# Garnaut Climate Change Review

## Impact of climate change on infrastructure in Australia and CGE model inputs

Prepared by
Maunsell Australia Pty Ltd, in association with CSIRO Sustainable Ecosystems

June 2008

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**Disclaimer**

The information contained in this study is based on the current science and input from expert consultation and interpretations drawn from these inputs and is provided for information to the Garnaut Climate Change Secretariat to assist in their preparation of the Garnaut Climate Change Review Report. This report is not based on field inspections, sampling, testing or other means of physical inspection. Infrastructure varies according to its age, material components and condition and therefore Maunsell Australia do not represent that the information contained in this study shows completely the extent of the likely climate change impacts on all infrastructure in Australia. Readers of this study shall make their own interpretations, deductions and conclusions from the information made available and shall accept full responsibility for such interpretations, deductions and conclusions.
Executive summary

Introduction
In April 2007 Professor Ross Garnaut was commissioned by Australia’s State and Territory Governments to undertake an independent study titled the Garnaut Climate Change Review (GCCR). This GCCR examines the impacts of climate change on the Australian economy and recommends medium to long-term policies to achieve sustainable prosperity and address key climate change issues.

Maunsell Australia Pty Ltd (Maunsell) was engaged by the GCCR Secretariat to identify and assess the impacts of climate change on infrastructure in Australia, focusing on four key climate change impact storylines namely:

- buildings in coastal settlements
- electricity distribution and transmission networks
- water supply infrastructure in major cities
- port infrastructure and operations.

The four storylines were used to develop four economic shock matrices to inform the economic model for climate change impacts and associated mitigation policies.

The purpose of this report is to qualitatively describe the impacts of climate change on infrastructure and to provide further quantitative information relating to assumptions made for specific economic shocks that could be estimated for input into the economic modelling conducted by the Queensland Department of Treasury and Finance on behalf of the Garnaut Review.

Seven climate change scenarios, provided by CSIRO Marine and Atmospheric Research, were used to assess each of the four key infrastructure areas. Three of these climate scenarios were based on an unmitigated ‘business as usual’ growth in emissions, where global mean temperature reaches approximately 4.5°C by 2100, representing a hot and dry climate through to a warm and wet climate. Of the other four mitigation scenarios considered, three of which model global mean temperature reaching approximately 2.0°C by 2100, and one which limits temperature increase to 1.5°C by 2100.

In assessing the impacts and associated economic shocks, three yearly timeframes were used:

- 2007–2030
- 2031–2070
- 2071–2100.

The methodology utilised initial research and data gathering, a series of workshops bringing Maunsell infrastructure experts, Maunsell climate change specialists and CSIRO Sustainable Ecosystems (CSE) representatives together to identify and prioritise impact storylines. Once the four key impact storylines were explored, publicly available information was gathered in regard to current revenue and costs associated with the four key areas. This information was then used as a baseline to assess the potential changes to capital and operational expenditure associated with changes in climate variables which could be used to determine shocks to economic modelling.

Buildings in coastal settlements
Figure 1 outlines the impact storyline identified for buildings in coastal settlements. This storyline was assessed against climate conditions considered in seven climate scenarios (U1, U2, U3, M1, M2, M3 and M4) to develop the matrix of impacts for each coastal state and territory. In assessing the likely
impacts on buildings in coastal settlements, consideration was given to those buildings that are located within the coastal zone (i.e. within of 50km of the coast).

Figure 1  Impact storyline for buildings in coastal settlements

<table>
<thead>
<tr>
<th>Climatic Variables</th>
<th>Impacts</th>
<th>Implications</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Increase in temperature</td>
<td>Extreme rainfall, wind and storm surge events leads to increased impacts on buildings, facilities, coastal protection and drainage infrastructure</td>
<td>IMPPLICATIONS CONSIDERED IN ECONOMIC IMPACTS</td>
</tr>
<tr>
<td>• Increase in frequency of storms</td>
<td>Includes the potential failure of facilities such as sewerage treatment plants from inundation and flooding</td>
<td>• Increased residential and community property damage</td>
</tr>
<tr>
<td>• Increase in extreme rainfall and wind</td>
<td></td>
<td>• Increased commercial property damage</td>
</tr>
<tr>
<td>• Increased height and land penetration of storm surge</td>
<td></td>
<td>• Increased maintenance, repair and replacement of residential and commercial buildings</td>
</tr>
<tr>
<td>• Increase in strength of cyclones and areas exposed to cyclones *</td>
<td></td>
<td>ADDITIONAL IMPLICATIONS</td>
</tr>
<tr>
<td>• Gradual increase in sea level</td>
<td></td>
<td>• Increased maintenance, repair and replacement of utility infrastructure e.g. sewage treatment plants, power etc</td>
</tr>
</tbody>
</table>

*NOTE: The impact of cyclones on buildings has not been factored into the impacts of this study as it is being considered under a separate assessment of the GCCR.

A summary of the findings of the matrix of impacts is provided in Table 1, which shows the range of impacts anticipated. The detailed impact matrix is provided in section 2.1. In assessing the likely economic impacts, all climate variables outlined in Figure 1 were considered with the exception of cyclones.

Table 1  Summary of magnitude of impacts on buildings in coastal settlements for seven climate scenarios

<table>
<thead>
<tr>
<th></th>
<th>2008–2030</th>
<th>2031–2070</th>
<th>2071–2100</th>
</tr>
</thead>
<tbody>
<tr>
<td>U1</td>
<td>Low to Moderate</td>
<td>Moderate to Extreme</td>
<td>Moderate to Extreme</td>
</tr>
<tr>
<td>U2</td>
<td>Low to Moderate</td>
<td>Moderate to High</td>
<td>Moderate to Extreme</td>
</tr>
<tr>
<td>U3</td>
<td>Low to Moderate</td>
<td>Moderate to Extreme</td>
<td>Moderate to Extreme</td>
</tr>
<tr>
<td>M1</td>
<td>Low to Moderate</td>
<td>Moderate to High</td>
<td>Moderate to High</td>
</tr>
<tr>
<td>M2</td>
<td>Low to Moderate</td>
<td>Moderate to High</td>
<td>Moderate</td>
</tr>
<tr>
<td>M3</td>
<td>Low to Moderate</td>
<td>Moderate to High</td>
<td>Moderate to High</td>
</tr>
<tr>
<td>M4</td>
<td>Low to Moderate</td>
<td>Low to Moderate</td>
<td>Neutral to Moderate</td>
</tr>
</tbody>
</table>

Table 1 illustrates that the magnitude of the impacts of climate change on coastal buildings increases over time, and that a range of impacts are anticipated across different States. The most significant impacts are experienced under the U1 and the U3 scenarios, where the most dramatic changes in temperature and rainfall are modelled; for example Queensland is likely to experience extreme
impacts between 2031 and 2100 due to the increased potential for extreme storms, flash flooding and riverine flooding.

**Electricity transmission and distribution networks**

Figure 2 outlines the impact storyline identified for electricity transmission and distribution (T&D) networks. This storyline was assessed against climate conditions considered in the seven climate scenarios (U1, U2, U3, M1, M2, M3 and M4) to develop the matrix of impacts for each state and territory.

**Figure 2** Impact storyline for electricity distribution and transmission networks

<table>
<thead>
<tr>
<th>Climatic Variables</th>
<th>Impacts</th>
<th>Implications</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Increase in intensity of extreme wind</td>
<td>Damage to transmission and distribution above ground assets resulting in increased blackouts</td>
<td>Increased capital and maintenance expenditure on electricity transmission and distribution infrastructure</td>
</tr>
<tr>
<td>• Increase frequency and intensity of storms</td>
<td>Reduced network capacity</td>
<td>Increased number of blackouts</td>
</tr>
<tr>
<td>• Increase in frequency and intensity of bushfires</td>
<td>Accelerated deterioration of assets</td>
<td>Increased length of blackouts</td>
</tr>
<tr>
<td>• Increase in temperature</td>
<td>Potential blackout due to demand exceeding supply</td>
<td>Increased demand for skilled staff leading to shortage of skilled staff</td>
</tr>
<tr>
<td>• Increase in number of hot days</td>
<td></td>
<td>Lost revenue to Transmission and Distribution companies (short term)</td>
</tr>
<tr>
<td>• Decrease in rainfall</td>
<td></td>
<td>Accelerated depreciation and deterioration of assets</td>
</tr>
<tr>
<td>• Increase in localised electrical storms*</td>
<td></td>
<td>Increased power prices to consumer</td>
</tr>
</tbody>
</table>

*NOTE: The impact of climate change on electrical storms is currently not well understood; as such it has not been included in the considerations of this report.

A summary of the findings of the matrix of impacts is provided in Table 2, which shows the range of impacts anticipated. Table 2 illustrates that the magnitude of impact increases over time, for most scenarios with the highest magnitude of impact being experienced in 2100 under ‘business as usual’ scenarios (U1, U2 and U3). Under the U1 scenario of higher temperatures and lower rainfall, T&D networks face a number of pressures towards 2070 including: growing demands from higher temperatures and increasing air conditioner penetration and usage; more rapid deterioration of assets from greater network strain due to operating at near or over capacity; increased outages from extreme events, in particular wind-borne debris, airborne pollution and bushfires; and potentially amplified degradation of line assets due to ground movement or reduction in ground water.

The cumulative affect of these factors gives the potential for extreme impacts to 2070. U3 shows similar potential impacts, though with greater emphasis on flooding risks and some mitigation of the bushfire risk due to the wetter scenario. Under the mitigation scenarios similar types of impacts are expected. Although, given that the temperature increases under the mitigation scenarios (M’s) are expected to be only 40% of the increases expected under the business as usual scenarios (U’s), the
frequency and intensity of events and their related impacts are expected to be less than the ‘business as usual’ climate scenarios. The impacts are expected to peak in the 2031–2070 timeframe as investment in new capital and improved design standards better address the new climate.

Table 2 Summary of magnitude of impacts on electricity distribution and transmission networks for seven climate scenarios

<table>
<thead>
<tr>
<th></th>
<th>2008–2030</th>
<th>2031–2070</th>
<th>2071–2100</th>
</tr>
</thead>
<tbody>
<tr>
<td>U1</td>
<td>Low to Moderate</td>
<td>Moderate to Extreme</td>
<td>Moderate to Extreme</td>
</tr>
<tr>
<td>U2</td>
<td>Low to Moderate</td>
<td>Moderate to High</td>
<td>Moderate to Extreme</td>
</tr>
<tr>
<td>U3</td>
<td>Low to Moderate</td>
<td>Low to High</td>
<td>Moderate to Extreme</td>
</tr>
<tr>
<td>M1</td>
<td>Low to Moderate</td>
<td>Moderate to High</td>
<td>Moderate to High</td>
</tr>
<tr>
<td>M2</td>
<td>Low to Moderate</td>
<td>Low to High</td>
<td>Low to Moderate</td>
</tr>
<tr>
<td>M3</td>
<td>Low to Moderate</td>
<td>Low to High</td>
<td>Low to Moderate</td>
</tr>
<tr>
<td>M4</td>
<td>Low to Moderate</td>
<td>Low to Moderate</td>
<td>Neutral to Moderate</td>
</tr>
</tbody>
</table>

Water supply infrastructure in major cities

This storyline focused on water supply infrastructure in capital cities, as regional centres have a different supply profile and constraints. Figure 3 outlines the impact storyline identified for water supply infrastructure in capital cities. This storyline was assessed against climate conditions considered in the seven climate scenarios (U1, U2, U3, M1, M2, M3 and M4) to develop the matrix of impacts for each state and territory.

Figure 3 Impact storyline for water supply infrastructure in major cities

A summary of the findings of the impact matrix is provided in Table 3 which shows the range of anticipated impacts. Table 3 clearly illustrates that the magnitudes of impact on water supply infrastructure will be significant across all time periods. As early as 2030 we see Extreme magnitude
impacts under all climate scenarios except those anticipating an increase in rainfall i.e. U2 and M2. The range of Neutral to Extreme impacts under the U1 scenario by 2030 and 2070 reflects regional differences. Under the U1 scenario, Perth and Brisbane require the development of new water sources as an immediate priority and a significant response in the short term.

The scenarios with either higher rainfall or lower temperature increases and evaporative potential (U2, M2) still indicate high impacts up to 2070, reflecting both varying socio-economic pressures and the uneven distribution of increased rainfall under these scenarios. The impact under climate scenarios M2, M3 and M4 are anticipated to be Neutral to Moderate between 2071–2100 as new water supply infrastructure investment between 2031–2070 better address the new climate conditions thereby being less reliant on rainfall and more focused on alternative water supply (i.e. desalination, recycled water). The new investment is likely to be in response to the lack of available water supply as a result of reduced annual rainfall and increased evaporation.

Table 3 Summary of magnitude of impacts on water supply infrastructure for major cities for seven climate scenarios

<table>
<thead>
<tr>
<th></th>
<th>2008–2030</th>
<th>2031–2070</th>
<th>2071–2100</th>
</tr>
</thead>
<tbody>
<tr>
<td>U1</td>
<td>Neutral to Extreme</td>
<td>High to Extreme</td>
<td>Extreme</td>
</tr>
<tr>
<td>U2</td>
<td>Neutral to Extreme</td>
<td>Low to Extreme</td>
<td>Moderate to Extreme</td>
</tr>
<tr>
<td>U3</td>
<td>Neutral to High</td>
<td>Neutral to High</td>
<td>Neutral to High</td>
</tr>
<tr>
<td>M1</td>
<td>Neutral to Extreme</td>
<td>Low to Extreme</td>
<td>Low to High</td>
</tr>
<tr>
<td>M2</td>
<td>Neutral to Extreme</td>
<td>Neutral to Extreme</td>
<td>Neutral to Moderate</td>
</tr>
<tr>
<td>M3</td>
<td>Neutral to High</td>
<td>Neutral to High</td>
<td>Neutral to Moderate</td>
</tr>
<tr>
<td>M4</td>
<td>Neutral to Extreme</td>
<td>Neutral to High</td>
<td>Neutral to Moderate</td>
</tr>
</tbody>
</table>

Port infrastructure and operations

Figure 4 outlines the impact storyline identified for port infrastructure. This storyline was assessed against climate conditions considered in the seven climate scenarios (U1, U2, U3, M1, M2, M3 and M4) to develop the matrix of impacts.
A summary of the findings of the matrix of impacts is provided in Table 4 which shows the range of impacts anticipated. By 2070 the most significant impacts are experienced under the U1, U3, U2 and M3 scenarios. This reflects a combination of increased port downtime in relation to extreme events such as cyclones, severe storms and severe heat, coupled with climatic conditions that are more conducive to corrosion and degradation of port assets. Between 2071 and 2100, ports under the U1 and U3 scenarios experience ‘extreme’ impacts primarily due to increased cyclone activity. Cyclone intensity and location is expected to change in Queensland and Western Australia between 2031 and 2070 with cyclones migrating further south along the east and west coast of Australia. This modelled change includes the area around Brisbane (CSIRO, 2007), which is not currently affected by cyclone events. It is anticipated that climate change will also lead to an increase in severe storms. CSIRO (2007) estimates that climate change may lead to a 60% increase in intensity of category three to five severe storms by 2030, and 140% increase by 2070. The anticipated change in frequency of cyclones requires further research.

Table 4  Summary of magnitude of impacts on port infrastructure and operations for seven climate scenarios

<table>
<thead>
<tr>
<th>Scenario</th>
<th>2008–2030</th>
<th>2031–2070</th>
<th>2071–2100</th>
</tr>
</thead>
<tbody>
<tr>
<td>U1</td>
<td>Low to Moderate</td>
<td>Moderate to High</td>
<td>Moderate to Extreme</td>
</tr>
<tr>
<td>U2</td>
<td>Low to Moderate</td>
<td>Moderate to High</td>
<td>Moderate to High</td>
</tr>
<tr>
<td>U3</td>
<td>Moderate to High</td>
<td>Moderate to High</td>
<td>Moderate to Extreme</td>
</tr>
<tr>
<td>M1</td>
<td>Low to Moderate</td>
<td>Moderate</td>
<td>Low to Moderate</td>
</tr>
<tr>
<td>M2</td>
<td>Low to Moderate</td>
<td>Low to Moderate</td>
<td>Low to Moderate</td>
</tr>
<tr>
<td>M3</td>
<td>Moderate to High</td>
<td>Moderate to High</td>
<td>Low to High</td>
</tr>
<tr>
<td>M4</td>
<td>Low to Moderate</td>
<td>Low to Moderate</td>
<td>Low to Moderate</td>
</tr>
</tbody>
</table>
Topics for further exploration

There is uncertainty as to the potential sea level rise and the frequency of extreme events over the next century. Warrick and Rahman (1992) indicate that the climate system has the potential for a sea level rise of 18 centimetres by 2100. Other studies indicate that sea level could rise by 70cm (Weller (2005) or even 2 to 12 metres (Hansen, Sato, Kharecha & Sidall, 2007). Similar uncertainty exists regarding extreme events. However, it is anticipated that as the average temperature increases, economic impacts related to sea level rise and extreme events are likely to also increase over time for all storylines. Additional research, improving the certainty of how changes in climate will affect extreme events and sea level rise, will assist the planning and delivery of adaptation measures limiting the potential economic impacts of such events.

Economic impacts for CGE modelling

For each storyline, quantitative shocks were estimated to assist with the economic modelling process. Key limitations to the development of the economic impacts were the time and budget constraints for the study and the availability of public documentation on the potential impacts of climate change on infrastructure. The impact categories for which shocks were defined for each storyline were:

- **Buildings in coastal settlements**: impact on new buildings, impact on existing buildings, reduced life expectancy of buildings and operational expenditure;
- **Electricity distribution and transmission networks**: capital expenditure and operational expenditure;
- **Water supply infrastructure in major cities**: capital expenditure for supply assets, capital expenditure for distribution assets and operational expenditure; and
- **Port infrastructure and operations**: productivity, capital expenditure and operational expenditure.

Conclusion

In reviewing the seven climate change scenarios (U1, U2, U3, M1, M2, M3 and M4) for Australia, the U1 scenario is the worst case scenario for water supply infrastructure in major cities and for electricity distribution and transmission networks. The U3 scenario is the worst case scenario for buildings in coastal settlements and port infrastructure and operations. The rate of change to temperature and rainfall under the U scenarios is extreme and is likely to require ongoing costly investment in infrastructure adaptation to the end of the century and beyond.

By 2100, the temperature increases and rainfall changes under the M scenarios are expected to be only 40% of the changes expected under the business as usual scenarios (U scenarios). The temperature and rainfall changes under the M scenarios level out in the middle of the century, at which point the U scenarios significantly outpace the changes expected under the M scenarios.

The frequency and intensity of impacts under the M scenarios are likely to be less after the middle of the century when compared to the impacts under the U scenarios. This provides a longer time period for infrastructure adaptation measures to be implemented and society to respond to changes in climate. Of all the scenarios (mitigation and business as usual), the M4 scenario provides the ‘best case scenario’ for the least significant climate change impacts across all infrastructure storylines. This is principally due to the fact that the M4 scenario is expected to have the lowest changes in temperature and rainfall.

Although only a fraction of the total infrastructure for Australia was assessed in this report, the likely climate change impacts in this study indicates that infrastructure investment in replacement and maintenance will increase as global temperatures rise and rainfall patterns change. Climate Change adaptation response for infrastructure in Australia is inevitable to maintain the current level of infrastructure services and benefits. The adaptation responses are likely to be a combination of regional or state responses specific to particular sectors or localities as well as national policy, regulation and standards mechanisms.
1 Introduction

1.1 Background
On 30 April 2007 Professor Ross Garnaut was commissioned by Australia’s State and Territory Governments to undertake an independent study titled the Garnaut Climate Change Review (GCCR). This GCCR is to examine the impacts of climate change on the Australian economy and recommend medium to long-term policies to achieve sustainable prosperity and address key climate change issues.

The Terms of Reference provided by the States and Territories require the GCCR to report on:

1) The likely effect of human induced climate change on Australia’s economy, environment and water resources in the absence of effective national and international efforts to substantially cut greenhouse gas emissions; and

2) The possible ameliorating effects of international policy reform on climate change and the costs and benefits of various international and Australian policy interventions on Australian economic activity.

To achieve this the GCCR Secretariat, appointed to facilitate the review, proposes to undertake economic modelling of both the impacts of climate change and associated mitigation policies using a computational general equilibrium (CGE) model. Five sectors are to be modelled, these are: human health, terms of trade, agriculture, infrastructure, and social and political disruption.

Maunsell Australia Pty Ltd (Maunsell) was engaged by the Secretariat to identify and assess the impacts of climate change on infrastructure in Australia. Maunsell has explored four key climate change impact storylines:

- buildings in coastal settlements
- electricity distribution and transmission networks
- water supply infrastructure in major cities
- port infrastructure and operations.

These storylines have been used to develop four economic shock matrices to inform the CGE model.

The purpose of this report is to qualitatively describe the impacts of climate change on the relevant infrastructure for each storyline and to provide further quantitative information for specific economic shocks that could be estimated for input into the CGE model given the short timeframe for the study and limited publicly available climate change impacts on infrastructure data for Australia.

1.2 Methodology
The methodology utilised in development of the four infrastructure impact storylines is provided in Figure 5. Following the project inception and initial information and data gathering, two workshops were held bringing Maunsell infrastructure experts, Maunsell climate change specialists and CSIRO Sustainable Ecosystems (CSE) representatives together to identify and prioritise impact storylines. Once the four key impact storylines were explored, publicly available information was gathered as available in regard to current revenue and costs associated with the four key areas: buildings in coastal settlements, electricity distribution and transmission networks, water supply in major cities and port infrastructure and operations. This information was then used as a baseline to assess the potential changes to capital and operational expenditure associated with changes in climate variables which could be used to determine shocks to input into the CGE model.

The assessments provided in this report are not predictions or forecasts but rather scenarios of impacts based on publicly available information, and CSIRO Atmospheric and Marine Research
(CMAR) climate modelling information and by the judgement of Maunsell’s and CSIRO Sustainable Ecosystems’ climate change and infrastructure specialists.

1.3 Climate change information

Seven climate change scenarios were used to assess each of the four key infrastructure areas. The climate scenarios are as follows:
‘Business as usual’ scenarios

- **Unmitigated Scenario 1 (U1).** Hot, dry business as usual scenario, using A1FI emission path, 10th percentile rainfall and relative humidity surface for Australia (dry extreme), 90th percentile temperature surface. Mean global warming reaches ~4.5°C in 2100.

- **Unmitigated Scenario 2 (U2).** Best estimate (median) business as usual scenario using A1FI emissions path, 50th percentile rainfall and relative humidity surface for Australia, 50th percentile temperature surface. Mean global warming reaches ~4.5°C in 2100.

- **Unmitigated Scenario 3 (U3).** Warm, wet business as usual scenario under A1FI emissions path, 90th percentile rainfall and relative humidity surface for Australia (wet extreme), 50th percentile temperature surface. Mean global warming reaches ~4.5°C in 2100.

**Strong mitigation scenarios**

- **Mitigation Scenario 1 (M1).** Dry mitigation scenario where stabilisation of 550ppm CO₂ equivalent (CO₂ stabilised at 500ppm) is reached by 2100, 10th percentile rainfall and relative humidity surface for Australia (dry extreme), 90th percentile temperature surface. Mean global warming reaches ~2.0°C in 2100.

- **Mitigation Scenario 2 (M2).** Best estimate (median) mitigation scenario where stabilisation of 550ppm CO₂ equivalent (CO₂ stabilised at 500ppm) is reached by 2100, 50th percentile rainfall and relative humidity surface for Australia, 50th percentile temperature surface. Mean global warming reaches ~2.0°C in 2100.

- **Mitigation Scenario 3 (M3).** Wet mitigation scenario where stabilisation of 550ppm CO₂ equivalent (CO₂ stabilised at 500ppm) is reached by 2100, 90th percentile rainfall and relative humidity surface for Australia (wet extreme), 50th percentile temperature surface. Mean global warming reaches ~2.0°C in 2100.

- **Mitigation Scenario 4 (M4).** Best estimate (median) strong mitigation scenario where stabilisation of 450ppm CO₂ equivalent (CO₂ stabilised at 420ppm) is reached by 2100, 50th percentile rainfall and relative humidity surface for Australia), 50th percentile temperature surface. Mean global warming reaches ~1.5°C in 2100.

Climatic variables incorporated into the assessment of impacts on the four key infrastructure areas include rainfall, average temperature, maximum temperature, relative humidity, cyclone intensity, storm frequency and intensity, wind, ocean acidification and sea level rise.

