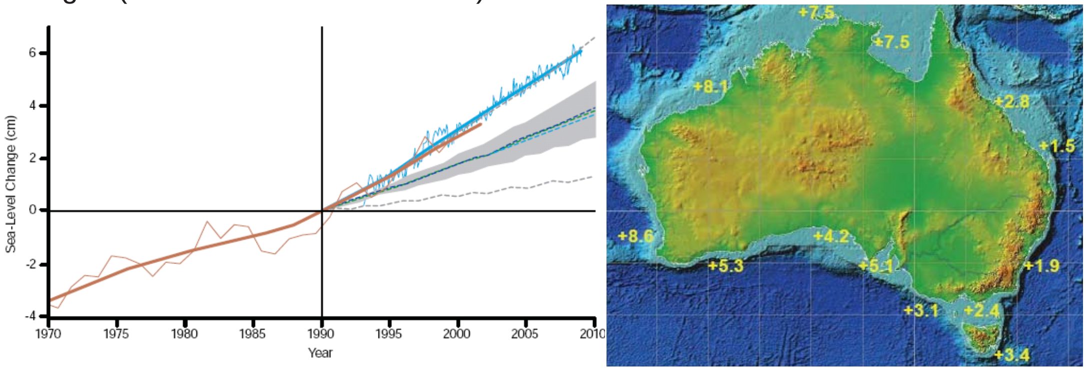


Figure 11: (Left) Global sea level changes in centimetres from 1970 – 2008. The envelope of IPCC scenario projections are shown for comparison (Steffen 2009). (Right) Australian sea level changes (mm/year) from the early 1990s when the National Tidal Centre Sea Level Rise project started to end June 2009. The measurements take into account changes due to tectonic subsidence and uplift and seasonal climatic influences (Source: National Tidal Centre 2009).

When carbon dioxide is absorbed by the oceans a chemical reaction converts it to carbonic acid and subsequently drops in the pH of the water. Recent measurements indicate that the oceans are now about 0.1 pH unit lower than they were prior to the industrial era (30% more acid) (Allison, Bindoff et al. 2009). This level of acidity is the highest recorded in the past 25 million years and is fast approaching one that is unfavourable for coral formation. Low pH in sea water also leads to the erosion of calcium carbonate shells built by other organisms such as oysters, sea urchins, mussels, crustaceans and calcifying plankton species (Steffen 2009). Warming of the oceans has also led to a measurable decrease in dissolved oxygen (Allison, Bindoff et al. 2009).

2.2.6 Extreme events

Globally and in Australia, hot days and nights and the frequency of heatwaves have increased in many areas. Conversely, the frequency of cold days, cold nights and frosts has decreased (CSIRO and BoM 2007; IPCC 2007). For example, since 1970 the number of very hot days (days above 40°C) in South Australia has increased by between 4.5 and 9.0 days (Figure 12). In March 2008 Adelaide had a record 15 days over 35°C and 11 days over 38°C (Bureau of Meteorology 2011).

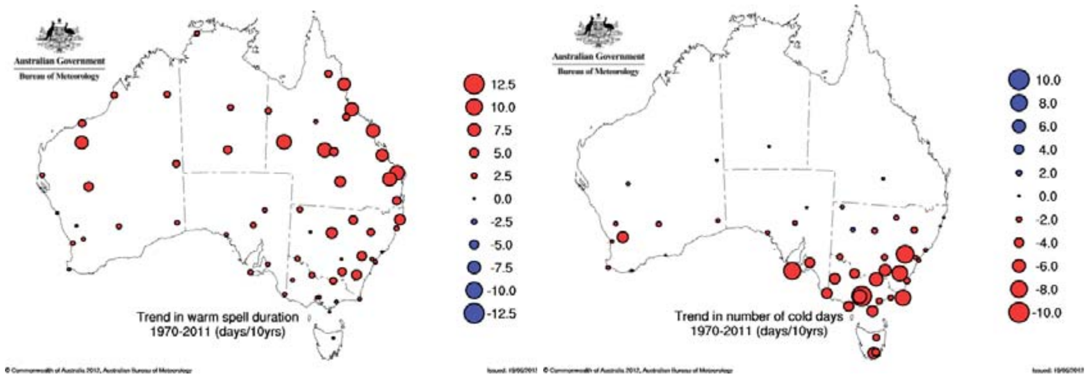


Figure 12: (Left) Increase in warm spell duration (a measure of heatwaves) and number of cold days in number of days from 1970 – 2010 (Source: Bureau of Meteorology 2011).

The number of extreme daily rainfall has increased in north-west and central Australia but decreased across the south-west, south-east and central east coast (CSIRO and BoM 2007). The observed trend towards extreme hot and extreme wet conditions occurring at the same time is not consistent with processes that cause natural climate variability (Bureau of Meteorology 2011). At Spencers Creek in the Snowy Mountains, spring snow depth has declined by up to 40% since 1962 (CSIRO and BoM 2007).

2.2.7 Bushfire incidence

The intensity of bushfires is a combination of a number of factors including temperature, fuel loads, humidity and wind. The recent drying trend across southern Australia has made the fuel load more susceptible to burning (Steffen 2009; Garnaut 2011). Over the past decade an upward trend in the median seasonal Forest Fire Danger Index (FFDI), a measure of fire risk, indicates increased fire danger across south-east Australia. Fire danger weather has increased in many areas by 10 – 40% from 2001 – 2007 compared to the 1980 – 2000 period (Steffen 2009). In addition, four of the last five fire seasons (to 2007) have been among the longest on record since 1942, a trend that has increased since the early 1990s (Lucas, Hennessy et al. 2007). Conditions recorded in the 2009 “Black Saturday” fires in Victoria are considered to be consistent with expectations for a warming world (Garnaut 2011).

2.3 Climate Change – Future Trends

Projections of future changes in the climate are made by using global climate models that have been tested for accuracy against historical data. As the climate model projects further into the future there are uncertainties that will affect how accurate the projections will be. Uncertainties include how much aerosols and clouds will influence future temperatures (Sherwood 2011), what the future human emissions of greenhouse gases will be and how sensitive the climate is to the extra warming. For these reasons future projections of climate are expressed as a range of different emissions scenarios and climate sensitivity scenarios. In 2007, the IPCC estimated that the global average temperature was likely to rise by 3^{o}C with a doubling of greenhouse gases in the atmosphere, an estimate that has been since confirmed by more recent research (Garnaut 2011).

For Australia, there have been no updated climate projections since the IPCC AR4 scenarios were undertaken by CSIRO in 2007. For the IPCC AR4, climate projections made by global climate models were based on future emissions scenarios in the Special Report on Emissions Scenarios (SRES) used in previous assessments (Figure 13). For the upcoming IPCC Fifth Assessment Report (AR5), new emissions scenarios to be known as “Representative Concentration Pathways” (Figure 13) will be used instead (Moss, Edmonds et al. 2010). The four pathways will represent the full range of greenhouse gas emission concentrations that may occur in the atmosphere by the year 2100 and will range from 450 ppm up to 1300 ppm CO_2 equivalents. The climate projections from these scenarios are expected to be released in 2014.

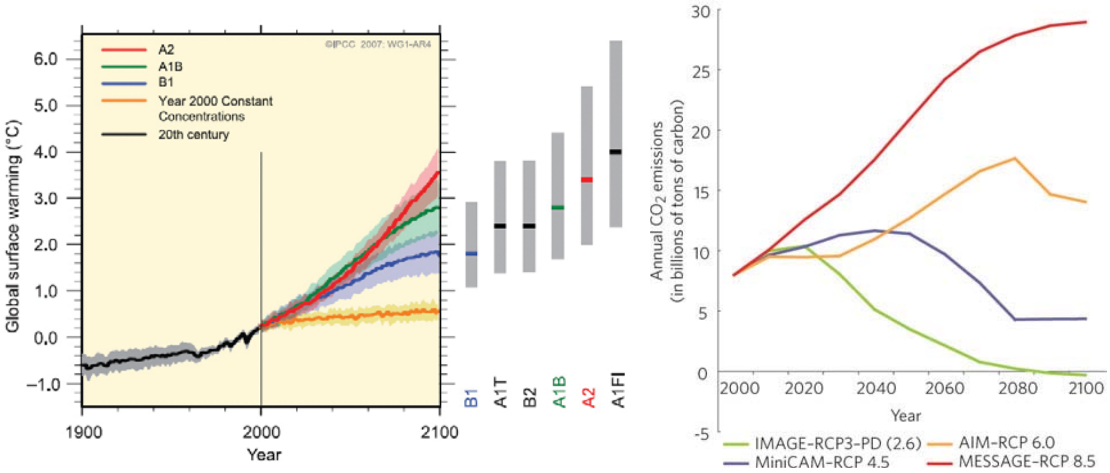


Figure 13: (Left) Global model average warming for each of the IPCC AR4 future climate scenarios (IPCC 2007) and (right) annual CO2 equivalent emissions "representative concentration pathways" scenarios to be used for future climate projections in the IPCC AR5 global climate model simulations (Source: Moss, Edmonds et al. 2010).

2.3.1 Greenhouse gas emissions

Regardless of efforts to reduce greenhouse gas emissions in the future, much of the climate change over the coming years will be the result of greenhouse gases already in the atmosphere – "committed warming" (IPCC 2007). It is likely that the earth is now committed to at least 2.4°C of warming above pre-industrial levels since the concentration of greenhouse gas emissions has exceeded the 450 ppm level and it is likely there will be future reductions of aerosols from Asia (Ramanathan and Feng 2008). Carbon dioxide remains in the atmosphere for many centuries and so despite the best efforts to reduce future emissions the planet will continue to warm into the future because of a lag in the climate system. Greenhouse gas concentrations of 650 ppm (likely without the severe and prompt emissions reductions required) will likely see global increases in temperatures soar over 4°C (Nature Reports - Climate Change 2009).

2.3.2 Temperature

The AR4 predicted mean global temperature to increase by 1.1 to 6.4°C over the 1990 – 2100 period (IPCC 2007), although if greenhouse gas emissions continue at the high end of the scale the increase in global temperature may be as much as 7.0°C (Allison, Bindoff et al. 2009). Globally averaged sea surface temperatures are also expected to increase with a trend towards more 'El Niño like' conditions, although, changes to the frequency and intensity of these El Niño events is still unclear. It is highly likely that hot days and heat waves will become more frequent with greatest increases over land areas where soil moisture decreases will occur. Cold events and frosts are likely to decrease in frequency (IPCC 2007).

An increase in average annual temperature of between 0.6°C and 2.0°C by 2030 and 1.0°C and 5°C by 2070 compared to 1990 levels is predicted for Southern Australia. Spatial patterns of warming are expected to be consistent with current observations – greater warming inland and less along the coastal strip (Figure 14).

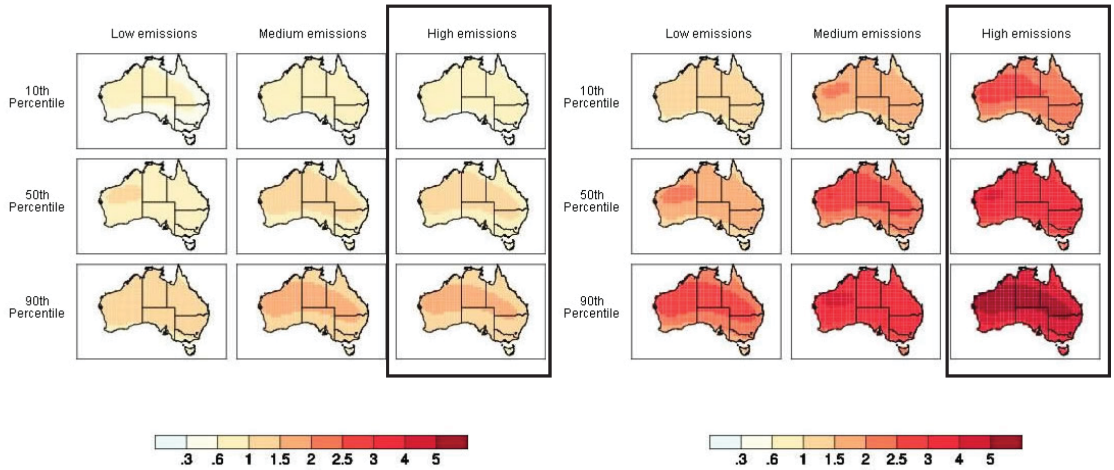


Figure 14: Expected range of changes to annual temperature (°C) for Australia as predicted by a suite of Global Climate Models under low medium and high greenhouse gas emissions scenarios for the year 2030 (left) and 2070 (right) (Source: Bureau of Meteorology 2009). The median change across all models is shown in the 50th percentile row.

2.3.3 Rainfall

Globally averaged atmospheric water vapour, evaporation and precipitation are all projected to increase under climate change. Increases in rainfall are very likely in the tropics, while decreases are likely in most subtropical land regions (IPCC 2007).

The majority of models predict a future that is drier for southern Australia than was experienced from 1900 to 2000 (Garnaut 2011). The increase in the number of both El Niño events and positive Indian Ocean Dipole events over the past decades are thought to be a result of global warming and each results in drier conditions across eastern and southern Australia (Cai 2011). Climate projections for Southern Australia indicate that annual median rainfall is expected to change by 0% to +10% by 2030 and by –5% to -20% by 2070 compared to 1990 levels (Figure 15) (Bureau of Meteorology 2011). Recent CSIRO and Bureau of Meteorology model projections show with a very high level of confidence (up to 90%) that there will be a drop in winter rainfall across Victoria and southern South Australia (Steffen 2009).

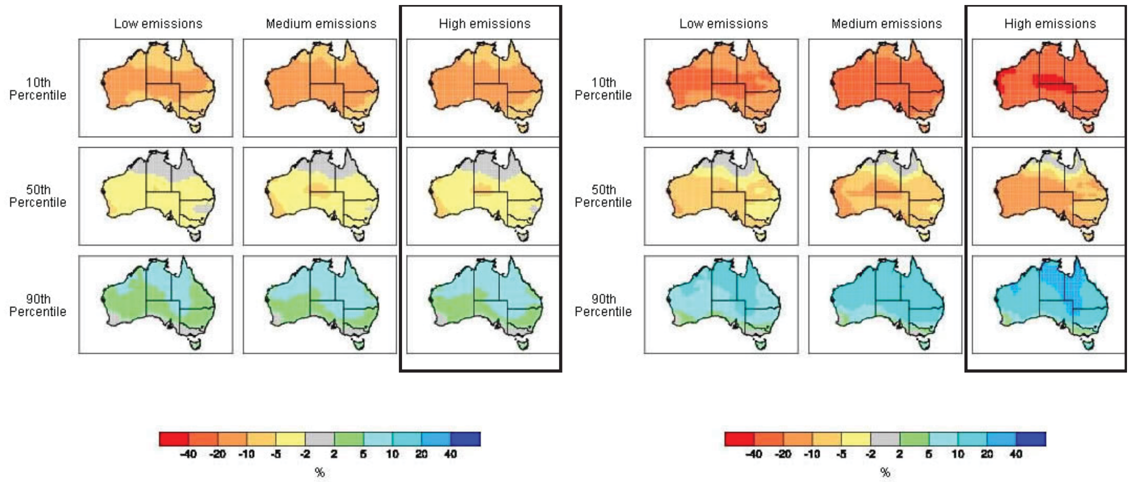


Figure 15: Expected range of changes to annual rainfall (% change) for Australia as predicted by a suite of Global Climate Models under low, medium and high emissions scenario for the year 2030 (left) and 2070 (right) (Source: Bureau of Meteorology 2011). The median change across all models is shown in the 50th percentile row.

2.3.4 Ocean changes

The AR4 projections for global sea level rise were between 0.20 and 0.59 m by 2090 – 2099 across the range of climate scenarios (IPCC 2007). These estimates included thermal expansion from oceans and freshwater contributions from glaciers, Greenland and Antarctica, but did not include uncertainties pertaining to changes in ice sheet flow. It has been estimated that if the West Antarctic Ice Sheet were to collapse (the currently grounded ice), sea levels could be expected to rise by between 4 – 6 m (Rahmstorf 2010). Research since AR4 suggests that there is a "considerable body of evidence now that points toward a sea level rise of 0.5 – 1.0 m by 2100" and that "sea level rise… towards 1.5 m cannot be ruled out" (Steffen 2009). There is certainly no credible research that predicts sea levels to be less than that predicted in the AR4 (Garnaut 2011).

It should be noted that even moderate increases in sea level rise can result in extreme sea level events associated with high tides and storm surges to occur hundreds of times more frequently than they currently do. As an example, an event that now occurs once every 100 years could be expected to occur two or three times *every* year by the end of the century (Steffen 2009). In Australia more than 85% of the population lives in coastal regions and so the impacts of sea level rise may be significant (Garnaut 2011).

Business as usual trajectories of greenhouse gas emissions and associated increases in ocean acidification and warming are likely to "overwhelm even the most resilient of reefs sometime in the second half of the century" (Hoegh-Guldberg, Mumby et al. 2007) and hinder the production of shells for invertebrates. It is now predicted that by 2050 that ocean acidity could increase by 150% (Garnaut 2011). Reductions in dissolved oxygen levels will cause severe difficulties for many species.

2.3.5 Extreme events

As has been the trend since 1970, the number of extreme hot days is likely to increase under climate change. For example, projections indicate that by 2030 in Adelaide there will be several more days/year above 35^{o}C and that by the year 2070 under a high greenhouse gas emissions scenario there may be twice as many extreme hot days as are experienced now (Bureau of Meteorology 2009). Cold events and frost will decrease in a warmer world (Garnaut 2011).

Rainfall intensity across Australia is expected to increase generally, particularly in tropical areas although not by the same amount everywhere. For example, in South Australia global climate models suggest an increase of only 1 to 2% in autumn by 2050 and only small changes in the return periods of such rainfall events in the Adelaide region. Slight *decreases* are possible in other seasons, a trend that has been observed already in southern South Australia (Darren Ray, Climatologist, Bureau of Meteorology South Australia, *pers. comm*. November 2009). There are likely to be fewer severe wind events.

2.3.6 Bushfire

For the high greenhouse gas emissions scenarios, the number of "very high" fire days (when the FFDI is greater than 25) are expected to increase by between 20 – 100% by 2050 and the number of "extreme" fire days (when the FFDI is greater than 50) is expected to increase by 100 – 300%. In addition, it is expected that fire seasons will start earlier, end later and be "generally more intense throughout their length". In some regions (e.g. the interior of New South Wales), recent jumps in the number of very high and extreme fire danger days have already exceeded these projections – either a result of decadal variability in climate or because of conservative modelling or projections (Lucas, Hennessy et al. 2007).

Each of the climate changes identified above have the capacity to affect the maintenance schedules and useful life of infrastructure owned and managed by Local Government across southern Australia. The following chapter examines how climate change has been considered in current asset and financial management planning.

3 LOCAL GOVERNMENT ASSET MANAGEMENT

To develop a financial model and decision support tool for the assessment of climate change impacts on Local Government coastal assets, it was important to understand the approaches to managing assets in the face of climate change and the asset and financial management guidelines currently in place. To this end, this chapter reviews climate change adaptation approaches to infrastructure both overseas (briefly) and in Australia (in more detail) and then examines asset and financial management guidelines and tools currently in use by Australian Councils.

3.1 International Approaches to Asset Management and Climate Change

International approaches to climate change have focused on both mitigation and adaptation. However, as delays to achieving international consensus have slowed the mitigation effort, it has become clear that serious impacts of climate change are unlikely to be avoided. Adaptation principles and practices have therefore come into international focus, as nations and organisations realise that they will be required to manage large-scale impacts of climate change sooner rather than later. The IPCC analysis of climate change impacts on industry, settlement and society provides a high-level view of the context in which the responses of local authorities, particularly with respect to infrastructure, is undertaken (Wilbanks et al. 2007). Among their key findings are the following (p. 359):

1. *Climate-change vulnerabilities of industry, settlement and society are mainly related to extreme weather events rather than to gradual climate change. Where extreme weather events become more intense and/or more frequent with climate change, the economic and social costs of those events will increase.*
2. *The significance of climate change (positive or negative) lies in its interactions with other non-climate sources of change and stress, and its impacts should be considered in such a multi-cause context.*
3. *Vulnerabilities to climate change depend considerably on specific geographic, sectoral and social contexts.*

The report distinguishes between physical and institutional infrastructure (p. 370):

> *Infrastructures for industry, settlements and society include both ‘physical’ (such as water, sanitation, energy, transportation and communication systems) and ‘institutional’ (such as shelter, health care, food supply, security, and fire services and other forms of emergency protection). In many instances, such ‘physical’ and ‘institutional’ infrastructures are linked.*

With respect to transport, the IPCC Working Group notes that increases in both temperature regimes and precipitation will have significant impacts (note that in temperate and cool climates some benefits are anticipated)(p. 371):

> *A general increase in temperature and a higher frequency of hot summers are likely to result in an increase in buckled rails and rutted roads, which involve substantial disruption and repair costs. In temperate zones, less salting and gritting will be required, and railway points will freeze less often. Most adaptations to these changes can be made gradually in the course of routine maintenance, for instance by the use of more heat-resistant grades of road metal when resurfacing.*

National studies support this general analysis. A recent United Kingdom (UK) study identified the probable effects of climate change on highway infrastructure, among which were (Lugg 2011):

- increased risk of flooding from rivers, streams and inadequate drainage;
- deterioration and damage to highway structures from subsidence and high temperatures; and
- increased risk of landslips.

Well-established frameworks for climate change adaptation have been developed by UK agencies, in particular the UK Environment Agency (EA) and the Department of Environment, Food and Rural Affairs (DEFRA). Noting that historically adaptation has lagged mitigation, the Environment Agency (2008) identifies a number of key drivers of a renewed focus on adaptation, including Local Area Agreements. Under these agreements, Local Authorities work with performance indicators, among which is now included an 'Adapting to Climate Change' indicator: "a five-stage process of assessing climate risks, developing an action plan to address those risks, through to implementation and monitoring". Regions in England and Wales are similarly targeted, a policy that influences both planning and economic development to ensure they take account of climate change.

In the United Kingdom (UK) the UK Climate Change Act (2008) governs action on climate change. Five priority areas have been identified: land-use planning, national infrastructure, designing and renovating buildings, managing natural resources, and emergency planning (DEFRA 2011). National infrastructure incorporates communications, emergency services, finance, food, health, transport, energy government and water. Adaptation action is approached through the stakeholders working with government:

1. investors in infrastructure, e.g. infrastructure investment funds and pension funds;
2. infrastructure owners, e.g. owners of ports and energy infrastructure;
3. infrastructure operators, e.g. organisations that operate airports and those that are contracted to build new infrastructure and run maintenance contracts;
4. economic regulators; and
5. professional bodies such as engineers.

It is emphasised that climate change is a long-range challenge and that the climate resilience of infrastructure should be handled on two fronts:

- existing infrastructure has been engineered and built for a past or current climate and may not be resilient to the future climate; and
- new infrastructure will often have a life of 50 to 100 years (or more). To ensure its viability over its lifetime, it needs to be resilient to a climate that could be significantly different.

In particular, path dependency and the preservation of options are seen as essential components of adaptation:

> *When making decisions about the provision of national infrastructure it will therefore be important to allow for future climate change and avoid closing off options, making it harder and costlier to adapt infrastructure in the future (p. 26).*

Again, action at the local level is seen as critical (p. 39):

> *...the strategic approach to adapting national infrastructure can be replicated at the sub-regional and local level by local authorities and the new Local Enterprise Partnerships (LEPs). Both have a potential role in encouraging and coordinating action to adapt infrastructure at the sub-national level to boost local resilience to climate change, minimise economic risk and maximise any economic opportunities. Other potential benefits could be:*

1. *Facilitating localised cross-sector adaptation initiatives leading to more targeted adaptation action.*
2. *Action locally may also lead to more action nationally.*

One local UK authority that has taken a lead on climate change adaptation is the City of London (Bara et al. 2010). Since the early 1990s, the City has been developing a practical risk management framework, in consultation with its major stakeholders. Key risks identified are flooding, water resources, heat and air pollution, and ground conditions. Adaptation options are then categorised as follows (p. iii):

1. *'No-regrets' measures deliver benefits that exceed their costs, whatever the extent of climate change.*
2. *Low-regrets' measures are low cost, and have potentially large benefits under climate change.*
3. *'Win-win' measures contribute to climate adaptation and also deliver other benefits.*
4. *'Flexible' measures are useful for dealing with uncertainties in the extent of longer-term climate change.*

An informed, qualitative risk rating method is employed (p. 19):

> *The risk rating method involves considering the two components of risk: likelihood of hazard; and magnitude of consequence (impact). The likelihood assessment relates to the probability of the hazard occurring over the lifetime of the particular asset or service in question. The magnitude is based on a qualitative assessment of the consequence of the hazard, by considering four categories of consequence: health, social, economic, environment.*

A simple risk rating matrix is then used to prioritise the risk as very high, high, medium or low. Policy, practical action, and research options are then developed for each of the major risk areas.

The effectiveness of local ownership for the analysis and planning of climate change responses with respect to infrastructure is emphasised by the 3 Counties Alliance Partnership (3CAP) that was developed by three East Midland counties (3CAP 2011). Part of their joint mission states: "Conscious of the importance of sustainability, 3CAP is working jointly to minimise its effect on the environment, to adapt to climate change and to reduce the carbon impact of highway works." In 2009 3CAP undertook a detailed study of potential impacts of climate change on their common highway network (3CAP 2009), noting the importance, and relative absence, of local analysis: "Local authorities should take into account their geography, topography, geology and risks particular to their area when developing adaptation plans". In addition to the above factors, the following were identified as potentially damaging the highway network:

- pavement failure from prolonged high temperatures;
- lack of capacity in the drainage system and flooding of the network;
- surface damage to structures from hotter and drier summers;
- scour to structures from more intense rainfall;
- damage to pavement surface layers from more intense rainfall;
- scour and damage to structures as a result of stronger winds and more storminess; and
- severe damage to light-weight structures from stronger winds and more storminess.

Asset management and accounting practice in the UK has been documented by Dent (1997), in a survey of local authorities. The results of the survey indicated that over 90% of local authorities regularly value their assets. Of the valuation methods used, 32% used a revaluation model (Sales Comparison), 33% a cost model (Depreciated Replacement Cost), 20% an income model (Discounted Cash Flow), and 15% other methods. An example of other methods is the S curve rental method, where the pattern of depreciating value is determined empirically from the opinions of expert valuers (Connellan 1997).

North American practice in asset management at the local level has been discussed by Vanier (2001). Noting that over one trillion dollars is annually expended on maintenance and repair and on capital renewal across North America, the view of the author is that infrastructure work is still underfunded (p. 3):

> *Because not enough is spent on maintenance and repair, owners are accumulating an ever-increasing maintenance deficit, which leads to premature failures and premature renewals. Indeed, even though Canadian cities, for example, currently spend between $12 billion and $15 billion every year on maintaining and renewing their infrastructure, there is an accumulated shortfall estimated at $44 billion to return these assets to an acceptable condition.*

Climate change impacts clearly have the potential to exacerbate this funding shortfall. An argument is presented for the use of decision-support tools in managing assets and infrastructure, including GIS systems, Computer-Aided Design (CAD), relational database management systems, Computerised Maintenance Management System (CMMS), and other such approaches. No one approach is seen as able to handle all demands at the local level. Hence, various tools will be required in combination, and their integration is a key systems and management challenge.

The New Zealand government has also established specific principles for Local Government in dealing with climate change (New Zealand Ministry for the Environment 2011). Their approach has been to take the general principles mandated for Local Government by law and ‘good practice’ and apply them to the issues of climate change. In particular, the following principles are relevant to the issue of infrastructure and climate change:

> ***Sustainability:*** *[defined as] the ongoing ability of communities and people to respond and adapt to change in a way that avoids or limits adverse consequences and enables future generations to provide for their needs, safety and well-being. [Responses] involve applying adaptive, and sometimes limitation responses that will not be regretted, irrespective of the eventual nature and magnitude of climate change effects. However, more recent understanding has developed of the variability of climate change effects, and the possible implications of decisions made in a framework of uncertainty. This has meant a shift to risk-based assessments of climate change effects and responses by local authorities, prior to decisions being made in the interests of long- term sustainability.*
>
> ***Precautionary Principle:*** *It requires an informed but cautious approach to decisions where full information on effects is not available at the time of decision-making, particularly when there is a high level of uncertainty and where decisions are effectively irreversible.*
>
> ***Financial responsibility****: Local Government is expected to act within normal codes of financial responsibility on behalf of the community. For infrastructure enhancements anticipating future effects of climate change, evaluation of risks as well as the costs of different levels of service will need to be expressed in a transparent manner.*

__Liability:__ Local Government can be financially liable for decisions that are shown to have been made in the face of information that should have led to a different decision.

The checklist of questions for Local Governments planning for climate change includes the following, all of which are relevant to the present project:

- *How is the timeframe of climate change effects handled? Is there adequate explanation of the need to act within the framework of the current plan, although effects may become apparent only during the preparation of future plans?*
- *If a change in level of service, or additional capacity, is planned owing to climate change (i.e., requirements will be beyond the level of service or capacity based on other considerations), is this explicit and explained?*
- *Are adaptive responses to potential climate changes identified in relation to specific assets or activities (water supply, wastewater, stormwater, roading, pest management, parks and reserves management, etc.)?*
- *Are the levels of uncertainty involved in the forecasts of climate change explained, and an estimate of the uncertainty provided?*
- *Are the budget requirements, in relation to climate change responses, identified in the Long-term Council Community Plan, explicitly followed through?*
- *Are specific Annual Plan provisions relating to climate change reported appropriately, including asset management?*

The critical point made in the New Zealand guidelines is that climate change adaptation potentially runs across all categories of Local Government business, and must be explicitly considered in all business planning and decision-making.

3.2 Australian Approaches to Asset Management and Climate Change

The response of Local Government in Australia to the challenges of climate change are governed by the National Planning Systems Principles (Local Government and Planning Ministers' Council 2009b). These principles are applied to issues including those that relate to climate change: the design of urban structures; infrastructure coordination; environmental protection and restoration; and sustainable transport. The demands placed on Local Government in planning for climate change and associated challenges are recognised to be increasing:

> *At the same time, emerging or evolving issues, including climate change, energy security, traffic congestion and housing affordability, have presented challenges to Australia's planning systems. Many issues that were previously entirely local in character have assumed regional or even national dimensions, for example security of water supply and waste management. Existing planning policy frameworks are struggling to respond. (p. 4)*

The methods of planning proposed to address these issues include dimensions that are familiar from the above literature: requirements for integration and coordination, certainty, and responsiveness.

A comprehensive risk assessment of infrastructure under climate change was undertaken by the CSIRO for the Victorian Government (Holper et al. 2007). The risk management framework used in the assessment was that provided by Australian Standards, now AS/NZA ISO 31000:2009 (Council of Standards Australia 2009a). Under the framework, eleven principles of risk management were presented, including the following, which are directly relevant to the modelling task of the present study: making risk management part of all decision-making; explicitly addressing uncertainty; using the best available information; taking into account human and cultural factors;

remaining flexible and responsive to change; and facilitating continual improvement. Infrastructure elements reviewed were water, energy, telecommunications, transport, and buildings. General adaptation principles include shared responsibility of government, business and the community; risk analysis to achieve best cost-benefit outcomes; flexibility to allow integration of new information, technology and changes; and integration of social, financial and economic factors. A matrix of infrastructure type against climate change impacts provided for a risk rating negligible/definite risk. Qualitative measure of consequence included infrastructure service, social, governance and finance on a five-fold scale of likelihood. Low and high scenarios were investigated for 2030 and 2070 time horizons.

Infrastructure assets are generally defined as stationary (or fixed) systems that serve defined communities where the system as a whole is intended to be maintained indefinitely to a specified level of service by the continued replacement and refurbishment of its components (INGENIUM 2012). Infrastructure assets are typically found in:

- Transport networks – e.g. roads, rail, ports, airports;
- Energy supply systems – e.g. gas electricity generation and transmission;
- Parks and recreation – e.g. tennis courts;
- Water utilities – e.g. water supply, sewer;
- Stormwater management – e.g. flood detention systems, pipes;
- Community facilities –e.g. libraries, community halls; and
- Telecommunication networks.

Local Government in Australia is typically responsible for a significant range and extent of infrastructure assets with a total value of approximately $245 billion including 650,000 km of local roads and other fixed assets worth more than $180 billion (ACELG 2012). The largest proportion of these Local Government assets (by dollar value) in Australia is long-lived infrastructure. Roads are typically by far the largest category of infrastructure assets for most Local Governments (Figure 16). Many Local Governments also have significant stocks of footpaths, stormwater drainage systems, water supply and waste water systems and buildings and structures. These assets are constructed and operated for the provision of local services.

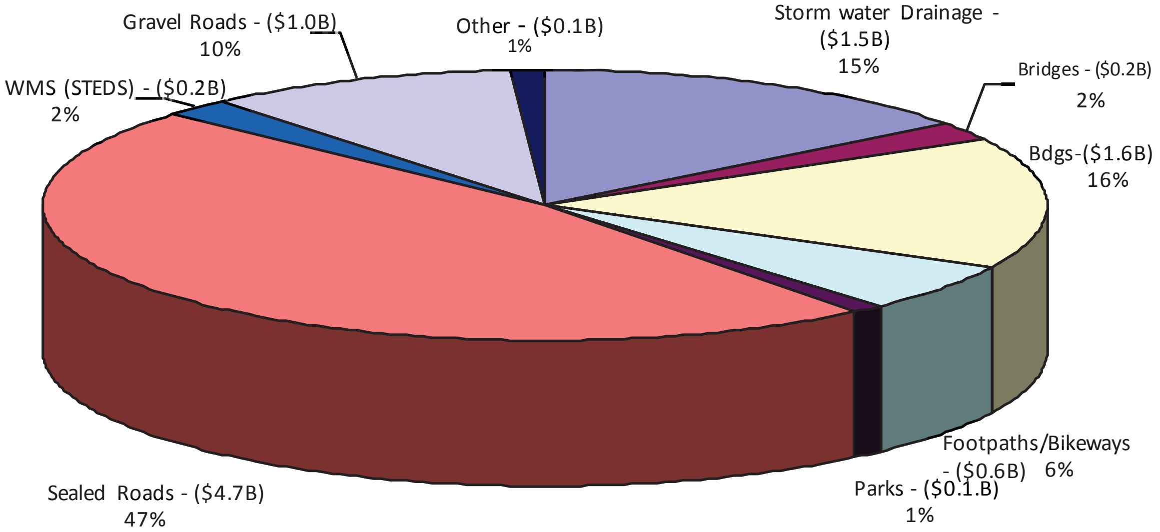


Figure 16: South Australian Local Government infrastructure asset stock 2006 (Source: OSLGR 2010).

The study by Holper et.al. (2006) identified three primary risks for roads from climate change impacts, with associated implications for management (p. 129-120):

1. *Asphalt degradation (increased solar radiation; increased temperature and heatwaves):*
   - *increased maintenance and renewal of road and pavement surfaces in localised regions;*
   - *increase in short-term loss of public access or increased congestion to sections of road and highway (regional and Melbourne) during repair and replacement;*
   - *increase in road replacement costs due to greater rate of degradation; and*
   - *likely financial impact to local Councils.*
2. *Road foundations degradation (increased variation in wet/dry spells, decrease in available moisture):*
   - *Degradation, failure and replacement of road structures due to increases in ground and foundation movement, shrinkage and changes in groundwater;*
   - *Increased maintenance and replacement costs of road infrastructure;*
   - *Short term loss of public access or increased congestion to sections of road and highway (regional and Melbourne) due to increased maintenance and replacement regime; and*
   - *Regional cost to Councils and state.*
3. *Flood damage (increase in extreme daily rainfall, increase in frequency and intensity of storms):*
   - *degradation, failure and replacement of road structures due to increased damage from flooding, inundation of foundations and changes in groundwater;*
   - *increased maintenance and replacement costs of road infrastructure;*
   - *short term loss of public access or increased congestion to sections of road and highway (regional and city) due to increase maintenance and replacement regime;*
   - *regional cost to Councils and state.*

Under both low and high scenarios these risks were rated moderate for both 2030 and 2070, with the exception of flood damage, which was rated high for 2070.

3.3 Australian Local Government Asset Management

Many infrastructure assets have very long service lives. For example, road bridges and concrete structures, including buildings, are typically designed to have a useful service life of up to 100 years. Modern road pavements can have a useful service life in excess of 50 years (there are remnants of roads constructed in England during the Roman occupation, still in use today –although these are exceptional cases). Typical, modern bitumen road surfaces have been shown to have a useful service life of between 7 and 25 years (ARRB 1994), depending on a number of influencing factors. This usually results in the financial modelling and planning for renewals generally being required to extend beyond political terms of government.

Many Local Governments have not kept a register or inventory of assets so the number and condition of assets was not widely understood within the organisation and decisions regarding renewal and intervention treatments often relied on the knowledge of long-serving staff. The combination of a largely unknown extent of the network and long life and renewal intervals typically meant renewal planning tended to be discretionary and highly dependent on the expertise or influence of the Council engineer or overseer responsible for the management of the road network (Andrew Thomas, IPWEA, *pers. comm*. 21 February 2012). Decisions to renew or reconstruct roads were often dependent on availability of funding and prioritised against other competing funding options, for instance new community facilities.

Development of asset management financial systems in Australia, particularly for road pavement management, can be partly attributed to a response in the growth in motor vehicle use. Increased road traffic volumes led to led to deteriorating road conditions and development in the United States of the American Association of State Highway Officials (AASHO) Road test by the United States Highway Research Board in the 1960s (National Research Council 1961). The AASHO test was a research project established to study the performance of pavement structures of known thickness under moving loads of known magnitude and frequency.

The results from the AASHO road test were used to develop a road pavement design guide, first issued in 1961 as the "AASHO Interim Guide for the Design of Rigid and Flexible Pavements". Observation of the failure mode of pavements under various axle loads in this early work identified trends in the development of rutting or cracking, or “roughness”. Analysis of the testing resulted in the establishment of road condition indicators, primarily related to roughness, that were determined by measuring vertical movement and pavement distortions including cracking, rutting, localised failures and patching. Predictive models were developed utilising the data obtained from the roughness measurements and compared to pavement depth and strength, axle loads and environmental conditions. These predictive models identified and demonstrated the finite nature of pavement life - under continued traffic loading conventional road pavements will eventually deteriorate and ultimately fail. If traffic loads and or volumes are to be maintained, pavement reconstruction or renewal is required. This finding led to the adoption of “service life” estimates for road pavements, and in many State and Federal road authorities, long-term planning for road pavement renewal.

Although, in some Australian states, legislation required Councils to maintain a register of roads (for example, section 312 of the South Australian Local Government Act 1934) the information in the register often did not extend beyond a basic description of the location of the road and its width, so the number or extent and physical condition, or value of assets was not widely understood within the organisation or community. Additionally, urban growth, and increased traffic volume led to considerable investment in new road networks, and the extent of the road networks grew, often without any adequate attempts to keep track of this growth.

It was not until the mid-1980s that the first steps were taken to accurately identify the extent of network assets like road, or drainage systems. The findings typically revealed that initial estimates of the extent and value fell well short of the true extent (Government of SA 1987). Collection of more accurate data on road type, extent and condition across the network provided an overall picture of the state of the network, and research undertaken into Local Government infrastructure and investment policies and practice by Burns et.al. (1998) identified a trend of condition deterioration in existing infrastructure due to a shortfall in investment in renewal works, and at the same time, a focus on investment in new infrastructure. This finding suggested that at some future time, some Councils may reach a point where they could not adequately fund the renewal of failing assets.

3.4 Australian Local Government Financial Management

The general context for Local Government financial management in Australia are the Local Government Financial Sustainability Nationally Consistent Frameworks developed under the Local Government and Planning Ministers’ Council (2007, 2009a, 2009b). Under the framework, each state is responsible for a system of (and ‘rules’ for)

Local Government in their jurisdiction. These rules are effectively set out in the Local Government Acts in each state, together with the supporting regulations, codes, guidance, advices and so on. Generally the legislation requires compliance with Australian Accounting Standards, although there are some exceptions and additional requirements.

Financial planning at the Local Government level is operationalised through the strategic plan, budget, and annual reports. The relevant accounting standard is AASB 116 Property, Plant and Equipment (Australian Accounting Standards Board 2009). The standard provides for the recognition of assets, determination of their carrying amounts, depreciation charges, and impairment losses. Definitions that are important to the current project are:

> ***Property, plant and equipment*** *are tangible items that:*
> - *are held for use in the production or supply of goods or services, for rental to others, or for administrative purposes; and*
> - *are expected to be used during more than one period.*
>
> *The* ***residual value*** *of an asset is the estimated amount that an entity would currently obtain from disposal of the asset, after deducting the estimated costs of disposal, if the asset were already of the age and in the condition expected at the end of its useful life.*
>
> ***Useful life*** *is:*
> - *the period over which an asset is expected to be available for use by an entity; or*
> - *the number of production or similar units expected to be obtained from the asset by an entity.*
>
> ***Carrying amount*** *is the amount at which an asset is recognised after deducting any accumulated depreciation and accumulated impairment losses.*

With specific reference to Local Government, the Standard notes:

> *Examples of property, plant and equipment held by not-for-profit public sector entities and for-profit government departments include, but are not limited to, infrastructure, cultural, community and heritage assets.*

After recognition, assets are carried in the accounts under either a cost model (cost less any accumulated depreciation and any accumulated impairment losses) or a revaluation model (fair value at the date of the revaluation less any subsequent accumulated depreciation and subsequent accumulated impairment losses).

Importantly, since climate change impacts flow into asset management plans via useful life, that concept is held to be a matter of judgement by each entity (in this case, each Local Government):

> *The useful life of an asset is defined in terms of the asset's expected utility to the entity. The asset management policy of the entity may involve the disposal of assets after a specified time or after consumption of a specified proportion of the future economic benefits embodied in the asset. Therefore, the useful life of an asset may be shorter than its economic life. The estimation of the useful life of the asset is a matter of judgement based on the experience of the entity with similar assets.*

In applying the standard to the management of infrastructure assets, Howard, Dixon and Comrie, (2007) identify three key steps:

- *Recognition: the asset is identified at component level;*
- *Measurement after recognition: the asset is revalued at 'fair value' option (under the revaluation model); and*
- *Reporting asset consumption: the depreciable amount of an asset is to be allocated over the asset's useful life in a manner reflecting the pattern of consumption of future economic benefits.*

Components of complex assets are the units recognised in asset registers and financial management accounts:

> *Infrastructure assets are typically large, interconnected networks or portfolios of composite assets. The components of these assets may be separately maintained, renewed or replaced so that the required level and standard of service from the network of assets is continuously sustained. Infrastructure assets by their very nature include items that are known as complex assets. Complex assets are physical items of property plant and equipment that are capable of disaggregation into significant components. The component is the unit of account at which the asset is recognised in the asset register.*

Thus, an urban (sealed) road has components such as kerb and channel, seals, pavement, and earthworks. Each component is accounted for separately. The authors emphasise the importance of both long-term asset management plans and long-term financial plans:

> *Every organisation with a significant stock of long-lived infrastructure needs a long-term financial plan. It is impossible to effectively and equitably manage service level, asset management and revenue raising decisions without one. A long-term financial plan should show the financial impact over time (at least 5 years) from any material proposals e.g. regarding variations in asset stocks, service levels, operating costs and revenue. Asset management plans should be based on maintaining an organisation's preferred, long-term affordable service levels and minimising the whole of economic life costs of assets.*

A useful summary of these principles of asset management and accounting in Australia has been recently developed by the Queensland Government, working with the Institute of Public Works Engineering Australia (IPWEA) and the Local Government Association of Queensland (Department of Infrastructure and Planning Queensland 2010). IPWEA (originally known as the Institute of Municipal Engineering Australia (IMEA)) is an industry association with divisions in all Australian states established originally with a membership base consisting primarily of engineers in Local Government.

The association has constitutional objectives to:

- advance the science and practice of all aspects of public works and services among members and practitioners generally,
- enhance the quality of life of our communities through the application of continuous improvement and best practice principles in all aspects of public works and services; and
- promote the Association within Local Government, the public works and services industry and the community as the principal source of credible, authoritative advice on all public works and services matters.

3.5 AAS27 – A Turning Point

Adoption of the Australian Accounting Standard 27 (AAS 27) (Howard and Boscoe 1993) and the transition from cash to accrual accounting by Australian Local Government heralded a significant change in the way Councils accounted for and managed their inventory of infrastructure assets. Implementation of the AAS27 commenced in 1994, and had a timeline that would commit Local Government to identifying and bringing to account for all of their "infrastructure assets" over a three to four year period.

From an accounting perspective, compliance with the reporting requirements of AAS27 was generally observed to be at a high level. However, at the engineering practitioner level, interpretation of the requirements of the AA27 varied considerably, and the framework and form of asset management varied considerably (Laing 2007). Importantly, although the accounting practices now were able to demonstrate the financial impacts of a Councils asset management practice (or lack, or deficiency in) the introduction of AAS27 did not necessarily result in an immediate and quantum change in the way Local Governments managed their infrastructure assets.

Feedback from IMEA members on AAS27 implementation identified that Local Government staff did not necessarily have expertise or resources to be able to either adequately implement the requirements of AAS27, or develop the framework or asset management plans required to support the management of these long- lived community assets.

3.6 The Infrastructure Manual

Despite the formal obligation on Local Governments in most Australian jurisdictions to comply with AAS27 there was no national mandate, nor nationally adopted code of practice, nor technical standard for asset management. In response to the need for a national code of practice, in 1994, IMEA in conjunction with the Australian Road Research Board (ARRB) and with funding from the Local Government Minister's Activities Fund, published the "National Infrastructure Manual". The manual was developed by engineers and accountants working in and for Local Government, with the specific intent of providing consistent guidelines for the interpretation of AAS27 and adoption of a consistent asset management practice. Despite wide publication, the National Infrastructure Manual was not formally adopted nationally as the guiding technical standard or commonly applied in asset management related decision-making.

In 1996, the New Zealand equivalent of the IMEA, The Association of Local Government Engineering New Zealand (Ingenium) released its own version of the Infrastructure Manual. Subsequent collaboration of the IMEA and Ingenium resulted in the publication of the "International Infrastructure Management Manual" (IIMM). The IIMM included much of the detail provided in the original Infrastructure Manual, but also provided new, and significantly updated and enhanced guidelines and information.

The publication of the IIM also coincided with a change of name for IMEA to the Institute of Public Works Engineering Australia (IPWEA) and a change in membership eligibility that widened its membership base to allow membership by "any person involved in public works engineering". This change has resulted in steady national membership growth, by attracting membership of technical and supervisory staff, many of whom were already working in asset management. This increased market penetration and adoption by practitioners working in the Local Government public works sector has helped build wide acceptance of the IIMM as a national "standard".

Further updates of the IIMM were published in 2002 and 2006 and 2011 as knowledge developed and so as to reflect developments in accounting standards and practice.

The 2011 International Infrastructure Management Manual states that effective asset management involves:

- taking a whole of lifecycle approach;
- developing cost-effective management strategies for the long term;
- providing a defined level of service and monitoring performance;
- managing risks associated with asset failures;
- sustainable use of physical resources; and
- continuous improvement.

Additionally, prerequisites to this approach include:

- a management commitment towards asset management;
- determining and establishing roles and responsibilities;
- collection and active management of sufficient relevant technical data on assets;
- undertaking condition assessment and valuation;
- development of service level standards and assessment of level of compliance; and
- implementing an optimised decision making process.

The manual sets out the fundamental principles behind asset management, outlined the processes required to develop an asset management plan, provided tools for developing an asset management plan, and provided guidance on technical interpretation and determination of useful life and condition of a range of common infrastructure asset types. The focus of the asset management plan is to allow a Council to see at a glance what the value of its assets are, and what the driving forces are for growth, ownership, useful life, and renewal. Importantly, it encourages Councils to consider the implications of adopting effective asset management practices, by providing an assessment of the financial implications for the long term management of asset network, based on the assumptions made.

The manual targeted practitioners responsible for asset management implementation, but it was also written for Council Members in Local Government and acknowledged that many of these “decision makers” also had very limited understanding of the principles of asset management. It was recognised that without management and Council support for the principles and commitment of resources, the asset management process was most likely to fail.

The IIMM included details and recommendations for an asset management plan “template” for universal adoption. The intent of such a universal template was to facilitate consistency in development and reporting of asset management plans, noting that asset management in a Local Governments or public infrastructure setting has many common denominators.

3.7 The NAMS PLUS Asset Management Framework and Tools

In 2004 IPWEA established the National Asset Management Strategy and Committee (NAMS). The committee’s objective is to support and facilitate adoption of a nationally consistent framework for infrastructure asset management based on the IIMM, and thereby provide an active forum and focus for ongoing development of asset management. The committee is currently chaired by Peter Way, one of the section authors and peer reviewers of the National Infrastructure Management Manual, and has representation from all IPWEA state divisions. NAMS has subsequently developed the ‘NAMS.PLUS’ program subscription service and range of products to assist with implementation of the nationally consistent asset management framework.

The ‘NAMS.PLUS’ program products include:
- training and support workshops;
- a suite of asset management planning MSWord and MS Excel templates and guidelines;
- a guided pathway to sustainable service delivery (in the form of an eBook);
- downloadable graphs, reports and tables generated by online modelling tools;
- on-line Help Desk support service
- NAMS.PLUS users and specialists in an online discussion forum; and
- how to Guides and Practice Notes to assist with the planning process and condition/performance assessment of infrastructure assets.

For a modest fixed fee Local Governments can subscribe to the NAMS.PLUS program and have access to the tools and products. In some states, the subscription has been funded through the national Local Government Sustainability program.

Through continued collaboration between IPWEA, NAMS and the various State and Federal Governments and Local Government Associations, the asset management template developed by NAMS has been promoted as best practice across most Australian States. The Western Australian standard is based on the Western Australian Asset Management Improvement Program (WAAMI) framework, developed and piloted by a group of Western Australian Councils but based on and similar to the NAMS plus template. Similarly, Victorian Councils adopted a Municipal Association of Victoria (MAV) “STEP” asset management framework, for development of asset management plans, also based on the NAMs template.

The NAMS.PLUS template provides a framework for asset management plans. The template guides Councils to identify key factors influencing asset provision, and encourages them to complete relevant background research and develop policy and responses as they develop the asset management plan. The focus of the plan is the provision of a medium term (usually 10 to 20 years) maintenance and renewal plan for infrastructure assets, which takes into account the likely service life, or useful life of the asset, its replacement cost, and any requirements for maintenance to ensure the service life is achieved and upgrade, replacement or renewal arrangements are provided for.

Depending on the size and complexity of a Local Government and the range of infrastructure assets it owns, it may have one or more asset management plans. For instance, a small, rural Council may have just one asset management plan covering all of its infrastructure asset classes, while a large urban Council may have separate asset management plans for each of its asset classes.

Typical Local Government asset categories include:
- roads (sealed or unsealed);
- footpaths;
- kerb and watertable;
- stormwater drainage;
- property and buildings;
- traffic control ;
- water supply;
- effluent/sewer;

- open space; and
- coastal.

Where a number of class asset management plans are provided, a single, over-arching plan may be developed to aggregate the individual class asset management plans into a single summary document.

The NAMs asset management plan template typically includes the following:

1. Executive Summary – a short summary of the plan, providing an overview of the plan, for quick reference and reproduction in corporate documents.
    "What Council Provides" –A summary of the scale, extent and type of infrastructure assets.
    "What does it Cost" – A summary of the ownership, renewal and extension costs associated with the class of assets.
    "Plans for the Future" –A summary of anticipated trends in the use, life, type, or level of service to be provided by the asset(s).
    "Measuring our Performance" – A comparison of past asset management performance, compared to performance anticipated for the life of the plan.
    "Safety" – A summary of risk management implication associated with the asset class.
    "The Next Steps" – An improvement strategy, identifying key activities required to be undertaken to improve management capacity and performance and efficiency of the asset class.
2. Introduction – Provides context for the interpretation of the asset management plan
    2.1. Background – The historical context of asset management, and the drivers of development of asset management plans including financial sustainability, balancing between service level and capacity to afford to maintain the service level.
    2.2. Goals and objectives of asset management – a concise statement which sets out the intent of the asset management plan based around and reflecting the principles outlined in the IIM.
    2.3. Plan framework – A description of the document, outlining its key components and the relationships between the components.
    2.4. Core and Advanced Asset Management. This section identifies the level of sophistication that the asset management planning process has reached.
    Core asset management is the lower level of sophistication, whereby information on assets may be somewhat limited, and assumptions have been made but not necessarily confirmed by detailed data collection or investigation and financial modelling. For instance, core asset management may only be able to be achieved in smaller rural Councils where resources available for detailed asset data inventory development are limited. Assumptions may be made regarding the total extent of assets, and their useful life.
    Advanced asset management reflects a higher level of certainty and detail regarding the level of knowledge of the asset(s), projections regarding future trends, costs of ownership and renewal. Larger urban Councils that have invested in advanced data collection systems and have sophisticated and extensive data on their asset classes would normally aspire to advanced asset management.
3. Levels of Service – A key driver of asset management. The level of service is an expression of the 'quality" of service delivered by the assets (often linked to the cost/quality of the asset itself). The cost of provision of service

from assets to a nominated standard must be compared with the Council's capacity to be able to afford to provide and maintain the level of service.

3.1. Customer research and expectation – An examination of consumer expectation, including any customer/ratepayer surveys where expectations regarding the level and types of serves are considered. What would the community like to see provided? – for instance, do they prefer smooth, hotmix roads, or are they prepared to accept unsealed (gravel) surfaced roads, an undercover football stadium, or traditional "footy oval"?

3.2. Legislative requirements – an assessment of any legislative obligations relevant to the asset or asset class, for instance, provision of disability access, statutory requirements for traffic control, minimum building sizes and services, which must be taken into account when renewing, extending, or maintaining the assets.

3.3. Current levels of service – An objective assessment of the service level of the asset inventory – as currently provided, this may reflect historical development of the area, and changes in trends over time – for instance, bitumen surfaced footpaths may have been historically provided (even though community expectation is for brick paved footpaths), or flood protection may not be provided for all residential properties.

3.4. Desired levels of service – an assessment of what the Council can realistically afford to pay, (and ratepayers and users are prepared to pay in taxes and charges) for various different service levels, taking into account community expectation, existing service levels, legislative requirements, and likely impacts on financial resources.

4. Future demand – an assessment of what impacts may be anticipated due to changes in trends in the future.

4.1. Demand forecast – an assessment of the possible impact changes in social structure and demographics or other influences may have on requirements for provision of infrastructure assets – for instance, a possible influx of younger families, impacts of ageing populations or 'sea change" migration of families from urban areas to country towns, or impacts of climate change, for instance, due to sea level rise or temperature increase etc.

4.2. Changes in technology – an assessment of emerging technologies and how they may impact on useful life of assets, necessity for certain asset types, and construction/renewal costs of assets

4.3. Demand management plan – an assessment of how the demands of changed service levels, population trends, and financial limitations may be addressed while still achieving overall desired outcomes.

4.4. New assets from growth – an assessment of the impacts of population growth, development of new urban areas, or renewal of older areas on the value and extent of the asset category as this may increase long term maintenance and renewal obligations.

5. Life cycle Management Plan – an assessment of the lifecycle management costs and obligations to ensure optimum life and performance of the asset with data presented in tabular and graphical form to assist interpretation by readers.

5.1. Background data – an overview of and performance in life expectancy of assets to date, emerging industry observations.

5.2. Risk Management Plan – Another key component of asset management – risk management takes into account likelihood and consequence of risk, and the concepts are consistent for asset management – what are the implications from a risk management perspective for chosen courses of actions for management of the asset(s) and helps drive intervention and renewal strategies, and focuses on minimum levels of service.

    5.3. Routine Maintenance Plan – an assessment of the minimum requirements to allow infrastructure assets to perform effectively for the term of their useful life – if there are requirements for maintenance intervention to ensure long life of the asset then they should be addressed as part of the plan.
    5.4. Renewal/replacement plan – an assessment of the renewal/replacement requirements of the assets) taking into account the assessments of useful life, future trends, and desired service levels (i.e. what assets will need to be renewed/replaced when?) expressed in terms of expenditure requirements over a medium term (usually 10 years minimum).
    5.5. Creation/acquisition/upgrade plan – an assessment of requirements for new assets, or upgraded assets, based on future trends, and service levels – what assets will require upgrade or improvement and not just replacement with the same asset?
    5.6. Disposal Plan – What assets can be retired as they are no longer required, and what process will be used to account for the value of assets which still retain some value even when they reach the end of their useful life?
6. Financial Summary – A summary of the financial implications of the above described asset management strategy – what are the costs and how will the costs be met? This information is provided in both tabular format showing required expenditure, and graphical format, showing required expenditure, and income compared to actual budget forecasts. This presentation provides for visual assessment of trends, shortfalls, or variations in funding arrangements to assist decision making.
    6.1. Financial statements and projection – a forward prediction of costs, taking into account renewal upgrade, extension, changes in service level and obligations for maintenance,
    6.2. Funding strategy – An explanation of how funds will be provided to deliver the asset management strategy adopted and, if there is a funding shortfall, what steps will be taken to overcome the problem.
    6.3. Valuation forecasts – an assessment of the value of the assets over the period of the plan, taking into account loss of value associated with wear, ageing and deterioration of the assets, and their likely renewal or replacement costs. If the valuation forecast predicts a trend of reducing value then this could be a sign that the condition of the assets is reducing and the service level is reducing.
    6.4. Key assumptions made in financial forecasts – a justification for the assumptions made, for instance, method of depreciation adopted to reflect interpretation of useful life, and the proportion of retained value remaining at the expiry of the useful life.
7. Asset Management Practices – An outline of the accounting, policy and administrative procedure and framework which guides the asset management strategy.
    7.1. Accounting/financial systems – an overview of the adopted accounting practices and procedures used by the organisation, with relevance to asset management.
    7.2. Asset management systems – a description of the methods and systems used to manage the asset data inventory, methods and forms of data collection and condition assessment, and data integrity and security assurances and processes.

7.3. Information flow requirements and processes – process flow charts or procedures which guide staff and operators to follow adopted guidelines and methodology.
7.4. Standards and Guidelines – a summary of references for accounting standards, asset management, governance and statutory provisions which have guided the development of the plan, and requirements for reporting against the plan.

8. Plan Improvement Plan and Monitoring- A critical assessment of known deficiencies or limitations in the current plan, and a forward plan to rectify and improve the plan.
    8.1. Performance Measures – the methods and key performance indicators, which will be used to asses performance against delivery of the plan, for instance, tracking of trends in condition.
    8.2. Improvement Program – a table/list/set of actions which address the deficiencies of the plan, identifying who will undertake the actions, what is required, and when it will be done by.
    8.3. Monitoring and review processes – An explanation of the overall process proposed to ensure the plan is delivered, as proposed, taking into account the performance measures and indicators and statutory and management requirements for reporting.
9. References - A list of reference sources used for development of the plan.
10. Appendices – Attachments showing detail information, for instance, detailed asset listings, condition assessment reports, valuation reports, guideline documents for condition and valuation assessment.

As noted above, to assist with long-term financial planning for asset renewals, the NAMS.PLUS template includes graphs that show asset renewal cost calculations based on the useful and remaining life of each asset as determined from the asset inventory information provided by Local Government (Figure 17 and Figure 18).

The long-term asset renewal graphs can be calculated by the NAMS support staff as a service provided to NAMS.PLUS subscribers, although there is nothing to prevent individual Local Governments from doing the calculations themselves.

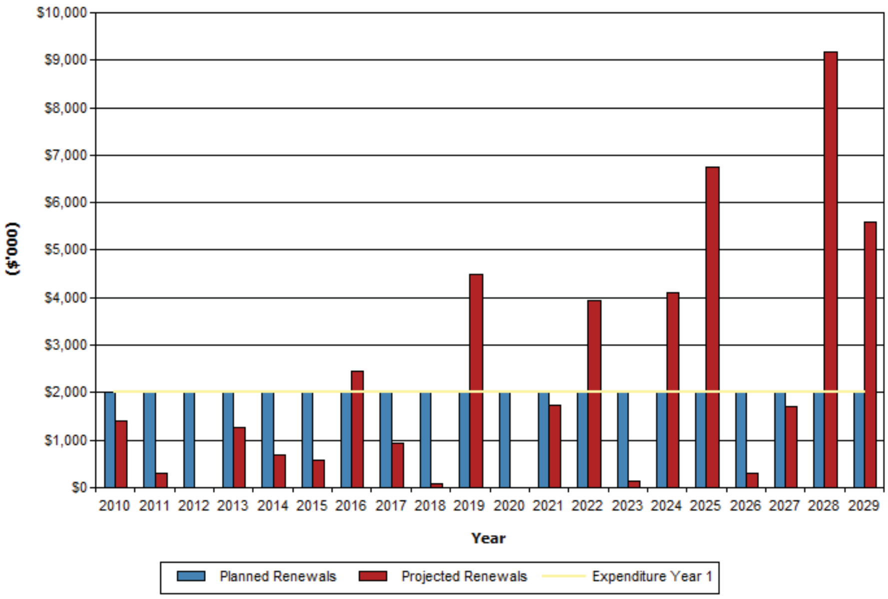


Figure 17: Example graphical output from the NAMS.PLUS asset management tool developed by IPWEA.

Year End June 30	Total Operations Expenditure ($'000)	Total Maintenance Expenditure ($'000)	Projected Capital Renewal Expenditure ($'000)	Planned Capital Upgrade/New Expenditure ($'000)	Planned Disposals ($'000)	Planned Capital Renewal Expenditure ($'000)	Shortfall in Renewal Expenditure (Projected - Planned) ($'000)	Cumulative Renewal Funding Shortfall ($'000)
2010	$50.45	$908.07	$1,392.12	$300.00	$0.00	$2,000.00	-$607.88	-$607.88
2011	$50.90	$916.15	$293.00	$300.00	$0.00	$2,000.00	-$1,707.00	-$2,314.88
2012	$51.35	$924.22	$0.00	$300.00	$0.00	$2,000.00	-$2,000.00	-$4,314.88
2013	$51.79	$932.29	$1,275.04	$300.00	$0.00	$2,000.00	-$724.96	-$5,039.85
2014	$52.24	$940.37	$698.29	$300.00	$0.00	$2,000.00	-$1,301.71	-$6,341.56
2015	$52.69	$948.44	$566.35	$300.00	$0.00	$2,000.00	-$1,433.65	-$7,775.21
2016	$53.14	$956.51	$2,464.21	$300.00	$0.00	$2,000.00	$464.21	-$7,311.00
2017	$53.59	$964.59	$939.50	$300.00	$0.00	$2,000.00	-$1,060.50	-$8,371.50
2018	$54.04	$972.66	$73.33	$300.00	$0.00	$2,000.00	-$1,926.67	-$10,298.17
2019	$54.49	$980.73	$4,495.37	$300.00	$0.00	$2,000.00	$2,495.37	-$7,802.80
2020	$54.93	$988.81	$0.00	$300.00	$0.00	$2,000.00	-$2,000.00	-$9,802.80
2021	$55.38	$996.88	$1,742.56	$300.00	$0.00	$2,000.00	-$257.44	-$10,060.24
2022	$55.83	$1,004.95	$3,938.83	$300.00	$0.00	$2,000.00	$1,938.83	-$8,121.40
2023	$56.28	$1,013.03	$136.15	$300.00	$0.00	$2,000.00	-$1,863.85	-$9,985.25
2024	$56.73	$1,021.10	$4,114.46	$300.00	$0.00	$2,000.00	$2,114.46	-$7,870.79
2025	$57.18	$1,029.17	$6,749.20	$300.00	$0.00	$2,000.00	$4,749.20	-$3,121.60
2026	$57.62	$1,037.25	$293.00	$300.00	$0.00	$2,000.00	-$1,707.00	-$4,828.59
2027	$58.07	$1,045.32	$1,713.20	$300.00	$0.00	$2,000.00	-$286.80	-$5,115.39
2028	$58.52	$1,053.39	$9,160.93	$300.00	$0.00	$2,000.00	$7,160.93	$2,045.54
2029	$58.97	$1,061.47	$5,588.69	$300.00	$0.00	$2,000.00	$3,588.69	$5,634.23

Figure 18: Example tabular output from the NAMS.PLUS asset management tool developed by IPWEA.

To determine the useful life of its assets, section 5.1 of the asset management planning process requires Local Governments to take into account the variety of influences that may impact on the useful service life of the asset" including:

- age;
- condition;
- change in usage;
- increasing/decreasing demand;
- criticality; and
- risk.

Currently there is a certain degree of subjectivity associated with estimates of useful lives of long lived assets due to changing usage patterns and development in technology. However the forecasting of asset useful lives, failure modes and failure thresholds is improving, due to industry wide adoption of asset management philosophy and ongoing research and development. Impacts on road assets associated with increased or decreased traffic volumes and loadings has been demonstrated and modelled with some confidence, but the potential impacts of increased temperature associated with climate change has not, until now, been quantified or modelled.

3.8 Funding Asset Management in Australian Local Government

Compared to State or Commonwealth Governments, Local Governments in Australia are responsible for managing a much larger ratio of assets relative to annual income. In other words, operating expenses (maintenance and depreciation) associated with assets are a much higher proportion of total expenses for Local than State or Federal Government.

As previously noted, recent compliance with the AAS27 by Local Governments from an accounting practice perspective has generally been good. Many Local Governments have also had road pavement management systems that have been used to develop long-term road reconstruction programs. However, the correlation in practice between accounting information for asset management performance (recorded value of assets, rate of consumption, remaining useful lives etc.) and that in asset management systems used for projecting long-term renewal programs has not been strong to date. Additionally, the development of asset management plans has revealed significant medium to long-term financial gaps for many Local Governments between projected asset renewal needs and financial capacity.

In collaboration with the National Local Government Financial Forum (a group of representatives from Local Government Departments and representative Finance Manager type associations in each state), the NAMS committee commissioned the development the Australian Infrastructure Financial Management Guidelines (AIFMG) to bridge the gap between asset management and financial plans. The guidelines were first published in 2009 and provide tools for asset management and financial management practitioners, service managers and auditors to achieve financial sustainability in providing services from infrastructure (AIFMG V1.1 2010 p1.2).The AIFMG also sets out principles and procedures to improve the linkage between asset management plans and financial management plans for Local Government.

The largest sources of revenue for most Local Governments to maintain assets and provide services are general and specific rates and charges on properties determined and levied by Councils on based on their specific funding needs[1]. The Commonwealth also provides Financial Assistance Grants to Local Governments (secured by legislation that provides for their continuation on an ongoing basis with the pool adjusted for the impacts of growth and inflation). These federal grants are untied and intended to build capacity for service delivery and are the second largest source of revenue for Local Governments collectively. Individual Local Governments with greater need and less capacity to raise revenue receive a larger share of the grants. As a result these Financial Assistance Grants are the largest revenue source for many small and remote Local Governments.

Local Governments are also relatively free to borrow funds as required. Borrowings are not deemed to be a source of income and are typically used to help finance the acquisition of additional assets and in some cases asset renewal. Most Local Governments have low levels of borrowings relative to annual operating income[2].

Up until the introduction of requirements for compliance with AAS27 in 1994, most Local Governments in Australia set annual rates to ensure they raised sufficient cash each year to fund outlays net of any borrowings. In other words, budget revenue raising decisions were based on expected cash-flow needs (a cash accounting approach). Non-cash costs such as depreciation were ignored. Over the past decade or so it has become widely accepted that the cash accounting approach is not appropriate for Local Governments given the asset-intensive nature of their service provision. Generally speaking, assets have been run-down at a rate faster than they have been replaced. Many Local Governments did not have the revenue necessary (and were unwilling to borrow) to renew or replace their infrastructure assets when required.

Local Governments are now encouraged (and in some jurisdictions required) to base their budgets on accrual accounting information - to have regard to the consumption of assets (depreciation) in their revenue raising and service level decisions[3].In all

[1] While there are formal obligations on Local Governments in the way they go about preparing budgets (some format and consultation requirements) they are free to determine rating levels. In New South Wales rate revenue increase limits are set but can be conditionally waived for individual Local Governments.
[2] Local governments in aggregate nationwide have more financial assets than borrowings
[3] Depreciation represents about 25 to 30% of total operating expenses for Local Governments on average.

Australian jurisdictions, Councils are now (or very soon will be) required to have long-term financial plans and asset management plans (both for at least a 10 year forward timeframe). The asset management plan is intended to identify asset renewal and maintenance needs and identified outlay needs should be accommodated in the long-term financial plan. Where it is not financially possible to fully accommodate identified asset management funding needs, Local Governments are encouraged to review their projected revenue raising proposals and service levels based on projected future outlays and revenue.

Many Local Governments are still learning how to prepare soundly based long-term financial and asset management plans and then use the information generated to determine affordable service levels and inter-generationally equitable revenue raising decisions. Often, Local Governments have not explicitly determined preferred service levels from assets or what can be afforded on a long-run basis. In many cases they currently do not have sufficient, reliable data to determine optimal asset renewal timeframes and maintenance schedules for their major long-lived assets. In addition, there are variations in local operating environments and preferred service levels will vary between individual Local Governments. Finally, a range of factors will affect useful lives and can (and do) change during the period of control of long-lived infrastructure (e.g. the pattern and intensity of road usage). As a result, even with good data, objectivity and expertise, there will be a degree of subjectivity when determining sustainable financial and asset management plans. For these reasons, the estimated useful life of long-lived Local Government infrastructure assets cannot be predicted with certainty and will vary from year to year.

Recent research, legislative changes and support programs have resulted in most Local Governments becoming more mindful of their asset management responsibilities and the importance of balancing service levels with revenue-raising options that will be accepted by their communities. Although considerable improvements in asset management have been made, a significant proportion (but less than half) of all Australian Local Governments still have large or moderate ongoing operating deficits (that is, greater than 10% of operating expenses). However, some Local Governments that are now operating sustainably previously had significant deficits over a long period of time.