Data provided by CMAR specifically for the project incorporated rainfall, temperature, maximum temperature, evaporation and relative humidity data for the seven climate scenarios (U1, U2, U3, M1, M2, M3 and M4). Information relating to cyclones, wind, sea level rise and ocean acidification was not available to directly correspond with the seven climate scenarios assessed in this study. However, available information for these climate variables was extrapolated where possible to inform the assessment. Table 5 outlines the key sources of climate change information used in this assessment.
Table 5  Climate data and sources used in development and assessment of four key impact storylines

<table>
<thead>
<tr>
<th>No.</th>
<th>Source</th>
<th>Data</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CSIRO, Marine and Atmospheric Research</td>
<td>Average annual rainfall</td>
<td>Quantitative model data from 1990–2100 for capital cities, based on A1FI. Data available for U1, U2, U3, M1, M2, M3 and M4 (See Appendix C).</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Average annual temperature</td>
<td>Quantitative model data from 1990–2100 for capital cities, based on A1FI. Data available for U1, U2, U3, M1, M2, M3 and M4 (See Appendix C).</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Average annual relative humidity</td>
<td>Quantitative model data from 1990–2100 for capital cities, based on A1FI. Data available for U1, U2, U3, M1, M2, M3 and M4 (See Appendix C).</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Average annual evaporation</td>
<td>Quantitative model data from 1990–2100 for capital cities, based on A1FI. Data available for U1, U2, U3, M1, M2, M3 and M4 (See Appendix C).</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Maximum temperature</td>
<td>Quantitative model data from 1990–2100 for capital cities, based on A1FI. Data available for U1, U2, U3, M1, M2, M3 and M4 (See Appendix C).</td>
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<tr>
<td></td>
<td></td>
<td>Days over 35ºC</td>
<td>Quantitative model data from 1990–2100 for capital cities, based on A1FI. Data available for U1, U2, U3, M1, M2, M3 and M4 (See Appendix C).</td>
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<tr>
<td></td>
<td></td>
<td>Evaporation</td>
<td>Quantitative model data from 1990–2100 for capital cities, based on A1FI. Data available for U1, U2, U3, M1, M2, M3 and M4.</td>
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<tr>
<td></td>
<td></td>
<td>Ocean acidification</td>
<td>Section 5.8.2 in the Technical Report (Appendix C).</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wind</td>
<td>Section 5.5.1 and 5.5.2 in the Technical Report (Appendix C).</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sea level rise</td>
<td>Section 5.7 in the CSIRO Technical report (Refer to Section 3.1 for additional discussion).</td>
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<tr>
<td>4</td>
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<td><a href="http://www.bom.gov.au/cgi-bin/silo/cyclones.cgi">http://www.bom.gov.au/cgi-bin/silo/cyclones.cgi</a></td>
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<tr>
<td>5</td>
<td>Geoscience Australia</td>
<td>Cyclone information</td>
<td>Geoscience Australia (2008)</td>
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</table>

1.4 Limitations

Maunsell was unable to assess and model the impacts of climate change on all infrastructure assets due to the budgeted scope of the project. Examples of other infrastructure that is likely to be impacted by climate change but not considered in this report include drainage, roads and bridges, telecommunication, coastal protection and power generation.

The availability of public documentation of the impacts of climate change on infrastructure is minimal as the assessment of such impacts is only a newly emerging field of research and expertise.

The climate change modelling used by CSIRO does not adequately capture the extent of change in extreme storm events across Australia to allow an in-depth analysis of the likely economic shocks to buildings in coastal settlements that could be quantified into inputs into the CGE modelling process.

This report provides a valuable initial analysis of climate change impacts. However, it should not be inferred to as a complete analysis of the likely impacts on all infrastructure in Australia. Based on the authors’ understanding, the total of Australian infrastructure analysed for economic impacts is deemed to be less than 5%. Table 6 provides a list of key infrastructure types in Australia and indicates those that are likely to be affected by climate change primarily through extreme events, accelerated
degradation of materials and structures or impacts on resource demand. The table also indicates the infrastructure types that are considered in the assessment of economic impacts in this report.

Table 6 Infrastructure likely to be affected by climate change and infrastructure considered in this report

<table>
<thead>
<tr>
<th>Infrastructure Type</th>
<th>Affected by Climate Change*</th>
<th>Considered in this report in assessing economic impacts of climate change</th>
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<tbody>
<tr>
<td>Utilities</td>
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<tr>
<td>• Electricity transmission and distribution</td>
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<td>Yes</td>
</tr>
<tr>
<td>• Electricity generation</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>• Water supply infrastructure</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>• Gas and oil extraction and supply</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>• Offshore infrastructure (mining/drilling platforms)</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>• Sewage treatment and distribution</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Buildings</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Residential</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>• Commercial</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
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<td>• Storage structures</td>
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<td>Transport</td>
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<tr>
<td>• Roads</td>
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<td>• Rail</td>
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<td>• Marine ports</td>
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<td>• Bridges and tunnels</td>
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<td>• Fixed line network</td>
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<td></td>
</tr>
<tr>
<td>• Mobile networks</td>
<td>Yes</td>
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<tr>
<td>• Broadcasting (i.e. television and radio)</td>
<td>Yes</td>
<td></td>
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<tr>
<td>Water management</td>
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<td></td>
</tr>
<tr>
<td>• Stormwater drainage</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>• Flood protection (protective dams and dykes)</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>• Natural waterway management</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>• Coastal and foreshore protection (sea walls)</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Public facilities (recreational, community and public space facilities i.e. major event facilities)</td>
<td>Yes</td>
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<td>• Cultural icons</td>
<td>Yes</td>
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<td>• Health services facilities</td>
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<td>• Defence and emergency services facilities</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>• Resource facilities (i.e. mines)</td>
<td>Yes</td>
<td></td>
</tr>
</tbody>
</table>

*NOTE: This column refers to infrastructure types that are impacted by climate change induced extreme weather events, accelerated degradation of materials or structures and/or impacts on resource demand (i.e. direct: water supply or indirect: power supply)
1.5 Scoring criteria

Scoring procedure

In undertaking the assessment the following relative qualitative scoring procedure was used to score the net impacts (economic) of the various climate change scenarios (U1, U2 etc) for each state and territory. The key steps in undertaking the scoring involved:

1. Considering the climate change impacts for the relevant infrastructure stories based on the climate scenario trends, story assumptions and any available supporting documentation;

2. Scoring the impacts of climate change on scenario U1 used the impact scoring criteria in Table 7 considering relative qualitative scoring between the different states and over the three timeframes indicated below. Where additional or relevant assumptions were made regarding adaptation responses over time to achieve scoring outcomes, these were noted as assumptions; and

3. U1 was used as the baseline to inform the relative scoring for scenarios U2, U3, M1, M2, M3 and M4 as a repeat of step 2 above.

Assumptions underpinning the scoring

There are a number of assumptions underpinning the scoring of the magnitude of net impacts (economic) for each story for each climate change scenario. Of particular note are the following:

1. The aim was to explore the relativities between the magnitude of impacts; timeframes; and climate change projections using the climate change scenarios, stories and assumptions developed to date and to add or clarify any assumptions as they arose;

2. Not to use the economic development and population forecast information as a primary driver, as the focus for scoring was climate change impacts on infrastructure, while the context of economic development and population was embedded in the economic modelling process by Queensland Department of Treasury and Finance (QTF); and

3. The relative net impact means that if there are positive and negative impacts for an infrastructure story that a net result should be indicated.

Timeframes

The assessment of impacts was completed over the following time:

- 2007–2030
- 2031–2070
- 2071–2100.
Table 7 Impact criteria

<table>
<thead>
<tr>
<th>Magnitude of net impact</th>
<th>Description of Impact</th>
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<tr>
<td>N</td>
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<td>Moderate</td>
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<td>H</td>
<td>High</td>
</tr>
<tr>
<td>E</td>
<td>Extreme</td>
</tr>
</tbody>
</table>

1.6 Economic shock impacts for CGE modelling

For each infrastructure story a range of specific economic shock impacts were developed for input into the CGE modelling process. The storylines described in this report qualitatively describe the likely climate change impacts to infrastructure. However, only some of the described impacts have been quantitatively assessed for the CGE modelling due to the lack of detailed data available (i.e. the impacts of extreme events are described in the storylines but insufficient data was available to incorporate them into the economic shocks).

Refer to Appendix B for further information regarding the economic shocks that have been reviewed and refined in consultation with the QTF CGE modelling team.
2 Climate change impact storylines

The following section provides a storyline for each of the four infrastructure types: buildings in coastal settlements; electricity transmission and distribution; water supply infrastructure in major cities; and port infrastructure and operations. A description of the likely climate change impacts under each climate scenario is provided along with assumptions that have informed each story and the related economic impacts. Where appropriate, indications have also been provided as to potential correlated impacts from the storyline to other areas of the economy or society. Proposed areas of additional research that would provide further clarity to each storyline have also been outlined.

2.1 Buildings in coastal settlements

The climate change projections considered in the coastal settlements storyline are projections from the ‘current’ climate, given an assumed greenhouse gas emission trajectory, climate sensitivity and probability of change. In assessing the likely impacts on buildings in coastal settlements, consideration has been given to those buildings that are located within 50km of the coast. Today over 80% of the Australian population lives within the ‘coastal zone’ (50km from the coast). In recent years coastal regions have experienced significant growth and are projected to continue to show the largest population growth (IPCC, 2007a). The Australian Capital Territory has not been considered in this impact storyline as it is located inland and away from coastal climatic influences.

Flooding is anticipated to be a significant cause of the impacts to this storyline. There are three main types of flooding referred to in the story; riverine flooding, coastal flooding and flash flooding, each is defined below:

- **Riverine flooding**, also referred to as catchment flooding, is caused when ‘runoff from major storms exceeds the channel capacity of a river or creek and over flows onto the surrounding flood plain’ (Melbourne Water, 2006 p 14).

- **Coastal flooding** occurs when ‘ocean tides affect normal sea levels and cause flooding along the coastline and lower reaches of tidal rivers, especially when combined with high rainfall’ (Melbourne Water, 2006 p 15). Coastal flooding can be compounded by the effects of storm surge and the gradual rise in sea level.

- **Flash flooding** ‘occurs when runoff from severe storms exceeds the capacity of the underground drainage system. When flows exceed the capacity of the underground system, water begins to flow downhill over the surface of the land along natural flow paths or valleys towards the nearest creek or river. Overland flows usually occur with little or no warning following intense rainfall often associated with short duration thunderstorm activity. They can be localised or widespread depending on the path or extent of storm activity’ (Melbourne Water, 2006 p 14).
Figure 7 outlines the impact storyline identified for buildings in coastal settlements. This storyline was assessed against climate conditions considered in seven climate scenarios U1, U2, U3, M1, M2, M3 and M4 to develop the matrix of impacts for each coastal state and territory.

The impacts of each of these flooding types (riverine, coastal and flash) have been considered in developing the matrix of impacts for coastal settlements illustrated in Figure 8.
Case study: Flash floods and storms, south-east Queensland and north-east New South Wales, June 2005

This case study demonstrates how extreme rainfall and flood events can cause extensive damage to building infrastructure, disruption to essential community services and business operations in coastal regions.

The southeast Queensland and northeast New South Wales (NSW) regions were affected by severe flooding in June 2005 when heavy rain fell over the coastal region. The rain caused the Wilson River to flood the town of Lismore in NSW and surrounding areas.

Heavy rain began to fall over the southeast Queensland and northeast NSW regions on 27 June 2005. Within 24 hours, the Bureau of Meteorology recorded 368mm of rain fall over the southern end of the Gold Coast in Queensland and up to 500mm of rain fall within 48 hours over Lismore, NSW (EMA, 2006).

The floods had significant impacts on the community, damaged building infrastructure and affected business and tourism operations in both regions. Approximately 3,000 people were evacuated from their homes in Lismore, NSW, 75 residents from a nursing home were evacuated in Benora, Queensland and 67 people were evacuated from their homes on the Gold Coast, Queensland (EMA, 2006). Many apartment basement car parks were also flooded.

Flooded road conditions caused major traffic delays and a number of motor vehicle accidents. In southeast Queensland, 23 traffic accidents were reported and the Royal Automotive Club in Queensland received hundreds of phone calls for road side assistance (EMA, 2006). The storm also caused a rockslide in Cunningham’s Gap, which blocked the Cunningham Highway in both directions.

The floods disrupted the provision of essential community services. Thousands of people in northern NSW remained stranded by the floodwaters for days after the storm and were reliant on food and medical supplies by boat or helicopter. More than 26,000 residents in southeast Queensland were left without power due to fallen powerlines.

Many Gold Coast businesses were also affected by the storms. Flooding shut down the Gold Coast Airport in Coolangatta, delaying flights; Pacific Fair, a major Gold Coast shopping centre, closed down and Warner Village Theme Parks had to close all four of its parks for the first time in history (EMA, 2006).

The economic costs of the flood and storms were also extreme. Insured damage was approximately $54 million in Queensland and $25 million in New South Wales.
Figure 8  
Buildings in coastal settlements—Matrix of Impacts

### Timeframe 2008 - 2030

<table>
<thead>
<tr>
<th>Climate Scenario</th>
<th>U1</th>
<th>U2</th>
<th>U3</th>
<th>M1</th>
<th>M2</th>
<th>M3</th>
<th>M4</th>
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<th>U3</th>
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<th>M2</th>
<th>M3</th>
<th>M4</th>
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</table>

NOTE: The impact for ACT is not applicable (N/A) as it does not have coastal settlements. Refer to Table 7 for an explanation of the impact criteria.

### Climate change scenario storylines

#### Business as usual scenarios

The business as usual climate change scenarios provided by the CSIRO on behalf of the Garnaut Climate Change Review Secretariat and considered in the buildings in coastal settlements storyline are discussed in turn below.

**U1:** **Hot, dry business as usual scenario, using A1FI emission path, 10th percentile rainfall and relative humidity surface for Australia (dry extreme), 90th percentile temperature surface. Mean global warming reaches ~4.5°C in 2100.**

This scenario adopts a ‘business as usual’ approach to greenhouse gas emissions and assumes the highest level of temperature increase. The A1FI emissions scenario, upon which U1 is based, 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' (IPCC, 2007b). A1FI has a fossil fuel-intensive technological emphasis. It is with this guide that these 'business as usual' developments are based.

This scenario is expected to result in low to moderate economic impacts by 2030 and moderate to extreme impacts between 2031 and 2100 depending on the region considered. The increase in temperature is a key influence on storm energy in the climate system generating volatile and more extreme storm events (CSIRO, 2007). The increase in extreme storm events U1 is only moderated by having the greatest decline in annual rainfall and relative humidity.

Perth and Adelaide are likely to experience the greatest reductions in annual rainfall in comparison to other capital cities. As a result of the drying, Perth and Adelaide are likely to experience less riverine flooding than other capital cities but are still likely to experience impacts from flash flooding events. In U1, Brisbane, Darwin and Hobart are expected to experience greater extreme rainfall events resulting in riverine flooding.

U1 is more likely to generate increased localised extreme rainfall events when combined with low soil moisture, which will lead to greater flash flooding. Low soil moisture (due to increase evaporation, temperature and a reduction in annual rainfall) prior to rainfall events can increase the impact and magnitude of flash flooding. While the implications of flash flooding are likely to be shorter in duration compared to riverine flooding, they are likely to cause significant impacts to buildings.

The necessary data for assessing frequency of future extreme wind events requires further modelling in order to determine smaller scale systems such as intense convective events (e.g. those associated with tropical storms) and frontal activity or low pressures systems further south (CSIRO 2007). However, it is assumed that there will be an increase generally in extreme wind event intensity due to increases in global temperatures as the key driver of storm energy in the climate system. Therefore areas that will experience significant decreases in rainfall are also likely to still experience an increase in storm strength but the proportion of classified wind and dust storm events experienced is expected to increase compared to the storms generating riverine flooding.

The impacts of extreme wind are varied and include:

- direct damage to buildings and related infrastructure (i.e. garages, fences and sheds)
- direct damage from wind carried debris (i.e. trees, unsecured items (wheelbarrow, construction site materials, trampolines))
- weakening of the structural integrity of buildings and related infrastructure.

The effects of direct damage are often compounded by an increase in wind carried debris, for example roof tiles removed by extreme wind may cause damage to a neighbouring property.

The decrease in annual rainfall and increase in temperature and evaporation in U1 is likely to lead to the greatest increase in ground movement of the seven climate scenarios and therefore generate the greatest degradation in building foundations.

Increased magnitude of storm events combined with gradual sea level rise will exert significant pressure on low lying coastal buildings in the form of storm damage, inundation and flooding. For U1, sea level rise is expected to be approximately 17cm by 2030, 50cm by 2070 (CSIRO 2007; Hennessy, Macadam, & Whetton 2006), and 70cm by 2100 (Weller 2005). This rise in sea level will have different effects across Australia according to regional climate; coastal elevation; exposure and topography; coastal development; land use and coastal protection infrastructure.

Increases in sea level and extreme rainfall events are expected to exponentially affect storm surge height causing the inundation area of current 1 in 100 year average recurrence interval (ARI) events to potentially double, in low lying areas (McInnes et al, 2003). This inundation in areas not previously at risk of flooding is likely to cause a significant increase in damage in these areas due to current building standards being at a lower resilience level.
Due to the high proportion of properties currently susceptible to riverine flooding in Queensland (36% of residential properties), New South Wales (33%) and Victoria (25%) (McAneney, Crompton, Chen, Leigh & Hunter, 2007), these states are anticipated to be impacted more dramatically than the other states under the U1 climate scenario. Toward the latter half of the century this is expected to be compounded in Queensland and New South Wales by an anticipated increase in extreme storm events.

In U1, there is likely to be a significant increase in the number of bushfire danger days per annum due to increased temperature, wind events, evaporation (drying) and decreased rainfall. The bushfire season is likely to grow, and areas previously not considered to be prone to bushfires will be threatened. These newly threatened buildings will need to change their building design to meet bushfire prone building standards. It is also expected that the number of buildings destroyed by bushfires will significantly increase.

The expected increase in the number of hot days and heatwaves will reduce the ability of buildings to maintain acceptable indoor temperature environments without adjustment to design standards for insulation, shading and window glazing. The expected increase in minimum temperatures will however reduce the need for winter heating in southern states.

With the high levels of settlement and commercial activity in the coastal zone, the U1 scenario suggests impacts will be significant in the medium term (i.e. 2031 and 2070). Building standards and planning schemes are expected to improve the resilience of buildings by 2070. However, the magnitude of climate change leading up to 2100 is still expected to generate high to extreme impacts.

Sea level rise is expected to be gradual, increasing by 90cm by the end of the century. The change in sea level is likely to have a significant impact on low lying coastal buildings from a combination of inundation and increased vulnerability to storm surge events.

U2: Best estimate (median) business as usual scenario using A1FI emissions path, 50th percentile rainfall and relative humidity surface for Australia, 50th percentile temperature surface. Mean global warming reaches ~4.5°C in 2100.

This scenario is most closely related to U1 due to the modelled reduction in rainfall. However, the drying and humidity is less extreme than U1 as is the temperature increase. The temperature increase and evaporation is the same as U3.

Temperature is a key driver of extreme weather events. As the expected increase in temperature under U2 is similar to that of U1 up to 2030, the impacts under the U2 storyline are also anticipated to be similar to U1 over this time period. During the remainder of the century, the cities likely to experience the highest degree of impact under U2 are anticipated to be the same as those that experience the highest degree of impacts under the U1 scenario, although the magnitude or severity is anticipated to be less than U1. This scenario is expected to result in low to moderate economic impacts by 2030, moderate to high impacts by 2070 and moderate to extreme impacts by 2100 depending on the region considered.

Recent studies (Preston and Jones, 2006) have shown that storms may become more intense with warming of just 1–2°C. Therefore, under the U2 scenario, with warming of up to 4.7°C in Australia (depending on the region) by 2100, storm events are likely to increase in intensity and impact buildings. This, combined with the expected gradual sea level rise up to 2100, would result in higher storm surge events causing increased frequency and extent of flooding, including areas previously not prone to flooding.

The level of annual temperature increase under the U2 scenario will significantly influence extreme weather events. The high proportion of settlements (80% of population (IPCC, 2007a)) in the coastal zone will be at risk from these extreme weather events such as; storm damage, inundation and flooding (Preston and Jones, 2006).

Similar to the U1 scenario, the U2 is likely to generate increased, localised, extreme rainfall events. When combined with low soil moisture, this is likely to lead to greater localised flash flooding. Under
the U2 scenario rainfall and relative humidity declines, which indicates that it is likely that regions in southern Australia (with the exception of much of Tasmania and East Gippsland in Victoria) will experience less riverine flooding events compared to places like Darwin and Brisbane, which are not expected to have as significant reductions in rainfall.

Due to the high proportion of properties susceptible to riverine flooding in Queensland, New South Wales and Victoria (McAneney, Crompton, Chen, Leigh & Hunter, 2007), these states are anticipated to be impacted more dramatically when riverine flooding events do occur than the other states under the U2 climate scenario. In the last quarter of the century, impacts in South Australia are likely to increase as it has the next highest portion of properties at risk of riverine flooding. In the latter half of the century, the effects of riverine flooding are expected to be compounded the most in Queensland by the anticipated increase in extreme storm events.

In U2, there is likely to be an increase in the number of bushfire danger days per annum, due to increased temperature wind events and evaporation (drying) as well as decreased rainfall. The bushfire season is likely to grow and areas previously not considered to be prone to bushfires will be threatened. These newly threatened buildings will need to change their building design to meet bush fire prone building standards. It is expected that the number of buildings destroyed by bushfires will significantly increase. This impact is likely to be greater for Western Australia, South Australia, Victoria and parts of New South Wales.

With the high levels of settlement and commercial activity in the coastal zone, the U2 scenario suggests impacts will be significant in the medium term (i.e. 2031 and 2070). Building standards and planning schemes are expected to improve the resilience of buildings by 2070. However, the magnitude of climate change leading up to 2100 is still expected to generate high to extreme impacts.

**U3:** Warm, wet business as-usual scenario under A1FI emissions path, 90th percentile rainfall and relative humidity surface for Australia (wet extreme), 50th percentile temperature surface. Mean global warming reaches ~4.5°C in 2100.

This scenario adopts a ‘business as usual’ approach to greenhouse gas emissions and statistically it assumes the most likely level of temperature increase, along with the greatest increase in rainfall and relative humidity. Depending on the region considered, this scenario is expected to result in low to moderate economic impacts by 2030 and moderate to extreme impacts between 2031 and 2100.

The impacts of U3 are characterised by increased extreme rainfall events and riverine flooding. The northern and eastern coastlines are expected to experience significant increases in rainfall. Rainfall is projected to increase at the greatest rate in Darwin (32% by 2100), Brisbane (26%) and Hobart (25%) with a considerable increase in Sydney (17%). However, Melbourne (>0.5% by 2100), Adelaide (4%) and Perth (>0.5%) are likely to experience little or no increase in average annual rainfall. The significant increase in rainfall and extreme rainfall events, when combined with the high proportion of properties susceptible to riverine flooding, is a major driver impact for this climate scenario.

The increase in humidity in most states indicates increased conditions for extreme storms, flash flooding and riverine flooding. U3 is more likely to generate riverine flooding resulting from longer periods of high rainfall with average rainfall being expected to increase the frequency and magnitude of flooding events. Under the U3 scenario it is anticipated that extreme rainfall events will become more frequent and more severe.

As described in U1, the necessary data for assessing frequency of future extreme wind events requires further investigation. However, it is assumed that there will be an increase generally in extreme wind event intensity due to increases in global temperatures, a key driver of storm energy in the climate system.

Sea level rise is expected to be gradual, increasing by 90cm by the end of the century. As for U1, the change in sea level is likely to have a significant impact on low lying coastal buildings from a combination of inundation and increased vulnerability to storm surge events.
The expected increase in the number of hot days and heatwaves (although less than U1) will reduce the ability of buildings to maintain acceptable indoor temperature environments without adjustment to design standards for insulation, shading and window glazing. An increase in minimum temperatures will however reduce the need for winter heating in southern states of Australia.

With the high levels of settlement and commercial activity in the coastal zone, the U3 scenario suggests impacts will be significant in the medium term (i.e. 2031 and 2070). Building standards and planning schemes are expected to improve the resilience of buildings by 2070. However, the magnitude of climate change leading up to 2100 is still expected to generate high to extreme impacts.