Some Local Governments will continue to under-fund annual asset maintenance relative to the optimal levels necessary to minimise whole of life costs for a particular preferred level of service. However, it doesn't necessarily follow that whole of life costs associated with assets (that is capital and maintenance costs) will be higher in future. For example, the Council may hold assets longer before renewal and accept the consequences of a resulting lower standard of service from aged assets. Many Local Governments will not have sufficient internally generated funds to renew assets when warranted and will be reluctant to borrow to do so.[4] In this case, asset useful lives will be extended and the service levels provided will in consequence fall.

Generally, however, Local Government asset management expertise has improved and will lead to better decision-making with regard to service levels and revenue-raising. It needs to be recognised though that the whole-of-life, or annualised, cost of services from (and optimal useful lives of) long-lived Local Government assets are difficult to reliably measure. Even where such information is available, decisions regarding the range and level of services and maintenance and renewal outlays will be

[4] Even when a Local Government could afford to allocate more money for asset maintenance or renewal and it is cost-effective to do so it may choose not to. This may be rational. Service level preferences can change over time. The community may prefer the funds be used to increase other services or a lower level of rating than would have otherwise been necessary.

driven not only by cost and funding considerations but also by community preferences expressed through the political process.

It is important to note that Local Governments generally don't make a specific funding allocation in their annual budgets to make safe and repair as warranted assets that may be damaged by extreme weather events. Generally there is sufficient flexibility in maintenance budgets to undertake minor works. If necessary, reactive work is undertaken at the expense of proactive programmed maintenance. If the scale of damage is too big to be accommodated within an existing budget allocation a Local Government will need to consider either deferring specific programmed works to address the need, or raising additional borrowings to carry-out repairs as necessary. In some cases repairs can be delayed and progressively undertaken in future years.

In each state there is an arrangement in place that provides grant funding from the state for part of the cost of repair work as a result of extreme events where such costs are very significant. The threshold for which this funding support is available, and the proportion of a Council's costs that are reimbursed, varies widely between states.

The recently completed Federal Government National Disaster Insurance Review (Natural Disaster Insurance Review Inquiry into flood insurance and related matters September 2011) proposed a number of recommendations relating to both insurance of private risk but also public risk, including:

> *"That an agency sponsored by the Commonwealth Government be created to manage the national coordination of flood risk management and to operate a system of premium discounts and a flood risk reinsurance facility, supported by a funding guarantee from the Commonwealth".*

This recommendation and others from the review set the scene for potential new architecture for public risk insurance in Australia especially in regard to disasters, or extreme events.

4 IMPACT OF CLIMATE ON ROAD DETERIORATION

The scope of this study required that a financial model and decision making tool would be developed for a minimum of two asset classes likely to be affected by climate change (Appendix 1). As identified in the previous chapter, roads are by far the most important asset as measured by value to most Local Governments in Australia (Figure 16).

Typically in Australia, highways and major roads (arterials and main roads) are managed by state transport authorities and the dominant cause of deterioration of these assets is traffic volumes. Local Governments, on the other hand, generally manage roads that have lower traffic volumes - collector and local roads. Local Government roads are generally either sealed (sprayed seal or hotmix asphalt) or unsealed (gravel) roads and can be constructed using a variety of techniques and located within an urban or rural environment. In this chapter the various established mathematical models for calculating road deterioration for different road types, and in particular their usefulness for predicting road surface deterioration under changed climate conditions, is assessed with the aim of identifying those that may be used in the development of the financial model.

4.1 Deterioration of Sealed Roads

Sealed roads are a complex construction of a variety of components made from different materials (Figure 19). As it is the surface of the pavement that is subject to the highest level of climatic stress, the sub-base and subgrade are sealed from any effects of the climate by the weather proof binder applied to the surface layer as either a sprayed seal, or mixed hot with an aggregate to create asphalt. In both cases the binder is bitumen.

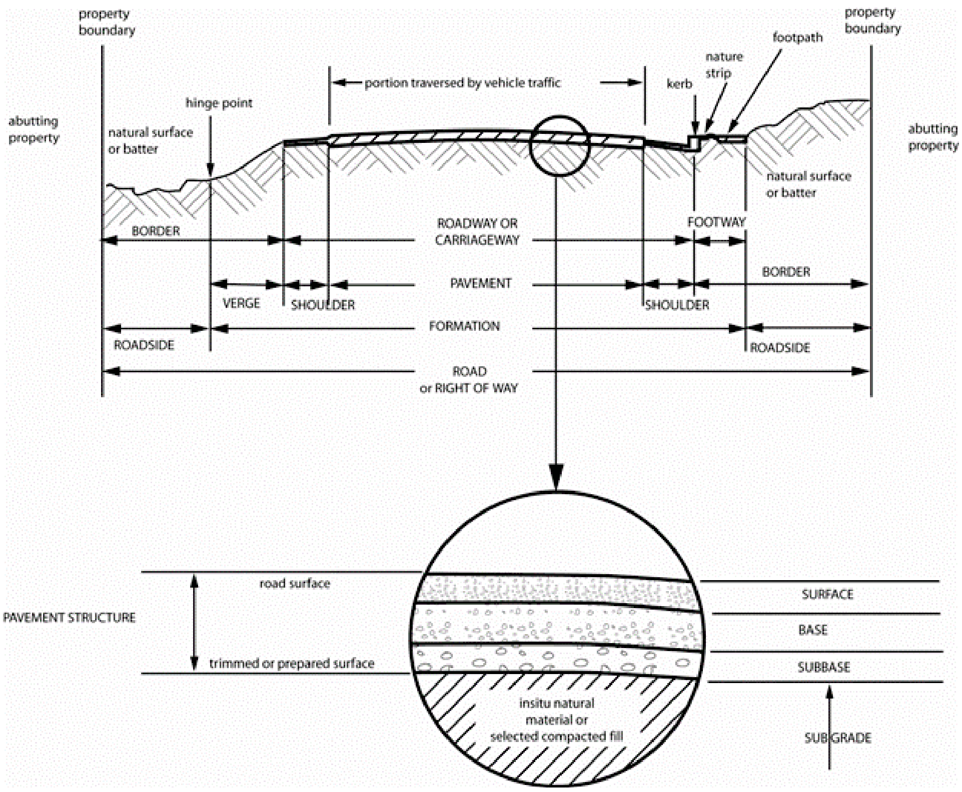


Figure 19: Diagrammatic depiction of the components of a sealed road (Source: Austroads 2005).

Often, the terms asphalt, tarmac and bitumen are used interchangeably - a linguistic eccentricity between the culturally congruent UK, US, Canada and Australia. Specifically, bitumen is a binder used to hold together the aggregate to create the weather proof surface layer (asphalt/tarmac) of the pavement. Only the term bitumen is used within this document. Each of these terms as used in this report is defined below:

- *Pavement – That portion of a road designed for the support of, and to form the running surface for, vehicular traffic (see page 94, Austroads 2010a).*
- *Aggregate – A material composed of discrete mineral particles of specified size or size distribution, produced from sand, gravel, rock or metallurgical slag, using one or more of the following processes: selective extraction, screening, blasting or crushing (see page 8 "Glossary of Terms", Austroads 2010a)*
- *Binder –*
  1. *A material used to fill the interstices between small stones or coarse gravels. It provides mechanical, chemical and physical bonding and holds the aggregate particles together as a coherent mass. Normally, bitumen is most commonly used in Australian road construction.*
  2. *A manufactured material used in small amounts in stabilisation to change the properties of the existing material.*
  3. *A bituminous material used for waterproofing the surface and holding an aggregate layer to the base (see page 19 "Glossary of Terms", Austroads 2010a).*
- *Bitumen – A very viscous liquid or a solid that consists essentially of hydrocarbons and their derivatives, which are soluble in carbon disulphide. It is substantially non-volatile and softens gradually when heated. It possesses waterproofing and adhesive properties. It is obtained from native asphalt or by processing the residue from the refining of naturally occurring crude petroleum (see page 19 "Glossary of Terms", Austroads 2010a).*
- *Sprayed seal – A thin layer of binder sprayed onto a pavement surface with a layer of aggregate incorporated and which is impervious to water (see page 132 "Glossary of Terms", Austroads 2010a).*
- *Asphalt/Tarmac – A mixture of bituminous binder and aggregate with or without mineral filler, produced hot in a mixing plant, which is delivered, spread and compacted while hot. (see page 12 "Glossary of Terms", Austroads 2010a). This is also known as Hot Mix, or Hot Mix Asphalt.*

4.1.1 Impact of the environment on pavement surface deterioration

A survey of Local Governments by Oliver (1999) found that there was significant variation in road pavement seal service life across Australia. Figure 20 shows the mean/average road pavement seal life for the Australian states and New Zealand. The following reasons for differences in seal life were identified:

1. *Bitumen durability – Road Authorities in Western Australia, South Australia and Victoria have a bitumen durability specification, but this is not the case elsewhere;*
2. *Climate – bitumen oxidation and hardening (leading to cracking) will occur more rapidly in hot climate locations, while stone loss will be exacerbated in wet locations;*
3. *Aggregate quality;*
4. *Traffic (including rutting);*
5. *Pavement strength and soil conditions; and*
6. *Construction and maintenance practices (including structural contributions) (*see page 6, Oliver 1999*).*

The list of factors suggests that non-climatic factors may have a dominant impact on road pavement seal service live. As such, the impact of climate change on the road surface should be considered within the broader context of these non-climatic factors.

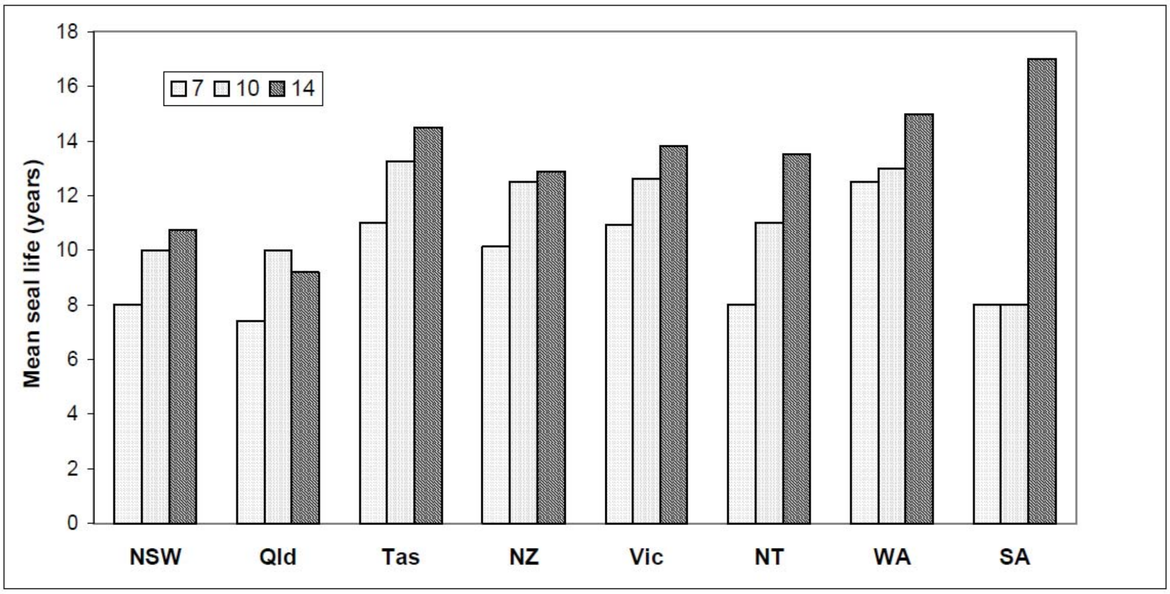


Figure 20: Local Government survey results for mean road pavement seal life. The results are grouped by state and aggregate size (Source: Oliver 1999).

An Australian Road Research Board (ARRB, now ARRB Group) study in 2001 estimated the percentage of road deterioration (%Ret) caused by the environment (Martin 2001). Figure 21 and Figure 22 show the contribution of different deterioration factors to the total roughness of sprayed seal and hot mix asphalt roads respectively. This difference in the percentage of environmental degradation of the road surface for sprayed seal and hot mix asphalt road pavements is shown in Figure 23 where one can see that the environmental contribution to sprayed seal road deterioration becomes constant after time and the environmental contribution to asphalt road deterioration continuously increases with time. Nevertheless, for both road pavement types, the graphs show that the environment is a significant factor in road deterioration.

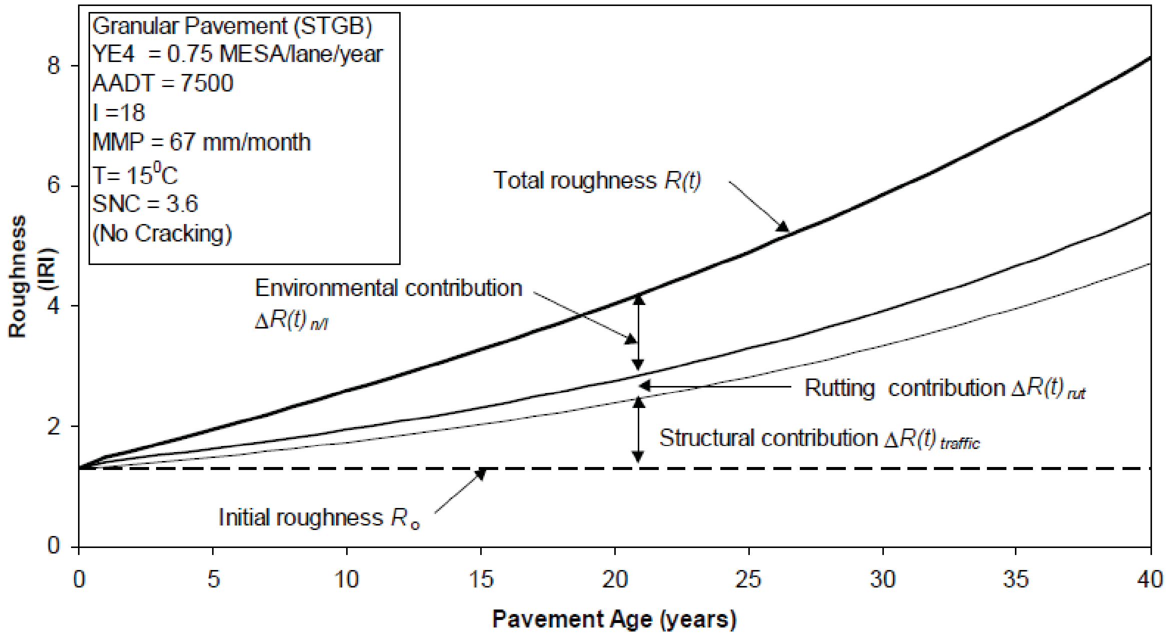


Figure 21: Distress contributions due to roughness progression for a fully maintained sprayed seal granular road pavement (Source: Martin 2001). (Note: MESA = Million Equivalent Standard Axles; AADT = Average Annual Daily Traffic; MMP = Mean Monthly Precipitation; T = Average annual air temperature (degrees C); I = Thornthwaite Index; SNC= Modified structural Number; L = Traffic Load in MESA; EXP – e = Raised to the power).

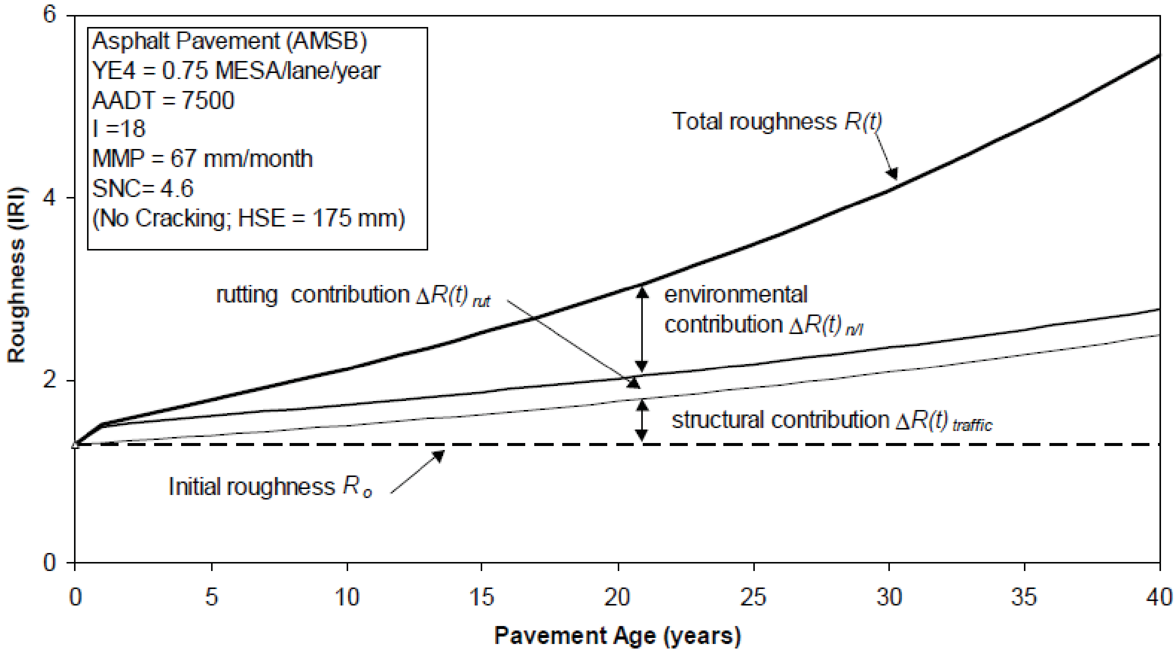


Figure 22: Distress contributions due to roughness progression for a typical deep strength asphalt road pavement (Source: Martin 2001). Note: MESA = Million Equivalent Standard Axles; AADT = Average Annual Daily Traffic; MMP = Mean Monthly Precipitation; T = Average annual air temperature (degrees C); I = Thornthwaite Index; SNC= Modified structural Number; L = Traffic Load in MESA; EXP – e = Raised to the power).

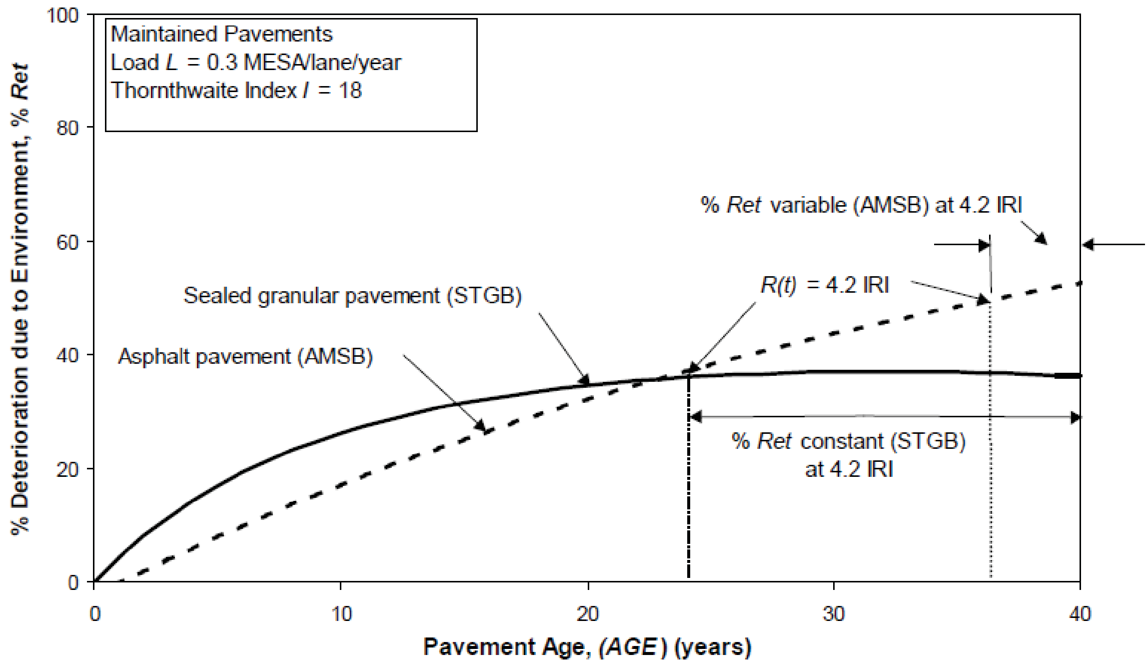


Figure 23: Comparison of the percent (%) deterioration due to the environment by pavement age for sprayed seal and hot mix asphalt road pavements (Source: Martin 2001). Note: MESA = Million Equivalent Standard Axles; AADT = Average Annual Daily Traffic; MMP = Mean Monthly Precipitation; T = Average annual air temperature (degrees C); I = Thornthwaite Index; SNC= Modified structural Number; L = Traffic Load in MESA; EXP – e = Raised to the power).

It is important to note that attributing road deterioration to deterioration caused by the environment or deterioration caused by traffic is a somewhat artificial and unrealistic delineation of impact. The deterioration related to traffic always occurs in the presence of the environment. However, the simplification is necessary to allow reasonable estimations of the effect of the changing environment on road maintenance costs.

The ARRB study (Martin 2001) used several models to predict the percentage of road deterioration related to environment for various traffic volumes. The results from the study are displayed in Figure 24. The study found that the model developed by Rosalion and Martin (1999) predicted that the component of road deterioration as a result of the environment decreased as traffic volume increased. However, models developed as part of the study (2001) calculated that the component of road deterioration as a result of the environment remained constant for traffic volumes greater than approximately 0.1 Million Equivalent Standard Axles (MESA) - about 30% for spayed seal surfaces and 50% for hot mix asphalt surfaces. When traffic volume is less than 0.1 MESA loads, the share of road deterioration related to environment rapidly decreases from 100% for road with no traffic to its constant value for road with 0.1 MESA traffic.

Modelling road deterioration

The ARRB study (Martin 2001) used several models to predict the percentage of road deterioration related to environment for various traffic volumes. The study found that the model developed by Rosalion and Martin (1999) predicted that the component of road deterioration as a result of the environment decreased as traffic volume increased. The studies also suggest that the environmental contribution to sprayed seal road deterioration becomes constant after a time and the environmental contribution to asphalt road deterioration continuously increases with time. Subsequent modelling work has refined and built upon these initial models.

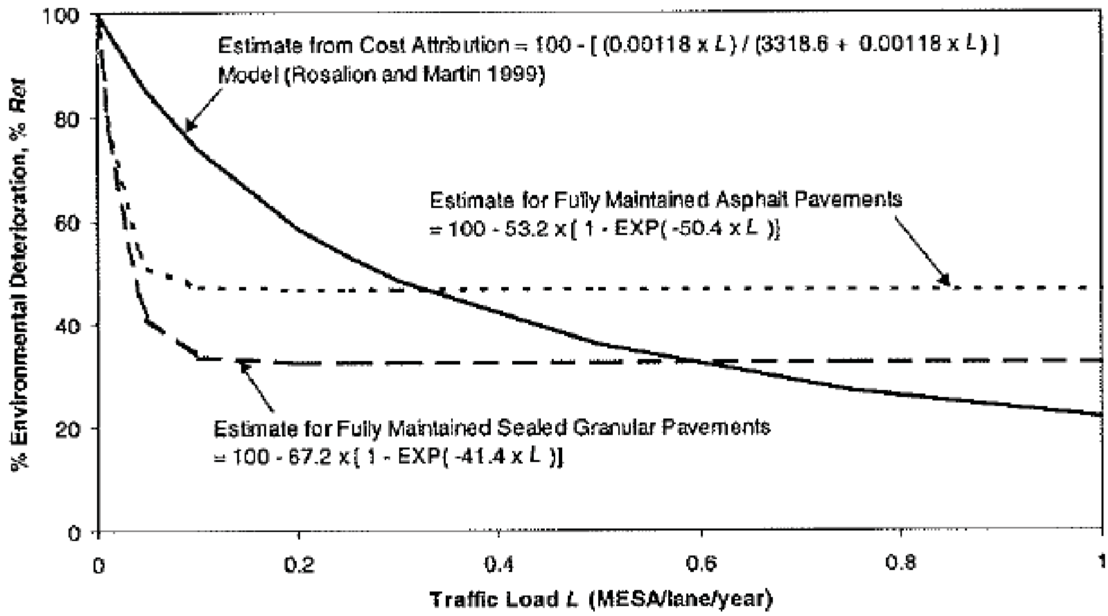


Figure 24: Comparison of percent (%) deterioration due to the environment versus traffic volumes for sprayed seal and hot mix asphalt road pavements. The displayed relationships are valid only for maintained pavements (Source: Martin 2001). Note: MESA = Million Equivalent Standard Axles; AADT = Average Annual Daily Traffic; MMP = Mean Monthly Precipitation; T = Average annual air temperature (degrees C); I = Thornthwaite Index; SNC= Modified structural Number; L = Traffic Load in MESA; EXP – e = Raised to the power).

4.1.2 Durability of Bitumen

The maximum service life of a sealed road surface is primarily dependent on the service life of the binder. With time, the binder hardens and loses its flexibility and in turn this makes the road surface vulnerable to cracking and loss of aggregate material due to the stress load from traffic, especially in the case of heavy traffic.

Bitumen is the most commonly used binder in Australia and so this report investigates what impact climate change might have on the service life of bitumen sealed roads. Over the past 70 years, more than 50 different types of bitumen have been used in Australia - a consequence of the continuous improvement in bitumen quality, and changing requirements for bitumen resilience in the different climatic zones. Nevertheless, given that the focus of this report is on the impact of climate change on existing and potential future road surfaces, consideration is only given to those bitumen types that have been applied over the last decade.

A key factor influencing the duration of the service life of bitumen in the field is its durability. As expected, the better the durability, the more resilient it is to hardening. Bitumen durability is typically measured in laboratory testing programs. In Australia ARRB Transport Research Pty. Ltd. durability tests are used to determine the durability of different bitumen types (see Standards Australia 1997). The tests expose samples of bitumen to prolonged extreme heat and observations are made to determine the time it takes, in days, for the bitumen to reach a standard specified viscosity. The durability measures for various types of bitumen used in Australian can be found in “Durability of Australian Bitumens 1956-2004” report (Austroads 2007).

Table 1 shows the durability for bitumen types used between 2000 and 2004. This study has assumed that bitumen durability is equal to the average of the listed entries in the (8.2 days) for each of the performed analyses. However, when applying the results of the information below on Local Government roads it is suggested that the most recent and relevant data be used. In the case where a Council is unable to determine the durability rating for the bitumen used on their roads, then the average value of 8.2 days can be used.

Table 1: Durability measures for samples of bitumen that is used for surfacing of Australian roads and bitumen sample information (Source: Austroads 2007).

Date	Bitumen	Grade	Asphaltenes (%)	Durability (days)	Description
2001	B01/382	C170	-	7	BP Bulwer Island
2004	B04/526	C320	-	9	March 2004, Caltex NSW, C320 404511(1)
2004	B04/545	C170	-	9	Mobil Tank 403 301-335 sampled 13 May 2004
2004	B04/546	C320	-	6	Mobil Tank 381 302-501 sampled 13 May 2004
2004	B04/583	C320	-	7	November 2004, BP, Class 320 Bitumen
2004	B04/584	C170	17.0	10.5	November 2004, BP Class 170 Bitumen
2004	B04/585	C320	-	9	November 2004, Caltex NSW, C320 Bitumen

4.1.3 Models for bitumen hardening

According to Read and Whiteoak (2003 p.157), when the surface material of a bituminised road is exposed to the environment, the hardening of the surface can have a detrimental effect on the service life and performance of the surface. It is for this reason, it is important to consider bitumen hardening in the context of a changing climate.

Specifically, bitumen hardening is caused by bitumen oxidation, a process that is affected by temperature at the site and binder film thickness (Austroads 2007). The current models for bitumen hardening use air temperature, bitumen durability and road pavement seal surface thickness as their key input parameters. Knowing these three parameters, Local Governments can calculate bitumen hardening likelihoods and timeframes based on local conditions.

The literature review of bitumen hardening models found that Australian road and transport authorities rely predominately on models based on ARRB research for their road management program (Oliver 1999; Martin, Toole et al. 2004; Oliver 2006; Giummarra, Martin et al. 2007; Martin 2010). The last 30 year period has culminated in models that have been developed via a continuous process of evolution and improvement. Investigation of the models reveals the following:

1. all models have as independent variables the annual average daily air temperature at the site, the bitumen durability at the site, and the age of the bitumen;
2. the latest model (Oliver 2006) includes an additional independent variable – the nominal seal size, which is the thickness of the road surface seal;
3. the interaction between the independent variables differs in the models. In most cases, bitumen age is non-linearly related to the other independent variables. However, exceptions exist: e.g. the model that is used in (Giummarra, Martin et al. 2007); and
4. there are some differences in the estimates for the coefficients of the independent variables.

The combined effect of the identified differences between the models could lead to considerable variations in the estimated impact from climate change on binder service life. Although a concerted effort was made to identify the most accurate and suitable model, Local Governments should be aware of the limitations in model capacity to replicate actual road pavement deterioration rates.

Two models for bitumen hardening were shortlisted for consideration in this study and the justification for their selection is briefly discussed to assist Local Governments decide which model they may wish to use. The first model is from the Austroads guidelines for road management (Austroads 2007). The model requires the yearly mean average temperature and the durability of the bitumen as input parameters. It is expected that Local Governments have access to these data. When no information regarding durability of bitumen is available a default value of 8.2 days can be assumed.

Equation 1: Model for bitumen hardening (Austroads 2007)

$$\log \eta = 0.0476TY^{0.5} - 0.0227DY^{0.5} + 3.59$$

Where:

- η = the viscosity of bitumen recovered from the sprayed seal (Pa.s at 45°C)
- T = the average temperature of the site (°C), calculated as
- $T = \frac{(T_{max}+T_{min})}{2}$ where
    - o T_{max} = the yearly mean of the daily maximum air temperature (°C)
    - o T_{min} = the yearly mean of the daily minimum air temperature (°C)
- D = the ARRB Durability Test result (days)
- Y = the number of years since the seal was constructed.

The second model is by Oliver (2004) and it contains the extra independent variable - the thickness of the road pavement seal surface. The model is summarised in Oliver (2006).

Equation 2: Model for bitumen hardening (Oliver 2006)

$$\log \eta = 0.0498T^{0.5} - 0.0216DY^{0.5} - 0.000381S^2 Y^{0.5} + 3.65$$

Where:

- η = the viscosity of bitumen recovered from the sprayed seal (Pa.s at 45ºC and 5 x 10^{-3} s^{-1}),
- T = the average temperature of the site (ºC), calculated as
- $T = \frac{(T_{max}+T_{min})}{2}$ where
    - o T_{max} = the yearly mean of the daily maximum air temperature (°C)
    - o T_{min} = the yearly mean of the daily minimum air temperature (°C)
- D = the ARRB Durability Test result (days),
- S = nominal seal size (mm); and
- Y = the number of years since the seal was constructed.

The inclusion of an extra independent variable in the model is considered an advantage as it may ensure a more realistic representation of local conditions affecting binder service life.

4.1.4 Models for bitumen distress viscosity

The next factor in bitumen distress is to determine bitumen distress viscosity — that is the viscosity at which the bitumen no longer has the necessary flexibility to ensure that the road surface can sustain the stress generated from traffic. Bitumen distress viscosity levels have been shown to depend on the climate at a specific site, specifically average minimum annual air temperature (Oliver 2005). Models for bitumen distress viscosity are developed by using regression analysis. Oliver (2005) developed the following model for bitumen distress viscosity:

Equation 3: Model for bitumen distress viscosity (Oliver 2005)

$$\log\eta = 0.172T_{\min} + 3.65$$

Where:

- η = the viscosity of bitumen recovered from the sprayed seal (Pa.s at 45 °C and $5 \times 10^{-3} s^{-1}$); and
- T_{min} = the yearly mean of the daily minimum air temperature (°C).

Further research by (Oliver 2006) has shown that the inclusion of an extra independent variable improves the reliability of the model. In the improved model, an ordinal independent variable 'risk factor – R' is used to represent the amount of time resealing can be delayed. When the risk factor is high a delay can have serious consequences. A low risk factor indicates a delay in resealing will have minimal consequences. Generally, sites with high traffic volumes and a wet climate are typically associated with higher risk factors. As a guide, the risk factor for Local Government roads is three (R=3). However, this value is a generality and Councils may need to consider a different 'R' value for their situation. Other factors that determine the value of 'R' are rainfall intensity and frequency, heavy vehicle traffic volumes, the type of pavement base, the materials and technology used for pavement construction and the age of the seal. More information about the how to assign a risk factor can be found in Oliver (2006).

Equation 4: Model for bitumen distress viscosity (Oliver 2006)

$$\log\eta = 0.156T_{\min} - 0.093R + 4.45$$

Where:

- η = the viscosity of bitumen recovered from the sprayed seal (Pa.s at 45 °C and $5 \times 10^{-3} s^{-1}$)
- T_{min} = the yearly mean of the daily minimum air temperature (°C);
- R = risk factor on a scale of 1 to 10 as described above.

The model described in Equation 4 is recommended by Austroads as appropriate for use in Australian road management. The advantage of the model is that it provides an opportunity for Councils to actively take part in the estimation of road surface service life. In the cases where the assignment of risk factor 'R' is a challenge, Equation 3 can assist in the calculation of bitumen distress viscosity.

Service life of binder

The maximum service life of a sealed road surface is primarily dependent on the service life of the binder. Two factors are important to binder life namely, bitumen distress viscosity and hardening rate. Bitumen hardens faster and bitumen distress viscosity is higher in warmer/hotter climates. In this study models for hardening by Austroads (2007) and Oliver (2006) have been used. For bitumen distress viscosity, models by Oliver (2005) and Oliver (2006) are used.

4.1.5 Service life of bituminous surfaces

Service Life of Sprayed Seal Surface
Based on the models for bitumen hardening and distress viscosity described above, Oliver (2006) proposed a methodology for the estimation of sprayed seal road surface maximum life that Austroads uses in its published guidelines for road management (Austroads 2007). The sprayed seal surface maximum life is obtained by equating the right hand sides of two models and so can be calculated for a specific site with known parameters for average daily temperature, minimum daily temperature, bitumen durability, seal surface thickness, and risk factor 'R'. By using Equation 2 and Equation 4 the following formula for binder life is derived.

Equation 5: Model for sprayed seal surface maximum life

$$Y = \left[\frac{(0.158T_{\min}) - (0.107R) + 0.84}{(0.0498T) - (0.0216D) - (0.000381S^2)}\right]^2$$

Where:

- *Y* = the number of years since the seal was constructed
- *T* = the average temperature of the site (ºC), calculated as
- $T = \frac{(T_{max}+T_{min})}{2}$ where
  - o T_{max} = the yearly mean of the daily maximum air temperature (°C)
  - o T_{min} = the yearly mean of the daily minimum air temperature (°C)
- *D* = the ARRB Durability Test result (days),
- *S* = nominal seal size (mm); and
- *R* = risk factor on a scale of 1 to 10 as described above.

Graphically the derivation of seal surface life is shown in Figure 25:

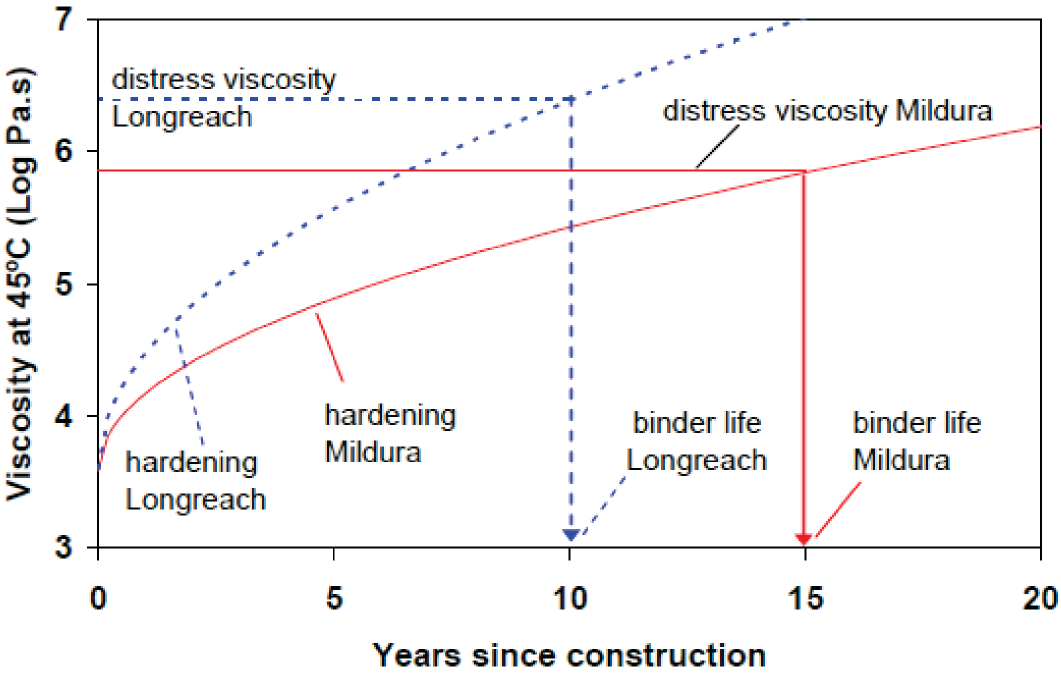


Figure 25: Example for estimation of road seal life at two locations (Mildura and Longreach) (Source: Oliver 2006).

Alternative formulas for the calculation of binder maximum life include a formula based on the bitumen distress model shown in Equation 3:

Equation 6: Binder maximum life (Oliver 2005)

$$Y = \left[\frac{(0.172T_{\mathbf{min}})}{(0.0498T) - (0.0216D) - 0.000381S^2}\right]^2$$

And a formula published in Giummarra, Martin et.al. (2007):

Equation 7: Binder maximum life (Giummarra, Martin et al. 2007)

$$Y = \left[\frac{(0.0394T) - (0.105T_{\mathbf{min}}) - 1.44}{(0.023D)}\right]^2$$

The three models described in equations 5, 6 and 7 to calculate the maximum life of the binder may be used to evaluate the impact of different climate scenarios on the degradation of the binder over time. An increase in the daily temperatures will have a positive correlation with the rate of bitumen hardening, and bitumen distress viscosity. Bitumen hardens faster and bitumen distress viscosity is higher in warmer/hotter climates. However, the effect of the increased hardening rate on binder service life is more significant than the effect of the higher distress viscosity on binder service life. Thus, binder life is shorter in warmer climates. This relationship can be seen in Figure 25 where the binder service life at two geographical sites is shown. The town of Longreach (Queensland, northern Australia, T_{max} = 31.2°C, T_{min} =15.4°C) has a warmer climate than the town of Mildura (Victoria, southern Australia, T_{max} = 23.6°C, T_{min} = 10.3°C). Although the site at Longreach has higher bitumen distress viscosity, the steeper slope of hardening rate leads to shorter binder service life. Figure 26 displays the estimated service life of sprayed seal surface in Australia. The figure is developed by Martin using Equation 5 (Martin 2001).

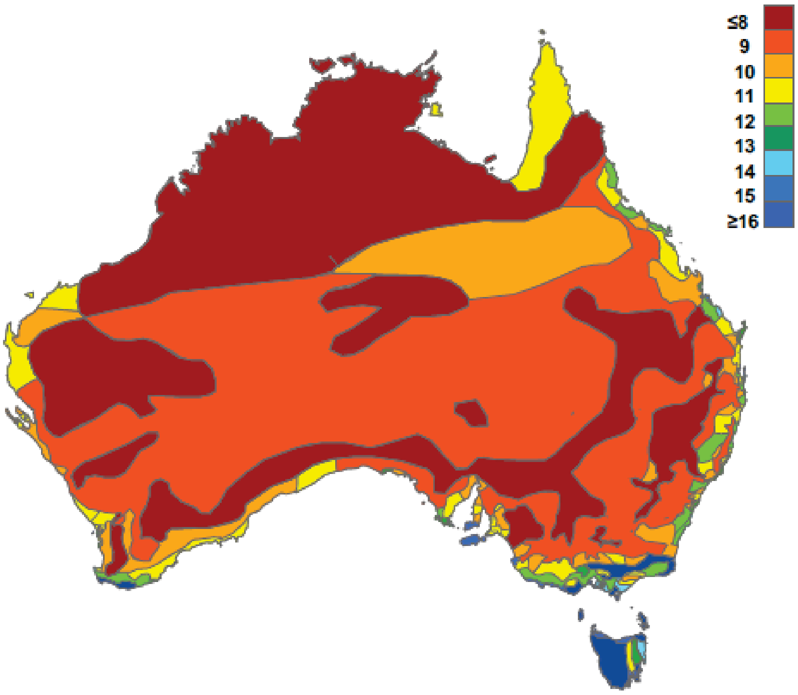


Figure 26: Estimated service life of sprayed seal surface in different temperature regions across Australia (Source: Martin 2001).

Service life of asphalt surface

Similar to the sprayed seal surface life, ARRB developed a model for hotmix asphalt surface life (Austroads 2010b). The model was developed using data from a sufficient number of sample sites across Australia using regression analyses to develop estimates for bitumen hardening rate and bitumen distress viscosity. The model is only applicable for asphalt surface with a thickness less than 40 mm, but none-the-less represents the majority of Australian local roads. The formulae of the model as given by (Choi 2009) is:

Equation 8: Model for maximum surface life of hotmix asphalt

$$Y = \left(0.323T_{\min} - 0.169T - 0.848\sqrt{A_v} + 5.217\right)^2$$

Where:

- T_{min} = the yearly mean of the daily minimum air temperature (°C)
- T = the average temperature of the site (ºC), calculated as
- $T = \frac{(T_{max}+T_{min})}{2}$ where
  - o T_{max} = the yearly mean of the daily maximum air temperature (°C)
  - o T_{min} = the yearly mean of the daily minimum air temperature (°C)
- A_v = air voids of the asphalt surfacing at the time of sampling (%, usually 4 to 6%)

Road Surface Treatment

In this study we distinguish between spray sealed and hotmix asphalt road surfaces. The sprayed seal surface maximum life can be calculated for a specific site with known parameters for average daily temperature, minimum daily temperature, bitumen durability, seal surface thickness, and risk factor 'R'. Generally, sites with high traffic volumes and a wet climate are typically associated with higher risk factors. For hotmix asphalt, maximum surface life can be calculated with known parameters for yearly mean of daily minimum air temperature, site average temperature and surface air void data. The model assumes seal surface thickness less than 40 mm.

Discussion regarding presented models for service life of bituminous surfaces

The models for calculating the service life of bituminous surfaces reviewed primarily consider climate conditions. The models do not take into account other important factors for surface deterioration such as traffic load and the underlying state of the pavement. Also, the models do not consider specific local conditions, such as reactive soils that can cause significant deformation and distress within the pavement base and thereby reduce surface life. These limitations suggest that the models for hotmix asphalt should only be used as generic guidelines and local knowledge and expertise should refine the calculations for the length of road surface service life.

Martin (2001) undertook a desktop analysis to compare the modelled service life for sprayed seal and hotmix asphalt surfaces as predicted by Equation 5 and Equation 8. The results of the study confirmed that the hotmix asphalt has a longer service life than the spayed seal. In only one of 13 selected locations assessed across Australia and New Zealand did the sprayed seal surface have a modelled service life that was longer than the hotmix asphalt surface. In some instances the duration of the hotmix asphalt service life was double the sprayed seal life.

4.1.6 Climate representation and the Thornthwaite Moisture Index

As the equations and field measurements show, the climate influences road deterioration rates and is calculated in the mathematical models by including climatic variables such as temperature, humidity and precipitation. Each of these climate variables affects road deterioration in a unique way. Modelling the impact of each variable individually and then aggregating impacts to obtain a total climate impact on road deterioration is a challenging task. For this reason, road authorities in Australia adopted a simplified approach in which road deterioration is related to a single climate index that embodies the interconnected influences of all important climate variables for road deterioration. The Thornthwaite Moisture Index (TI) has been selected as an appropriate parameter for the majority of models to explain climate impacts on road deterioration.

The TI (Thornthwaite 1948) was originally developed for the classification of agricultural climate types in different regions. Later the index was adopted for civil engineering applications when considering utilities and structures located on or beneath the ground surface. The index is a combination of annual climate and environmental effects and includes rainfall, evapotranspiration, soil water storage, moisture deficit and runoff. In its original form the TI was defined as:

Equation 9: Original form of Thornthwaite Moisture Index (TI but shown here as TMI).

$$TMI = I_h - I_a$$

$I_h = 100\frac{D}{PET}$ and $I_a = 100\frac{R}{PET}$

Where:

- *D* = moisture deficit
- *R* = moisture surplus
- *PET* = potential evapotranspiration

However, subsequent applications of the index (see Austroads 2010b; Austroads 2010c) have used the following simplified form on the basis that water can enter soil more easily than it can be extracted:

Equation 10: Austroads formulae for Thornthwaite Moisture Index (TI but shown here as TMI).

$$TMI = I_h - 0.6I_a$$

A further simplification of the index was given by Gentilli (1972), and produces a TI that uses 'effective annual rainfall' (P_e):

Equation 11: Simplified formulae for Thornthwaite Mositure Index (TI but shown here as TMI).

$$TMI \approx 1.25P_e - 60$$

Where:

$$P_e = \sum_{m=1}^{12} P_{em}$$

$$P_{em} = 1.65\frac{P_{Tm}}{(M_m + 12.2)^{1.1111}}$$

Where: P_{Tm} is monthly total rainfall and M_m is mean monthly temperature.

An Australian map of the TI was developed by Aitchison and Richards (1965) (Figure 27). Climate change is expected to cause deviations of the TMI value from its historical average value. When considering the value of the TI for planning future road management, Austroads developed a tool that allows easy access to simulated future climate data, that includes the TI (Austroads 2010c). The stimulated future TI values are based on CSIRO scenarios for climate change in Australia. The tool requires GPS coordinates of a location and outputs a prediction of the TI or the specified location for any year until 2100.

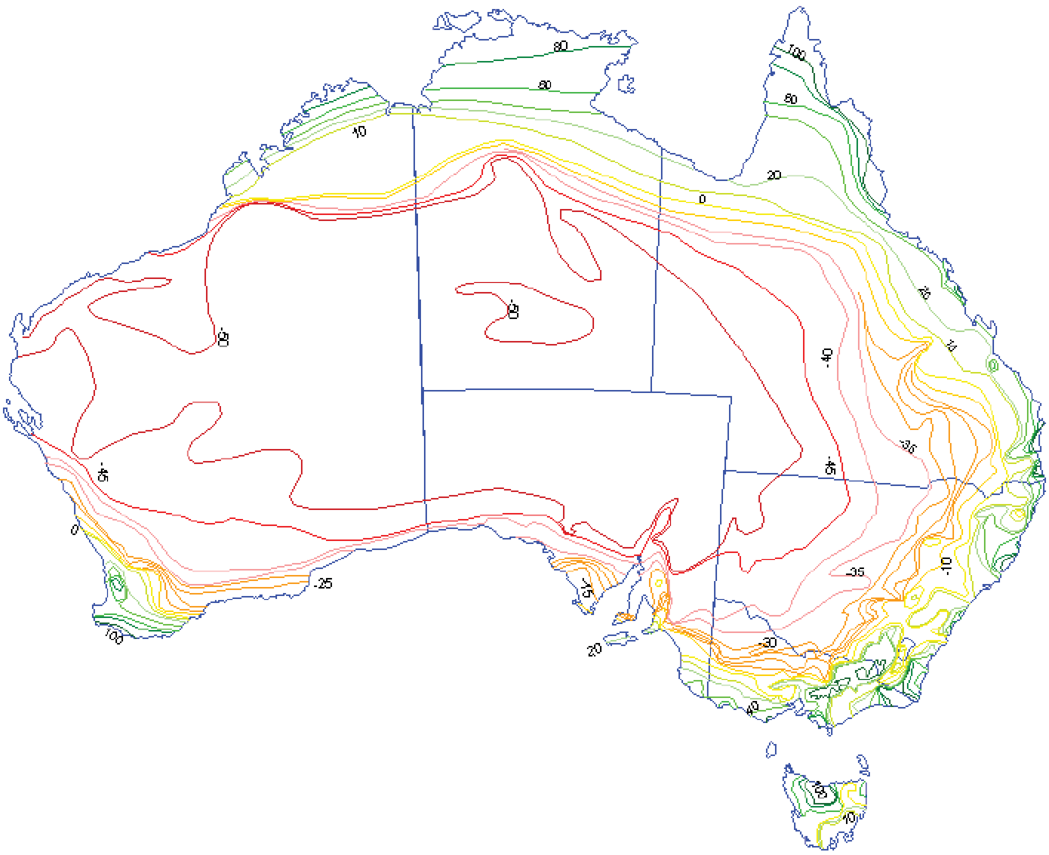


Figure 27: Contours of Thornthwaite Moisture Index (TI) for Australia (Source: Aitchison and Richards 1965).

4.1.7 On an approach to the estimation of the effect of climate change on sprayed seal road surface deterioration

In a 2011 paper, Martin developed a relationship between the TI and road maintenance cost for sprayed seal roads (Martin 2001). Figure 28 shows the relationship between values of TI on the x-axis and values of percent maintenance cost differences on the y-axis. To demonstrate the relationship between the TI and road maintenance cost, Martin uses two reference points. These reference points are associated with values of the TI equal to 18 and 25. In the graph, two lines cross the x-axis at the two reference point values. The line can be used to find out how much more or less it costs to maintain a road at a location with a specific TMI value when compared to a reference point. For example, by using the graph we can estimate that maintaining a road at a location with a TI equal to 50 costs approximately 6% more than maintaining the road at a location with a TI equal to 25. The knowledge inferred from the graph can be used to calculate the percent maintenance cost difference due to the climate for any two locations with known TI values. Unfortunately, the publication of Martin’s work does not contain the mathematical formulae for the inferred relationship between road maintenance cost and the TI.

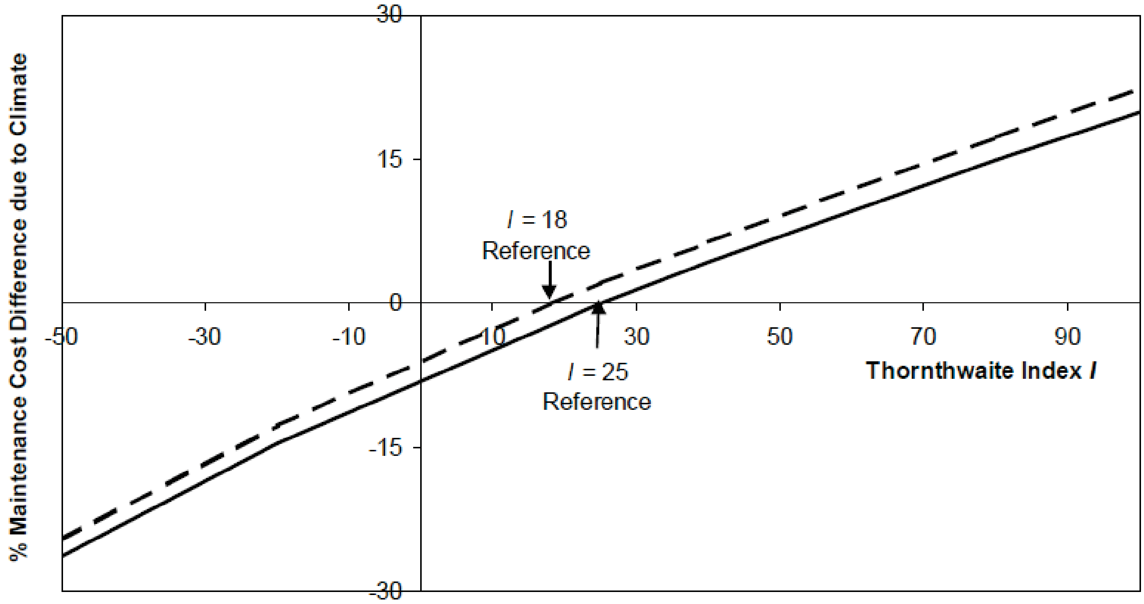


Figure 28: Percent maintenance cost difference due to climate vs the Thornthwaite Moisture Index (TI) for maintained sprayed seal roads (Source: Martin 2001).

During the last decade ARRB continued to update the developed relationship between the TMI and deterioration of sprayed seal surfaces. In one of their latest publications Martin discusses results from an experimental study performed at an accelerated load testing facility where different environmental conditions were simulated (Martin 2010). The broader aim of this study was to compare the observed deteriorations of road surfaces of several types. The investigated surfaces are cracked single seal (ckdss), uncracked single seal (unckdss), uncracked geotextile seal (unckdgeo), and uncracked double seal (unckdds). These surfaces are tested in dry (d) and wet (w) conditions. Based on the observations from the tests, the regression models for cumulative rutting (Δrut) and cumulative roughness (ΔIRI) were developed. Results from the models were used to obtained relative performance factors(rpfs) for rutting(rpf_{mrut}) and roughness (rpf_{miri}). The rpfs demonstrate how the deterioration rate of a particular surface compares to the deterioration rate of another surface. For example, if $\text{rpf}_{mrut}\left[\frac{(\text{unckdss}(w))}{(\text{unckdss}(d))}\right]$ equals 1.14, this means that cumulative rutting on an uncracked single seal road in wet conditions is 1.14 times higher than the cumulative rutting on an uncracked single seal road in dry conditions.

Martin's study uses rpfs for wet and dry conditions to quantify the influence of climate on road surface deterioration. To do so, an appropriate classification of climate is required. The study uses the TI to represent climatic conditions at the site of interest. This is not an unusual selection, given the fact that the TI is widely used by Austroads in their road deterioration analyses. More information about TI can be found in Thornthwaite (1948). The range of TI for Australia is from -50 to 100. For dry climate conditions, the approximate TMI is -50, whereas in constantly wet conditions the approximate TI is closer to 100 (Aitchison and Richards 1965).

Based on the framework of using rpfs and a climate index along with the assumptions that:

1. rpfs and TI have a linear relationship;

2. dry conditions are approximately equal to *TI* -50; and
3. wet conditions are approximately equal to *TI* +100.

Martin derives the following linear equations for relationship between rpfs and TI for uncracked and cracked sealed roads.

Equation 12: Relative Performance Factors for rutting at a specific Thornthwaite Moisture Index (TI) for an uncracked single sealed road relative to dry conditions (d).

$$rpf_{mrut}\, unckdss\left(\frac{TI}{d}\right) = 1.047 + (0.000933TI)$$

Equation 13: Relative Performance Factors for roughness at a specific Thornthwaite Moisture Index (TI) for an uncracked single sealed road relative to dry conditions (d).

$$rpf_{miri}\, unckdss\left(\frac{TI}{d}\right) = 1.073 + (0.00147TI)$$

Equation 14: Relative Performance Factors for rutting of a cracked single seal relative to an uncracked single seal at a specific Thornthwaite Mositure Index (TI) for dry conditions.

$$rpf_{mrut}\frac{ckdss}{unckdss}\left(\frac{TI}{d}\right) = 1.45 + (0.009TI)$$

Equation 15: Relative Performance Factors for roughness of a cracked single seal relative to an uncracked single seal at a specific Thornthwaite Moisture Index *(*TI*)* for dry conditions.

$$rpf_{miri}\frac{ckdss}{unckdss}\left(\frac{TI}{d}\right) = 1.463 + (0.00927TI)$$

A graphical representation of the four relationships above is shown in Figure 29 and Figure 30. 'Double seal' and 'geotextile' surfaces are considered to be unaffected by climate in the study performed by Martin (2010).

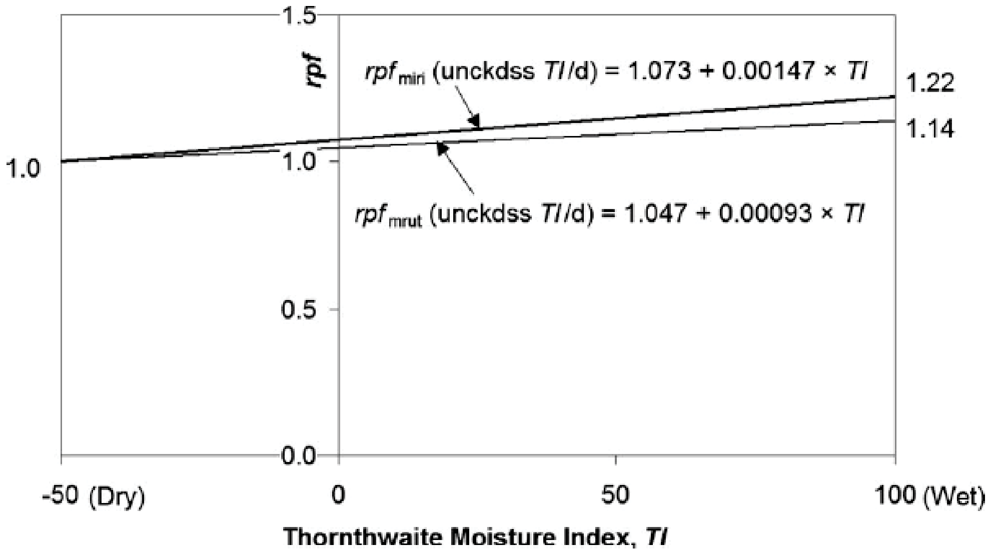


Figure 29: $rpf_{mrut}\ unckdss\left(\frac{TI}{d}\right)$ and $rpf_{miri}\ unckdss\left(\frac{TI}{d}\right)$ variation with Thornthwaite Moisture Index (TI) (cracked single seals relative to uncracked single seals) (Source: Martin 2010).

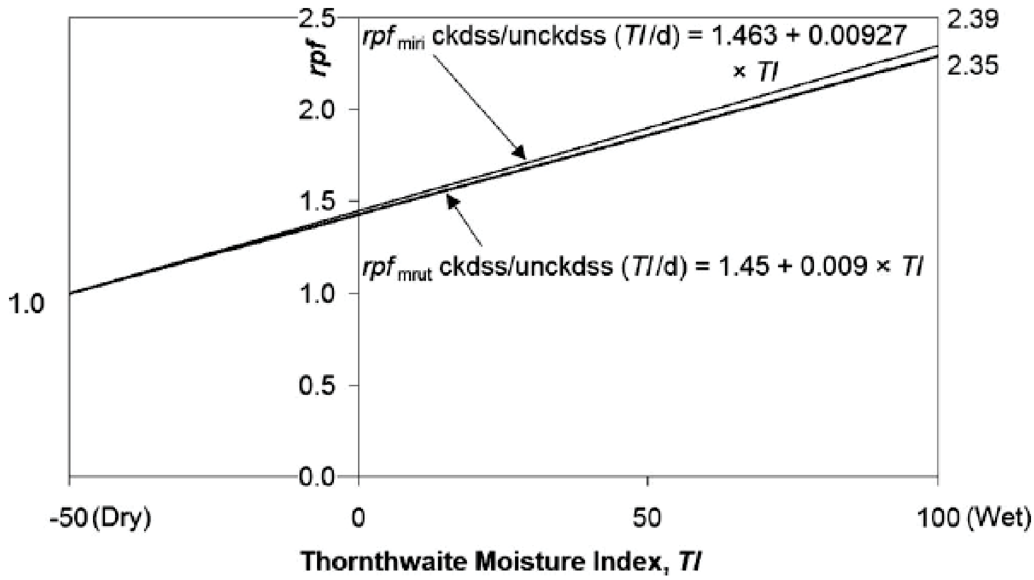


Figure 30: $rpf_{mrut}\ ckdss/unckdss\ (TI/d)$ and $rpf_{miri}\ ckdss/unckdss\ (TI/d)$ variation with Thornthwaite Moisture Index (TI) (cracked single seals relative to uncracked single seals) (Source: Martin 2010).

Based on this methodology, it is possible to calculate the cumulative road surface deterioration (rutting and roughness) for any climatic condition if the cumulative road surface deterioration for another climate condition is known (given that both climate conditions are expressed by the TI).To do so, it is necessary to use two relative performance factors. The first one represents the relation between road deterioration for the first climate condition and road deterioration for dry climate (that is TI = -50). The second one represents the relation between road deterioration for the second climate condition and road deterioration for dry climate (that is TI = -50). The formula for this calculation is:

Equation 16: Calculation of road deterioration based on rpfs.

$$\Delta d_i(TI_i) = \frac{rpf_m\ unckdss\left(\frac{TI_i}{d}\right) \times \Delta d}{rpf_m\ unckdss\left(\frac{TI_i}{d}\right)}$$

Where:

- *Δd* is the cumulative deterioration (rutting and roughness) due to treatment *j*
- Δd_i is the cumulative deterioration (rutting and roughness) due to treatment *i*
- *TI* is the Thornthwaite Moisture Index for climate pavement condition *j*
- TI_i is the Thornthwaite Moisture Index for climate pavement conditions *i*

The formulas presented in Equation 12 to Equation 15 are the result of rigorous and methodological research performed by ARRB. These formulas are derived by utilisation of road deterioration models for various climates and road type surfaces. The road deterioration models are developed by linear regression analyses on sufficient and robust experimental data obtained at a highly sophisticated accelerated load testing facility. All regression models have a highly significant F-statistic value and a highly significant t-statistic for included regression coefficients. Most importantly, the r-squares values are around 0.8 (the lowest r-square value is 0.73 and the highest is 0.89) - this is a satisfactory goodness of fit value that suggests small variation in the data around the predicted expected values. Therefore, one can have high confidence in the estimate of road surface deterioration by using rpfs. However, the above presented study would greatly benefit from additional research that verifies the predicted road deterioration against real world observed data. Such further investigation would make the research more comprehensive and would provide valuable information on how to apply the developed rpf methodology in practice. The future research agenda of the ARRB team (responsible for the development of above presented rpf methodology) considers these research directions. At the time of writing this report neither ARRB nor other independent body has published results regarding these matters. When such results are published, it is advisable that stakeholders in this project consider them as the information would further enhance and strengthen the tools developed for climate change adaptation in this project.

The significance of Martin's paper for this project

The formula presented in Equation 16 has the potential to predict the rate of road surface deterioration under changed climatic conditions. If under the current climate (represented by *TI*) road deterioration is Δd, then by using the formula it is possible to calculate what is going to be the road deterioration Δd_i under changed climatic condition (represented by TI_i). The data for current road surface deterioration is available, or in most cases it can be easily obtained from Council records for road management. However, this approach is only applicable for deterioration occurring during the gradual phase of road surface deterioration. Figure 31 provides a visualisation of phases of road surface deterioration.

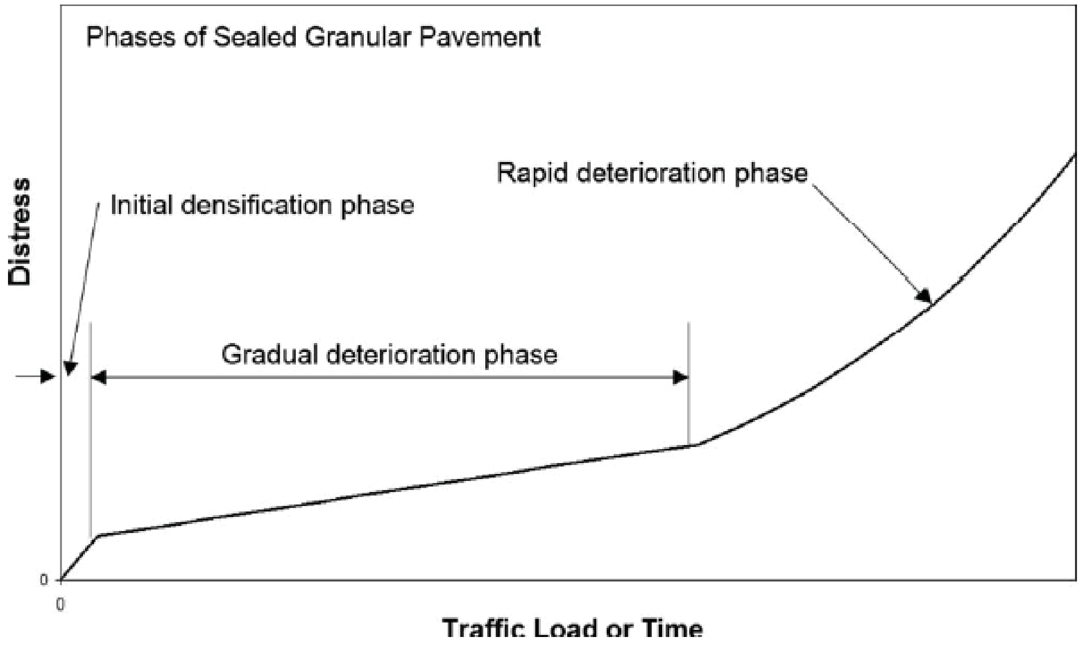


Figure 31: Three phases of pavement deterioration (Source: Freeme 1983).

The Thornthwaite Moisture Index as a proxy for climatic conditions

Climate influences road surface deterioration in a compound way through a combination of climate factors such as temperature, humidity and precipitation, each of which impact on road deterioration in a unique way. But modelling each of these variables to obtain a total climate impact on road deterioration is challenging. So road authorities in Australia have adopted a simplified approach to modelling climate impacts on road deterioration via the Thornthwaite Moisture Index (referred as TMI or TI in the literature). A TI of -50 represents an arid climate such as central Australia while a TI of 100 represents a wet climate such as Western Tasmania. The TI relates road deterioration to a single climate index that embodies the interconnected influences of all important climate variables for road deterioration. The relationship of deterioration to the TI can be modelled and so deterioration in respect of a given TI may be calculated.

4.1.8 Models for road deterioration

HDM-4 models for road deterioration
Highway development management (HDM) models are used worldwide for the prediction of road deterioration. In Australia, the HDM-4 models are used for the management of the national highway system and includes highways/freeways, arterial roads, collectors, and rural arterials. These are roads with high volumes of traffic and so there is limited application of HDM-4 model in this project where low traffic Local Government roads are of interest. Austroads report AP-T97-08 (2008) provides the calibrated HDM-4 models for Australia. The report also includes HDM-4 models for roads with low traffic. These models can find some application when Local Government road deterioration is analysed. However, HDM-4 models demand extensive data that Councils probably do not possess and that they find challenging to obtain.

HDM-4 models consist of sub-models for roughness, cracking, rutting, etc. and are very detailed models that intend to consider every possible factor that has potential for a significant influence on road deterioration (Odoki and Kerali 2000; Morosiuk, Riley et al. 2001). Table 2 displays the models developed for road deterioration and independent variables used in the models. However, environmental variables in the majority of the sub-models are not apparent from scrutiny. Only the models for roughness and rutting (more specifically the 'Structural deformation after cracking' component of rutting model) have MMP (mean monthly precipitation (mm/month)) as independent variable. It is therefore unclear why the last column of the table has so many ticks (Ivan Iankov, University South Australia School of Natural and Built Environments, pers. comm. 2011).

Table 2: Types of distress and independent variables. Source: (Austroads 2008)

Distress mode	Distress type	Pavement strength	Material properties	Traffic loading	Environment
Cracking	Structural	✓	✓	✓	✓
	Reflection	✓		✓	
	Traverse thermal		✓		✓
Disintegration	Ravelling		✓	✓	✓
	Potholing	✓	✓	✓	✓
	Rutting–surface wear			✓	✓
	Edge break		✓	✓	✓
Deformation	Rutting–structural	✓	✓	✓	✓
	Rutting–plastic flow		✓	✓	✓
Profile	Roughness	✓	✓	✓	✓
Friction	Texture depth		✓	✓	
	Skid resistance		✓	✓	

HDM-4 modelling is a step by step process. In other words, the result from a HDM-4 sub-model is fed into the next HDM-4 sub-model. For example, the result from the cracking sub-model is used in the rutting sub-model and the result from the rutting sub-

model is used in the roughness sub-model. Also, every (sub-) model consists of several components, for example, the rutting sub-model has four components: initial densification, structural deterioration, plastic deformation, and wear from studded tyres. The final output from the HDM-4 modelling is the result from the roughness sub-model which calculates the value of International Roughness Index (*IRI*).
The HDM-4 model is:

Equation 17: HDM-4 roughness model

$$\Delta IRI = K_{gp}\ [\Delta IRI_s + \Delta IRI_c + \Delta IRI_r + \Delta IRI_t] + \Delta IRI_e$$

Where:

- ΔIRI is the total incremental change in roughness during the analysis year (IRI m/km),
- K_{gp} is the calibration factor for roughness progression,
- ΔIRI_s is the incremental change in roughness due to structural deterioration during the analysis year (IRI m/km),
- ΔIRI_c is the change in roughness due to cracking during the analysis year (IRI m/km),
- ΔIRI_r is the incremental change in roughness due to rutting during the analysis year (IRI m/km),
- ΔIRI_t is the incremental change in roughness due to potholing during the analysis year (IRI m/km), and
- ΔIRI_e is the incremental change in roughness due to environment during the analysis year (IRI m/km).

The environmental component ΔIRI_e is calculated as follows:

Equation 18: Environmental component of the HDM-4 model

$$\Delta IRI_e = mK_{gm} \times IRI_a$$

Where:

- ΔIRI_e is the incremental change in roughness due to environment during the analysis
  year (IRI m/km),
- IRI_a is the roughness at the start of the analysis year (IRI in m/km),
- K_{gm} is the calibration factor for the environmental component of roughness, and
- *m* is the environmental coefficient.

The values for coefficient '*m*' for various climates are currently commercial in confidence and so cannot be shown here. The calibrated coefficients K_{gm} for all Australian states can be found in (Austroads 2008).

From the coefficients, it is possible to make an *intelligent guess* about the change in '*m*' from climate change for specific locations. Then we can use the inferred value for '*m*' to obtain the effect of climate change on environmental component in roughness model. However, it should not be assumed that climate change would not affect other components (for example ΔIRI_c) in the roughness model.

Austroads model for highway deterioration

The 'International Roughness Index', *IRI*, is a standard indicator for road conditions. *IRI* considers all appropriate indicators for road state (such as the extent of surface cracking and rutting). When a road is constructed or rehabilitated, its *IRI* is IRI_0. After time t, the road *IRI* is IRI_t. Road deterioration is assessed by the cumulative change in *IRI* over a period of time.

$\Delta IRI = IRI_t - IRI_0$, is the deterioration that a road experiences since the initial time period. Austroads (2010d) uses the following equation to find *IRI* at specific time t:

Equation 19: Austroads model for sealed road deterioration

$$IRI(t) = 1.04e^{\lambda t}\left[IRI_0 + 263\frac{N(t)}{(1+S)^5}\right]$$

Where:

- IRI_t is the International Roughness Index at time t
- IRI_0 is the International Roughness Index at $t = 0$
- λ is the environmental coefficient which is given by $\lambda = 0.0197 + 0.000155TI$ where TI is Thornthwaite Moisture Index
- $N(t)$ is the cumulative number of *ESA* at time t (10^6 ESA/lane)
- S is the modified structural number of the pavement (cf. Austroads 2010d)

Thus, by using the above equation, TI can be used as an indicator of environmental and climatic impact on road pavement deterioration. Austroads uses Equation 19 for the assessment of highway deterioration. Local roads and highways differ significantly in their structural characteristics and are subject to different traffic loads. Therefore, it was necessary to verify the appropriateness of Equation 19 for this project.

The nonlinear relationship between TI, S, and N in Equation 19 implies that similar changes in climate may have different impact on roads with different structural properties or traffic volumes. That means that climate change impacts on road pavements depend on road characteristics and traffic volumes. Consequently, to determine climate change impact on a particular road, one needs to know the structural number and the traffic volume associated with the road. These data might be unavailable and difficult to estimate. In such cases, Equation 19 should be applied with caution to avoid conclusions that are based on vague assumptions.

ARRB model for the deterioration of local sealed roads

ARRB developed mathematical models for the deterioration of local sealed roads by analysing data from experimental sites located across Australia. These models calculate structural deterioration, rutting, total cracking, and roughness prediction. The adopted methodology for development of the models consists of the following stages. First, international models for road deterioration are selected as prototypes for Australian models. Second, the collected data from experimental sites are fitted into prototype models and statistical analyses for significance of independent variables are carried out. Finally, modified models are presented as Australian models for road deterioration (Choummanivong and Martin 2009).

This project can use model roughness prediction for the assessment of climate change impacts on local sealed roads. However, the roughness model requires input from the cracking model, and therefore cracking and roughness models are presented in this report. The cracking model is:

Equation 20: ARRB cracking model

$$\Delta crack = k \times EXP\,(a_1 \times Sealage + a_2 \times SNC_i)$$

Where:

- $\Delta crack$ is the cumulative total cracking as a percentage of observed lane area (%)
- k is the calibration factor
- a_1 and a_2 is the model coefficients
- *Sealage* is the age of seal after last surfacing (years)
- SNC_i is the modified structural number for pavement/subgrade strength at time i

The values for coefficients for the cracking model for South Australia are also commercial in confidence and so cannot be given here. However, a low r^2 for the developed cracking model raises concerns about level of confidence in any calculations. An extra caution is necessary when results from cracking model are used. The roughness model is:

Equation 21: ARRB roughness model

$$\Delta IRI = a_3 \times \Delta crack + a_4 \times IRI_{env}$$

Where:

- ΔIRI is the cumulative increase in overall roughness since the initial roughness (IRIo)
- $\Delta crack$ is the cumulative total cracking as a percentage of observed lane area (%)
- IRI_{env} is the cumulative roughness increase due to environmental effects, equation (B4d)
- a_3 and a_4 is the model coefficients
- IRI_{env} is the cumulative roughness due to environment effect (m/km)
    - $IRI_{env} = mIRI_0 \times AGE_i$ where $m = 0.0197 + (0.000155TI)$
- AGE_i is the pavement age, the lesser of the number of years since construction and last rehabilitation
- IRI_o is the initial roughness (m/km) at pavement age, $AGE_i = 0$

The values for the coefficients for the roughness model for South Australia as for the cracking model for South Australia are also commercial in confidence and so cannot be given here. Equation 21 suggests that the TI can be used as an indicator of environmental and climatic impacts on road pavement deterioration. The nonlinear relationship in the definition of IRI_{env} implies that climate change impacts depend on the age of the road. That means that road age is an important parameter when road deterioration is predicted because similar changes in climate may have different impact on roads with different ages. Data regarding road age can be easily obtained from available records for road rehabilitation works.

4.1.9 Comparison of the models assessed for the deterioration of sealed roads

The section above reviewed several models for sealed road deterioration. All models aim to accurately estimate the future condition of a road by considering road characteristics such as traffic volume and the climate at the road location. For this project it was important to analyse the level of agreement between the most appropriate models - two models were compared. The first model is represented in Equation 19 (the Austroads model for highway deterioration) and is referred to as ‘Model A’ in the following discussion. The second model is represented by Equation 21 (the ARRB model for local road deterioration) and is referred to as ‘Model B’ in the discussion.

The analysis compared outputs of Model A with those with the outputs from Model B. Both models required input parameters for road characteristics (including the Structural Adjusted Number (SNG) and the period of time since the road was last rehabilitated), and the climate (for example, the Thornthwaite Moisture Index (TI)). These input parameters define the various scenarios under which road deterioration may occur in the future. The scenarios selected in our analysis ensured a representative coverage of possible combinations between road characteristics and climate conditions. SNG_0 was used to simulate different road construction designs. TI was used to simulate feasible climates in Australia. The chosen SNG_0 values for the scenarios were 3, 4, and 5 and correspond to low, medium and high structural road capacity. The thirty values of TI used in the scenarios are five units apart from each other and cover the entire feasible range for TI in Australia (-50 to 100). In all scenarios, it was assumed that road was rehabilitated 10 years before the start date of the model exercise and that the road roughness (IRI_0) immediately after the rehabilitation is equal to 2.0. It is a common practice to assume IRI_0 =2, when data is not available (Choummanivong and Martin 2009)[5].

In the analysis, Model A and Model B were used to predict what the expected road roughness would be 5, 10, and 15 years after resealing (i.e. 15, 20, 25 years after rehabilitation) for each scenario and the difference between projected outputs were analysed. The (performed) empirical analysis revealed that Model A and Model B returned similar road roughness projections for all tested scenarios. The difference in outputs was approximately 5% from their average (Figure 32).

This result means that when the models estimated a roughness value (*IRI*) of about 3.0, the discrepancy between them was about 0.15, for *IRI* = 4 the discrepancy was about 0.20, and for an *IRI* = 5.0 the discrepancy was about 0.25. The maximum observed difference in the outputs of Model A and Model B was 16% of their average. On the basis of the analysis either Model A or Model B were considered equally appropriate for use in this project, and their applicability depended instead on the quality of the available data.

[5] There is a formula that may used to calculate IRI_0 based on the current IRI, the current road age and the planned road design life. Optionally, a more detailed formula may be used to obtain an estimate for IRI_0. As well as the above mentioned parameters, the formula includes parameters for climate and traffic.

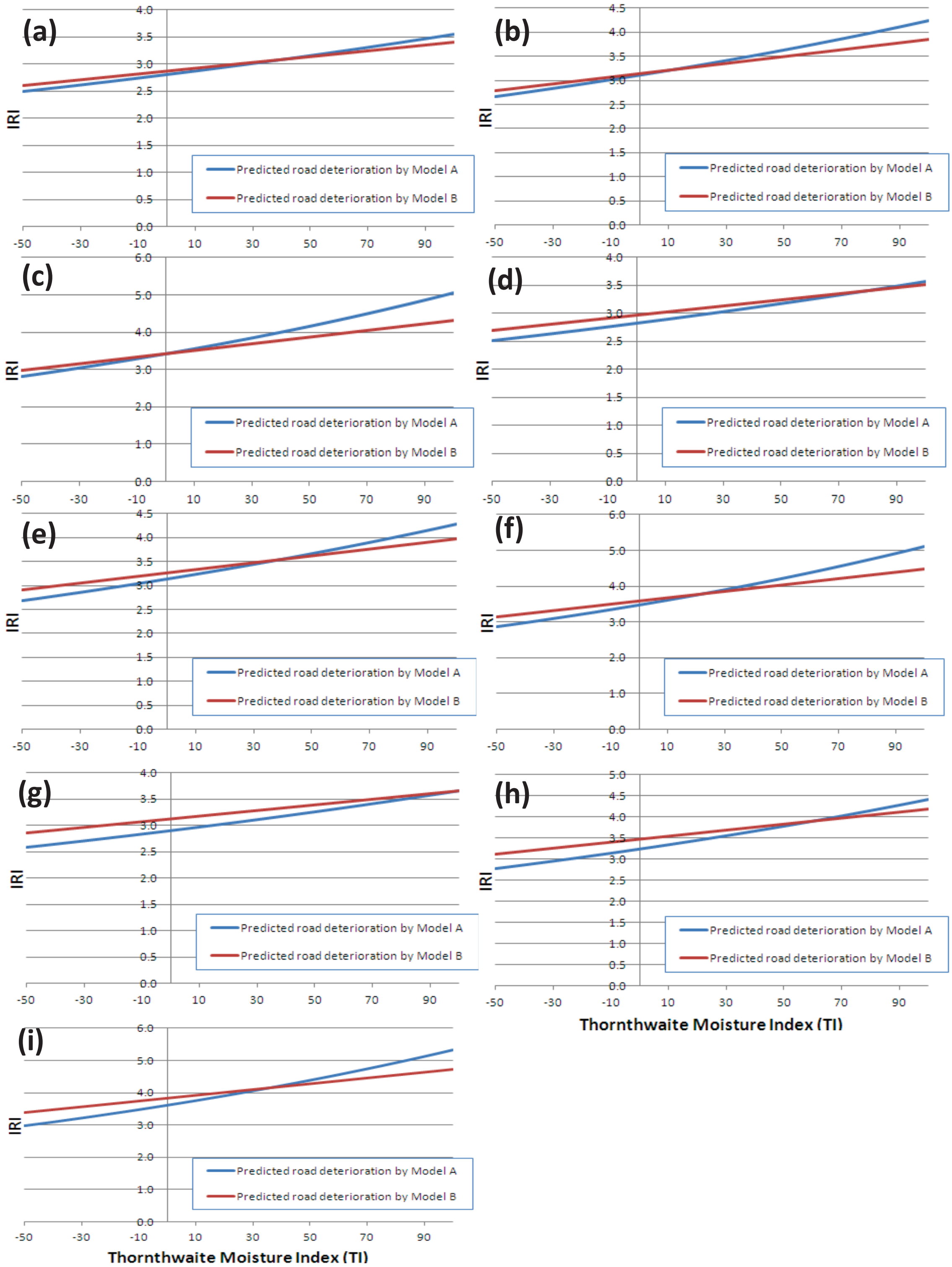


Figure 32: Predicted road deterioration versus the Thornthwaite Index after (a) 15 years; and (b) 20 years; (c) 25 years. Assumptions: SNG0=5, Resealing after 10 years, MESA=0.02, Road design life=30 years, IRI0=2.0. Predicted road deterioration after (d) 15 years; and (e) 20 years; (f) 25 years. Assumptions: SNG0=4, Resealing after 10 years, MESA=0.02, Road design life=30 years, IRI0=2.0. Predicted road deterioration after (h) 15 years; and (h) 20 years; (i) 25 years. Assumptions: SNG0=3, Resealing after 10 years, MESA=0.02, Road design life=30 years, IRI0=2.0.

4.1.10 Estimating road deterioration from Relative Performance Factors (rpf)

Section 10.1.7 describes how Relative Performance Factors (rpfs*)* can be used to estimate road surface deterioration when the baseline scenario deterioration is known. This section analyses the applicability of rpfs for predicting road deterioration. In other words, can we use rpfs to estimating road deterioration in the same way we are using them to estimate road surface deterioration.

In the empirical analysis, baseline road deterioration and the rpfs described by Equation 12 to Equation 15 were used to estimate road deterioration in thirty different climates. The TI values for the selected climates were five units apart and they cover the entire feasible range for TI in Australia. The analysis was carried out for several baseline road deteriorations. The selected baseline scenarios (under which the baseline road deteriorations occur) were defined by TI and SGN_0. The values of TI in the baseline scenario were -20, 0, 20, 40, and 60 and the values of SNG_0 in the baseline scenario were 3.0, 4.0 and 5.0. The analysis considered estimated road deterioration after 5, 10 and 15 years. The outputs were compared with projections from the model represented by Equation 21 (the ARRB model for local road deterioration).

The analysis reveals that the value of IRI predicted by rpfs for deterioration of cracked surfaces is similar to the value of IRI predicted by Equation 21 (ARRB model). Figure 33 (following page) displays results for selected baseline scenarios. When SGN_0 is equal to 4 or 5, then the two approaches yield very similar results for entire range of TI. When SGN_0 is equal to 3, then the discrepancy between calculations is less than 5%, when the predicted deteriorations are for climate that is represented by TI that is within +/-10 units of the assumed TI that represents the baseline scenario. That implies than *rpfs* can be used to predict road deterioration and would be valid to use to estimate the impacts of climate change on road deterioration if it can be assumed that climate change will not change TI with more than 10 units.

4.1.11 Conclusions and recommendations

Section 4.1 analysed several models for road deterioration and assessed their merits for application in this project. The analyses concluded that climate change impacts on sprayed seal surface deterioration can be assessed by Martin's model (Equation 16), which uses *rpfs* and a baseline scenario. Oliver's models (e.g. Equation 5) and Choi's model (Equation 8) can be used to estimate the impact of climate change on the maximum life of road surface. Austroads (Equation 19) and ARRB (Equation 21) models are appropriate to estimate climate change impacts on road deterioration. A key component of these models is the Thornthwaite Moisture Index (TI) which is used as proxy for climatic conditions. Thus future road deterioration may be modelled assuming different climatic conditions using the Thornthwaite Moisture Index as a key input to the model.

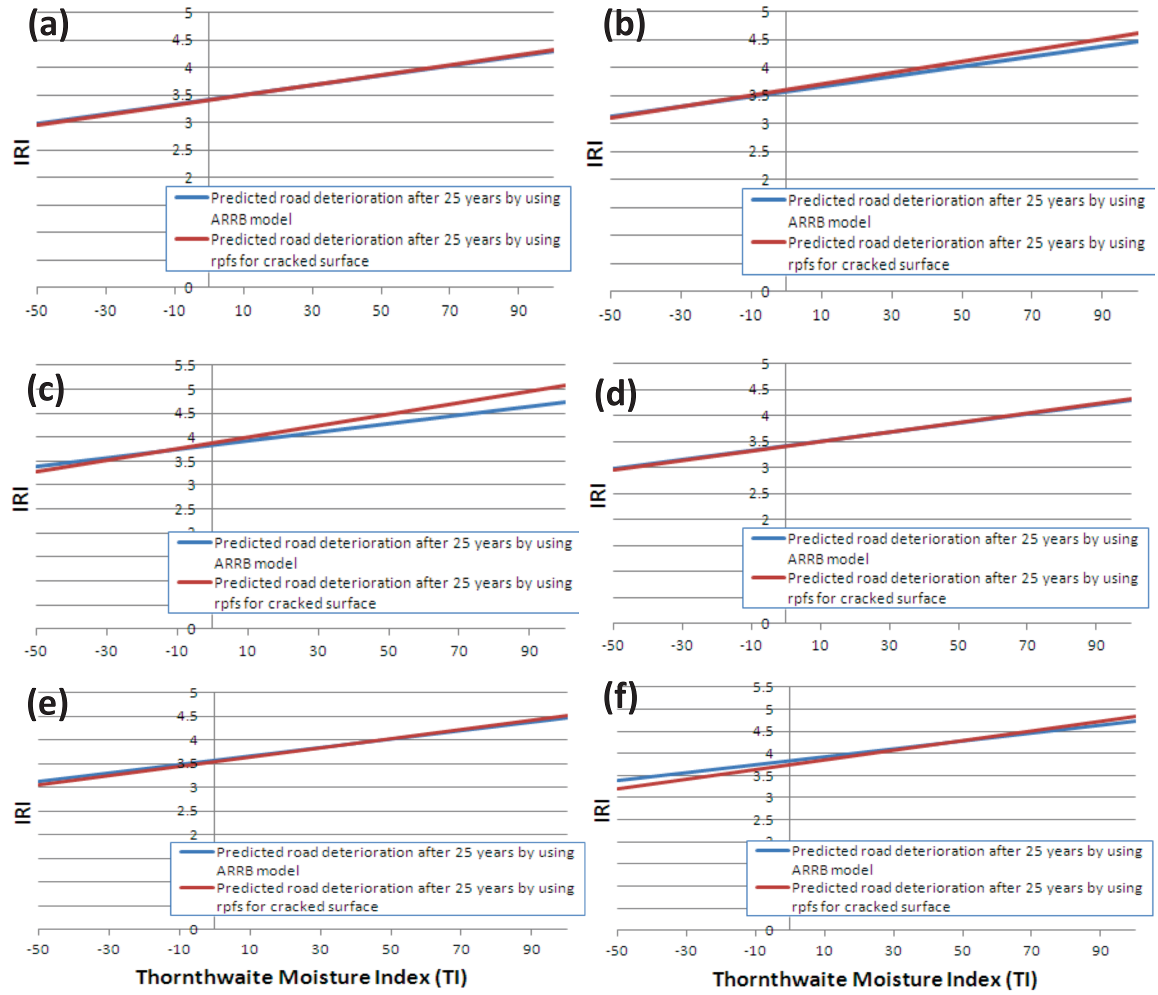


Figure 33: Comparison of predicted road deterioration by ARRB model with road deterioration that is predicted by using relative performance factors. (a) Assumptions:SNG0=5, Resealing after 10 years, Road design life=30 years, IRI0=2.0, TI for baseline scenario is equal to -20. (b) Assumptions:SNG0=4, Resealing after 10 years, Road design life=30 years, IRI0=2.0, TI for baseline scenario is equal to -20; (c) Assumptions: SNG0=3, Resealing after 10 years, Road design life=30 years, IRI0=2.0, TI for baseline scenario is equal to -20; (d) Assumptions: SNG0=4, Resealing after 10 years, Road design life=30 years, IRI0=2.0, TI for baseline scenario is equal to 40; (e) Assumptions: SNG0=3, Resealing after 10 years, Road design life=30 years, IRI0=2.0, TI for baseline scenario is equal to 40.

4.2 Deterioration of Unsealed Roads

4.2.1 Prospect for unsealed roads

Unsealed roads are important for local road networks across Australia. Accessibility to numerous vital services for many communities in rural Australia is highly dependent on the condition of unsealed roads. In addition to sealed roads, this project sought also to determine how unsealed roads will be affected by climate change.

A study from New Zealand (Ferry 1998) found that unsealed roads are a more sustainable solution for low volume traffic roads (that is, less than 100 vehicles per day). The study argues against several myths regarding unsealed roads and concludes that there are advantages to unsealed roads when compared to sprayed seal roads, including that they:

- do not require non-renewable resources (depending on the type of aggregate used);
- have a lower construction cost;
- have a lower maintenance cost;
- are usually quicker to repair after damage from natural disasters such as floods and washouts.

The study also argued that unsealed roads "can be nearly as efficient as sealed surfaces regarding vehicle operating costs, if 'good practice' techniques are implemented". On the other hand, the study finds that dust is an issue for unsealed roads but an appropriate wearing course could keep it to tolerable levels.

The finding that unsealed roads have shorter periods for repair after damage raises a debate about the future of unsealed roads. Dealing with the consequences of natural climate disasters is likely to become an increasingly important aspect of road network management. The usual public view is that a sealed road will suffer less damage in the event of floods and washouts because it has a more resilient structure when compared to unsealed roads. However, sealed road repair is more expensive and takes longer. The reason for this is that sealed roads provide significantly higher levels of service (for example, higher driving speeds) than unsealed roads. To satisfy these requirements for level of service, sealed roads must have significantly higher standards for construction than the standards for unsealed roads. Restoring or repairing roads to higher standards is more expensive and time consuming and means the communities may lose accessibility for significant periods of time. On the other hand, a local network of unsealed roads provides less for significantly lower maintenance costs. For these reasons, it remains likely that unsealed roads will continue to be serviced into the future.

4.2.2 Assessment of unsealed road conditions

In this section, the term "unsealed road" refers to road constructed with an imported compacted gravel layer. These roads are also known as "gravelled roads" and are designed and built to certain engineering principles to satisfy standards for alignment, drainage, etc. This project does not cover "dirt roads" that do not have imported high quality added gravel material, although some of these roads can have a reasonably well-defined cross section.

Unsealed roads are highly dynamic systems, particularly as they require more frequent maintenance when compared to sealed roads. In most cases an assessment of the condition of the unsealed road is made and then a decision regarding future maintenance action/s is made. During an assessment an observation of road characteristics is made using defined guides for unsealed road assessment. Examples of such guides are the South African rating system (Jones and Paige-Green 2000) and the United States army rating system (Department of the Army 1995). Australia does not have a common rating system and it is up to the assessor's judgement to define the assessment principles. However, unsealed road assessment is still determined by an evaluation of several key road characteristics. These include, but are not limited to, road profile, road drainage, corrugation, loose material, potholes, ruts, and erosion.

Predominantly, the deterioration of the road surface is caused by traffic and rain. According to Austroads report AGPT06-09 (Austroads 2009), examples for rain induced surface wear of unsealed road are:

- potholes formed from permeable surfaces and poor crossfall, allowing water to pond;
- lateral erosion on crossfalls;

- total loss of trafficability during floods, particularly fine grained surfaces (silts and clays); and
- surface gouging on soft surfaces during/after rainstorms.

4.2.3 Maintenance of unsealed roads

The two most common maintenance works for repairing unsealed roads are blading and re-gravelling. Blading (also known as grading) is smoothing of the surface by taking a thin top layer off the surface. Sometimes the blading involves collection of the loose material from the windrows and the spreading and compacting of it to the top of the road surface. Re-gravelling is the importation of additional gravel material to compensate for loss of material. The new material is compacted and the necessary thickness of the wearing surface is restored.

Blading and re-gravelling are different in terms of planning and cost. Blading can often be performed on demand and it does not require substantial finances. However, re-gravelling requires planning in terms of logistics and finance. Re-gravelling is fairly expensive and its accountability is essential in Local Government financial plans. Therefore, it is understandable that Local Government would like to have accurate timeframes for future re-gravelling works.

4.2.4 Models for unsealed roads

This aspect of the project aims to identify road deterioration models for use in the financial assessment for the re-gravelling and road blading of unsealed roads. The approach undertaken was to identify suitable models that are able to estimate the climate change impact on unsealed road maintenance routines. For re-gravelling (repair/works) the most important process that requires investigation is loss of gravel over time. To predict the frequency of road blading it is necessary to investigate how road roughness changes with time.

The mathematical modelling of gravel loss can assist significantly in the management of unsealed roads. In many cases, the re-sheeting of gravelled roads is performed when the subgrade shows through. This practice is considered poor, as it can lead to serious road damage including deep potholes and weakened road foundation and causes the road to become unsafe. A better way to manage unsealed roads is to have timely intervention, and action that can be determined by using a model to calculate gravel loss.

Models for gravel loss predict how much gravel material will be lost for given period of time. As input they require three types of parameters, those regarding: road traffic, climate at the site, and road design and materials used in construction. Five models for gravel loss are reviewed here.

Kenyan model

Jones (1984) developed model for gravelled loss that is based on observations in Kenya.

Equation 22: Kenyan model for unsealed road deterioration:

$$GLA = f\,(0.133(ADT)^2)/((0.133ADT^2 + 50)) \times (4.2 + 0.0336ADT + 504MMP^2 + 1.88VC)$$

Where:

- *GLA* is the annual gravel loss (mm/year)
- *ADT* is the average daily traffic in both directions (veh/day)
- *MMP* is the mean monthly precipitation (metres/month)

- *VC* is the gradient (%) for uniform road length
- *f* is the constant for various gravels (laterite: 1.3,quartzite:1.5, volcanic:0.96, coral:1.5, sandstone:1.4, calcretes: 2.0-4.5)

The strength of this model is that it considers the interaction between parameters for traffic, rainfall, road design, and gravel quality. The approach appears to be realistic for describing the unsealed road deterioration process.

Visser's model
Visser (1981) developed the following model for deterioration of unsealed roads.

Equation 23: Visser's model for unsealed road deterioration:

$$GL = D \cdot (1.58 + 0.366G + 0.083SV - 0.210PI + 0.0132NC + 0.0081NT + 420.45/R)$$

Where:

- *GL* is the gravel loss in mm
- *D* is the number of days since last blading in hundreds (days/100)
- *NC* is the average daily light vehicles in both directions
- *NT* is the average heavy vehicle traffic in both directions
- *G* is the absolute grade in percentage
- *SV* is the percentage of surface material passing the 0.074 mm sieve
- *PI* is the plasticity index of surfacing material (%)
- *R* is the radius of horizontal curve.

Visser's model requires very detailed and comprehensive input for road design and road materials but it does not require any climatic data. Therefore, the model is unsuitable for sensitivity analysis on climate variation. Furthermore, the model is developed by analysing data from areas with a sub-humid and humid climate. For this reason the model is considered inappropriate for southern Australia where the climate ranges from arid to temperate.

World Bank HDM models
Highway Development Management (HDM) models (HDM-III and HDM-4) were developed in a project funded by the World Bank. The project aimed to assist developing countries in their management of unsealed roads. Peterson (1987) describes the HDM-4 model as follows:

Equation 24: HDM model for unsealed road deterioration:

$$GLA = 12.63 + 0.898(MMP \times G) + 3.65(KT \times ADT))$$

Where:

- *GLA* is the predicted annual material loss (mm/year)
- *MMP* is the mean monthly precipitation (mm/month)
- *G* is the average longitudinal gradient of the road (%)
- *ADT* is the average daily traffic in both directions(veh/day)
- *KT* is the traffic-induced material whip-off coefficient

And:

$$KT = MAX\left(0, 0.022 + 0.969\left(\frac{KCV}{57300}\right) + 0.00342(MMP \times P075) - 0.0092(MMP \times PI) - 0.101(MMP)\right)$$

Where:

- *PI* is the Plasticity Index
- *KCV* is the average horizontal curvature of the road (deg/km)
- *P075* is the amount of material finer than the 0.075 mm sieve

This model takes into account rainfall data and so makes it possible to assess unsealed road deterioration sensitivity to rain. However, the formula engages model parameters in a complex (that is, discontinuous) functional relationship. Thus, the isolation of the effect of rainfall from the effects of the road geometry and materials characteristics would be challenging and subject to many uncertainties.

South African model

Paige-Green (1990) developed a model for gravel loss of unsealed road in South Africa. The model is as follows:

Equation 25: Paige-Green (South African) model for unsealed road deterioration:

$$GLA = 3.65(ADT(0.059 + 0.0027N - 0.0006P26) - 0.367N - 0.0014PF + 0.0474P26)$$

Where:

- *GLA* is the annual gravel loss (mm)
- *ADT* is the average daily traffic in both directions
- *N* is the Weinert N-value (a climate index value)
- *PF* is the plastic factor (plastic limit x per cent passing the 0.075 mm sieve)
- *P26* is the percentage of material passing through a 26.5 mm sieve

When the above model is used it is recommended that the particle size distribution be recalculated assuming that 100% was passing a 37.5 mm sieve and that the Weinert N-value (12 x evaporation in the hottest month (mm)/annual precipitation (mm)) be limited to a maximum value of 11 (Jones, Sadzik et al. 2001).

Paige-Green's model considers climate by using a climate index that is defined as the Weinert N-value. Different climates have different Weinert N-values. The model is capable of capturing the superimposed effect of climate and traffic due to the nonlinear relation between them in the model formula.

The South African climate (from dry arid to moist humid) is similar to southern Australian and this fact so strengthens the relevance of the model to this project. If the model is used to make calculations for gravel loss of southern Australian roads then the prediction will be within the data range used in model development. This ensures satisfactory confidence in model calculations.

Some disadvantages of applying the South African model to Southern Australia may arise from reliance in the model to the Weinert N-values. Australia does not have records for this South African climate index. The way Weinert N-value is calculated suggests that it should be not problematic to obtain its values for regions of interest across Australia. The data for historic monthly evaporation and rainfall, and their projections in the future is expected to be available and reliable. Further analysis is necessary to determine how appropriate it is to use Wienert N-values for representing the climate in Southern Australia.

4.2.5 Comparison of the Jones, Peterson and Paige-Green models

Three of the above reviewed models (Jones , Peterson, and Paige-Green) were compared in a 2009 Austroads study (2009), and the results from the comparison are shown in Table 3. The report notes that expert knowledge and historic observations suggest that gravel loss along the experimental roads is between 7 and 14 mm per year. It can be seen that the World Bank model provides calculations that significantly exceed the expected range of deterioration rates. The calculations from the other two models are within the expected deterioration range. The comparison confirmed that the Jones and Paige-Green models can be validly applied to Australian roads.

Table 3: Prediction for annual gravel loss by various gravel loss models (Jones 1984 – 1st column, Peterson 1987 – 2nd column, Paige-Green 1990 – 3rd column) (Source: Austroads 2009).

Location: Unsealed Road through Flinders Ranges, South Australia		
Predictive Model 1: TRRL	Predictive Model 2: HDM-III	Predictive Model 3: Paige-Green
Input Parameters:		
Material f = 1.4	PI = 20, P075 = 22	P26 = 95, P075 = 23, PL = 15, PF = 345
Traffic ADT = 92 vehicles per day	ADT = 92 vehicles per day	ADT = 92 vehicles per day
Rainfall MMP = 0.026 metres/month	MMP = 0.026 metres/month	N = 11
Alignment VC = 0	G = 0, KCV = 0, KT = 0.017	
Annual Gravel Loss		
G_{LA} = 10 mm	G_{LA} = 18 mm	G_{LA} = 11 mm

The study from Austroads (2006) “Asset management of unsealed roads” analyses the HDM-III and Paige-Green models and recommends “further research into climatic requirements such as an Australasian equivalent of the Weinert N-values developed in South Africa (possibly based on the Thornthwaite Index)”. The study also recommends the development of Australian models that suit Australian conditions. In response to these recommendations, an Australian model for gravel loss was developed by Giummarra (2007). The model is:

Equation 26: ARRB model for unsealed road deterioration:

$$GL = D \cdot (\alpha ADT + \beta MMP + \gamma PF)$$

Where:

- *GL* is the average gravel thickness loss (mm) across roadway
- *D* is the time period in hundreds of days (days/100)
- *ADT* is the average daily vehicular traffic in both directions, in vehicle/day
- *MMP* is the mean monthly precipitation, in mm/month
- *PF* is the plasticity factor
- *P075* is the amount of material passing the 0.075 mm sieve, in per cent by mass
- *PI* is the plasticity index
- *α, β, γ* are model coefficients

The coefficients *α, β, γ* are subject to a licensing agreement.

When the model was developed the objective was to infer specific coefficients for every state in Australia. However, the final results found insignificant differences across the coefficients for all the southern states of Australia and so led to the adoption of one set of coefficients for those states.

The Giummarra model was developed by using regression analysis on data that measured the deterioration of Australian unsealed roads. The mathematical representation of the model allows straightforward sensitivity analyses on climate variation. The required climate data, monthly rainfall, is available and reliable. Use of the model reveals that in southern Australia a 1 mm increase in mean monthly precipitation (MMP) would cause an additional gravel thickness loss which is equal to $\beta \cdot D$ mm, on average per year.

However, there are several concerns regarding the Giummarra model. First, the mathematical representation of the model states that the three prime factors for road deterioration, ADT, MMP, and PF, act independently - that is, there is no superimposed effect that is caused by their interaction. The report explaining the model development does not indicate that these interactions between factors were tested for significance during the regression analysis. If the Giummarra model is based on the assumption that the interaction between traffic, climate and construction materials does not have significant effect on unsealed road deterioration rate, then the model's outputs may be unrealistic. This concern is reinforced by the fact that the other models (the Jones and the Paige-Green model) consider interactions between factors. The second concern is that the regression r-square (r^2) value is equal to 0.091, a result that means that less than 10% of variation in gravel loss can be explained by the model. Users of the model should accept wide confidence intervals if they demand satisfactory significance levels for their analysis.

Roughness model for unsealed road deterioration
Several roughness models were also assessed:

First, Vesser's (1981) model for road roughness:

Equation 27: Vesser's model for unsealed road deterioration:

$$LDQ = D\begin{bmatrix} 0.4314 - 0.1705T_2 + 0.001159NC + 0.000895NT - \\ 0.000227NT \times G + S\begin{pmatrix} -0.1442 - 0.0198G + 0.00621SV - \\ 0.0142PI - 0.000617NC \end{pmatrix} \end{bmatrix}$$

Where :

- *LDQ* is the change in log (roughness) in QI – counts/km
- *D* is the number of days since last blading in hundreds (days/100)
- T_2 is the surface type factor (1 if surfacing is clay, 0 otherwise)
- *NC* is the average daily light vehicles in both directions
- *NT* is the average heavy vehicle traffic in both directions
- *G* is the absolute grade in percentage
- *S* is the seasonal factor (S=0 for dry season and 1 for wet season)
- *SV* is the percentage of surface material passing the 0.074 mm sieve
- *PI* is the plasticity index of surfacing material (%).

The model does not consider, in great detail, the climatic influence on gravel road deterioration. The input for climatic conditions is very limited – only one binary variable for either the wet or dry season, and so limits its applicability for sensitivity analysis on climate variation. Research has shown that the model performs relatively well for wet seasons but it has poor prediction power for dry seasons (Visser 1981).

Secondly, Giummarra's (2007) model for road roughness:

Equation 28: Giummarra's roughness model for unsealed road deterioration:

$$IRI_{TG2} = IRI_{MAX} - e^{\left[-0.001\left(F0 + F1 \times ADL + \frac{F2 \times ADT \times MMP}{1000}\right)\right](TG2 - TG1)} \times (IRI_{MAX} - IRI_{TG1})$$

Where:

- IRI_{TG1} is the roughness at time *TG1*, in m/km *IRI*
- IRI_{TG2} is the roughness at time *TG2*, in m/km *IRI*
- IRI_{MAX} is the maximum allowable roughness for specified material, m/km IRI
- *TG1, TG2* is the time elapsed since latest grading, in days
- *ADL* is the average daily light traffic (GVW < 3500kg) in both directions, in vehicle/day
- *ADT* is the average daily vehicular traffic in both directions, in vehicle/day
- *MM*P is the mean monthly precipitation, in mm/month
- *F0, F1* and *F2* are the model coefficients.

The coefficients *F1*, *F2* and *F3* are subject to licensing agreements. The coefficient value depends on location of the road and is State specific. This model could be used by Australian Local Governments for planning the blading frequency of unsealed roads.

4.2.6 Conclusions and recommendations

Unsealed roads will continue to have a vital role in local road networks, particularly in rural settings. Climate change will bring new challenges to unsealed road management because it will affect deterioration. The literature review reveals that unsealed road deterioration is a complex process that is primarily influenced by traffic, climate, road design, and construction materials. Thus, consideration of the temporal-spatial characteristics of the location of any section of unsealed road is an essential requirement for accurate prediction of unsealed road deterioration. Based on this, it could be argued that the linear additive models (such as Giummarra's model), might have a limited potential to describe the deterioration of unsealed roads.

The prediction of gravel loss is essential for Local Government financial planning. Several models could assist in the assessment of climate change on gravel loss. Although the South African (Paige-Green) model appeared to be a suitable option for the analysis in this project, it would have required further work to adjust the Wienert N-value climate index to the Australian climate. The Australian (Giummarra) model was considered superior in terms of its relevance to current Australian unsealed roads (that is, time and location of data collection) as it is based on the Paige-Green model that has the better predictive capacity.

5 MODELLING ISSUES AND APPROACHES IN CLIMATE CHANGE ADAPTATION PRACTICE

Once the climate of southern Australia and the likely future changes had been described, the assets of value to Local Government that are likely to be affected by climate changes identified and mathematical models to calculate the impact of changes in the climate to these assets examined, the following step in the project was to review the methods employed to model climate change impacts and determine an approach to be implemented in this study. This chapter reviews the approaches to modelling climate change impacts and financial modelling approaches in particular and also examines how uncertainties are dealt with.

5.1 General Approaches to Modelling the Impacts of Climate Change

Modelling the impacts of climate change, and the impacts of different adaptation strategies to it, presents significant technical problems. The size and variability of the climate systems (and the complexity of their data sets), the links between climate variables and engineering models, the cross-linkages between all factors, the existence of non-linear, threshold, and feedback effects at many levels and the collective implications of these factors for asset management present a high level of complexity to the modelling task. However, the foundations of applied mathematics and computing in the relevant disciplines — climate science, engineering, finance, economics and management science — and in the contemporary approach to modelling risk and uncertainty, provide useful and relevant tools for the modelling task of the current project.

Peter Larsen and his co-workers have conducted a number of studies to model the potential costs of climate change adaptation for infrastructure in Alaska (Larsen et.al. 2008; Larsen et al. 2011). This work attempted to derive a base replacement cost level for Alaskan infrastructure, and then to estimate the additional replacement cost that climate change could require. The studies used Global Climate Models (GCMs) to generate projections of future temperature and precipitation regimes (with a particular focus on permafrost) for 2030 and 2080. A wide range of infrastructure assets were examined, including harbours, schools, roads, airports, community buildings, hospitals, telecommunication and electrical systems, water and wastewater systems, and bridges. In the modelling undertaken the following steps were implemented:

- construct public infrastructure database;
- calculate Present Value (PV) of base case replacement costs of infrastructure, for 2030 and 2080;
- import high resolution climate projections (six regions, temperature and precipitation);
- import historical climate information (six regions, temperature and precipitation);
- produce probability distributions of projected climate by region;
- import infrastructure-climate depreciation matrix;
- repeatedly draw from distributions of projected climate (Monte-Carlo simulation) by region;
- adjust useful lifespan of infrastructure based on drawn climate combination using depreciation matrix and probability of extreme events;
- calculate PV of climate scenario replacement costs of infrastructure: 2030 and 2080;
- subtract PV of base case costs from PV of climate scenario costs; and
- output additional replacement costs due to climate change by community and infrastructure type with probabilities.

Simulation methodology was used to handle the probabilistic nature of many inputs. The additional costs due to climate change were then allocated to five risk categories and mapped across the state.

In a study by Maoh et al. (2007) the focus was on the linkages between regional transportation systems and the economy. A multi-regional input-output model was used to predict inter-regional trade flows by truck and rail among the 76 economic regions of Canada for 43 commodities. The impact of climate on the base pattern of trade flows was captured through reduction in travel speeds due to changes in the frequency of various weather events, such as extreme heat or cold and extreme precipitation as rain or snow. Again, the impact of probabilistic variables was handled with simulation modelling. The results indicated that the transport system performance degraded as measured by a significant overall increase in travel time in the system, as the frequency of severe weather events increased. Trade flows also appeared to be influenced by a change in weather conditions.

Simonovic and Li (2003) developed a methodology for assessing the impacts of climate change on a large-scale flood protection system in Manitoba, Canada. The assessment was conducted in three steps:

1. development of the climate change scenarios;
2. modelling of the hydrologic processes; and
3. development and application of the system performance assessment model.

In the first step, temperature and precipitation data were generated as input into the second step. The hydrologic modelling task generated river flows for assessing performance of the flood protection system in the third step (Simonovic and Li 2003, p.363). System dynamics modelling was used to capture watershed dynamics and flood protection performance factors. A schematic diagram of the modelling process and structure is given as follows in Figure 34 (Simonovic and Li 2003, p.367):

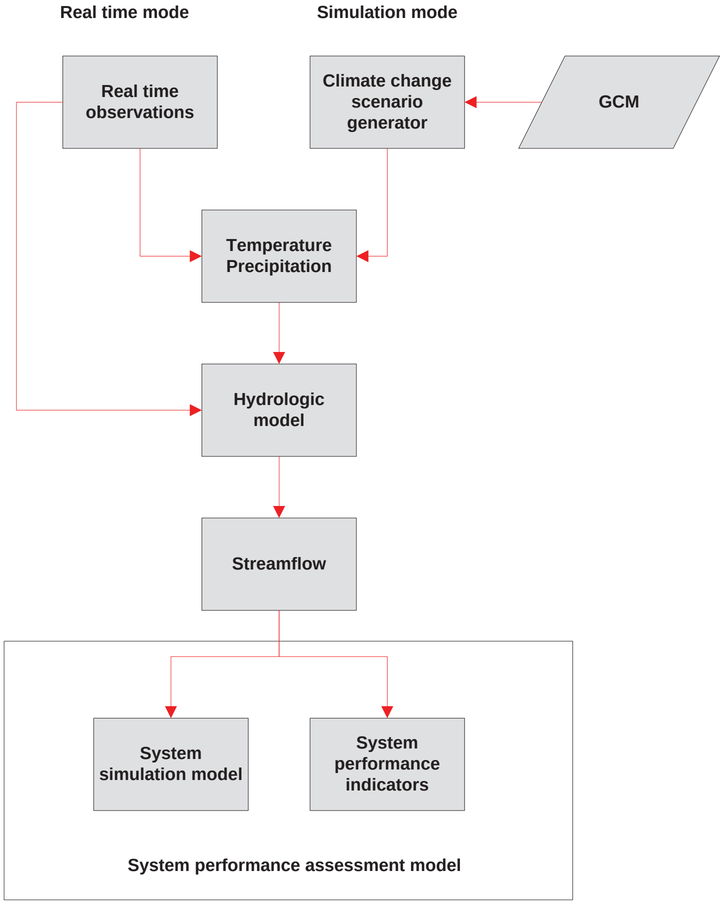


Figure 34: A methodology for assessing the impacts of climate change on a large-scale flood protection system in Manitoba, Canada (Source: Simonivic and Li 2003).

The authors note the challenges that are presented by the lack of fine-grained temporal and spatial resolution of GCM data:

> *The main weakness of the assessment methodology is in the use of GCM scenarios for the future climate. Proper assessment of the flood protection system requires detailed daily data that are not always available from GCMs. Spatial resolution of these data can also be a problem for smaller watersheds. (p. 369)*

As might be expected, the study concludes that:

> *Changes in temperature and precipitation under climate variation have serious impact on the hydrologic processes related to floods that are caused by snowmelt. Usual changes are observed in the shift of flood starting time and the magnitude of flood peak. Therefore, serious consequences may be expected in the ability of existing large-scale flood protection systems to serve their function.*

Stapelberg (2010) examined risk inter-linkages in multiple infrastructure systems. Such systems are defined as:

> *...interlinked infrastructure systems that are connected at multiple points through a wide variety of mechanisms, such that a bi-directional relationship exists between the states of any given pair of infrastructures.*

The complexity introduced by these relationships is emphasised:

Such bi-directional relationships (interdependencies) among infrastructure systems dramatically increase the overall complexity of multiple infrastructure systems.

With respect to climate change, the following infrastructure systems were assigned priority:

- built environment infrastructure and building codes;
- energy supply and distribution systems;
- water and wastewater management systems;
- transportation systems design and management;
- public works operations and management;
- public health care management services; and
- public safety and emergency preparedness.

For modelling climate change impacts on infrastructure, it was argued that a focus on individual asset classes was insufficient. Their relationships must be included in the modelling:

The key effects to model, and gain an understanding of, are the chains of influence that cross multiple infrastructure systems and induce potentially unforeseen effects. These chains, potentially composed of multiple interdependency types, constitute the physical connectivity paths between network nodes of infrastructure system components. The network paths represent cascading consequences of a risk event, or the derived dependency of one component from another.

Moreover, modelling must capture the non-linear and time-dependent behaviour of many of these systems, based both on empirical data, and on the hypothetical data associated with probabilistic behaviour.

In meeting this complex challenge, Stapelberg argues for the use of System Dynamics in the modelling process:

Considering the detail interrelationships of the critical infrastructure systems …and the integrated nodal framework of the critical infrastructure systems interdependencies... System Dynamics models of the interrelated nodes and their links can now be modelled taking into account the complexity of these relationships and impact scenario analysis of infrastructure risks induced by natural, technological and intentional hazards.

5.2 Handling Uncertainty

As all of the discussions on climate change so far reviewed have emphasised, uncertainty is a central reality of climate change projections, and a central technical challenge in modelling its impact on infrastructure assets. It is important to realise that in any climate change assessment such as this there is a cascade of uncertainties in the process. Our lack of perfect knowledge in understanding how the climate system works, how individual systems will respond to the impacts of climate change, how dependant systems will respond to primary changes, the level of future greenhouse gas mitigation, and the complexities of economic repercussions all contribute to the uncertainty when attempting to quantify climate change impacts.

5.2.1 Climate complexity and sensitivity

The first level of uncertainty is a result of our imperfect knowledge of the climate system. Projections of future changes in the climate are made by using global climate models that calculate changes in the big-picture aspects of the atmosphere using the laws of physics to describe the transfer of heat and moisture through the atmosphere for thousands of grids across the surface of the earth, vertically into the atmosphere and deep into the ocean (Figure 35). The models take into account changes in solar radiation from the sun, volcanic eruptions and changes in aerosols (including smog and clouds), natural climate variability (for example as a result of large climate cycles), ocean and atmospheric circulations and feedback from ice sheets, and have been tested for accuracy against historical data.

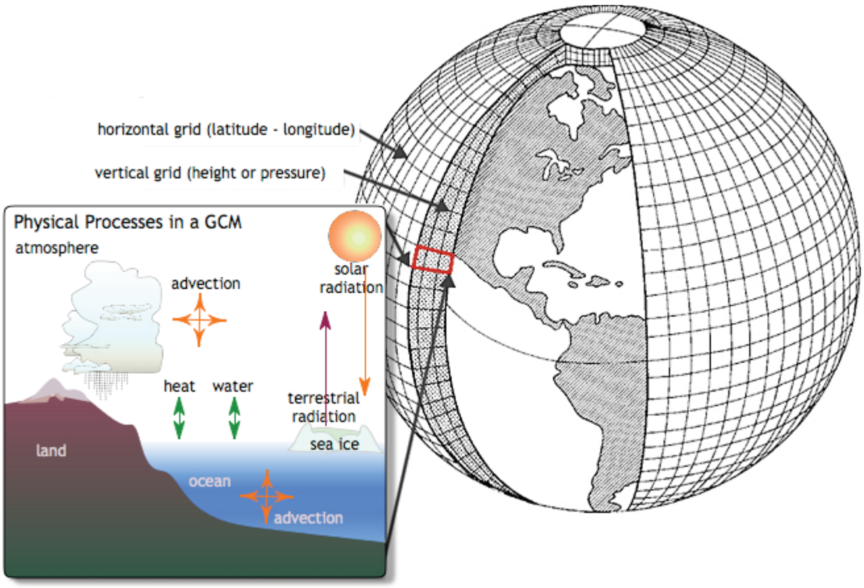


Figure 35: Schematic showing how global climate models work (Source: Centre for Multiscale Modelling of Atmospheric Processes 2011).

By changing some of the parameters in the models (e.g. the concentration of greenhouse gases in the atmosphere) outputs describe how the climate will change on the broad scale. As the models are not calculating the day-to-day weather, but instead the changes in the underlying trends of the climate, they do not estimate short-term changes but instead provide a projection of how the climate will change over decades. Only when greenhouse gas emissions from human activities are included in the models do they accurately calculate the changes that have been observed over the past century of historical records, a result that confirms that it is human released greenhouse gas emissions that are the cause of the changes we are now recording in the climate. Once climatologists know that the model is performing well on the basis of historical data, it can be run into the future to provide estimates of future climatic conditions.

However, as the climate projections are run further into the future, there will be uncertainties that will affect how accurate the projections will be. Uncertainties within the models include how much aerosols and clouds will influence future temperatures and how sensitive the climate is to additional greenhouse gasses. In 2007, the IPCC estimated that the global average temperature was likely to rise by approximately 3^{o}C in response to a doubling of greenhouse gases in the atmosphere – an estimate that has since been confirmed by more recent research. However, whether the temperature increase occurs as a smooth trend overlaid by the noise of climate variability, or in a non-linear more complex trajectory is as yet unknown (IPCC 2007).

5.2.2 Future greenhouse gas emissions

The second level of uncertainty is that we don’t know how many tonnes of greenhouse gases will be emitted by human activities in the future. For these reasons future projections of the climate are expressed as a range of different emissions scenarios. In the IPCC Forth Assessment Report (AR4) in 2007, climate projections made by global climate models were based on future emissions scenarios in the Special Report on Emissions Scenarios (SRES) used in previous assessments. For the upcoming IPCC Fifth Assessment Report (AR5), new emissions scenarios to be known as "Representative Concentration Pathways" will be used instead (Moss, Edmonds et al. 2010). The four pathways will represent the full range of greenhouse gas emission concentrations that may occur in the atmosphere by the year 2100 and will range from 450 ppm up to 1300 ppm CO_2 equivalents.

In addition to uncertainty about future emissions, it is also difficult to accurately quantify the size of future sinks. Carbon dioxide is sunk (or extracted) out of the atmosphere as a result of natural processes in the deep and shallow oceans, terrestrial systems such as forests and other components of the natural carbon cycle. Although we have a good estimate of how much of the greenhouse gases these natural sinks have absorbed already, it is difficult to accurately predict how quickly and how much they will be able to continue to extract from the atmosphere in the future.

5.2.3 Sensitivity of systems to climate stressors

Due to the complexity of the natural world and our social and economic systems that sit within it, there are gaps in our knowledge about the severity of future climate change impacts because we don't readily understand how sensitive things are to changes in the climate. Systems will respond not only to the magnitude of the climate changes but also the rate of change. In this study, the degree to which roads are impacted by changes in the climate is not well understood yet and although we have used the best available models for calculating climate change impacts on the useful life of road infrastructure the models introduce another level of uncertainty and error in their calculations. Generic models will rarely accurately predict changes at a particular site due to the myriad of additional factors in effect that are unique to the location. In the case of roads these factors will include the soil type, aspect, topography, construction method, traffic stresses, maintenance schedules and so on. Finally, the future adaptive capacity of humans and their economic systems introduce another level of uncertainty that may affect our capacity to manage the impacts of climate change into the future (although this is a dimension beyond the scope of this study).

There is, then, what is called a cascade of uncertainty when modelling the impacts of future climate change on a system that gets greater the more steps one is away from the observed of greenhouse gases in the atmosphere.

5.2.4 How to deal with uncertainty in modelling climate change impacts

As explained, uncertainties relating to climate change impact assessments and the identification of adaptation options will continue into the future and no doubt, what we thought we understood today we might not be so certain about in a number of years hence. However, the presence of uncertainty is no reason for inaction. In this study we have dealt with the layers of uncertainties by:

- understanding and explaining uncertainty in the analysis;
- explaining what assumptions we have made and the methods we have used to deal with the uncertainty so the process is transparent and comparable to other assessments;
- providing a level of confidence in the outcome on the basis of the amount of uncertainty;
- by considering more than one future climate scenario to ensure that we cover the range of uncertainty that may occur in the future as a result of both the climate and financial changes.

Stapelberg (2010) noted that as uncertainty increases modelling moves from deterministic models, to simulation, to scenarios and that scientific consensus decreases along that continuum: this could hardly have been more the case historically than it is with contemporary climate change studies. Nevertheless, it is clear that uncertainty must be handled appropriately if climate change adaptation proposals are to be developed with any degree of rigour. This report argues that the modern tools of probabilistic risk analysis can be effectively applied to produce rigorous and reliable projections, and accordingly coherent financial management responses. In this section we provide a background to this modelling task.

Heal and Kristrom (2002) analyse the uncertainty challenge in some detail, from the perspective of economics. They note three levels of analytic uncertainty: in the IPCCs scenario modelling; in the derivation of economic impacts; and in the development of the policies that implement climate change adaptation. The importance of path dependencies and learning, and consequently the importance of keeping options open, is emphasised. Non-linear functions, thresholds, and irreversibility are seen as endemic to the environmental systems that are responsible for producing climate change, and in responding to it. The authors point to the long-time horizons of climate change projections, and the uncertainty introduced by attitudes and values, and therefore discounting, over that time.

In developing estimates of climate change cost impacts under different scenarios, the following variables are central (p. 11):

1. *the probability distribution of the effects of climate change;*
2. *the degree to which we are risk averse;*
3. *the date at which the climate change will occur; and*
4. *the rate at which we discount future benefits and costs relative to those in the present.*

The discount rate is critical: elementary sensitivity analysis makes it clear that in all PV calculations it is the most influential parameter. Setting the discount rate is not primarily a technical matter, but a matter of policy and ethics:

> *The issue of the right discount rate is a controversial one: one of the founders of dynamics economics, Frank Ramsey declared in a paper that is still in many ways definitive that "discounting of future utilities is unethical, and arises purely from a weakness of the imagination." This implies a discount rate of zero, which in turn implies a willingness to spend from 15% to 30% of income to prevent global warming. Most contemporary commentators have implicitly disagreed with Ramsey, in many cases without clearly stating their reasons, and for the very long time horizons involved in climate change have worked with discount rates of 1% or 2%. (p. 14)*

The authors note the possibility of using logarithmic or hyperbolic discounting, under which discount rates are lower the further into the future are the flow of costs and benefits. It is argued that there is evidence that this is the way people behave in making long-range temporal decisions. It is noted that such an approach would lead to a significant increase in the amount that society should be willing to pay to avoid climate change.

The study reviews a number of modelling approaches that are modifications to the standard stochastic dynamic model of optimal growth. The growth output is produced from capital and labour inputs, with natural capital included in the capital stocks. Irreversibility is linked to the possibility of using Real Options Analysis (ROA):

...the preconditions necessary for the existence of an option value seem to be satisfied in the context of climate change. We expect to learn about the costs of climate change and about the costs of avoiding it over the next decades. We expect that some of the decisions that we could take will have consequences that are irreversible. These are the hallmarks of decisions that give rise to option values associated with conservation - the pioneering studies by Arrow and Fisher and by Henry have exactly these properties. (p. 24).

Approaches to modelling the precautionary principle are also investigated in the literature, as is the well-established modelling methods of non-linear dynamical systems. Patt et al. (2005) offer a critique of vulnerability assessment in climate change modelling from the perspective of cascading uncertainties. They distinguished climate change vulnerability assessment from standard natural hazard assessment on three dimensions of uncertainty—complexity, integration, and time:

Climate-change vulnerability is different, for three reasons. First, the complexity of the system is greater, in terms of requiring consideration of multiple triggering events, control variables, and forms of harm. Modelling the connections between these multiple factors may be exceedingly difficult. Second, there is no way to validate the integrative models, and test whether the various pieces of the system interact in the way that is proposed. Only the most basic statements can be made with confidence. Third, climate-change vulnerability assessment requires projecting possible states of a complex adaptive system far into the future, with enough accuracy to differentiate between the effectiveness of competing present policy options. (pp. 421-422)

The study reports the results an European Union (EU) funded modelling project, *The Advanced Terrestrial Ecosystem Analysis and Modelling (ATEAM)*, conducted from 2001-2004. The ATEAM modelling process proceeded in four stages:

1. Meeting with European stakeholders to determine what ecosystem services they considered most valuable;
2. Modelling of how these ecosystem services might change over time, as a result of climate change, changes in nitrogen deposition, land use change, and changes in other natural and socio-economic drivers, utilising IPPC SRES projections;
3. Integration of modelling results into a single mapping tool that allows a computer user to compare the exposure and sensitivity of particular ecosystem services, and the vulnerability of specific sectors across Europe at different times;
4. Stakeholder workshops to assess modelling results.

Stakeholders agreed that the impact assessment component of the vulnerability maps, in terms of examining changes in the potential production of ecosystem services, was useful, but found maps of vulnerability flawed: the vulnerability maps failed to capture the multi-dimensionality of the sectors specific to different regions. In addition, assumptions about adaptive capacity were not well-founded:

To speak of the anticipated impacts of global changes on their land is important, but translating this into useful information about their vulnerability requires making inappropriate assumptions about their lives and the sources of their livelihoods. (p. 420)

The authors conclude that reduction of uncertainty should be the primary justification for no-regrets modelling of climate change vulnerabilities:

"No-regrets options should be evaluated on their more certain payoffs, not simply because people believe they will generate significant future benefits through the reduction of vulnerability." (p. 422)

New and Hulme (2000) are among many authors who, as noted above, have taken a Monte-Carlo simulation approach to modelling climate change impacts and adaptations. They noted that in climate change modelling uncertainties cascade, from emission levels, through the carbon cycle, atmospheric concentrations, the climate system response, and regional climate change, to the impact unit (such as Local Government). The authors advocate the use of a Bayesian Monte-Carlo approach to handle these uncertainties, through the familiar three phases of modelling (Morgan and Henrion 1990; Goodwin and Wright 2004; Hassett and Stewart 2009):

(a) the definition of prior probabilities for the parameters of the model in question;
(b) multiple simulations of the outcome(s) of the model by randomly sampling the parameter space according to the pre-defined probability distributions; and
(c) the definition of the posterior probability (or frequency) distribution of the outcomes.

The modelling defined a multi-level model that sampled several greenhouse gas emissions scenarios, a range of climate sensitivities, and the results from fourteen international climate change simulations made using GCMs. Having defined a hierarchical probabilistic model to predict climate change in the 2080s over Scotland and Eastern England, a Monte-Carlo simulation of the model was run, with 50,000 iterations and using *apriori* probability distributions for different factors, as appropriate. The predicted outcomes for change in temperature and precipitation due to climate change at 2080 were analysed to produce a two-dimensional posterior probability histogram for each region, contoured by percentiles.

The authors note that further data is required to strengthen the validity of the model, including data about the rates of cycling, and sources and sinks, for CO_2 and other gases, and the conversion of atmospheric concentrations into global warming potentials. Moreover, data is lacking concerning low-probability, high-impact events ("extreme events", discussed below) in the climate system whose impacts may outweigh by some orders of magnitude the cumulative impact modelled in the simulations. However, the study seems to confirm that Monte-Carlo simulation represents a valid and useful approach to the quantification of uncertainty associated with regional climate change.

5.3 Extreme Events

As noted above, extreme events have the capacity to demolish the best-developed infrastructure asset management plans. However, because of their relatively low frequency and random distribution, relative to more stable, incremental changes of temperature and precipitation, they are more difficult to model.

Two studies may represent Australian approaches to modelling extreme events, one for flooding and the other for drought. The Inland Flooding Study undertaken by the Queensland Government, together with the Local Government Association, attempted to derive a percentage increase factor due to climate change for the intensity of precipitation in flooding projections (Department of Environment and Resource Management 2010). The study draws on the simulations of climate change scenarios with respect to mean precipitable water, column water vapour and global mean surface temperature under climate change (Schneider et al. 2010), and on Australian work (Rafter and Abbs 2009). It recommends an increase factor of 5% in rainfall intensity per degree of global warming. This factor is to be applied by Local Government to the state policy guideline governing flood events (Department of Local Government and Planning 2003) with the following temperature increases and planning horizons: 2°C by 2050, 3°C by 2070 and 4°C by 2100.

Hennessy et al. (2008) examined future patterns of drought under climate change. Importantly, the study noted that the definition of drought extends to physical, economic, and social domains: meteorological, hydrological, agricultural, and socio-economic droughts are recognised. The criteria for the current Exceptional Circumstances event is as follows (Department of Agriculture Fisheries and Forestry 2010):

1. *the event is rare and severe, occurring on average once in 20 to 25 years, and on a significant scale in terms of the area and proportion of farm businesses affected;*
2. *the event has resulted in a rare and severe down-turn in farm income over a prolonged period; and*
3. *the event was not predictable or part of a process of structural adjustment.*

The study attempted to determine whether, given the projections of temperature and precipitation under climate change, these criteria may need to be amended. It analysed changes in the areal extent and frequency of exceptionally high temperatures, low rainfall and low soil moisture for seven Australian regions from 1900 to 2040, using both observed and simulated data. In the study the historical data carried different levels of uncertainty: greatest reliability was with the temperature data, less with the rainfall data, and least with the soil moisture data.

The analysis showed that the areal extent and frequency of exceptionally hot years have been increasing rapidly over recent decades and that trend is expected to continue. By 2010-2040, the mean area is likely to increase to 60-80%. On average, exceptionally high temperatures are likely to occur every one to two years. If rainfall were the sole trigger for EC declarations, then the mean projections for 2010-2040 indicate that more declarations would be likely, and over larger areas. If soil moisture were the sole criterion for EC declarations, more declarations would be likely by 2030, particularly in the southern regions. The principal finding of this study is that the existing EC trigger is not adequate under the conditions of projected climate change.

The approaches to modelling extreme events in actuarial practice has been summarised by Sanders (2005). He noted that an extreme event model is highly dependent on its parameters:

> *Extreme event models are very dependent on the parameterisation. Parameters can be derived from observed data; but, if an extreme event has not occurred within those data; then modelling, and hence prediction, might be difficult. Unlike normal statistical analysis, where outliers are ignored, such data are precisely what drives the extreme process. Indeed, it is the 'normal' data which are ignored, as these may lead to miss-estimation of the key extreme event parameters. In a simulation type model, the key parameters may, themselves, vary stochastically. (p. 522)*

The extended time horizon characteristic of climate change parameters presents challenges to data completeness:

> *Prediction of events becomes difficult, because the data are incomplete. How can you predict the one-in-200 years' storm if you have less than 25 years' data? Pure statistical models can suffer in this respect, and pure reliance on such models can lead to misdiagnosis. Data may also need adjusting to reflect seasonality and other factors, such as changes in values of property. Ideally,*

any model needs to be a combination of statistical and physical considerations. (p. 523)

Modelling extreme events then focuses in analysing the behaviour of the distribution tails, rather than measures of central tendency, such as the mean. The Generalised Extreme Value (GEV) family of distributions operationalises this requirement (Hassett and Stewart 2009, pp. 232-239). These are cumulative distribution functions. One is the Weibull distribution (with a finite upper bound, indicating an absolute maximum). Another is the generalized Pareto distribution (often termed the '80-20' rule, as in wealth distribution, where 20% of the population may control 80% of the wealth). A third, not mentioned by Sanders but discussed by Hassett and Stewart (2009, pp. 126-132), is the Poisson distribution: this is the law of small numbers, that expresses the probability of a given number of events occurring in a fixed interval of time and/or space if these events occur with a known average rate and independently of the time since the last event.

Sanders described the basic modelling process for extreme events as following the diagnostic/ investigative/ predictive sequence. The diagnosis determines the appropriate distribution, and estimates the parameters. The investigative component will determine the selected model, and the predictive element will result in variations in rate projections (as in the Queensland inland flood study above), often employing a Monte Carlo simulation. Sanders accepted that modelling climate change impacts with this methodology is at the higher end of difficulty:

Certain extreme events are neither understood or predictable. Climate change is currently one example, with conflicting models and theories. Many systems are much too complex to model, and have implicit chaotic structures. (p. 554)

However, he continues to assert the importance of utilising probabilistic methods in enabling the development of better informed public policy:

It is clear that, in order that meaningful and constructive decisions can be made regarding extreme events, the types of process and the uncertainty need to be understood. Science, itself, is restricted to the development of predictions and generalisations, supported by quantitative data and formal deductive methods, and judged through a scientific peer review process. Actuarial science adds a further important layer, with the concept of uncertainty on the predictions, and placing a cost value on that uncertainty. (p. 555)

Zhang et al. (2004) provided experimental evidence, through a Monte Carlo simulation, for the advantage of using extreme-value theory and GEV distributions for analysing extreme climatic events:

Extreme values are scarce by definition, meaning that estimates are often required for levels of a process that are greater than have already been observed. This calls for a proper analysis of extremes. Our analysis demonstrates very clearly the advantage of using extreme- value theory in analyzing trends for extremes. There have been relatively few studies that have used extreme-value theory to model, detect, or project trends in extremes of weather and climate. (p. 1951)

5.4 Financial Risk Assessment Techniques

As outlined in earlier sections, Local Government managers in Australia are required to develop both strategic financial plans and infrastructure asset management plans that extend well into the future. This requires making physical and financial projections that must be as well-founded as possible. Managing uncertainty and risk is critical to such work. Courtney (2001) proposes a useful four-tier structure for assessing and managing strategic uncertainty:

Levels of uncertainty	Representative analytic tools
Level 1 A clear, single view of the future	Financial forecasting Discounted cash flow (DCF)/net present value (NPV) valuation models
Level 2 Alternate futures: A defined set of mutually exclusive and collectively exhaustive set of possible outcomes.	Decision or event trees Game theory Scenario planning Decision-tree Real Option Value (ROV) techniques.
Level 3 A range of futures: a representative set of outcomes within the range of possible outcomes.	Scenario planning Systems dynamics modelling Simulation ROV techniques based in option-pricing models Game theory
Level 4 True ambiguity: uncertainties are unknown and unknowable.	Foresighting Scenario development and analysis Analogy and reference cases Simulation

It is clear from the above discussion that climate change and adaptation uncertainties range across all four levels. It follows that all the analytic tools referenced here are likely to find places in developing projections of climate change impacts and in developing appropriate adaptation measures.

Finance theory and practice has developed a rich field of risk analysis and risk management techniques (Damodaran 2006) that are applied primarily to the first three levels of uncertainty cited above. Discounted Cash Flow (DCF) valuations can be subjected to standard sensitivity analysis by One-Way Data Sensitivity testing or by Tornado Charts (Powell and Baker 2009). A more sophisticated approach is through simulation. Strong et al. (2009) present approaches to financial risk management using Monte Carlo simulation:

> *Simulation enables us to obtain substantially more information than can be obtained from a small number of user-defined scenarios …where the input parameters (demand growth rate, initial annual demand, variable cost inflation rate, and initial fixed costs) are varied one-at-a-time with all other input parameters fixed. Using simulation, we may generate a large number of observations of the NPV and IRR metrics computed from a set of randomly generated scenarios in which all input parameters subject to uncertainty are simultaneously varied. We achieve this by defining appropriate probability distributions for those input parameters based on whatever information is available about those parameters. Then on each replication of the simulated project, we randomly sample new values of those input parameters from their corresponding distributions. (p. 110)*

Most of the tasks of modern financial analysis can be augmented by this approach, including the determination of Value-at-Risk (VAR). Strong notes the following advantages of the approach:

> *First, spreadsheet-based Monte Carlo simulation can provide the user with a powerful tool for implementing financial models to perform risk assessment in complex applications. Second, Monte Carlo simulation enables the user to do the following: (i) check the validity of the assumptions underlying a financial*

model; (ii) explore the sensitivity of the model results to the input parameters whose values are uncertain or are subject to random variation; and (iii) honestly represent the inherent variability of the final results. (p. 117)

As noted above, discount rates are critical to the outcomes of DCF valuations. Oxera (2011) investigates the probably evolution of discount rates in the context of low-carbon and renewable generation technologies, which are increasingly held to be central to climate change adaptation, particularly at the Local Government level (Passant and McLaren 2011, pp. 25-26). Analysing a number of high-level policy scenarios, the study concludes that the level of risk associated with technologies will decline over time, and will be reflected in the cost of equity, debt premium and gearing. It is estimated that the discount rate for these technologies could be up to as 2–3% lower over the next decade, and could fall by a further 1–2% by 2040.

As the Courtney uncertainty model summarised above points out, ROV models (Dixit and Pindyck 1994) can be valuable in handling risk at higher levels of uncertainty. Option pricing models can be applied to value intangible assets which have the potential to create cash flows in the future but do not produce them now. In this situation DCF models tend to understate the value of assets with option characteristics; that is, where there is a significant benefit obtained from learning and flexibility. Decisions about natural resource investment and development, for example have been widely handled through option valuations, since the decision to develop an undeveloped resource is closely related to the trajectory of the price of the resource over time (Damodaran 2006, pp.427-432).

Blyth et al. (2007) presented a model of decision-making under uncertainty, with respect to the investment decisions of a power generation company under the possible policy conditions responding to climate change. In the study climate change policy uncertainty was represented as a potential step-change shock, either positive or negative at some point in time, to carbon prices. The value to stakeholders of waiting for information on the sign and magnitude of this change in prices is calculated using ROV modelling techniques. The authors note that this modelling approach can be applied to a range of sources of risk, and can investigate the impact of different assumptions about the nature of climate change policy risks.

6 FINANCIAL MODELLING IN THIS PROJECT

On the basis of the review of assets of value to Local Government and the availability of both mathematical models and data to allow for a simulation of the impact of climate change on these asses and the project team made the decision to focus on road assets in developing its analysis and modelling. Specifically, the decision to select roads as the asset classes to focus on, was driven by the following criteria:

1. roads represent approximately 50% of the financial asset value handled by most Councils;
2. roads service levels are central to the community expectations of Local Government;
3. because of their importance to Local Government work, many Councils routinely gather detailed data, both physical and financial, on the repair, maintenance and rehabilitation of their road network. This potentially delivers clean historical data which can generate baseline conditions;
4. roads are core elements in Local Government asset management frameworks, such as the IPWEA NAMS.PLUS management system;
5. a significant engineering literature on road performance under different conditions is available; and
6. as noted in the literature review above, a number of international studies have identified the key risks to road service levels, in potential degradation of surface and foundation structures, and in potential impact of extreme events.

The scope of the project focused on developing an analytic and quantitative framework that links climatic and engineering data and analyses, to financial modelling, and ultimately to Local Government asset management frameworks and practice. In the judgement of the project team, road assets provide a clear path to the development of this linked analysis, across all four domains. Climate change impacts were examined, analysed and modelled for two types of road: sealed roads and unsealed road.

Sealed roads are found in two subcategories / asset classes and unsealed roads in one:

Asphalt Hotmix roads (AHR) are found in all Local Government areas, and represent almost all the road network in metropolitan Councils. The seal is a manufactured product made with much the same type of ingredients as concrete except bitumen is used to bind the mixture together instead of cement. A blend of aggregates (crushed rock), sands and fillers are passed through a heating drum to completely dry them and raise the temperature to around 160°C adding hot bitumen in the process. There are many types of mixes for various types of applications. The most commonly used mixes are 14 mm, 10 mm and 7 mm, where the measurement refers to the largest aggregate in the mix - 14 mm and 10 mm are typically used on roads. The thickness the hot mix is laid depends on the traffic loading it will be subjected to.

Spray sealed roads (SSR) are found predominantly in rural Local Government, although they also occur in urban fringe Councils. In this method, bitumen material of different types (conventional bitumen, multigrade bitumen, cutback bitumen, and bituminous emulsion) is sprayed on a prepared road surface. Spray seal is cheaper than surfacing in an asphaltic concrete pavement. Seals are constructed by evenly distributing a thin base of hot bitumen or bitumen emulsion onto an existing pavement and then embedding finely graded aggregate into it. The aggregate is evenly distributed over the chip seal, and then rolled into an even surface. Newer techniques use bitumen emulsion (a mixture of liquid bitumen, surfactant, and water) instead of hot sprayed pure bitumen.