**Strong mitigation scenarios**

The four climate change scenarios with mitigation provided by CSIRO, on behalf of the Garnaut Climate Change Review Secretariat and considered in the buildings in coastal settlements storyline are discussed in turn below.

**M1:** *Dry mitigation scenario where stabilisation of 550ppm CO₂ equivalent (CO₂ stabilised at 500ppm) is reached by 2100, 10th percentile rainfall and relative humidity surface for Australia (dry extreme), 90th percentile temperature surface. Mean global warming reaches ~2.0°C in 2100.*

This scenario adopts a policy intervention that leads to a greenhouse gas emissions trajectory that stabilises atmospheric greenhouse gas concentrations at a level that constrains the temperature increase to 2.0°C in 2100; as compared to 4.5°C in 2100 under the business as usual scenario U1. This scenario is expected to result in low to moderate economic impacts by 2030 and moderate to high impacts between 2031 and 2100 depending on the region considered.

Under this scenario, the CMAR climate modelling indicates that changes in rainfall (decline), humidity (decline), temperature (increase) and evaporation (increase) are anticipated to be marginally greater than U1 at 2030. The temperature and rainfall changes for M1 are approximately 55% of the U1 changes at 2070 and 40% of U1 at 2100. From the middle of the century the M1 temperature and rainfall changes begin to level out. However, the temperature and rainfall changes modelled in U1 significantly outpace the M1 scenario after this time period. The M1 temperature increases at 2100 are reached in the middle of the century under the U1 scenario. Under scenario M1, the change to rainfall and relative humidity (decline) is greater than business as usual scenario U2. However, the modelled temperature increase is less than U2.

The reduced level of temperature increase relative to the U1 scenario is likely to lessen the impact of increased extreme rainfall and flash flooding, with less additional temperature driven storm energy in the climate system relative to U1. The decrease in annual rainfall and increase in temperature and evaporation are likely to lead to a lesser increase in ground movement and degradation in building foundations than under the U1 scenario.

The level of annual temperature increase under the M1 scenario will still significantly influence an increase in extreme weather events. At a temperature rise of approximately 2°C Preston and Jones (2006) project a 20–30% increase in tropical cyclone rainfall; a 5–10% increase in tropical cyclone wind speed; and a 12–16% increase in 100-year ARI storm tides along the eastern coast of Australia. The high proportion of settlements (80% of population (IPCC, 2007a)) in the coastal zone will be at risk from these extreme weather events such as; storm damage, inundation and flooding (Preston and Jones, 2006).

Sea level rise is expected to be gradual up to 2100 in a similar trajectory as U1.

Due to the high proportion of properties susceptible to riverine flooding in Queensland, New South Wales and Victoria, these states are anticipated to be impacted more dramatically than the other states at 2030. The change in rainfall and temperature reduces in the latter half of the century for M1, which is expected to soften the impacts for all states and territories due to capital investment in improved design standards to better address the new climate system. The driver for capital investment is likely to be the combined effect of increases in maintenance costs, increases in failure
of assets and reduced life expectancy of assets. The result of these increases in costs and investment is likely to drive policy change.

In M1, increased bushfire danger and heatwaves will still be of a magnitude to require changes to building design standards. There is likely to be a significant increase in the number of bushfire danger days per annum (compared to 2007) due to increased temperature wind events and evaporation (drying) as well as decreased rainfall (Lucas et al (2007) refer to Figure 99 in Appendix C). The bushfire season is likely to grow and areas previously not considered to be prone to bushfires will be threatened. These threaten existing buildings and indicate a strong need for new design to meet bushfire prone standards. Additional investment may also be required to protect buildings that were not previously under threat. It is expected that the number of buildings destroyed by bushfires will significantly increase.

The expected increase in the number of hot days and heatwaves will reduce the ability of buildings to maintain acceptable indoor temperature environments without adjustment to design standards for insulation, shading and window glazing. The expected increase in minimum temperatures will however reduce the need for winter heating in southern states.

**M2: Best estimate (median) mitigation scenario where stabilisation of 550ppm CO₂ equivalent (CO₂ stabilised at 500ppm) is reached by 2100, 50th percentile rainfall and relative humidity surface for Australia, 50th percentile temperature surface. Mean global warming reaches ~2.0°C in 2100.**

This scenario adopts a policy intervention that leads to a greenhouse gas emissions trajectory that stabilises atmospheric greenhouse gas concentrations at a level that constrains the global temperature increase to 2°C in 2100. This compares favourably to the global temperature increase of 4.5°C in 2100 under the business as usual scenarios U1, U2 and U3.

The M2 climate changes are similar to the U2 climate changes. The climate models provided by CMAR indicated that for the M2 scenario, the changes in rainfall (decline), humidity (decline), temperature (increase) and evaporation (increase) are anticipated to be marginally greater than U2 at 2030. However, the temperature and rainfall changes modelled in U2 significantly outpace the M2 scenario after this time period. From the middle of the century the M2 temperature and rainfall changes begin to level out. The M2 temperature increases at 2100 are reached in the middle of the century under the U2 scenario. The temperature and rainfall changes for M2 are approximately 55% of the U2 changes at 2070 and 40% of U2 at 2100. This scenario is expected to result in low to moderate economic impacts by 2030, moderate to high impacts by 2070 and moderate impacts between 2071 and 2100 depending on the region considered.

The impacts at 2030 are likely to be similar to those experienced under U2 with increased localised, extreme rainfall events. When combined with low soil moisture, this is likely to lead to greater localised flash flooding. The most significant impacts are likely to occur in Queensland, New South Wales and Victoria. Beyond 2030 the impacts are likely to increase across all states except for Tasmania as the increase in temperature (a key driver of storm intensity) is anticipated to be the least in that state. Queensland is anticipated to experience the highest impacts associated with extreme events compared to other states and territories. The impact exposure is anticipated to stabilise across all states in the last quarter of the century. This is due to the changes in rainfall and temperature levelling off and improved design standards better addressing the ‘new’ climate conditions.

**M3: Wet mitigation scenario where stabilisation of 550ppm CO₂ equivalent (CO₂ stabilised at 500ppm) is reached by 2100, 90th percentile rainfall and relative humidity surface for Australia (wet extreme), 50th percentile temperature surface. Mean global warming reaches ~2.0°C in 2100.**

This scenario adopts a policy intervention that leads to a greenhouse gas emissions trajectory that stabilises atmospheric greenhouse gas concentrations at a level that constrains the temperature increase to 2.0°C in 2100; as compared to 4.5°C in 2100 under the business as usual scenario U3. The scenario assumes an increase in temperature, along with an increase in rainfall and relative humidity.
Under this scenario, the CMAR climate modelling indicates that changes in rainfall (increase), humidity (increase), temperature (increase) and evaporation (increase) are anticipated to marginally increase marginally greater than U3 at 2030. However, the temperature and rainfall changes modelled in U3 significantly outpace the M3 scenario after this time period. From the middle of the century the M3 temperature and rainfall changes begin to level out. The M3 temperature and rainfall increases at 2100 are reached in the middle of the century under the U3 scenario. The temperature and rainfall changes for M3 are approximately 55% of the U3 changes at 2070 and 40% of U3 at 2100. Depending on the region considered, this scenario is expected to result in low to moderate economic impacts by 2030 and moderate to high impacts between 2031 and 2100.

The extreme rainfall events generating riverine flooding are likely to increase relative to 2008, but to a lesser extent than U3, as the expected increase in temperature that drives extreme storm, wind and rainfall events is less by comparison. Rainfall is projected to increase at the greatest rate in Darwin, Brisbane and Hobart with a considerable increase in Sydney. The increase in rainfall when combined with the high proportion of properties susceptible to riverine flooding is the main impact for this climate scenario.

Sea level rise is expected to be gradual up to 2100 in a similar trajectory to U1. The impact exposure under this scenario is anticipated to soften in the latter half of the century as the changes in rainfall and temperature reduce, and the implementation of design standards better address the ‘new’ climate.

**M4:** Best estimate (median) strong mitigation scenario where stabilisation of 450ppm CO₂ equivalent (CO₂ stabilised at 420ppm) is reached by 2100, 50th percentile rainfall and relative humidity surface for Australia), 50th percentile temperature surface. Mean global warming reaches ~1.5°C in 2100.

This scenario is the ‘best-case’ of the group of scenarios assessed. The temperature and rainfall changes are modelled to stabilise around 2080 and begin to reverse toward 2100, therefore reducing the pressures generating increased storm related impacts. Of the scenarios that result in a decline in rainfall and relative humidity (scenarios U1, U2, M1, M2 and M4), this scenario is expected to lead to the least impact from climate change induced storm, wind and flooding impacts. Depending on the region, this scenario is expected to result in low to moderate economic impacts up to 2070 and neutral to moderate impacts between 2071 and 2100.

Sea level rise is expected to be gradual up to 2100.

This scenario would result in the lowest level of climate change impacts on buildings over time and hence would result in the lowest level of economic impact for buildings in coastal settlements. As with the other ‘drying’ scenarios, the most significant impacts are likely to occur in Queensland, New South Wales and Victoria in the first half of the century. The impacts would then soften as the investments in asset protection and improved design standards better address the new climate conditions.

**Key assumptions**

- In relation to the reduced life expectancy and operational expenditure, commercial, industrial and residential dwellings have been considered in developing the matrix of impacts as the impacts would be across the spread of these industries.
- Due to the availability of information, only residential buildings have been included in the consideration of the economic impacts related to capital expenditure on new and existing buildings.
- Cyclones have not been included in the consideration of economic impacts for buildings in coastal settlements.
- In assessing the likely impacts on buildings in coastal settlements, consideration has been given to those buildings that are located within 50km of the coast.
The value of different buildings and different regions has not been factored into the development of economic impacts.

All coastal settlements could be affected by flash flooding, riverine flooding storm surge and sea-level rise with areas of greater risk being low lying areas; areas with older and high density infrastructure e.g. older suburbs, central business districts; and areas expecting most significant changes in relevant climate variables. Queensland is expected to be the most effected, followed by NSW and Victoria, then Northern Territory. WA, SA and Tasmania are expected to be the least effected.

In assessing the economic impacts to buildings, all climate variables outlined in Figure 7 were considered with the exception of cyclones. Cyclones are being covered in a separate assessment by Geoscience Australia for the GCCR.

Coastal assets other than buildings (i.e. drainage, roads, coastal protection and utilities) have not been included in the matrix of impacts for this report.

It is assumed that buildings will return to full utility after damage (i.e. short term loss) from climate impacts, with the exception of damage associated with sea level rise. Impacts from sea level rise are likely to generate a long term loss of utility.

Insurance claims, impacts on premiums and reduction in available cover have not been factored into economic impacts identified in this report.

The key industries to be excluded, due to their typical location being away from the coast, include the agricultural, horticultural, forestry and plant nursery industries.

**Storms**

- The frequency and intensity of storms is an important factor impacting buildings in coastal settlements.

- Increased maintenance is likely to be the main adaptation mechanism to reduce impacts up to 2030. For example, drainage pipes filled with rubbish causing increased flood impacts is likely to be overcome by higher maintenance of drainage pits and pipes.

- Queensland is expected to be the worst impacted by extreme storm events.

- Air-borne debris (trees, roofs) is more of a problem during high wind events than wind itself. Insurance studies show that a 25% increase in peak wind gust strength can generate a 6.5-fold increase in building claims (IAG 2003).

**Storm surge**

- Sea level rise and increased storm surge makes sea wall protection less effective and prone to failure.

- Sea walls protecting buildings and infrastructure are designed for certain sea/storm surge levels. As levels go up then increases in building and facilities operational delays and usage are expected.

**Buildings**

- Older infrastructure is more vulnerable to flood, wind and storm surge damage and failure making the low lying consolidated inner city and CBD building more prone to significant flash flooding.

- Damage to land through flooding, erosion and ground movement can lead to loss of integrity of foundations impacting building stability and utilisation.

- Based on the fact that the Australian Building Code Board is currently investigating changes to the building code in response to climate change (refer to DEWR, 2007), it is assumed new building stock from 2015–30 is likely to be designed to new 1 in 100 year ARI planning levels. The
redundancy built into these standards will determine the length of time these standards provide suitable resilience. It is expected these standards will be assessed and updated over time with a 15–20 year planning window.

- It is assumed that only minor improvements in design standards and criteria will be made voluntarily without government intervention.
- Government intervention is likely to take the form of changes to design standards, required maintenance regimes and operational planning.
- Policy change is likely to occur after initial impacts of climate change reach a public expectation threshold.
- Private investment in infrastructure is also likely to increase its scrutiny of climate change adaptation for security of investment.
- Service life of most infrastructure is reducing by 10–20% (Dacre, 2007) due to climate change impacts (this is already occurring). It is assumed that the effect of reduced service life will affect newer infrastructure (built today and over the next few years under current standards). By 2030 structures built should have adaptation features incorporated in their design to reduce vulnerability of structures to climate change. This is a general rule for all service infrastructure. A level of service decline is likely to be experienced in the short term as increased maintenance becomes necessary. Between 2030 and 2070 additional maintenance expenditure justifies higher capital cost for upgrades.
- The life cycle of assets is likely to reduce over time due to reduced durability of materials from drier climate and more extreme events. The reduction in lifecycle is likely to be greater under the Wet scenarios (U3 and M3) as the presence of additional water is likely to enhance the degradation of materials.
- The slow upgrading of infrastructure with update of design standards is assumed across all areas, based on renewal of existing assets.
- It is anticipated that there will be investment in new and existing buildings to counteract the effects of overheating (insulation and double glazing). In cooler climates, the take up of these changes is likely to be slower due to cost effectiveness (particularly double glazing).
- Currently, building floor levels are designed for 1 in 100 year ARI floods plus ‘freeboard’\(^1\) yet there are a significant number of buildings that are below this level. The majority of new commercial and residential buildings have a freeboard of 0.5m.
- Based on renewal of buildings, it is assumed that design standards for infrastructure, such as buildings, utilities, facilities and coastal protection, are assumed to commence using climate forecasting to adapt standards, guidelines and building codes for design by 2030. However, only a minority (approximately 20%) of stock is expected to comply with these requirements by 2030. By 2070, at least half (50–60%) is expected to comply and by 2100, the majority (80%) of stock is expected to comply due to the likely requirement for the standards to increase between 2070 and 2100 to proactively manage impacts.
- It is anticipated that impacts may be bigger for areas with high economic activity or significant facilities/businesses (e.g. airports). However, it has not been built into the matrix of economic impacts.
- Up to 2030, costs increases are likely to be as a result of increased repair, maintenance, clean up and emergency response activities.

\(^1\) Freeboard refers to a factor of safety above a design flood level, typically expressed in metres.
• Up to 2070, costs for preventative activity are likely to be higher, i.e. altered design standards, higher sea wall protection, higher capital expenditure on improved drainage, planning and building design.

• Greater use of rainwater tanks will reduce the impact of frequent (1:2 and 1:5 year) rainfall events, more passive storage (WSUD) retarding basins will also assist.

• Coastal planning schemes are expected to have a slow take up of prohibiting coastal development. It is anticipated such strong measures will be relative to the frequency and significance of extreme events in the short term.

• An increase in coastal housing density and commercial activity will likely lead to an increase in operational and capital expenditure in the short term as more assets of the same standard are at risk.

2.2 Correlated impacts

• The climate change impacts on buildings will have correlated impacts on movements of population in Australia and internationally and therefore impacts on the geo-political landscape and social-cohesion.

• Reduction in productivity of business and industry affected by damage to buildings.

Further research

Further research to increase the knowledge of specific distribution and magnitude of extreme wind events for the seven scenarios for major coastal settlements would be beneficial.

2.3 Electricity transmission and distribution networks

This storyline only considers the impact of climate change on electricity transmission and distribution infrastructure; electricity generation was not included due to scope restrictions and time available for this assessment. Demand side impacts (i.e. impacts to electricity consumers) have also been excluded (these are listed in Figure 11), and are not considered in the economic impacts of this study. Allowances have been made for increased air conditioner penetration and usage as a consequence of increasing temperatures associated with the different scenarios.

The following definitions are used for the purpose of this storyline:

• Electricity generation: ‘A generator creates electricity by using energy to turn a turbine, which makes large magnets spin inside coils of conducting wire. In Australia electricity is mainly produced by burning fossil fuels, such as coal and gas to create pressurised steam.’ (AER 2007, p60);

• Electricity transmission: ‘Transmission networks transport electricity from generators to distribution networks, which in turn transport electricity to customers. …A transmission network consists of towers and the high-voltage wires that run between them, underground cables, transformers, switching equipment, reactive power devices, monitoring and telecommunications equipment.’ (AER 2007, p118); and

• Electricity distribution: ‘Distribution networks move electricity from the transmission network to residential and business electricity customers. A distribution network consists of low-voltage substations, transformers, switching equipment, monitoring and signalling equipment and the poles, underground cables and overhead wires that carry electricity.’ (AER 2007, p143).
Figure 9  Damage to an electricity transmission tower as a result of extreme wind

Figure 10 provides a schematic illustrating key infrastructure necessary for the supply of electricity to end users.

**Figure 10  Schematic of the electricity supply chain (Source: AER 2007)**

Figure 11 outlines the impact storyline identified for electricity transmission and distribution (T&D) networks. This storyline was assessed against climate conditions considered in the seven climate scenarios U1, U2, U3, M1, M2, M3, M4 to develop the matrix of impacts for each state and territory as provided in Section 2.2.
Figure 11  Impact storyline for electricity distribution and transmission networks

<table>
<thead>
<tr>
<th>Climatic Variables</th>
<th>Impacts</th>
<th>Implications</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Increase in intensity of extreme wind</td>
<td>Damage to transmission and distribution above ground assets resulting in increased blackouts</td>
<td>IMPLICATIONS CONSIDERED IN ECONOMIC IMPACTS</td>
</tr>
<tr>
<td>• Increase frequency and intensity of storms</td>
<td>Reduced network capacity</td>
<td>• Increased capital and maintenance expenditure on electricity transmission and distribution infrastructure</td>
</tr>
<tr>
<td>• Increase in frequency and intensity of bushfires</td>
<td>Accelerated deterioration of assets</td>
<td>• Increased number of blackouts</td>
</tr>
<tr>
<td>• Increase in temperature</td>
<td>Potential blackout due to demand exceeding supply</td>
<td>• Increased length of blackouts</td>
</tr>
<tr>
<td>• Increase in number of hot days</td>
<td></td>
<td>• Increased demand for skilled staff leading to shortage of skilled staff</td>
</tr>
<tr>
<td>• Decrease in rainfall</td>
<td></td>
<td>• Lost revenue to Transmission and Distribution companies (short term)</td>
</tr>
<tr>
<td>• Increase in localised electrical storms*</td>
<td></td>
<td>• Accelerated depreciation and deterioration of assets</td>
</tr>
</tbody>
</table>

*NOTE: The impact of climate change on electrical storms is currently not well understood; as such it has not been included in the considerations of this report.
Case study: January 2006 Victorian bushfire

This case study provides an example of the impacts of bushfires on electricity infrastructure and the cascading effects when the power supply to a state is disconnected.

A bushfire, started by a single lighting strike in Tatong (located north east of Victoria), caused significant electricity blackouts in Victoria on 16 January 2007. The fire conditions were extreme with high temperatures (Melbourne recorded the second hottest summer day on 16 January 2007) and resulted in 166 active fires across the state.

Victoria’s main electricity infrastructure (power stations, terminal stations and transmission lines) is located in the east of the state. The bushfire tripped two 330kV transmission lines from Dederang and South Morang and six other network transmission lines. These are main transmission lines were that supply power to Victoria from the Snowy Mountains Hydro-electric Scheme (Snowy) and New South Wales. As a result of the bushfires, the lines automatically disconnected by the control systems at both ends in order to protect and prevent further infrastructure damage. This effectively severed Victoria’s main electricity link to the Snowy and New South Wales.

Following the loss of the transmission lines to the Snowy and New South Wales, the power flow from South Australia to Victoria increased and could not be sustained. This tripped two 275kV transmission lines connecting Victoria to South Australia. Victoria lost power supply from South Australia and remained connected only to Tasmania’s power supply via the Basslink undersea cable.

The disconnection of these two electricity systems left 480,000 Victorians without electricity for approximately 6.5 hours (NEMMCO, 2007). Victoria effectively lost one quarter of its electricity supply in a matter of seconds (Hughes and Wallace, 2007). More significantly, the blackout led to many more impacts on transport, telecommunication and healthcare infrastructure services, including:

- major traffic delays across the metropolitan area
- road traffic signal failure in Melbourne and Geelong, with 1,200 intersections losing lights
- shutdown of 40% of computers at VicRoads’ traffic control centres causing loss of visibility of sections on the system
- deployment of police for traffic management
- loss of power supply at rail boom gates
- hospitals and health facilities in blacked out areas reverted to their back-up supply to maintain core services
- loss of mobile phone services at 140 base stations in blacked out areas and loss of coverage to 750 square kilometres in metropolitan and country areas
- disruption of internet connection services to at least 25,000 users (Yates, 2007, p10)

The cumulative cost of the blackout is estimated to be in the tens of millions of dollars (Hughes and Wallace, 2007).

Figure 12 outlines the economic impacts for each state, across the seven climate scenarios and three time periods.
**Figure 12** Electricity transmission and distribution networks—Matrix of Impacts

<table>
<thead>
<tr>
<th>Climate Scenario</th>
<th>U1</th>
<th>U2</th>
<th>U3</th>
<th>M1</th>
<th>M2</th>
<th>M3</th>
<th>M4</th>
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Refer to Table 7 for an explanation of the impact criteria.

**Climate change scenario storylines**

*Business as usual scenarios*

The impact of the business as usual climate change scenarios provided by the CSIRO on behalf of the Garnaut Climate Change Review Secretariat on Australia’s electricity transmission and distribution is described below.

**U1:** Hot, dry reference scenario—A1FI emissions path, 3°C climate sensitivity, 10th percentile rainfall and relative humidity surface for Australia (dry extreme), 90th percentile temperature surface. Mean global warming reaches 4.5°C in 2100.

This ‘hot and dry’ scenario adopts a ‘business as usual’ approach to greenhouse gas emissions and therefore assumes the highest level of temperature increase, along with the greatest decline in rainfall and relative humidity. With this level of emissions, mainland Australia experiences a 1 degree temperature increase by 2030 and generally exceeds 5°C by 2100. Varying in different regions, rainfall decreases across the country, particularly in the southern areas.
The A1FI emissions scenario, upon which U1 is based, 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’ (IPCC, 2007b). A1FI has a fossil fuel-intensive technological emphasis. It is with this guide that these ‘business as usual’ developments are based. This scenario is expected to result in low to moderate economic impacts by 2030 and moderate to extreme impacts between 2031 and 2100 depending on the region considered.

The above-ground assets of some electricity transmission and distribution (T&D) networks are already feeling the strain of increased frequency and intensity of extreme weather events, lower rainfall, bushfires and rising temperatures. The combination of increased energy demand and intense environmental conditions means that T&D networks experience significant impacts. Strain on the network is likely to be intense as networks face greater challenges with worsening weather conditions, less predictable increase in peak demand and higher temperatures for U1. This will increase the deterioration of network assets and escalate maintenance costs and depreciation rates. This rise in asset renewal rates will also affect capital expenditure budgets and renewal cycles.

Service reliability is a regulated mandate of T&D businesses; this reliability can be breached in situations when energy demand exceeds supply or damages to the network affect supply reliability. Heatwaves, or days over 35°C, already strain the system capacity of most Australian capital cities due to the added drain of air-conditioning use. All states are forecast to see both increased air-conditioning market penetration and usage and hot days over 35°C under U1 and U2 (refer to Appendix C). This may cause increased outages during heatwaves in the short term, or until network capacity is expanded accordingly. Peak demand experienced during high temperatures will coincide with some reduced capacity (Thomas 2002), placing additional stress on the system.

Outages due to asset damages caused during extreme events such as storms, floods or bushfires are also of increasing concern in consideration of a U1 future. While wind load thresholds of network assets are generally high, flying debris is the most damaging factor during these events. As such, the potential increased wind intensity of U1 will likely increase storm-related damages and outages. Up to 2030 the impact on Western Australia and Northern Territory is anticipated to be less than other states due to their networks being less exposed through existing design to extreme events including cyclones. Higher impacts are expected in Queensland between 2031 and 2070. Between 2071 and 2100 extreme impacts are expected for Queensland, Northern Territory and Northern Western Australia as a result of greater increase in extreme events than networks will be designed for. The most vulnerable infrastructure will be that which is directly exposed to prevailing climatic conditions, such as transmission towers and lines, distribution poles and wires and, to a lesser extent, substations.

During extended dry periods, projected for U1, degradation in the structural integrity of transmission lines may be amplified by increased ground movement or reductions in ground water. This could affect the chemical structure of foundations, causing more rapid fatigue of structures from extreme weather events (CSIRO 2007). Also degradation of transmission line insulators will increase leading to increased outages and shorter insulator life.

Bushfire mitigation is already of high priority and cost to electricity T&D entities, and a recent study forecasts unprecedented extreme fire danger conditions in future years, particularly under an U1-like scenario (Lucas et al 2007). Not only is the intensity and frequency of bushfires projected to increase in areas which already experience significant bushfire damage (i.e. south east Australia), but those areas exposed to fire danger is expected to expand. For example, reductions in rainfall in areas such as southern Queensland could lead to new areas being susceptible to bush fire risk. This would likely see expanded impacts from bushfires on system reliability and T&D resources under the U1 climate scenario.

The power system is operated to design capacity that can cope with ‘credible’ (likely) supply interruptions. These events are foreseeable to an extent, and can be avoided through appropriate investment or management practices. However, an increase in currently non-credible events (e.g. from more frequent extreme weather events, more numerous simultaneous events, or rapid increases...
in peak demand due increased penetration and concurrent use of air-conditioners during heatwaves) will mean T&D networks are exposed to these types of events more regularly. Networks are not currently designed to standards which can withstand these cumulative events, therefore significant investments may be required in order to increase capacity and reliability. This is likely to cause subsequent increased electricity prices for consumers. Without such upgrades, the probability of power supply interruptions is increased.

For U1, sea level rise is expected to be approximately 17 cm by 2030, 50 cm by 2070 (CSIRO 2007, Hennessy et al, 2006) and 70 cm by 2100 (Weller 2005). Toward the end of the century, coastal T&D assets could be affected by inundation and likely to require relocation in line with settlement retreat or increased coastal protection investment. This will lead to moderate economic impacts for all state and territory capital cities (except for the ACT) which are situated in proximity to the coast.

**U2:** Best estimate (median) business as usual scenario using A1FI emissions path, 50th percentile rainfall and relative humidity surface for Australia, 50th percentile temperature surface. Mean global warming reaches ~4.5°C in 2100.

This scenario is most closely related to U1 due to the modelled reduction in rainfall. However, the drying and humidity is less extreme than U1 as is the temperature increase. The temperature increase and evaporation is modelled to be the same as U3.

Temperature is a key driver of extreme weather events. As the expected increase in temperature under U2 is similar to that of U1 up to 2030, the impacts under the U2 storyline are also anticipated to be similar to U1 over this time period. During the remainder of the century, the cities likely to experience the highest degree of impact under U2 are anticipated to be the same as those that experience the highest degree of impacts under the U1 scenario, although the magnitude or severity is anticipated to be less than U1. Depending on the region considered, this scenario is expected to result in low to moderate economic impacts by 2030, moderate to high impacts by 2070 and moderate to extreme impacts by 2100.

Under the U2 scenario mainland Australia experiences a gradual increase in temperature. Between 2030 and 2070 all capital cities exceed a 2°C increase in temperature. Rainfall decreases in most of the country, with the exception being Greater Hobart and Darwin. The greatest reduction in rainfall is anticipated to be in Perth, followed by Adelaide and then Melbourne.

T&D networks already feel the strain of increased frequency and intensity of extreme weather events, bushfires and rising temperatures. Similarly to U1, under the U2 scenario the strains of extreme weather events are expected to be intense. Recent studies by Preston and Jones (2006) identified that a 2–3°C increase in temperature will increase peak electricity demand in Adelaide, Brisbane and Melbourne by 3–15%. This combination of increased demand and increased deterioration of the network due to higher temperatures will likely increase the risk of blackouts and increase in capital and maintenance costs and depreciation rates.

The increase in extreme events under an U2 scenario is likely to increase the frequency of outages due to asset damages as a result of extreme events such as storms, floods or bushfires. The most damaging impact during storm events is wind and flying debris. The damage from extreme events will increase maintenance costs and depreciation rates. This rise in asset renewal rates will also affect capital expenditure budgets and renewal cycles. The impact of extreme events is anticipated to be the greatest in Western Australia, Northern Territory and Queensland, particularly in the latter half of the century.

Similarly as under U1 service reliability is likely to become challenged under increasingly rising temperatures. Heatwaves and days over 35 °C, already strain the system capacity of most Australian cities due to the added drain of air-conditioning use. Peak demand experienced during high temperatures will coincide with reduced capacity, placing additional stress on the system (SPI Powernet, 2004).

Under U2 extended dry periods are expected due to increased temperatures and evaporation and reduced rainfall and relative humidity. As in the U1 scenario, this will likely cause degradation of the
structural integrity of transmission lines which may be amplified by increased ground movement or changes in ground water levels. The extended dry periods under U2 will likely exacerbate bushfire risk in areas prone to bush fires but may also expand the risk to areas previously not at risk. Impacts from bushfires on systems reliability and T&D resources in the U2 are expected to increase.

Sea level rise is expected to be gradual up to 2100. Coastal T&D assets could be affected by inundation and likely to require relocation in line with settlement retreat or require increased coastal protection investment.

**U3:** *Warm, wet business as-usual scenario under A1FI emissions path, 90th percentile rainfall and relative humidity surface for Australia (wet extreme), 50th percentile temperature surface. Mean global warming reaches ~4.5°C in 2100.*

This scenario adopts a ‘business as usual’ approach to greenhouse gas emissions and statistically it assumes the most likely level of temperature increase, along with the greatest increase in rainfall and relative humidity.

The impacts of U3 are characterised by increased extreme rainfall events and a less severe temperature increase to U1. Rainfall is projected to increase at the greatest rate in Darwin, Brisbane and Hobart with a considerable increase in Sydney. However, Melbourne, Adelaide and Perth are likely to experience little or no increase in annual rainfall and are therefore likely to experience similar impacts to those described in U1. However, northern Western Australia is likely to experience a significant increase in annual rainfall events which increase the net exposure of Western Australia. This scenario is expected to result in low to moderate economic impacts by 2030, low to high impacts by 2070 and moderate to extreme impacts by 2100 depending on the region considered.

Although less extreme than the U1 scenario, temperatures are anticipated to also continue to increase under U3. Under U3, strain on the network is therefore also likely to be intense as networks must cope with increasing and less predictable peak demand and higher temperatures.

The increase in temperature and humidity in most states indicates increased conditions for extreme storms, flash flooding and riverine flooding. U3 is more likely to generate urban flash flooding resulting from short periods of high rainfall. Higher rainfall will facilitate the higher growth of bushfire load, however shorter and less extreme dry periods will somewhat reduce bushfire risk. Under the U3 scenario it is anticipated that extreme storm events will become more frequent and severe. This will likely see increased storm damage and related outages, perhaps more significantly than U1, in the northern and eastern regions of Australia. As Melbourne, Adelaide and Perth are unlikely to have an increase in rainfall; these areas are likely to be more aligned to conditions and implications of the U1 scenario with respect to drying such as bushfires.

As with U1, the increases in temperature and the cumulative extreme events are likely to exacerbate asset deterioration and increase asset renewal and depreciation rates. The most vulnerable infrastructure will be that which is directly exposed to prevailing climatic conditions, such as transmission towers and lines, distribution poles and wires, and to a lesser extent, substations.

As in the U1 scenario, under U3, sea level is anticipated to rise gradually over the century. Toward the end of the century, coastal T&D assets could be inundated and likely to require relocation in line with settlement retreat or further investment in coastal protection.

**Strong mitigation scenarios**

The four climate change scenarios with a policy intervention provided by CSIRO, on behalf of the Garnaut Climate Change Review Secretariat and considered in the electricity transmission and distribution storyline are discussed in turn below.
M1: **Dry mitigation scenario where stabilisation of 550ppm CO₂ equivalent (CO₂ stabilised at 500ppm) is reached by 2100, 10th percentile rainfall and relative humidity surface for Australia (dry extreme), 90th percentile temperature surface. Mean global warming reaches ~2.0°C in 2100.**

This scenario adopts a policy intervention that leads to a greenhouse gas emissions trajectory that stabilises atmospheric greenhouse gas concentrations at a level that constrains the temperature increase to 2.0°C in 2100; as compared to 4.5°C in 2100 under the scenario U1.

Under this scenario, the CMAR climate modelling indicates that changes in rainfall (decline), humidity (decline), temperature (increase) and evaporation (increase) are anticipated to be marginally greater than U1 at 2030. From the middle of the century the M1 temperature and rainfall changes begin to level out. However the temperature and rainfall changes modelled in U1 significantly outpace the M1 scenario after this time period. The M1 temperature increases at 2100 are reached in the middle of the century under the U1 scenario. The temperature and rainfall changes for M1 are approximately 55% of the U1 changes at 2070 and 40% of U1 at 2100. This scenario is expected to result in low to moderate economic impacts up to 2070 and moderate to high impacts between 2071 and 2100 depending on the region considered.

The reduced rate and level of temperature increase relative to the U1 scenario has the impact of lessening the impact of increased extreme rainfall and flash flooding with less additional temperature driven storm energy in the climate system relative to U1. This would see similar impacts due to storms, bushfires and heatwaves during this period. However, there would be some difference in responses, as greater capital investment is likely in 2070 scenario U2 to minimise future operating expenditure. Capital investments as a response to climate change in Western Australia and Northern Territory are anticipated to peak in the period 2031–2070, as the impact of rising temperatures and increased extreme events requires these states to make similar investments that were required earlier in the other states.

A decrease in annual rainfall and increase in temperature and evaporation will lead to a lesser increase in ground movement and degradation in the foundations of network assets than under the business as usual scenario U1. Sea level rise is expected to be gradual up to 2100 in a similar trajectory as U1. The economic impacts are anticipated to soften in the latter half of the century as the rate of change in rainfall and temperature reduces and investment in asset protection and improved design standards better address the ‘new’ climate.

M2: **Best estimate (median) mitigation scenario where stabilisation of 550ppm CO₂ equivalent (CO₂ stabilised at 500ppm) is reached by 2100, 50th percentile rainfall and relative humidity surface for Australia, 50th percentile temperature surface. Mean global warming reaches ~2.0°C in 2100.**

The modelled M2 climate changes are similar to the U2 climate changes. The climate models provided by CMAR indicated that for the M2 scenario, the changes in rainfall (decline), humidity (decline), temperature (increase) and evaporation (increase) are anticipated to be marginally greater than U2 at 2030. From the middle of the century the M2 temperature and rainfall changes begin to level out. However, the temperature and rainfall changes modelled in U2 significantly outpace the M2 scenario after this time period. The M2 temperature increases at 2100 are reached in the middle of the century under the U2 scenario. The temperature and rainfall changes for M2 are approximately 55% of the U2 changes at 2070 and 40% of U2 at 2100. Depending on the region considered, this scenario is expected to result in low to moderate economic impacts by 2030, low to high impacts by 2070 and low to moderate impacts between 2071 and 2100.

The impacts at 2030 are likely to be similar to that experienced under U2 with increased outages due to a combination of increased demand for electricity, and deterioration of assets due to extreme events, bushfires and increased temperatures. Beyond 2030 the impacts are likely to increase moderately across all states except for Tasmania as the change in temperature and rainfall is anticipated to be minimal.
Queensland is anticipated to experience the highest impacts as a greater level of extreme events is still anticipated compared to the other states and territories. The impacts are anticipated to soften across all states in the last quarter of the century. This is due to the changes in rainfall and temperature levelling off and investment in asset protection and improved design standards better addressing the ‘new’ climate conditions.

**M3: Wet mitigation scenario where stabilisation of 550ppm CO₂ equivalent (CO₂ stabilised at 500ppm) is reached by 2100, 90th percentile rainfall and relative humidity surface for Australia (wet extreme), 50th percentile temperature surface. Mean global warming reaches ~2.0°C in 2100.**

This scenario adopts a policy intervention that leads to a greenhouse gas emissions trajectory that stabilises atmospheric greenhouse gas concentrations at a level that constrains the temperature increase to 2.0°C in 2100; as compared to 4.5°C in 2100 under the scenario U3. The scenario assumes an increase in temperature, along with an increase in rainfall and relative humidity.

The climate models provided by CMAR indicated that under this scenario, the changes in rainfall (decline), humidity (decline), temperature (increase) and evaporation (increase) are anticipated to be marginally greater than U3 at 2030. From the middle of the century the M3 temperature and rainfall changes begin to level out. However, the temperature and rainfall changes modelled in U3 significantly outpace the M3 scenario after this time period. The M3 temperature and rainfall increases at 2100 are reached in the middle of the century under the U3 scenario. The temperature and rainfall changes for M3 are approximately 55% of the U3 changes at 2070 and 40% of U3 at 2100.

Depending on the region considered, this scenario is expected to result in low to moderate economic impacts by 2030, low to high impacts by 2070 and low to moderate impacts between 2071 and 2100. The extreme rainfall events generating riverine flooding are likely to increase but to a lesser extent than U3, as the expected increase in temperature that drives extreme storm, wind and rainfall events is reduced. The moderate temperature increase post 2050 would also reduce the increased likelihood of heatwaves and bushfires and the associated damages, outages and mitigation costs.

Western Australia and Queensland are predicted to have a greater impact from extreme events than the other states in the middle of the century. The impacts under this scenario are anticipated to soften in the 2071–2100 time period as the changes in rainfall and temperature reduce and investment in asset protection and improved design standards better address the ‘new’ climate.

Sea level rise is expected to be gradual up to 2100.

**M4: Best estimate (median) strong mitigation scenario where stabilisation of 450ppm CO₂ equivalent (CO₂ stabilised at 420ppm) is reached by 2100, 50th percentile rainfall and relative humidity surface for Australia), 50th percentile temperature surface. Mean global warming reaches ~1.5°C in 2100.**

This scenario is the ‘best-case’ of the group of scenarios assessed. The temperature and rainfall changes are modelled to stabilise around 2080 and begin to reverse toward 2100 therefore reducing the pressures generating increased storm related impacts. Of the scenarios that result in a decline in rainfall and relative humidity (scenarios U1, U2, M1, M2 and M4), this scenario would have the least impact on climate change induced storm, wind and bushfire impacts. Depending on the region considered, this scenario is expected to result in low to moderate economic impacts up to 2070 and neutral to moderate impacts between 2071 and 2100.

Sea level rise is expected to be gradual up to 2100.

This scenario would result in the lowest level of climate change impacts and hence would result in the lowest level of economic impact to electricity transmission and distribution assets. Impacts are likely to be similar across most states and territories over the century. After 2030 the Australian Capital Territory (ACT) and Tasmania are anticipated to have the lowest impacts as they have the least dramatic shift in climate.
Key assumptions

- The regulations of the Australian National Electricity Market were considered to likely remain largely consistent with the current framework and planning horizons in developing this storyline.

- The Regulated Asset Base (RAB) provides a useful indicator of the value of T&D networks. The RAB is calculated by the jurisdictional regulator and is equal to the replacement value of the asset (at the date of installation), plus capital expenditure, less depreciation. The RAB is reviewed every five years and has a ten year planning window.

- Existing T&D infrastructure is expected to remain above ground due to the significant cost and disturbance to put it below ground. Should extreme events damage above-ground assets with significant frequency, it may improve the commercial viability of this shift.

- Damage costs, due to increased extreme events, may reach a threshold that warrants increased expenditure to achieve higher resilience standards and reduce vulnerability and remediation costs. This has been factored into the impacts and is reflected in the capital and operational expenditure.

- Design standards are expected to respond between 2030 and 2070, reducing the vulnerability to subsequent events. The driver for capital investment and improved design standards is likely to be increased maintenance costs, increased failure of assets and reduced life expectancy of assets. The result of these increases in costs and investment is likely to drive policy change.

- Frequency of storms, wind intensity, lightning, rainfall and storm surges can all contribute to increased blackouts.

- The increased resources required to remediate asset damages may also pressure human resources in the form of skills shortages and wage increases. This would drive up maintenance costs and cause delays in getting networks back online.

- All new Greenfield urban developments are expected to have underground distribution networks resulting in those areas being less vulnerable to damage in extreme events.

- New urban developments that have underground distribution networks will have somewhat less vulnerability to bushfire.

- As extreme events increase in frequency and severity it is anticipated that improved materials, techniques and equipment will be utilised to increase infrastructure resilience. This will reduce the potential vulnerability to future events presuming the increased standards can respond to the further increasing climatic pressures.

- Reduced line capacities will be experienced at higher sustained ambient temperatures, and are likely to occur at times of maximum system demand (Thomas 2002);

- Air-borne debris (trees, roofs) is more of a problem during high wind events than wind itself. Insurance studies show that a 25% increase in peak wind gust strength can generate a 6.5-fold increase in building claims (IAG 2003).

- Assets above ground and near the coast will likely require increasing maintenance due to increased corrosion rates primarily from increased temperatures. The effects of climate change on salinisation in Australia are not currently fully understood, but in areas experiencing a decrease in rainfall, there will be a reduction in surface water runoff and less water available to dilute existing levels of ground water discharge (AGO 2002). In scenarios where coastal areas become inundated by sea water, infrastructure would be exposed to high levels of salinity. Given the corrosive nature of salt, more rapid degradation of T&D structures and foundations would be expected.

- Increased maintenance costs have been presumed to increase with the potential increase in extreme event frequency. It is perhaps reasonable to assume some years may be better than
others, thereby averaging the overall financial impacts; however the potential significant and far reaching impact of a combined or multiple extreme event should still be considered. Such an event is more likely to happen as a result of an additional pressure on an already at-capacity system, such as a bushfire or storm during an extended heatwave. During the business as usual scenarios the system is expected to be under stress more frequently, especially for U1.

- The effectiveness of increased capacity and resilience measures through capital and operational expenditure largely relies on the accuracy of the planning and quality of implementation. Any underestimation of capacity needs or network performance will clearly result in performance outcomes more detrimental than described in this study.

- Reliability standards for transmission networks tend to be more conservative than distribution networks. A transmission outage has the potential to affect hundreds of thousands of downstream customers as transmission lines form the backbone of the national power system and transport large volumes of high voltage electricity sold in the National Electricity Market (NEM). Distribution networks receive high voltage electricity from the transmission lines via terminal stations, and supply low voltage electricity to a smaller customer base. Distribution outages therefore affect a more confined, localised number of end users. Distribution networks are more extensive than transmission networks and by their nature, are more exposed to our built and natural environments. Distribution networks therefore experience a significantly greater level of interference caused by external factors and therefore a greater number of network interruptions compared to transmission interruptions.

- Additional capital expenditure required for any network augmentation and development can be submitted to the Australian Energy Regulator (AER) for review and approval, each five years with a ten year planning horizon (AER 2007). If considered reasonable and then approved, these costs will be passed on to consumers.

- An increase in the frequency of smaller, yet still significant, events and the increase in less frequent, yet high impact events, will likely cause increased disruption and damage in the short term. It is presumed infrastructure improvements and more informed planning will deliver improved system resilience. If climatic changes exceed the baseline projections networks may still be negatively affected.

**Demand side impacts considered**

- It is expected the T&D entities will adequately plan for the required increased capacity within the required planning windows to ensure a reasonable growth in network capacity and maintained reliability. Such planning accuracy will require quality data and responsive timeframes. Although population and economic growth will both contribute to the need for increased capacity, only the growth attributable to climate change (i.e. greater penetration and use of air conditioning) has been considered in the economic impacts.

- The upgrading of networks is expected to lag slightly behind air-conditioner penetration growth, especially in the high growth states which are also forecast to experience more hot days. By 2030 most mainland states will have reached close to market saturation in air-conditioners and network capacity is likely to match this penetration.

- Capital expenditure is required to meet electricity demand growth. Recently, demand has been exceeding GDP, largely due to the increased market penetration of air conditioners, which has risen sharply since 2000. As air conditioning levels saturate, demand is expected to level off and networks are likely to generally have capacity to meet peak demand (refer to Figure 34—Penetration trends of Air Conditioners by state (Appendix A)).

- The Centre for Distributed Energy and Power (CenDEP) foresees a gradual increase in micro-generation and distributed energy over the course of the century, leading to more decentralised energy networks (CSIRO 2007). This would decrease demand pressure on transmission networks and to a lesser extent on distribution networks. Decentralisation of infrastructure helps to provide insulation against climate change related economic impacts.
• While population growth may further increase air conditioning load, over time increased energy efficiency technologies and standards are presumed to deliver countering benefits in energy demand.

Correlated impacts
• Increased outages during heatwaves may place more pressure on the elderly (over 65) and infirmed who are more vulnerable to heat stress deaths.
• Outages due to extreme events are likely to have follow-on impacts to business productivity.
• Outages due to extreme events are likely to have follow-on impacts on emergency services responses.

Further research
• Energy generation will also be affected under all scenarios and should be considered for further assessment.
• Technological innovation has been assumed where indicated (i.e. this is a characteristic of A1FI) based on likely future developments such as energy efficiency and improved resilience to increasing temperatures. This may benefit from more in-depth analysis.
• Under the U1 ‘hot and dry’ scenario water scarcity will be an issue and may cause pressures for electricity thermal generators. As air-cooled thermal generators and other energy technologies are already being developed it is considered water shortage will not affect generation in the medium to long term. While generation is not within the scope of this review on transmission and distribution, it should be noted that extreme water shortages can impact electricity generation in the short term unless alternative water cooling sources are identified.
• More in-depth analysis of technological innovation would benefit T&D networks in managing non-credible but possible events involving numerous simultaneous but unrelated incidents that have a cumulative impact and the response of network systems to handle such events.

2.4 Water supply infrastructure in major cities
This study focuses on capital cities as regional centres have a different supply profile and constraints. The climate change projections considered in the water supply infrastructure in major cities storyline are projections from the ‘current’ climate, given an assumed greenhouse gas emission trajectory, climate sensitivity and probability of change.

The ‘current’ climate has experienced a degree of climate change already—although the certainty of this varies from region to region across the country and from climate variable to climate variable. Therefore it is likely that the early impacts of climate change are already being felt in some areas of the country (i.e. Perth and South Western Australia), but potentially not yet in others (CSIRO 2007, pp 29–35). The projected climate change scenarios being considered therefore represent change on change.

Figure 13 outlines the impact storyline identified for water supply infrastructure in major cities. This storyline was assessed against climate conditions considered in the seven climate scenarios U1, U2, U3, M1, M2, M3 and M4 to develop the matrix of impacts for each state and territory as provided in this section.
Figure 13  Impact storyline for water supply infrastructure in major cities

**Climatic Variables**
- Increased temperature and heatwaves
- Decreased annual rainfall
- Increased variability of rainfall (annual and seasonal)
- Increase in potential evaporation
- Decrease in soil moisture
- More intense rainfall events

**Impacts**
- Reduction in available water for consumptive use—potable, commercial and industrial (agriculture not part of this storyline)
- Declining water quality leading to higher treatment costs
- Accelerated degradation and increased failure of water distribution infrastructure (i.e. pipe breakage due to increased ground movement)

**Implications**
- IMPACTS CONSIDERED IN ECONOMIC IMPACTS
  - Investment in alternative water supply (desalination, recycling, storage infrastructure, piping etc)
  - Increased maintenance expenditure on water distribution infrastructure
- ADDITIONAL DEMAND SIDE IMPLICATIONS
  - Local business investment in efficient use of water
  - Water security impacts on price, availability and interruption of supply to residents and businesses
  - Mechanisms to encourage efficiency and conservation (technology, behavioural and pricing solutions and incentives)
  - Increase in investment to protect ecosystems from decreased environmental flows
  - Reduction in commercial income from ecosystems (tourism, fisheries etc)
  - Increase in water cost per unit of production
  - Lower water consumption per unit of production

Figure 14  Photos of Lake Eildon (Victoria) and the Old Homestead that used to be submerged by the lake (2004)
Case study: Declining rainfall and increase temperatures in south-western Australia

This case study explains how the effects of climate change has already affected water supply and stimulated a response for new water infrastructure in southern Western Australia.

The region in the southwest of Western Australia is particularly vulnerable to the effects of climate change. Historical evidence shows that an abrupt or step change down in rainfall is already happening in this region. This region has seen a 10 to 20% decrease in winter rainfall over the last 30 years and temperatures have also increased substantially over the last half century (Allen Consulting Group, 2005, p87). As a result, the total average annual stream flow into Perth dams have declined nearly 30% from 161GL (for the period between 1974 to 2002) to 115GL (for the period between 1997 to 2002) (WCWA, 2005, p. 9). The decline in yearly stream flow since 1911 for major water sources in south Western Australian is shown below.