Unsealed roads (USR) are found along a continuum of structure, from tracks, to clay/dirt roads, to constructed gravel roads, often laid with a binder or liquid dust suppressant. For the purposes of this study, unsealed roads were taken to be constructed gravel roads as these have the most significant financial impact on Local Government asset management; data on repair and maintenance, and on construction and rehabilitation is available; and degradation modelling can draw on a substantial body of work on these roads in the engineering literature.

6.1 Modelling Approach: Monte Carlo Simulation

Given the uncertainty of climate change projections, as explained in the previous chapter, a standard approach to value the impacts of climate change is to use a Monte Carlo simulation.

Monte Carlo simulation is a computerised mathematical technique that allows users to account for risk in quantitative analysis and decision making. Since its introduction in World War II, Monte Carlo simulation has been used by professionals in such widely disparate fields as finance, project management, energy, manufacturing, engineering, research and development, insurance, oil and gas, transportation and the environment. The methodology provides the decision-maker with a range of possible outcomes and the probabilities they will occur for any choice of action. It shows the extreme possibilities — the outcomes of going for broke and for the most conservative decision — along with all possible consequences for middle-of-the-road decisions.

Monte Carlo simulation performs risk analysis by building models of possible results by substituting a range of values — a *probability distribution* — for any factor that has inherent uncertainty. It then calculates results over and over, each time using a different set of random values from the probability functions. In this way, Monte Carlo simulation produces distributions of possible outcome values. There are many software packages available for Monte Carlo simulation. For this project, we used @Risk developed by Palisade Corporation.

In our model, we consider the three asset classes of roads described above (AHR, SSR and USR). Each road type has different mechanism of dependence on climate variables. As described in Chapter 4, the useful life of an asphalt/hotmix sealed road (AHR) is directly determined by temperature only. For a spray sealed road (SSR), it is dependent on the Thornthwaite Moisture Index (TI) which is dependent on both temperature and rainfall parameters. For an unsealed road (USR), the useful life of the road is dependent on the rainfall parameter only.

To illustrate our approach, let us use SSR as an example. The first step is to quantify the TI without climate change based on the historical data only (i.e. we assume that the future will repeat the past). To quantify TI with climate change, we access the projected change for temperature and rainfall at each location and then shift the historical distributions at a monthly scale for each climate parameter (temperature and rainfall). From these new climate change distributions we can calculate the distribution of TI for the terminal year (e.g. 2100). The distribution for each year in the time horizon is then obtained by interpolation using the TI values of the current and the terminal year. It should be noted that the model is designed in a way so that the fitted distribution for TI is automatically updated when a different Council location is selected. The fitted distributions for climate parameters are automatically updated for each simulation.

Given the simulated values of TI over the time horizon (e.g. 80 years), we can calculate the change in useful life over each year relative to the previous year based on the engineering formula identified. The calculation can then be translated into the change of annual cost via the equivalent annual cost (EAC) method. For example, let TC be the total cost of resurfacing, then equivalent annual cost can be calculated via the following annuity formula:

$$TC = \frac{EAC}{r}[1 - \frac{1}{(1+r)^T}]$$

where r is the discount rate and T denotes the useful life. Therefore, if the useful life changes from T1 to T2, then the EAC changes from EAC1 to EAC2 which satisfy the following relationship:

$$\frac{EAC2}{EAC1} = \frac{1 - \frac{1}{(1+r)^{T1}}}{1 - \frac{1}{(1+r)^{T2}}}$$

One important underlying assumption here is that the total cost of resurfacing over the time horizon remains constant in real terms over time. In this way, we can calculate the annual cost based on the previous year's cost. Hence, we can calculate the total cost over the time horizon by summing all the annual costs. The total costs with/without climate change can be calculated similarly. The difference between them is the dollar impact of climate change. By running the simulation repeatedly, we can then obtain a distribution of the cost impact of climate change.

Similarly, when we know the total cost over the 80-year period, we can calculate the equivalent annual cost figure EAC. On the other hand, the given annual resurfacing cost (RSC) and expected useful life (UL) can give us a total cost for each resurfacing. Combining the TC and EAC, we can calculate the useful life T from the above annuity formula. In this way, the average useful life with/ without climate change can then be obtained. Further, the climate change impact on the useful life can be determined and the distribution can be obtained.

6.2 Model Structure and Components

The formal structure of the financial modelling is displayed in the chart following. As shown, two categories of inputs into the financial model are required: inputs from climate scenarios, relating specifically to temperature and rainfall distributions across the modelling period; and engineering inputs, relating specifically to the three road types and the key parameters of their performance and useful lives over the modelling period.

The first level of simulation modelling provides distributions relating to the base case for Useful Life of ‘no climate change’ against ‘climate change’. In parallel, cost impacts with climate change are simulated for maintenance, resurfacing, and rehabilitation, as appropriate to the road network of the specific Council, utilising standard Net Present Value (NPV) calculations.

The financial model is thus comprised of the following elements:

- *Inputs and Outputs*: Inputs are provided by Councils, and the model then runs simulations to generate distributions of cost results.
- *Historical Climate Data*: The historical database for all relevant Councils is linked to the model for access by modelling software.
- *Thornthwaite Moisture Index and MMP*: These distributions are determined from the historical and predicted climate. These are used as inputs to the simulations.

- *Asphalt Hotmix sealed roads (AHR)*: The climate change impacts on asphalt hotmix sealed road performance are calculated by the model. The accumulated changes in useful life are also calculated.
- *Spray Seal Roads (SSR)*: The climate change impacts on spray sealed road performance are calculated. The accumulated changes in useful life are also calculated.
- *Unsealed road (USR)*: The climate change impacts on unsealed road performance are calculated. The accumulated changes in useful life are also calculated.

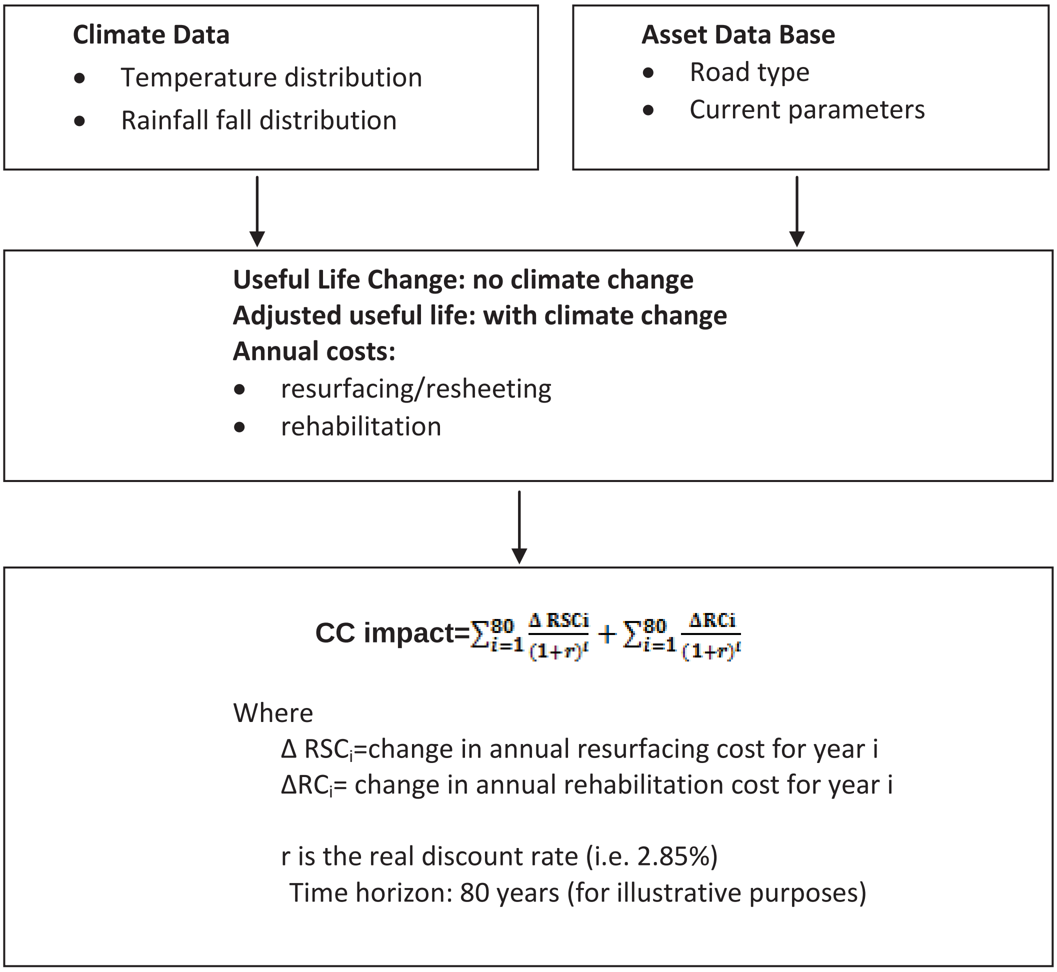


Figure 36: Structure and flow of the financial model developed.

6.3 Climate Data

The review of climate impacts on road assets identified the following climate variables for inclusion in the road deterioration and financial models:

Asphalt hotmix sealed roads (AHR):

Tmin: annual mean of the mean monthly minimum temperature

T: annual mean of the mean monthly temperature

Spray sealed roads (SSR):

TI: Thornthwaite Moisture Index – monthly mean minimum temperature and total monthly precipitation

Unsealed roads (USR):

MMP: mean monthly precipitation

A number of options were considered for integrating the required climate data into the models. Consultation with the technical panel, full stakeholder group and participating Councils determined a number of key requirements and constraints:

- it was beyond the scope of the project to develop new climate data sets and so an existing data set needed to be used;
- the model would need to have the capacity to calculate both historic baseline and future climate change projected road deterioration to provide estimates of a change in useful life or maintenance costs for road assets;
- the upcoming AR5 and future updates of the IPCC SRES emissions scenarios and resulting regional GCM climate projections mean that the model needed to be able to access future projections from an external source or would require climate projection data upgrades in the future;
- the selection of climate change scenarios and data for the model needed to be simple and publically accessible for use by IPWEA and Local Government operators;
- as described in Chapter 3, Councils generally make financial asset management plans on a whole of Council area basis and at an annual resolution. For these reasons, and because of computer data storage limitations, it was not necessary or user friendly for users to have to input climate data at a fine spatial or temporal resolution (e.g. latitude or longitudinal points for example).

On the basis of these constraints, the desire by the LGA SA and IPWEA that the approach would ensure the feasible longevity of the model, and discussions with the Bureau of Meteorology, the following approach was taken: High quality gridded baseline (historic) data sets averaged over the Local Government Area (LGA) were included in the model at a monthly resolution to generate baseline climate distributions for the variables required. The baseline distributions are then shifted mathematically within the model by the mean change as projected by a selected GCM output and scenario. In other words, the baseline data distributions that are used by GCMs as a comparative data set for their projections are shifted by the model by the average change projected for each variable.

There are both advantages and limitations to this approach. First, the historic baseline data set will not change and so does not need to be updated in the future regardless of change in IPCC scenarios or GCM projection outputs. In this way the requirements for maintaining the model into the future are minimal. Secondly there is no need to house the substantial GCM modelled output data for the nation in the model. Thirdly, users are not limited to a single set of GCM outputs but can select those at a spatial resolution and scenario that are appropriate to their needs and location. And finally, users can undertake sensitivity testing for various future temperature and rainfall scenarios without having to have access to GCM outputs or when modelling policy driven scenarios. The limitations are twofold: first, because climate changes will not be linear, calculations of climate impacts over long time periods (e.g. out to 2100) will over estimate early changes and underestimate later ones. Secondly, the shifted baseline climate variable distribution may not accurately represent the distribution that would have been generated by the GCM as not only the mean of the distribution will change but possibly also the shape of the distribution. Advice from the Bureau of Meteorology climate staff indicated that shifting the mean of a temperature distribution by the median projected value is unlikely to introduce significant errors, but that the shape of the rainfall distribution may change into the future and so not be accurately depicted by the shift in mean alone (Bertrand Timbal, Climate Forecasting Group, Bureau of Meteorology, Melbourne *pers. comm*. October 2011).

To minimise these errors, two modifications to the model were made. First, the user is able to select an end point for the projections of climate change impacts at a five-year resolution so that calculations can be undertaken for short through to long time frames. This option provides two benefits: first, the user is able to easily update the calculations in the future, and secondly, by selecting shorter steps for the projection of climate changes, the overestimation of near-term scenarios is removed and yet long-term scenarios can still be calculated if required.

To minimise errors introduced by shifting the rainfall distributions by a projected annual mean, changes to rainfall were made at the monthly scale prior to calculating annual values to take into account the uneven distribution of rainfall throughout the year. To do this, the projected change in rainfall is applied to the baseline distribution on the basis of monthly MMP adjustment factors unique to each month. The monthly factors are obtained from the projected mean figures for each month over the sample period and are then used to generate a climate change adjusted mean monthly precipitation distribution. For example, the monthly factors for Campbelltown (the Greater Adelaide area) are given in Figure 37.

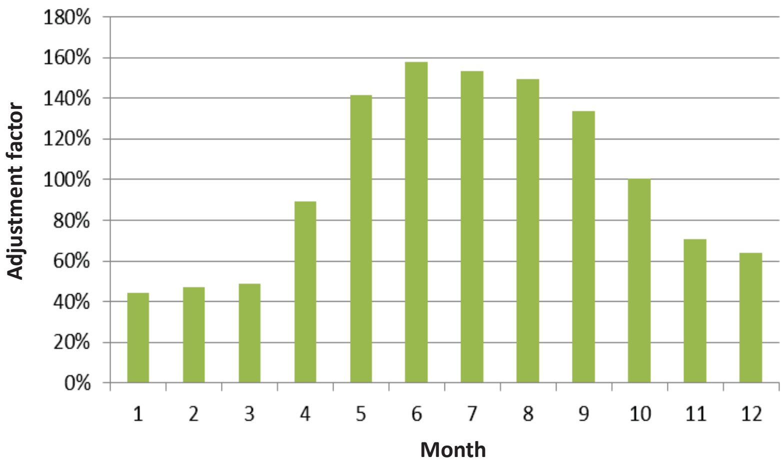


Figure 37: Example of the factors used in the road deterioration model for adjusting mean monthly precipitation for calculating changes in the distribution of annual precipitation as a result of climate change.

In the example, if the mean annual precipitation is projected to decrease by 6 mm, then the February median precipitation will be decreased by 2.82 mm, June will decrease by 9.48 mm, and so on. Factors for each LGA vary depending on the monthly distribution of rainfall throughout the year as calculated from the historical baseline data. The historical monthly baseline data were taken from the Bureau of Meteorology High Quality National Real Time Monitoring (RTM) gridded data set (previously known as the Australian Water Availability Project data set (AWAP)) at a 0.05^o x 0.05^o grid (~5 km by ~5 km) resolution (Jones, Wang et al. 2009).

The GIS boundaries of each of the ten case study Councils were sourced from the PSMA Australia Digital Administrative Boundaries Database and used to develop a mask in ArcInfo® (Figure 38). All data points on the 0.05^o x 0.05^o grid within the boundaries of the LGA mask were extracted from the RTM dataset and averaged to create an area-averaged timeseries for Ptm, Tmin and Tmax from 1911 to 2010 and entered into the road deterioration model (*pers. comm.* Alex Evans, Climatologist, Bureau of Meteorology Climate Group, Kent Town, Adelaide 2011). Calculations were then made by the model to generate monthly distributions for MMP and Tmean that were then used in conjunction with Ptm, Tmin and Tmax to calculate annual baseline distributions for each of the required variables. These historical baseline distributions are used by the financial model to simulate baseline annual costs for each road type (no climate change).

When deciding which future climate change projections to use, timelines are of critical importance. Compared to the normal year-to-year variability that occurs naturally across Australia as a result of various combinations of the climate patterns, the amount of warming and associated climate changes as a result of human induced climate change will be minor over the next decade. The range of warming out to about 2030 or 2040 will be mostly a result of the greenhouse gas emissions already in the atmosphere and so various future scenarios does not make much difference to these projections. Instead, the majority of the difference in projections will be a result of how sensitive the climate is to changes in future greenhouse gas emissions. For a doubling of carbon dioxide from 280 ppm (pre-industrial) to 560 ppm (mid to late century) the average temperature of the planet would be expected to rise by 1.7°C (low sensitivity), 2.6°C (moderate sensitivity) and 4.2°C (high sensitivity). Beyond the middle of the century the projections for future warming also include the uncertainties associated with the future emissions of greenhouse gases and how effective global agreements to reduce carbon dioxide emissions have been.

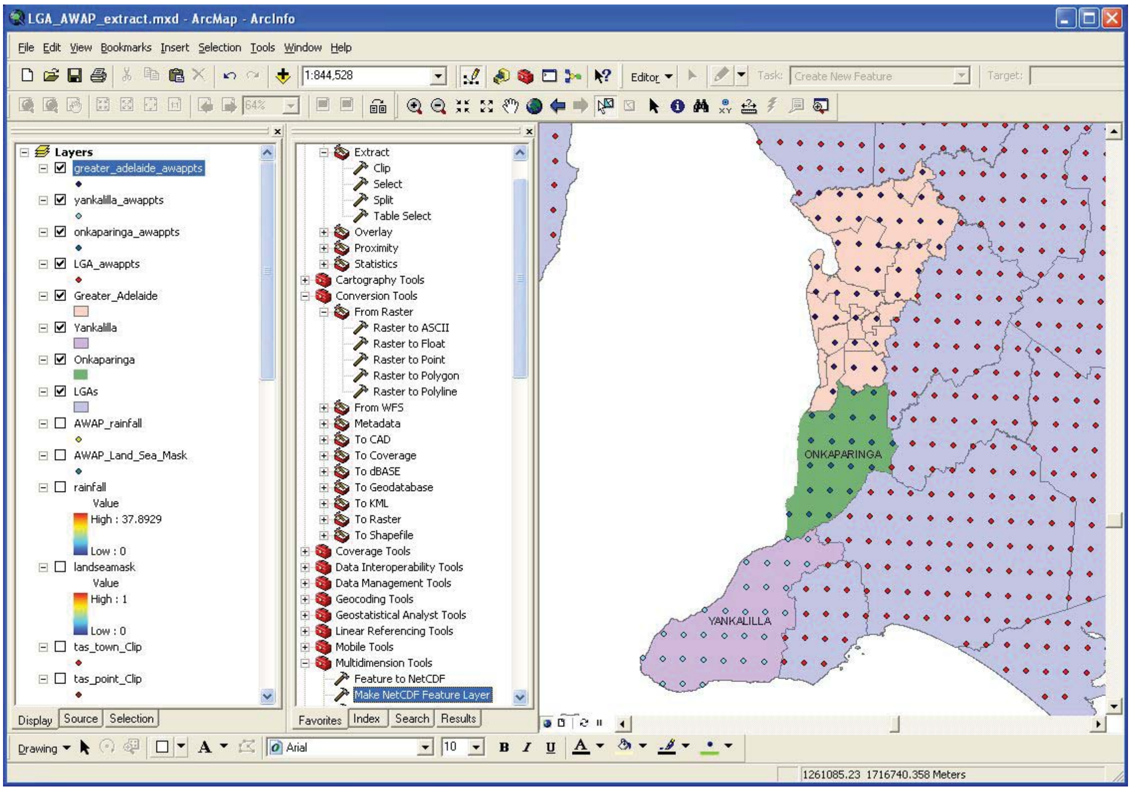


Figure 38: Example of the process developed in ArcInfo to mask Local Government Areas (Yankalilla, Onkaparinga) and regions (Greater Adelaide Region) and overlay the high quality AWAP 0.05o resolution gridded climate data set to extract area averaged baseline data for inclusion in the road degradation model.

As current increases in greenhouse gasses are within or higher than the worst case scenario predicted in the IPCC AR4, the high emissions scenarios as described by the IPCC SRES report were used for the long term projections in this study: “The A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: fossil-intensive (A1FI), non-fossil energy sources (A1T) or a balance across all sources (A1B) (where balanced is defined as not relying too heavily on one particular energy source, on the assumption that similar improvement rates apply to all energy supply and end use technologies)" (IPCC 2007). The A1FI and A1B scenarios do not differ greatly out to 2030 but by 2050 and further the A1FI scenario has the higher emissions and therefore greatest impact.

The model allows for the calculation of any future climate change scenario with the input of the projected change in the mean temperature and rainfall. To demonstrate the outputs of the model and provide an estimate of climate change impacts for each of the ten case study Councils, projections of the expected change in mean temperature and rainfall for the business as usual A1FI scenario in the years 2050 and 2100 as projected by the ECHAM model with a high climate sensitivity were extracted from the publically available OZCLIM (http://www.csiro.au/ozclim/home.do) climate change scenario generator developed by CSIRO (2007). This high emissions and high sensitivity emissions scenario was selected on purpose to represent a 'worst case scenario' for road deterioration in the financial model.

For each of the two scenarios (2050 and 2100), the projected change in annual temperature and rainfall under a A1FI SRES were recorded for each of the ten case study areas by reading the results from the maps produced (Figure 39 and Figure 40). The values for each location are summarised in Table 4.

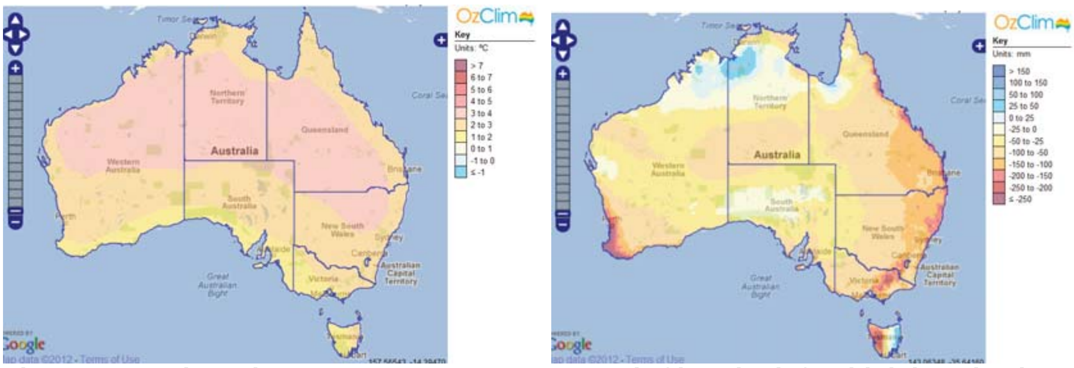


Figure 39: Projected annual average temperature (left) and rainfall (right) projections for a high emissions scenario (A1FI) and high regional warming (ECHAM model) for the year 2050.

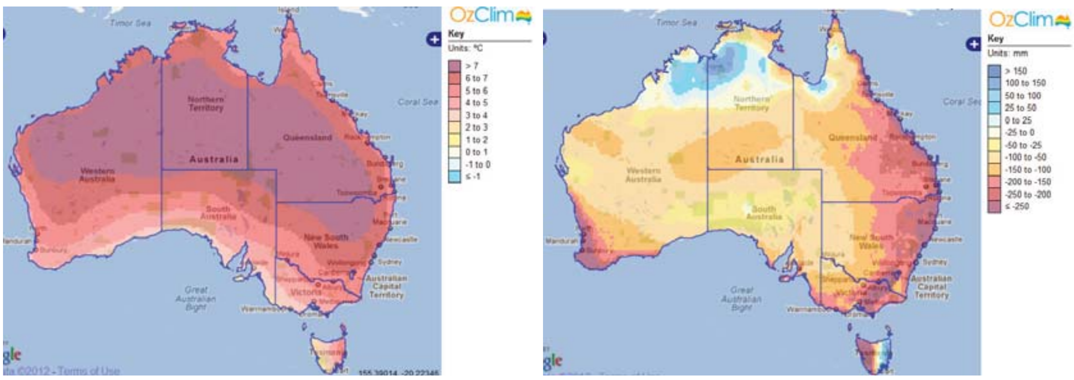


Figure 40: Projected annual average temperature (left) and rainfall (right) projections for a high emissions scenario (A1FI) and high regional warming (ECHAM model) for the year 2100.

Table 4: Projected changes in average annual temperature and annual total rainfall for each of the case study Council sites as determined from the CSIRO OZCLIM climate generator for the years 2050 and 2100. These values are entered into the financial model developed to run the trial results presented.

		2050				2100			
State	Case study area	Change in average annual Temperature (°C)	Mean change in average annual temperature (°C)	Change in total annual Rainfall (mm)	Mean change in total annual Rainfall (mm)	Change in average annual Temperature (°C)	Mean change in average annual temperature (°C)	Change in total annual Rainfall (mm)	Mean change in total annual Rainfall (mm)
WA	Esperance	1 to 2	1.5	-50 to -150	-100	3 to 5	4	-150 to -250	-200
SA	Tumby Bay	1 to 2	1.5	-50 to -100	-75	3 to 4	3.5	-50 to -150	-100
	Cambelltown	1 to 2	1.5	-50 to -100	-75	3 to 4	3.5	-150 to -200	-175
	Barossa	1 to 2	1.5	-50 to -100	-75	3 to 4	3.5	-100 to -150	-125
	Port Adelaide / Enfield	1 to 2	1.5	-50 to -100	-75	3 to 4	3.5	-150 to -200	-175
	Onkaparinga	1 to 2	1.5	-50 to -100	-75	3 to 4	3.5	-100 to -150	-125
	Wattle Range	1 to 2	1.5	-100 to -150	-125	2 to 3	2.5	-200 to -250	-225
VIC	Hume	1 to 2	1.5	-50 to -100	-75	4 to 5	4.5	-150 to -200	-175
	Bass Coast	1 to 2	1.5	-50 to -100	-75	4 to 5	4.5	-200 to -250	-225
TAS	Brighton	1 to 2	1.5	0 to +25	+12.5	4 to 5	4.5	+25 to +50	+75

6.4 Extreme Events Modelling

As noted in the literature review above, extreme events are well recognised, by both researchers and practitioners, as important for managing the impact of climate change on infrastructure. The use in the research literature of a number of probability distributions to model the behaviour of extreme was discussed. In this project, extreme event of most relevance is extreme rainfall, particularly when concentrated in a short time period. Flash flooding can wash away even sealed road segments and can have a devastating effect on unsealed roads.

Despite the material relevance of extreme events to the impacts of climate change on infrastructure, they present complex challenges to modelling in this case. As noted in the literature review, debate exists about the thresholds that define an extreme event and even if there were agreement, a climatological threshold (e.g. a one in 100 year event) is not necessarily an event that will cause damage to a road. Their typically short temporal periods and irregular occurrence makes them difficult to record, and in many cases it unlikely that they will have been captured in historical climatic datasets. Most locations do not have the ‘tipping bucket’ rainfall gauges necessary to detect events at the sub-daily time scale (usually only automatic stations and airports) and those that do are limited in the historical records of such events as the technology is relatively recent. In addition, precipitation linked to thunderstorm or frontal activity can be quite spatially localised even within a Council area.

The impacts of an extreme rainfall event when it does occur is also highly localised and linked to local geomorphology, hydrology, soils, infrastructure, permeability of the landscape and drainage patterns – factors that change at a variety of time scales from weeks to decades. As a result, even the same rainfall event in the same location may or may not generate damage to a road. Additionally, historical records of the costs associated with extreme rainfall events are not recorded in many instances and those that are sit in various databases around the country. For example, meetings with the State Disaster Resilience Fund in South Australia resulted in a spread sheet containing the name of the Council, date of the grant request, type of event, date of the event, non-adjusted amount requested and the amount provided. Supporting documents include the full request for funding from the Council. However, the applications must exceed a defined proportion of Council income and so applications from small Councils are of a lower value than those of large Councils and the data is available only from September 1992 to the present.

In projecting the likely future occurrence of an extreme event, the difficulties increase further. Because of the rare nature of extreme events, there are by definition very few recorded events and so in the climate data extreme events are at the extreme tail of the distribution. When modelling future climate projections, these tails in the distribution are not well estimated by the GCMs and there is currently little confidence in the accuracy of projections for an event that have never occurred in recorded history. For the next round of IPCC Fifth Assessment Report global climate models (CMIP 5 GCMs) there will be some models that will be run at the hourly and half hourly time step. However, they will be limited in number, will provide a small number of scenarios, and will not be available for a number of years yet. In addition, the output from these types of models is huge (60 petabytes) and would not be readily available to the public (Darren Ray, Senior Meteorologist, South Australian Climate Section, Bureau of Meteorology, Adelaide *pers. comm*. October 2011).

All these limitations make defining, recording, analysing and projecting the impacts of extreme weather events accurately in either the past or the future impossible. For these reasons, the project team was advised not to include extreme events in the formal simulation modelling. However, an input field to allow for the inclusion of an extreme events budget allocation is included in the spread sheet input page if the data is available at the LGA level. The team notes, however, that this is an important topic in the field, and presents an opportunity for critical future research.

It is also worth noting that extreme events are not usually included in the financial budget of Local Governments. Instead, money to cover damage from extreme events is sourced from extraordinary or contingency funds, existing projects that are postponed, disaster relief funding from the state and possibly federal governments in the case that the event was declared to be a disaster under the State Emergency Act. Alternatively the asset may be left unrepaired if considered to be a low priority and repaired at a later stage.

In addition, it was agreed by the stakeholder group that extreme events only affect a small proportion of the total asset (e.g. 1 or 2 km of a 500 km road) and are by nature infrequent in occurrence. Also, that future changes in design specifications will take in to account the increased frequency of extreme rainfall events and so will reduce the exposure to the risk over time.

6.5 Engineering Foundation and Financial Modelling for Asphalt Hotmix Sealed Roads (AHR)

Asphalt / Hotmix sealed roads (AHR) account for over 70% of the roads in city Councils. The engineering analysis of these roads is based on:

1. a bitumen binder hardening model that was developed from 257 samples across Australia; and
2. a distress viscosity model that used 35 of the 257 bitumen samples where surface cracking was visually identified to range from 1% to 50% of the lane area.

When these models were equated, the following model was developed for predicting the life, Y (years), of asphalt surfacing (Choi 2009):

$$Y = \left(0.323T_{\min} - 0.169T - 0.848\sqrt{A_v} + 5.217\right)^2$$

Where:
A_v = air voids of the asphalt surfacing at the time of sampling (usually 4 - 6%) and all other terms are as defined above.

All the independent variables in this equation were statistically significant (Student 't' $p < 0.05$). The equation does not include a risk factor, R, to allow for the different traffic levels and climatic impacts, apart from temperature, at each site. The equation is also not recommended for use where the asphalt thickness is greater than 40 mm.

To assess the climate change impact, we considered three types of costs each year:

- the normal maintenance costs (MC);
- resurfacing costs (RSC);
- rehabilitation costs (RC).

In calculating the climate change impact, we proceeded in the financial model as follows:

1. simulate the mean temperature variables T and Tmin;
2. calculate the life of the BSR for each year based on the above formula and the percentage change of useful life (UL) relative to the previous year can be obtained;
3. calculate the resurfacing cost (RSC) and rehabilitation costs (RC) based on the percentage change as the UL via an annuity amortization procedure;
4. sum the PV of future costs for each scenario (no climate change/with climate change). The difference between the two PV's is taken as the impact of climate change; and
5. after running a simulation, we obtain a distribution of the climate change impact.

The MC is assumed to be constant in real terms with or without climate change. Whether the MC changes due to climate change is left as an input choice for the Councils. We believe that the change is not likely to be significant, thus the default growth rate is set as 0. In summary, the input requirements for AHR are as shown in Table 5.

Table 5: Inputs to the financial model for Asphalt Hotmix Sealed Roads (AHR).

Maintenance Cost-normal (MC)	Current annual cost
Resurfacing cost (RSC)	Current annual cost
Resurfacing Life (RSL)-in years	Expected life
Rehabilitation cost (RC)	Current annual cost
Rehabilitation Life(RL) in years	Expected life

6.6 Engineering Foundation and Financial Modelling for Sprayed-Sealed Roads (SSR)

Sprayed-sealed roads (SSR) are found mostly in rural Councils. Clearly they are cheaper and easier to construct compared to the bitumen sealed roads. As explained in the engineering section of this report for these roads, the climate change impact for SSR is included in the model by calculating the Thornthwaite Moisture Index (TI) – a function of monthly rainfall and mean monthly temperature:

$$TI \approx 1.25P_e - 60$$

The relative performance of the road service is then given by the following equations that include defined relative performance factors (rpfs):

$$rpf_{miri}\, unckdss\left(\frac{TI}{d}\right) = 1.073 + (0.00147TI)$$

$$\Delta d_i(TI_i) = \frac{rpf_m\, unckdss\left(\frac{TI_i}{d}\right) \times \Delta d}{rpf_m\, unckdss\left(\frac{TI_i}{d}\right)}$$

To assess the climate change impact, we consider three types of costs each year: the normal maintenance costs (MC); resurfacing costs (RSC); and rehabilitation costs (RC), which are essentially reconstruction costs.

In calculating the climate change impact, we proceed in the financial model as follows:

1. simulate the variable TI based on historical data;
2. calculate rpf for each year based on the above formula;
3. obtain the percentage change of rpf relative to the previous year;
4. the deterioration formula reveals that an increase in rpf would lead to some decrease in the useful life and vice versa. Thus, a key assumption here is that the increase rate in rpf means the same rate of decrease in UL and vice versa;
5. the change in UL determines the change in annual resurfacing cost (RSC) and rehabilitation costs (RC) via an annuity amortization procedure;
6. sum the total PV of future costs for each scenario (climate change/no climate change). The difference between the two PV's is taken as the impact of climate change; and
7. after running a simulation, we obtain a distribution of the climate change impact.

MC is handled as above for AHR. In summary, the input requirements for spray sealed roads are as shown in Table 6.

Table 6: Inputs to the financial model for Spray sealed Roads (SSR).

Maintenance Cost-normal (MC)	Current annual cost
Resurfacing cost (RSC)	Current annual cost
Resurfacing Life (RSL)-in years	Expected life
Rehabilitation cost (RC)	Current annual cost
Rehabilitation Life(RL) in years	Expected life

6.7 Engineering Foundation and Financial Modelling for Unsealed Roads

Unsealed roads (USR) are mostly located in rural Councils. As explained in the engineering section of this report, for these roads the key climate change-related factor is the mean monthly precipitation (MMP), which can be used to predict gravel loss as described in the following.
We utililse the ARRB model for unsealed road deterioration:

$$GL = D \cdot (\alpha ADT + \beta MMP + \gamma PF)$$

Where:

- *GL* is the average gravel thickness loss (mm) across roadway
- *D* is the time period in hundreds of days (days/100)
- *ADT* is the average daily vehicular traffic in both directions, in vehicle/day
- *MMP* is the mean monthly precipitation, in mm/month
- *PF* is the plasticity factor $(PI \cdot P075)$
- *P075* is the amount of material passing the 0.075 mm sieve, in per cent by mass
- *PI* is the plasticity index
- *α, β, γ* are model coefficients

To assess the climate change impact, the principal cost of relevance is the annual re-sheeting cost (RSC). Changes in other costs due to climate change are assumed to be insignificant.

The only relevant climate factor is the precipitation MMP, which is simulated on historical data. In calculating the climate change impact, we proceed in the financial model as follows:

1. calculate change of average gravel thickness loss (GL) relative to the previous year for each year based on the above formula;
2. obtain the percentage change of GL relative to the previous year;
3. assume that the useful life (UL) will have the same percentage change as the GL;
4. calculate the new annual RSC;
5. sum the PV of future RSC costs for each scenario (no climate change/with climate change). The difference between the two PV's is taken as the impact of climate change; and
6. after running a simulation, we obtain a distribution of the climate change impact.

MC is handled as above. In summary, the input table for unsealed roads is as shown in Table 7.

Table 7: Inputs to the financial model for Unsealed Roads (USR).

Maintenance Cost-normal (MC)	Current annual cost
Resheeting cost (RSC)	Current annual cost
Resheeting Life (RSL)-years	Expected resheeting interval
Current Gravel Loss	Current annual figure

7 COUNCIL TESTING OF FINANCIAL MODEL AND INPUT TOOL

We conducted pilot field studies of the financial model and user input tool with the following Councils:

South Australia	Victoria	Western Australia	Tasmania
Barossa Campbelltown Port Adelaide / Enfield Onkaparinga	Bass Coast Hume	Esperance	Brighton

Two other South Australian Councils, Tumby Bay and Wattle Range, were also involved in the study but indicated that they did not have the data in the form required to support the modelling work.

Data was obtained from Councils through both site meetings, teleconferencing and electronic communication. It is noted that there were significant differences between Councils on data availability and accuracy, due in part from different types, stages and implementations of asset management systems. The modelling results for each Council are presented below.

7.1 Key to Council Results Charts

Results of the modelling for each Council are in two parts:

1. *Fitted climate parameter distributions:*
   - TI: Thornthwaite Moisture Index
   - MMP: mean monthly precipitation
   - Tmin: yearly mean of the monthly mean minimum temperature
   - T: yearly mean of the monthly mean temperature

The methodology for developing these historical distributions is described in Section 12.3. The distributions for each climate parameter are displayed as the first part of each Council report. In addition, the fitted distribution generated by @RISK is also displayed; this is a best-fit function, and generates a range of probability distributions, such as Normal, Lognormal, Gamma, Weibull, Triangular, and so on. The Minimum, Maximum, Mean and Standard Deviation for each distribution are also displayed.

2. *Output of the model for the three road types*:

As described in Sections 12.5, 12.6 and 12.7 the engineering inputs for Asphalt Hotmix Roads (AHR), Spray Seal Roads (SSR), and Unsealed Roads (USR), along with the climate change inputs, were entered into the model to generate estimates of the impact of climate change on these roads. The results display two kinds of impact, the first on Useful Life (UL) and the second on Costs. Two scenarios were modelled, 2050 and 2100. The results of simulations are labelled accordingly: thus “USR-CC impact in %/Costs” means “Unsealed Road Climate Change impact in percentage Costs”; “USR-CC impact in %/UL-RS” means “Unsealed Road Climate change impact in percentage Useful Life, Resurfacing”; “AHR-CC impact in %/UL-RH” means “Asphalt Hotmix impact in percentage Useful Life, Rehabilitation”, and so on, self-evidently.

All simulations are run with 5000 iterations. As all the simulation results become stable after about 2000 iterations there is no need for a higher number of iterations to be done.

The results display the distributions resulting from the simulations, and give values for the maximum, minimum, mean and standard deviation of each distribution. The climate parameter distributions are the historical climate variable distributions. The graphs that have been adjusted to include climate change are similar but are not presented here due to space limitations. The fitted climate parameter distributions graphs show the values of each fitted probability density function on the vertical axis (not the frequency numbers).

For completeness, the results of all simulations are displayed here. A summary of the key modelling outputs is given in the next section (Tables 8 and 9), together with concluding comments. It will be noted that, because of the different road configuration for different Councils, and different levels of data availability, outputs on all three road types are not available for every Council. For example, for the Barossa Council, predominantly rural, outputs are displayed only for unsealed roads. In aggregate, however, the pilot studies provided robust outputs across all three road types, for urban, peri-urban and rural Councils, as the summary table indicates.

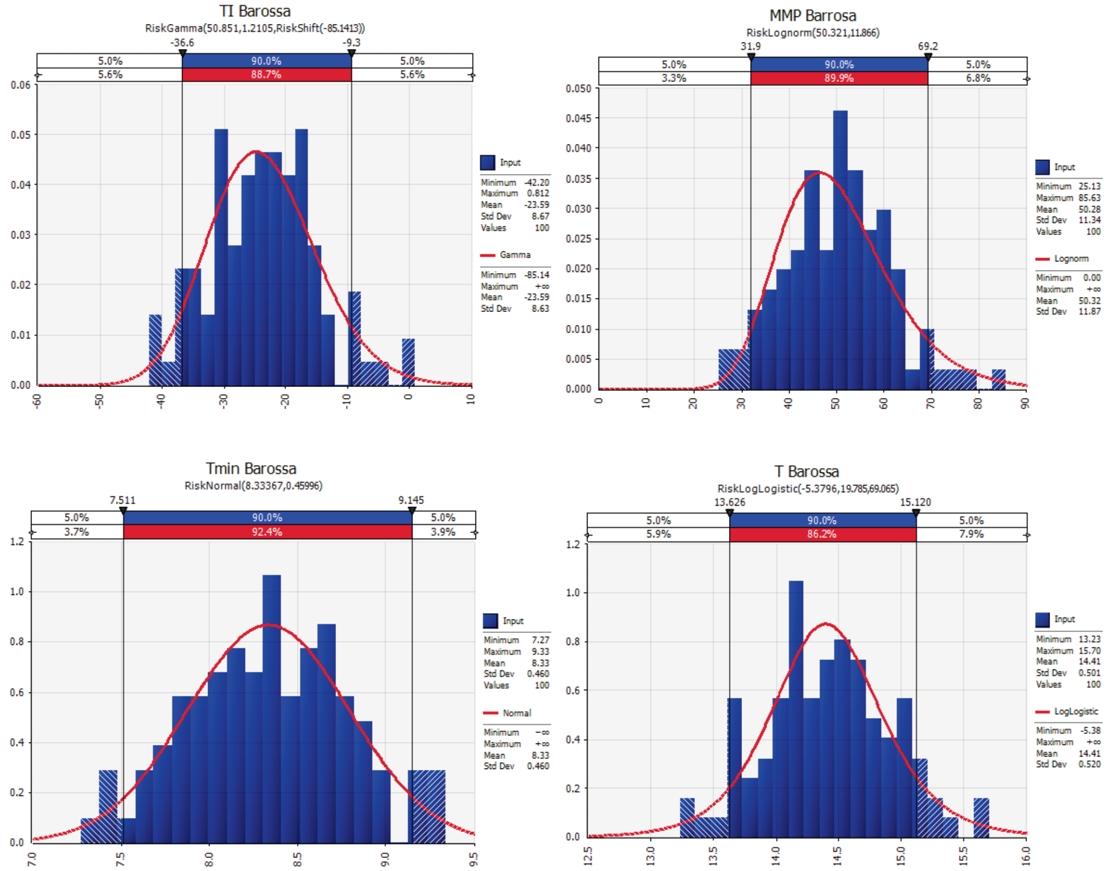
7.2 The Barossa Council

The Barossa Council area takes in the major towns of Mount Pleasant, Angaston, Nuriootpa, Tanunda, Lyndoch and Williamstown. The Council's principal office is located in Nuriootpa, 70 kilometres north-east of the Adelaide Central Business District. The Council area covers 912 square kilometres. Estimated population as at 30 June 2007 was about 22,000.

The Barossa region has a typical Mediterranean climate with dry summers and mild winters. Major industries include wine making, grape and grain growing, spirit distillation, dried fruit processing and packing. Tourism associated with the wine region is a major industry. The Barossa Council has detailed records for its road networks, and a sophisticated framework of analysis. In particular, as a rural Council, it has a substantial network of unsealed roads, unique in this respect among the pilot Councils. In the pilot field work with the Barossa Council we therefore focused on unsealed roads.

7.2.1 Fitted climate parameter distributions: temperature and precipitation: TI, MMP, T and Tmin: Barossa Council

Here we show four historical climate distributions for the Barossa Council: (Top left) the Thornwaite Index (TI); (Top right) mean monthly precipitation (MMP); (Bottom left) minimum temperature (Tmin); and (Bottom right) temperature (T). The displayed graphs are the historical distributions - that is, without climate change. The graphs that have been adjusted to include climate change are similar but are not presented here due to space limitations.

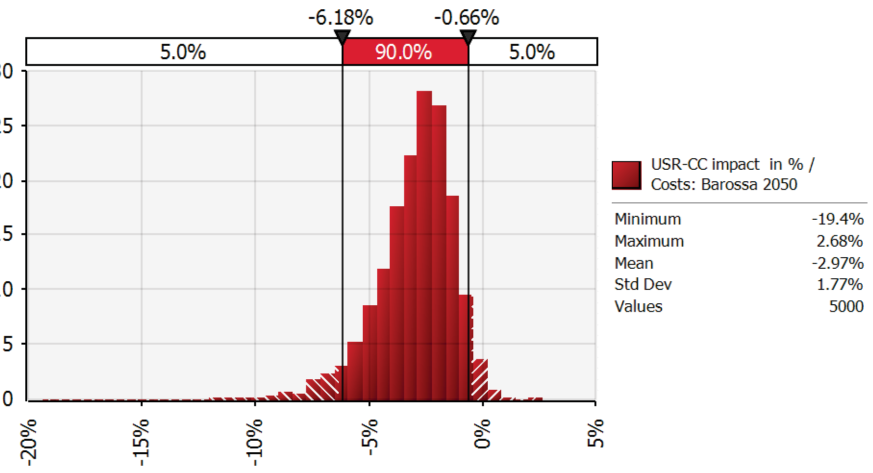


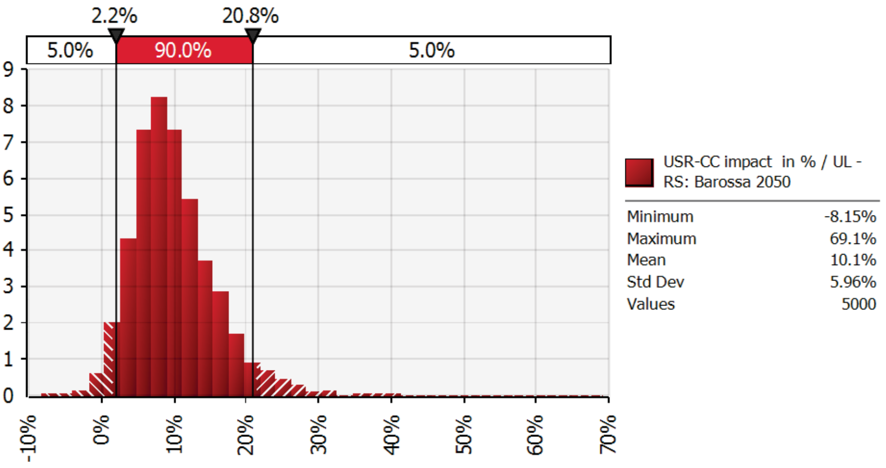
Note: For each graph, the vertical axis represents the fitted probability density function and the horizontal axis represents the values of the climate variable, with the statistics in the legend on the right hand side.

7.2.2 Barossa Council Output: Unsealed Roads (USR)

The results are based on a simulation with 5000 iterations. With the inputs derived from the climate data provided, the following simulations were performed. Roads with extreme annual gravel loss (<3 mm thickness) were eliminated from the analysis as these roads are likely to be low in use and not appropriately maintained. Two climate change scenarios were modelled for the A1FI SRES emissions scenario: 2050, and 2100. The percentage of climate change impacts on costs and on useful life over those periods was calculated. As noted, the Barossa Council area has a high proportion of unsealed roads and modelling of these roads could be supported by sufficient data. The modelling results shown therefore focus on unsealed roads. Results of the scenarios explored were as follows:

Barossa Council USR 2050 Scenario





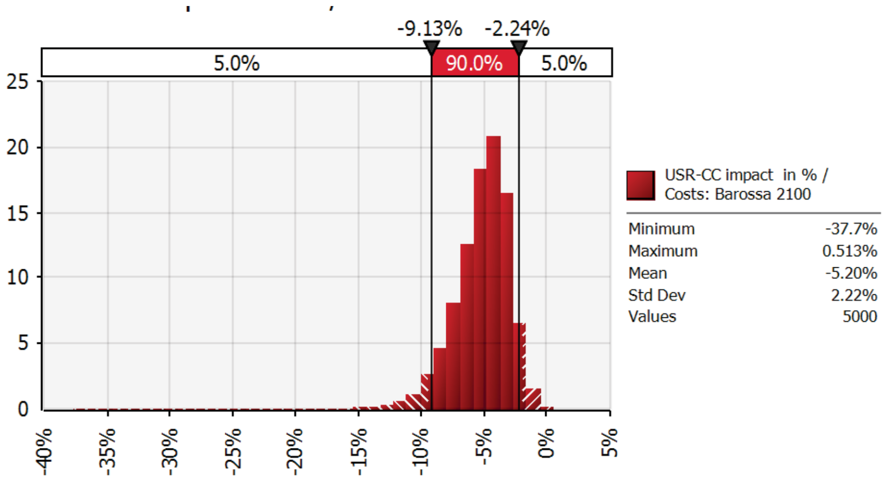
Note: The top graph shows the impact of climate change in costs (% change) and the lower graphs shows the impact of climate change in UL (% change). In both graphs the vertical axis represents frequency, and the horizontal axis represents the values of climate change impact with the statistics in the legend on the right hand side.

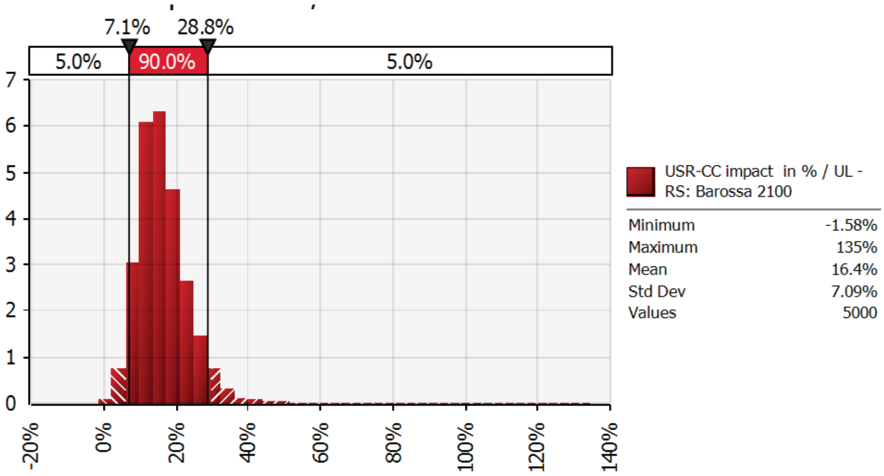
Comments:

These graphs show the following for unsealed roads for Barossa Council:

- the impact of climate change on costs is expected to be 2.97% reduction over the period to 2050; and
- the impact of climate change on useful life is expected to be 10.1% increase over the period to 2050.

Barossa Council USR 2100 Scenario
The results increase in the 2100 scenario:





Note: The top graph shows the impact of climate change in costs (% change) and the lower graphs shows the impact of climate change in UL (% change). In both graphs the vertical axis represents frequency, and the horizontal axis represents the values of climate change impact with the statistics in the legend on the right hand side.

Comments:
These graphs show the following for unsealed roads for Barossa Council:

- the impact of climate change on costs shows a mean percentage reduction of 5.20%; and
- the impact of climate change on useful life shows a mean percentage increase of 16.40%.

It will be noted from the summary of results that these are at the high end for the Councils sampled.

7.3 Campbelltown City Council

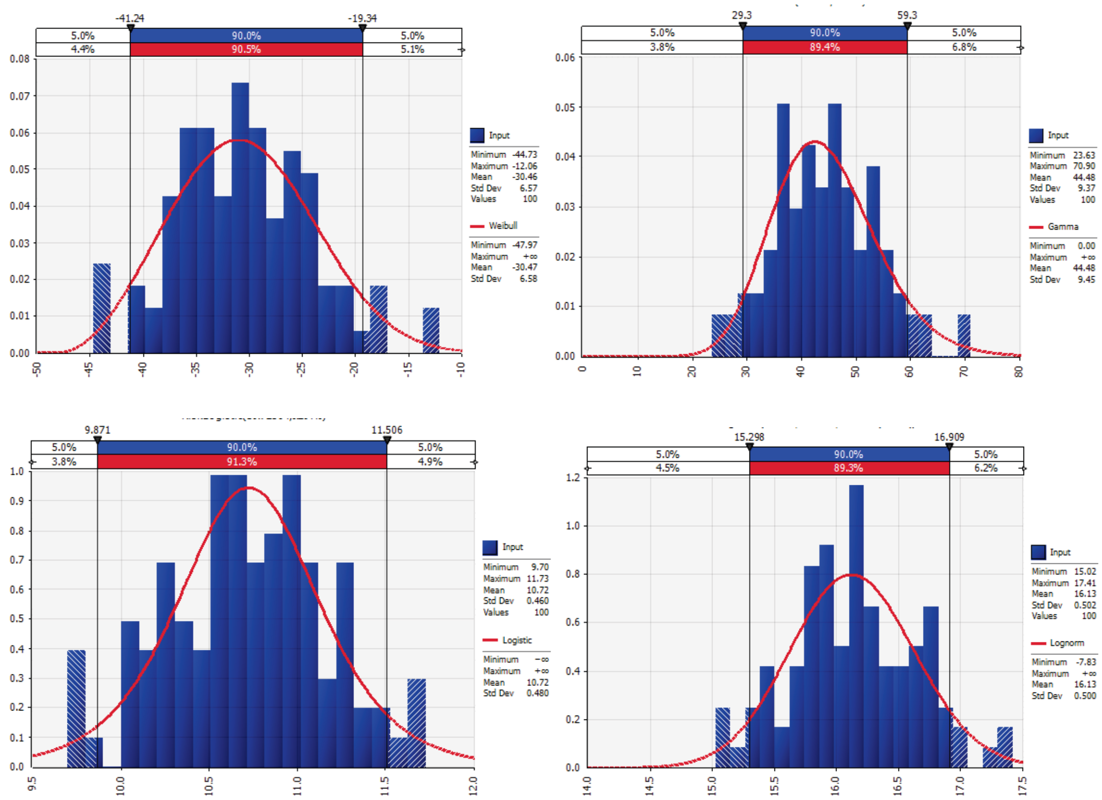
The City of Campbelltown is located in Adelaide's inner eastern suburbs - about 6 kilometres from the Adelaide GPO. Total population of the Council area is about 50,000. An analysis of the jobs held by the resident population in the City of Campbelltown in 2006 shows the three most popular industry sectors were: retail trade (2,681 persons or 13.0%), health care and social assistance (2,597 persons or 12.5%)

and manufacturing (1,993 persons or 9.6%). In combination these three industries employed 7,271 people in total or 35.1% of the employed resident population.

Roads are mainly sealed, some spray sealed, and some unsealed. For the purposes of this study, AHR and USR were considered, as SSR were a small percentage. A particular challenge to road service levels is generated by the relatively large coverage in the Council area of soils subject to cracking and movement. The Campbelltown City Council has a well-developed asset management system and was therefore able to provide detailed information and data at both aggregate and sub-set levels.

7.3.1 Fitted climate parameter distributions: temperature and precipitation: TI, MMP, Tmin and T: Campbelltown City Council

Here we show Here we show four historical climate distributions for the Campbelltown City Council: (Top left) the Thornwaite Index (TI); (Top right) mean monthly precipitation (MMP); (Bottom left) minimum temperature (Tmin); and (Bottom right) temperature (T). The displayed graphs are the historical distributions: that is, without climate change. The graphs that have been adjusted to include climate change are similar but are not presented here due to space limitations.

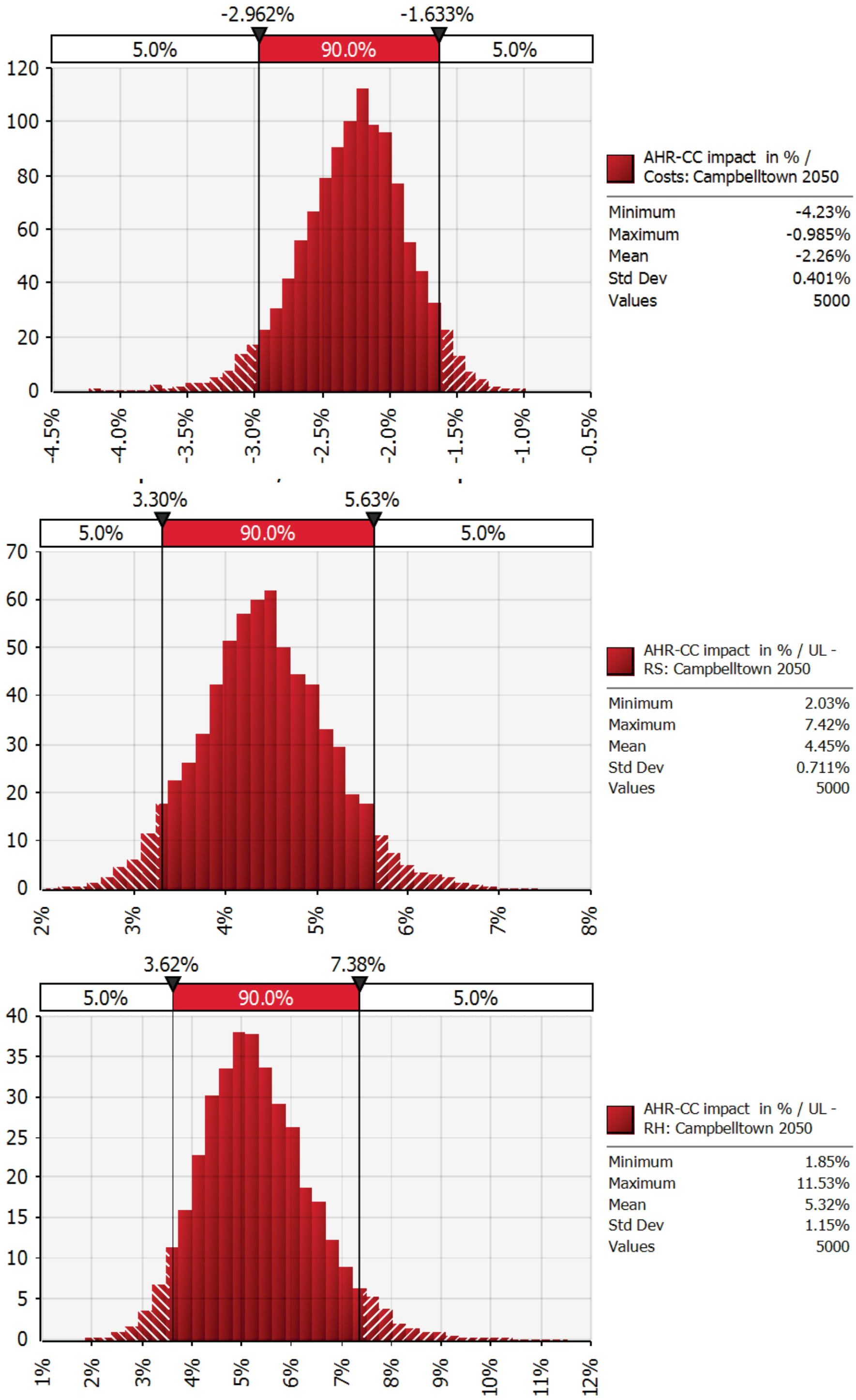


Note: For each graph, the vertical axis represents the fitted probability density function and the horizontal axis represents the values of the climate variable, with the statistics in the legend on the right hand side.

7.3.2 Campbelltown City Council Output: Asphalt / Hotmix Sealed Road (AHR)

Asphalt/Hotmix sealed roads (AHR) represent the majority of roads in this Council area. The reported results are based on a simulation with 5000 iterations. Two scenarios were modelled: years 2050, and 2100, each with percentage climate change impacts on costs and on useful life over those periods.

Campbelltown City Council AHR 2050 Scenario



Note: The top graph shows the impact of climate change in costs (% change); the second graph shows the impact of climate change on useful life (resurfacing) (% change); and the third graph shows the impact of climate change on useful life (rehabilitation) (% change). In all graphs the vertical axis represents frequency, and the horizontal axis represents the values of climate change impact with the statistics in the legend on the right hand side.

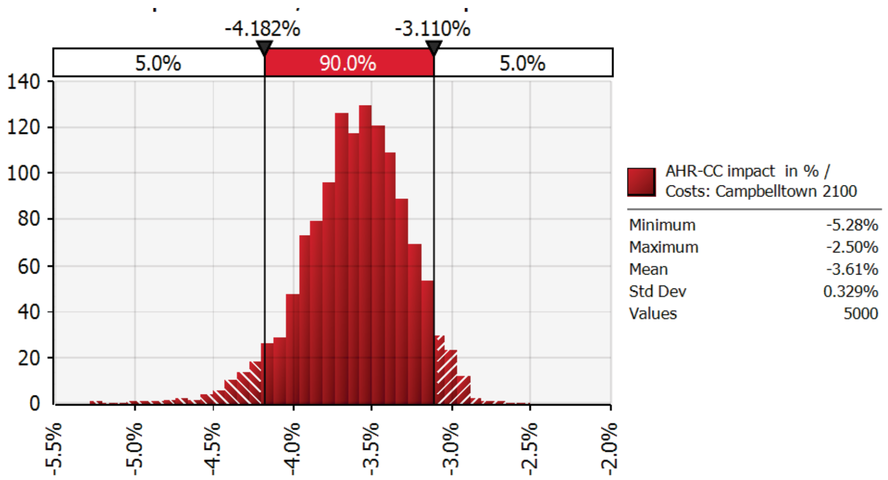
Comments:

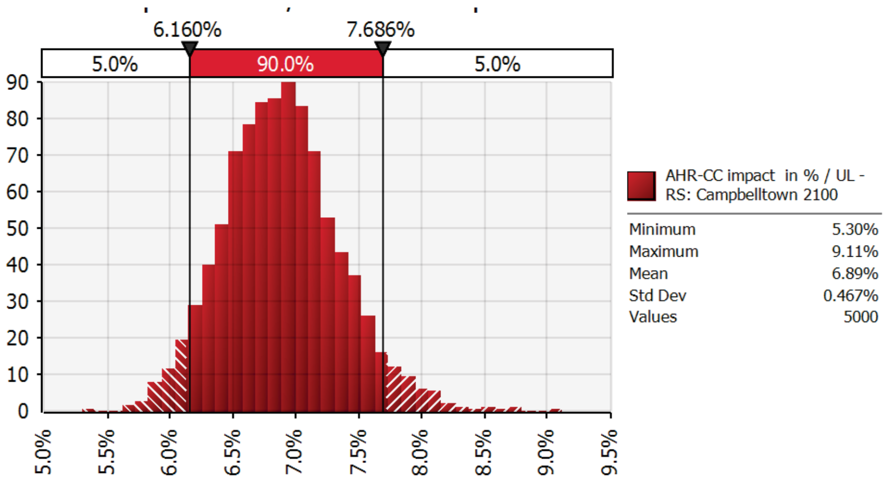
These graphs show the following for asphalt/hotmix sealed roads for Campbelltown City Council:

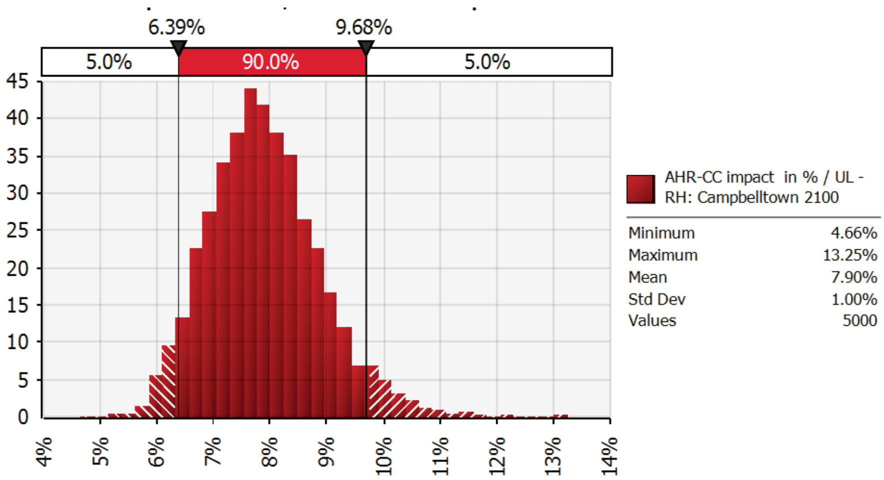
- the impact of climate change on costs is expected to be 2.26% reduction over the period to 2050;
- the impact of climate change on useful life (resurfacing) is expected to be 4.45% increase over the period to 2050; and
- the impact of climate change on useful life (rehabilitation) is expected to be 5.32% increase over the period to 2050.

Campbelltown City Council AHR 2100 Scenario

The 2050 results increase in the 2100 scenario:







Note: The first graph (previous page) shows the impact of climate change in costs (% change); the second graph (previous page) shows the impact of climate change on useful life (resurfacing) (% change); and the third graph (this page) shows the impact of climate change on useful life (rehabilitation) (% change). In all graphs the vertical axis represents frequency, and the horizontal axis represents the values of climate change impact with the statistics in the legend on the right hand side.

Comments:
These graphs show the following for asphalt/hotmix roads in the Campbelltown City Council:

- the impact of climate change on costs is expected to be 3.61% reduction over the period to 2100;
- the impact of climate change on useful life (resurfacing) is expected to be 6.89% increase over the period to 2100; and
- the impact of climate change on useful life (rehabilitation) is expected to 7.90% increase over the period to 2100.

It will be noted from the summary of results) that both 2050 and 2100 scenarios are at or around mean values for the Councils sampled.

7.4 Port Adelaide Enfield City Council

The City of Port Adelaide Enfield is one of the largest metropolitan Councils within South Australia (established in 1996). The LGA extends from the River Torrens to Outer Harbor across the north-east, north, and north-west of the city, and covers an area of approximately 97 square kilometres. At the 2006 census the City of Port Adelaide Enfield had a resident population of 102,929. The most recent estimated resident population (June 2011) is 114,783. The Aboriginal/Torres Strait Islander population represents 18.1% of Metropolitan Adelaide's indigenous population. The main industry sectors in the Council area are manufacturing, health care and social assistance, and retail. Compared to Metropolitan Adelaide unemployment is higher, labour force participation is lower and school education attainment and qualifications are lower in the City of Port Adelaide Enfield. There is a significantly lower proportion of managers and professionals in the City of Port Adelaide Enfield and a higher proportion working in manufacturing. Almost all roads in the Council area are asphalt hotmix sealed.

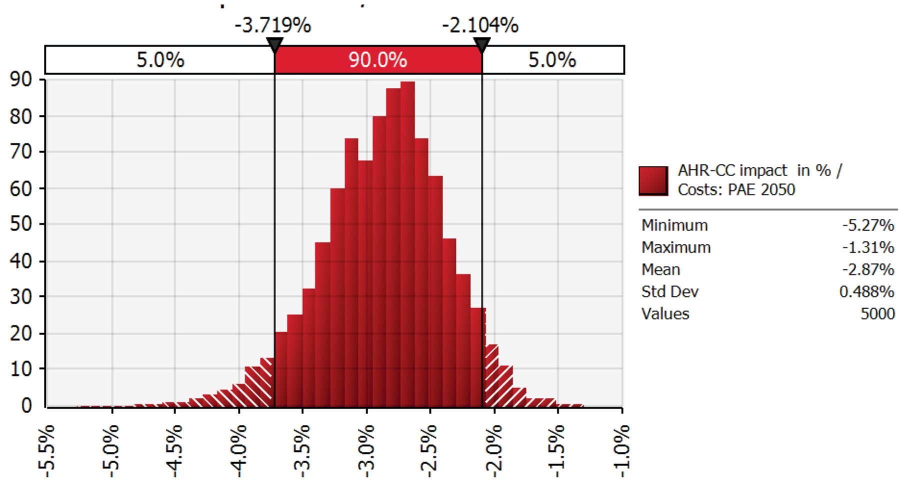
7.4.1 Fitted climate parameter distributions: temperature and precipitation: TI, MMP, Tmin and T: Port Adelaide / Enfield City Councils

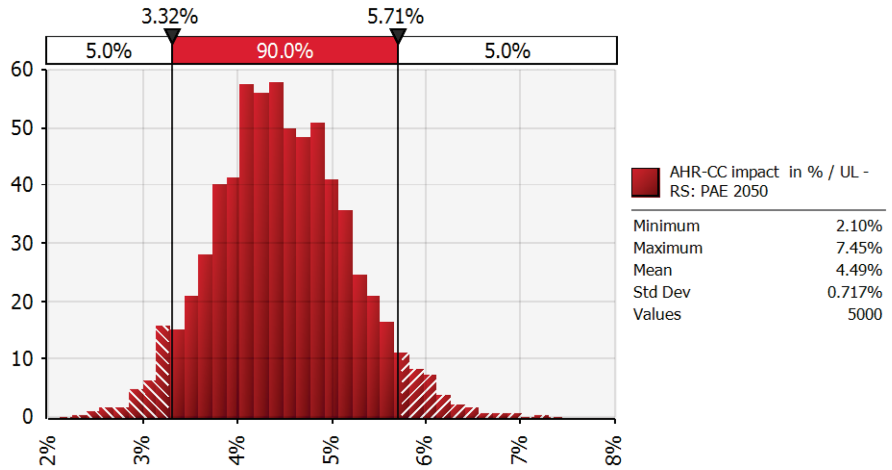
Climate distributions for Port Adelaide Enfield are the same as for Campbelltown as both Councils lie within the Greater Adelaide climate area.

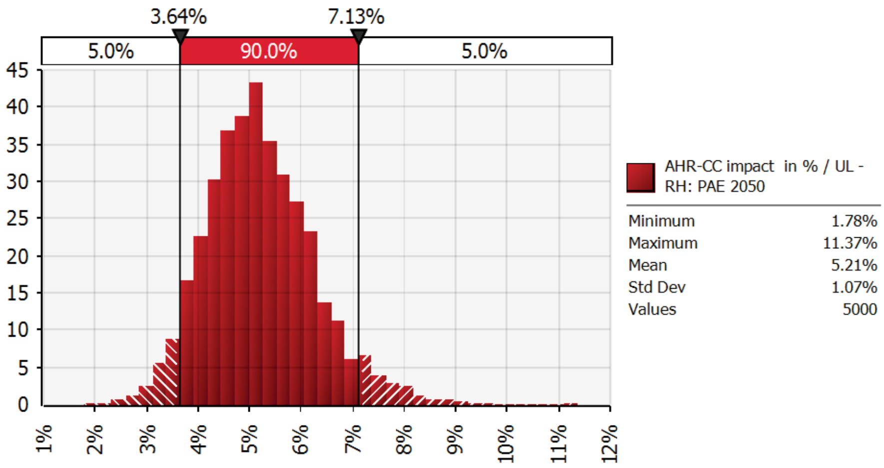
7.4.2 Port Adelaide Enfield City Council Output: Asphalt / Hotmix Sealed Road (AHR)

Asphalt/Hotmix sealed roads (AHR) represent the majority of roads in this Council area. The reported results are based on a simulation with 5000 iterations. Two scenarios were modelled: years 2050, and 2100, each with percentage climate change impacts on costs and on useful life over those periods.