Yearly stream flow for major metropolitan surface water sources in south Western Australia, 1911 to 2004

Studies by the Indian Ocean Climate Initiative (IOCI) indicate that the decrease in rainfall has been accompanied, and ‘apparently associated with’, human-induced climate change (Allen Consulting Group, 2005, p87). IOCI note that climate change alone is not solely responsible for the decline in rainfall levels or rise in temperature in the region, however these climate pressures remain. CSIRO indicate that in addition to natural variability, increased concentrations of greenhouse gases are leading to climate change, inducing a long term trend which superimposes on the natural variability, as is the case with a winter drying trend over south-west Western Australia since the late 1960s. (CSIRO 2008).

Significant changes in rainfall levels and temperature have a dramatic effect on water supply. The south western region is Western Australia’s most densely populated region and the powerhouse of the state’s timber, wool, dairy, beef, wheat and grape/wine industries. Higher temperatures lead to increased evaporation, which, when coupled with lower rainfall levels, places water supplies and resources under great stress.

The historical trends of reduced rainfall and increased temperatures in south Western Australia indicates that the region needs to prepare for a drying climate and seek alternative water sources as a result of climate change. The decline in rainfall and an increase in temperatures have provided a strong case for the construction of alternative water supply infrastructure such as desalination plants and water recycling facilities. To meet future water demand, Western Australia has built a $387 million desalination plant, which now supplies 17% of Perth’s water consumption (Rule, 2007). The annual running cost of the plant is approximately $20 million (WTN, 2007). It is likely that a second desalination plant will be built in the future, to supply up to 30% of Perth’s water use (The Age, 2007).
Figure 15 outlines the economic impacts for each state and territory, across the seven climate scenarios and three time periods.

**Figure 15 Water supply infrastructure in major cities—Matrix of Impacts**

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Refer to Table 7 for an explanation of the impact criteria.

**Climate change scenario storylines**

**Business as usual scenarios**

The Business as usual climate change scenarios provided by the CSIRO on behalf of the Garnaut Climate Change Review Secretariat and considered in the water supply infrastructure for major population centres storyline are discussed below.
**U1: Hot, dry business as usual scenario, using A1FI emission path, 10th percentile rainfall and relative humidity surface for Australia (dry extreme), 90th percentile temperature surface. Mean global warming reaches ~4.5°C in 2100.**

This scenario adopts a ‘business as usual’ approach to greenhouse gas emissions and assumes the highest level of temperature increase, along with the greatest decline in rainfall and relative humidity.

For water supply infrastructure within capital cities, this is considered to be the ‘worst-case’ of the seven scenarios being considered. It is the ‘worst-case’ because it has the maximum increase in temperature and potential evaporation and maximum rainfall decline, which are the most dominant climatic drivers for both water availability and consumption. This scenario would result in the highest degree of climate change induced economic impact to water supply infrastructure across the country, progressively worsening at each time scale.

The combined impact of maximum heating, maximum drying and maximum decrease in relative humidity (increasing potential evaporative demand) will result in the greatest level of climate change induced water scarcity in all of the major population centres considered as part of this storyline. Other climate change impacts will also have implications for water supply, such as declining water quality (from higher temperature surface waters, lower volumes of surface waters and impacts of bushfires in catchments) requiring higher levels of and more expensive treatment. However, these are considered to be second order impacts on water availability and quality, which intensify the decline in available water, rather than acting as a principal driver. Depending on the region considered, this scenario is expected to result in neutral to extreme economic impacts by 2030, high to extreme impacts by 2070 and extreme impacts by 2100.

There will be differential impacts across the states/territories, with Perth being the most severely impacted by climate change induced water scarcity followed by Adelaide. Greater Hobart is expected to be the least impacted by climate change induced water scarcity, followed by Darwin.

When economic development, population growth and demographic change are considered in combination with climate change, the water deficit is exacerbated for Western Australia and Queensland. South Australia will have to address a climate change induced water scarcity initially but progressively economic development and population growth reduce in importance as drivers of water scarcity. Tasmania will be least impacted by the combined factors, with any impacts capable of being managed without a shift in typical practice with the new regime being considered the new ‘business as usual’.

Given the degree of combined factor impact, ‘new’ water sources will have to be utilised in most major population centres across the country. The development of ‘new’ water sources will need to occur as an immediate priority and require a significant response in the short-term, especially for Perth, Adelaide, Brisbane, Canberra, Melbourne and Sydney.

The increase in temperature, evaporation and reduced rainfall will reduce soil moisture and generate increased ground movement accelerating the degradation and failure of water distribution infrastructure such as mains water pipes. The reduced soil moisture will also mean that relatively larger rainfall events are required before water storage catchments receive inflows.

**U2: Best estimate (median) business as usual scenario using A1FI emissions path, 50th percentile rainfall and relative humidity surface for Australia, 50th percentile temperature surface. Mean global warming reaches ~4.5°C in 2100.**

This scenario is most closely related to U1 due to the modelled reduction in rainfall. However, the drying and changes in humidity is less extreme than U1 as is the temperature increase. The temperature increase and evaporation is the same as U3. Compared to the projected impacts under the U1 scenario, the impacts projected under the U2 scenario are fairly similar.

From a water supply infrastructure for capital cities perspective, the U1 scenario is the ‘worst-case’ scenario from all scenarios considered. As the climatic conditions under the U2 scenario are very similar to the U1 scenario, the implications for the water supply infrastructure are also similar but less
extreme over time. This scenario is expected to result in neutral to extreme economic impacts by 2030, low to extreme impacts by 2070 and moderate to extreme impacts by 2100 depending on the region considered.

The impact of increasing temperatures and evaporation combined with reducing rainfall and relative humidity (the most dominant climatic drivers for water availability and consumption) will result in a high level of climate change induced water scarcity. There will be differential impacts across the states and territories, with Perth being the most severely impacted by climate change induced water scarcity, whereas Greater Hobart will be the least impacted.

Given the degree of impact that water scarcity will have on major population centres across the country, the utilisation of ‘new’ water sources would appear to be essential. The development of these ‘new’ water sources will need to occur as an immediate priority and require a significant response in the short term, especially for Perth, Adelaide, Brisbane, Melbourne and Sydney.

Under this scenario, the increase in temperature, evaporation and reduced rainfall will reduce soil moisture and generate increased ground movement accelerating the degradation and failure of water distribution infrastructure such as mains water pipes. The reduced soil moisture will also mean that relatively larger rainfall events are required before water storage catchments receive inflows.

**U3: Warm, wet business as-usual scenario under A1FI emissions path, 90th percentile rainfall and relative humidity surface for Australia (wet extreme), 50th percentile temperature surface. Mean global warming reaches ~4.5°C in 2100.**

This scenario adopts a ‘business as usual’ approach to greenhouse gas emissions, and statistically it assumes the most likely level of temperature increase, along with the greatest increase in rainfall and relative humidity. Depending on the region considered, this scenario is expected to result in neutral to high impacts across all timeframes to 2100.

From a water supply infrastructure for capital cities perspective, this is considered to be the ‘best case’ of the seven scenarios being considered. It is the ‘best-case’ because it has the maximum increase in rainfall and relative humidity (decreasing potential evaporative demand) at the continental scale. This scenario would result in the lowest relative degree of climate change induced economic impact to water supply infrastructure Australia wide.

However, there are strong differential impacts between the capital cities. Perth, Melbourne and Adelaide experience little increase in rainfall and may in fact experience no change from the current climatic conditions. By comparison Darwin, Brisbane and Greater Hobart are all projected to have an increase in annual rainfall of greater than 25% per degree of global warming, and between 10% to 20% for Canberra and Sydney by 2100.

In the near term (i.e. from the current situation to 2030) projected rainfall increases are not going to be adequate to meet the current water scarcity that is being experienced and/or to supply the increased demand resulting from economic development, population growth and demographic change in the capital cities.

When an increase in temperature and evaporative demand is factored in for Melbourne there is still a potential for a climate change induced water deficit—despite there being little change in rainfall—especially for 2031–2070 and 2071–2100 timeframes. For Melbourne the development of ‘new’ water sources will need to occur and require a significant response in the medium term.

In most of the population centres, the combined impact of economic development, population growth and demographic change will result in a water deficit in the near term. As the changes in rainfall and relative humidity intensify over time, climate change induced water deficit will become less of an issue for 2070 and 2100, with the exception of Perth, Adelaide and Melbourne where there is little increase in rainfall.
Tasmania and the Northern Territory will be least impacted by the combined factors (climatic and socio-economic), with any impacts capable of being managed without a shift in typical practice with the new climatic regime being considered the new ‘business as usual’.

Along with an increase in overall annual rainfall, it would be anticipated that rainfall would also become more intense and this factor would need to be considered in water storage design for dam safety and flooding implications. But it is considered that this would be the ‘new’ business as usual and should be captured as the water industry evolves to the new climatic conditions.

The increase in temperature and evaporation will reduce soil moisture and generate increased ground movement accelerating the degradation and failure of water distribution infrastructure such as mains water pipes. This impact is likely to be tempered by an increase in rainfall and in therefore likely to be a less of an impact than for U1.

**Strong mitigation scenarios**

The climate change scenarios with a policy intervention provided by CSIRO on behalf of the Garnaut Climate Change Review Secretariat and considered in the water supply infrastructure for major population centres storyline are discussed in turn below.

**M1: Dry mitigation scenario where stabilisation of 550ppm CO₂ equivalent (CO₂stabilised at 500ppm) is reached by 2100, 10th percentile rainfall and relative humidity surface for Australia (dry extreme), 90th percentile temperature surface. Mean global warming reaches −2.0°C in 2100.**

This scenario adopts a policy intervention that leads to a greenhouse gas emissions trajectory that stabilises atmospheric greenhouse gas concentrations at a level that constrains the temperature increase to 2.0°C in 2100; as compared to 4.5°C in 2100 under the business as usual scenario U1.

Under this scenario, the CMAR climate modelling indicates that changes in rainfall (decline), humidity (decline), temperature (increase) and evaporation (increase) are anticipated to be marginally greater than U1 at 2030. However, the temperature and rainfall changes modelled in U1 significantly outpace the M1 scenario after this time period. From the middle of the century the M1 temperature and rainfall changes begin to level out. The M1 temperature increases at 2100 are reached in the middle of the century under the U1 scenario. The temperature and rainfall changes for M1 are approximately 55% of the U1 changes at 2070 and 40% of U1 at 2100. This scenario is expected to result in neutral to extreme economic impacts by 2030, low to extreme impacts by 2070 and low to high impacts by 2100 depending on the region considered.

Because of the relationship between rainfall, potential evaporation (as derived from relative humidity) and available surface water, less stress on the water supply industry will be experienced, relative to the dry business as usual scenario U1.

From the scenarios that have a policy intervention built into them, this is considered to be the ‘worst-case’ from a water supply perspective. The combined impacts of heating, drying and increasing evaporative demand will result in there being a water deficit in all of the population centres being considered, progressively worsening until the middle of the century when the climate changes level out. This scenario would result in the highest degree of climate change induced economic impact to water supply, for the policy intervened scenarios considered. But the impact would be less than under the scenario U1.

The patterns of vulnerability for the population centres being considered are similar to those presented under scenario U1 although the impacts are less severe. Hence, similar responses are necessary, but the degree of impact is moderated for most of the capital cities. It is noted that in the last quarter of the century the impacts are likely to soften as previous capital investments in ‘new’ water supply will ease the pressure on the system.

The development of ‘new’ water sources will still need to occur as an immediate priority and require a significant response in the short-term.
Under this scenario, the increase in temperature, evaporation and reduced rainfall will reduce soil moisture and generate increased ground movement accelerating the degradation and failure of water distribution infrastructure such as mains water pipes. The reduced soil moisture will also mean that relatively larger rainfall events are required before water storage catchments receive inflows. However, this impact is likely to be less than for U1.

**M2:** Best estimate (median) mitigation scenario where stabilisation of 550ppm CO₂ equivalent (CO₂ stabilised at 500ppm) is reached by 2100, 50th percentile rainfall and relative humidity surface for Australia, 50th percentile temperature surface. Mean global warming reaches ~2.0°C in 2100.

This scenario adopts a policy intervention that leads to a greenhouse gas emissions trajectory that stabilises atmospheric greenhouse gas concentrations at a level that constrains the global temperature increase to 2.0°C in 2100. This compares favourably to 4.5°C by 2100 under the ‘business as usual’ scenarios U1, U2 and U3.

The relationship between the modelled M2 climate changes and the U2 climate changes is very similar to that shared by U1 and M1, and U3 and M3. For the M2 scenario, the CMAR climate modelling indicates that changes in rainfall (decline), humidity (decline), temperature (increase) and evaporation (increase) are anticipated to be marginally greater than U2 at 2030. From about 2050 the M3 temperature and rainfall changes begin to level out.

However the temperature and rainfall changes modelled in U2 significantly outpace the M2 scenario after this time period. The M2 temperature increases at 2100 are reached in the middle of the century under the U2 scenario. The temperature and rainfall changes for M2 are approximately 55% of the U2 changes at 2070 and 40% of U3 at 2100. This scenario is expected to result in neutral to extreme up to 2070 and neutral to moderate impacts between 2071 and 2100 depending on the region considered.

As is the case for all of the seven scenarios assessed, there will be differential impacts across the population centres being considered. Darwin and Greater Hobart experience little change in annual rainfall. All of the other population centres experience a decline in annual rainfall of between 5.5% and 10.5% with the exception of Perth which is anticipated to have a reduction of 16.8% by 2100. Evaporative demand is anticipated to increase for all capital cities of the same period enhancing the water deficit.

The impacts are anticipated to be similar in distribution but less severe than U2, with Perth and Adelaide having the highest impact. However, the impacts are anticipated to peak in the period 2031–2070 and then reduce after 2071 as capital investment reduces the water deficit.

As this scenario represents a further decline in available water for population centres that are currently experiencing water supply stress, the combination of population growth, demographic change, economic development and climate change induced water scarcity will still result in a need to identify and develop additional ‘new’ water supplies for the majority of the population centres being considered.

Under this scenario, the increase in temperature, evaporation and reduced rainfall will reduce soil moisture and generate increased ground movement accelerating the degradation and failure of water distribution infrastructure such as mains water pipes. The reduced soil moisture will also mean that relatively larger rainfall events are required before water storage catchments receive inflows. However, this impact is likely to be less than U2.
**M3:** *Wet mitigation scenario where stabilisation of 550ppm CO₂ equivalent (CO₂-stabilised at 500ppm) is reached by 2100, 90th percentile rainfall and relative humidity surface for Australia (wet extreme), 50th percentile temperature surface. Mean global warming reaches ~2.0°C in 2100.*

This scenario adopts a policy intervention that leads to a greenhouse gas emissions trajectory that stabilises atmospheric greenhouse gas concentrations at a level that constrains the global temperature increase to 2°C in 2100. This compares favourably to the global temperature increase of 4.5°C in 2100 under the business as usual scenarios U1, U2 and U3.

The climate models provided by CMAR indicated that under this scenario, the changes in rainfall (decline), humidity (decline), temperature (increase) and evaporation (increase) are anticipated to be marginally greater than U3 at 2030. However, the temperature and rainfall changes modelled in U3 significantly outpace the M3 scenario after this time period. From the middle of the century the M3 temperature and rainfall changes begin to level out. The M3 temperature and rainfall increases at 2100 are reached in the middle of the century under the U3 scenario. The temperature and rainfall changes for M3 are approximately 55% of the U3 changes at 2070 and 40% of U3 at 2100. This scenario is expected to result in neutral to high up to 2070 and neutral to moderate impacts between 2071 and 2100 depending on the region considered.

Because of the relationship between rainfall, evaporation demand (as derived from relative humidity) and available surface water, less stress on the water supply industry will be experienced relative to either the U1, U2, U3, or M1 climate change scenarios. Despite the majority of the capital cities experiencing an increase in rainfall and therefore a reduced climate change induced water deficit, when combined with economic development, population growth and demographic change a water deficit is still anticipated.

The patterns of vulnerability for the population centres being considered are similar to those presented under business as usual scenario U3, but less severe due to a lower increase in temperature. However, climate change induced water deficits are anticipated for the population centres that experience little overall change in rainfall such as Perth, Melbourne and Adelaide.

Under the wet scenario, ground movement and failure of water distribution infrastructure such as mains water pipes is less likely to experience an impact. However, increased rainfall may add extra pressure to the water distribution system such as stormwater drainage to catchments.

**M4:** *Best estimate (median) strong mitigation scenario where stabilisation of 450ppm CO₂ equivalent (CO₂-stabilised at 420ppm) is reached by 2100, 50th percentile rainfall and relative humidity surface for Australia), 50th percentile temperature surface. Mean global warming reaches ~1.5°C in 2100.*

Depending on the region considered, this scenario is expected to result in low to neutral to extreme economic impacts by 2030, neutral to high impacts by 2070 and neutral to moderate impacts by 2100. The temperature and rainfall changes are modelled to stabilise around 2080 and begin to reverse toward 2100 therefore reducing the pressures contributing to a water deficit. Of the scenarios that result in a decline in rainfall and relative humidity (scenarios U1, U2, M1, and M2), this scenario would have the least impact on climate change induced water scarcity. Hence this scenario is the ‘best-case’ of the group of scenarios that result in declining rainfall and relative humidity (translating to a water deficit). This scenario would result in the lowest level of climate change induced water scarcity and hence result in the lowest level of economic impact for water supply (with the exception of scenarios U3 and M3, which contemplate increasing rainfall).

As with M2, Darwin and Greater Hobart experience little change in annual rainfall and as such are not anticipated to have a significant economic impact under this scenario. All of the other population centres experience a decline in annual rainfall of between 4.2% and 8% with the exception of Perth which is anticipated to have a reduction of 12.8% by 2100. Evaporative demand is anticipated to increase for all capital cities over the same period enhancing the water deficit.
The impacts are anticipated to be similar in distribution but less severe than M2, with Perth having the highest impact. However, the impacts are anticipated to peak in the period 2031–2070 and then reduce after 2071 as capital investment reduces the water deficit.

Under this scenario, the increase in temperature, evaporation and reduced rainfall will reduce soil moisture and generate increased ground movement accelerating the degradation and failure of water distribution infrastructure such as mains water pipes. The reduced soil moisture will also mean that relatively larger rainfall events are required before water storage catchments receive inflows. However, this impact is likely to be less than M2.

Key assumptions

- The storylines and analysis for Water Supply Infrastructure in Major Cities only deal with water supply infrastructure. Stormwater collection/drainage, waste water treatment and water supply for agriculture are not considered in this assessment.

- The storylines and analysis are for capital cities and surrounding areas where the majority of Australia’s population reside.

- The analysis has assumed that progressively over time for the drying scenarios, and immediately for the cities facing immediate water supply stress, additional water to meet demand will be generally provided through ‘new water sources’ such as desalinisation and recycling. These water sources are climate independent and hence more secure. It is also assumed that ‘new water sources’ have higher operating and capital costs and hence would represent a larger economic shock.

- The analysis has not sought to consider the impacts that the introduction of an emissions trading system may have on the cost of electricity inputs to the water supply industry.

Climate

- Increase in temperature and heat waves will impact peak water demands.

- Increased climatic variability means that urban water suppliers need to consider not only rain dependent supply options, but also non-rain dependent options such as desalination.

- A warmer climate, with its increased climate variability, will increase the risk of both floods and droughts (IPCC, 2007a).

- The number of extreme drought events per 100 years and mean duration of drought conditions are likely to increase by factors of two and six, respectively, by the 2090s (IPCC, 2007a).

- The most dominant climatic drivers for water availability are precipitation, temperature and evaporative demand (IPCC, 2007a). The most dramatic climatic impact will be reduced rainfall. Where an increase in evaporation and a decrease in rainfall occur together, there will be a greater magnitude of impact.

- The choice of climate scenario dictates the estimate of the system yield, which in turn dictates the required additions to supply and therefore levels of forward capital and operating expenditures and ultimately the level of the volumetric charge of the tariff (Marsden Jacob Associates, 2006).

- Higher water temperature and variations in runoff are likely to produce adverse changes in water quality (IPCC, 2007a), installation of different/new treatment technologies and higher operational costs because of a greater power usage to run them.

- Change in seasonality will also be a factor, particularly in areas with storage relying on higher summer rainfall (one-year capacity storages).

- Decreased soil moisture will lead to decreased run off and lower storage. The size of the rainfall event needed to top up storage is larger when there is decreased soil moisture.
Supply

- All capital cities with the exception of Darwin and Hobart now have inadequate water supplies and most are relying on increasingly severe restrictions to balance demand and available supply. Significant investment in water conservation and new water supplies are required (Marsden Jacob Associates, 2006).

- For Australia’s coastal cities, an extensive array of additional water supply and demand management options are available which potentially allows diversification of supply against climate variability and climate change (Marsden Jacob Associates, 2006).

- For Australia’s major inland cities and towns, some of which are facing the most severe drought in the country, in recorded history, recycled water and purchase of irrigation entitlements may be among the few alternative water supplies available (Marsden Jacob Associates, 2006).

- Limited augmentation will occur through the development of new dam infrastructure, since the easy sites have already been developed. This option is also limited due to environmental concerns over new dams and is not climate independent.

- There is some potential for cities to purchase water entitlements from irrigators. Significant trades have already occurred in Adelaide and Perth, but have, to date, been excluded as a matter of policy for other capital cities (Marsden Jacob Associates, 2006).

- As emphasised by the National Water Commission in its June 2006 report to CoAG, all feasible water supply options should be on the table for consideration. The Wentworth Group of Concerned Scientists endorse a similar view, stating that there is now a need to ‘accept that desalination, potable reuse, and recycling and urban-rural trade are all legitimate options for our coastal cities and often better options than building new dams and damaging more coastal rivers.’ (Marsden Jacob Associates, 2006).

- Choice of additional water supplies and demand management measures involves more than comparison of unit costs. In times of uncertainty and increased risk, ‘security through diversity’ and rainfall independent sources are potentially powerful criteria supplementing a triple bottom line assessment (Marsden Jacob Associates, 2006).

- A managed risk approach will be necessary to reduce the potential for water supply disruptions—reduced reliance on surface water sources (which is currently predominant for all capital cities with the exception of Perth).

- As soil moisture progressively declines in catchments, the relative size of a rainfall event required for inflows into surface water storages increases.

- Progressively water supply managers will make greater use of seasonal forecasting to trigger and relieve water use restrictions.

Infrastructure responses over time

- In the next two to three decades it is anticipated that operational and maintenance costs of existing water supply infrastructure will generally increase by a moderate amount attributable to increased materials degradation and reduced life spans of water supply infrastructure.

- Mid-century operational and maintenance costs should decline as new planning and engineering standards will be applied to new infrastructure. This is because a degree of adaptation to the new climate will have occurred, specifically technological development and standards will have been modified to reflect the new climate and aging assets will have been replaced.

- By end-century the operational and maintenance costs should start to increase again as infrastructure developed mid-century comes towards the end of its design life.

- Impacts on capital costs are largely attributable to additional infrastructure required to both diversify water sources and build resilience through the delivery on climate independent sources.
The capital costs for ‘new’ water sources will reduce over time because of ‘learning by doing’ and economies of scale resulting from a high level of ‘new’ water infrastructure development reducing their relative cost. Also any development of new ‘traditional’ water sources (i.e. dams) will occur in locations that are more technically and environmentally challenging, hence increasing their relative costs. Any climate change driven increase in water supply infrastructure (new or traditional) will have a significant economic impact.

- The cost of traditional and renewable energy sources will tend to equalise over time as a national emissions trading scheme develops making renewable energy sources more cost competitive—so operational costs of desalination will moderate as renewable energy become more cost competitive. This will be enhanced as technological advancement means that progressively less power is required to produce a unit of water. No assumptions and/or considerations have been made or taken with respect to the impacts on capital cost equalisation.

- The need to produce the same goods and services with less water will positively influence productivity—less water used to produce a given output even if the water is more expensive than currently.

- From a productivity perspective it is anticipated that the demand to deliver ‘new’ water sources relatively quickly in a number of the population centres will result in a productivity loss initially. But over time, and consistent with the current trend, the water industry will be able to deliver a unit of water more cheaply and hence represent an overall gain in productivity.

- Capital expenditure is anticipated to be the area in which the greatest degree of economic ‘shock’ is experienced initially across the majority of the population centres being considered. For the centres with high levels of ‘shock’ this will be an ongoing situation. This is a result of water supply authorities having to, and relatively rapidly, deploy infrastructure to deliver ‘new’ sources of water to meet the shortfall between supply and demand as impacted by the combined effects of climate change, economic development, population and demographic change.