Port Adelaide Enfield City Council AHR 2050 Scenario







Note: The first graph (previous page) shows the impact of climate change in costs (% change); the second graph (previous page) shows the impact of climate change on useful life (resurfacing) (% change); and the third graph (this page) shows the impact of climate change on useful life (rehabilitation) (% change). In all graphs the vertical axis represents frequency, and the horizontal axis represents the values of climate change impact with the statistics in the legend on the right hand side.

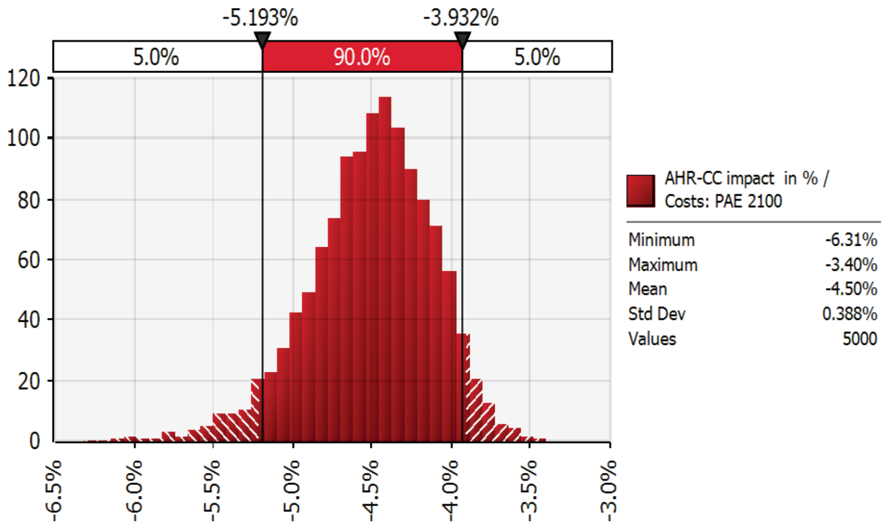
Comments:

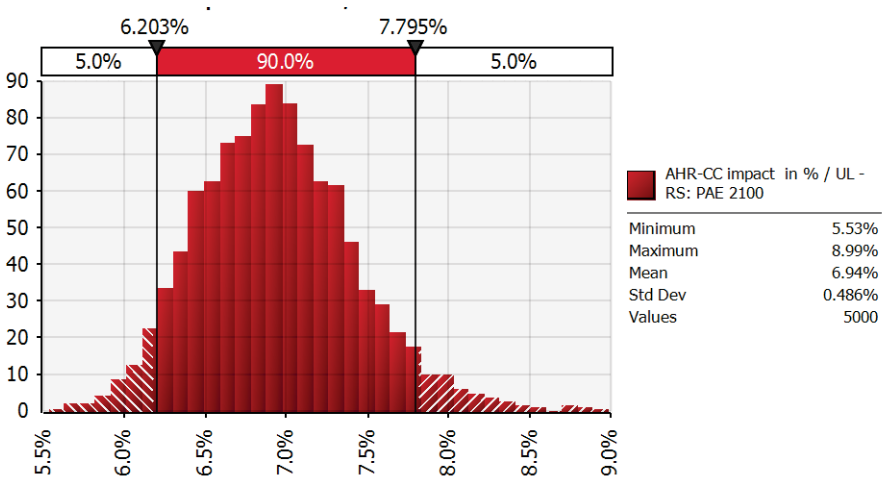
These graphs show the following for asphalt/hotmix sealed roads for Port Adelaide Enfield City Council:

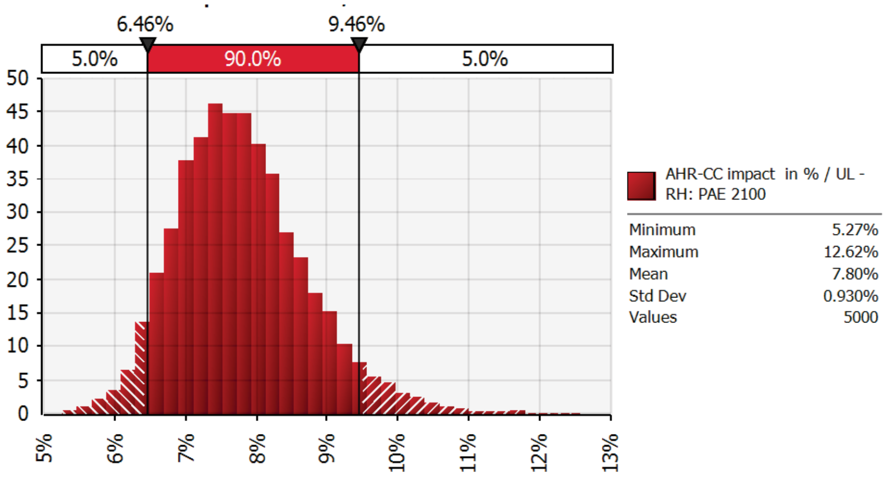
- the impact of climate change on costs is expected to be 2.87% reduction over the period to 2050;
- the impact of climate change on useful life (resurfacing) is expected to be 4.49% increase over the period to 2050 and
- the impact of climate change on useful life (rehabilitation) is expected to 5.21% increase over the period to 2050.

Port Adelaide Enfield City Council AHR 2100 Scenario

The 2050 results increase in the 2100 scenario:







Note: The first graph (previous page) shows the impact of climate change in costs (% change); the second graph (top this page) shows the impact of climate change on useful life (resurfacing) (% change); and the third graph (bottom this page) shows the impact of climate change on useful life (rehabilitation) (% change). In all graphs the vertical axis represents frequency, and the horizontal axis represents the values of climate change impact with the statistics in the legend on the right hand side.

Comments:

These graphs show the following for unsealed roads for Port Adelaide Enfield City Council:

- the impact of climate change on costs is expected to be 4.50% reduction over the period to 2100;
- the impact of climate change on useful life (resurfacing) is expected to be 6.94% increase over the period to 2100; and
- the impact of climate change on useful life (rehabilitation) is expected to 7.80% increase over the period to 2100.

It will be noted from the summary of results that both 2050 and 2100 scenarios are at or around mean values for the Councils sampled with respect to costs, as the useful life values increases at a slightly lower level than the mean.

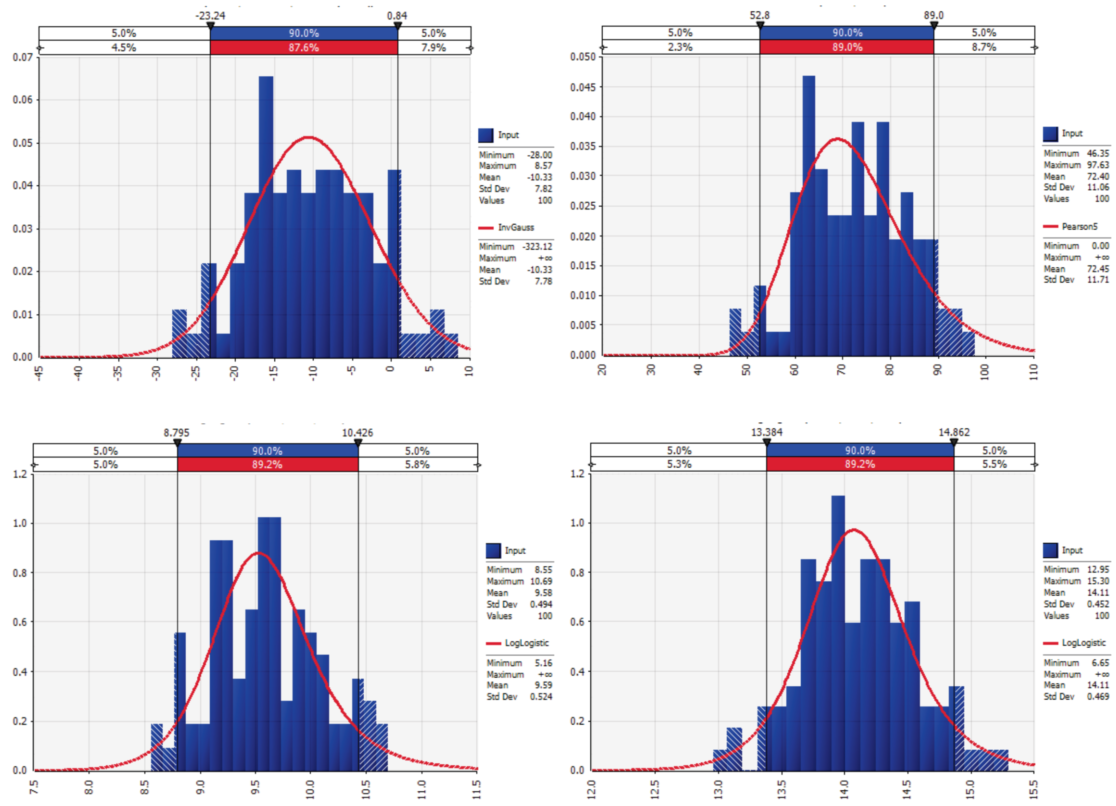
7.5 Bass Coast Shire Council

Bass Coast Shire is located in south-eastern Victoria, about 130 kilometres south-east of Melbourne. Bass Coast Shire is bounded by Western Port Bay in the north and west, Cardinia Shire in the north-east, South Gippsland Shire in the east, and Bass Strait in the south. Bass Coast Shire is a rural, residential and holiday area. The Shire encompasses a total land area of about 860 square kilometres, including substantial coastal areas. The major towns are Wonthaggi, Cowes, Inverloch, San Remo and Grantville. The major industries of the Shire are tourism and agriculture, particularly cattle and sheep grazing.

The Council was able to provide detailed data on all categories of its road network, bitumen sealed, spray sealed, and unsealed. As a result all three categories of road surface were modelled.

7.5.1 Fitted climate parameter distributions: temperature and precipitation: TI, MMP, T and Tmin: Bass Coast Shire Council

Here we show four historical climate distributions for the Bass Coast Shire Council: (Top left) the Thornwaite Index (TI); (Top right) mean monthly precipitation (MMP); (Bottom left) minimum temperature (Tmin); and (Bottom right) temperature (T). The displayed graphs are the historical distributions: that is, without climate change. The graphs that have been adjusted to include climate change are similar but are not presented here due to space limitations.

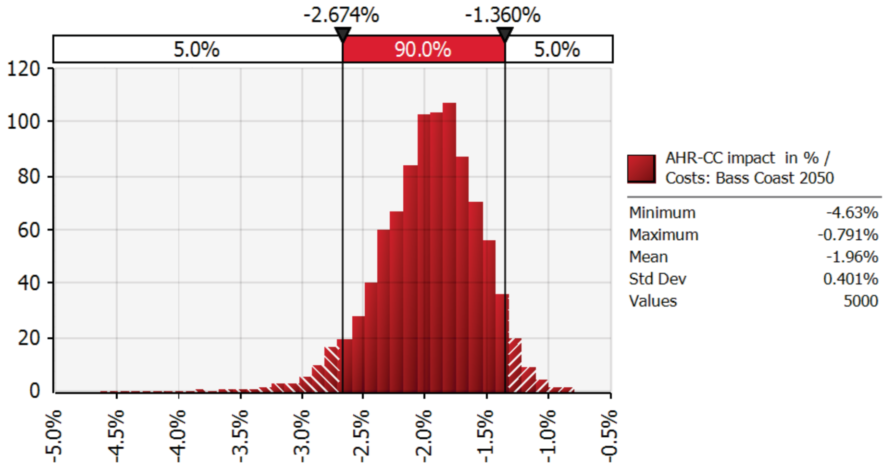


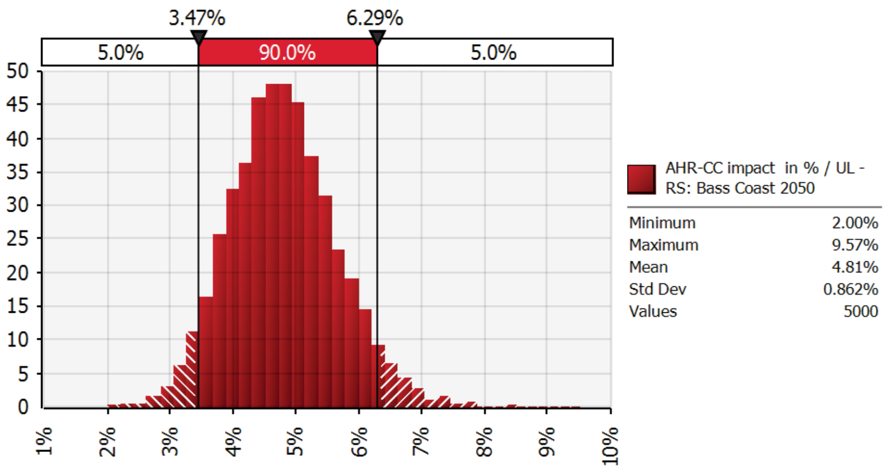
Note: For each graph, the vertical axis represents the fitted probability density function and the horizontal axis represents the values of the climate variable, with the statistics in the legend on the right hand side.

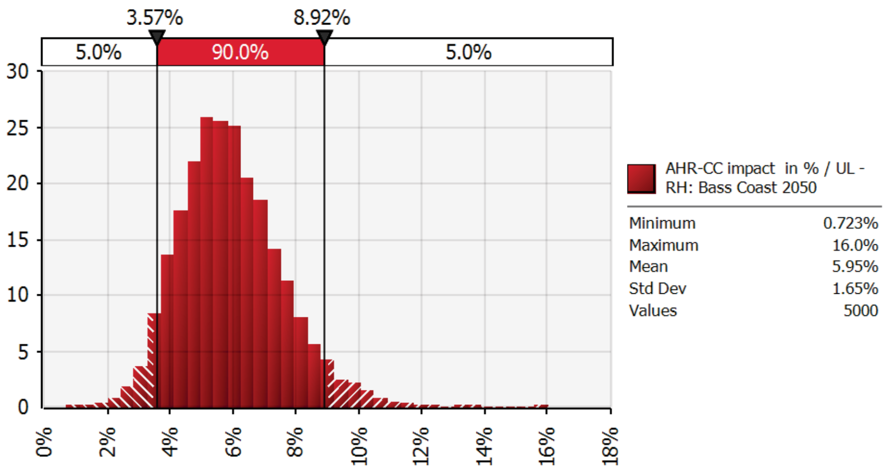
7.5.2 Bass Coast Shire Council Output: Asphalt / Hotmix Sealed Road (AHR)

The reported results are based on a simulation with 5000 iterations. Two scenarios were modelled: years 2050, and 2100, each with percentage climate change impacts on costs and on useful life over those periods.

Bass Coast Shire Council AHR 2050 Scenario





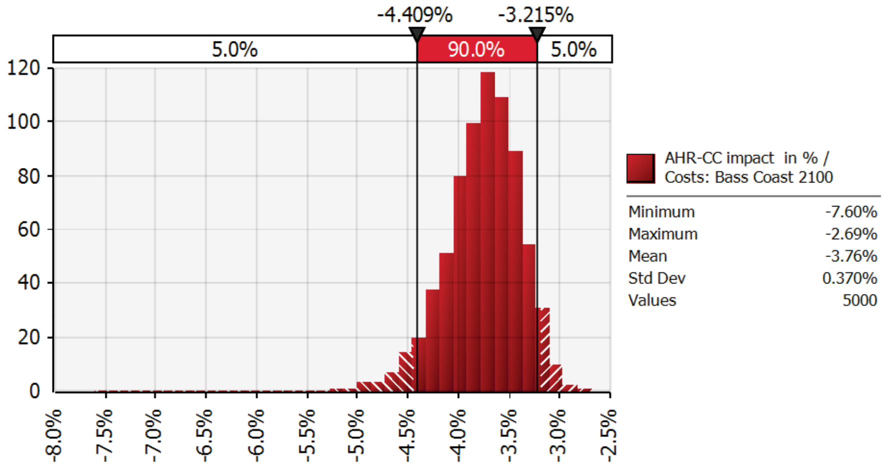


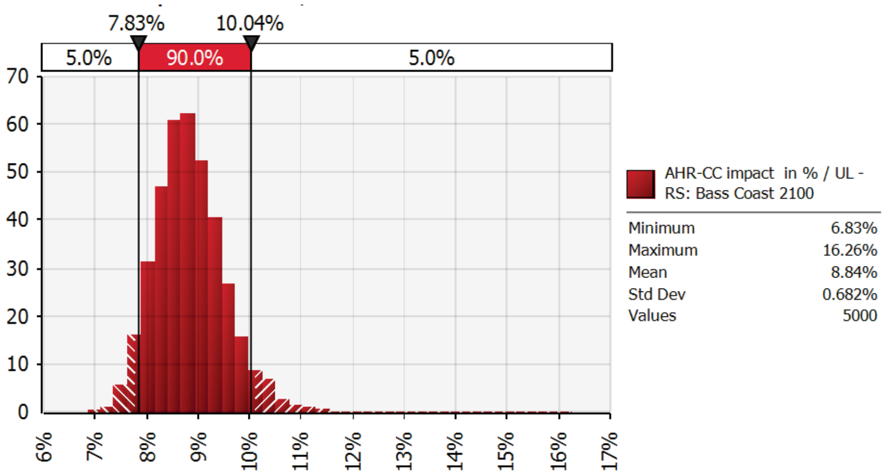
Note: The top graph shows the impact of climate change in costs (% change); the second graph shows the impact of climate change on useful life (resurfacing) (% change); and the third graph shows the impact of climate change on useful life (rehabilitation) (% change). In all graphs the vertical axis represents frequency, and the horizontal axis represents the values of climate change impact with the statistics in the legend on the right hand side.

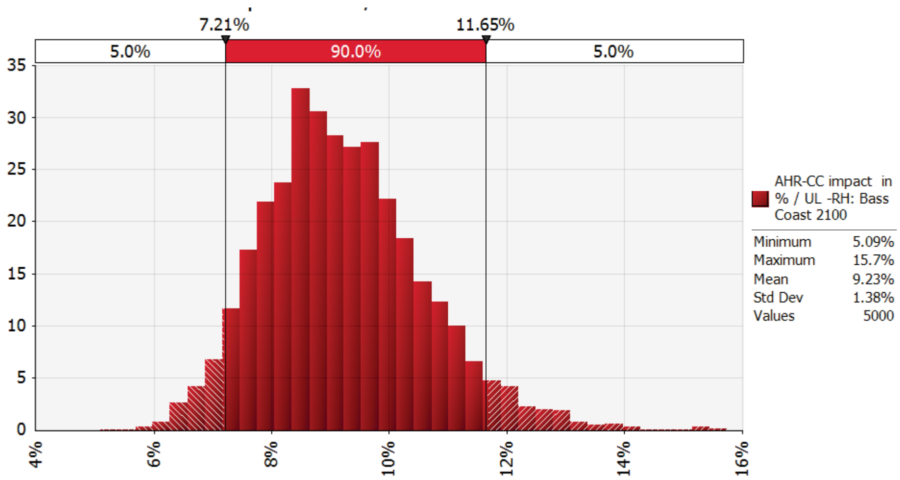
Comments:
These graphs show the following for asphalt/hotmix sealed roads for Bass Coast Shire Council:

- the impact of climate change on costs is expected to be 1.96% reduction over the period to 2050;
- the impact of climate change on useful life (resurfacing) is expected to be 4.81% increase over the period to 2050; and
- the impact of climate change on useful life (rehabilitation) is expected to 5.95% increase over the period to 2050.

Bass Coast Shire Council AHR 2100 Scenario
The 2050 results increase in the 2100 scenario:







Note: The first graph (previous page) shows the impact of climate change in costs (% change); the second graph (previous page) shows the impact of climate change on useful life (resurfacing) (% change); and the third graph (this page) shows the impact of climate change on useful life (rehabilitation) (% change). In all graphs the vertical axis represents frequency, and the horizontal axis represents the values of climate change impact with the statistics in the legend on the right hand side.

Comments:

These graphs show the following for asphalt/hotmix roads for Bass Coast Shire Council:

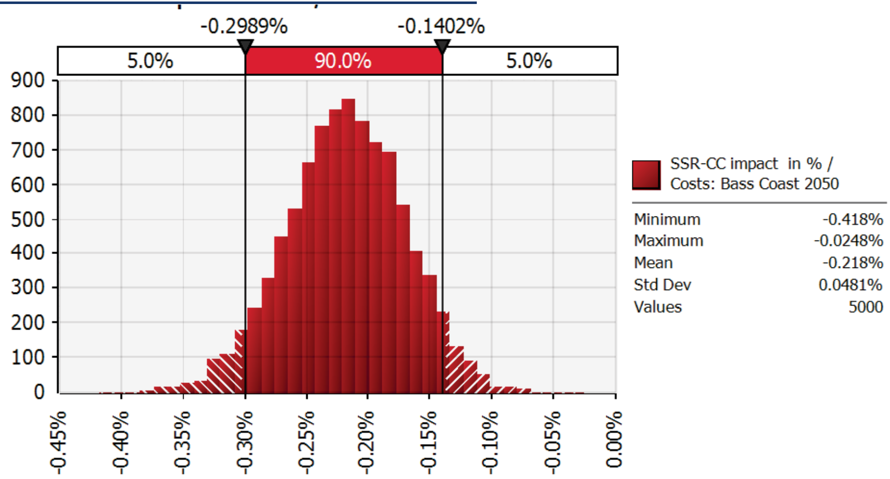
- the impact of climate change on costs is expected to be 3.76% reduction over the period to 2100;
- the impact of climate change on useful life (resurfacing) is expected to be 8.84% increase over the period to 2100; and
- the impact of climate change on useful life (rehabilitation) is expected to 9.23% increase over the period to 2100.

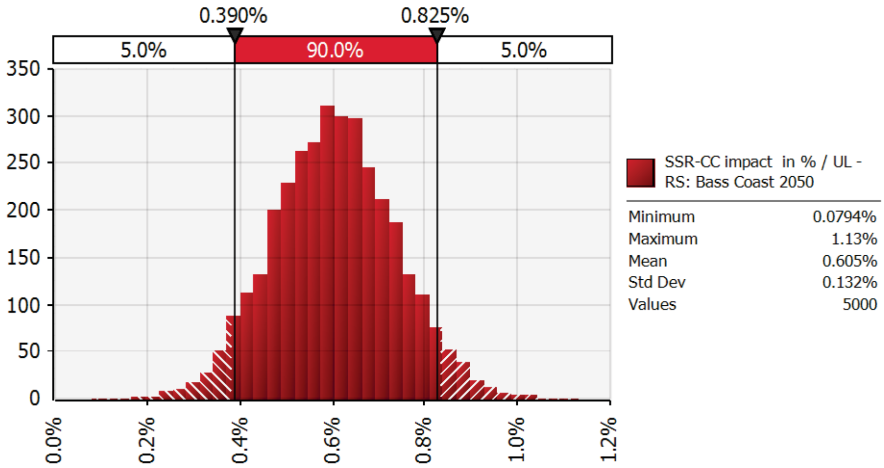
It will be noted from the summary of results that for asphalt/hotmix roads both 2050 and 2100 scenarios are below the mean values for the Councils sampled with respect to both costs and useful life.

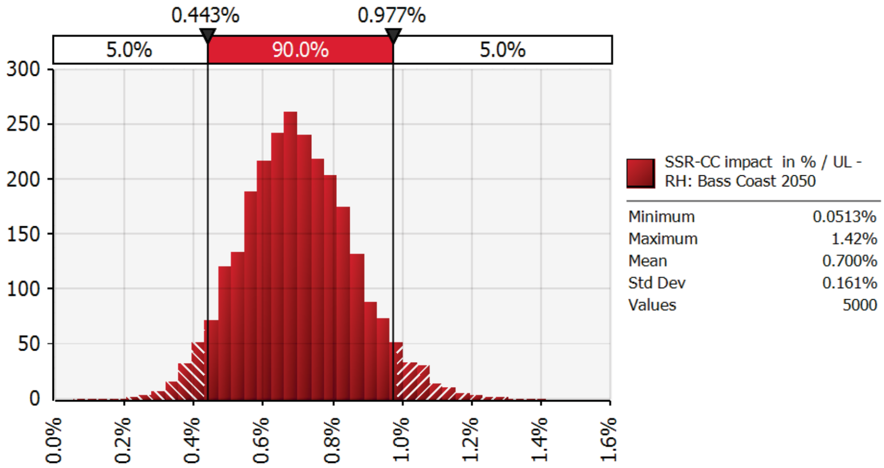
7.5.3 Bass Coast Shire Council Output: Spray sealed Road (SSR)

The reported results are based on a simulation with 5000 iterations. Two scenarios were modelled: years 2050, and 2100, each with percentage climate change impacts on costs and on useful life over those periods.

Bass Coast Shire Council SSR 2050 Scenario







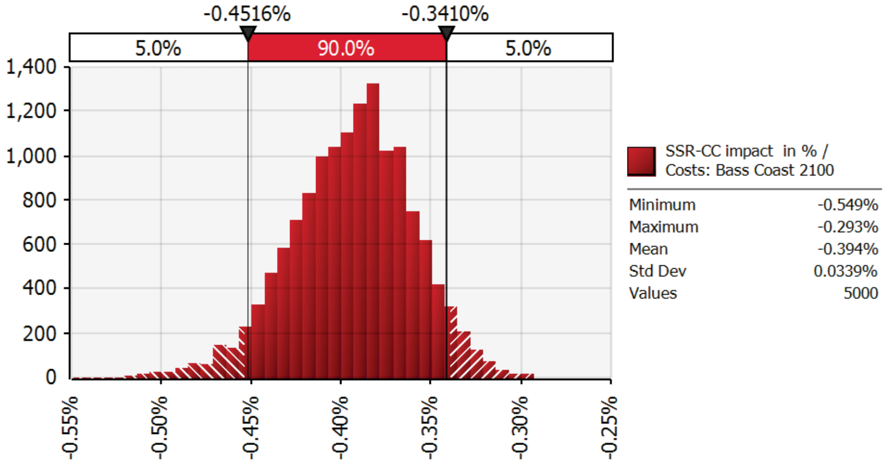
Note: The top graph (previous page) shows the impact of climate change in costs (% change); the second graph shows the impact of climate change on useful life (resurfacing) (% change); and the third graph shows the impact of climate change on useful life (rehabilitation) (% change). In all graphs the vertical axis represents frequency, and the horizontal axis represents the values of climate change impact with the statistics in the legend on the right hand side.

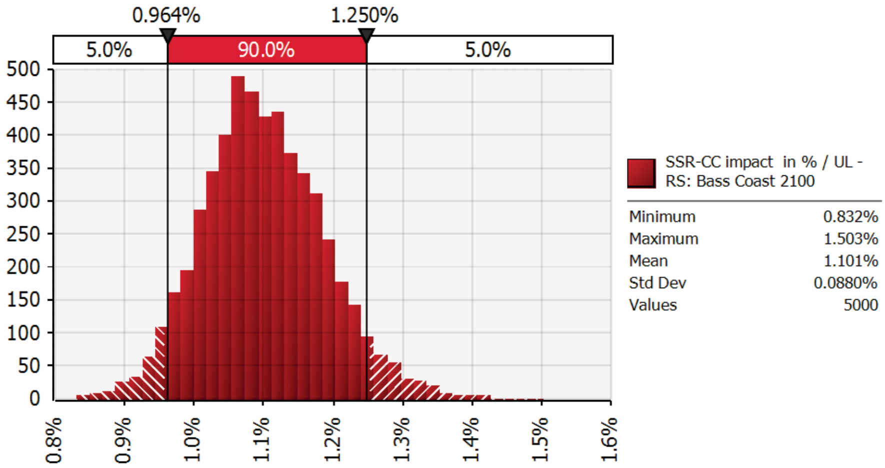
Comments:

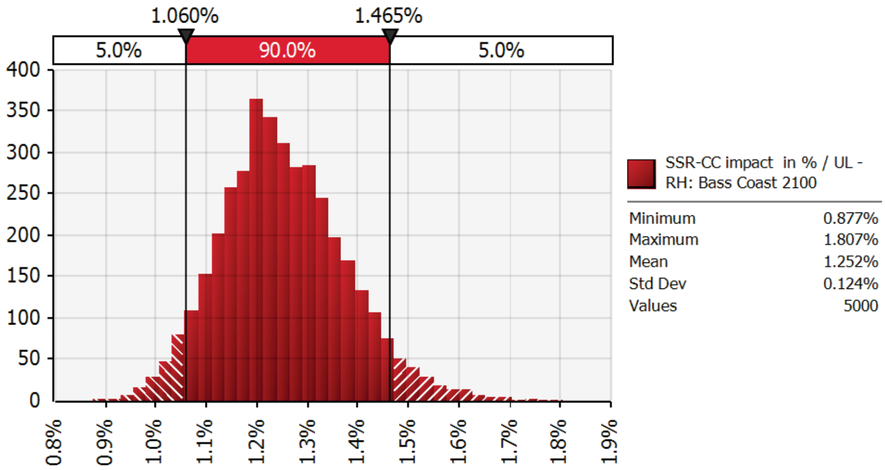
These graphs show the following for sprayed-sealed roads for Bass Coast Shire Council:

- the impact of climate change on costs is expected to be 0.22% reduction over the period to 2050;
- the impact of climate change on useful life (resurfacing) is expected to be 0.61% increase over the period to 2050; and
- the impact of climate change on useful life (rehabilitation) is expected to be 0.70% increase over the period to 2050.

Bass Coast Shire Council SSR 2100 Scenario







Note: The first graph shows the impact of climate change in costs (% change); the second graph shows the impact of climate change on useful life (resurfacing) (% change); and the third graph shows the impact of climate change on useful life (rehabilitation) (% change). In all graphs the vertical axis represents frequency, and the horizontal axis represents the values of climate change impact with the statistics in the legend on the right hand side.

Comments:
These graphs show the following for sprayed-sealed roads for Bass Coast Shire Council:

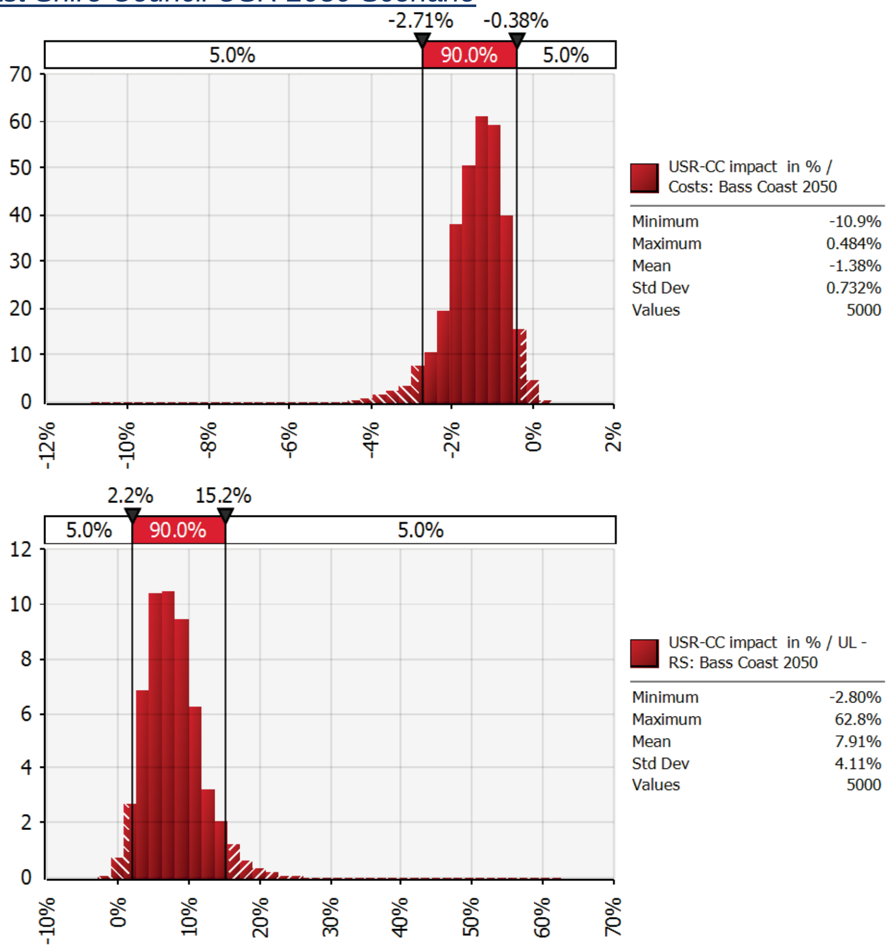
- the impact of climate change on costs is expected to be 0.39% reduction over the period to 2100;
- the impact of climate change on useful life (resurfacing) is expected to be 1.10% increase over the period to 2100; and
- the impact of climate change on useful life (rehabilitation) is expected to be 1.25% increase over the period to 2100.

It will be noted from the summary of results below that for sprayed-sealed roads under both 2050 and 2100 scenarios values are significantly smaller than for hotmix/asphalt roads. In the case of Bass Coast the cost reductions are below the mean for the Councils sampled.

7.5.4 Bass Coast Shire Council Output: Unsealed roads (USR)

The reported results are based on a simulation with 5000 iterations. Two scenarios were modelled: years 2050, and 2100, each with percentage climate change impacts on costs and on useful life over those periods. Roads with extreme annual gravel loss (<3 mm thickness) were eliminated from the analysis as these roads are likely to be low in use and not appropriately maintained.

Bass Coast Shire Council USR 2050 Scenario

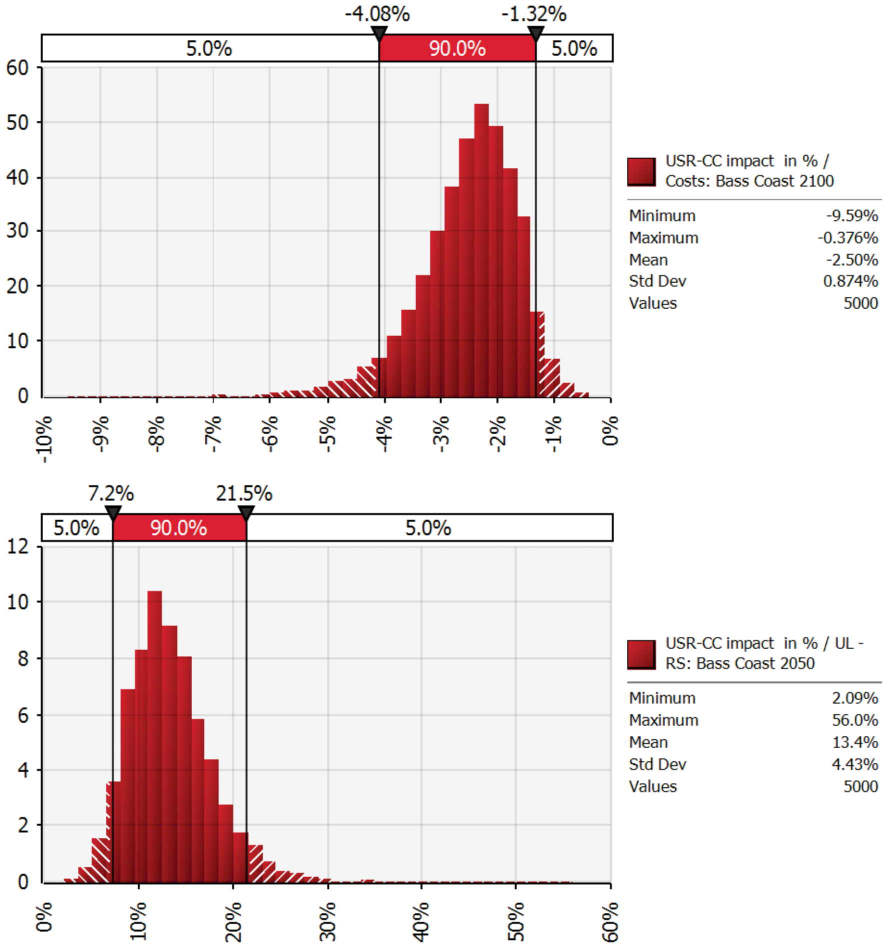


Note: The top graph shows the impact of climate change in costs (% change) and the lower graphs shows the impact of climate change in UL (% change). In both graphs the vertical axis represents frequency, and the horizontal axis represents the values of climate change impact with the statistics in the legend on the right hand side.

Comments:
These graphs show the following for unsealed roads for Bass Coast Shire Council:

- the impact of climate change on costs is expected to be 1.38% reduction over the period to 2050; and
- the impact of climate change on useful life (resurfacing) is expected to be 7.91% increase over the period to 2050.

Bass Coast Shire Council USR 2100 Scenario



Note: The top graph shows the impact of climate change in costs (% change) and the lower graph shows the impact of climate change in UL (% change). In both graphs the vertical axis represents frequency, and the horizontal axis represents the values of climate change impact with the statistics in the legend on the right hand side.

Comments:
These graphs show the following for unsealed roads for Bass Coast Shire Council:

- the impact of climate change on costs shows a mean percentage reduction of 2.50%; and
- the impact of climate change on useful life shows a mean percentage increase of 13.40%.

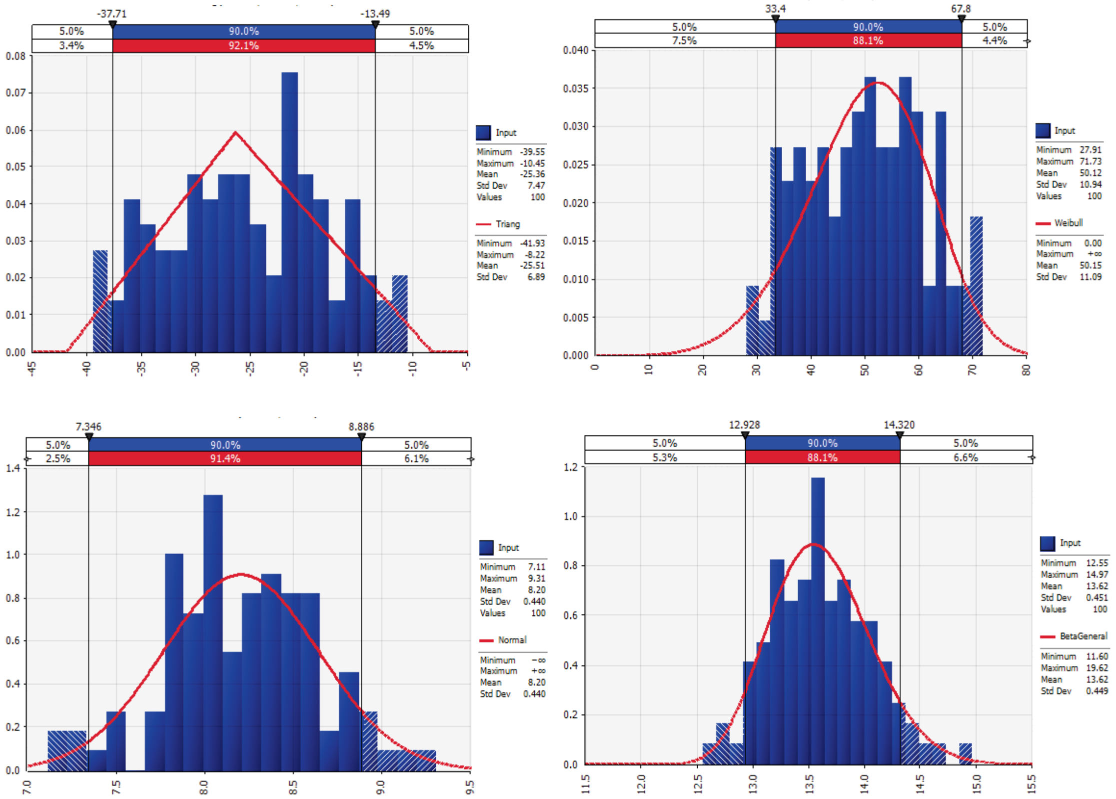
It will be noted from the summary of results that these are at the high end of the results in the Councils sampled.

7.6 Hume City Council

Hume City Council is located on the urban-rural fringe, just 20 kilometres north-west of Melbourne. It occupies 504 square kilometres, comprising approximately 65% rural land, 25% urban land and 10% occupied by the Melbourne Airport. The Council is bounded by Merri Creek, the Maribyrnong River, Western Ring Road, the Calder and Tullamarine Freeways, and the foothills of the Macedon Ranges. It includes the rapidly growing urban centres of Craigieburn, Roxburgh Park and Sunbury, and the rural areas and townships of Bulla, Mickleham and Kalkallo. Approximately 70% of its road networks is Asphalt Hotmix, 22% Spray Sealed and the remainder Unsealed. Data was available for all three road types.

7.6.1 Fitted climate parameter distributions: temperature and precipitation: TI, MMP, T and Tmin: Hume City Council

Here we show four historical climate distributions for the Hume City Council: (Top left) the Thornwaite Index (TI); (Top right) mean monthly precipitation (MMP); (Bottom left) minimum temperature (Tmin); and (Bottom right) temperature (T). The displayed graphs are the historical distributions: that is, without climate change. The graphs which have been adjusted to include climate change are similar but are not presented here due to space limitations.

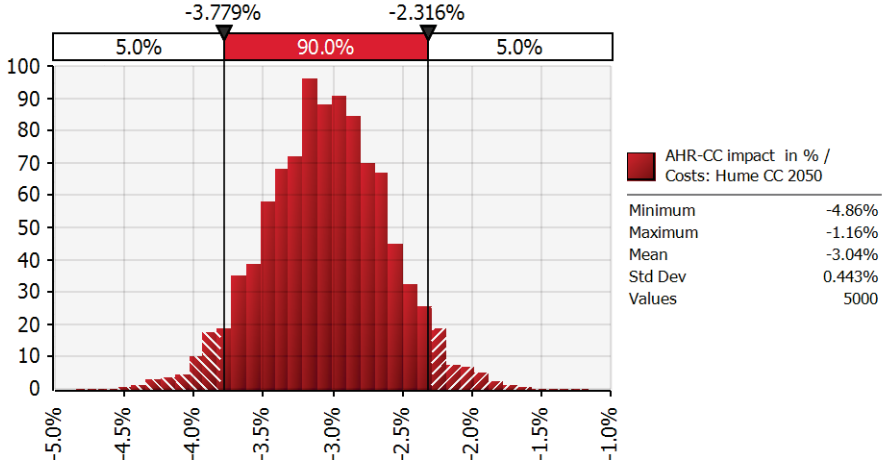


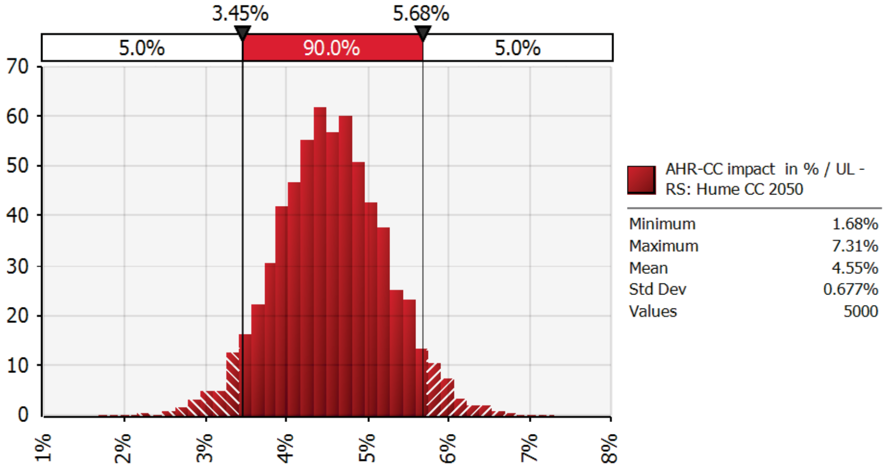
Note: For each graph, the vertical axis represents the fitted probability density function and the horizontal axis represents the values of the climate variable, with the statistics in the legend on the right hand side.

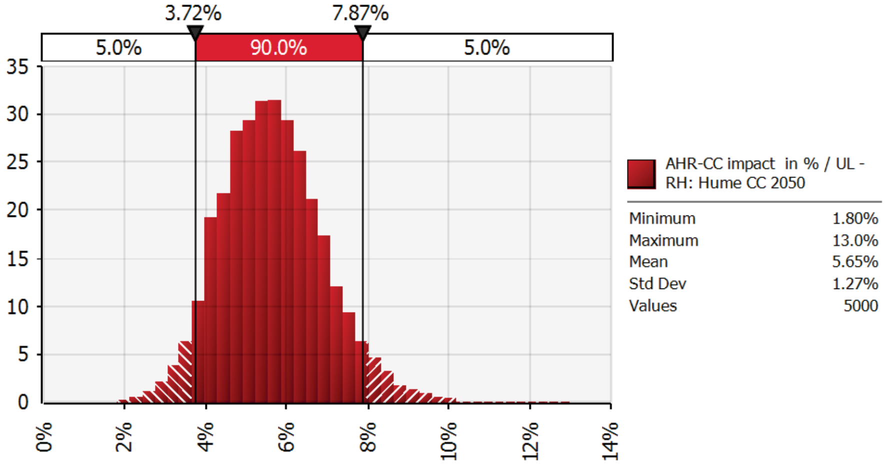
7.6.2 Hume City Council Output: Asphalt / Hotmix Sealed Road (AHR)

The reported results are based on a simulation with 5000 iterations. Two scenarios were modelled: years 2050, and 2100, each with percentage climate change impacts on costs and on useful life over those periods.

Hume City Council AHR 2050 Scenario





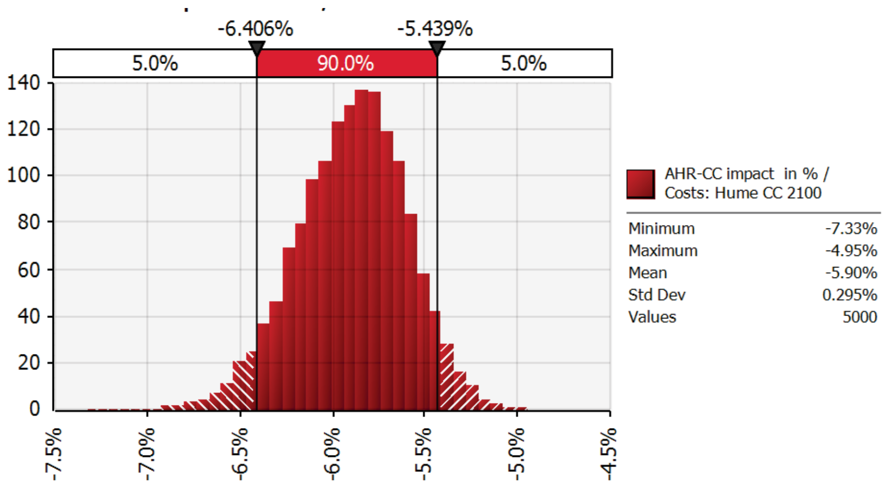


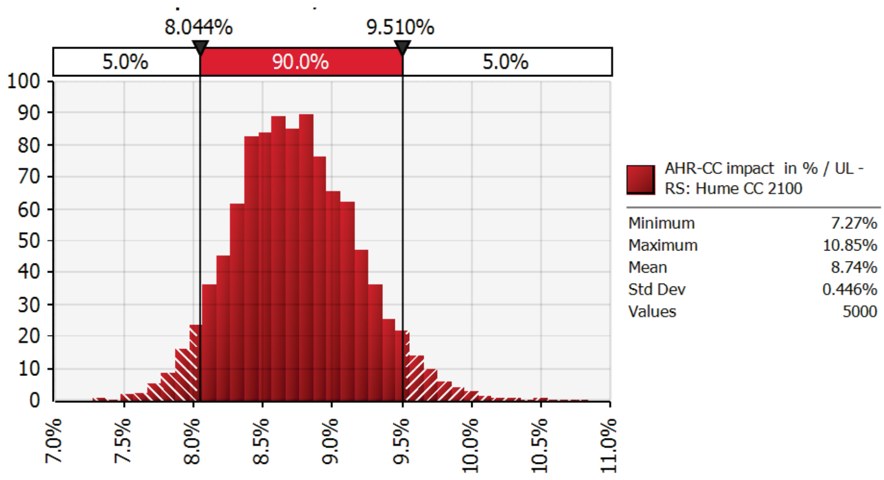
Note: The top graph shows the impact of climate change in costs (% change); the second graph shows the impact of climate change on useful life (resurfacing) (% change); and the third graph shows the impact of climate change on useful life (rehabilitation) (% change). In all graphs the vertical axis represents frequency, and the horizontal axis represents the values of climate change impact with the statistics in the legend on the right hand side.

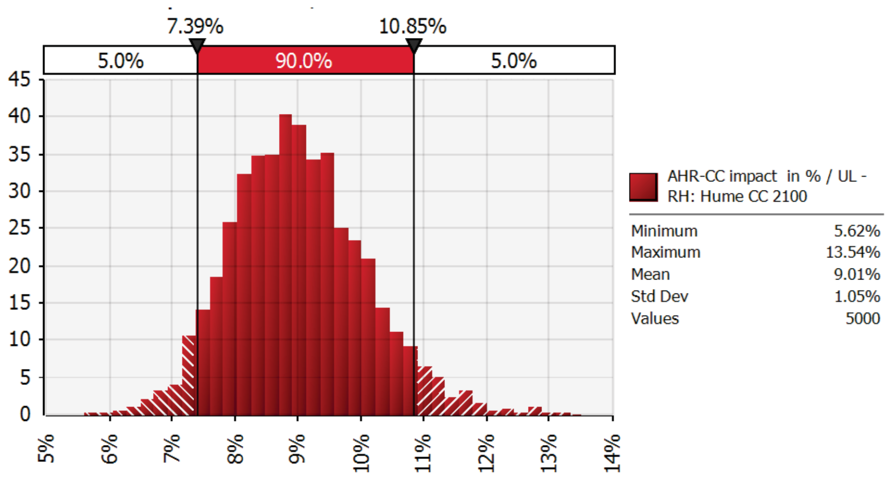
Comments:
These graphs show the following for asphalt/hotmix sealed roads for Hume City Council:

- the impact of climate change on costs is expected to be 3.04% reduction over the period to 2050;
- the impact of climate change on useful life (resurfacing) is expected to be 4.55% increase over the period to 2050; and
- the impact of climate change on useful life (rehabilitation) is expected to be 5.65% increase over the period to 2050.

Hume City Council AHR 2100 Scenario
The 2050 results increase in the 2100 scenario:







Note: The first graph (previous page) shows the impact of climate change in costs (% change); the second graph (previous page) shows the impact of climate change on useful life (resurfacing) (% change); and the third graph (this page) shows the impact of climate change on useful life (rehabilitation) (% change). In all graphs the vertical axis represents frequency, and the horizontal axis represents the values of climate change impact with the statistics in the legend on the right hand side.

Comments:
These graphs show the following for asphalt/hotmix roads for Hume City Council:

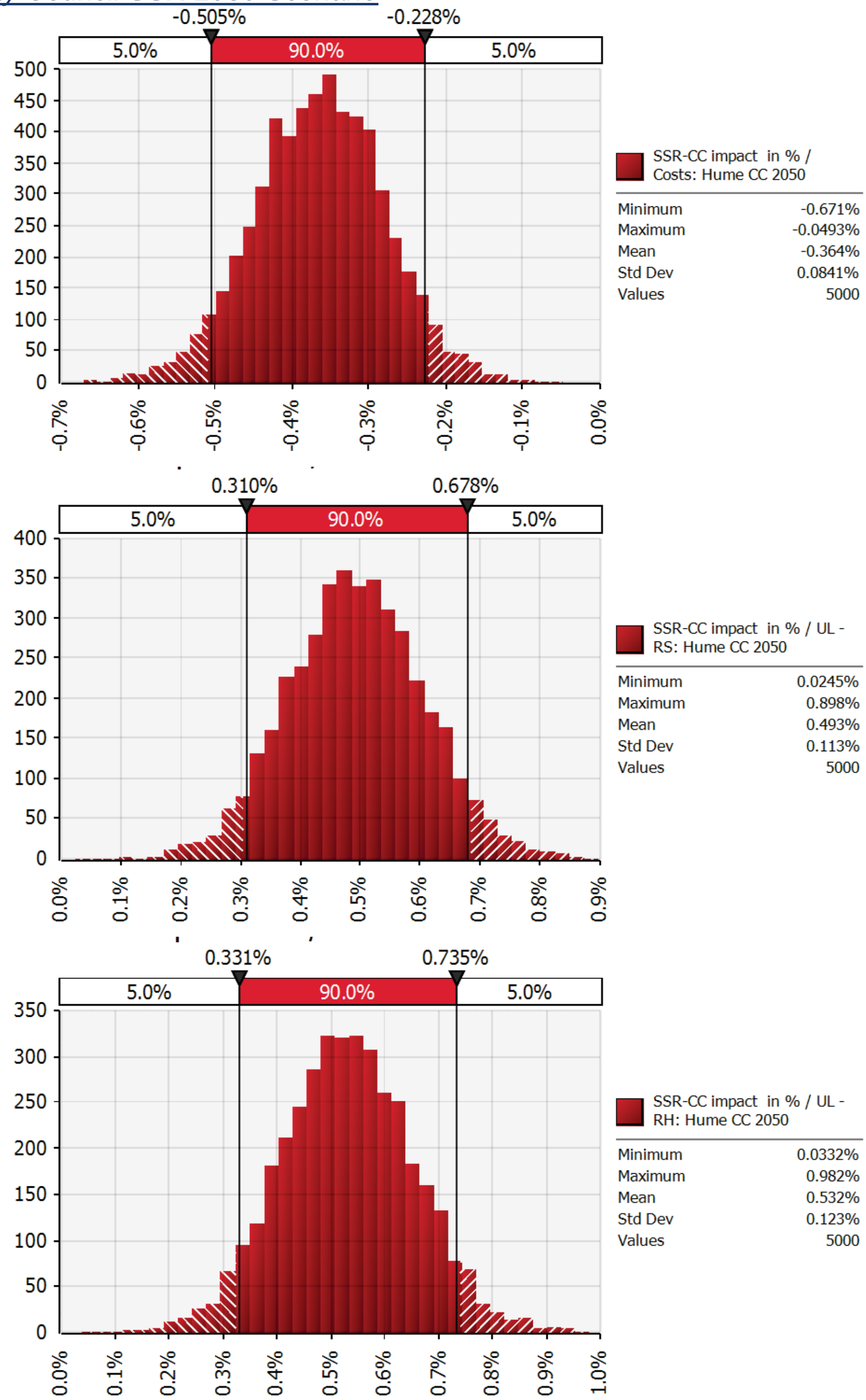
- the impact of climate change on costs is expected to be 5.90% reduction over the period to 2100;
- the impact of climate change on useful life (resurfacing) is expected to be 8.74% increase over the period to 2100; and
- the impact of climate change on useful life (rehabilitation) is expected to be 9.01% increase over the period to 2100.

It will be noted from the summary of results that for asphalt/hotmix roads both 2050 and 2100 scenarios are below the mean values for the Councils sampled with respect to costs.

7.6.3 Hume City Council Output: Spray sealed roads (SSR)

The reported results are based on a simulation with 5000 iterations. Two scenarios were modelled: years 2050, and 2100, each with percentage climate change impacts on costs and on useful life over those periods.

Hume City Council SSR 2050 Scenario

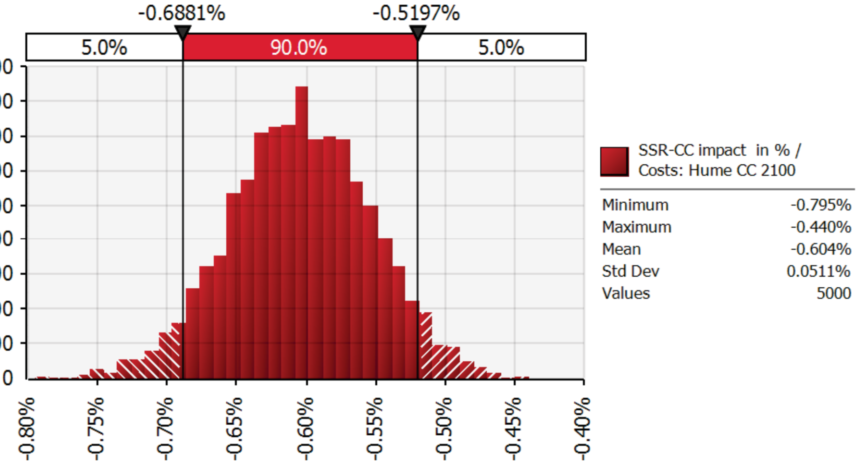


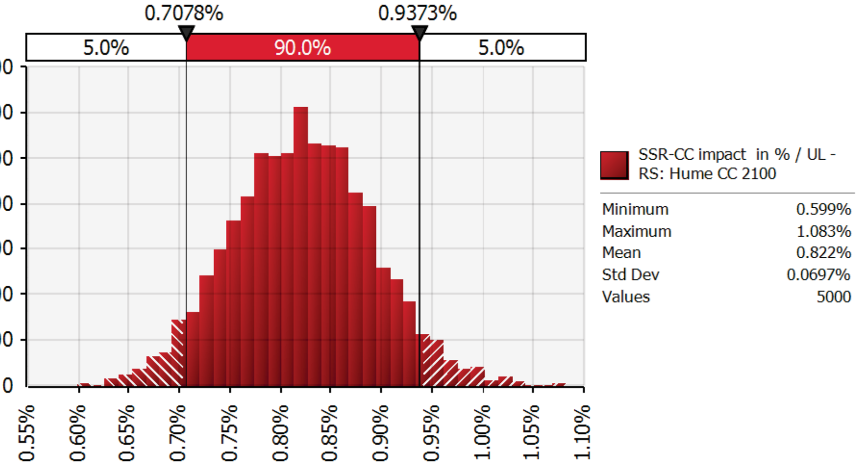
Note: The top graph shows the impact of climate change in costs (% change); the second graph shows the impact of climate change on useful life (resurfacing) (% change); and the third graph shows the impact of climate change on useful life (rehabilitation0 (% change). In all graphs the vertical axis represents frequency, and the horizontal axis represents the values of climate change impact with the statistics in the legend on the right hand side.

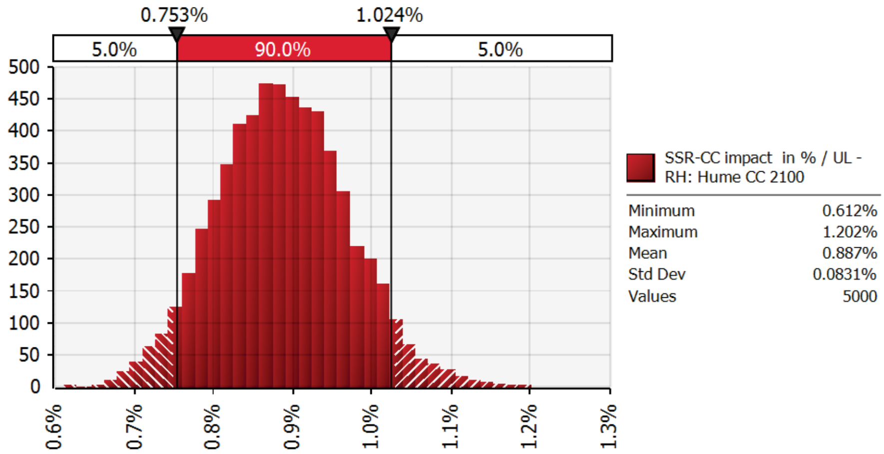
Comments:
These graphs show the following for sprayed-sealed roads for Hume City Council:

- the impact of climate change on costs is expected to be 0.36% reduction over the period to 2050;
- the impact of climate change on useful life (resurfacing) is expected to be 0.49% increase over the period to 2050; and
- the impact of climate change on useful life (rehabilitation) is expected to be 0.53% increase over the period to 2050.

Hume City Council SSR 2100 Scenario
The 2050 results increase in the 2100 scenario:







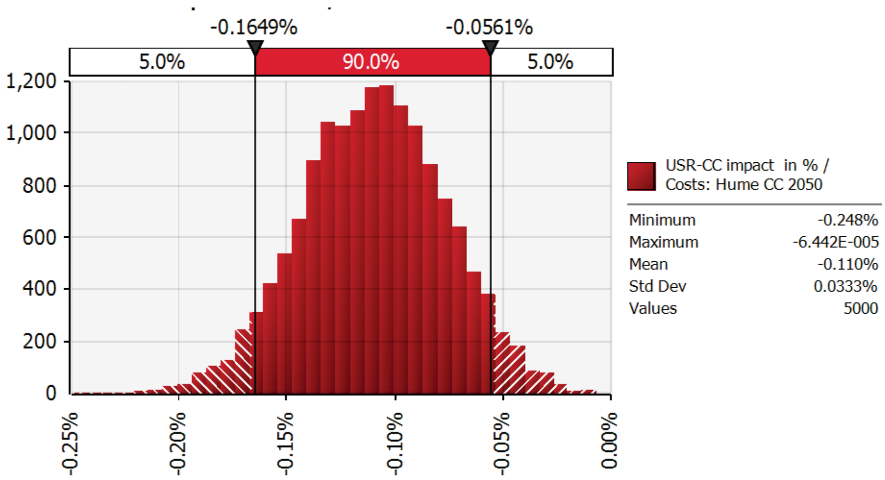
Note: The first graph (previous page) shows the impact of climate change in costs (% change); the second graph (previous page) shows the impact of climate change on useful life (resurfacing) (% change); and the third graph (this page) shows the impact of climate change on useful life (rehabilitation) (% change). In all graphs the vertical axis represents frequency, and the horizontal axis represents the values of climate change impact with the statistics in the legend on the right hand side.

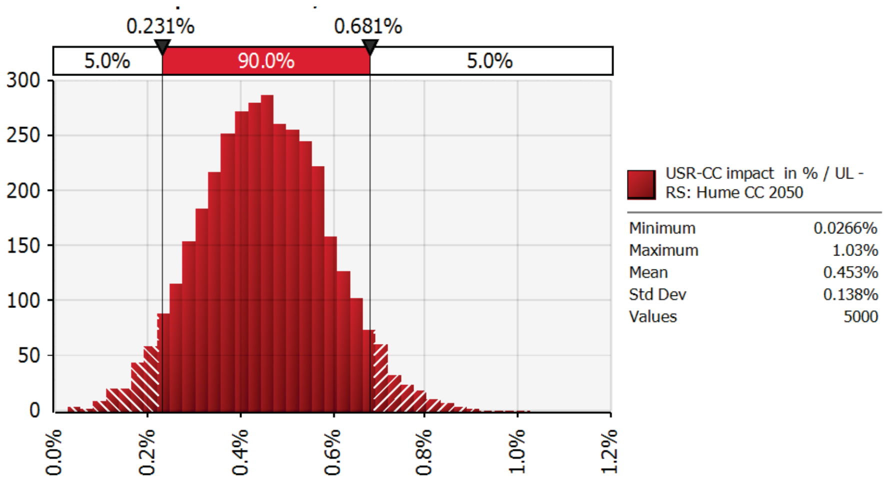
Comments:
These graphs show the following for sprayed-sealed roads for Hume City Council:

- the impact of climate change on costs is expected to be 0.60% reduction over the period to 2100;
- the impact of climate change on useful life (resurfacing) is expected to be 0.82% increase over the period to 2100; and
- the impact of climate change on useful life (rehabilitation) is expected to be 0.89% increase over the period to 2100.

It will be noted from the summary of results that for sprayed-sealed roads under both 2050 and 2100 scenarios values are significantly smaller than for hotmix/asphalt roads. In the case of Hume City Council the results are around the means.

Hume City Council USR 2050 Scenario
The reported results are based on a simulation with 5000 iterations. Two scenarios were modelled: years 2050, and 2100, each with percentage climate change impacts on costs and on useful life over those periods. Roads with extreme annual gravel loss (<3 mm thickness) were eliminated from the analysis as these roads are likely to be low in use and not appropriately maintained.





Note: The top graph shows the impact of climate change in costs (% change) and the lower graph shows the impact of climate change in UL (% change). In both graphs the vertical axis represents frequency, and the horizontal axis represents the values of climate change impact with the statistics in the legend on the right hand side.

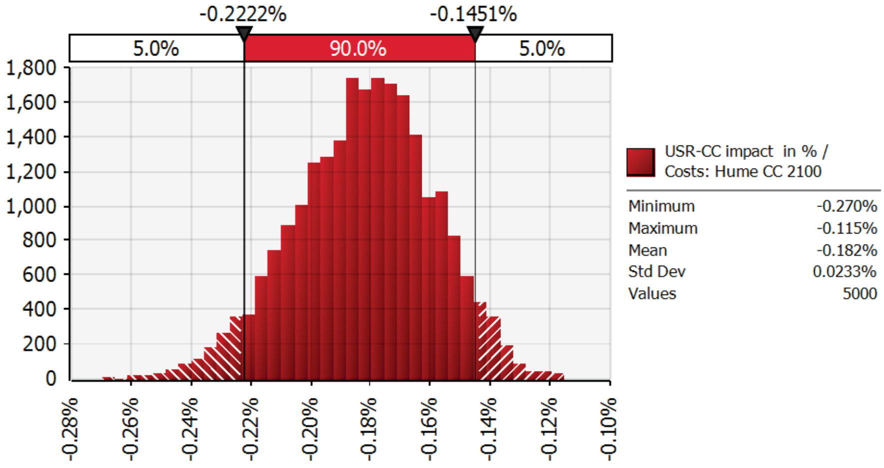
Comments:

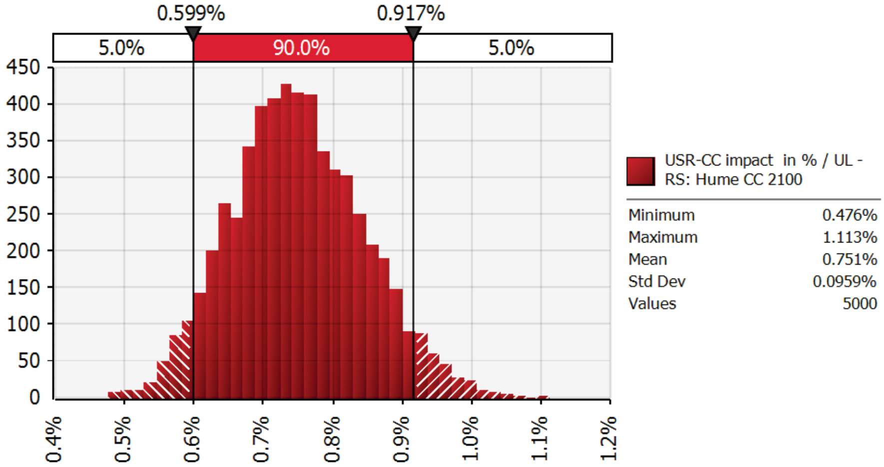
These graphs show the following for unsealed roads for Hume City Council:

- the impact of climate change on costs is expected to be 0.11% reduction over the period to 2050; and
- the impact of climate change on useful life (resurfacing) is expected to be 0.45% increase over the period to 2050.

Hume City Council USR 2100 Scenario

The results increase in the 2100 scenario:





Note: The top graph shows the impact of climate change in costs (% change) and the lower graph shows the impact of climate change in UL (% change). In both graphs the vertical axis represents frequency, and the horizontal axis represents the values of climate change impact with the statistics in the legend on the right hand side.

Comments:

These graphs show the following for unsealed roads for Hume City Council:

- the impact of climate change on costs shows a mean percentage reduction of 0.18% over the period to 2100; and
- the impact of climate change on useful life shows a mean percentage increase of 0.75% over the period to 2100.

It will be noted from the summary of results that these are at the low end of the results in the Councils sampled.

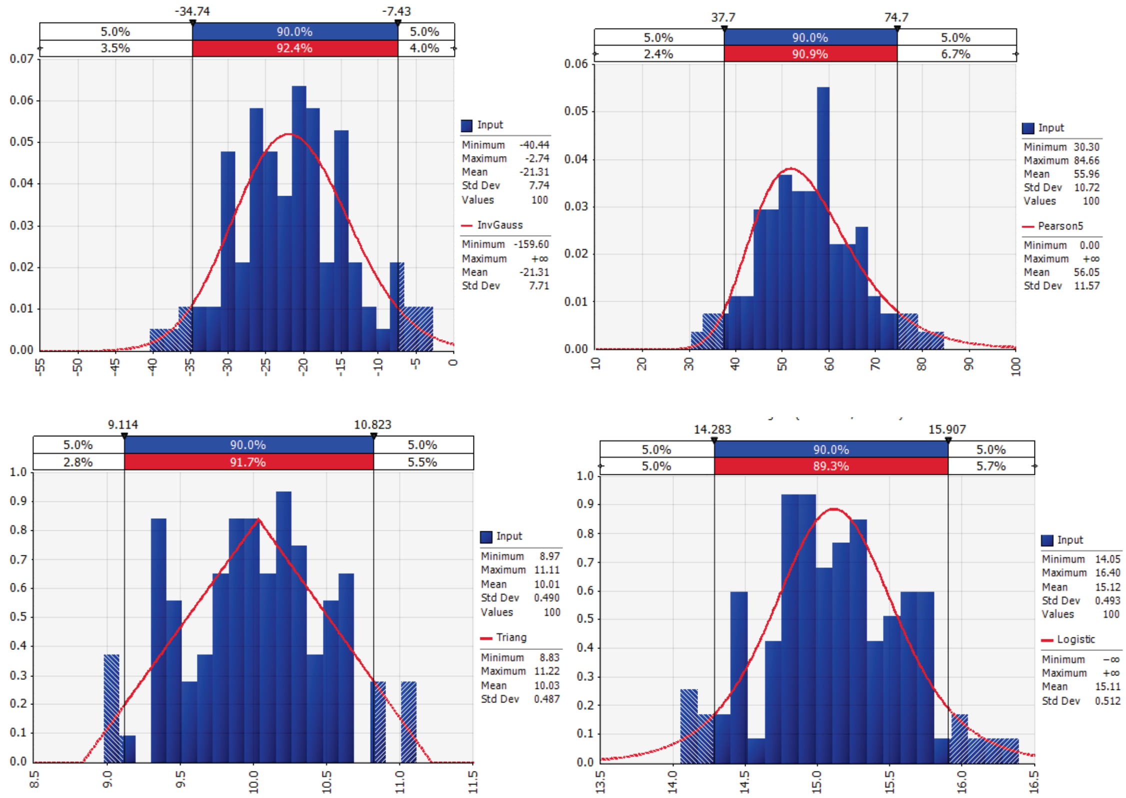
7.7 City Of Onkaparinga

The City of Onkaparinga occupies an area of 518 square kilometres in Adelaide's southern suburbs and urban fringe, with 31 km of coastline. Its population of approximately 163,000 lives in 51 suburbs. It falls into two general land uses. To the north and north-west are suburban and industrial areas, growing rapidly at the fringes; to the east, south and south-east are largely rural areas with small townships. The top three categories of employment are construction, property and business services and retail, comprising over 50% of the working population; agriculture accounts for 9%. Like The Barossa Council, the City of Onkaparinga includes a first-class wine region at McLaren Vale, with the association tourism industry.

The majority of roads in Onkaparinga Council are sealed roads. Among the sealed roads, AHR accounts for roughly 75% of the total. There is also the issue of good and poor soils in this Council. Further, among the unsealed roads, there are two types, one of which is more like a sealed road.

7.7.1 Fitted climate parameter distributions: temperature and precipitation: TI, MMP, T and Tmin: Onkaparinga City Council

Here we show the fitted distributions for the climate parameters: TI, MMP, Tmin and T for the Onkaparinga City Council. The displayed graphs are the historical distributions: that is, without climate change. The graphs that have been adjusted to include climate change are similar but are not presented here due to space limitations.

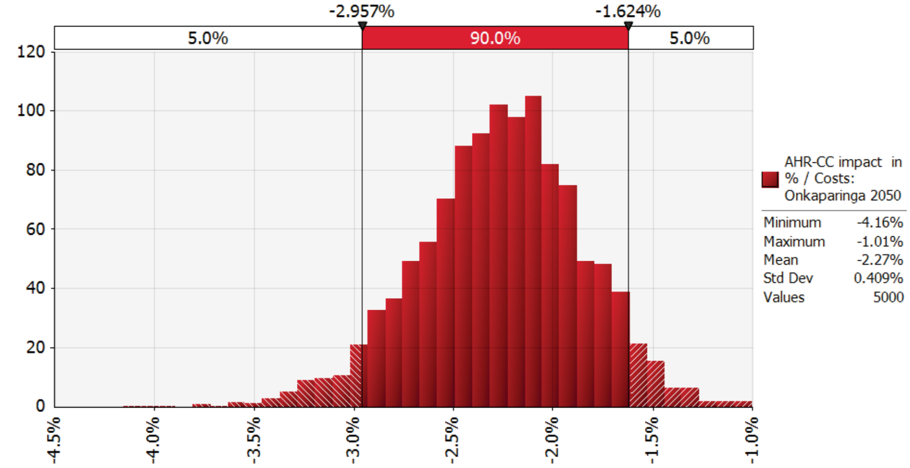


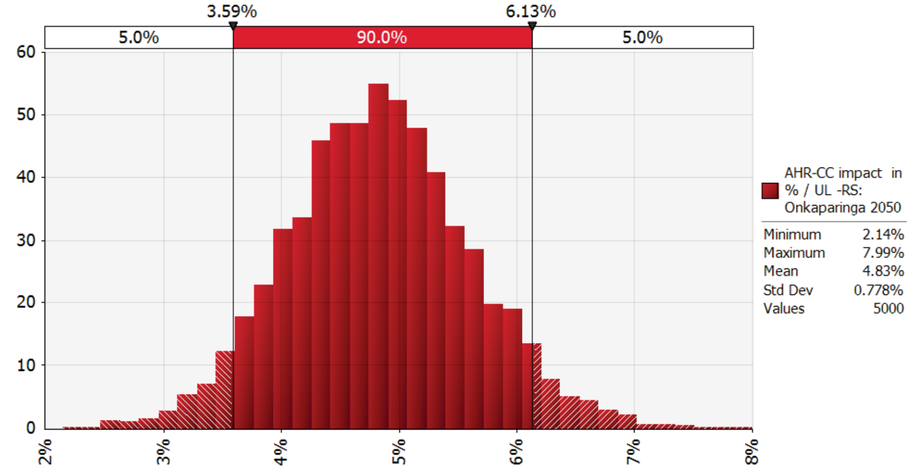
Note: For each graph, the vertical axis represents the fitted probability density function and the horizontal axis represents the values of the climate variable, with the statistics in the legend on the right hand side.

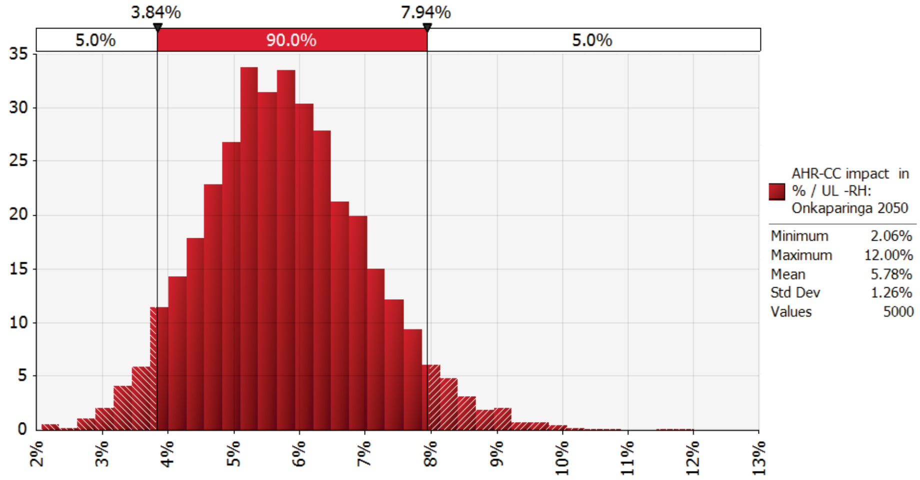
7.7.2 City of Onkaparinga Output: Asphalt / Hotmix sealed road (AHR)

The reported results are based on a simulation with 5000 iterations. Two scenarios were modelled: years 2050, and 2100, each with percentage climate change impacts on costs and on useful life over those periods.

Onkaparinga City Council AHR 2050 Scenario





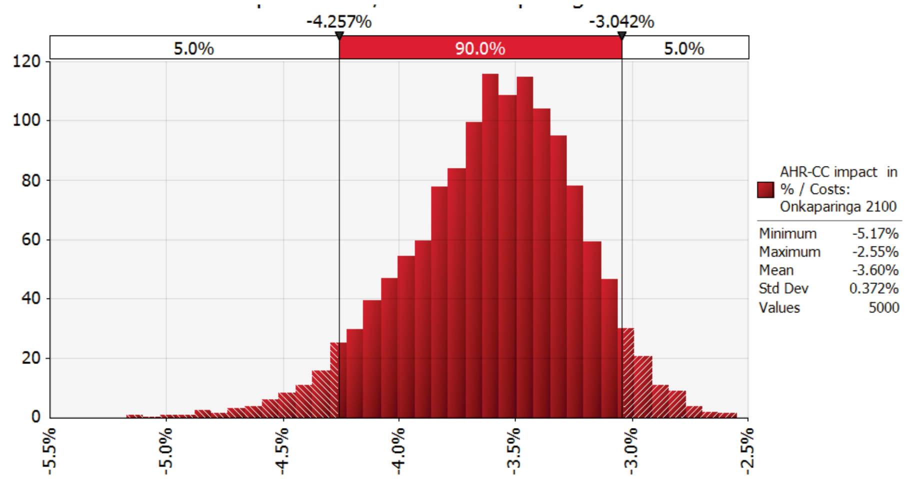


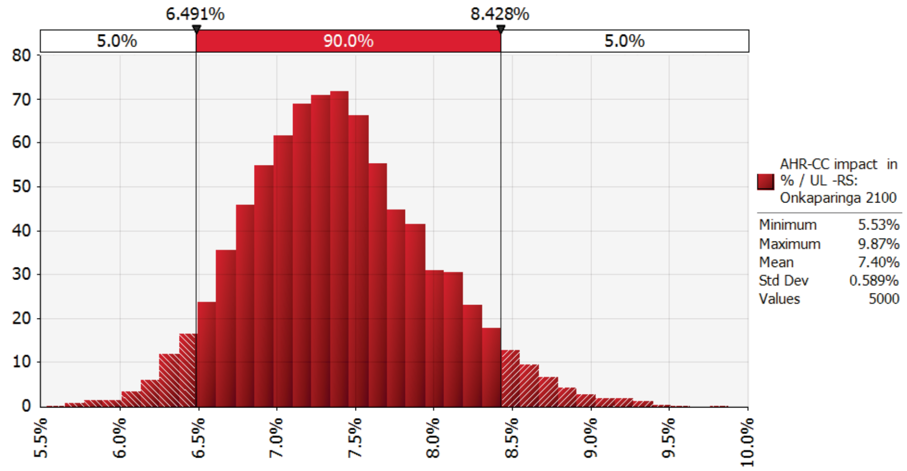
Note: The top graph shows the impact of climate change in costs (% change); the second graph shows the impact of climate change on useful life (resurfacing) (% change); and the third graph shows the impact of climate change on useful life (rehabilitation) (% change). In all graphs the vertical axis represents frequency, and the horizontal axis represents the values of climate change impact with the statistics in the legend on the right hand side.

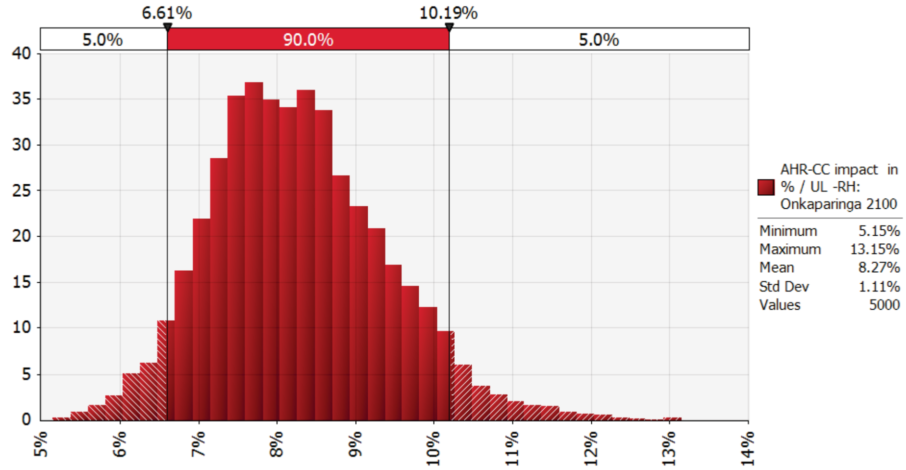
Comments:
These graphs show the following for asphalt/hotmix sealed roads for Onkaparinga City Council:

- the impact of climate change on costs is expected to be 2.27% reduction over the period to 2050;
- the impact of climate change on useful life (resurfacing) is expected to be 4.83% increase over the period to 2050; and
- the impact of climate change on useful life (rehabilitation) is expected to 5.78% increase over the period to 2050.

Onkaparinga City Council AHR 2100 Scenario
The 2050 results increase in the 2100 scenario:







Note: The first graph (previous page) shows the impact of climate change in costs (% change); the second graph (previous page) shows the impact of climate change on useful life (resurfacing) (% change); and the third graph (this page) shows the impact of climate change on useful life (rehabilitation) (% change). In all graphs the vertical axis represents frequency, and the horizontal axis represents the values of climate change impact with the statistics in the legend on the right hand side.

Comments:
These graphs show the following for asphalt/hotmix roads for Onkaparinga City Council:

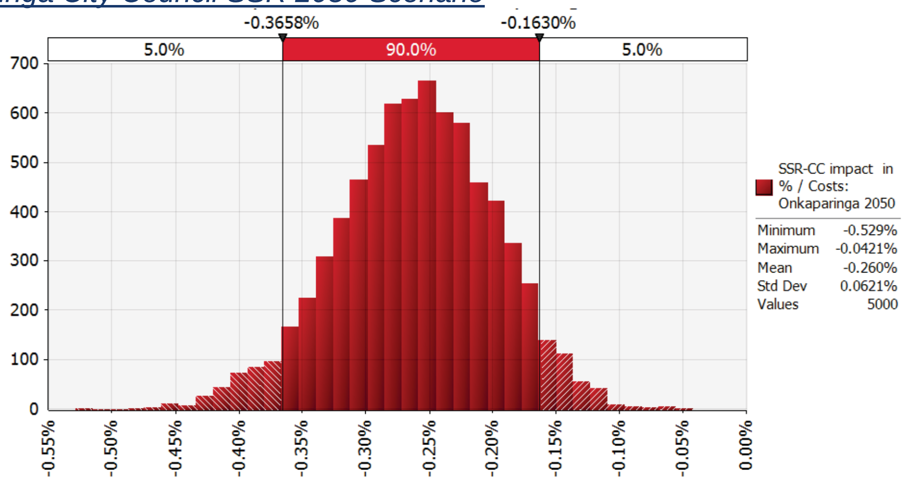
- the impact of climate change on costs is expected to be 3.60% reduction over the period to 2100;
- the impact of climate change on useful life (resurfacing) is expected to be 7.40% increase over the period to 2100; and
- the impact of climate change on useful life (rehabilitation) is expected to be 8.27% increase over the period to 2100.

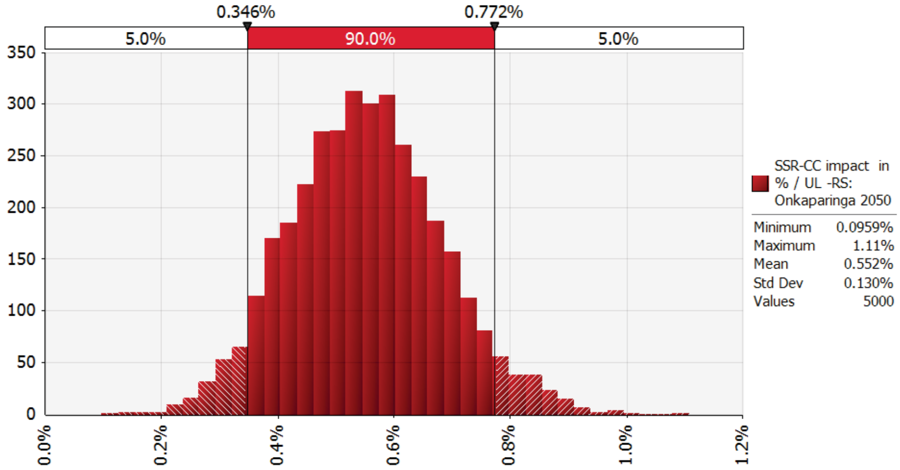
It will be noted from the summary of results that for asphalt/hotmix roads both 2050 and 2100 scenarios are below the mean values for the Councils sampled with respect to both cost reduction and useful life increase.

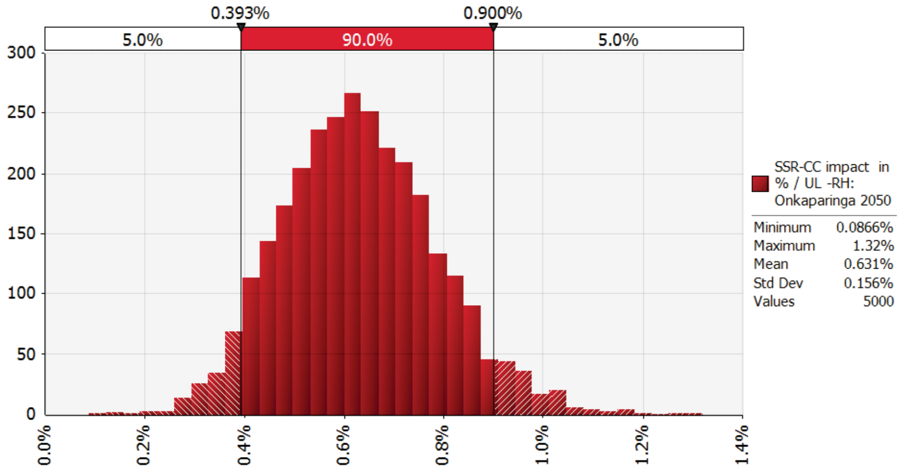
7.7.3 City of Onkaparinga Output: Spray sealed roads (SSR)

The reported results are based on a simulation with 5000 iterations. Two scenarios were modelled: years 2050, and 2100, each with percentage climate change impacts on costs and on useful life over those periods.

Onkaparinga City Council SSR 2050 Scenario





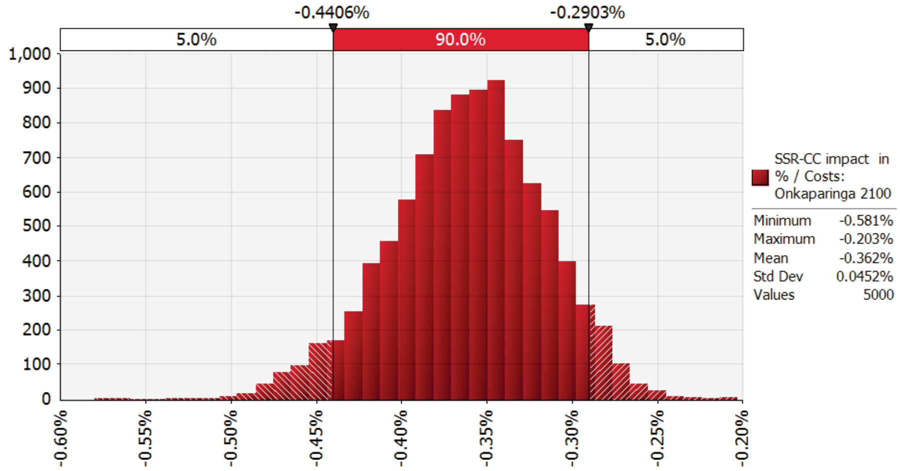


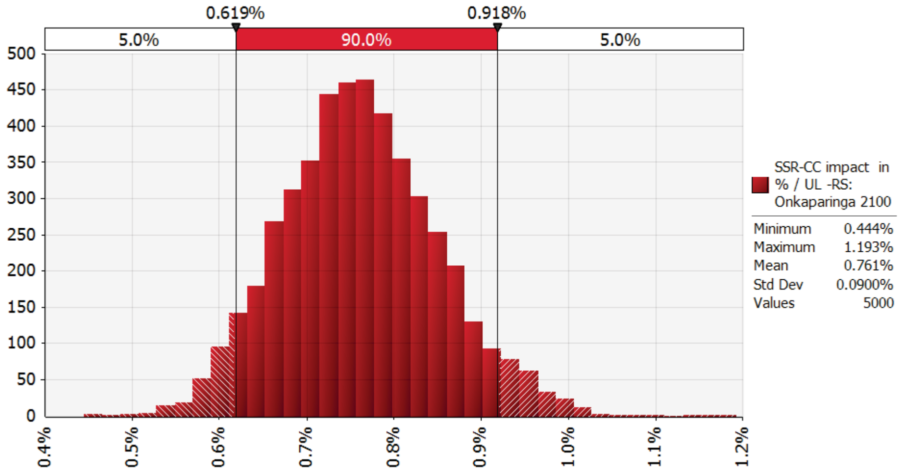
Note: The top graph shows the impact of climate change in costs (% change); the second graph shows the impact of climate change on useful life (resurfacing) (% change); and the third graph shows the impact of climate change on useful life (rehabilitation) (% change). In all graphs the vertical axis represents frequency, and the horizontal axis represents the values of climate change impact with the statistics in the legend on the right hand side.

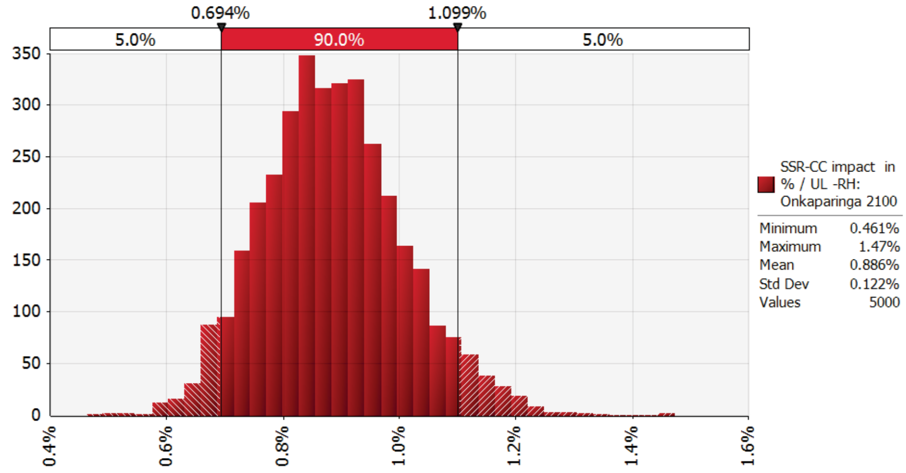
Comments:
These graphs show the following for sprayed-sealed roads for Onkaparinga City Council:

- the impact of climate change on costs is expected to be 0.26% reduction over the period to 2050;
- the impact of climate change on useful life (resurfacing) is expected to be 0.55% increase over the period to 2050; and
- the impact of climate change on useful life (rehabilitation) is expected to be 0.63% increase over the period to 2050.

Onkaparinga City Council SSR 2100 Scenario
The 2050 results increase in the 2011 scenario:







Note: The first graph (previous page) shows the impact of climate change in costs (% change); the second graph (previous page) shows the impact of climate change on useful life (resurfacing) (% change); and the third graph (this page) shows the impact of climate change on useful life (rehabilitation) (% change). In all graphs the vertical axis represents frequency, and the horizontal axis represents the values of climate change impact with the statistics in the legend on the right hand side.

Comments:

These graphs show the following for sprayed-sealed roads for Onkaparinga City Council:

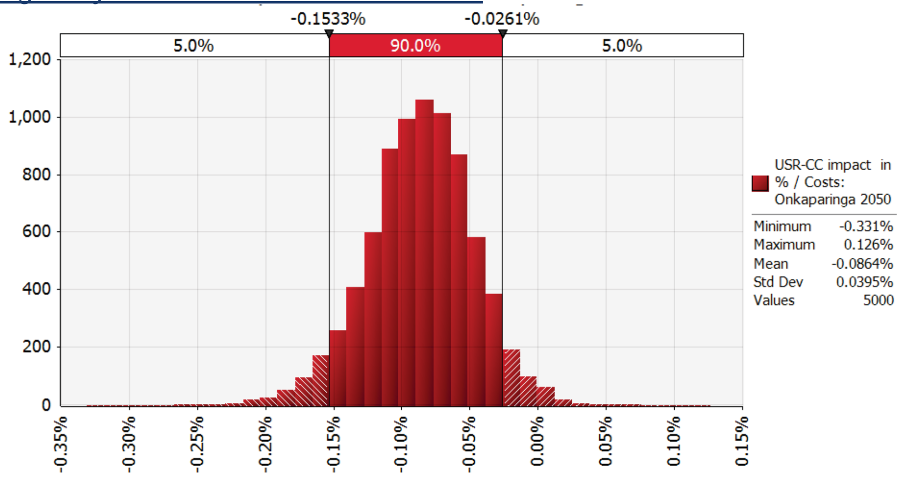
- the impact of climate change on costs is expected to be 0.36% reduction over the period to 2100;
- the impact of climate change on useful life (resurfacing) is expected to be 0.76% increase over the period to 2100; and
- the impact of climate change on useful life (rehabilitation) is expected to be 0.89% increase over the period to 2100.

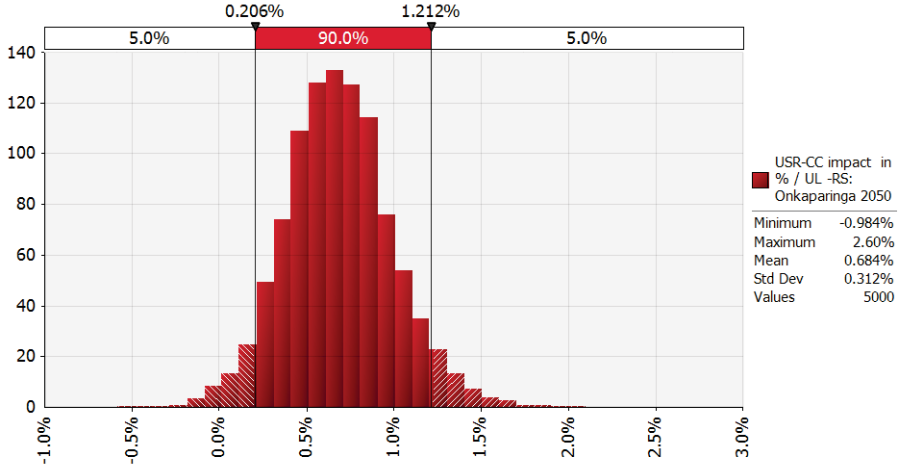
It will be noted from the summary of results that for sprayed-sealed roads under both 2050 and 2100 scenarios values are significantly smaller than for hotmix/asphalt roads. In the case of Onkaparinga City Council the results are close to the means for the Councils sampled.

7.7.4 City of Onkaparinga Output: unsealed roads (USR)

The reported results are based on a simulation with 5000 iterations. Two scenarios were modelled: years 2050, and 2100, each with percentage climate change impacts on costs and on useful life over those periods. Roads with extreme annual gravel loss (<3 mm thickness) were eliminated from the analysis as these roads are likely to be low in use and not appropriately maintained.

Onkaparinga City Council USR 2050 Scenario





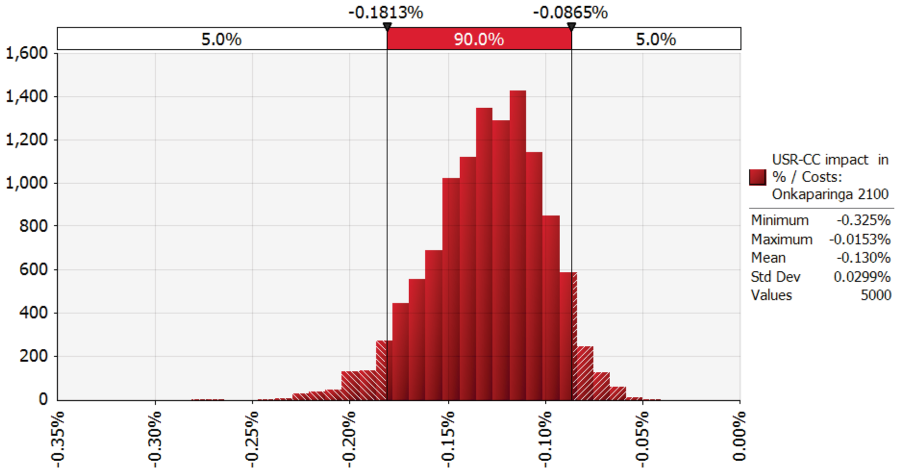
Note: The top graph shows the impact of climate change in costs (% change) and the lower graph shows the impact of climate change in UL (% change). In both graphs the vertical axis represents frequency, and the horizontal axis represents the values of climate change impact with the statistics in the legend on the right hand side.

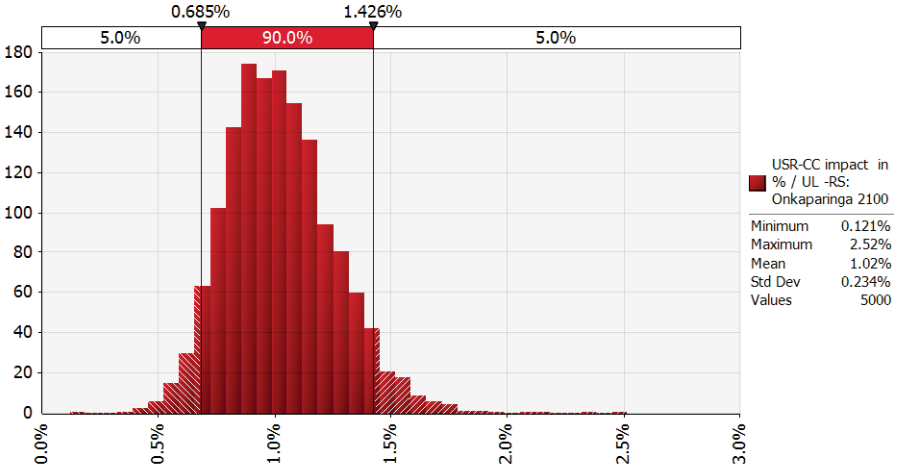
Comments:

These graphs show the following for unsealed roads for Onkaparinga City Council:

- the impact of climate change on costs is expected to be 0.09% reduction over the period to 2050; and
- the impact of climate change on useful life (resurfacing) is expected to be 0.68% increase over the period to 2050.

Onkaparinga City Council AHR 2100 Scenario
The results increase in the 2100 scenario:





Note: The top graph shows the impact of climate change in costs (% change) and the lower graph shows the impact of climate change in UL (% change). In both graphs the vertical axis represents frequency, and the horizontal axis represents the values of climate change impact with the statistics in the legend on the right hand side.

Comments:
These graphs show the following for unsealed roads for Onkaparinga City Council:

- the impact of climate change on costs shows a mean percentage reduction of 0.13% over the period to 2100; and
- the impact of climate change on useful life shows a mean percentage increase of 1.02% over the period to 2100.

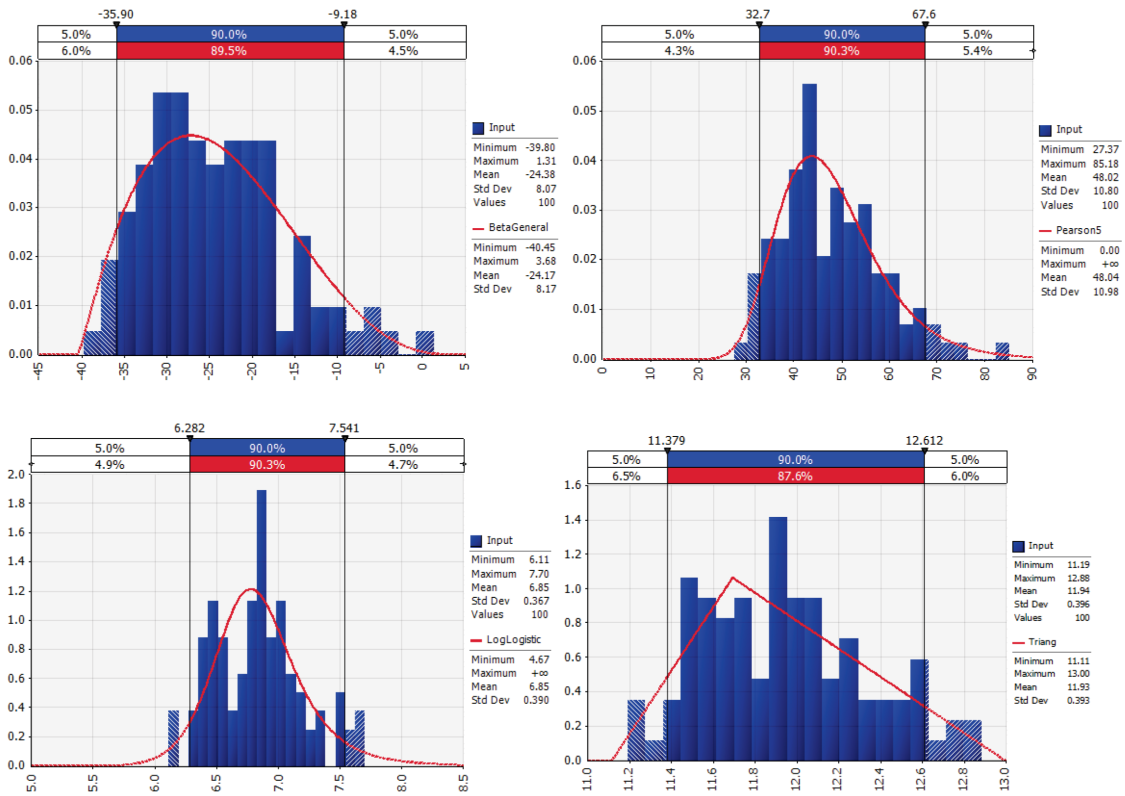
It will be noted from the summary of results that these are at the low end of the means for the Councils sampled.

7.8 Brighton Council

The Brighton Council area is located approximately 25 kilometres north-east of Hobart. The municipality is bordered by the municipalities of Derwent Valley, Southern Midlands and the City of Clarence and is traversed by the Midland Highway, the major corridor linking the north and the south of Tasmania. It covers an area of approximately 168 square kilometres. Prior to the early 1970's, Brighton was principally a rural municipality, but with the establishment of public housing estates in the late 1980's and early 1990's, the municipality is now considered to be a small urban Council. Brighton has a population of approximately 16,500 with a median age of 29 years and 95% of the population are under 65 years of age. As a peri-urban area, data for all three types of roads was available.

7.8.1 Fitted climate parameter distributions: temperature and precipitation: TI, MMP, T and Tmin: Brighton Council

Here we show the fitted distributions for the climate parameters: TI, MMP, Tmin and T for the Brighton Council. The displayed graphs are the historical distributions: that is, without climate change. The graphs that have been adjusted to include climate change are similar but are not presented here due to space limitations.

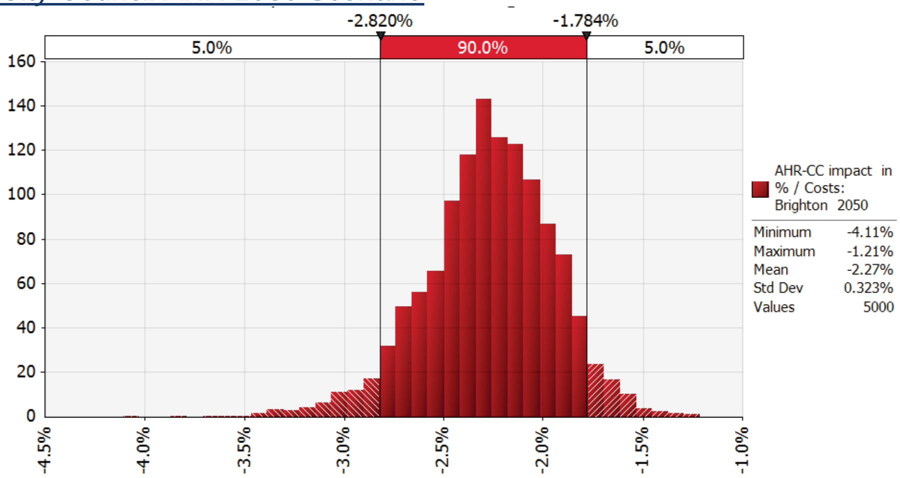


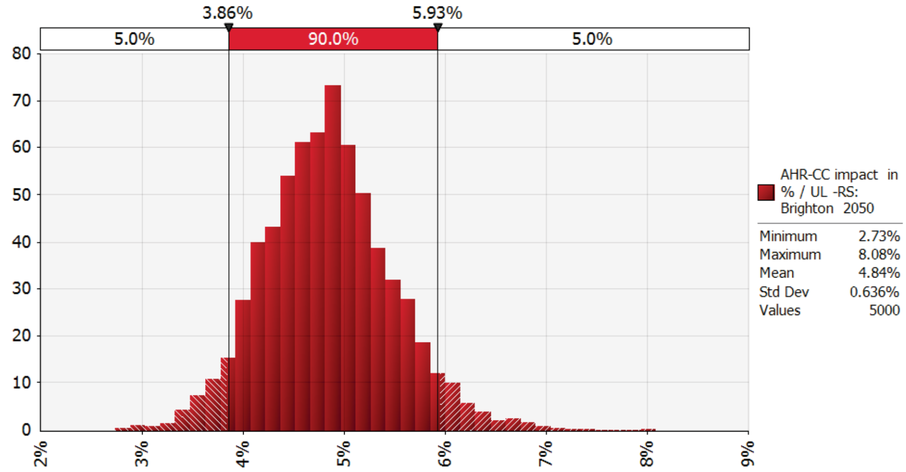
Note: For each graph, the vertical axis represents the fitted probability density function and the horizontal axis represents the values of the climate variable, with the statistics in the legend on the right hand side.

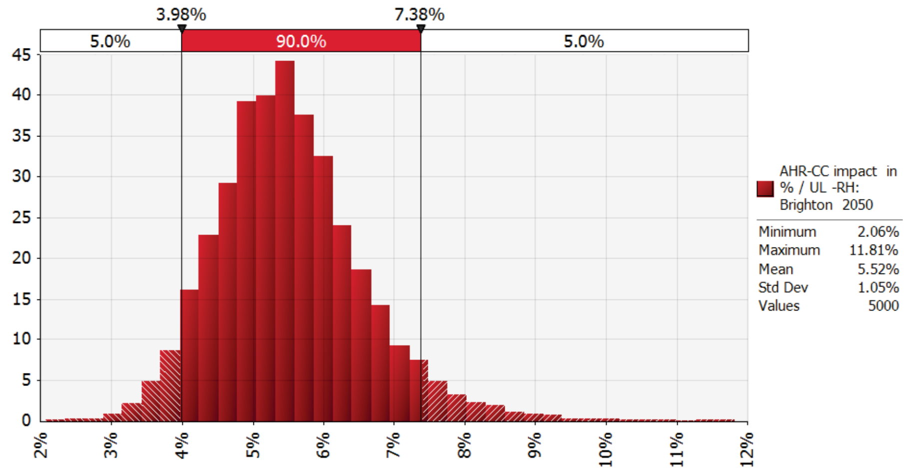
7.8.2 Brighton Output: Asphalt / Hotmix sealed road (AHR)

The reported results are based on a simulation with 5000 iterations. Two scenarios were modelled: years 2050, and 2100, each with percentage climate change impacts on costs and on useful life over those periods.

Brighton City Council AHR 2050 Scenario





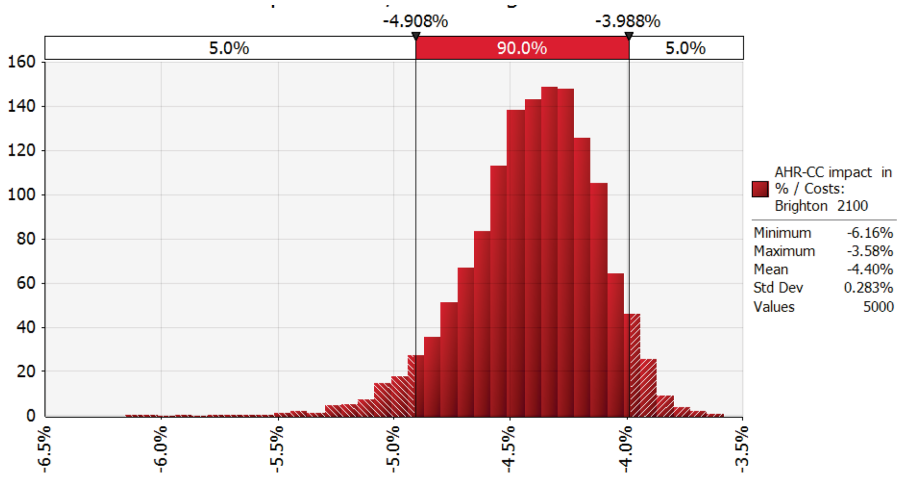


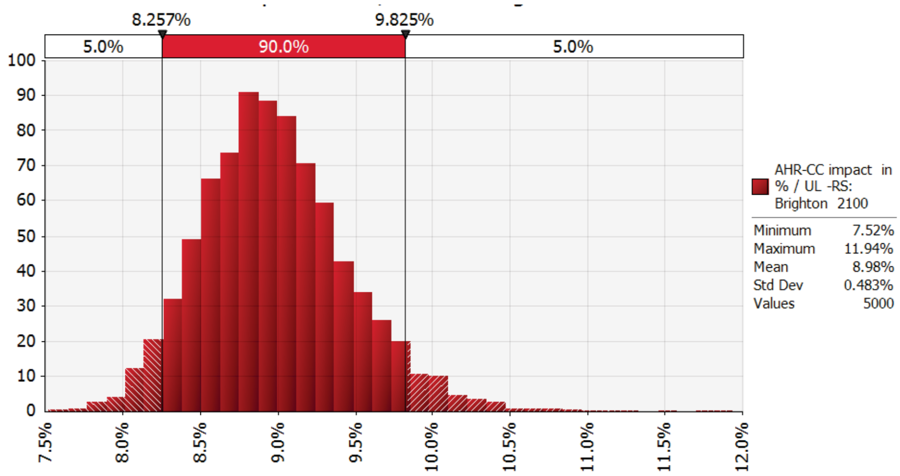
Note: The top graph shows the impact of climate change in costs (% change); the second graph shows the impact of climate change on useful life (resurfacing) (% change); and the third graph shows the impact of climate change on useful life (rehabilitation) (% change). In all graphs the vertical axis represents frequency, and the horizontal axis represents the values of climate change impact with the statistics in the legend on the right hand side.

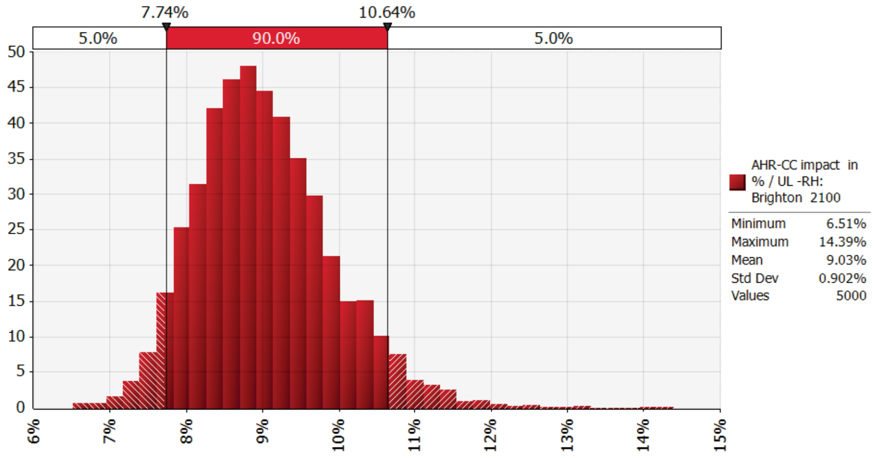
Comments:
These graphs show the following for asphalt/hotmix sealed roads for Brighton Council:

- the impact of climate change on costs is expected to be 2.27% reduction over the period to 2050;
- the impact of climate change on useful life (resurfacing) is expected to be 4.84% increase over the period to 2050; and
- the impact of climate change on useful life (rehabilitation) is expected to 5.52% increase over the period to 2050.

Brighton City Council AHR 2100 Scenario
The 2050 results increase in the 2100 scenario:







Note: The first graph (previous page) shows the impact of climate change in costs (% change); the second graph (previous page) shows the impact of climate change on useful life (resurfacing) (% change); and the third graph (this page) shows the impact of climate change on useful life (rehabilitation) (% change). In all graphs the vertical axis represents frequency, and the horizontal axis represents the values of climate change impact with the statistics in the legend on the right hand side.

Comments:
These graphs show the following for asphalt/hotmix roads for Brighton City Council:

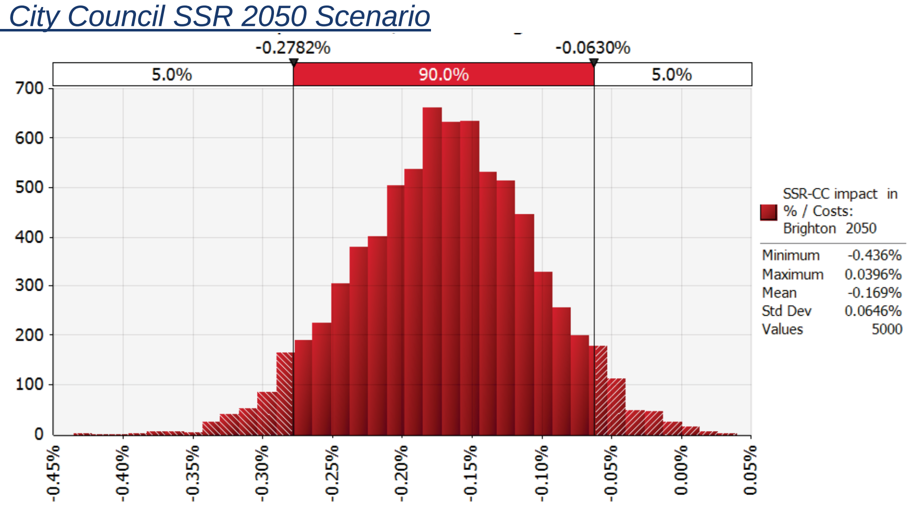
- the impact of climate change on costs is expected to be 4.40% reduction over the period to 2100;
- the impact of climate change on useful life (resurfacing) is expected to be 8.98% increase over the period to 2100; and
- the impact of climate change on useful life (rehabilitation) is expected to be 9.03% increase over the period to 2100.

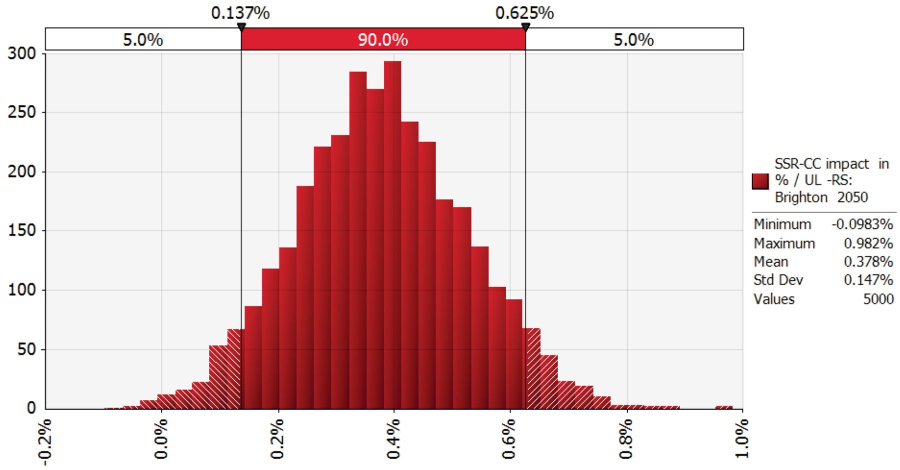
It will be noted from the summary of results that for asphalt/hotmix roads both 2050 and 2100 scenarios are at or slightly above the mean values for the Councils sampled.

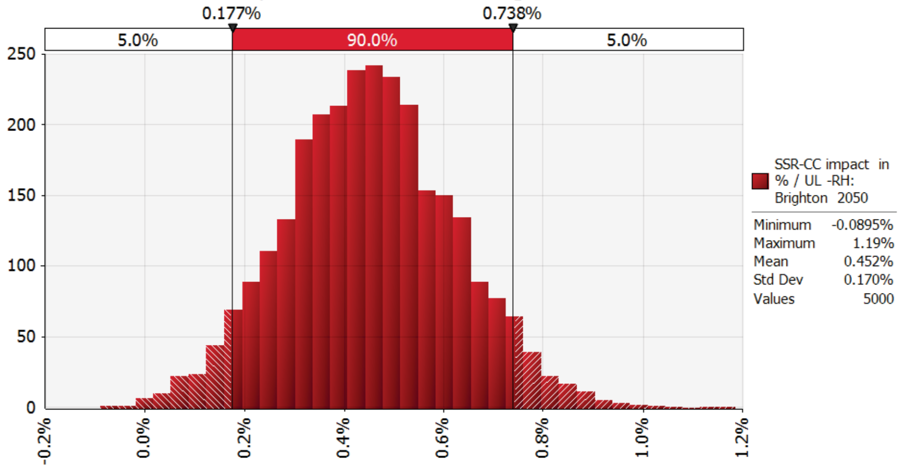
7.8.3 Brighton Output: Spray sealed roads (SSR)

The reported results are based on a simulation with 5000 iterations. Two scenarios were modelled: years 2050, and 2100, each with percentage climate change impacts on costs and on useful life over those periods.

Brighton City Council SSR 2050 Scenario







Note: The first graph (previous page) shows the impact of climate change in costs (% change); the second graph shows the impact of climate change on useful life (resurfacing) (% change); and the third graph shows the impact of climate change on useful life (rehabilitation) (% change). In all graphs the vertical axis represents frequency, and the horizontal axis represents the values of climate change impact with the statistics in the legend on the right hand side.

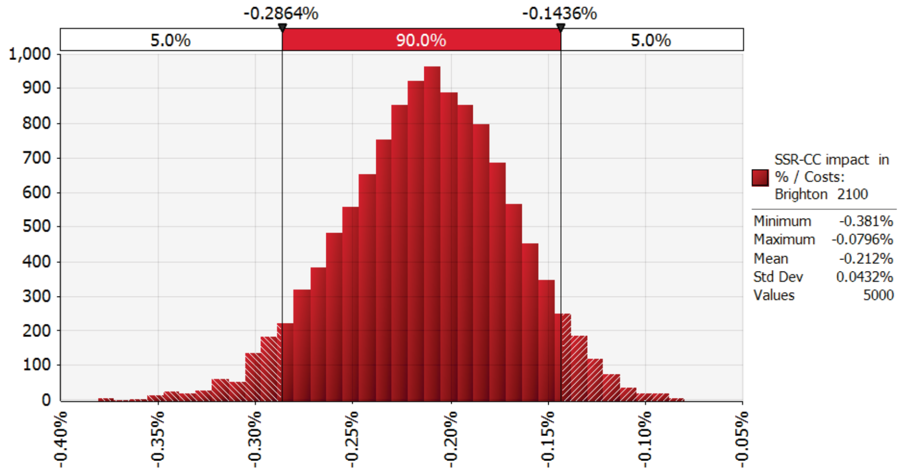
Comments:

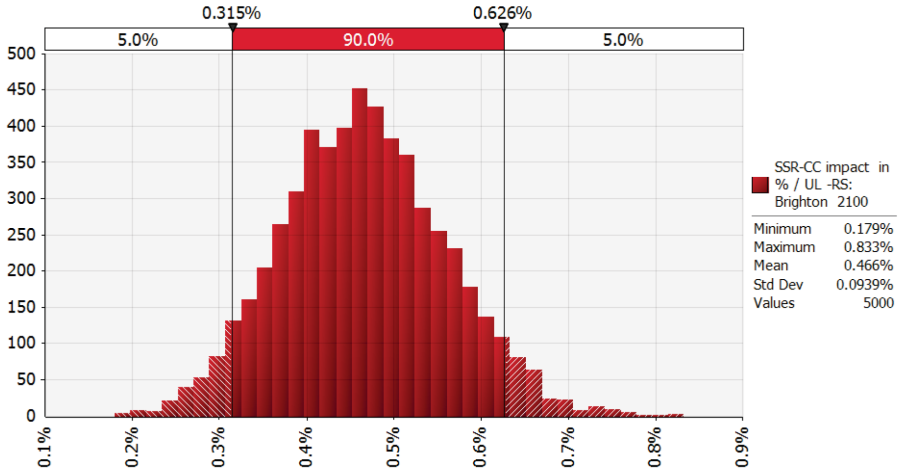
These graphs show the following for sprayed-sealed roads for Brighton City Council:

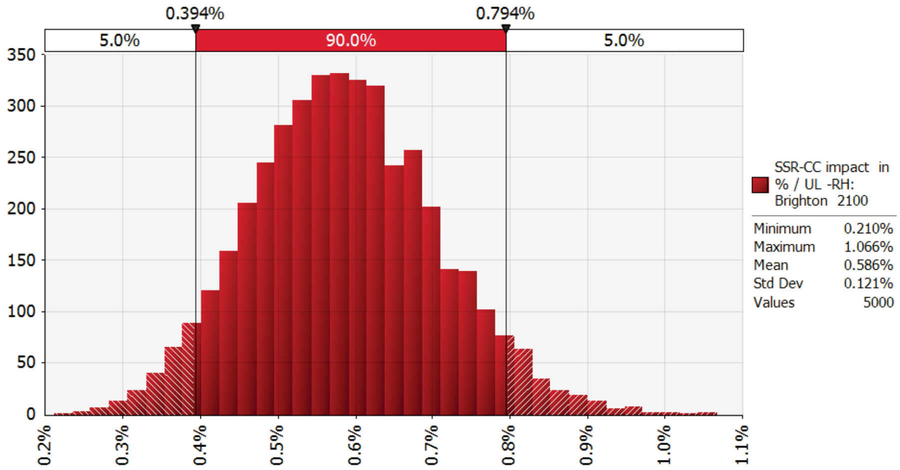
- the impact of climate change on costs is expected to be 0.17% reduction over the period to 2050;
- the impact of climate change on useful life (resurfacing) is expected to be 0.38% increase over the period to 2050; and
- the impact of climate change on useful life (rehabilitation) is expected to be 0.45% increase over the period to 2050.

Brighton City Council SSR 2100 Scenario

The 2050 results increase slightly in the 2011 scenario:







Note: The top graph shows the impact of climate change in costs (% change); the second graph shows the impact of climate change on useful life (resurfacing) (% change); and the third graph shows the impact of climate change on useful life (rehabilitation) (% change). In all graphs the vertical axis represents frequency, and the horizontal axis represents the values of climate change impact with the statistics in the legend on the right hand side.

Comments:

These graphs show the following for sprayed-sealed roads for Brighton City Council:

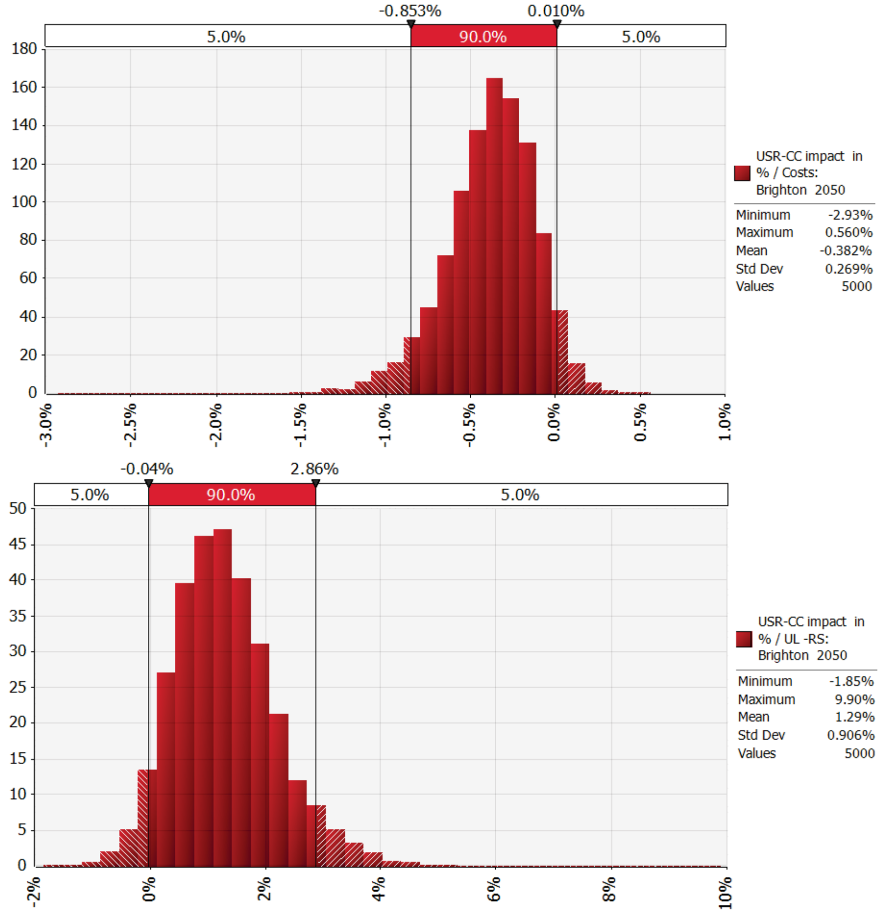
- the impact of climate change on costs is expected to be 0.21% reduction over the period to 2100;
- the impact of climate change on useful life (resurfacing) is expected to be 0.47% increase over the period to 2100; and
- the impact of climate change on useful life (rehabilitation) is expected to be 0.59% increase over the period to 2100.

It will be noted from the summary of results that for sprayed-sealed roads under both 2050 and 2100 scenarios values are significantly smaller than for hotmix/asphalt roads. In the case of Brighton Council the results are below the means for the Councils sampled.

7.8.4 Brighton Output: unsealed roads (USR)

The reported results are based on a simulation with 5000 iterations. Two scenarios were modelled: years 2050, and 2100, each with percentage climate change impacts on costs and on useful life over those periods. Roads with extreme annual gravel loss (<3 mm thickness) were eliminated from the analysis as these roads are likely to be low in use and not appropriately maintained.

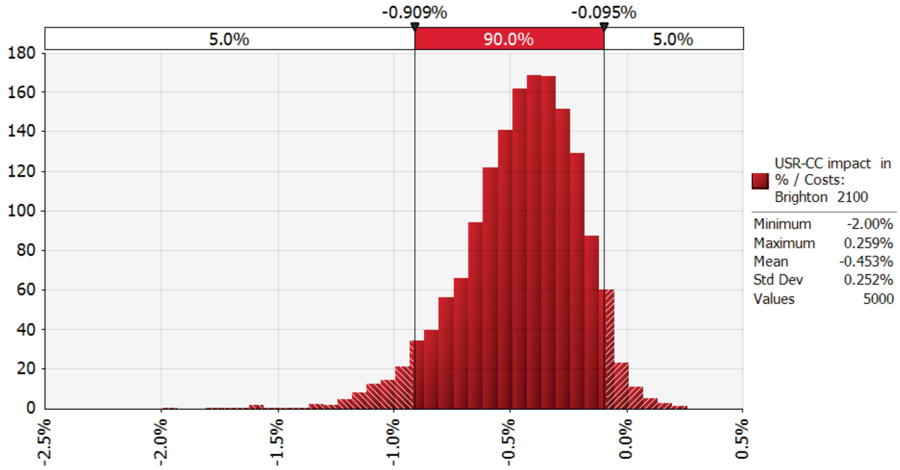
Brighton City Council USR 2050 Scenario

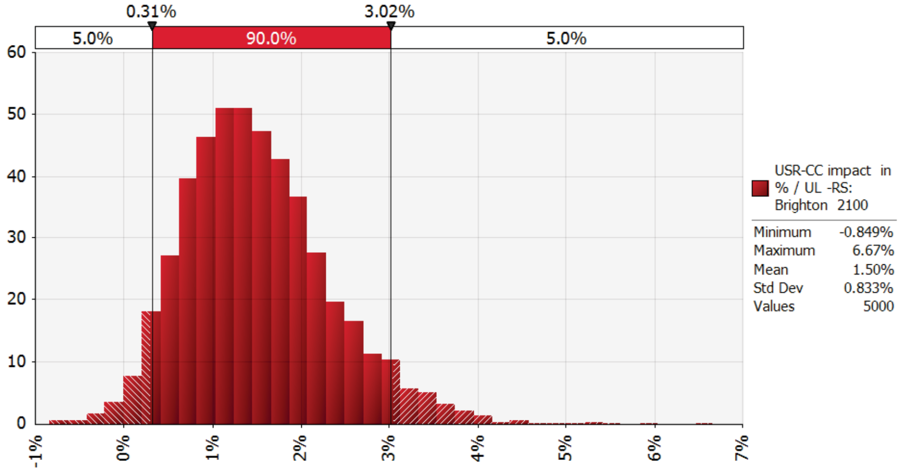


Note: The top graph shows the impact of climate change in costs (% change) and the lower graph shows the impact of climate change in UL (% change). In both graphs the vertical axis represents frequency, and the horizontal axis represents the values of climate change impact with the statistics in the legend on the right hand side.

Comments:
These graphs show the following for unsealed roads for Brighton City Council:
- the impact of climate change on costs is expected to be 0.38% reduction over the period to 2050; and
- the impact of climate change on useful life (resurfacing) is expected to be 1.29% increase over the period to 2050.

Brighton City Council USR 2100 Scenario
The results increase slightly in the 2100 scenario:





Note: The top graph shows the impact of climate change in costs (% change) and the lower graph shows the impact of climate change in UL (% change). In both graphs the vertical axis represents frequency, and the horizontal axis represents the values of climate change impact with the statistics in the legend on the right hand side.

Comments:
These graphs show the following for unsealed roads for Brighton Council:
- the impact of climate change on costs shows a mean percentage reduction of 0.45% over the period to 2100; and
- the impact of climate change on useful life shows a mean percentage increase of 1.50% over the period to 2100.

It will be noted from the summary of results that these are significantly below the means for the Councils sampled.

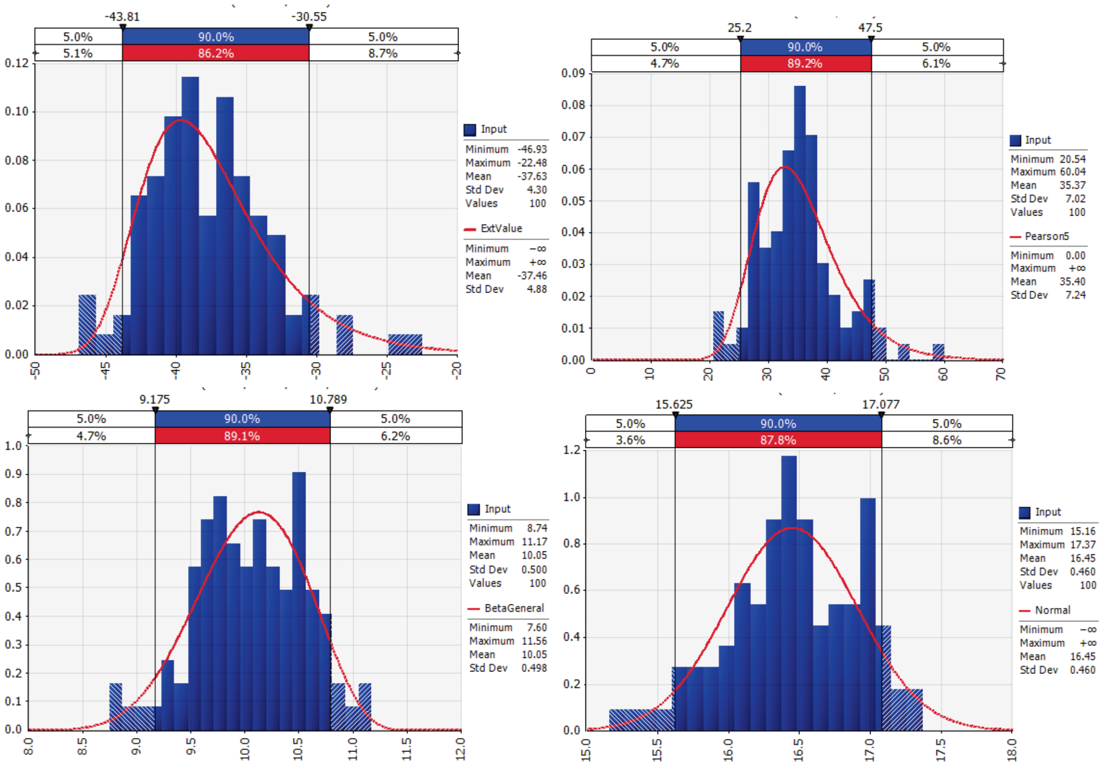
7.9 Shire of Esperance

The Shire of Esperance is located on Western Australia's southeast coast about 725 kilometres from Perth. The Shire has an area of 44,336 square kilometres, giving the region one of the lowest population densities in Australian Local Government. It includes over 400 kilometres of coastline, ranging from bays and the islands of the Recherche Archipelago to the cliffs of the Great Australian Bight. Its total population is approximately 14,500, and outside Esperance occupations are almost entirely in agriculture and associated industry.

Road surfaces are sealed within townships and on major highways, but a substantial proportion of the road network is unsealed.

7.9.1 Fitted climate parameter distributions: temperature and precipitation: TI, MMP, T and Tmin: Shire of Esperance

Here we show the fitted distributions for the climate parameters: TI, MMP, Tmin and T for the Shire of Esperance. The displayed graphs are the historical distributions: that is, without climate change. The graphs that have been adjusted to include climate change are similar but are not presented here due to space limitations.

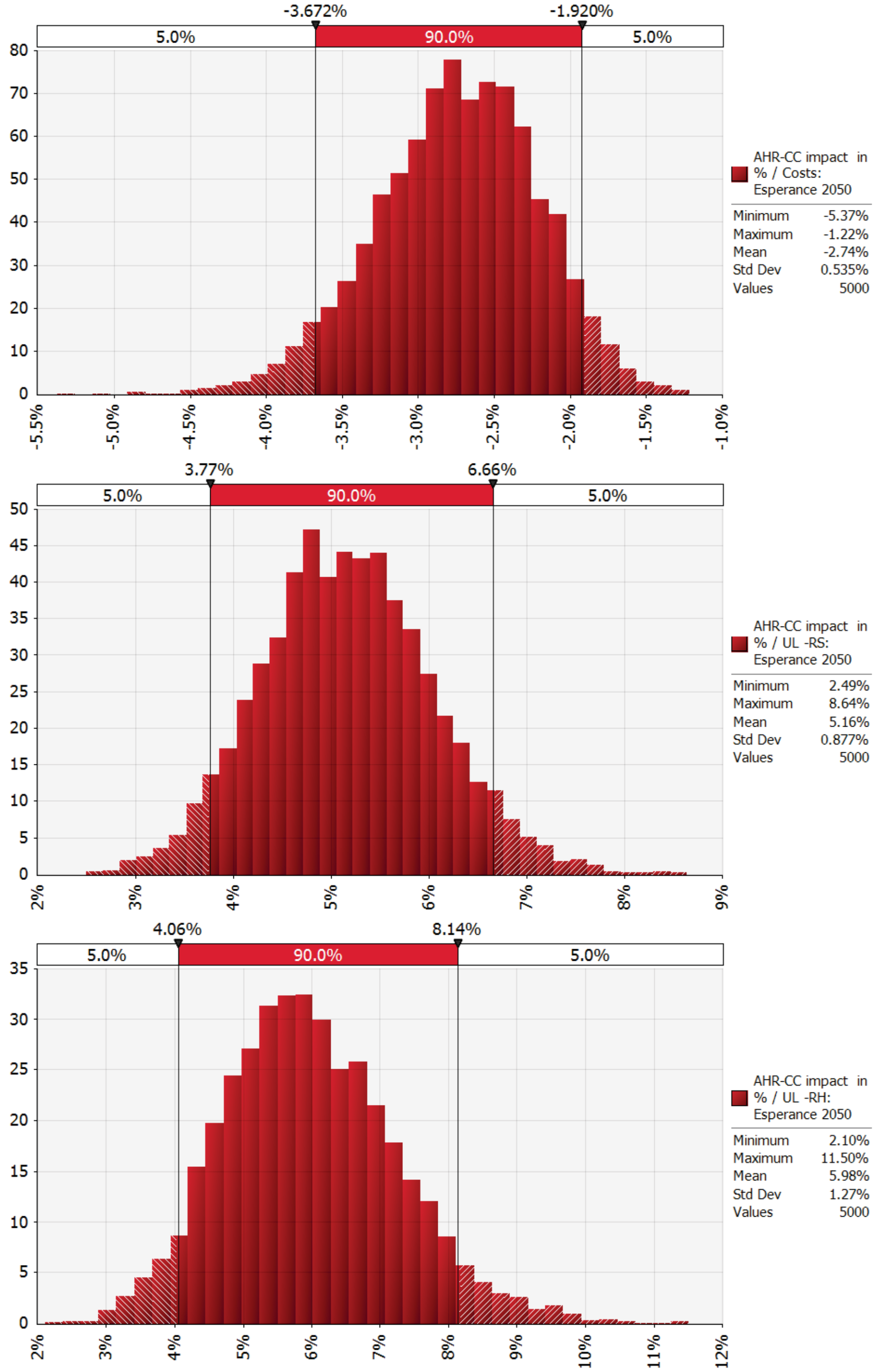


Note: For each graph, the vertical axis represents the fitted probability density function and the horizontal axis represents the values of the climate variable, with the statistics in the legend on the right hand side.

7.9.2 Shire of Esperance Output: Asphalt / Hotmix sealed road (AHR)

The reported results are based on a simulation with 5000 iterations. Two scenarios were modelled: years 2050, and 2100, each with percentage climate change impacts on costs and on useful life over those periods.