- Operational expenditure is anticipated to increase between 10% and 20% over twenty to thirty years as the operational life of existing assets is reduced due to degradation caused by the early impacts of climate change. Progressively, the relative impact of this should diminish as the impacts of climate change are considered in new engineering/design standards and life-cycle analyses. However, increased extreme events will increase operational expenditure for scenarios that are expected to experience significant increase in extreme events.

**Correlated impacts**

- Reduction in water supply is likely to have flow on effects to electricity distribution.

- Reduced water supply may impact the profitability of certain industries.

**Further research**

- Research and modelling of the impact of carbon trading on operational expenditure of desalination and water recycling operations is required to better inform estimates of future operational expenditure for the water supply industry for major cities.

- Climate change will affect groundwater recharge rates. However, knowledge of current recharges and levels is poor. There has been very little research on how the impacts of climate change will impact the relationship between surface waters and aquifers that are hydraulically connected (IPCC, 2007a).

- Variation in costs from location to location impedes simple understandings of comparative costs. This means that solutions appropriate to one area may be inappropriate to another and that options favoured by popular opinion may not always be cost effective. This issue appears particularly relevant to popular supply options such as recycling or rainwater tanks (Marsden Jacob Associates, 2006).
Further research and development is required to better link hydrological analysis and assessment models with climate change projects and seasonal forecasting so as to provide a better tool for forecasting short and long-term water supply yields.

2.5 Port infrastructure and operations

As an island nation, Australia is reliant on its broad range of port facilities in every state and the Northern Territory for a significant portion of its international trade. The ports range greatly in their type, volume and level of activity. Melbourne and Sydney ports handle the greatest value of throughput annually. Western Australia and Queensland have a range of bulk port facilities that handle significant volumes of material (from 19 million tonnes to 110 million tonnes across various ports) annually. Figure 17 illustrates the location of Australian Ports and the type and volume of material handled.

Figure 16  Container port, Sydney, NSW

Figure 17  Map of Australian ports by cargo type

Source: Prepared by Urban Systems Programs of CSIRO Sustainable Ecosystems for Garnaut Climate Change Review 2007
Figure 18 outlines the impact storyline identified for port infrastructure. This storyline was assessed against climate conditions considered in the seven climate scenarios U1, U2, U3, M1, M2, M3 and M4 to develop the matrix of impacts.

Figure 18  Impact storyline for port infrastructure

<table>
<thead>
<tr>
<th>Climatic Variables</th>
<th>Impacts</th>
<th>Implications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increase in intensity of cyclones and areas exposed to cyclones</td>
<td>Increased number of extreme events including cyclones, hot days, rainfall and wind</td>
<td>IMPLICATIONS CONSIDERED IN ECONOMIC IMPACTS</td>
</tr>
<tr>
<td>Increase in extreme rainfall and wind</td>
<td></td>
<td>• Increased frequency and length of port closures leads to reduction in port through-put and decreased productivity</td>
</tr>
<tr>
<td>Increase in sea level</td>
<td></td>
<td>• Increased maintenance, repair and replacement of port infrastructure due to extreme events (flooding, extreme wind)</td>
</tr>
<tr>
<td>Increase in temperature</td>
<td></td>
<td>• Increase in preventative expenditure on measures to mitigate sea level rise</td>
</tr>
<tr>
<td>Increase in number of hot days</td>
<td></td>
<td>• Increased property damage</td>
</tr>
<tr>
<td>Increase in ocean swell</td>
<td></td>
<td>• Corrosion</td>
</tr>
<tr>
<td>Increase ocean acidification</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The climate change impacts on port infrastructure and operations storyline uses projections from the 'current' climate, given an assumed greenhouse gas emission trajectory, climate sensitivity and probability of change.
Case study: Tropical cyclones, Port Hedland, Western Australia, 2007

This case study describes how tropical cyclones can impact port operations and infrastructure.

Port Hedland is located in the Pilbara region in northern Western Australia and is one of Australia’s largest tonnage export ports (PHPA, 2007). From January to March 2007, the Port Hedland region was hit with four tropical cyclones (TCs). All TCs formed off the coast of Western Australia, however only TCs George, Jacob and Kara crossed the mainland. TC Isobel was a Category 1 and TCs Jacob and Kara were Category 3. Of the four, TC George was considered very intensive and physically large; it was the most destructive cyclone to affect Port Hedland since 1975 (BOM, 2007 p1). TC George intensified to a Severe Tropical Cyclone (Category 3) on the evening of 7 March 2007 and reached Category 5 as it approached the coast (BOM, 2007 p1).

These four cyclones caused significant impacts on port operations and infrastructure at Port Hedland. The port was closed to all vessels for a total of 146 hours due to these tropical cyclones (PHPA, 2007, p 21). The table below shows how the four tropical cyclones affected port operations in 2007.

<table>
<thead>
<tr>
<th>Cyclone</th>
<th>Date</th>
<th>Total hours of operation affected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isobel</td>
<td>2 January 2007</td>
<td>26</td>
</tr>
<tr>
<td>George</td>
<td>8 March 2007</td>
<td>100</td>
</tr>
<tr>
<td>Jacob</td>
<td>12 March 2007</td>
<td></td>
</tr>
<tr>
<td>Kara</td>
<td>27 March 2007</td>
<td>20</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>146</td>
</tr>
</tbody>
</table>

Source: (PHPA, 2007)

NOTE: TC George and Jacob are separate events however the port did not open or resume operations between these two cyclones.

In addition to closing the Port for four days, the Port infrastructure itself sustained minimal damage in the form of roof sheeting and wall panel damage to some sheds and buildings with minor fence and vegetation damage as a result of TC George (PHPA, 2007, p 21).

The overall insurance cost of TC George alone was $8 million (EMA, 2007). The cost on commercial and industry has not been estimated.
Figure 19 outlines the economic impacts for each state, across the seven climate scenarios and three time periods.

### Figure 19  Port infrastructure and operations—Matrix of Impacts

<table>
<thead>
<tr>
<th>Climate Scenario</th>
<th>U1</th>
<th>U2</th>
<th>U3</th>
<th>M1</th>
<th>M2</th>
<th>M3</th>
<th>M4</th>
</tr>
</thead>
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<td>M</td>
<td>M</td>
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<td>L</td>
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<tr>
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NOTE: The impacts for ACT are not applicable (N/A) as it is an inland location and therefore does not have ports. Refer to Table 7 for an explanation of the impact criteria.

### Climate change scenario storylines

**Business as usual scenarios**

The business as usual climate change scenarios provided by the CSIRO on behalf of the Garnaut Climate Change Review Secretariat and considered in the port infrastructure storyline are discussed in turn below.
U1: Hot, dry reference scenario—A1FI emissions path, 3°C climate sensitivity, 10th percentile rainfall and relative humidity surface for Australia (dry extreme), 90th percentile temperature surface. Mean global warming reaches 4.5°C in 2100.

This scenario adopts a ‘business as usual’ approach to greenhouse gas emissions and assumes the highest level of temperature increase, along with the greatest decline in rainfall and relative humidity.

From a port infrastructure perspective this scenario is expected to result in low to moderate economic impacts by 2030, moderate to high impacts by 2070 and moderate to extreme impacts by 2100 depending on the region considered. This is due to a combination of impacts on:

- port operations—resulting from increased downtime leading to impacts on productivity and operational expenditure
- port infrastructure—resulting from accelerated asset deterioration leading to impacts on operational and capital expenditure.

Port operations are affected by extreme climatic events such as cyclones and to a lesser extent ocean swell, extreme wind and increased temperature. Extreme weather events can lead to port downtime causing loss in productivity and increases in operational expenditure.

The level to which ports are affected by extreme climatic conditions is strongly correlated with port type (exposed/sheltered, bulk/container) and location; as well as intensity and frequency of extreme events. Container ports tend to be located in sheltered harbour locations, close to population centres. Bulk ports are more likely to be located on open-ocean, in locations with good proximity to the production and transportation of the bulk commodities.

Ports located in cyclone prone areas, such as northwest Western Australia, the coast of the Northern Territory and the Queensland coast are already affected by downtime associated with cyclones (See Figure 37, Appendix A). Climate change is expected to exacerbate this. Port closure due to cyclones can occur due to a direct cyclone hit or a ‘near miss’ event in which the cyclone passes through an area designated in a specific port’s emergency management plan calling for a shut down. For example, some ports require closure should a cyclone occur within a 300km radius of the port. Cyclone intensity and location is expected to change in Queensland and Western Australia between 2031 and 2070 with cyclones migrating further south along the east and west coast of Australia. This modelled change includes the area around Brisbane (CSIRO, 2007), which is not currently affected by cyclone events. This is anticipated to lead to a high level of impact on port operations in Queensland between 2031 and 2070 leading to reduced productivity. In addition cyclones may also cause damage to port infrastructure leading to costs associated with repairs.

It is anticipated that climate change will also lead to an increase in severe storms. CSIRO (2007) estimates that climate change may lead to a 60% increase in intensity of category three to five severe storms by 2030 and 140% increase by 2070. This is not an expectation exclusive to the U1 scenario but can be used as a guide. Ocean exposed ports (i.e. no harbour) such as Fremantle on the southwest coast of Western Australia are susceptible to increases in ocean swell. Projected increase in the frequency and severity of storms off the coast may lead to increased swell; these conditions will result in downtime at exposed ports.

Projected increased frequency of storm events and intensity in storms located on the coast may lead to increased local storm surge; the effects of this may be exacerbated over time due to rising sea levels. Severe storm surge has the potential for inundation of ports. Applying a mid-range IPCC estimate of sea level rise of 20cm and a projected increase in cyclone intensity, a 1:50 year storm surge event will produce sea level height of 2.4m, compared to 2m (McInnes et al, 2003). Inundation events would result in both port shutdown and likely damage to infrastructure. Extreme weather events may also lead to infrastructure damage increasing capital expenditure associated with replacement and operational expenditure associated with maintenance.

An increase in maximum temperature (hot days) associated with the U1 scenario may lead to reduced port productivity associated with lost work time due to increased number of hot days. Typically in
Australia stevedores\(^2\) stop work at 38°Celsius. They then stand-by until the temperature drops below 38°Celsius to resume working. The U1 model shows a small increase in the number of days over 38°Celsius across the majority of Australian capital cities in 2030. This increase will have minimal to no impact on productivity by 2030.

However, the number of hot days exceeding 38°Celsius increases dramatically by 2070 in areas such as Western Australia and the Northern Territory resulting in losses in productivity. By 2100 the number of days exceeding 38°Celsius has risen significantly in a number of areas. The most extreme is Darwin which goes from zero days above 38°Celsius in 2007 to almost 200 days over 38°Celsius in 2100. It is estimated that the percentage increase in port revenue loss associated with hot days only, in Darwin will be 2% between 2030 and 2070 and 88% between 2070 and 2100. However, as port closure increases due to hot days, it is expected that additional capital and operational expenditure will be used to reduce port down time through air conditioning and additional compensation for workers.

Port downtime will result in various flow on economic impacts including costs associated with the backlog of ships waiting to enter or leave the port, costs associated with providing assistance to vessels caught up in storm events and broader economic impacts on port reliant businesses, freight transport networks and consumers.

Port infrastructure can also be degraded by changes in climate variables not associated with extreme events. An increase in temperature associated with U1, in conjunction with projected sea-level rise and increased ocean acidification will exacerbate corrosion of infrastructure leading to increased maintenance and replacement costs. The typical design life for port infrastructure is approximately 40 years. The service life of infrastructure has already been observed to be reducing by between 10% and 20% due to climatic changes (Dacre 2007).

Large high value through-put ports such as those in Melbourne and Sydney are expected to outlay higher capital expenditure between 2031 and 2070 to upgrade and replace infrastructure to combat these impacts, while smaller ports such as Adelaide are expected to spend less up-front on replacement and rely on increased maintenance.

Key commodities handled by Australia’s bulk ports include coal, bauxite, iron ore, aluminium and salt. The handling (loading and unloading) of bulk commodities is impacted by moisture content, as is the potential for perishable commodities to spoil. Moisture content of bulk commodities may be affected by climatic changes. In U1 an increase in average annual temperature, accompanied by reduced relative humidity may mean that bulk port commodities become too dry for transferring between land and ships. This may mean bulk commodities need to be wetted down to replace moisture content to facilitate loading/unloading.

\textbf{U2: Best estimate (median) business as usual scenario using A1FI emissions path, 50th percentile rainfall and relative humidity surface for Australia, 50th percentile temperature surface. Mean global warming reaches \textasciitilde4.5°C in 2100.}

This scenario is most closely related to U1 due to the modelled reduction in rainfall. However, the drying and humidity is less extreme than U1 as is the temperature increase. The temperature increase and evaporation is the same as U3.

The U2 scenario, similarly to the U1 scenario, is expected to experience an increase in extreme events which is a key influencing factor on port operations. Temperature is a key driver of extreme weather events. As the expected increase in temperature under U2 is similar to that of U1 up to 2030. During the remainder of the century the spread of the impacts is anticipated to be similar to U1 although the magnitude or severity is anticipated to be less than U1.

Increased cyclone intensity and movement south along the Queensland and Western Australian coastline, under the U2 scenario, will lead to a high level of impact on port operations in these states.

\(^2\) Workers employed to load and unload ships
between 2071–2100 leading to reduced productivity and additional damage and repairs of port infrastructure.

Similarly to the U1 scenario it is expected that climate change will lead to an increase in severe storms under the U2 scenario. This means that ocean exposed ports will increasingly be subject to increased swell, resulting in port downtime. The projected increase in storm events may lead to increased storm surges. Studies by McInnes et al. (2006) illustrate that the combination of storm surges and gradually rising sea levels has the potential to cause extensive inundation and coastline change.

The increase in temperature associated with the U2 scenario may lead to significantly reduced port productivity by 2100 associated with lost work time due to an increase in the number of days over 38°C.

Port infrastructure can also be degraded by changes in climate variables not associated with extreme events. Similarly to the U1 scenario, an increase in temperature in conjunction with projected sea level rise and increased ocean acidification will exacerbate corrosion of infrastructure leading to increased maintenance and replacement costs.

The temperature increase associated with U2 scenario and the associated reduced relative humidity may mean that bulk port commodities may become too dry to be transferred between land and ships. This may lead to additional operational expenditure. This may mean bulk commodities need to be wetted down to replace moisture content to facilitate loading/unloading.

**U3:**  
*Warm, wet business as-usual scenario under A1FI emissions path, 90th percentile rainfall and relative humidity surface for Australia (wet extreme), 50th percentile temperature surface. Mean global warming reaches ~4.5°C in 2100.*

This scenario adopts a ‘business as usual’ approach to greenhouse gas emissions, and statistically it assumes the most likely level of temperature increase, along with the greatest increase in rainfall and relative humidity.

Depending on the region considered, this scenario is expected to result in moderate to high economic impacts up to 2070 and moderate to extreme impacts by 2100 on port operation and infrastructure. From a port infrastructure perspective, U3 is considered to be the ‘worst-case’ of the seven climate scenarios considered.

The warm-wet climate conditions associated with U3, particularly on the eastern seaboard and northern regions suggests more tropic-like prevailing conditions in Australia. Potential increases in cyclone range and intensity may be greater compared to the U1 scenario, with subsequent increases in port closures compared to U1 due to cyclones hitting ports and near-misses. As with U1 ports in Queensland, northern Western Australia and the Northern Territory are likely to be the most affected.

In addition wetter conditions are expected to be associated with more severe storms leading to increased swell and storm surge again impacting on port downtime. Increased downtime will lead to reduced productivity and increased operational expenditure associated with longer ship delays, backlogs on freight transport networks, costs associated with increased storage times and costs associated with protecting and freeing stranded ships.

As in U1, the projected increased frequency of storm events and intensity in storms located on the coast may lead to increased local storm surge; the effects of this may be exacerbated over time due to rising sea levels. As U3 is characterised with lower average annual temperatures compared to U1, sea level rise in U3 may be less. Increased cyclone and severe storm activity expected under U3 will also lead to increased operational and capital expenditure associated with infrastructure maintenance and replacement.

As stated previously, stevedores in Australia typically stop work at 38°Celsius. While U3 follows a similar trend to U1 with a small increase in the number of hot days above 38°Celsius between now and 2030, and then a dramatic increase in hot days above 38°Celsius in 2070 and beyond the overall
number of hot days in U3 is significantly lower than U1. Therefore the amount of downtime attributed to hot days will be less in U3 compared to U1.

Moisture content of bulk commodities may be affected by climatic changes, such as an increase in average annual temperature, accompanied by higher rainfall levels, more intense rainfall, and higher humidity associated with U3. While in U1 a reduction of moisture may affect the transport of bulk commodities due to bulk commodities drying out, in U3 extensive rainfall and increased relative humidity may result in bulk commodities becoming too wet. Impacts on the transport of bulk commodities due to changes in moisture content are expected to be greater under U3 than U1.

An increase in temperature, rainfall and relative humidity associated with U3 accompanied by sea level rise and increased ocean acidification will exacerbate corrosion of infrastructure leading to increased maintenance and replacement costs. Lower temperatures and potentially smaller sea level rise in U3 in comparison than U1 may reduce this corrosion affect. However this would probably be offset by higher humidity and rainfall, with an overall net increase in corrosion in U3 compared to U1.

**Strong mitigation scenarios**

The climate change scenarios with a policy intervention provided by CSIRO on behalf of the Garnaut Climate Change Review Secretariat and considered in the port infrastructure storyline are discussed in turn below.

**M1:** Dry mitigation scenario where stabilisation of 550ppm CO₂ equivalent (CO₂stabilised at 500ppm) is reached by 2100, 10th percentile rainfall and relative humidity surface for Australia (dry extreme), 90th percentile temperature surface. Mean global warming reaches ~2.0°C in 2100.

This scenario adopts a policy intervention that leads to a greenhouse gas emissions trajectory that stabilises atmospheric greenhouse gas concentrations at a level that constrains the temperature increase to 2.0°C in 2100; as compared to 4.5°C in 2100 under the business as usual scenario U1.

Under this scenario, the CMAR climate modelling indicates that changes in rainfall (decline), humidity (decline), temperature (increase) and evaporation (increase) are anticipated to be marginally greater than U1 at 2030. However the temperature and rainfall changes modelled in U1 significantly outpace the M1 scenario after this time period. From the middle of the century the M1 temperature and rainfall changes begin to level out. The M1 temperature increases at 2100 are reached in the middle of the century under the U1 scenario. The temperature and rainfall changes for M1 are approximately 55% of the U1 changes at 2070 and 40% of U1 at 2100.

Depending on the region considered, this scenario is expected to result in low to moderate economic impacts by 2030, moderate impacts by 2070 and low to moderate impacts by 2100 on port operation and infrastructure.

As in U1, scenario M1 is associated with an increase in annual average temperature which is anticipated to result in an increase in intensity and southern migration of cyclones in the northern regions of Australia. However the rate of global warming in scenario M1 is significantly less than in U1 by 2070 leading to less intense cyclones and storms than U1. Impacts on productivity in cyclone prone areas such as tropical Queensland and Western Australia are expected to be low in 2030, gradually increasing disruption in port operations up to 2070 and 2100.

An increase in temperature associated with scenario M1, in conjunction with projected sea level rise and increased ocean acidification will exacerbate corrosion of infrastructure leading to increased maintenance and replacement costs. As with U1 and U3, large ports such as Melbourne and Sydney are expected to outlay higher capital expenditure between 2031 and 2070 to upgrade and replace infrastructure to combat these impacts, while smaller ports such as Adelaide, Darwin and those in Tasmania are expected to spend less up-front on replacement and rely on increased maintenance. In the 2071–2100 time period, the impacts to South Australia and Tasmania are likely to reduce as the previous capital investment compensates for the changes in climate. The driver for capital investment is likely to be the combined effect of increases in maintenance costs, increases in failure of assets and reduced life expectancy of assets.
**M2:** Best estimate (median) mitigation scenario where stabilisation of 550ppm CO$_2$ equivalent (CO$_2$ stabilised at 500ppm) is reached by 2100, 50th percentile rainfall and relative humidity surface for Australia, 50th percentile temperature surface. Mean global warming reaches ~2.0°C in 2100.

The modelled M2 climate changes are similar to the U2 climate changes. The climate models provided by CMAR indicated that for the M2 scenario, the changes in rainfall (decline), humidity (decline), temperature (increase) and evaporation (increase) are anticipated to be marginally greater than U2 at 2030. From the middle of the century the M2 temperature and rainfall changes begin to level out. However the temperature and rainfall changes modelled in U2 significantly outpace the M2 scenario after this time period. The M2 temperature increases at 2100 are reached in the middle of the century under the U2 scenario. The temperature and rainfall changes for M2 are approximately 55% of the U2 changes at 2070 and 40% of U2 at 2100.

Scenario M2 is expected to result in low to moderate impacts across all time periods on port operation and infrastructure. As with the six climate scenarios Western Australia, the Northern Territory and Queensland port operations will be effected by increased cyclone intensity and severe storm activity, with the magnitude of impacts increasing over time. However, it is anticipated that scenario M2 will be associated with less intense cyclones and severe storms compared to the other scenarios (with the exception of M4) and therefore impacts on downtime and productivity associated with these events are anticipated to be less.

Impacts on port downtime associated with increased hot days will be minimal. Likewise impacts on bulk commodities due to changes in moisture content will be much smaller than for the other scenarios (with the exception of M4).

An increase in temperature, rainfall and relative humidity associated with M2, accompanied by gradual sea level rise and increased ocean acidification will exacerbate corrosion of infrastructure leading to increased maintenance and replacement costs. Once again these affects are likely to be smaller for M2 compared to the other climate scenarios (excluding M4), with moderate impacts on capital and operational expenditure expected by 2100.

**M3:** Wet mitigation scenario where stabilisation of 550ppm CO$_2$ equivalent (CO$_2$ stabilised at 500ppm) is reached by 2100, 90th percentile rainfall and relative humidity surface for Australia (wet extreme), 50th percentile temperature surface. Mean global warming reaches ~2.0°C in 2100.

This scenario adopts a policy intervention that leads to a greenhouse gas emissions trajectory that stabilises atmospheric greenhouse gas concentrations at a level that constrains the global temperature increase to 2.0°C in 2100; as compared to 4.5°C in 2100 under the business as usual scenarios U1, U2 and U3.

The climate models provided by CMAR indicated that under this scenario, the changes in rainfall (decline), humidity (decline), temperature (increase) and evaporation (increase) are anticipated to be marginally greater than U3 at 2030. However, the temperature and rainfall changes modelled in U3 significantly outpace the M3 scenario after this time period. From the middle of the century the M3 temperature and rainfall changes begin to level out. The M3 temperature and rainfall increases at 2100 are reached in the middle of the century under the U3 scenario. The temperature and rainfall changes for M3 are approximately 55% of the U3 changes at 2070 and 40% of U3 at 2100.

The M3 scenario is expected to result in moderate to high economic impacts up to 2070 and low to high impacts by 2100 on port infrastructure and operations depending on the region considered.

As in U3, scenario M3 is associated with an increase in annual average temperature and rainfall which is anticipated to correlate with an increase in intensity and southern migration of cyclones in the northern regions of Australia. However, global warming in M3 is significantly less than in U3 leading to comparatively reduced intensity of cyclones and storms. Impacts on productivity in cyclone prone areas such as tropical Queensland and Western Australia are expected to be low in 2030, with increasing disruption in port operations in 2070 and 2100.
Impacts on productivity due to hot days exceeding 38°Celsius are reduced in comparison to U3. Compared to U3, scenario M3 will have less impact on corrosion of infrastructure but will still lead to increased maintenance and replacement costs due to an increase in temperature, rainfall, relative humidity, gradual sea level rise and ocean acidification. The impacts on New South Wales and Victoria are likely to scale back in the last quarter of the century as capital investment compensates for the changes in climate.

**M4:** Best estimate (median) strong mitigation scenario where stabilisation of 450ppm CO₂ equivalent (CO₂ stabilised at 420ppm) is reached by 2100, 50th percentile rainfall and relative humidity surface for Australia), 50th percentile temperature surface. Mean global warming reaches ~1.5°C in 2100.

This scenario is the ‘best-case’ of the group of scenarios assessed. The temperature and rainfall changes are modelled to stabilise around 2080 and begin to reverse toward 2100 therefore reducing the pressures generating increased storm related impacts. Of the scenarios that result in a decline in rainfall and relative humidity (scenarios U1, U2, M1, M2 and M4), this scenario would have the least impact on climate change induced storm, flooding and extreme heat impacts.

This represents the most aggressive of the policy interventions from a greenhouse gas emissions reduction perspective, resulting in the lowest level of temperature increase, and consequently the lowest degree of change in rainfall and relative humidity when assessed on a per degree of global warming scale.

Scenario M4 is expected to result in low to moderate impacts across all time periods on port operations and infrastructure depending on the region considered. From a port infrastructure and operations perspective, this is considered to be the ‘best case’ for ports. The initial impacts are likely to be similar to that of U1 at 2030. It is anticipated that the impacts will be of a similar magnitude and distribution across capital cities up to 2070 and then ease after this time as the climate changes plateau.

**Key assumptions**

- Cyclones have been included in the consideration of economic impacts for ports infrastructure.

- The intensity and location of cyclones are important factors affecting port downtime. It is assumed that climate change will exacerbate the effects of cyclones on ports and that the seven climate scenarios will affect ports due to cyclone events (from largest to smallest impacts) in the following order: U3, U1, M3, U2, M1, M2, and M4. Information and assumptions relating to cyclone events affecting ports in Australia are as follows:
  - From discussions with Geoscience Australia working on cyclones for the Garnaut Review, the average number of cyclones in Australia is 5.5 per year based on 1990 to 2005 data. These are distributed around the coasts of Queensland, northern coast of Western Australia and the Northern Territory. Ports affected include Townsville, Darwin, Dampier and Port Hedland;
  - In northeast Australia it can be assumed for all scenarios that by 2030 cyclone events will have extended lives and increased intensity. This intensity will continue to increase as temperature increases by 2070 and 2100. In addition there is expected to be an extension in the southern range leading to potential cyclone impacts in Brisbane;
  - The increase in the frequency of cyclones is uncertain and so no increase in events have been taken into account in this assessment; and
  - Typically a cyclone, regardless of category, occurring within a radius of 300 km or a port will result in port downtime of up to 48 hours per event.

- An increase in hot days will result in stevedores stopping work more frequently and for longer periods of time. Australian port operators must instruct stevedores to stop work at 38°Celsius. It is assumed that the 38°Celsius threshold is reached for 4 hours of each hot day recorded in the
climate models. Should days over 38°Celsius become a regular occurrence at a port, it is assumed that investments in capital and operational expenditure would be made over time in order to make use of alternative operational procedures.

- Moisture content is a limiting factor for some bulk commodities. The increase in temperature in U1 may dry out some stock piled commodities too much and moisture may need to be added to facilitate loading/unloading. The increase in rainfall associated with U3 may lead to moisture sensitive stockpiled commodities becoming too wet to be loaded or unloaded.

- Port infrastructure is vulnerable to corrosion associated with increased ocean acidification, sea level rise and increased temperature.

- An approximate asset life of 40 years has been attributed to port infrastructure. The asset life of port infrastructure is currently decreasing by 10% to 20% (Dacre, 2007). Depreciation of port assets is closely correlated with this reduction in asset life.

- Sea level rise and increased storm surge make existing sea wall protection less effective and prone to failure. Sea walls protecting ports are designed for certain sea/storm surge levels. As sea levels go up, increases in operational delays and usage are expected.

- Large ports with high value through-put such as Melbourne and Sydney will invest in infrastructure upgrades to address potential climate change impacts sooner than smaller, operating ports. Smaller ports will rely on maintenance in the first instance.

- Port infrastructure built in the past ten years or by current design standards will require replacing around 2030. This renewal will likely incorporate design to reduce on-going maintenance costs and to overcome any decrease in asset service life. Maintenance costs will then normalise. By 2070 for climate scenarios U1, U3, U2 and M3, infrastructure life will again be likely to deteriorate therefore increased expenditure on maintenance and capital expenditure will be required. Design and construction techniques will likely adapt with climatic changes. Maintenance will again normalise and capital expenditure will reduce. This cycle will continue to repeat itself up until 2100 in U1 and U3 as climatic conditions continue to shift.

**Correlated impacts**

- The through-put of ports is directly correlated with the availability of commodities. Disruptions to mining, agriculture or other sectors related to port imports and exports will result in impacts on port through-put and therefore value. Conversely port downtime may affect markets such as agriculture and mining. These impacts have not been included in this assessment.

- Port downtime may have flow on implications for freight transport networks. This needs to be considered when assessing the impacts of climate change on transport.

- Offshore infrastructure such as oil rigs are susceptible to changing climatic conditions. An increase in storm intensity may lead to damage to offshore infrastructure damage while additional costs may be associated with improving structure reinforcement (preventative), increased maintenance, rebuilding and down time. Impacts to offshore infrastructure such as oil rigs have not been incorporated in this assessment due to time constraints.

- Insufficient drainage capacity around port areas and increased potential for flooding may result in damage to commodities stored at ports.

- Impacts on ports will have flow on effects on recreational and commercial fishing. Fishing may be impacted because the fishing fleet may not be able to leave port due to extreme climatic conditions and disruptions in port operations may effect fishing operations.
Further research

- Extreme wind events may affect the loading and unloading operations of any port, regardless of whether the port is located within or outside a harbour. The maximum wind speed for crane operation is typically 36km/hour (Mobile Crane Code of Practice 2006 Queensland Government). If this threshold is exceeded then loading and unloading of cargo will stop until extreme conditions have passed. Increased wind speeds will likely increase service disruption unless advances in weather proof loading/unloading can be developed. The necessary data for assessing frequency of future extreme wind events requires further modelling in order to determine smaller scale systems such as intense convective events (e.g. those associated with tropical storms) and frontal activity or low pressures systems further south (CSIRO 2007).

- As stated above key commodities handled by Australia’s bulk ports include coal, bauxite, aluminium and salt. The handling (loading and unloading) of bulk commodities is impacted by moisture content, as well as the potential for perishable commodities to spoil. The change in moisture content of key commodities due to climate change is currently unknown and requires further investigation.

- The maximum temperature thresholds for the loading, unloading and transporting of livestock requires further investigation.

- Assumptions regarding change in frequency of cyclones associated with climate change are not well understood. Therefore, there is a significant level of uncertainty in determining the impacts of cyclones on ports due to climate change. Further investigation into the change in the frequency of cyclones due to climate change is required.

- Further studies to model the climate change impacts on swell for various regions are required to assess impacts on offshore infrastructure such as oil rigs.
3  Topics for further exploration

3.1  Sea level rise

Oceans are a central part of the global climate system. Sea level rise is one of the many important variables used to understand and correctly project the future consequences of climate change. The world’s oceans absorb carbon dioxide naturally from the atmosphere. During the 20th century, global average sea level rose between 10 and 20 centimetres (Weller, 2005—ACIA article). Over the next 100 years, sea level is expected to continue to rise due to the warming from 20th and 21st century greenhouse gas emissions. Ocean thermal expansion will likely dominate global sea level rise in the 21st century. It has been noted that present-day observations of Greenland and Antarctica show increasing surface melt, loss of buttressing ice shelves, accelerating ice streams and increasing overall mass loss (Hansen et al, 2008). Based on these findings, melting of glaciers, polar ice caps and ice sheets will be the next largest contribution to global sea level rise.

This chapter outlines the predictions of sea level rise globally and for Australia. It also addresses the consequences of increased sea levels on each of the four infrastructure areas: buildings and port, electricity and water infrastructure. The impacts of sea level rise for each infrastructure type are discussed separately here, but in reality sea level impacts are interlinked.

Sea level rise predictions

In a U1 scenario, sea level rise is expected to be gradual with a 17 centimetre increase by 2030 and 50 centimetre increase by 2070 (CSIRO 2007; Hennessy et al, 2006).

The Intergovernmental Panel on Climate Change’s (IPCC) Fourth Assessment Report estimates that relative to the 1990 level, global average mean sea level is projected to increase by 18 to 59 centimetres by 2100, with a further contribution from ice sheets of 10 to 20 centimetres (CSIRO Technical Report, 2007). This level of sea rise has also been estimated by Weller (2005) in 2005: ‘glacier contributions combined with the effects of thermal expansion, is likely to rise sea levels by 20cm to 70cm by the end of the 21st century’.

The effects of rising sea levels will be vary regionally. In Australia, CSIRO has investigated the spatial pattern of sea level rise in the Australian region for 2070. The oceans surrounding Australia are predominantly influenced by two dominant climate variations: the El Niño – Southern Oscillation (ENSO) and the Southern Annular Mode (SAM). ENSO and SAM are likely to increase the global mean sea level rise, resulting in significant regional variability in the scale and trend of sea level rise in the oceans surrounding Australia (CSIRO Technical Report, 2007). For example, the mean sea level rise for the Bass Strait is projected to increase between three to 17 centimetres by 2030 and 7 to 49 centimetres by 2070 (CSIRO, 2007).

Global climate models indicate that mean sea level rise on the east coast of Australia may be greater than the global mean sea level rise because of the ENSO and SAM climate variations (CSIRO Technical Report, 2007).

Information provided by the GCCR Secretariat indicates that we are committed (Warrick and Rahman, 1992) to an 18cm increase in sea level by the end of the century. Table 8 compares the ‘committed’ sea level rise over this century to the predicted sea level rise under the A1FI climate scenario, which is comparable to the U1 and U3 scenarios. This information is illustrated in Figure 20. Please note that with the exception of A1FI, the other climate models referred to in Figure 20 are not directly comparable to climate scenarios assessed in this report.

A step change in sea level for U1, U2 and U3 due to the extreme temperature rise pressure on land based Antarctica and Greenland ice sheets (Hansen, Sato, Kharecha, Lea, & Siddall, 2007) could potentially occur by 2100. A step change in sea level could range from a 2 to 12 metre rise. The potential for a step change in sea level; this century requires further investigation.
Table 8 Committed and projected sea level rise up to 2100

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Garnaut</th>
<th>2000</th>
<th>2010</th>
<th>2020</th>
<th>2030</th>
<th>2040</th>
<th>2050</th>
<th>2060</th>
<th>2070</th>
<th>2080</th>
<th>2090</th>
<th>2100</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1FI U1&amp;U3</td>
<td>3.0</td>
<td>7.0</td>
<td>9.0</td>
<td>11.5</td>
<td>14.4</td>
<td>17.8</td>
<td>22.3</td>
<td>28.2</td>
<td>35.3</td>
<td>42.0</td>
<td>48.4</td>
<td></td>
</tr>
<tr>
<td>Committed</td>
<td>3.0</td>
<td>6.5</td>
<td>8.0</td>
<td>10.0</td>
<td>11.5</td>
<td>13.5</td>
<td>14.5</td>
<td>15.5</td>
<td>16.5</td>
<td>17.5</td>
<td>18.5</td>
<td></td>
</tr>
</tbody>
</table>

NOTE: Figures (in centimetres). All scenarios level to 1990 sea-level as baseline (0.0)
Source: Church (2008) and (CSIRO, Marine and Atmospheric Research) and (Warrick and Rahman, 1992)

Figure 20 Projected sea level rise 1990 to 2100

Source: Church, Gregory, Huybrechts, Kuhn, Lambeck, Nhuan, Qin, & Woodworth, 2001

Implications of a step change in sea level on infrastructure

Rising sea levels will affect a significant portion of Australia’s building infrastructure along coastal settlements and coastal population. Storm surges occurring on higher mean sea levels will enable inundation and damaging waves to penetrate inland, which would increase coastal erosion, flooding and damage to built infrastructure (CSIRO, 2007, p94).

Over 80% of the Australian population lives within the ‘coastal zone’ (within 50km from the coastline) which has experienced significant growth in recent years. By 2050, ongoing coastal development and population growth in some coastal areas of Australia are projected to intensify risks from sea level rise and increases in the severity and frequency of storms and coastal flooding (IPCC, 2007, p50).

The inundation of areas not previously at risk will likely cause increased damage due to building standards of that infrastructure being at a lower resilience level. In addition, sea level rise to coastal regions is likely to have long term loss of utility to buildings resulting in loss of essential community services, loss property and real estate, damage to recreational infrastructure and coastal infrastructure used for transportation (for instance, roads and ports).

The impact of sea level rise combined with storm surge (less than five metres) will vary across each state and territory. Table 9 provides an estimation of the number and percentage of properties under threat in each state. The impacts for Melbourne and Brisbane are illustrated in Figure 21.
Table 9  Approximate number and percentage of addresses under threat from sea level rise and storm surge

<table>
<thead>
<tr>
<th>State/Territory</th>
<th>Approximate number of properties under threat</th>
<th>Approximate percentage of properties in the state under threat</th>
</tr>
</thead>
<tbody>
<tr>
<td>New South Wales</td>
<td>208,320</td>
<td>6%</td>
</tr>
<tr>
<td>Victoria</td>
<td>83,520</td>
<td>4%</td>
</tr>
<tr>
<td>Queensland</td>
<td>246,720</td>
<td>13%</td>
</tr>
<tr>
<td>South Australia</td>
<td>61,440</td>
<td>8%</td>
</tr>
<tr>
<td>Western Australia</td>
<td>94,080</td>
<td>10%</td>
</tr>
<tr>
<td>Tasmania</td>
<td>17,280</td>
<td>7%</td>
</tr>
<tr>
<td>Northern Territory</td>
<td>17,280</td>
<td>18%</td>
</tr>
<tr>
<td>Australian Capital Territory</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Source: Adapted from McAneney et al (2007) and ABS (2007)

Figure 21  Buildings under threat from sea level rise and storm surge in Melbourne and Brisbane

Coastal electricity T&D infrastructure in Australia will be susceptible to impacts of a step change in sea level rise. Step change in low-lying areas would result in widespread inundation and loss of major coastal T&D infrastructure, such as low-lying substations. Increased storm surges and coastal erosion would also exacerbate the damage to T&D infrastructure. Loss of T&D infrastructure would require relocation and potentially reconstruction of infrastructure assets. In the long term, electricity networks would need re-examination of design standards for transmission and distribution. Sea level rise may also increase maintenance in flooded areas.

The impacts of step change in sea level rise on water supply infrastructure are likely to be minimal. However, capital cities which have significant water supply infrastructure located along coastlines (such as water recycling facilities and desalination plants) may be prone to flooding.

Sea level rise is likely to increase the risk of salination of surface and groundwater sources in coastal areas that may be part of the water supply system, for a city such as ground water currently utilised in Perth.

Extreme impacts to ports would be generated from a step change in sea level rise, leading to extensive inundation and coast line change making the use of current port areas prohibitive and requiring extensive protection and replacement of port assets.
Further research is required to assist adaptation planning to limit the potential impacts to infrastructure from a step change in sea level.

### 3.2 Extreme events

Extreme events or natural disasters cover a variety of event types, principally floods, storms (including hailstorms), cyclones, storm surge, bushfire, earthquakes and landslides. It is projected that climate change will increase the frequency and severity of extreme events or natural disasters.

There are limitations to the information available relating to the type and frequency of extreme events occurring in Australia as well as the associated costs resulting from the events. A report by the Commonwealth Bureau of Transport Economics (CBTE, 2001) titled ‘The Economic Costs of Natural Disasters in Australia’ provides a leading source of information for extreme events. The report defines a natural disaster as ‘any emergency defined by the Commonwealth for the purposes of the Natural Disaster Relief Arrangements (NDRA) which are administered by the Department of Finance and Administration’ (CBTE, 2001 p.xiii). The report only considers disasters with an associated cost impact greater than $10 million.

While the report provides a substantial amount of information on extreme events it states a range of limitations to its findings. The report cautions that the conclusions derived from the data analysis ‘must be interpreted as indicative or approximate only, and any conclusions drawn must be regarded as tentative’ (CBTE, 2001, p.xix). The findings of the report (CBTE, 2001, p.xiv) have been limited by:

- ‘Heavy reliance on media reporting, which limits the accuracy and quality of the database;
- Incomplete datasets. Some of the earlier events that occurred in Australia, especially smaller ones, are not likely to have been recorded, as they were not reported in the media;
- Inaccurate method of estimating multiple insurance costs; and
- Costs not indexed to 1998 dollars. However, low inflation levels experienced over the past three to four years would have had little impact on the cost estimates.’

While the data is limited, the information may provide an indication of the frequency of future events and associated costs. However, it is important to note that the economic costs associated with extreme events needs to be revised with updated understanding of climate change impacts on infrastructure. Further investigation is recommended to determine more accurate economic costs from extreme weather events.

The following subsections (0, 0, 0) provide additional information on past extreme events in Australia and the potential increase in future extreme events.

#### Costs of natural disasters in Australia

Increased frequency and severity of natural disasters from climate change will produce economic impacts. The role of insurance in underwriting weather-related risk is an integral part of Australia’s economy. A report from the Insurance Australia Group (IAG) advised that ‘any reduction in the industry’s availability to underwrite weather-related risk will have serious ramifications for the economies of those vulnerable regions where climate and weather risk is greatest’ (IAG, 2002, p1).

The CBTE assessed the economic costs associated with natural disasters in Australia between 1967 and 1999 as shown in Figure 5. The report estimated that the total cost of natural disasters in Australia over the period was $36.4 billion (in 1999 prices) (CBTE, 2001). The average annual cost of disasters over this period was $1.10 billion. For the period from 1980 to 1999 alone, the average annual cost of disasters was $1.13 billion (in 1999 prices) (CBTE, 2001). However, the effects of extreme weather events on an economic scale can potentially be greater. In New South Wales alone, IAG paid over $1,300 million in weather-related home and motor insurance claims from 1987 to 2002 (IAG, 2002).

Figure 22 provides illustrates the annual total cost of disasters in Australia from 1967 to 1999.
The impact of events varies greatly from year to year. The overall cost of events is dominated by three large events during 1967 and 1999. The events and their share of the total cost for the period are:

- Cyclone Tracy (1974) (12 per cent)
- Newcastle Earthquake (1989) (13 per cent)

The total cost of most disasters is between $10 million to $50 million (CBTE, 2001 p24). However, despite the number of events in the $10 million to $50 million range the sum of their impact is only approximately 10% of the total cost for the period between 1967 and 1999.

Figure 23 illustrates the average cost per event for each year from 1967 to 1999.
Figure 23 Average cost per event, 1967–1999


Figure 24 illustrates the number of events per year during the study period. There was on average, eight events per year that cost over $10 million. From 1980 to 1999 there was an average of ten extreme events per year, with 1998 having recorded the most number of extreme weather events in a single year (17).

Figure 24 Number of natural disasters in Australia 1967–1999

Source: CBTE (2001) p27
Link between temperature rise and extreme weather events

While it is acknowledged that there are limitations in the study, it is indicated by CSIRO (2007) that there is likely to be an increase in the number of extreme events as the climate changes with temperature a key driver of the climate system. In an attempt to provide an estimation of the increase in extreme events for the purposes of this study a correlation has been drawn to temperature and the number of events.

The observed increase in temperature in Australia over the period of 1967 to 2000, as indicated in Figure 25, was approximately 0.6°C. Over the same time period the average number of annual events increased from eight per year to ten per year. Given this trend and while acknowledging its limitations, a conservative estimate of an increase of one natural disaster per 0.8°C increase was used as an expected minimum increase in natural disasters as outlined in Table 10.

Figure 25 Observed change in Australia's surface temperature

![Graph showing observed change in Australia's surface temperature from 1900 to 2000.](Source: CSIRO (2007) p31)

Table 10 Potential increase in the number of extreme events

<table>
<thead>
<tr>
<th>Temperature increase from 1990 (degrees Celsius)</th>
<th>Additional number of extreme events</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8</td>
<td>+1</td>
</tr>
<tr>
<td>1.6</td>
<td>+2</td>
</tr>
<tr>
<td>2.4</td>
<td>+3</td>
</tr>
<tr>
<td>3.2</td>
<td>+4</td>
</tr>
<tr>
<td>4.0</td>
<td>+5</td>
</tr>
<tr>
<td>4.8</td>
<td>+6</td>
</tr>
<tr>
<td>5.6</td>
<td>+7</td>
</tr>
</tbody>
</table>

To provide further confidence this was compared to the ‘worst year’ in the study period (1967 to 1999) which had 17 events in one year, which is considered likely as a minimum average for U1 scenario by 2100. An indication of the potential increase in extreme events over the timescale to 2100 for each climate scenario is provided in Figure 26.
Distribution of natural disasters and related costs in Australia

The impact of natural disasters varies for each state and territory. CBTE assessed the costs of natural disasters (principally floods, storms, cyclones, earthquakes, bushfires and landslides) for each state and territory. The two most costly hazard types for each state and territory are listed in Table 11.

Table 11: Two most costly hazard types for each State and Territory

<table>
<thead>
<tr>
<th>State/Territory</th>
<th>Two most costly hazards types</th>
</tr>
</thead>
<tbody>
<tr>
<td>New South Wales</td>
<td>Floods and Storms</td>
</tr>
<tr>
<td>Queensland</td>
<td>Floods and Tropical Cyclones</td>
</tr>
<tr>
<td>Victoria</td>
<td>Floods and Bushfires</td>
</tr>
<tr>
<td>Western Australia</td>
<td>Tropical Cyclones and Storms</td>
</tr>
<tr>
<td>South Australia</td>
<td>Floods and Storms</td>
</tr>
<tr>
<td>Tasmania</td>
<td>Bushfires and Floods</td>
</tr>
<tr>
<td>Northern Territory</td>
<td>Tropical Cyclones and Floods</td>
</tr>
<tr>
<td>Australian Capital Territory</td>
<td>Bushfires and Storms</td>
</tr>
</tbody>
</table>

Source: CBTE, 2001

Overall, floods were responsible for annual damages averaging $314 million, which represents 29% of all Australian weather-related damages (CBTE, 2001). A study on flooding in the Hawkesbury/Nepean catchment (an area which has approximately 35,000 properties at risk from flooding) projected that a 1 in 100 year flood event could be reduced to a 1 in 36 year event with the projected changes to climate (IAG, 2002). IAG (2002) indicated that this could increase the costs of average annual damages four-fold.
The second most expensive and extreme weather event was severe storm events (26%), followed by cyclones (24%). Figure 27 illustrates the spread of costs by disaster type for each state and territory.

Figure 27 Costs by type of disaster and State and Territory, 1967–1999

Source: CBTE (2001) p33

To assist in the consideration of the economic impacts of extreme events CBTE (2001) provides case studies on five extreme events of varying types (earthquake, bushfire, cyclone and flood). The case studies provide a breakdown of the costs from each event into the following cost types: buildings;
clean up; agriculture; vehicles and infrastructure; and other indirect costs. Figure 28 illustrates the proportional spread of costs for each of the case study events. In these case studies it is seen that costs to buildings is consistently the area with the greatest portion of the total cost. It accounts for approximately one-third to three-quarters of the total cost of each case study event.

Figure 28 Summary of distribution of disaster costs for selected disasters

Source: CBTE (2001) p115
4 Conclusion

In reviewing the seven climate change scenarios (U1, U2, U3, M1, M2, M3 and M4) for Australia, the U1 scenario is the worst case scenario for water supply infrastructure in major cities and for electricity distribution and transmission networks. The U3 scenario is the worst case scenario for buildings in coastal settlements and port infrastructure and operations.

Queensland is anticipated to have the most significant impacts across each of the four storylines. This is primarily due to the anticipated increase in extreme weather events in that region, particularly under the U1 and U3 scenarios. Western Australia is the state likely to receive the next most significant level of impacts across each of the storylines for similar reasons to that of Queensland, namely the expected increase in extreme storm events. Tasmania is anticipated to be the least effected state across each of the storylines and climate scenarios. This is primarily due to it receiving the least dramatic change in climate in comparison to the other states.

The frequency and intensity of impacts under the M scenarios are likely to be less after the middle of the century when compared to the impacts under the U scenarios. This provides a longer time period for infrastructure adaptation measures to be implemented and society to respond to changes in climate. It has been assumed that there will be greater emphasis on investment in responsive adaptation rather than pre-emptive adaptation measures between 2008 and 2070, such as installation of immediate ‘new water supply capacity’ to adapt to reduced rainfall and changes in design standards to adapt to increased temperature. After 2071 it is assumed that the general planning responses to climate change will be ‘business as usual’ and that investment in pre-emptive adaptation measures such as planned retreat of coastal settlements out of areas likely to be highly impacted by sea-level rise, i.e. such as in flood plains and low lying coastal areas. Scenario M4 provides the best case scenario for the least significant climate change impacts across all infrastructure storylines. This is principally due to the fact that the M4 scenario is expected to have the lowest changes in temperature and rainfall.