Esperance Shire Council AHR 2050 Scenario

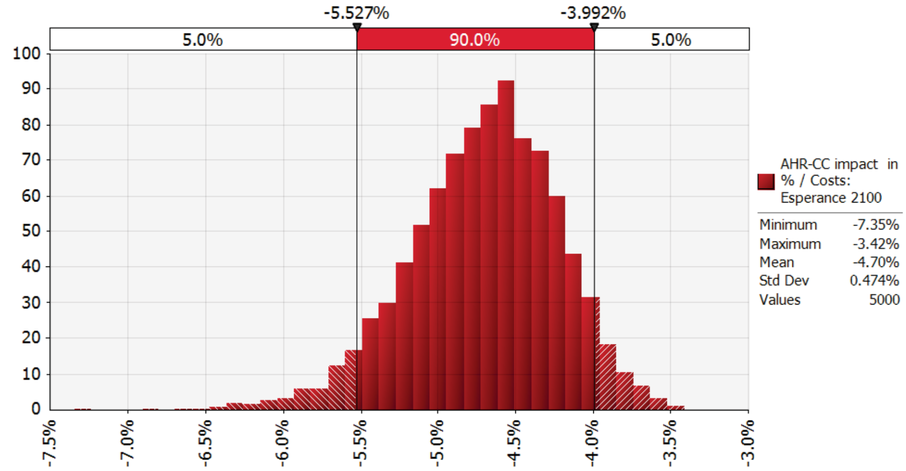


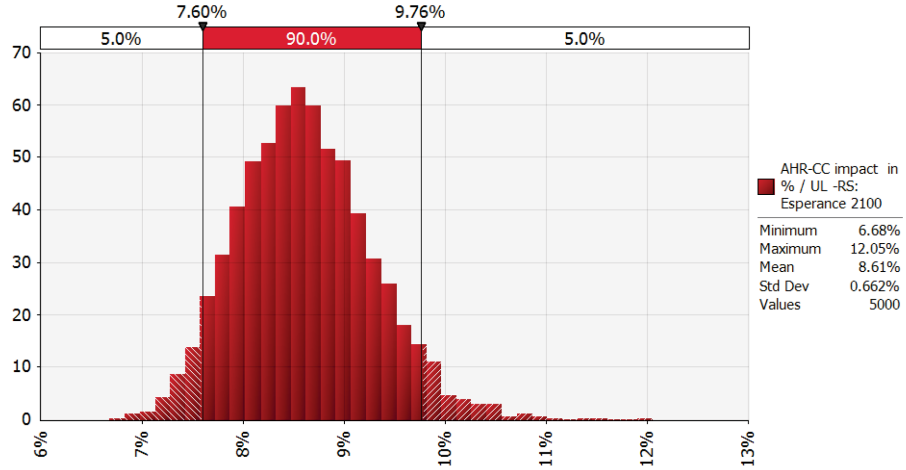
Note: The top graph shows the impact of climate change in costs (% change); the second graph shows the impact of climate change on useful life (resurfacing) (% change); and the third graph shows the impact of climate change on useful life (rehabilitation) (% change). In all graphs the vertical axis represents frequency, and the horizontal axis represents the values of climate change impact with the statistics in the legend on the right hand side.

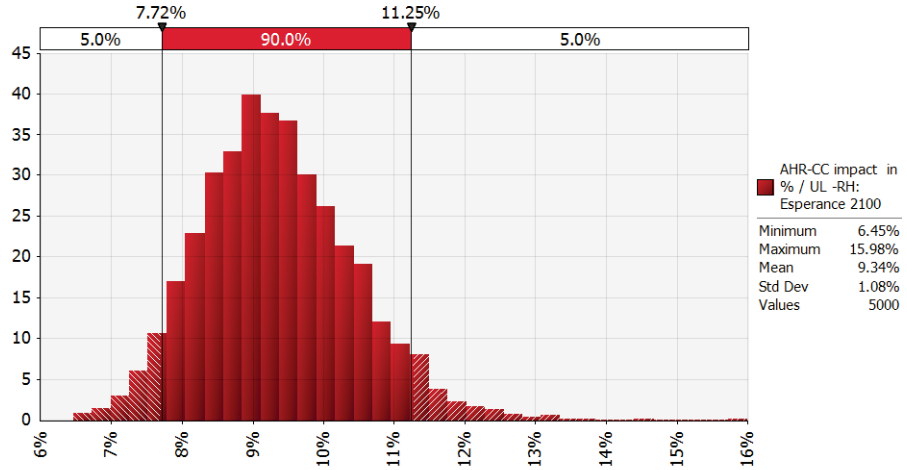
Comments:
These graphs show the following for asphalt/hotmix sealed roads for the Shire of Esperance:

- the impact of climate change on costs is expected to be 2.74% reduction over the period to 2050;
- the impact of climate change on useful life (resurfacing) is expected to be 5.16% increase over the period to 2050; and
- the impact of climate change on useful life (rehabilitation) is expected to 5.98% increase over the period to 2050.

Esperance Shire Council AHR 2100 Scenario
The 2050 results increase in the 2100 scenario:







Note: The first graph (previous page) shows the impact of climate change in costs (% change); the second graph (previous page) shows the impact of climate change on useful life (resurfacing) (% change); and the third graph (this page) shows the impact of climate change on useful life (rehabilitation) (% change). In all graphs the vertical axis represents frequency, and the horizontal axis represents the values of climate change impact with the statistics in the legend on the right hand side.

Comments:

These graphs show the following for asphalt/hotmix roads for the Shire of Esperance:

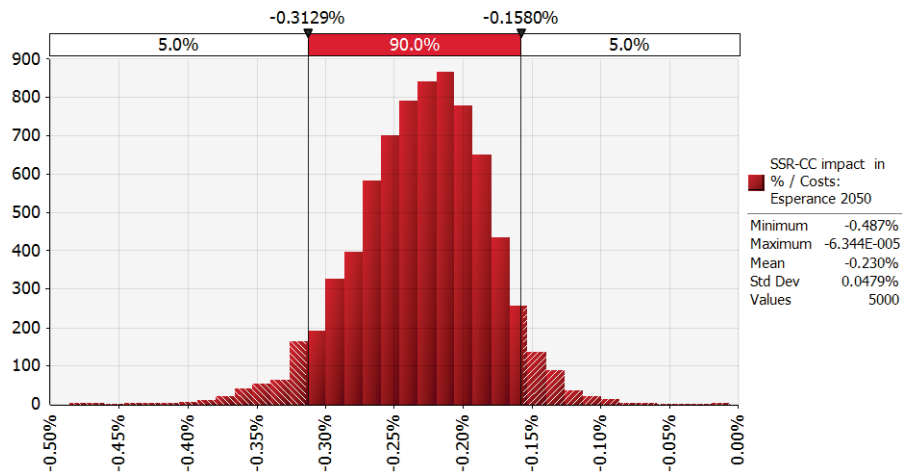
- the impact of climate change on costs is expected to be 4.70% reduction over the period to 2100;
- the impact of climate change on useful life (resurfacing) is expected to be 8.61% increase over the period to 2100; and
- the impact of climate change on useful life (rehabilitation) is expected to be 9.34% increase over the period to 2100.

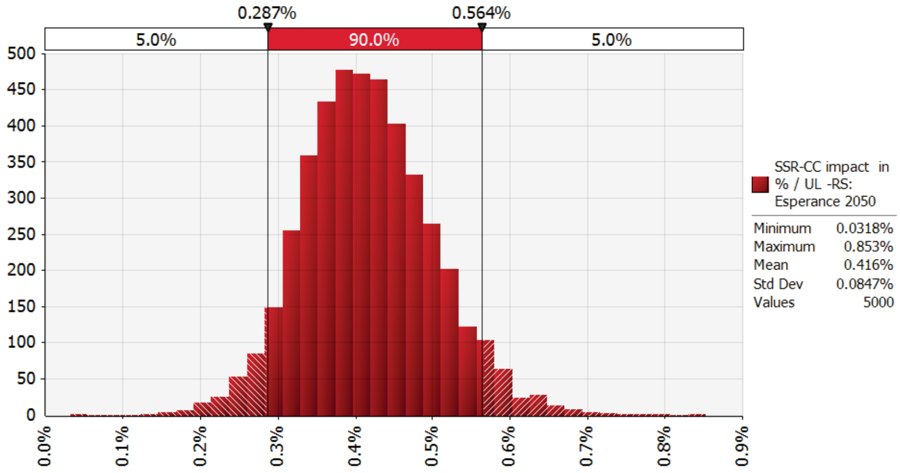
It will be noted from the summary of results that for asphalt/hotmix roads both 2050 and 2100 scenarios are at or slightly above the mean values for the Councils sampled.

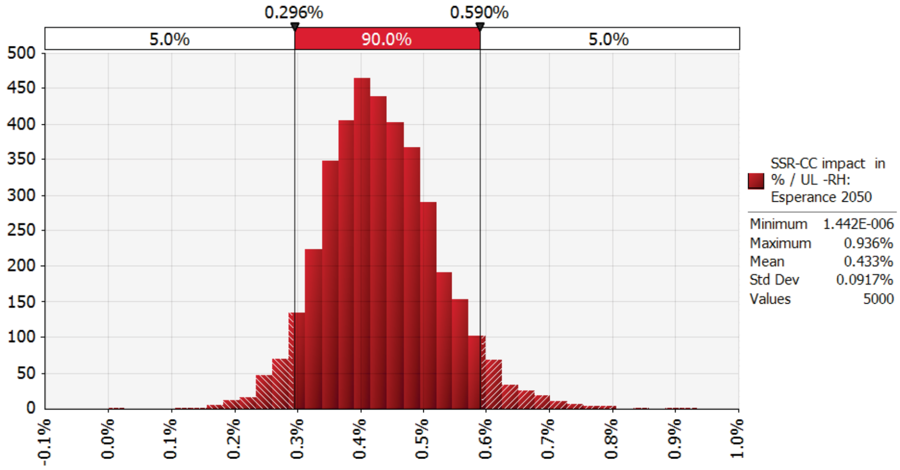
7.9.3 Shire of Esperance Output: Spray sealed roads (SSR)

The reported results are based on a simulation with 5000 iterations. Two scenarios were modelled: years 2050, and 2100, each with percentage climate change impacts on costs and on useful life over those periods.

Esperance Shire Council SSR 2050 Scenario







Note: The first graph (previous page) shows the impact of climate change in costs (% change); the second graph (previous page) shows the impact of climate change on useful life (resurfacing) (% change); and the third graph (this page) shows the impact of climate change on useful life (rehabilitation) (% change). In all graphs the vertical axis represents frequency, and the horizontal axis represents the values of climate change impact with the statistics in the legend on the right hand side.

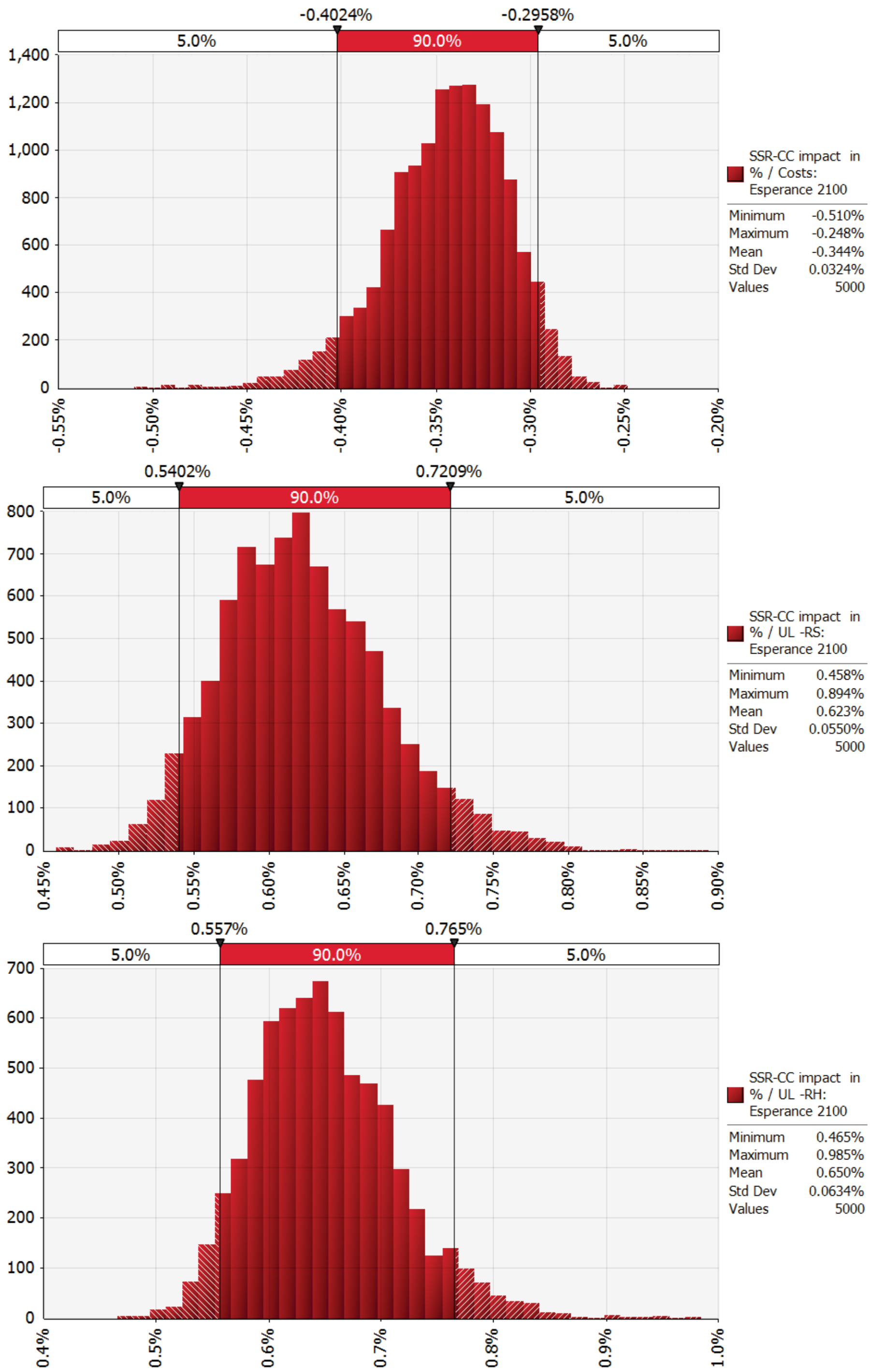
Comments:

These graphs show the following for sprayed-sealed roads for the Shire of Esperance:

- the impact of climate change on costs is expected to be 0.23% reduction over the period to 2050;
- the impact of climate change on useful life (resurfacing) is expected to be 0.42% increase over the period to 2050; and
- the impact of climate change on useful life (rehabilitation) is expected to be 0.43% increase over the period to 2050.

Esperance Shire Council AHR 2100 Scenario

The 2050 results increase slightly in the 2011 scenario:



Note: The top graph shows the impact of climate change in costs (% change); the second graph shows the impact of climate change on useful life (resurfacing) (% change); and the third graph shows the impact of climate change on useful life (rehabilitation) (% change). In all graphs the vertical axis represents frequency, and the horizontal axis represents the values of climate change impact with the statistics in the legend on the right hand side.

Comments:
These graphs show the following for sprayed-sealed roads for the Shire of Esperance:

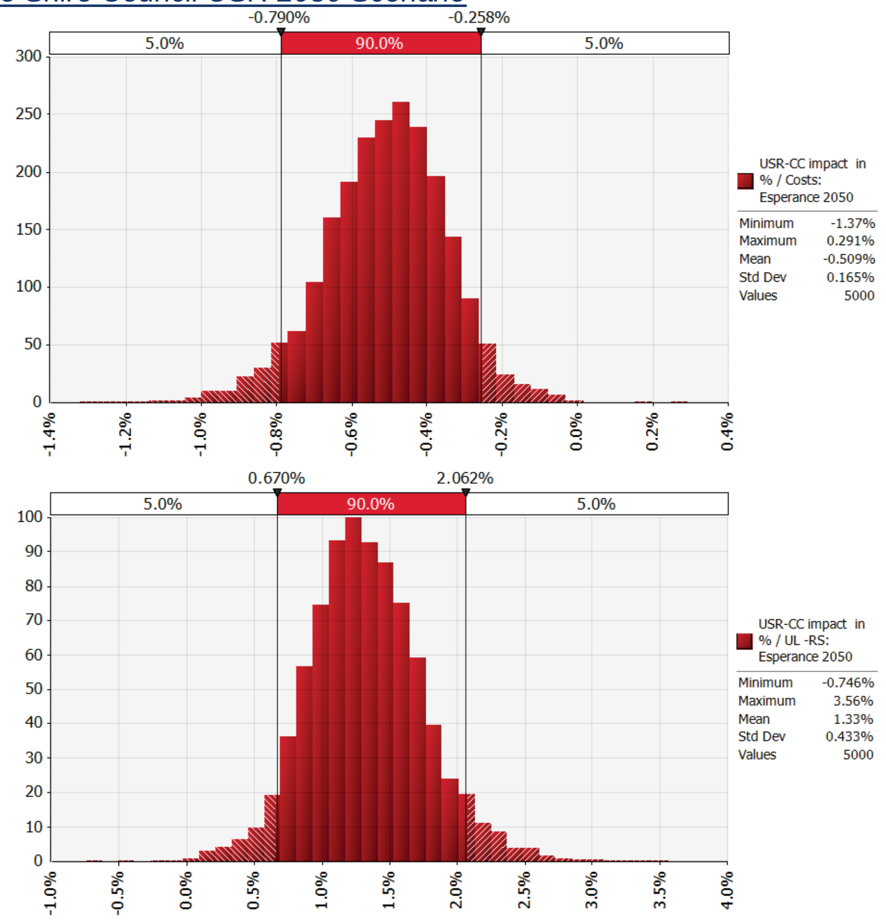
- the impact of climate change on costs is expected to be 0.34% reduction over the period to 2100;
- the impact of climate change on useful life (resurfacing) is expected to be 0.62% increase over the period to 2100; and
- the impact of climate change on useful life (rehabilitation) is expected to be 0.65% increase over the period to 2100.

It will be noted from the summary of results that for sprayed-sealed roads under both 2050 and 2100 scenarios values are significantly smaller than for hotmix/asphalt roads. In the case of the Shire of Esperance the results are at or below the means for the Councils sampled.

7.9.4 Shire of Esperance Output: unsealed roads (USR)

The reported results are based on a simulation with 5000 iterations. Two scenarios were modelled: years 2050, and 2100, each with percentage climate change impacts on costs and on useful life over those periods. Roads with extreme annual gravel loss (<3 mm thickness) were eliminated from the analysis as these roads are likely to be low in use and not appropriately maintained.

Esperance Shire Council USR 2050 Scenario

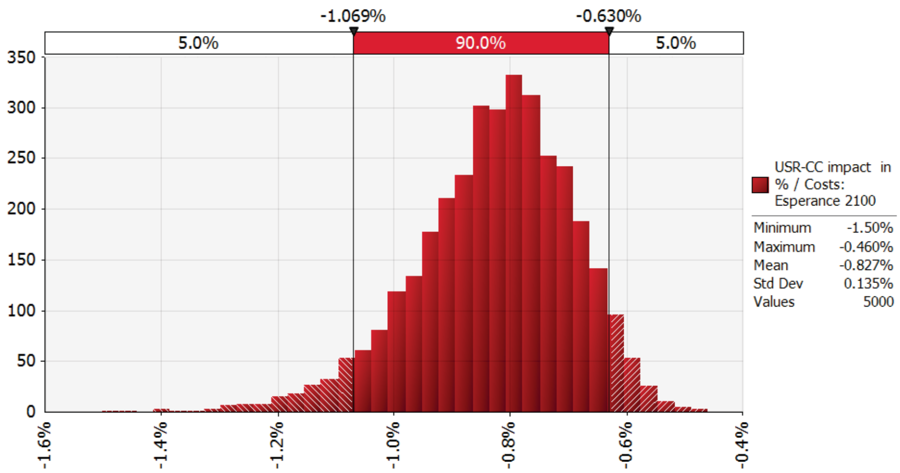


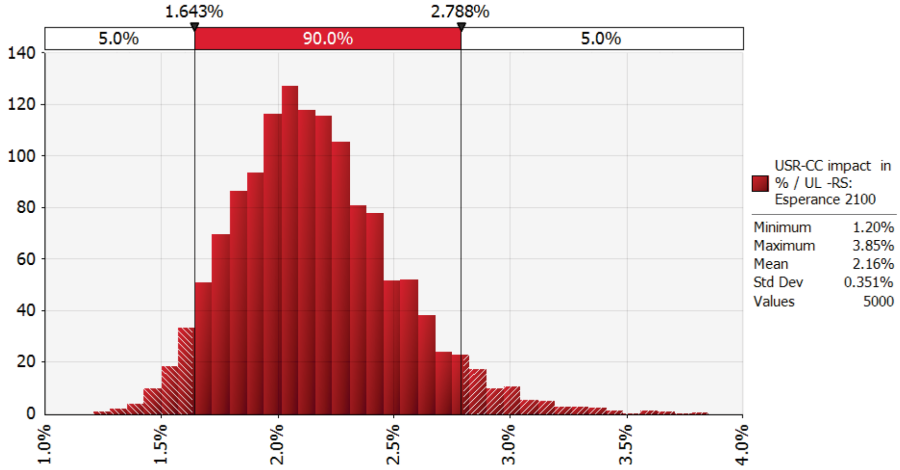
Note: The top graph shows the impact of climate change in costs (% change) and the lower graph shows the impact of climate change in UL (% change). In both graphs the vertical axis represents frequency, and the horizontal axis represents the values of climate change impact with the statistics in the legend on the right hand side.

Comments:
These graphs show the following for unsealed roads for the Shire of Esperance:

- the impact of climate change on costs is expected to be 0.51% reduction over the period to 2050; and
- the impact of climate change on useful life (resurfacing) is expected to be 1.33% increase over the period to 2050.

Esperance Shire Council USR 2100 Scenario
The results increase slightly in the 2100 scenario:





Note: The top graph shows the impact of climate change in costs (% change) and the lower graph shows the impact of climate change in UL (% change). In both graphs the vertical axis represents frequency, and the horizontal axis represents the values of climate change impact with the statistics in the legend on the right hand side.

Comments:
These graphs show the following for unsealed roads for the Shire of Esperance:

- the impact of climate change on costs shows a mean percentage reduction of 0.83% over the period to 2100; and
- the impact of climate change on useful life shows a mean percentage increase of 2.16% over the period to 2100.

It will be noted from the summary of results that these are significantly below the means for Councils sampled.

7.10 Summary and Discussion of Financial Modelling Trial Results

A summary of the financial modelling outputs for all Councils is provided in the following tables 8 and 9:

Table 8: Results from the financial model for each of the case study Councils for the 2050 climate scenario.

Terminal year=2050	Asphalt/Hotmix sealed roads			Spray sealed roads			Unsealed roads	
% change	Costs	UL-RS	UL-RH	Costs	UL-RS	UL-RH	Costs	UL-RS
Esperance SC	-2.74	5.16	5.98	-0.23	0.42	0.43	-0.51	1.33
Barossa							-2.97	10.1
Campbelltown City	-2.26	4.45	5.32					
Port Adelaide Enfield CC	-2.87	4.49	5.21					
Onkaparinga CC	-2.27	4.83	5.78	-0.26	0.55	0.63	-0.09	0.68
Bass Coast SC	-1.96	4.81	5.95	-0.22	0.61	0.70	-1.38	7.91
Hume CC	-3.04	4.55	5.65	-0.36	0.49	0.53	-0.11	0.45
Brighton	-2.27	4.84	5.52	-0.17	0.38	0.45	-0.38	1.29
Means	-2.49	4.73	5.63	-0.25	0.49	0.55	-0.91	3.63

Table 9: Results from the financial model for each of the case study Councils for the 2100 climate scenario.

Terminal year=2100	Asphalt/Hotmix sealed roads			Spray sealed roads			Unsealed roads	
% change	Costs	UL-RS	UL-RH	Costs	UL-RS	UL-RH	Costs	UL-RS
Esperance SC	-4.70	8.61	9.34	-0.34	0.62	0.65	-0.83	2.16
Barossa							-5.20	16.4
Campbelltown City	-3.61	6.89	7.90					
Port Adelaide Enfield CC	-4.5	6.94	7.80					
Onkaparinga CC	-3.60	7.40	8.27	-0.36	0.76	0.89	-0.13	1.02
Bass Coast SC	-3.76	8.84	9.23	-0.39	1.10	1.25	-2.50	13.4
Hume CC	-5.90	8.74	9.01	-0.60	0.82	0.89	-0.18	0.75
Brighton	-4.40	8.98	9.03	-0.21	0.47	0.59	-0.45	1.50
Means	-4.35	8.06	8.65	-0.38	0.75	0.85	-1.55	5.87

The key conclusions derived from the pilot financial modelling are:

1. Over the periods modelled, the incremental impact of climate change on road infrastructure of all three types appears to be at generally low levels.
2. Inspecting the direction and magnitude of values in both scenarios:
   (a) There are small cost reductions over the period for all road types, higher for AHR.
   (b) Useful life for resurfacing increases significantly more for AHR and USR than for SSR.
   (c) Useful life for rehabilitation increases significantly more for AHR than for SSR.

(d) For AHR and SSR, the range across Councils is narrow, clustering closely around the mean.
(e) For USR, although the range for costs is reasonably narrow (Barossa is an outlier), there is a significant range for useful life, with both Barossa and Bass Coast returning much higher results.
(f) The 2100 scenario maintains the directions of these results, at greater magnitudes.

3. As the engineering formulas show, an increase in temperature and decrease of precipitation is likely to improve road surface performance. This result is indicated by small reductions in total cost and small increases in useful life of all three road types. The range of effects is also largest for the USR category: this may reflect, in part, different methods of USR construction and different methods of data collection, both of which are more variable for USR.
4. The impacts of climate change, though small, are greatest for USR, because mean monthly precipitation is a direct driver of gravel loss; hence reductions in precipitation decrease gravel loss, as would be expected.
5. AHR ranks second in the size of effect, followed by SSR. This result may reflect the differential binding of aggregates, sands and fillers under a warming temperature regime.
6. This model, like all financial models, is based on key inputs from climate data and engineering road performance formulas, and is therefore subject to the theoretical assumptions, data structures, and empirical testing of those areas. In addition, important assumptions have been made in the financial modelling in the way climate inputs are configured and in the simulations conducted.

   Further, there are factors that have been identified as important, but which have not been incorporated fully in the modelling. For example, extreme events are not well understood and not well captured in the data, and are hence handled in situ, rather than through theoretically-driven variables, in the model.

   The pilot studies provide a first empirical test of these assumptions. However, the cumulative effect of assumptions, across disciplines, in the financial modelling should not be underestimated.
7. Subject to those caveats, we conclude that the approach taken in this section of the project has proven to be reliable and consistent. The simulation modelling is based on a sound theoretical and empirical foundation, in both engineering and climate science. The main achievement of this work, we believe, is to show that climate data can be effectively captured and configured as inputs to the engineering performance formula, and that the implications of this work can be taken as inputs to financial modelling to generate coherent cost and useful life projections. These then can become valuable inputs into Local Government management instruments. This integrated outcome, we believe, represents a practical and well-founded contribution to international work in the science and practice of climate change adaptation and management.
8. We should note that the above simulation results are based on a real discount rate of 2.85%. Our selection of discount rate is based on the following considerations:
   - Councils are different from commercial firms and they have low financial risk. Thus the discount rate should be close to the risk free rate as often measured by the long-term government bond yield in Australia;

- over the period from 1971 to 2008, the average rate of return on 10-year government bond is 9.2% while the average inflation rate during the same period is 6.2% (these figures can be derived based on the data from Reserve Bank of Australia). Thus, the average real rates of return over the period is about 3%;
- the current interest rates (around 2010) in Australia are low compared to historical interest rates; and
- we evaluated the climate change impacts over a longer period of 90 years.

We thus pick up a discount rate of 2.85% which is slightly lower than the average real rate of return on the 10-year government bonds over the period from 1971 to 2008. Of course, the discount rate for different Councils can be slightly different and it can also vary over time for the same Council. Thus discount rate can never be precise and can be a contentious issue. If necessary, a sensitivity analysis can be carried out with respect to the discount rate. However, in our case, the consistent results from the field studies do not appear render it as necessary.

We note that we have considered three asset road classes as part of this study: AHR, SSR and USR. Together they account for nearly all the roads owned by Local Governments across Southern Australia. Model outputs can provide a guide to Local Government regarding climate change policy, e.g. in terms of capital budgeting.

7.11 Incorporation of the Financial Model into the NAMS.PLUS Software Framework

The model developed is compatible with the NAMS.PLUS software described in Section 9.7 or any other Excel ® based financial or asset management system but does require the @RISK software plug in to run the simulations. Currently the NAMS.PLUS template includes projections on asset renewal requirements based on useful service life. Outputs from the model developed in this project are easily included in the NAMS.PLUS framework by using the expected change in useful service life of the asset, and the likely increased costs associated with this change, due to climate change and using the adjusted useful service life figure to calculate renewal costs. The NAMS.PLUS output can then provide a forward prediction of renewal costs incorporating the climate change impacts.

Currently NAMS.PLUS is undergoing an upgrade process and IPWEA are considering the inclusion of the model developed as part of this project in the next version of the software. Preliminary discussions with Palisade Corporation, the developers of @Risk, it is considered viable to link the @Risk output with the NAMS.PLUS platform. However, the cost for setting up the link and likely returns on a commercial scale product need to be considered in the evaluation of future options for the model as part of the NAMS.PLUS software and are currently under examination by IPWEA.

8 CONCLUSIONS AND FUTURE RESEARCH DIRECTIONS

8.1 Conclusions

As defined in the project scope, the aims of this project were to: describe the current and likely changes in the climate across Southern Australia; identify key Council assets that may be affected by climate change; determine the likely impacts of climate change on Council assets; undertake a financial risk modelling exercise to quantify in monetary terms the climate change asset risk; develop the necessary modifications to existing asset management and financial sustainability tools so that Councils may evaluate various climate change action scenarios at the management planning level.

Over the coming century, the greenhouse gas emissions already released into the atmosphere and those that will continue to be released will cause continued warming of the climate and oceans, increase the number of hot days and nights, increase the frequency and intensity of bushfire events in the mid-latitudes, drive changes in rainfall amount, timing and intensity, increase evaporation, and alter the coastal zone as a result of sea level rise, increased erosion and ocean acidification. Southern Australia will likely become drier as a result of decreased rainfall, increased temperatures and both evaporation and evapotranspiration. Each of these changes is detailed in Chapter 2.

Approaches for managing the impacts of climate change on Local Government infrastructure and assets are examined in Chapter 3, both internationally and in Australia. A range of risk assessment, asset management and financial management methodologies, practices and tools are reviewed within the context of Local Government infrastructure management with the aim of identifying current best practice and Council reporting obligations. In particular, the progress towards quantifying and managing roads as the largest asset class by value to Local Government is examined. The NAMS.PLUS asset management framework and tools developed by the Institute of Planners and Water Engineers Australia (IPWEA) was identified as providing the best vehicle by which to deliver the financial model developed as part of this study. On the basis of these findings the impact of climate change on three asset classes for roads (spray sealed, asphalt/hotmix sealed and unsealed roads) were the quantified and modelled.

Chapter 4 describes in detail the impact of climate on each of the three road types identified and provides a review of existing engineering road deterioration mathematical models that were assessed to determine suitability for the development of a climate change road impact model as part of this project. The impacts of climate on a range of other materials used in Local Government infrastructure (e.g. concrete and steel) were also reviewed and are included in Appendix 2.

Chapter 5 reviews approaches to mathematically modelling the impacts of climate change that have been developed both overseas and in Australia and ways in which uncertainty in future climate projections are treated. The methods used, model structure, data requirements and inputs for the financial model developed in this study are detailed in Chapter 6. The climate component of the model contains historical monthly temperature and rainfall data for the period from 1911 to 2010 averaged over the Local Government area that are then used to generate future climate distributions for the four key climate variables identified to affect the road types selected. By avoiding the use of Global Climate Model outputs in the generation of future climate scenarios, the historical distributions can be adjusted for a range of IPCC SRES forecasts or other arbitrarily selected climate change scenarios that might, for example, be used for sensitivity analysis. Adjustments to rainfall data are made at the monthly scale prior to calculating annual values, to take into account the uneven distribution of rainfall throughout the year. The climate change impact in terms of costs to road maintenance and repair is determined as the difference between the total present value of costs with and without climate change. Using an annuity formula, these costs were then also transformed to quantify the impact in terms of changes to the estimated useful life of the road asset.

As the mechanisms for the impact of climate change on different types of roads are different, the three road asset classes (Asphalt /Hotmix, Spray Sealed and Unsealed roads) were treated separately. To test the Model and illustrate the outputs, an A1FI SRES climate change scenario was modelled for two time periods (2010 to 2050 and 2010 to 2100) at each of eight case study Local Government locations across South Australia, Victoria, Western Australia, and Tasmania using real data provided by the Council. Data were obtained from Councils from both site meetings, teleconferencing and electronic communication. It is noted that there were significant differences between Councils on data availability and accuracy, deriving in part from different types, stages and implementations of asset management systems.

Key conclusions derived from the pilot modelling were: (1) Over the periods modelled the incremental impact of climate change on road infrastructure of all three types appears to be generally small and positive, with respect to both useful life and costs; and (2) Results across Councils clustered around the mean for asphalt/hotmix and spray sealed roads, but across a significantly wider range for unsealed roads. Trends evident in the 2050 scenario were amplified for the 2100 scenario. It is important to note, that although the most rigorous models available have been used in the development of our Financial Simulation Model, outputs of the Model are dependent on the capacity of the engineering road deterioration equations to predict the impacts of climate change on their maintenance costs and useful life.

The development and trialling of the Financial Simulation Model on selected case study Local Government areas has shown that climate change is likely to have an impact on the life of road assets, both unsealed and sealed, even though that impact is calculated to be quite small, in comparison to current life expectancy for the asset class. As the Model combines economic modelling, asset deterioration models, climate data and the option to test a range of climate projections to provide life cycle estimates as an output, it is well suited to interface with the NAMs industry standard asset management practice framework.

The use of the model, and its capacity for seamless future integration with the NAMs asset management approach, as well as other conventional asset management frameworks and forecasting systems provides a scientifically robust, easily replicable, and reasonably transparent means for Local Government authorities to take into account the possible impacts of climate change in the long term management of their largest infrastructure asset category.

Due to the significant level of investment and the long term planning time frame required to effectively manage this extensive network of long lived assets, long term financial planning is required, along with a degree of confidence in life cycle estimates. By modelling the potential impact of climate change on the useful life of this asset class, more informed decisions can be made regarding the potential cost, and timing of renewal investment. If the modelled impacts result in changed life cycles for the assets, armed with the knowledge of how climate change may impact on the life cycle, Councils can choose to make adjustments to service levels to help accommodate the required investment decisions, and therefore reduce the potential for a renewal funding “gap”, or seek to adapt investment levels to match desired outcomes.

The use of the Financial Simulation Model will therefore provide a means for Councils to reduce the level of uncertainty around these longer term investment decisions. Due to the high levels of investment involved in road asset renewal and management, use of the model offers the potential to reduce Council’s exposure to risk from prematurely, or unexpected failure of assets, poor investment decisions, or inadequate long term financial planning by allowing better informed decision making.

As a pilot study the development of this climate change Financial Simulation Model for road assets means there is now a framework that allows for integration of climate change research and predictions, economic modelling and asset deterioration models. In this way, the Model is also suited to future adaptation for other asset classes and types, as better deterioration models are developed for these assets.

Pending future development of suitable deterioration models for other asset classes and adaptation of the model framework to accommodate them, more widespread use of the model is envisaged to guide informed decisions on investment or service levels and contribute to reduced risk exposure.

Although as part of the project we visited each of the case study Councils and worked with them in the development of the Model and input tool, larger scale trials would be advisable before releasing the Model at a commercial scale. Current negotiations with IPWEA about inclusion of the Model into the NAMS.PLUS software are considering options for the possible extension of the Model to a wider audience. However, it may be the case that for some Local Governments that the analysis now possible is more detailed and sophisticated than the data and analysis currently contained in their infrastructure and asset management systems. In these cases there will be the need to improve the sophistication of asset management systems in parallel with this type of research.

8.2 Identified Gaps in Knowledge and Potential Future Directions

Identified gaps in knowledge and potential future directions for further research identified by the project team include:

- extending the engineering research on road performance to different climatic regimes e.g. northern desert, northern tropics;
- interface with Local Government management and expanded field testing of the model is required, across more Councils that differ in size, technical capability, data management, etc. the aim of the work would be to determine if the model can be used effectively in all these environments? Does it contribute effectively to asset management?
- review of the current state of engineering research with respect of climate change on other assets that may potentially be included in this or another model to capture potential changes in maintenance costs and useful life;
- extreme events are known to be important but there are many challenges in attempting to model them including: local impacts, definitions, data availability; and mathematical modelling approaches to simulating extreme events. Our understanding of the impact of severe storms, floods and high winds for example, on different infrastructure types is often case and location specific, since this represents the most straightforward approach to accumulating knowledge on these aspects of climate change. However we need to generate more in depth analysis which seeks to draw out trends and patterns in damage

to different infrastructure types from climatic events so we can predict and respond more effectively;

- there is the potential to apply this process including the development of asset management tools to other infrastructure: bridges, marinas, sea walls, buildings, with different materials;
- more research on material degradation which leads to the modelling of climate change impacts on assets is needed. This research would allow a better interface between the materials science, climate science and attempts such as this to model the impact of gradual climate change on infrastructure;
- further research is required on service level factors including how these can best be incorporated into an asset or financial model. For example, how are threshold effects included?
- from a mathematical perspective, cascading probabilities through the modelling including climate/engineering/financial layers can be captured as stochastic effects through simulation at the financial modelling level. However, can probabilistic variables be identified at all three levels, associated with probability distributions, nested and aggregated through the model?
- systematic interface/networking with international work being carried out, in the UK, Europe, US and under the auspices of the United Nations would be valuable for extending this work to an international scale; and
- systematic interface/networking with international commercial work on infrastructure exposure under climate change, particularly that being carried out by insurers, such as Munich Re would also be useful.

9 GLOSSARY

3CAP
3 Counties Alliance Partnership.

AADT
Average Annual Daily Traffic.

AASHO
American Association of State Highway Officials.

ADAPTATION
Adaptations are actions taken to help communities and ecosystems moderate, cope with, or take advantage of actual or expected changes in climate conditions.

AGGREGATE
A material composed of discrete mineral particles of specified size or size distribution, produced from sand, gravel, rock or metallurgical slag, using one or more of the following processes: selective extraction, screening, blasting or crushing.

AHR
Asphalt Hotmix roads are found in all Local Government areas, and represent almost all the road network in metropolitan Councils. The seal is a manufactured product made with much the same type of ingredients as concrete except bitumen is used to bind the mixture together instead of cement. A blend of aggregates (crushed rock), sands and fillers are passed through a heating drum to completely dry them and raise the temperature to around 160°C adding hot bitumen in the process. There are many types of mixes for various types of applications. The most commonly used mixes are 14 mm, 10 mm and 7 mm, where the measurement refers to the largest aggregate in the mix - 14 mm and 10 mm are typically used on roads. The thickness the hot mix is laid depends on the traffic loading it will be subjected to.

AIFMG
Australian Infrastructure Financial Management Guidelines.

ALGA
Australian Local Government Association.

AR4
The IPCC Fourth Assessment Report.

ARRB now ARRB Group
Australian Road Research Board.

ASPHALT/TARMAC OR HOTMIX ASPHALT
A mixture of bituminous binder and aggregate with or without mineral filler, produced hot in a mixing plant, which is delivered, spread and compacted while hot. This is also known as Hot Mix, or Hot Mix Asphalt.

ATEAM
The Advanced Terrestrial Ecosystem Analysis and Modelling.

AWAP
Australian Water Availability Project data set.

BINDER
A material used to fill the interstices between small stones or coarse gravels. It provides mechanical, chemical and physical bonding and holds the aggregate particles together as a coherent mass. Normally, bitumen is most commonly used in Australian road construction. A manufactured material used in small amounts in stabilisation to change the properties of the existing material. A bituminous material used for waterproofing the surface and holding an aggregate layer to the base.

BITUMEN
A very viscous liquid or a solid that consists essentially of hydrocarbons and their derivatives, which are soluble in carbon disulphide. It is substantially non-volatile and softens gradually when heated. It possesses waterproofing and adhesive properties. It is obtained from native asphalt or by processing the residue from the refining of naturally occurring crude petroleum.

BOM
Bureau of Meteorology.

CAD
Computer-Aided Design.

CARRYING AMOUNT
The amount at which an asset is recognised after deducting any accumulated depreciation and accumulated impairment losses.

CLIMATE
Climate summarises the average, range and variability of weather elements, e.g. precipitation, wind speed, air temperature, humidity, and sunshine hours (solar radiation), observed over many years (typically > 30 years) at a location or across an area (Bureau of Meteorology 2009).

CLIMATE VARIABILITY
Climate variability refers to variations in the mean state of climate on all temporal and spatial scales beyond that of individual weather events. Examples of climate variability include extended droughts, floods, and conditions that result from periodic El Niño and La Niña events.

CLIMATE CHANGE (global warming)
Climate change refers to shifts in the mean state of the climate or in its variability, persisting for an extended period (decades or longer). Contemporary climate change refers to anthropogenically driven changes in the climate as a result of changes to the composition of the atmosphere via the addition of greenhouse gases.

CMMS
Computerised Maintenance Management System.

CPRS
Carbon Pollution Reduction Scheme.

CSIRO
Commonwealth Scientific and Industrial Research Organisation.

DCF
Discounted Cash Flow.

DEFRA
UK Department of Environment, Food and Rural Affairs.

DEH
Department of Environment and Heritage.

DROUGHT
Drought in general means acute water shortage. When dry conditions are not relieved by equally wet periods over a number of years, or when a shorter period of dry is exceptional, it is commonly called drought.

DWLBC
The Department of Water, Land and Biodiversity Conservation, South Australia.

EA
UK Environment Agency.

EAC
Equivalent annual cost.

EU
European Union.

EXP – e
Raised to the power.

FFDI
Forest Fire Danger Index.

GCM
Global Climate model.

GEV
Generalised Extreme Value family of distributions.

GIS
Global Information Systems.

HDM
Highway development management.

HDM-4
Mathematical models used for the management of the national highway system and includes highways/freeways, arterial roads, collectors, and rural arterials.

IIMM
International Infrastructure Management Manual.

IMEA
Institute of Municipal Engineering Australia.

INGENIUM
The Association of Local Government Engineering New Zealand.

IRI
International Roughness Index.

IPCC
Intergovernmental Panel on Climate Change.

IPWEA
Institute of Public Works Engineering Australia.

L
Traffic Load in MESA.

LGAs
Local Government Areas.

LGA SA
Local Government Association South Australia.

LITTORAL
In coastal environments, the littoral zone extends from the high water mark, which is rarely inundated, to shoreline areas that are permanently submerged. It always includes the intertidal zone and is often used to mean the same as the intertidal zone. However, the meaning of "littoral zone" can extend well beyond the intertidal zone.

LGA
Local Government Association.

MAV
Municipal Association Victoria.

MC
Maintenance costs.

MESA
Million Equivalent Standard Axles.

MMP
Mean monthly precipitation.

MONTE CARLO SIMULATION
A computerised mathematical technique that allows users to account for risk in quantitative analysis and decision making.

NAMS
National Asset Management Strategy and Committee.

NAMS.PLUS
IPWEA NAMS.PLUS asset management software tools.

NCCARF
National Climate Change Adaptation Research Facility.

NPV
Net present value.

OZCLIM
A climate change scenario generator developed by CSIRO.

PARETO DISTRIBUTION
A distribution that expresses the ‘80-20’ rule, as in wealth distribution, where 20% of the population may control 80% of the wealth.

Pavement
That portion of a road designed for the support of, and to form the running surface for, vehicular traffic.

POISSON DISTRIBUTION
A distribution that expresses the probability of a given number of events occurring in a fixed interval of time and/or space if these events occur with a known average rate and independently of the time since the last event.

Property, plant and equipment
Tangible items that are held for use in the production or supply of goods or services, for rental to others, or for administrative purposes; and are expected to be used during more than one period.

PV
Present Value.

RC
Rehabilitation costs.

RCP
Representative Concentration Pathways.

Residual value of an asset
The estimated amount that an entity would currently obtain from disposal of the asset, after deducting the estimated costs of disposal, if the asset were already of the age and in the condition expected at the end of its useful life.

RISK
Risk is the product of consequences and likelihood - what can happen, and what are the odds of it happening. Both of these factors are important in determining whether and how we address specific risks.

ROA
Real Options Analysis.

RPF
Relative Performance Factors.

RSC
Resurfacing costs

RTM
Real Time Monitoring gridded dataset.

SA
South Australia.

SNC
Modified structural Number.

SPRAYED SEAL
A thin layer of binder sprayed onto a pavement surface with a layer of aggregate incorporated and which is impervious to water.

SRES
Special Report on Emissions Scenarios.

SSR
Spray sealed roads are found predominantly in rural Local Government, although they also occur in urban fringe Councils. In this method, bitumen material of different types (conventional bitumen, multigrade bitumen, cutback bitumen, and bituminous emulsion) is sprayed on a prepared road surface. Spray seal is cheaper than surfacing in an asphaltic concrete pavement. Seals are constructed by evenly distributing a thin base of hot bitumen or bitumen emulsion onto an existing pavement and then embedding finely graded aggregate into it. The aggregate is evenly distributed over the chip seal, and then rolled into an even surface. Newer techniques use bitumen emulsion (a mixture of liquid bitumen, surfactant, and water) instead of hot sprayed pure bitumen.

T
The annual mean of the mean monthly temperature.

TI or TMI
The Thornwaite Mositure Index, a function of monthly mean minimum temperature and total monthly precipitation.

T min
The annual mean of the mean monthly minimum temperature.

UK
United Kingdom.

UL
Useful life. The period over which an asset is expected to be available for use by an entity, or the number of production or similar units expected to be obtained from the asset by an entity. The useful life of an asset is defined in terms of the asset’s expected utility to the entity. The asset management policy of the entity may involve the disposal of assets after a specified time or after consumption of a specified proportion of the future economic benefits embodied in the asset. Therefore, the useful life of an asset may be shorter than its economic life. The estimation of the useful life of the asset is a matter of judgement based on the experience of the entity with similar assets.

USR
Unsealed roads are found along a continuum of structure, from tracks, to clay/dirt roads, to constructed gravel roads, often laid with a binder or liquid dust suppressant. For the purposes of this study, unsealed roads were taken to be constructed gravel roads as these have the most significant financial impact on Council asset management; data on repair and maintenance, and on construction and rehabilitation is available; and degradation modelling can draw on a substantial body of work on these roads in the engineering literature.

VAR
Value-at-Risk

VULNERABILITY
Vulnerability to the impacts of climate change is a function of exposure to climate conditions, sensitivity to those conditions, and the capacity to adapt to the changes. Vulnerability is typically described to be a function of three elements - exposure, sensitivity, and adaptive capacity. For example, agricultural vulnerability to climate change is described in terms of not only exposure to elevated temperatures, but also crop yield sensitivity to the elevated temperatures and the ability of farmers to adapt to the effects of that sensitivity, i.e. by planting more heat-resistant cultivars or by ceasing to plant their current crop altogether.

WAAMI
Western Australian Asset Management Improvement Program.

WALGA
Western Australian LGA.

WEATHER
Weather describes atmospheric conditions at a particular place in terms of air temperature, precipitation, wind speed, pressure, and humidity.

WEIBULL DISTRIBUTION
A distribution that has a finite upper bound, indicating an absolute maximum.

WEINERT N-VALUE
A South African climate index. Different climates have different Weinert N-values.

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APPENDIX 1 – AGREED PROJECT SCOPE DOCUMENT SUBMITTED WITH THE PROJECT FUNDING CONTRACT

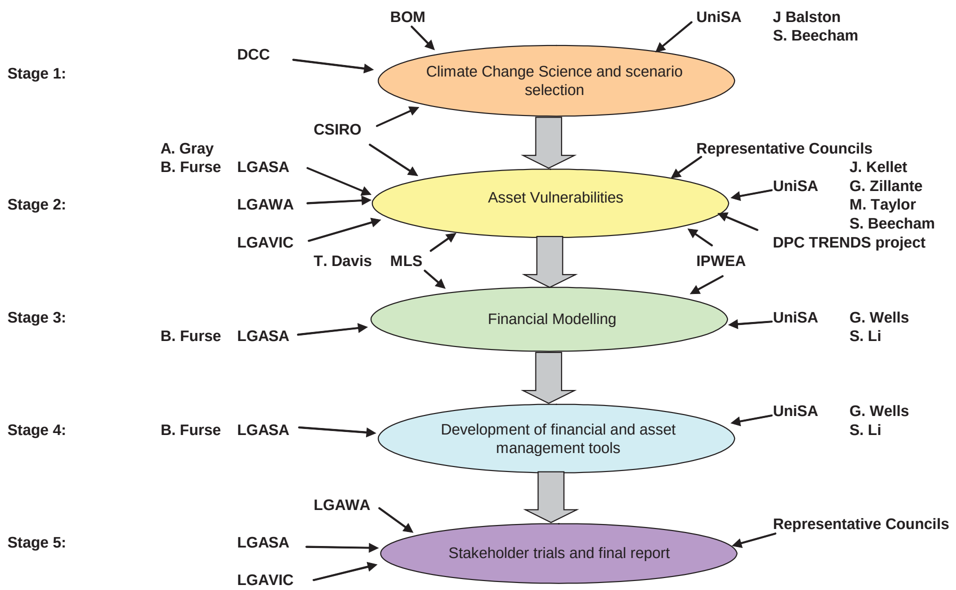
This project scoping document outlines the scope of the NCCARF Settlements and Infrastructure Project as understood by parties in attendance at the inaugural project stakeholders meeting on 9 December 2010. The scope as understood at this point is subject to changes under the adaptive management processes implemented for the project, the findings from literature reviews and the limitations and risks associated with novel research of complex multidisciplinary projects such as this. In the event of changes to the scope of this project, NCCARF and other stakeholders will be made aware of changes as soon as possible in writing by the Project Manager, Mr. Adam Gray, South Australian Local Government Association.

Project Title:
Development of tools that allow Local Governments to translate climate change impacts on assets into strategic and operational financial and asset management plans.

Project Objective:
The objectives of the project are to: identify key Council assets vulnerable to climate change; identify the likely impacts of climate change on Council assets; undertake a financial modelling exercise to quantify the identified climate change asset risks; develop the necessary modifications to existing asset management and financial sustainability tools so that Councils may evaluate various climate change action scenarios/options at the management planning level; guide service level standards.

The project aims to develop a transparent and reproducible methodology for linking the identified stages of the project: identifying likely future climate changes, identifying the likely impacts of these changes on hard infrastructure assets owned by Councils, quantifying the likely financial implications of these impacts, and developing tools for Councils to use to assess the climate change impacts. The deliverables will be tested on a case study basis with a maximum of eight Councils from across southern Australia for a minimum of two assets classes to ensure the processes and tools developed are rigorous and useable. The frameworks and tools developed will be designed to accommodate future changes to each of the input variables including for example climate scenarios and parameters, assets and costs.

Project stages:
The five stages of the project and key personnel and organisations to be involved at each stage are shown in the schematic on the following page.



Deliverables:
Outputs from the project will be:

1. A final project report detailing each of the five stages of the project including literature reviews, methodologies, results, conclusions and recommendations.

Sections of the final report will cover:

Section 1: An overarching chapter that describes the methodology employed to bring each of the multidisciplinary stages of the project together.

Section 2: Stage 1 of the project - A review of the likely climate changes for southern Australia, identification of climate parameters likely to impact on the selected Council assets from the literature, selection of SRES scenarios and time periods for which the data used in Council trials is to be collected, and sources of climate change parameter data identified.

Section 3: Stage 2 of the project - Key hard infrastructure assets owned by Councils that may be vulnerable to climate change and the likely impacts or consequences of climate change on these assets will be identified via the literature, consultation with LGASA, IPWEA, collaborating Councils and other relevant stakeholders in the project. The format of the output is expected to be an excel spreadsheet, look-up table or similar that identifies key climate parameters and likely impact factors (for example frequency, percentage, thresholds expressed as damage/deterioration) for each asset class identified and for which data exists.

Section 4: Stage 3 of the project - Methodology for the development of the financial model and description of its architecture, input capacity and output analysis.

Section 5: Stage 4 of the project - Methodology for the integration of the financial model developed into the chosen existing sustainable financial and asset management tool/s (e.g. NAMS Plus) and a description of the tools developed.

Section 6: Stage 5 of the project - Feedback from the Council trials of the products. Feedback will take the form of a summary report from testing of the tools and will outline how the identified problems were resolved if possible.

Section 7: Identified knowledge gaps, future research areas and key recommendations.

2. The financial model (stage 3), probably in excel format that enters the climate specifications/parameters determined in the review of climate impacts (stage 1) and identified key Council infrastructure assets (stage 2) to provide a financial assessment of climate/asset risks in format compatible with the selected financial / asset management tool identified (stage 4 - e.g. IPWEA designed NAMS Plus software and suite of support tools).

3. A financial / asset management tool or modification to an existing tool (stage 4 - e.g. NAMS Plus software and support tools developed by IPWEA) that will allows Councils to identify significant climate change impacts on their relevant asset classes and determine the likely costs of various options. Outputs will be in a format that is user friendly and meets the existing requirements of sustainable financial and asset management procedures, relevant regulations and standards. Serviceability and performance of assets will be taken into consideration and incorporated into the maintenance and asset value financial modelling where possible. The tool will have been trialled by 8 collaborating Councils across southern Australia (2 in WA, 2 in VIC and 4 in SA).

4. A set of guidelines / user manual for the output tools will be developed for use by Councils across Australia.

5. A minimum of one scientific paper will be submitted to a relevant high impact journal.

6. A minimum of one international peer-reviewed conference will be attended to present findings of the project.

7. Training for use of the workshop materials developed under the project will be run via the LGA Reform Fund Project and existing IPWEA NAMS Plus training schedules where appropriate.

Timeline:
Project will be completed 30 September 2012. Draft final project report and final milestone reports and payments will be on 31 May 2012. Stages of the project and timeframes for each are summarised in the Gantt Chart below.

		2010			2011												2012								
Stage		**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sept**
1	Climate change scenarios	■	■	■	■	■	■	■																	
2	Asset vulnerabilities	■	■	■	■	■	■	■	■	■															
3	Financial modelling	■	■	■	■	■	■	■	■	■	■	■	■	■											
4	Development of operational climate change impact asset and financial management tools								■	■	■	■	■	■	■	■	■								
5	Council trials and final reporting													■	■	■	■	■	■	■	■	■	■	■	■

Project Scope:
The scope of the project ***does include***:

Stage 1:
Use of climate change scenarios derived from the IPCC FAR and based on data relevant to Australian conditions and publicly available by 1 November 2010.
Climate change scenario data for the parameters identified to affect Council assets and selected SRES scenarios and time periods where available. Dependant on findings from the literature review, climate parameters may include a measure of: temperature, heatwave events (number of events each year when the maximum temperature

exceeds a specified threshold), rainfall, humidity, sea level changes, storm surge heights and frequency, maximum wind gusts, and hydrological flow data provided by the Goyder Institute Climate Change Project (see linkages section) for Councils with data and a calibrated hydrological model.

Stage 2:
For the purposes of asset management, accounting and financial sustainability, Councils identify assets under classes, categories and components. For example: Class – Road, Category – sealed, component – gutter, tarmac etc. The hard infrastructure assets that will be considered for inclusion into the structure of the tools developed will be at least one example of each of the following twelve asset classes and categories (in brackets). Those assets that will be populated with data and components and included in the model for testing by the collaborating Councils will be limited to those for which there is sufficient real world or model data to predict the likely climate impacts, and that are considered most relevant to Local Government - a minimum of two of the twelve asset classes (categories) (More than two asset classes will be included if data, time and funds allow):

1. Roads: Sealed (hotmix, spray seal, rigid pavement, base course)
2. Roads: Unsealed (pavement/surface course)
3. Footpaths: Hotmix, paved, concrete, rubble
4. Foreshore coastal: Jetties
5. Foreshore coastal: Marinas (not including buildings)
6. Foreshore coastal: Coastal protection works (sea walls, rip rap, sand management structures)
7. Foreshore coastal: Access ramps and steps (stairs and boardwalks timber, stairs and steps concrete, ramps concrete, ramps hotmix, vehicle access)
8. Stormwater: Pipes and culverts (pipes, box culverts)
9. Stormwater: Open channels (concrete, constructed earth)
10. Stormwater: Pits (SEPs, headwalls/outlet structures, junction boxes/ IPs)
11. Bridges: Trafficable / vehicle.
12. Fords: Fords, floodways, low-level crossings.

Asset classes as described are consistent with the LGA Act and relevant regulations and accounting standards as they are in place in November 2010. The tools developed will be designed to include future data for further asset classes and categories when data becomes available.

An initial literature review will identify available studies that consider physical, climate induced impacts on the performance and physical integrity of the infrastructure assets identified as priority to Councils. For each asset class key data requirements may include current and/or likely future changes to:

1. Date of construction / commissioning
2. Useful life
3. Service level
4. Maintenance record / schedules / thresholds
5. Location (eg. height above sea level, distance from coast, proximity to a flood zone)
6. Further parameters may emerge from the literature review in Stage 2.

Data from Stage 1 will be applied to each asset class identified and probability measures in respect of reduced performance and physical integrity determined on the basis of the literature. Where gaps exist in the literature an expert panel will determine the probability measures.

Stage 3:
Literature review.
Collaboration with software engineers on cross-stage coordinating data frames and software, including handling of probabilities and range.

Collation and configuration of outputs from Stages 1 and 2 as inputs to the financial modelling, including software linkages (this step will require ongoing coordination with the Stage1 and 2 teams throughout the period of their work).

Review of the NAMS PLUS systems, software and documentation.

Review of the statutory and regulatory requirements for Local Government financial analysis and reporting. Identification of relevant input factors and their interactions. Evaluation of the probability distributions for identified key probabilistic factors. Evaluation and selection of methods for probabilistic financial modelling: for example DCF, Options Pricing models.

Construction of nested influence models for financial outcomes, including all identified factors and their relationships.

Development of the financial model in Excel with software such as @RISK or Analytica simulations:

- develop modules;
- build prototype model;
- graph key relationships;
- identify key parameters and perform sensitivity analysis;
- refine model;
- derive and analyse results of simulations;
- compare results of different modelling approaches.

Ongoing discussions as required with the technical reference group.
Development of output formats suitable for inputs to Stage 4.
Draft journal paper for submission to a relevant journal.

Stage 4:
Literature review.
Identification of areas of financial reporting requirements impacted by modelled climate change impacts.

Mapping of outputs of Stage 3 onto the NAMS PLUS framework.
Design of technical enhancements to the NAMS PLUS framework if feasible, including changes to existing inputs, new inputs, module plug-ins, linked financial analysis packages or combinations of these.

Design of user-friendly financial management tools for the NAMS PLUS framework, in collaboration with LGA and Councils.

Pilot testing of tools with selected Councils.

Incorporation of feedback from Councils into final model.

Development and trial training of project outputs and supporting materials in conjunction with Councils and LGA.

Draft case study for submission to relevant professional journal.

Stage 5:
Trials of the final financial / asset management tools by eight Councils across southern Australia (2 in VIC, 2 in WA and 4 in SA).

Trials will incorporate if possible Councils that represent coastal, metropolitan, regional and inland areas.

Councils will be selected on the basis of a set of selection criteria developed to ensure a diversity of Council locations, conditions and size.

Training for Councils in the use of the outputs will be undertaken as part of the existing methodology and schedules in place for the LGA Reform Project and IPWEA NAMS plus where appropriate and will aim to reach 50 Councils by the end of 2012.

The scope of the project ***does not*** include:

Stage 1:
Use of IPCC Assessment report findings delivered since the FAR.

Use of climate change data or scenarios that are not readily available in published, peer reviewed articles by 1 November 2010.

Climate variables not included in the list of in-scope parameters.

Hydrological modelling and potential flood / flow data. The inclusion of this parameter will be dependent on its delivery via the Goyder Institute climate change project "Development of an agreed set of climate projections for South Australia". See project linkages section for details.

Climate change parameters for which there is insufficient data available at the time of the project to determine realistic future scenarios.

Stage 2:
Groundwater, biophysical, social or soft economic assets such as but not limited to trees, wetlands, aquifers, lakes, rivers, ecosystems, parks, gardens, playing fields, social or economic responses to climate changes and changes to infrastructure serviceability.

Stage 3:
A review or assessment of the different financial modelling theories and methods. Although the climate impacts will be identified based on specific responses in asset types, the tools developed will make assumptions at a category level and spatial context, and so is not intended to be applied to specific assets in isolation.

Stage 4:
Implementation of training materials in ongoing workshops and other Council business contexts.

Functional changes to the NAMS program or templates, or other reporting formats or requirements, other than to facilitate inclusion of climate change impacts at a regional and asset category scale.

Development of tools that address other factors that will need to be considered in the decision making processes of asset risk management such as population increase, infrastructure use, community expectations etc.

Stage 5:
Trials with other Local Governments except those eight Councils identified in the project as having sufficient data requirements to test the outputs or broad scale testing of the outputs across Local Government regions or areas.

Trials of the tools for Councils that do not meet the selection criteria developed.
Trials of the tools for assets or climate parameters that have not been included in the models.
Training that does not fit with existing extension activities with the LGA reform fund or IPWEA.

Project Constraints:
All project deliverables must be complete and submitted to NCCARF by 30 September 2012.
The total project budget cannot exceed $530,000 in cash as defined in the budget sheet.
In-kind contributions must not exceed the times allocated in the budget sheet.
Milestone reports to NCCARF are due as per the contractual arrangements (defined in the project schedule) unless otherwise re-negotiated.

Project Assumptions:
General:
There will be cooperation between all project stakeholders and partners and issues will be resolved in a timely and harmonious manner.
Project team identified will be available and able to work for the periods of the project for which they were identified.
In-kind contributions will be provided by stakeholders as agreed in the project funding proposal and budget sheet.
A Windows® environment will be used at all stages of the project.
Necessary software will be available for each stage of the project when required.
The SA LGA will host the knowledge sharing website for the duration of the project.
Contractual arrangements are finalised by 30 December 2010.
Project payments will be made on time by all parties.

Stage 1:
Necessary data exists as of 1 November 2010 in a publicly available form to support the chosen climate parameters.

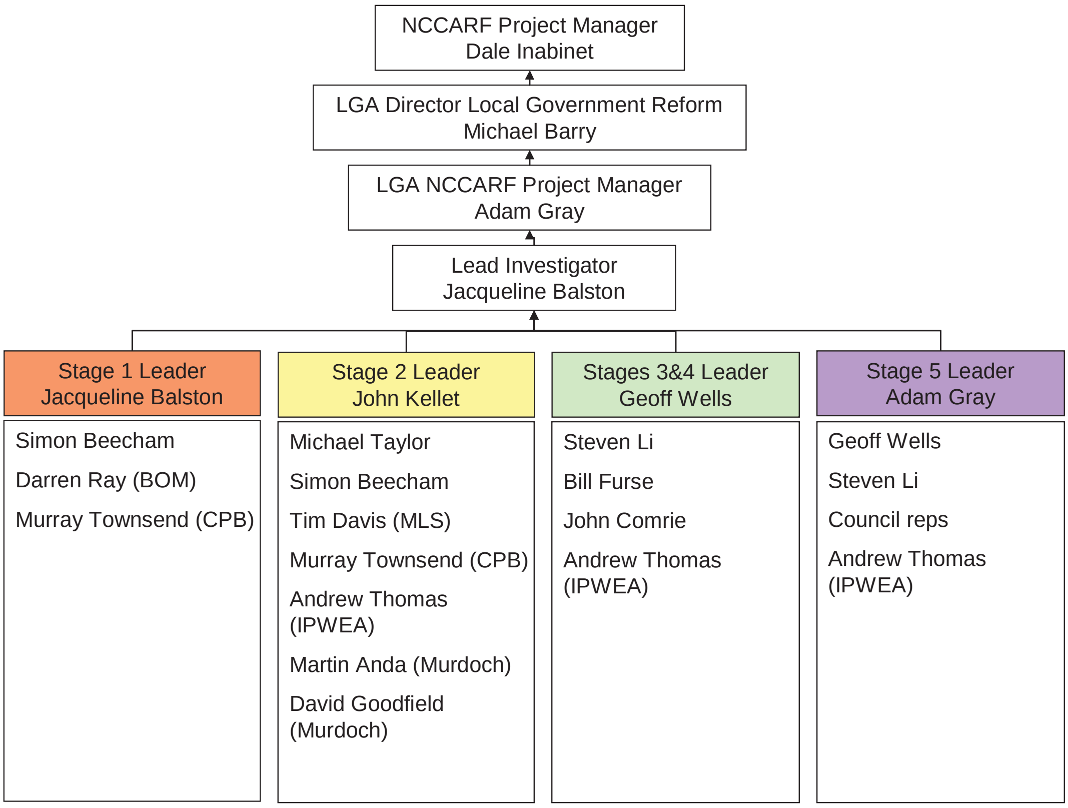
Stage 2:
That the criteria for the useability / service levels of assets remains the same as it is now (1 November 2010).
Existing asset data held by Councils will be used – no additional asset characteristics will be required to be identified and no additional asset data collected.

Stage 3:
Climate change attributes or impacts can be depicted (and interrogated/interpreted) spatially via industry standard GIS software.

Stage 4:
NAMS Plus is one of a number of approaches used by Councils to develop asset management plans. The project will focus on the NAMS interface, and assumes that it will be flexible enough to work with other templates and data sources developed.

Stage 5:
That the LGA Reform Fund project and existing IPWEA NAMS Plus training will provide enough coverage for training of the products developed to ensure national uptake.
That IPWEA will provide on-going support for the tools developed as part of this project.
That the methodology and linkages developed during the course of the project will ensure access to relevant data for future updates of the tools developed.

Project Governance:
The structure for project responsibilities and reporting is shown below.



The Project Manager is Adam Gray (LGA SA). Adam's responsibilities are:

- Organise contractual arrangements.
- Approve procurement and expenditure.
- Manage project budget.
- Deliver milestone reports to NCCARF.
- Provide progress reports to LGA management.
- Manage project stakeholder and all external communications.
- Engage and maintain project linkages with collaborating LGAs interstate and all Council representatives.
- Manage human resources.
- Manage the knowledge information system on the LGA website.

The Lead Investigator is Jacqueline Balston (UniSA). Jacqui's responsibilities are:

- To ensure key project deliverables are completed on time according to the project schedule and to the agreed scope and quality.
- Develop Project Scope documentation, Project Schedule and Issues Register.
- Monitor and maintain the Project Schedule and Issues Register.
- Track the progress of the project stages.
- Request procurement and expenditure from Project Manager.
- Provide a monthly progress report to the Project Manager on the project status.

The responsibilities of the Project Stage Leaders are:

- To ensure project stage deliverables are completed on time according to the project schedule and to the agreed scope and quality within budget.
- To engage with stakeholders involved in their stage of the project (researchers, technical panel, Council representatives etc.)
- To supervise the research assistant where appropriate.

The Technical Panel:
The technical panel consists of a selection of experts from each of the disciplines required for the project and are named in the funding proposal. The technical panel will:

- Provide relevant data and information to the best of their ability / resources.
- Provide expert judgement in the event of insufficient data
- Provide general guidance on the technical aspects of the project.

A project board of three representatives, one each from UniSA, LGA and IPWEA will:

- Ensure that the assumptions, expectations and economics remain valid and relevant.
- Resolve issues escalated to the project board by the project manager.
- Champion the cause of the project.
- Be accountable for the project outcomes
- Meet only on an as needs basis determined by the Project manager

Project Linkages:
The project aims to link with four other projects that are recently completed, currently running, or due to start soon and run concurrent to this project. The other projects are:

> ***The Local Government Association SA Reform Fund project*** is a joint Department of Planning and Local Government SA (DPLG), IPWEA and LGA SA activity that consists of two concurrent streams that aim to improve Local Government capacity to manage growth and continue to provide local services and infrastructure into the future. In stream one, there are six projects that address building capacity within Councils to ensure the long term focus of sustainable asset and financial management. As part of the full project a detailed audit of all SA Council asset and financial management plans will identify strategic and operational gaps for addressing climate change. Generic planning tools will be developed to aid Councils to adapt to climate change. Inputs from the Reform Fund project to this project will include the audit of Council management tools, identification of financial and asset management gaps and barriers. The Reform Fund project will also provide a vehicle through which the outputs of this project may be implemented throughout SA via a series of training workshops. The project is scheduled for completion December 2011. Outputs from this project will support Stage 5 of the NCCARF project.

The Mutual Liability Scheme Climate Change Adaptation project is a joint LGASA and Mutual Liability project that aims to identify a comprehensive list of key Council vulnerabilities from future climate change. Projected climate changes were described in detail by climate change researchers to Council employees and likely impacts to development and planning, recreation and community services, health and wellbeing, emergency management, sustainability and environmental management, community infrastructure and Council prosperity identified. All Councils across SA have now completed the project and a database of key likely impacts and associated risks to Council business has been collated. The data from the MLS Climate Change project will be fed into the second stage of this project where vulnerable Council assets are identified. The preliminary report from the MLS Climate Change Adaptation project is currently available on the LGA web and the final report is due to be released before June 2011. Outputs from this project will support Stage 2 of the NCCARF project.

The Premier's Science and Research Fund project "Adapting to Climate Change in SA: A Transect Analysis" sets out a framework for the incorporation of the human dimensions of adaptation to climate change within the Transect for Environmental Decision Making (TREND) network. The project will quantify how SA economy and society has / will be affected by climate change in the short, medium and long term. The transect runs from the south coast of SA near Victor Harbour north to the western fringes of the Flinders Ranges and will provide data on climate change impacts across a range of coastal, inland, city, rural, latitudinal and climatic regions. The project started in 2010 and is due for completion in 2013. Key outputs that will be relevant to this project include changes in the built environment, infrastructure needs and the performance of infrastructure over time. A socio-economic risk/vulnerability matrix and associated research tools, data on community vulnerability, and an infrastructure inventory along the transect that relates infrastructure type and condition to environmental and meteorological variables will be developed. This project has started already. Outputs from this project will support Stage 2 of the NCCARF project.

The Goyder Institute Climate Change Project has just been approved (16 December 2010) and aims to develop an agreed set of downscaled climate change projections for South Australia to support proactive responses to climate change in water resource planning and management. The Institute is a partnership between the State Government, CSIRO, University Adelaide, UniSA, Finders University, the South Australian Research and Development Institute (SARDI) and the Australian Water Quality Centre of SA Water. The project will involve identification of the key drivers of climate change in South Australia and then statistically downscaled distributions of rainfall, temperature and potential evapotranspiration for current climate variability and a suite of agreed GCM scenarios will be generated for the Onkaparinga catchment. Outputs will include a rigorous framework for generating the projections that can e employed on release of the AR5 modelling results when they become available, downscaled climate projections for all eight South Australian NRM areas, and the development of an applications test bed including catchment runoff models, reservoir management models, daily timestep water balance models, integrated surface/ground water models and an urban water decision support tool for use by Local Government. Hydrological model data / outputs from this project will be used as a climate parameter as defined in Stage 1 of the NCCARF project. Linkages with the Goyder project will ensure compatibility between projects with respect to the climate parameters identified (data formats) and the ongoing future availability of agreed downscaled data sets for the update to the NCCARF Council asset management tools for the AR5 GCM outputs and beyond. In return, the NCCARF project will provide access to the Council Asset Management tool developed for testing in the Goyder Institute project model test bed.

Quality Control:
The deliverables of the project will be assessed for relevance and quality by the technical panel throughout the project life under direction from the Project Manager and Principal Investigator and as a group at the quarterly Project Stakeholder Meetings.

Project tools and training materials will be assessed and trialled by the collaborating Councils across southern Australia and the relevant LGA representatives in each state.

Scientific publications will be reviewed by the technical panel and submitted for peer review to industry accepted journals.

Conference papers / posters will be reviewed by the technical panel prior to submission to the organisers of the conference.

Project performance will be monitored by the Project Manager and LGA executives.

The Project Board will provide high level feedback on the outputs of the project and resolve issues that arise during the course of the project that are brought to its attention.

The NCCARF project officer will provide sponsor feedback on the progress of the project at stakeholder meetings and on delivery of milestone reports and accept the final project deliverables.

Where it is determined that there are gaps in data or knowledge in the literature, information will be supplemented by expert knowledge sourced from the project technical panel.

Risk Assessment:
Risks identified in the project proposal are:

1. ***Staff turnover***
Solution: The collaboration of so many large organisations with a proven track record of working together means sourcing extra researchers or resources is considered achievable. Each stage of the project is led by two key researchers who will be in regular contact with each other throughout the life of the project. Data and drafts of all work will be stored in more than one location to ensure risks of electronic data loss is minimised.
2. ***The failure of other linked projects to deliver inputs or outputs.***
Solution: The project has been designed to work as a stand-alone piece of work if necessary. To date there is no indication that there are any problems with the identified linkage projects or their capacity to deliver.
3. ***The uncertainties associated with novel research.***
Solution: An adaptive management framework and project management processes recommended by the University of South Australia have been put in place to ensure that if there are limitations to the research as originally expected there is the opportunity to alter the project outputs to take into account identified problems.

4. Tight timeframes.

Solution: Each stage of the project will begin in a synchronised manner and involve significant on-going communication and collaboration with researchers in the other stage of the project to ensure that milestones are met within each stage and delays that are passed on form one stage to the next are minimal. Due to the late start of the project in response to delayed instruction by NCCARF, the first two milestone dates have been extended by two months to allow a realistic time frame for delivery in the early stages of the project.

5. Deliverables are too complex for Local Government use:

Solution: Because of the highly complex nature of the project and the need to link various multidisciplinary streams, it is possible that the outputs will become overly complicated and data hungry. The project aims to engage all stakeholders including the collaborating Councils at each critical stage of the project to ensure that deliverables are in a format that is easily used and updated by end-users in IPWEA and local Council offices.

6. General:

Issues that may arise will be identified early in the issues register and a course of action to offset the likely impacts put in place as soon as possible. Adaptive management frameworks and ongoing project management resources will ensure risks are identified early and action taken to reduce impacts.

APPENDIX 2 - CLIMATE IMPACTS ON LOCAL GOVERNMENT ASSETS

This appendix provides a supplementary literature review of the impact of climatic factors on infrastructure components and assets of relevance to Local Government in addition to roads. The principal materials used in the construction of Council owned infrastructure assets such as bridges, storm water drains, buildings, walkways, jetties and roads are concrete, steel and bitumen. The review examines the existing knowledge on material durability and the likely effect climatic factors such as temperature and moisture will have on material longevity.

10.1 Deterioration of Concrete

Concrete deterioration is usually classified into two primary types: physical and chemical. Each of these classes of deterioration can act simultaneously on the material and there is the potential for their effect to be compounded. Concrete that is subject to physical deterioration becomes more vulnerable to chemical deterioration and vice-verse (Mehta and Monteiro 2006).

Generally, concrete is resistant to deterioration in certain environments and not in others. Concrete durability can be improved by the use of technologies such as the inclusion of admixtures to alter the characteristics of the concrete before mixing, and by varying cement/water ratios prior to pouring (McCarthy and Giannakou 2002; Memon, Radin et al. 2002; Mehta and Monteiro 2006). As such, the final composition of the cement and pouring water ratio is determined on the basis of the environment in which the cement structure will be constructed (Mehta and Monteiro 2006). Australian Standard AS3600-2009 takes into account how concrete deteriorates and defines the appropriate concrete composition for use in different applications. The standard guarantees a sufficient level of performance for concrete structures in various environments (Council of Standards Australia 2009).

10.1.1 Chemical deterioration of concrete (concrete corrosion)

Corrosive chemicals such as chloride ions and carbon dioxide are able to penetrate concrete and when penetration is deep enough may destroy the protective passive layer of the internal reinforcing steel (rebar) – a process known as depassivation (Wang, Nguyen et al. 2010). As a result, corrosion of the reinforcement occurs and expansive defects that cause internal stress and ultimately damage to the concrete structure can result. During these processes rebar mass is lost, and the performance of the reinforcing changes. In addition, cracking and spalling caused by internal stress damage the integrity of the concrete. As a result, concrete structure serviceability and safety are affected. Temperature, humidity, and the concentration of carbon dioxide (CO_2) all have a significant influence on concrete corrosion and so changes in these variables due to climate change will affect the deterioration of concrete (Wang, Nguyen et al. 2010). Table 10 summarises the effects that climate change will likely have on concrete.

However, an understanding of concrete corrosion processes allows for a modification to concrete structures to adequately protect them from corrosion for the span of their useful life.

Table 10: Factors and potential consequences of climate change in association with concrete structures (Source: Wang, et al. 2010).

Climate Change	Implications
Increase of carbon concentration	Elevated carbon concentration accelerates carbonation and increases carbonation depth in concrete: this increases the likelihood of concrete structures exposed to carbonation induced reinforcement corrosion initiation and structural damage
Change of temperature	Elevated temperature accelerates carbonation, chloride penetration and corrosion rate of reinforcement that exacerbates the corrosion damage
Change of humidity	Lowered relative humidity may reduce or even stop carbonation and chloride penetration in the area with yearly average RH currently just above 40-50%, while increased humidity may result in them occurring in the regions where they are now negligible.

To analyse climate change impacts of carbonisation-induced and chloride-induced concrete corrosion Wang *et al*. examined the environmental exposure zones defined in Australian standard AS 3600, and considered these in relation to defined climate change scenarios.

Environmental exposure zones and concrete corrosion

Environmental exposure zones define areas of relatively homogenous temperature, humidity and corrosive chemicals concentrations so that all concrete structures in the zone are subject to similar deterioration rate. Zone boundaries are determined by a climatic zone and proximity to water. Each zone affects the rate of concrete corrosion and with climate change the geographical location of the zones will change. It should be noted that specific location/site characteristic (e.g. concentration of sulphates in soil) may also mean that the environmental exposure to corrosion inducing factors may be different to that indicated by its environmental exposure zones where only climatic zone and proximity to water bodies are considered. Figure 41 displays the environmental exposure zones for Australia according to AS 3600.

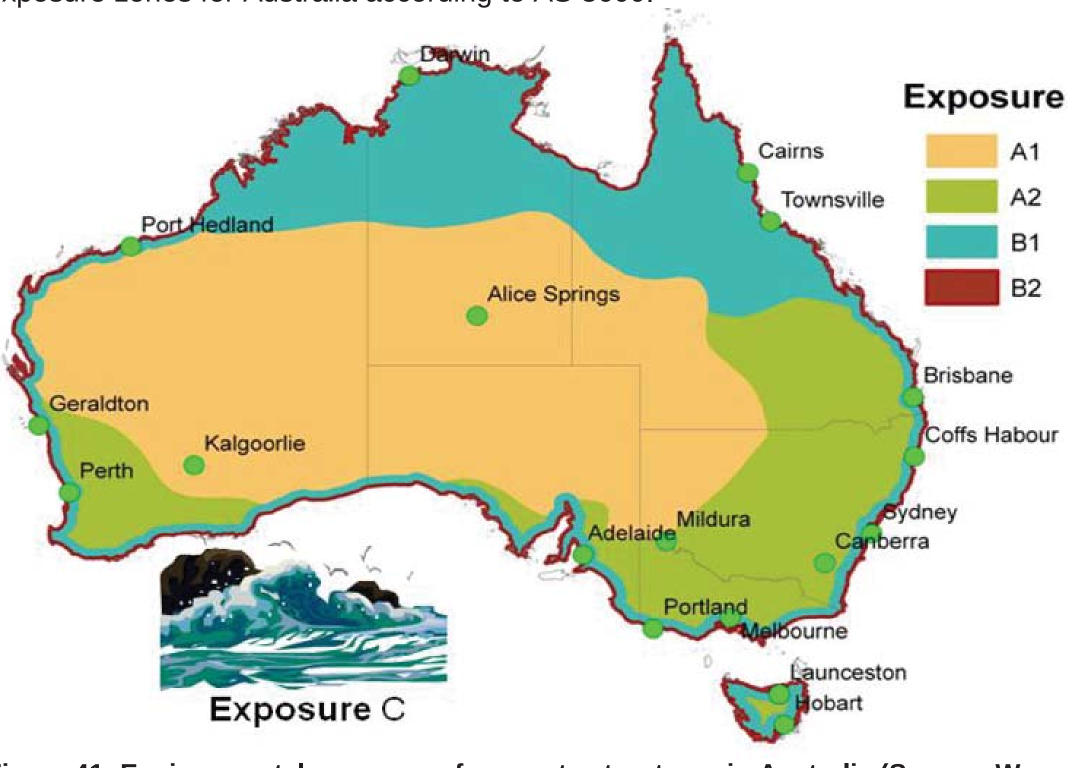


Figure 41: Environmental exposure of concrete structures in Australia (Source: Wang, Nguyen et al. 2010, Part I, page 37).

Australian standard AS 3600 takes into consideration the different environmental exposures in each region and requires concrete structures to adopt a specific durability protocol to ensure that deterioration during the structure's useful life is prevented. Concrete durability is achieved by applying minimum requirements for parameters such as concrete strength, concrete cover, concrete mix, water/cement ratio. For example, thicker concrete cover increases concrete durability and so the standard requires thicker cover for concrete structures in high exposure zones.

Climate change scenarios and concrete corrosion

To determine the likely impacts of climate change on concrete deterioration, Wang *et al.* considered the IPCC climate change scenarios for future concentrations of CO_2 in the atmosphere. Temperature and relative humidity projections for Australia for the year 2100 were extracted from the CSIRO Mk3.5 climate model, with a medium sensitivity to A1FI emissions for a grid size of 0.25 degrees.

A Monte-Carlo simulation was run within each grid using CSIRO models for concrete deterioration that describe concrete characteristics and environmental exposure. A sensitivity analysis of environmental exposure variables in the models then estimated the likely impact of climate change. In the analysis, the following variables were used to calculate the severity of concrete deterioration due to chloride- or carbonisation-induced corrosion at a given year in the future:

- Carbonisation depth by given year;
- Probability of corrosion initiation by given year;
- Probability of corrosion damage by given year;
- Mean rebar loss by given year.

The calculated values for each of these variables for different climate change scenarios were compared against a baseline scenario – a non-changing climate over the period from 2000 to 2100. The baseline scenario assumed the concentration of CO_2 in the atmosphere during the analysed period was fixed to that measured in 2000.

Modelled projections for climate change impacts on concrete deterioration

The modelled impact of climate change on concrete structures was presented for two cases (Wang, Nguyen et al. 2010). The first case estimates climate change impacts on new concrete structures assuming they were designed and built according to the current Australian standards (i.e. the concrete structure design follows Australian standards in terms of cover, cement content and water/cement ratio for the given environmental exposure). Figure 42 shows changes in the probability of corrosion initiation. The complete set of results for climate change impact is available in appendices B-J in Part II of the CSIRO report.

The second case estimated climate change impacts on existing concrete and includes several case studies of deterioration in existing concrete structures located in temperate or tropical climates. Attention was given to bridges and ports (particularly bridges in temperate climates) although in total the report presents eleven case studies investigating chloride-induced corrosion and seven case studies investigating carbonisation-induced corrosion from a broad range of geographical areas representing different environmental exposures, construction technologies, and times of construction. Figure 43 shows one example of the results for existing concrete structure deterioration. The complete set of results is available in Part III of the CSIRO report.

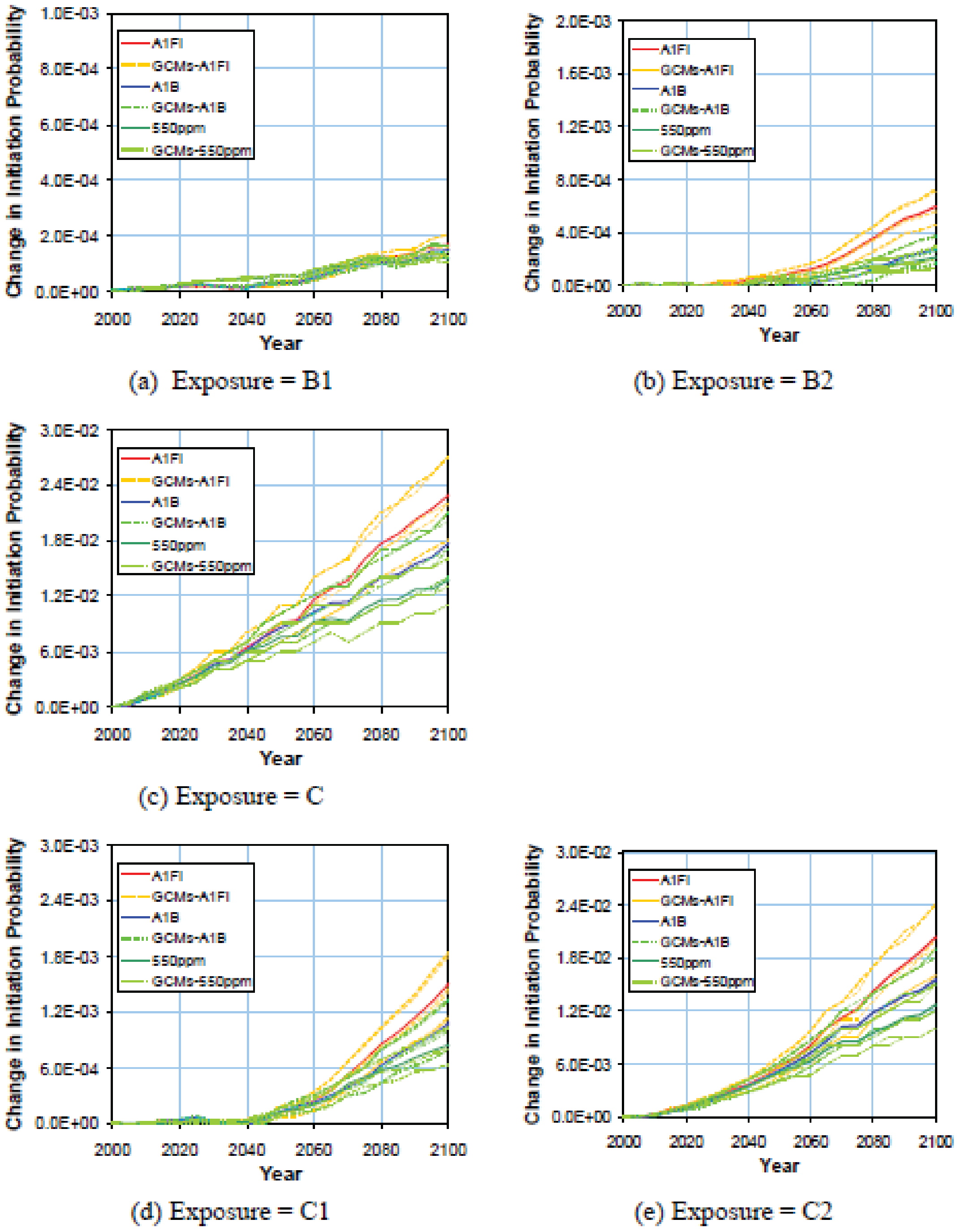


Figure 42: Changes in the probability of chloride-penetration-induced corrosion initiation in Adelaide at different environmental exposures from 2000 to 2100, in relation to A1FI, A1B and 550ppm stabilisation emission scenario, as simulated by nine GCMs (Source: Wang et al., 2010).

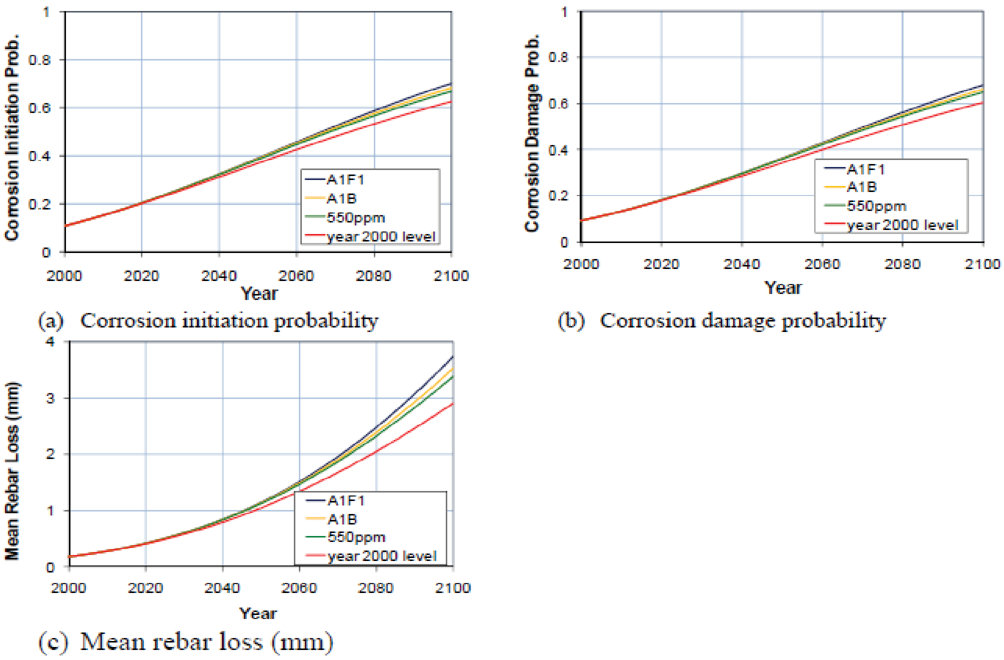


Figure 43: The probability of chloride-induced (a) corrosion initiation, (b) damage and (c) mean rebar loss for a Sydney bridge constructed in 1925 for three climate change and the baseline scenarios (Source: Wang et al., 2010).

The report also recommends actions that may offset climate change impacts on concrete structure including changes to concrete structure design as described in the Australian Standard AS 3600. The proposed changes guarantee that the probability of corrosion damage of concrete structures in a changing climate is no greater than that of concrete structures designed according to AS 3600 in a non-changing climate (the baseline scenario). The report recommendations define new requirements for minimum concrete cover, diffusion coefficient/s, and concrete strength. Figure 44 shows one example of the published recommendations. Appendices K-Q in the report contains a complete set of the report recommendations for the new design of concrete structures. The report also provides a methodology for the selection of the most suitable adaptation method to offset climate change impacts in a cost effective way.

Several methods for mitigating concrete deterioration in existing structures are presented and include estimates for effectiveness and cost including discounted, initial and on-going costs. Some of the methods provide permanent solutions, while the others reset or slow down deterioration rate. For example, replacing the existing cover on an asset with a new one so it meets current standards is estimated at about $2500 per m^2 and would have the effect of resetting the corrosion rate to the current standard. However, as each asset has a unique history with respect to its construction, maintenance, and environmental exposure, the report concludes that there is the need for case specific, /individualised adaptation strategies for asset maintenance in response to climate change.

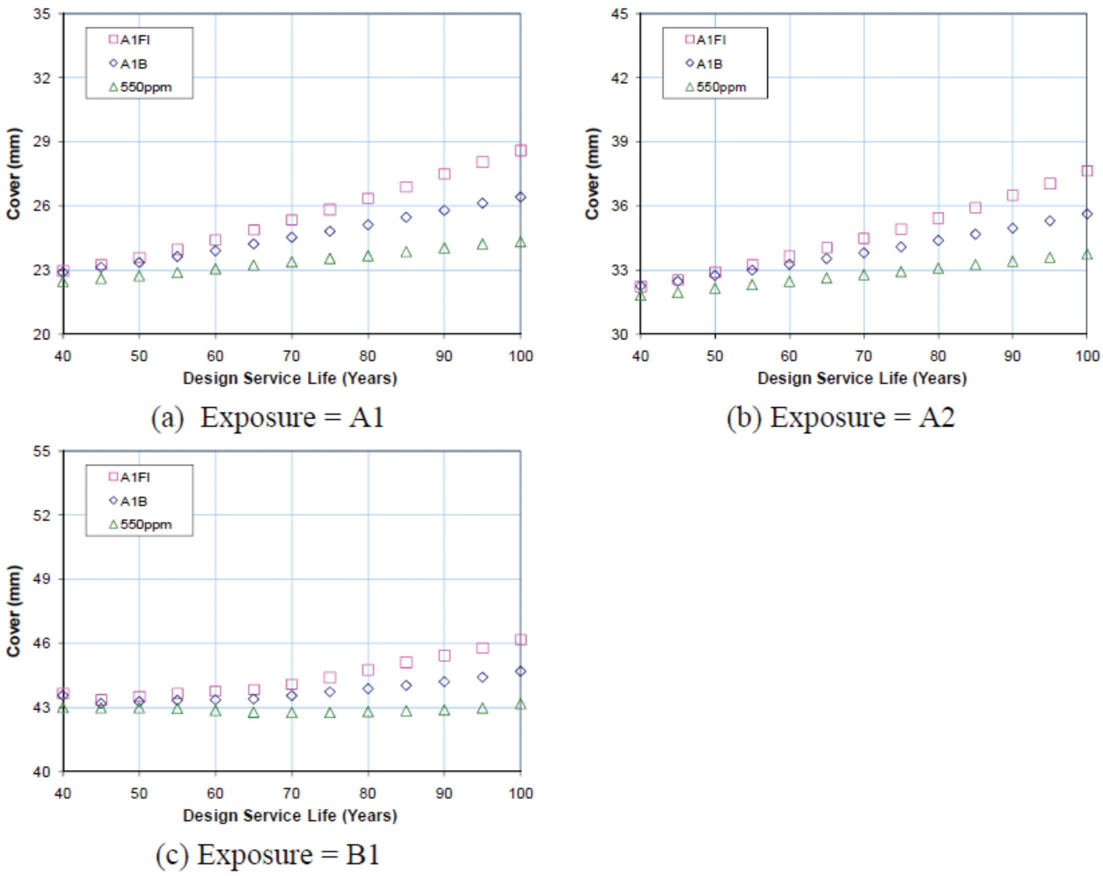


Figure 44: Cover requirement for carbonation-corrosion in Adelaide for different environmental exposures from 2000 to 2100 for climate change scenarios, based on the criteria that corrosion initiation probability is at least equal to the probability in the baseline scenario (Source: Wang et al., 2010).

The Wang et al. report concludes that existing concrete structures have been built under the assumption that the climate remains static. As the climate changes concrete structures may deteriorate more rapidly as a result of changes to environmental exposure, an effect that in turn might affect the serviceability and safety of concrete structures in their remaining useful life. The report recommends that Councils use the findings of the study to consider climate change impacts on concrete structures in the following ways:

1. The results can assist determination of useful life of new concrete component that will be built according to current Australian standard AS 3600; or

2. The results can assist in the determination of the remaining life of a relatively recently built concrete component (e.g. buildings constructed that meet the AS3600 standard described in 1994).

   Example: If a new concrete component is built according to the current standards, then its' useful life can be estimated by analysing graphs presented in the appendices B to J in part II of the CSIRO report. The graphs present changes in 1) probabilities of corrosion initiation; 2) probabilities of corrosion damage and; 3) mean rebar loss as a consequence of climate change.

3. The results can assist in the determination of extra cost/s required to build concrete components according the recommendations of the report.

Example: Current Australian standard AS 3600 defines specifications that guarantee minimum useful life of the component. If a Council would like the minimum useful life of the new concrete component to be consistent with the current Australian standards, then the new concrete components should be built according to the recommendations in the appendices K to Q in the CSIRO report.

4. The result can assist the determination of remaining useful life for existing concrete components built before 1995 (the implementation data of the AS 3600 standard).

Example: When the management of existing Council assets requires continuing maintenance of established concrete components, Councils may wish to consider the impact of climate change on the duration of the component's remaining useful life (and on the expected time for repair). This analysis should be carried out on a case specific basis. The case studies of the part III of the CSIRO report may assist Councils when they estimate the remaining useful life of the existing concrete component. Councils should select a case study that has similar characteristics to theirs in terms of component parameters and environmental exposure. By using the case study results, Councils could determine the approximate time for component repair.

5. The results can assist in determining of the most suitable adaptation method for existing concrete component that requires repair.

Example: When Councils need to consider the repair of the existing concrete components, they can use the proposed methodology for selection of most suitable method to mitigate concrete corrosion. Part III of the CSIRO report provides information for possible adaptation methods, their cost and effectiveness. Box 1 below provides the published summary of climate change adaptation methods for reducing deterioration of concrete (Wang, Nguyen et al. 2010).

Box 1: Effectiveness and cost of adaptation methods for existing concrete structures. All costs are presented as 'present value' as at 2010 (Source: Wang et al., 2010).

Adaptation measures for chloride-induced corrosion:

1. Electrochemical Chloride Extraction 90%: Correction factor for chloride concentration RChloride = 0.1, and correction factor for corrosion rate Ricorr = 0.1 accordingly. The cost is about $600/m^2. It is a permanent solution if a surface coating is applied and properly maintained.
2. Polyurethane sealer: It is able to reduce chloride diffusion coefficient. The estimation of diffusion coefficient is described in section 2.4.2, and relevant data described in Table 2-2. The cost is about $40/m^2. The coating is applied every 15 years.
3. Polymer-modified (p-m) cementious coating: Is able to reduce chloride diffusion coefficient. The estimation of diffusion coefficient is described in section 2.4.2, and relevant data described in Table 2-2. The cost is about $40/m^2. The coating is applied every 15 years.
4. Replacing existing cover: The new cover conforms to current concrete standards, as described in section 2.4.5. The cost is about $2,500/m^2.
5. Cathodic protection: Permanently stops corrosion initiation and damage. The cost includes $800/m^2 initial cost and $10/m^2/year operating cost.

Adaptation measure for carbonation-induced corrosion:

1. Realkalisation: A permanent solution if a surface coating is applied and properly maintained. The cost is about $600/m^2.
2. Acrylic-based coating: Able to reduce the carbonation diffusion coefficient as described in section 2.4.2 and relevant data described in Table 2-2. The cost is about $50/m^2. The coating is applied every 15 years.
3. Replacing existing cover: The new cover conforms to current concrete standards, as described in section 2.4.5. The cost is about $2,500/m^2.

10.1.2 Physical deterioration of concrete

Physical deterioration of concrete can manifest as surface wear or cracking.

Surface wear

There are three primary ways that surface wear can occur in concrete: abrasion, erosion, or cavitation.

Abrasion is the loss of material due to dry attrition with other objects and can happen in any number of ways including wear on footpaths due to the rubbing action of pedestrians walking, or road surfaces wearing due to the contact of the bitumen with rubber tyres, etc. The forces associated with abrasion are typically not directly related to climate change.

Erosion is the loss of material caused by wind and water. Generally, concrete is robust enough in most climatic conditions, including in the case of severe dust or sand storms, to resist erosion Concrete structures that are designed to be exposed to water flows are generally reinforced to ensure they are resistant to erosion (Council of Standards Australia 2009). Nonetheless, concrete can erode due to rapidly moving particles such as suspended sand particles within sea water currents (Liu, Yen et al. 2006). Changes to relative current strength and directional oscillation of water movement may impact on the rate of deterioration. However, the Australian standards for concrete already take into account the potential damage that may occur from extreme climatic events and stipulate concrete composition and reinforcements for specific location/environmental conditions to add strength to the final product (Council of Standards Australia 2009). Given the standards to which concrete infrastructure is constructed in Australia, particularly those components of infrastructure designed to be submerged, it is not expected that the changes to wind and water flows due to climate change will adversely affect the rate of wear due to erosion for infrastructure within its designed tolerance or normal environment. However, if concrete assets that were originally not designed to be submerged become so as a result of climate change, then the likelihood of erosion is increased.

Cavitation is the loss of mass by the formation of vapour bubbles on the surface of concrete and is caused by changes in water pressure, typically at water gates (Moskvin 1978; Woodson 2009). Climate change is not expected to have any additional impact on those factors already influencing concrete cavitation.

Cracking

Physical processes that cause concrete to crack are classified in the literature into three groups:

1. Significant volume change due to temperature and humidity gradient/s;
2. Severe structural loading; and
3. Exposure to extreme temperatures in freezing or fire (Mehta and Monteiro 2006).

It is known that under normal temperature and humidity conditions, the volume of concrete in a given section changes as conditions fluctuate. However, as current Australian climate change projections suggest that extreme heatwave and high-humidity events will become common, there is concern as to whether or not concrete can withstand sustained extreme climatic conditions.

Temperature and humidity fluctuations and extremes are considered within the Australian standard for concrete structures, and are addressed by including contraction and expansion joins to minimise cracking (Woodson 2009). If these control structures are not included severe static, or severely fluctuating temperature or humidity will impact detrimentally on a concrete structure. In a consistently hotter Australian climate these and other types of anti-cracking interventions will need to be included when commissioning new concrete assets and when maintaining existing concrete assets.

Extreme temperature includes the likelihood of extreme cold/freezing events and extreme heat events such as fire. The probability of extreme cold/freezing events in Australia is likely to reduce in the future and so the potential damage associated with the freeze-thaw cycle is not considered further. On the other hand, higher temperatures and dryer conditions will lead to more bushfire events that in turn will result in asset damage. Depending on the level of damage to the structure burnt, those sections of structural concrete in question are either rebuilt or have the appropriate segments replaced. As such the effect of fire events on concrete is not examined further in this document.

There are at least two other stressors that cause cracks in concrete:

1. the crystallisation of salts in concrete pores (Mehta and Monteiro 2006); and
2. inappropriate structural loading.

Climate change may increase salt concentration in the coastal environment due to gradual sea level rise or more frequent and severe storm surges. As a result, coastal concrete structures may experience higher deterioration rates. These scenarios are also addressed in section 16.1.4 - Concrete in the marine environment. In a typical inland environment it is not expected that climate change will contribute to increase of salt concentration in concrete structures and hence there is unlikely to be any change in deterioration rate due to that factor. Inappropriate structural loading is unaffected by climate change and so is not discussed further.

10.1.3 Deterioration of concrete by chemical reactions

In normal non-acidic environments there is no threat from chemical deterioration for concrete structures that are in good condition and have low permeability (Mehta and Monteiro 2006). However, concrete structures may be surrounded by environments that contain active chemical agents. In such circumstances, concrete durability can be weakened by chemical reactions that occur within the concrete that result from interactions with those active chemical agents. Concrete structures that have higher permeability are more susceptible to this sort of chemical deterioration.

The chemical reactions that can deteriorate concrete can be classified into two groups. The first is removal or replacement of Calcium (Ca_{2+}) ions in concrete and the second is the formation of expansive materials.

Reactions involving removal or substitution of Ca^{2+} ions

The removal or replacement of Ca_{2+} ions in concrete could lead to a loss of strength and rigidity, and therefore promote the deterioration process. The most common mechanisms for the removal or replacement of Ca_{2+} include the effect of:

- soft water by means of dissolving calcium-containing structures;
- acids on calcium based structures;
- oxalic acids emanating from animal waste and vegetable matter; and
- Magnesium (Mg_{2+}) replacing calcium in concrete structures that are submerged in sea water.

Each of these removal/replacement causes is discussed in greater detail.

Soft water comes from rain or melting snow and ice. The main characteristic of soft water is that it has a low concentration of calcium ions and so has a propensity to dissolve calcium-containing products when in contact. Soft water leaches the components of hardened cement paste by removing Ca_{2+} ions (Mehta and Monteiro 2006). Rainfall runoff is soft water and is in contact with many concrete structures including kerbs, drains and footpaths. Australian standards consider the effect of soft water and stipulate minimum standards for concrete to ensure that any soft water contact causes minimal decomposition (Council of Standards Australia 2009). However, in the case where climate change will lead to a significant increase in rainfall, it is expected that increased deterioration of concrete will occur due to soft water contact.

High concentration of acids can remove Ca_{2+} ions from concrete by forming soluble calcium salt solutions. For example, chloride, sulphate, and acetate ions react with Ca_{2+} ions in the concrete and form soluble calcium chloride, calcium sulphate and calcium acetate. Once these reactions take place the transformed compounds might be washed away and deterioration occurs from a loss of mass, strength and durability (Mehta and Monteiro 2006). If climate change leads to a higher concentration of acids in the surrounding soils and water, then potentially there will be an increase in concrete deterioration.

Concrete is also susceptible to oxalic acids that are present in decaying animal waste or vegetable mater. In these cases concrete loses its durability because Ca_{2+} ions are removed and the remanent material is transformed into a non-expansive insoluble product (Mehta and Monteiro 2006). In flooding events with sewage overflow this type of deterioration may take place in concrete that was not designed to withstand this form of chemical attack. Climate change may possibly increase the frequency of floods in some areas and therefore, attention should be paid to the potential for non-oxalic treated concrete structures deteriorating more rapidly in this situation.

The high concentration of Mg_{2+} ions in soils and especially in seawater may lead to the replacement of Ca_{2+} ions with Mg_{2+} ions in concrete and a loss of cementitious characteristics (Mehta and Monteiro 2006). At this stage, no evidence has been found to suggest that climate change might lead to an increase in Mg_{2+} in soil, underground/bore water supplies, in seawater or other sources. However, it should be noted that in the case where concrete structures have not been designed to cope with direct seawater contact, they may suffer increased levels of deterioration if climate change driven sea level rise lead to inundation of previously dry locations.

Reactions involving formation of expansive products

Chemical reactions involving the formation of expansive products cause concrete cracking, spalling, and deformation. Climate change influences on these types of chemical reactions is now discussed.

Sulphate attack on concrete is a common phenomenon and is broadly discussed in the research literature. Excessive amounts of sulphates cause the formation of ettringite and gypsum that in turn decrease concrete durability and elasticity (Neville 2004; Rozière, Loukili et al. 2009). Typically, sulphate attacks occur in seawater or clay soil environments.

Steel corrosion occurs in chloride- or sulphate- contaminated environments such as sea water. This phenomenon is well documented in the literature and there have been numerous analyses of steel corrosion within various types of concrete (Buenfeld, Newman et al. 1986; Thomas, Matthews et al. 1990; Gowripalan, Sirivivatnanon et al. 2000; Kumar 2000; McCarthy and Giannakou 2002; Memon, Radin et al. 2002; Pech-Canul and Castro 2002; Erdogdu, Kondratova et al. 2004; Thomas and Matthews 2004). The range of results is wide and depends on admixtures used. An increase in the sulphate or chloride concentration in the concrete surroundings will lead to higher deterioration rates due to sulphate attack or steel corrosion. However, it is unknown what impact climate change will have on sulphate or chloride concentrations in the environment.

Other chemical reactions that cause the formation of expansive products are Alkali-Aggregate Attack (AAA) and hydration of crystalline MgO or CaO. AAA (also known as Alkali-Silica Reaction (ASR)) affects concrete durability as a result of expansive chemical reactions between silica and alkalis. The corrosion can be regulated by using an appropriate selection of aggregate mix (Ichikawa and Miura 2007; Multon, Sellier et al. 2009). Hydration of crystalline MgO or CaO may also occur in concrete with high concentrations of MgO or CaO. In these cases, concrete may crack due to the crystallisation of the oxides, and resulting expansion (Mehta and Monteiro 2006). The nature of AAA and crystallisation of MgO or CaO suggests that climate change will not have any impact on them.

10.1.4 Concrete in the marine environment

Australian standards for concrete design and construction (that is, AS3600-2009: Concrete Structures) defines explicitly which technology should be used for concrete structures in the marine environment. According to the Australian Academy of Technological Sciences and Engineering (AATE) when structures satisfy legal requirements it is very likely that they will provide the intended service during the asset design life and they will able to withstand the environmental challenges of climate change (Stevens 2010). Furthermore, the AATE review indicates that in the cases where the marine environment is considered, concrete structures are not likely to experience negative effects from climate change. Advanced concrete technologies guarantee that concrete can maintain its durability when it is submerged in sea water or it is exposed to other influences from sea water (Memon, Radin et al. 2002; Pech-Canul and Castro 2002; Thomas and Matthews 2004; Shayan, Xu et al. 2008).

In marine environments, concrete, that does not comply with the Australian standards, deteriorates in short periods of time due to sulphate damage, steel corrosion, abrasion, and cracking from frequent wetting and drying (Ahmad 2006). This problem may become significant in the event of storm surges when previously dry concrete may be submerged by sea water. When the water retreats, chemical agents potentially remain in the concrete pores, and in turn may open the concrete to sulphate and chloride damage.

10.1.5 Summary of concrete resilience to climate change

The review into concrete durability has found that concrete is relatively resilient to climate change and that concrete in a carbon-rich atmosphere may continue to be an appropriate material given its excellent durability.

10.2 Deterioration of Steel

Steel that is used as a structural material should be protected against environmental factors according to Australian standards. The common approach to protecting steel components is to apply a protective coating to the surface. In the interest of completeness, this section examines protected and unprotected steel. The most widely used protective coating of steel is galvanising (Standards Association of Australia 1998). As a result, attention is given to corrosion of the zinc galvanising coat.

The scale of steel and galvanic coating corrosion depends on the nature of surrounding conditions, and so we have included separate analyses for corrosion from different types of environment. The accepted classification for corrosive environments is defined by the following classes: atmospheric environment, in-ground environment, sea, or fresh water environment. It could be assumed that the defined classes for surrounding environment cover nearly all existing surrounding circumstances for steel structures that are within the scope of this project.

10.2.1 Steel and galvanic coating corrosion in atmospheric conditions

Cole explains atmospheric corrosion of metals (Cole 2010), and concludes that the interaction of two primary parameters determines metal corrosion rates. These factors are length of time the metal is “wet” (length of time the surface has moisture on it) and acidity level of the moisture on the metal surface. The longer a metal surface is wet, the longer the metal is exposed to corrosive chemical reactions. The acid level is a measure of the concentration of acidic ions (e.g. chlorides, sulphates, nitrates) in solution. The higher the acidity, the more damage from corrosion is likely.

Climate change will impact on the length of time the metal is wet – a variable that depends on a complex interaction between temperature, rainfall, wind, humidity, etc. All these meteorological variables are influenced by climate change in various ways and uniquely for different regions in Australia. Therefore, to predict the time of wetness one needs to consider local circumstances. Acid levels in moisture on metal surfaces are dependent on levels of air pollutants, temperature and rainfall. For example, higher temperature stimulates water to absorb more chemicals of an acidic nature from the air.

Numerous studies have attempted to model the corrosion rate of steel and zinc coating for different atmospheric conditions (Haynie 1987; Feliu, Morcillo et al. 1993a; Feliu, Morcillo et al. 1993b; Svensson and Johansson 1996; Mendoza and Corvo 1999; Rodríguez, Hernández et al. 2003). A brief overview of the studies follows.

Rodriguez et al (2003) developed a model for steel corrosion in coastal areas that was based on the level of concentration of chloride and sulphur ions in the air, time of exposure, and time of wetness. The study suggests that the time of wetness is a factor of considerable importance for steel deterioration. Another finding from the study was that the magnitude of coastal winds has the potential to dramatically increase the geographic area where steel is subject to severe corrosion because of high concentration of chlorides blown in from the sea.

Mendoza et al (1999) observed samples of steel at several locations and found a noticeable difference between corrosion rates. The authors developed a model to predict the corrosion rate using environmental parameters for rainfall and temperature. It was found that "the influence of time of wetness on increasing corrosion rates is more significant when the temperature is lower than 25°C than when the temperature is over this value".

Feliu et al (1993) established models to predict annual metal corrosion of mild steel, zinc, copper and aluminium from meteorological and pollution parameters by using data that was collated from a literature review survey. Initially, time of wetness, average annual temperature, the number of rainy days, relative humidity, sulphur dioxide (SO_2) pollution, and chloride (Cl) pollution were considered. Employing stepwise regression analysis significant parameters were selected and included in the model. The corrosion models for steel and zinc include time of wetness, average temperature, SO_2 pollution, and Cl pollution as parameters. Based on the developed annual model, the authors then developed a long-term prediction model for atmospheric corrosion of metals. As well as the parameters that are used in the annual model the long-term model includes the number of rainy days as parameter (Feliu, Morcillo et al. 1993).

The influence of temperature on SO_2-induced atmospheric corrosion of zinc was studied by Svensson et al (1996) in a laboratory experiment. Results showed that the corrosion rate was inversely proportional to temperature. The lower temperatures cause a higher deposition rate of SO_2 from atmosphere and consequently make condensed water on the metal surface more corrosive.

Haynie (1987) developed a model to predict rate of corrosion for zinc galvanised steel. The initial model took into account time of wetness, temperature, and air pollution levels and concluded that the time of wetness was the second most significant factor after the air pollution levels of sulphur dioxide. However, the author notes that time of wetness should be considered as a function of meteorological parameters and the accumulation of dust on upper surfaces.

Several conclusions could be drawn from these studies:

There is non-linear relationship between meteorological and air pollution parameters in the models that implies that the unique combination of circumstances in each case is vital for the prediction of future corrosion rates. An alteration in temperature, rainfall, and other meteorological parameters must be considered in the context of the specific local circumstances.

Time of wetness appears to be a critical factor for metal corrosion rate. Alterations to time of wetness as a result of climate change may potentially require an adjustment to the existing management of steel structures. The effect of climate change on time of wetness could be predicted by analysing the expected impact of climate change on dew point.

In some specific circumstances, climate change could influence metal corrosion rates by affecting specific local parameters. For example, if climate change increased the magnitude of coastal winds it would lead to an extension of the chloride influence zone and to an increase in steel and zinc corrosion rates. This suggestion coincides with a statement from the Galvanizers' Specifiers Manual (Industrial Galvanizers Australian Galvanizing Division, 2011) that "in Australia the major driver of metal corrosion is chloride generated from ocean surf". Change in the magnitude and extent of this major driver of metal corrosion in Australia suggests a potentially significant effect on corrosion rates for atmospheric steel and zinc corrosion. Consequently coastal Councils should pay significant attention to the possible effect of climate change on their steel or galvanised steel structures.

The Australian standard AS 4312-2008 (Standards Association of Australia 2008) defines five environmental zones for atmospheric metal corrosion, and provides the expected annual steel corrosion rates listed in Table 11. The zones are defined in terms of meteorological and air pollution parameters. The predicted corrosive rates are a function of typical air pollution levels for each environment and the typical time of wetness, itself a function of typical meteorological parameters for that zone.

Table 11: Environmental zones for atmospheric metal corrosion according to AS 4312-2008 (Source: Standards Association of Australia 2008).

ISO 9223 category	Corrosivity rating	Steel corrosion rate – Microns/year	Typical environment
C1	Very low	<1.3	Dry indoors
C2	Low	1.3 - 25	Arid/urban inland
C3	Medium	25 - 50	Coastal/industrial
C4	High	50 - 80	Marine (calm water)
C5	Very high	80 - 200	Marine (Ocean surf)

The expected annual corrosion rates in different environmental zones for zinc coating are summarised in Table 12 where the "T" stands for tropical climate. The other zones are consistent with ISO 9223 classification used in AS 4312-2008.

Table 12: Annual corrosion rates of zinc coating (Source: INGAL - Industrial Galvanizer Australia 2008).

ISO 9223 category	Corrosivity rating	Zinc corrosion rate – Microns/year		Typical environment
		Average rate	Maximum rate	
C1	Very low	~ 0.5	~ 1	Dry indoors
C2	Low	~ 1.2	~ 2	Arid/urban inland
C3	Medium	~ 2	~ 4	Coastal/industrial
C4	High	~ 8	~ 15	Marine (calm water)
C5	Very high	~ 10	~ 20	Marine (Ocean surf)
T	Medium	~ 2	~ 4	Tropical

The effect of a single meteorological variable such as temperature, rainfall or wind velocity on metal corrosion is difficult to estimate. As Australian standards AS 4312

(Standards Association of Australia 2008) explains, the relationship between these factors and metal corrosion rate is not straightforward (Page 8):

(a) Rainfall has the effect of either stimulating or reducing corrosion depending on the environment. In polluted or coastal atmospheres, the washing effect of the rain may reduce corrosion by decreasing the time of wetness, while at less polluted sites or those well away from the ocean the situation is reversed and the rain increases time of wetness of the surface.

(b) Temperature also has contradictory effects. Increasing temperature increases the rate of corrosion reactions but leads to more rapid moisture evaporation, shortening the time of wetness and decreasing the corrosion rate.

(c) Wind may increase corrosion rate by carrying salts and other corrosion contaminants considerable distances from their source. Alternatively winds may dry a wet surface lowering the time of wetness and corrosion rate.

Table 13 displays a guide for the service life of various types of galvanised protective cover. The table lists expected service life of galvanised coating in the environmental zones that are defined in Australian standard AS 4312 (Standards Association of Australia 2008).

Table 13: Corrosion rate and estimated service life of galvanised coating (Source: Standards Association of Australia 2008).

System designation*	Nominal coating thickness	Service life, years					
		Atmospheric corrosivity category (As per AS/NZS 2312 and ISO 9223)					
		A Very low	B Low	C-F Medium Inland tropical	D High	E-I Very high industrial	E-M Very high marine
g/m² per side	µm	Indoor dry Air-conditioned	Outdoor rural inland— Occasional condensation	High humidity with some pollution— Urban coastal swimming pools, chemical plants	Industrial or urban coastal swimming pools, chemical plants	Industrial high humidity and high salinity, coastal	Seawater, offshore conditions
HDG300	42	†	25+	10–25	5–10	NR	2–5
HDG390	55	†	25+	15–25	5–15	NR	2–5
HDG500	70	†	25+	25+	10–25	NR	5–10
HDG600	85	†	25+	25+	15–25	2–5	5–15
ZB100/100	14	†	10–25+	2–10	NR	NR	NR
ZB300/300	42	†	25+	10–25	5–10	NR	2–5
ILG100	14	†	10–25+	2–10	NR	NR	NR
ILG300	42	†	25+	10–25	5–10	NR	2–5
PGS50	7	5–10	NR	NR	NR	NR	NR
PGS100	14	†	10–25+	2–10	NR	NR	NR

* Number which indicates coating thickness

† Indoor environment only, not relevant to this Standard.

NR = Not recommended

The information presented above in Table 11, Table 12 and Table 13 and quotes from Australian standards show how changes in temperature, rainfall, and wind strength can influence the corrosion rates of steel and zinc. For example, it can be assumed that for a given air pollution level, the change in time of wetness has a linear positive correlation with corrosion rate because the longer the metal is wet, the longer it is subject to corrosive attack. Based on this assumption, a simple model for each environmental zone can be developed. An important additional observation is that each developed model is applicable only to the individual case and should not be used as general approach.

Conclusion and remarks regarding atmospheric steel corrosion

Time of wetness and air pollution levels are the key parameters for modelling atmospheric steel and zinc corrosion. If it becomes possible to model these key parameters with respect to meteorological variables using a detailed local scale, then a reasonable quantitative estimation of the impact of climate change on the rate of steel and zinc corrosion might be obtained. However, meteorological factors such as rainfall, temperature and wind strength have contradictory effects on time of wetness and air pollution levels, and hence the compound effect of climate change (expressed as change in average meteorological variables) on atmospheric steel and zinc corrosion should be considered on an individual case by case basis.

One particular concern for coastal Councils is that climate change may increase atmospheric steel and zinc corrosion. This would happen if the velocity of prevailing coastal winds increases as a result of climate change. Councils should observe how the concentration of chloride and corrosion chemicals in the atmosphere increases and adjust accordingly the corrosion rate of steel and galvanised steel structures.

10.2.2 Steel and galvanic coating corrosion in in-ground environment

Steel and zinc corrosion in-ground requires oxygen, moisture, and dissolved salts. Steel and zinc will corrode in acidic environments and not, necessarily, in alkali environments. The availability of moisture and soil in ground varies significantly over time and this fact leads to extreme variations in the rate of corrosion. Generally, clay soils hold more water than the other types of soils and that so are more corrosive.

Alamilla et al (2009) developed a model for steel corrosion in the ground. In the model, the rate of steel corrosion is exponentially dependant on the pH – acid level of the soil, p – soil resistivity, E_{redox} – oxidation-reduction capacity of soil, and $E_{s\text{-}d}$ - soil electrical potential.

Australian standards (Standards Association of Australia and Standards Association of New Zealand 1998; Standards Association of Australia 2008) use soil resistivity and soil acidity (pH level) to determine how aggressive steel and zinc corrosion in the ground can be. Table 14 lists acceptable ranges for resistivity and acidity of soil that is in contact with metal structure. If soil resistivity or acidity fall outside the recommended ranges in Table 14 as result of climate change, then metal structures may experience severe corrosion.

Table 14: Recommended ranges for pH and resistivity of soil and water in contact with the corrugated metal surfaces (Source: Standards Association of Australia and Standards Association of New Zealand 1998).

Resistivity (ohm, cm)	Acceptable pH range			
	Galvanized steel	Aluminised steel	Aluminium	Steel or aluminium with barrier coating
10 000 or more	5–12	5–9	4–9	4–12
2 000–10 000	6–10	5–9	4–9	4–12
500–2 000	—	—	4–9	4–12

If soil resistivity or acidity approaches the limits of the recommended ranges in Table 14 as result of climate change, then zinc may experience corrosion rates according to Table 15 and steel may experience corrosion rates according to Table 16.

Table 15: Zinc coating loss rate versus soil acidity (pH level) or resistivity (Source: Standards Association of Australia and Standards Association of New Zealand 1998).

Soil pH	Average zinc coating loss rate (µm/yr)	
	Drained soils	Undrained soils
<4	>6.5	>20
4–4.9	2.6–5.2	6.7–13.3
5–7.9	2.2–4.3	5.5–11.0
8–9	3.3–6.5	6.1–12.1
>9	>8.6	>17.2
Soil resistivity (Ohm, cm)	**All soils**	
<500	>3.5	
500–1000	1.5–3.5	
1000–2000	1.3–1.5	
2000–5000	0.9–1.5	
>5000	<0.9	

NOTES:

1 For Class 1 and Class 2 structures which have been hot-dip galvanised a coating thickness of—

(a) 63 µm (per side) is applicable for wall thicknesses less than 5 mm; and

(b) 84 µm (per side) is applicable for wall thicknesses equal to or greater than 5 mm.

For Class 1 structures with Z600 coating, a coating thickness of 49 µm is applicable.

2 For aluminized Type II coating, a coating thickness of 48 µm is applicable.

3 Non-metallic barrier coatings are recommended in coastal installations where extended life is required.

4 In fully submerged conditions, metal loss rates of 1 µm per year can be expected.

5 In splash zones, metal loss rates may exceed those given for severe coastal conditions.

Table 16: Average steel loss rate in various soils (Source: Standards Association of Australia and Standards Association of New Zealand 1998).

pH	Chloride concentration		Resistivity ohm cm	Average metal loss rates (µm/year)	
	In soil (%)	In water (ppm)		Undrained soils	Drained soils
				Steel	Steel
>5	<0.5	>1 000	>5 000	<10	<10
4–5	0.5–2	1 000–10 000	2 000–5 000	10–20	<10
3–4	2–5	10 000–20 000	1 000–2 000	20–40	10–20
<3	>5	>20 000	<1 000	40–300	10–40
				Aluminium Note 1	Aluminium Note 1
4–9	1.0–1.5	<20 000	>500	5–13	5–7

NOTES:

1 For aluminium in contact with soils and water exhibiting properties within the limits given in Table C3, the metal loss rate becomes almost negligible after 2–5 years due to blockage of corrosion pits with insoluble corrosion products. For soils and waters with pH outside the 4–9 range or with high concentrations of soluble salts, a protective barrier coating is required to prevent accelerated corrosion. Studies done for the Florida Department of Transport show aluminium structures in a salt water environment have lower loss rates.

2 For steel in high pH soils with high sulphate or chloride concentrations, average metal loss rates of 20–60 µ/yr can be expected.

Conclusion and remarks regarding in-ground steel corrosion

If climate change affects soil resistivity and soil acidity, then this project can use the information in Table 15 and Table 16 to infer any possible impact of climate change on metal components in ground.

10.2.3 Steel and galvanic coating corrosion when immersed in water

The corrosion of steel in fresh water depends on water composition. A change in water composition will lead to changes in water corrosivity. The composition of Australian fresh water varies significantly between regions. Good building and maintenance practice requires the corrosivity of water to be considered when steel structures are immersed in fresh water.

According to the standards AS/NZS 2312 (Standards Australia/Standards New Zealand 2002) soft fresh waters causes around 50 µm/annum steel corrosion, while very hard fresh waters are not usually corrosive to steel. In the cases where climate change affects fresh water composition, appropriate adjustment to the management of steel structures immersed in water needs to be considered. The corrosion rate of steel in sea water is about 130 µm/annum during the first few years and around 50 µm/annum afterwards. The corrosion rate in tidal and splash zones is several times higher than the corrosion rate at full immersion. Water velocity also has influence on corrosion rate (Standards Australia/Standards New Zealand 2002).

Zinc coating also corrodes in water. Table 17 shows the corrosion rates of zinc in various water types. Sea water is more corrosive than the soft fresh water, which is more corrosive than the hard fresh water.

Table 17: Typical corrosion rate for zinc in waters (Source: Standards Association of Australia 2008).

Water type	Corrosion rate µm per year
Seawater	15 - 25
Hard fresh water	2.5 - 5
Soft fresh water	5 - 10
Distilled water	50 - 200

Water acidity (pH level) and water temperature are also important factors for determining the corrosion rate of zinc in water. The effect of water acidity on zinc corrosion is shown in Figure 45. When the pH is less than 6, a small decrease in pH will lead to a dramatic increase in corrosion rates. Thus, if the pH of water changes to values below 6 as result of climate change, then the zinc corrosion rate will change significantly.

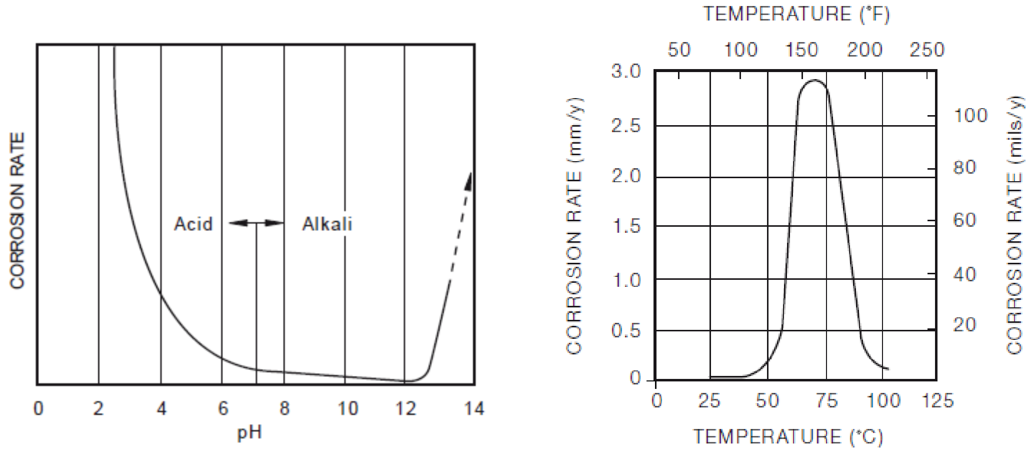


Figure 45: (Left) Effect of pH of water on zinc corrosion; and (Right) effect of water temperature on zinc corrosion (Source: (Standards Association of Australia 2008).

Figure 45 also shows the effect of water temperature on zinc corrosion rates and demonstrates that there can be a dramatic change in zinc corrosion rates as a result of changes in water temperature - particularly at temperatures above 35°C. There is a low probability that climate change will increase the temperature of water bodies (such as the sea, lakes, etc.) above 35°C in Australia. However, in the case where this does happen, then climate change will affect zinc corrosion rates.

Conclusion and remarks regarding aqueous steel corrosion

This project can use Figure 45 to estimate how corrosion rates of the zinc layer of submerged steel structures will be affected as result of climate change.

10.3 Conclusion

The choice of materials used for the construction and maintenance of assets is highly dependent on the environmental conditions. Australian standards (e.g. AS1684.1, AS 1684.2, AS 3600) specify under what conditions and circumstances which materials and construction technologies should be used for asset construction. The standards generally guarantee the serviceability of assets by ensuring they are durable to environmental influence and resilient to un/expected extreme events.

It is important to note that assets that were made to be resilient to specific environmental conditions may become vulnerable to new environmental factors as a result of climate change that they have not been previously exposed to during their service life. Therefore, there may be an increase in deterioration or maintenance costs or a reduction in the useful life of some assets in some regions where climate changes will lead to a dramatic change in environmental exposure. For example, asset environmental exposure that changes from a dry to a wet climate or an increase in the occurrence of heatwaves or other threshold events where they have not occurred historically. In these cases the “new” climate regime may significantly deteriorate asset conditions, shorten service or design life, affect the level of service or and require alterations to maintenance schedules.

APPENDIX 3 – HOW TO GUIDE DEVELOPED FOR USE OF THE TOOLS DEVELOPED

CALCULATING THE CLIMATE CHANGE IMPACT ON ROAD ASSETS

Introduction

This How To Guide explains how to use the Climate Change Impacts Financial Simulation Model to quantify the change in road asset useful life and corresponding maintenance and repair costs as a result of future climate changes. Road assets included in the model include spray sealed, asphalt (hotmix) and unsealed (gravel formation) roads. The impacts of climate change for each road asset type is modelled using road engineering equations that have been tested for appropriateness under Australian conditions by the Australian Road Research Board (ARRB) and climate data extracted from the Bureau of Meteorology High Quality National Real Time Monitoring (RTM) gridded data set (previously known as the Australian Water Availability Project data set (AWAP)).

The model was developed as part of a National Climate Change Adaptation Research Facility (NCCARF) research project funded by the Department of Climate Change and Energy Efficiency and collaborating partners including the Local Government Association South Australia (LGA SA), the Institute of Public Works and Engineering Australia (IPWEA), University of South Australia (UniSA),Bureau of Meteorology (BOM), Coast Protection Board South Australia, Western Australian LGA (WALGA) and Municipal Association Victoria (MAV).

1. Model overview

Inputs to the model by the user includes the selection of Local Government Area, current year, end year (up to 2100) and road asset type (spray sealed (SSR), asphalt / hotmix (AHR) and unsealed / gravel roads (USR), and entry of the expected change in mean annual temperature and rainfall for the location for the end year compared to the current year, estimated road useful life, maintenance and rehabilitation costs and discount rate as shown in the flow chart below. Outputs include the climate change impact in % for total costs and change to asset useful life. The outputs from the model can then be entered into the NAMS.PLUS spread sheets change in service life, change in asset life, or cost of maintaining current asset life.

Select Council Name

↓

Select terminal climate projection year (up to 2100)

↓

Enter expected change to the climate by the terminal year:
Input change to mean annual temperature
Input change to mean annual rainfall

↓

Select road asset type (AHR, SSR or USR)

↓

Input other asset and cost parameters required

↓

Run Climate Change Impact Financial Simulation Model

↓

Select Output: distributions for climate change impact in % for total costs, and useful life

↓

Enter output in the form of change in service life, change in asset life, or cost of maintaining current asset life into NAMS+ in the appropriate spreadsheets.

The following pages of the guide step the user through the inputs required and explain the outputs generated. User data entry cells in the model are highlighted in yellow. The values shown in the following screen grabs are examples only.

2. Select Local Government Area and year for climate change projection

The first step is to select the Local Government Area (LGA) of interest from the drop down menu at the top of the input page. Selecting the LGA links the correct long-term historical climate data to the model. All Australian LGAs are included in the model although some metropolitan LGAs are grouped together as they have the same climate. For example, the LGA “Greater Adelaide” includes the 15 Councils of the Adelaide Metropolitan area. The current year is set in the model as 2010 and is fixed. The terminal year is the year for which the climate change assessment is to be made and can be selected from the drop down menu (every five years to 2100).

INPUT				
			Notes	
Council name :	Onkaparinga CC		Please select one	
Current year	2010		The data set ends with 2100	
Terminal projection year	2100		Please select one	

3. Enter projected changes to climate for projection year

Next, the expected change in annual mean temperature and annual mean rainfall for the LGA is entered. This data shifts the historical climate data distributions in the model by the entered amount to create a new changed climate distribution. The expected change in the climate can be sourced from climate projections produced by the CSIRO and BOM at the Climate Change in Australia Website (www.climatechangeinaustralia.gov.au) or a downscaled climate projection (e.g. Climate Futures in Tasmania project outputs provides high resolution climate projections: http://www.dpac.tas.gov.au/divisions/climatechange/adapting/climate_futures/local_government_area_climate_profiles) if available for the region. Alternatively a policy climate scenario (as defined by a particular agency or State Government) or a range of climate values as part of a sensitivity analysis can be selected instead.

For temperature the mean annual temperature increase expected by the terminal year of the analysis is entered in degrees Celsius (up to a maximum of 10^{o}C).For rainfall the mean annual rainfall change expected by the terminal year of the analysis is entered in millimetres. For rainfall the value can be either positive or negative relative to the current year (2010). Note a reduction in anticipated rainfall would be shown as a negative number.

Terminal climate change				
Mean annual temperature change in ◦C	3.5	°C	prediction by e.g. IPCC	between 0 &10
Mean change in total annual Rainfall (mm)	-125	mm	prediction by e.g. IPCC	

4. Enter data for Asphalt / Hotmix Roads (AHR)

The next step is to enter the required road asset data. For AHR there are four parameters needed: maintenance cost (current annual cost of maintenance in dollars); resurfacing cost (current annual resurfacing cost in dollars); resurfacing life in years (current number of years for the road asset to be assessed); rehabilitation cost (current annual rehabilitation cost in dollars); and rehabilitation life (current number of years for the road asset to be assessed).

Road data		
For Asphalt/Hotmix Sealed Road (AHR)		
Maintenance Cost-normal (MC)	660	current annual cost
Resurfacing cost (RSC)	2,244	current annual cost
Resurfacing Life (RSL)-in years	30	current figure
Rehabilitation cost (RC)	2,904	current annual cost
Rehabilitation Life(RL) in years	73.95	current figure

Note that the equation to calculate the impact of climate on AHR does not include a factor to allow for the different traffic levels or climatic impacts, apart from temperature, at each site. The equation is also not recommended for use where the asphalt thickness is greater than 40 mm. Also, the maintenance cost is assumed to be constant in real terms with or without climate change.

5. Enter data for Spray Sealed Roads (SSR)

Data entry for SSR is the same for AHR as described above. The climate change impact for SSR is included in the model by calculating the Thornthwaite Moisture Index (TI) – a function of monthly rainfall and mean monthly temperature. Maintenance costs are handled as above for AHR.

For Spray Sealed Road (SSR)		
Maintenance Cost-normal (MC)	$320	current annual cost
Resurfacing cost (RSC)	1,088	current annual cost
Resurfacing Life (RSL)-in years	15	current figure
Rehabilitation cost (RC)	1,408	current annual cost
Rehabilitation Life(RL) in years	76.15	current figure

6. Enter data for Unsealed Roads (USR)

Required data for the USR model are maintenance cost (current annual coast in dollars); re-sheeting cost (current annual coast in dollars); re-sheeting life (expected re-sheeting interval in years; current gravel loss rates in millimetres per year. The key climate change-related parameter for USR is the mean monthly precipitation (MMP).

For Unsealed Road (USR)			
Maintenance Cost-normal (MC)	635.2		current annual cost
Resheeting cost (RSC)	100		current annual cost
Resheeting Life (RSL)-years	5		Expected resheeting interval
Current Gravel Loss	20	mm	current annual figure

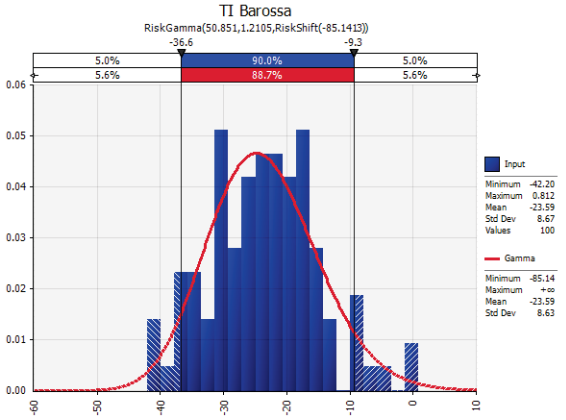
7. Enter Discount Rate

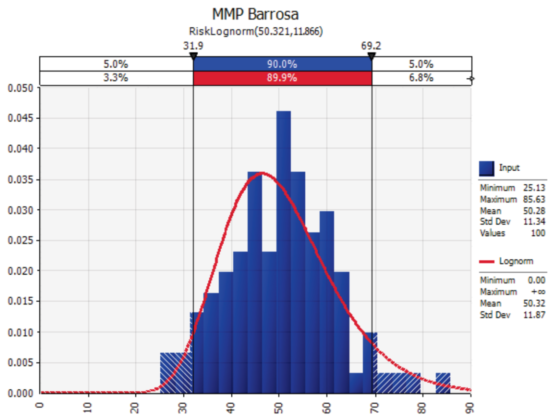
Finally the discount rate for the analysis is selected. It should be noted that the discount rate used in the model should be in real terms. Given that Councils have low financial risk relative to commercial firms and the historical average real rate of return on 10-year government bonds is about 3%, we recommend using a discount rate around 3% and takes into account the Council's credit rating and the long valuation time horizon. A sensitive analysis on discount rate can be carried out if necessary.

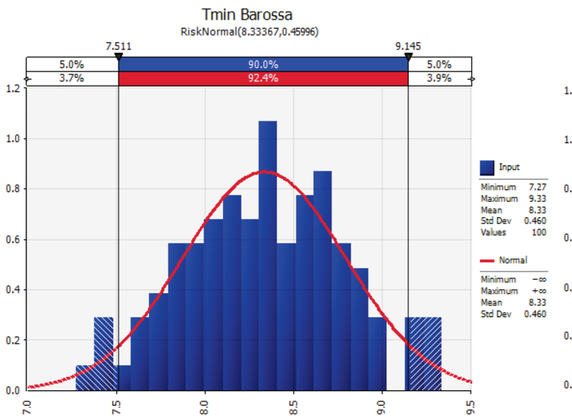
Model parameter	
Discount rate	2.85%

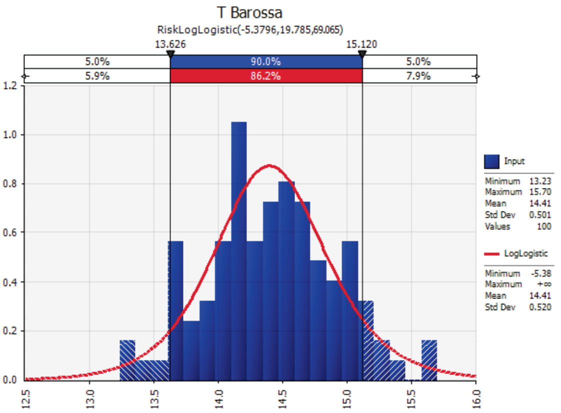
8. Interpreting the outputs

Outputs from the model include the historical and climate change parameter distributions calculated. The example on the following page shows the four historical climate distributions for the Barossa Council: the Thornthwaite Index (TI); mean monthly precipitation (MMP); minimum temperature (Tmin); and temperature (T). Note that for each graph, the vertical axis represents the fitted probability density function and the horizontal axis represents the values of the climate variable, with the statistics in the legend on the right hand side.

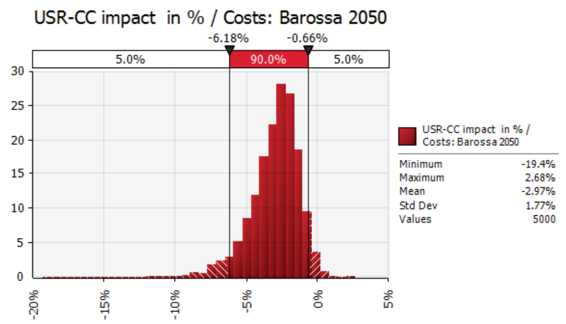


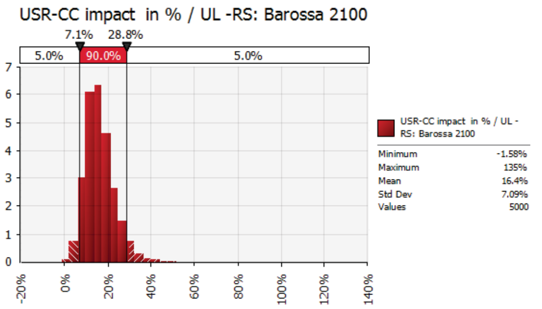






The percentage of climate change impacts on costs and on useful life of the asset over the selected time frame is then calculated using the engineering model identified for each road type and the climate distributions. The results are based on a simulation with 5000 iterations.





The output graph on the left shows the impact of climate change in costs (% change) for an Unsealed Road (USR) for the year 2050 and the graph on the right the impact of climate change on the Useful Life (% change) an Unsealed Road (USR) for the year 2100. In both graphs the vertical axis represents frequency, and the horizontal axis represents the values of climate change impact with the statistics in the legend on the right hand side. Statistics for each graph including the maximum, minimum, mean and standard deviation of the distribution are given on the right hand side. The results from the distribution can then be entered into the NAMS.PLUS framework Excel ® spread sheets or another asset management system of choice.

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