There remains uncertainty as to how the occurrence of extreme events and a potential step change in sea-level may occur. What is known with a level of confidence is that should they occur, they are likely to have very significant economic impacts to the regions in which they take place, particularly in low-lying coastal areas. Additional research, improving the certainty of how changes in climate will affect extreme events and sea level rise, will assist the planning and delivery of adaptation measures limiting the potential economic impacts of such events.

Although only a fraction of the total infrastructure for Australia was assessed in this report, the likely climate change impacts in this study indicates that infrastructure investment in replacement and maintenance will increase as global temperatures rise and rainfall patterns change. Climate Change adaptation response for infrastructure in Australia is inevitable to maintain the current level of infrastructure services and benefits. The adaptation responses are likely to be a combination of regional or state responses specific to particular sectors or localities as well as national policy, regulation and standards mechanisms.
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Appendix A  Technical considerations for magnitude of impacts

The following technical considerations provided useful contextual information in the development of the storylines. Refer to the assumptions section of each storyline for a list of the technical considerations that have been incorporated into the estimation of the shocks.

Buildings in coastal settlements

The following information was reviewed as background and informed the assumptions made in developing the buildings in coastal settlements storyline and determining the magnitude of the potential climate change impacts and calibrating them in the shock matrix.

- An approximate asset life of 40 years has been attributed to both residential and commercial building stock. There is a 2.5% depreciation rate for buildings.

- The average annual cost of floods in Australia has been approximately $315 million since 1967. For the past three decades the total cost of floods has ranged between $2.5 billion and $4 billion per decade. During the period from 1967 to 1999, two significant floods affected Australia, on average, each year. Overall, since 1967, Australia has recorded 77 flooding events (with a cost greater than $10 million) (Commonwealth Bureau of Transport Economics (CBTE) (2001)).

- Disaster reports indicate that, as a broad estimate, indirect costs are usually in the range of 25% to 40% of direct costs (contact of flood waters with buildings) Commonwealth Bureau of Transport Economics (2001).

- Buildings in Australia need to conform to the Australian Standard Wind loading AS1170.2-89 which determines the regional wind extremes for building design. As these extreme wind regions expand and develop in new areas, the building standards will be inadequate. The potential for wind damage is greatly increased.

- The Insurance Australia Group has found that a 25% increase in peak wind gust strength can generate a 6.5-fold increase in building claims, refer to Figure 29.

Figure 29  Relation between wind gust speed and increase in building claims

![Figure 29](image)

Source: Insurance Australia Group, 2003

Transitions over time

- Increased flood experience decreases the extent of damages incurred and the level of stress caused in residents. This increase in community knowledge has been incorporated into considerations of lessening damages of smaller events over time.
• Increased housing density and the associated increased impermeable surfaces may increase the likelihood and severity of flash flooding events.

• Continued efforts to reduce the number of houses at risk from 1:100 year flooding are expected (all states). No consideration of reduced real estate values due to properties seen as ‘at risk’ has been included in this review.

• The challenges of substantial cost and practicality of upgrading drainage system capacities to accommodate flows greater than a one in 5-year storm affect current flood risk and vulnerability levels.

• Design standards of new drainage infrastructure are likely to be a factor in more frequent and severe storm events. Increases in pipe sizes are expected to be implemented gradually between 2008 and 2070 in renewal of assets. As the pipe size is a small factor in cost of installation, it is not envisaged to have a material effect on capital expenditure.

Adaptation over time

• New building stock from 2015 will likely be designed to new 1:100 ARI planning levels. The redundancy built into these standards will determine the length of time these standards provide suitable resilience. It is expected these standards will be assessed and updated over time with a 15–20 year planning window.

• Coastal planning schemes are expected to have a slow take up of prohibiting coastal development. It is anticipated such strong measures will be relative to the frequency and significance of extreme events in the short term. Areas that experience higher financial and social costs are likely to ban coastal development earlier than areas less impacted. Limiting coastal development may cause shifts in local projected economic growth due to resulting changes in population migration and commercial development.

• Increased warning time prior to flood occurrences is likely to reduce damages incurred. With an increase in event frequency it is expected that warning systems will improve to provide a relative increase in warning time where possible.

• Over the five financial years to June 2004, Melbourne Water removed 323 properties from the risk of flooding in a 100-year storm at a total cost of $18.1 million, or $56,000 per property (Auditor General Victoria, 2005). At that rate and cost it would take 50 years and $136,000,000 (in today’s dollars) to remove the 3,000 homes in Melbourne at risk of flooding in a 100-year storm. This information has been included to provide an indicative rate and cost for adaptation and flood mitigation and as such has not been factored into the shock matrix.

State based considerations

• Figure 30 below indicated that Queensland, NSW and Victoria have the largest number of residential properties susceptible to mainstream riverine flooding by extreme rainfall events with a 100 year ARI. Figure 31 indicates that the most flood prone regions in Australia. Coastal settlements in Queensland, Victoria, South Australia and NSW are amongst the top ten most flood prone regions in Australia.
Figure 30  Number of residential properties susceptible to mainstream riverine flooding by an event with a 100-year ARI

<table>
<thead>
<tr>
<th>State</th>
<th>Number of residential properties</th>
<th>Proportion of total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Queensland</td>
<td>62,130</td>
<td>36%</td>
</tr>
<tr>
<td>New South Wales</td>
<td>55,677</td>
<td>33%</td>
</tr>
<tr>
<td>Victoria</td>
<td>42,376</td>
<td>25%</td>
</tr>
<tr>
<td>Western Australia</td>
<td>1,142</td>
<td>1%</td>
</tr>
<tr>
<td>South Australia</td>
<td>6,582</td>
<td>4%</td>
</tr>
<tr>
<td>Northern Territory</td>
<td>990</td>
<td>1%</td>
</tr>
<tr>
<td>Tasmania</td>
<td>723</td>
<td>&lt;0.5%</td>
</tr>
<tr>
<td>Australian Capital Territory</td>
<td>0</td>
<td>0%</td>
</tr>
<tr>
<td>TOTAL</td>
<td>169,620</td>
<td>100%</td>
</tr>
</tbody>
</table>


Figure 31  Ten most flood-prone regions in Australia based on a 100-year ARI flood

<table>
<thead>
<tr>
<th>Region or City</th>
<th>State</th>
<th>Number of flood-prone residential properties</th>
<th>Proportion of national total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gold Coast</td>
<td>QLD</td>
<td>20,128</td>
<td>12%</td>
</tr>
<tr>
<td>Brisbane &amp; Ipswich</td>
<td>QLD</td>
<td>18,010</td>
<td>10%</td>
</tr>
<tr>
<td>Shepparton</td>
<td>VIC</td>
<td>6,572</td>
<td>4%</td>
</tr>
<tr>
<td>Melbourne</td>
<td>VIC</td>
<td>6,000</td>
<td>3%</td>
</tr>
<tr>
<td>Mackay</td>
<td>QLD</td>
<td>5,924</td>
<td>3%</td>
</tr>
<tr>
<td>Brown Hill &amp; Keswick Creeks (Adelaide)</td>
<td>SA</td>
<td>5,000</td>
<td>3%</td>
</tr>
<tr>
<td>Hawkesbury-Nepean floodplain (Sydney)</td>
<td>NSW</td>
<td>4,862</td>
<td>3%</td>
</tr>
<tr>
<td>Wyong &amp; Tuggerah Lake</td>
<td>NSW</td>
<td>4,651</td>
<td>3%</td>
</tr>
<tr>
<td>Grafton</td>
<td>NSW</td>
<td>4,167</td>
<td>2%</td>
</tr>
<tr>
<td>Benalla</td>
<td>VIC</td>
<td>3,641</td>
<td>2%</td>
</tr>
</tbody>
</table>

Source: McAneney et al, 2007

Figure 32 indicates that all states and territories would be significantly impacted by sea level rise. Figure 33 indicates the percentage of coastal vulnerable addresses that are less than 3km from shore and on an elevation of less than 6m above sea level by state and territory. Queensland and NSW would impacted to the greatest extent by sea level rise.
Figure 32 Percentage of coastal addresses by state/territory and distance to shoreline

Figure 33 Percentage of coastal vulnerable addresses (less than 3km from shore and elevation less than 6m above mean sea level) by state and territory. Proportions refer to the total number of national addresses (9.6 million)

- New South Wales and Queensland accounted for 66 per cent of total disaster costs and 53 per cent of the total number of disasters over the period 1967 to 1999. Floods were the most costly of all disaster types, contributing $10.4 billion or 29 per cent of the total cost. Storms were the second most costly event at 26 per cent of total cost. (CBTE, 2001).

- Over ninety per cent of residential properties expected to be flooded by a 100-year ARI event are located in Queensland, New South Wales and Victoria (Figure 30) McAneney et al (2007).

Queensland

- In both the 2% and 1% AEP Scenarios, the greatest number of developed properties at risk from flooding fall within the Brisbane-Bremer catchment followed by the Pimpama-Coomera-Nerang-Tallebudgera – Currumbin river system. The percentage of developed properties having at least some water on the property in the Gold Coast area (20% during a 1% AEP flood event) is, however, much higher than in the Brisbane and Ipswich areas (10% in 1% AEP event). Of those properties inundated, the Brisbane-Bremer catchment has a higher percentage of buildings with overfloor flooding (65% in Brisbane-Bremer compared with 40% in the Gold Coast in a 1% AEP event). Australian Geological Survey Organisation (AGSO) (2000).
Electricity transmission and distribution networks

The following information was reviewed as background and informed the assumptions made in developing the electricity transmission and distribution networks storyline and determining the magnitude of the potential climate change impacts and calibrating them in the shock matrix.

Figure 34 Penetration trends of air conditioners by state

Water supply infrastructure in capital cities

The following information was reviewed as background and informed the assumptions made in developing the water supply infrastructure in capital cities storyline and determining the magnitude of the potential climate change impacts and calibrating them in the shock matrix.

- Water is essential to the functioning of the environment, the economy and a high level of public health.
- A less secure water and poorer quality supply can impact adversely on each of these and there are interconnections between the three.
- The supply of safe and reliable sources of water is a ‘given’ and disruptions to service in major urban settlements is not acceptable on policy, public health or political grounds. Interventions will be implemented to secure a water supply for major population settlements—as has/is occurring in Perth, Southeast Queensland and Sydney currently.
- As existing systems are stressed, they tend to lose their resilience and capacity to recover from impacts.
- Comparatively the greatest risk for the functioning of the water supply industry for capital cities is that of water shortage, followed by impacts of the catchments for surface waters and then physical impacts on the water industry’s infrastructure.
- The social costs or benefits of any change in water availability would depend on how the change affects potentially competing human water demands. Changes in water availability will depend on changes in the volume, variability, and seasonality of runoff, as modified by the operation of existing water control infrastructure and investments in new infrastructure (IPCC, 2007a).
• Projections based on expected changes in average rainfall are likely to be too optimistic, given the expectation that crucial variables, such as runoff, will exhibit more serious adverse changes than average rainfall. On the other hand, projections based on the weather of the past decade are likely to be too pessimistic, given past experience of reversion to the mean after long droughts (though none as severe as this one). What is called for is assumptions somewhere between the named extremes (National Economics and the Australian Local Government Association, 2007, pp 52).

• Climate change and the drought have now highlighted that urgent action is needed to expand water supply capacity to meet population growth and provide reserves for extended periods of low inflow. Governments are also recognising a need for greater diversity in the water supply sources to reduce dependence on rainfall runoff into surface storages. As a result a major investment program is planned—a program which in part reflects the inevitable problems of ensuring secure water supply for growing populations in a land of unreliable rainfall, and in part can be interpreted as an adjustment (or adaptation) to climate change (National Economics and the Australian Local Government Association, 2007, pp 103).

• Where interventions are not cost-effective because of the population size or location, existing measures will be used in smaller settlements in periods of drought such as water trucking.

• Historically, Australia’s capital cities have been almost totally reliant on traditional surface water supplies and are therefore susceptible to the impacts of drought and climate change (Marsden Jacob Associates, 2006).

• Current water supply capacity across Australia has been typically planned to require restrictions on demand as frequently as 1 in 25 years based on the long-term historical record. Many cities current supply capacity is now grossly inadequate and restrictions have become more frequent and more severe (Marsden Jacob Associates, 2006).

• Approximately 65% of water is used in 2004–05 for agriculture (ABS (2006) pp 9). However, this is excluded for the purpose of this storyline.

• Adverse effects of climate on freshwater systems aggravate the impacts of other stresses, such as population growth, changing economic activity, land use change, and urbanisation (IPCC, 2007a).

• Water demand will be met through a portfolio approach involving both supply-side and demand-side responses. This is the policy and investment profile of most urban settlements now, indicating that current drought conditions has initiated adaptive responses already in the water supply industry. The portfolio response will differ between urban settlements.

• Consistent with the National Water Initiative water charging will progressively transition to full cost recovery, and the current subsidies will be progressively reduced.

• The operation of an unimpeded water trading market and technological advancements will make the water supply industry more productive as this will encourage the use of the most-cost effective supply options.

• For the dry scenarios, ‘new’ water sources will increasingly predominate over ‘traditional’ surface water sources. ‘New’ water sources include desalination, stormwater capture and recycling.

**Economics**

• Changes in water policy and investment in infrastructure can lead to rather large changes in the shadow price—the price that equates supply with demand. The use of a portfolio approach reduces the change in shadow price. The use of ‘new’ water sources reduces the shadow prices for water after the introduction of full trading significantly (CSIRO and Monash University, 2006).
• By providing access to ‘new’ sources of water by constructing desalination plants or by finding a way to recycle sewage or capture and use stormwater at a cost equivalent to desalination, the worst affected city (Perth) has a three fold price increase (CSIRO and Monash University, 2006).

• A preliminary review of the evidence suggests that the State Treasuries have, in the past, acted to constrain investment in water infrastructure, but that these constraints have been lifted once water supply investment has become a clear priority (Marsden Jacob Associates, 2006).

• On a stand alone basis, virtually all water businesses supplying the capital cities have significant financial capacity to fund both increased levels of capital expenditure and the required dividends to the State Governments. Most of the businesses have paid dividends but have not increased capital expenditure significantly and certainly not increased it to the levels required to have avoided the current shortfall in supply (Marsden Jacob Associates, 2006).

• By contrast, many of the smaller regional and council-owned water businesses operate under far tighter cash constraints. These organisations would have to increase prices significantly to pay for major new water supply investments. This raises serious questions about affordability, particularly in those areas where the economy has already been affected by drought and in regional towns with a relatively high proportion of low or fixed income residents (Marsden Jacob Associates, 2006).

• On today’s consumption rates an additional 1036 gigalitres (GL) per annum would be required to cater for projected population growth (WSAA, 2007). This equates to 24GL per annum of (552GL total to 2030).

### Table 12 Estimated full cost of water supply to Australian capital cities

<table>
<thead>
<tr>
<th>City</th>
<th>Full annualised cost ($ million)</th>
<th>Cost per property per annum ($)</th>
<th>Levelised cost (cost per kilolitre—$/kL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sydney</td>
<td>775</td>
<td>460</td>
<td>1.47</td>
</tr>
<tr>
<td>Melbourne</td>
<td>633</td>
<td>413</td>
<td>1.47</td>
</tr>
<tr>
<td>Brisbane(a)</td>
<td>219</td>
<td>522</td>
<td>0.86</td>
</tr>
<tr>
<td>Adelaide</td>
<td>255</td>
<td>517</td>
<td>1.54</td>
</tr>
<tr>
<td>Perth</td>
<td>360</td>
<td>554</td>
<td>1.59</td>
</tr>
<tr>
<td>Hobart(b)</td>
<td>26</td>
<td>312</td>
<td>0.63</td>
</tr>
<tr>
<td>Darwin</td>
<td>37</td>
<td>863</td>
<td>1.06</td>
</tr>
<tr>
<td>Canberra</td>
<td>82</td>
<td>601</td>
<td>1.56</td>
</tr>
</tbody>
</table>

Notes:
(a) Includes bulk water purchases from SEQ Water
(b) Costs for Hobart exclude the retail costs associated with the councils that Hobart Water supplies.
Sources: WSAA facts 2005 and Marsden Jacob Associates analysis

• A further important consideration is that water restrictions and Government subsidies has promoted substantial growth in private expenditure on rain water tanks and grey water recycling. People are concerned that the only way they can support a garden is by way of supplying the water through their own initiatives. In some areas the growth in ‘behind the meter systems’ has been dramatic and it is expected that either a rain water tank and or a grey water system will be installed in 20–30 per cent of all residences by 2012. At an average cost of $2,000 per unit this amounts to substantial expenditure. It is also expected that rain water tanks/grey water will become mandatory for new homes within the next five years. Consequently the penetration of these behind the meter systems to 2025 will continue to increase (National Economics and the Australian Local Government Association, 2007, pp 104).

• The capacity for governments to spend is significant, over the next 20 years and including a PPP (Public Private Partnership) strategy, Australian governments could spend between $700 billion

- Marsden Jacob’s analysis of the costs of the major supply and demand options available to Australian cities (Figure 17) emphasises:
  - the very low cost of most options in favourable locations and situations;
  - the very high cost (>$3.00/kL) of many options in unfavourable locations and situations;
  - the corresponding lack of any simple universal cost ranking which can be simply applied to each and every situation;
  - the dominating influence of the cost of pipelines and pumping where water needs to be transported over distance;
  - that the relative cost of water management options can be counter-intuitive. For example, the cost of rainwater tanks and recycling schemes in some areas can be considerably higher than the cost of conventional water. Rainwater tanks deliver the highest benefit compared with cost in areas that receive consistent rainfall during the year. In areas that receive little rainfall during summer months, such as Perth, rainwater tanks supply relatively little water and at high unit cost with the result that other water sources are typically required to make up the shortfall during the heaviest periods of water use;
  - the need to examine water supply and demand management options on a situation-by-situation basis; and
  - there is some undesirable variation in the costing methodologies applied by the different States and a lack of disclosure for others (Marsden Jacob Associates, 2006).

**Figure 35** Direct costs of water supply/demand options—Sydney, Adelaide, Perth, Newcastle

The average cost for supply across all options and between the highest and lowest estimates calculated from the above figure is $1.38/kL.
Productivity

- There is significant opportunity to increase the productivity of the water supply industry.
- For the purposes of the storyline productivity is considered to be how much water can be delivered for a unit cost.
- With ongoing technological advancements the cost of desalinated water will decrease—as has been the case of recent experience.
- With ongoing technological advancements less power will be used to deliver a unit of water, however this will be offset at least in the medium term by increased electricity costs.
- Larger plants deliver water at a lower cost per unit and hence can be considered to be more productive.

Demand

- Demand side factors were identified to assist in consideration of storylines but did not inform the development of economic shocks.
- Demand for water will increase with population growth. However, it is assumed that this will be moderated to some degree by the progressive introduction of water efficiency measures and demand management schemes. It is also assumed that demand management and water efficiency measures will not close the gap between declining water availability from climate change and increasing demand resulting from, population growth, demographic change and economic development.
- Increasing numbers of single occupant households will increase the per capita water demand.
- Increasing affluence will increase the per capita water demand.
- Increasing temperatures will lead to an increasing demand.
• Demand side response depend on the cumulative actions of individuals and hence requires regular reinforcement and may have some societal barriers to generating further reductions in water demand.

• Permanent harsh restrictions will not be accepted by the community over the longer-term; the community view restrictions as an emergency measure to be in place for short durations; not a long term management response.

• Consideration of environmental flow requirements may lead to modified reservoir operations so that human use of the water resources might be restricted (IPCC, 2007a).

• Most major Australian urban centres are currently subject to policies and strategies to reduce per capita water usage by 20 per cent or more over time. However, water conservation alone is generally insufficient to meet the needs of an expanding population, particularly in fast growing regions such as Western Australia and south-east Queensland (Marsden Jacob Associates, 2006).

• Water conservation targets of 20 per cent or more are equivalent to the water that could be made available from a major new water source such as a desalination plant, recycling or a dam augmentation. Water conservation measures are typically environmentally and socially superior to conventional water source options. Water conservation is therefore a key strategy to address the water supply demand balance in Australia (Marsden Jacob Associates, 2006).

• Some regional cities are facing sharply diminished supply and extreme water restrictions.

Population

• Between 2030 and 2070 the greatest growth pressures will be experienced in Western Australia, Queensland and the Northern Territory (albeit from a low base). Least population growth pressures experienced in Tasmania and Adelaide between 2030 and 2070.

Infrastructure

• In a highly capital-intensive industry such as water, vigilance against unnecessary capital expenditure is essential. Equally, however, we need to ensure that we do spend when it is necessary to do so and that we have appropriate means/mechanisms to be able to make those decisions (Marsden Jacob Associates, 2006).

• In 2004/05 urban water infrastructure assets were worth $35.4B (ABS, 2007).

• 6.3% is the percentage (median) for operational expenditure against written down replacement cost of fixed water supply assets (WSAA Facts, 2005).

• Current annual operational expenditure is $2.2B per annum.

• About $25 billion of additional water supply projects have recently been announced over and above the normal capital program of water utilities throughout Australia. The additional annual cost (capital and operating) of these works when implemented is estimated to be about $2.3 billion (National Economics and the Australian Local Government Association, 2007, pp 101).

• Overall investment planned on water supply infrastructure over the next ten years is $25 to $30 billion with about $10 billion spent on desalination plants. The majority of the remaining $20 billion will be spent on pipelines. The average rate of spending of around $3 billion per year is around four times the historical annual expenditure over the past ten years on water supply infrastructure (National Economics and the Australian Local Government Association, 2007, pp 104).

• The Perth desalination plant delivered 45GL for $387M capital ($8.6M/GL) and $19M per annum operational expenditure for a unit cost of $1.16 per kilolitre (2005 dollars).

• The Sydney desalination plant has been contracted out at $960M to deliver 91Gl ($10.5M/GL).
• Climate change has the potential to adversely impact on water quality in catchments and this will increase treatment costs (IPCC, 2007a), therefore increasing operational expenditure and over time capital expenditure.

• Dams are not a very useful option in extended drought regimes. Best practice emphasises a diversity of water sources (Marsden Jacob Associates, 2006).

• New climate independent water sources such as desalination, sewage recycling and stormwater harvesting have similar capital and operational costs to each other.

**Transitions over time**

• The number of dams is very likely to remain stable (IPCC, 2007a).

• Consideration of environmental flow requirements may lead to modified reservoir operations so that human use of the water resources might be restricted (IPCC, 2007a).

• As yields from surface water storages become less reliable and water demand increases, new alternative sources become increasingly important.

• Water infrastructure, use patterns and institutions have developed in the context of current conditions (Conway, 2005 in IPCC, 2007a). Therefore as climate conditions change it is reasonable that these will also change over time and will have an associated cost.

• Impacts on capital costs are largely attributable to additional infrastructure required to both diversify water sources and build resilience through the delivery on climate independent sources. In the drying scenarios it can be anticipated that progressively new investment in capital infrastructure will favour climate independent water sources such as desalination and recycling (stormwater harvesting depends on there being rainfall and a capability to store the captured water) as these will be more secure water sources. The impacts on capital expenditure will be highest in areas already experiencing water stress—catch-up in infrastructure investment to address current water scarcity and then further investment to address future water scarcity in the drying scenarios. Overtime the differences in capital costs for traditional and new water sources will tend to equalise.

**Adaptation over time**

• Over time water will increasingly be supplied at a quality ‘fit for use’—i.e. a move away from using potable (drinking quality) water for all consumptive uses.

• The most general form of adaptation by infrastructures vulnerable to impacts of climate change is investment in increased resilience, for instance new sources of water supply (IPCC, 2007a) or dam safety.

• Uncertainties in climate change projections increase with the length of time horizon (IPCC, 2007a).

• Uncertainties in climate change impacts on water resources are mainly due to the uncertainty in precipitation (IPCC, 2007a).

• Increased expenditure for dam safety (larger spillways to cater for actual and expected increases in rainfall intensity) is considered to be ‘business as usual’ and hence likely to be addressed without a shift in typical practice.

• Proportionally over time out to 2030 there will be a greater spend on operational costs because of the reduced design life of water supply infrastructure related to the impacts of climate change on the infrastructure, rather than the water supplied per se. This should be addressed in design and engineering standards beyond this period so becomes less important for 2070 and 2100.
State based considerations

- States which have a large geographic range such as Queensland and Western Australia may appear to be rated lower than would be anticipated, especially in the drying scenarios. This is because, for example, Queensland is likely to experience wetter conditions in the tropical north and drier conditions on average in the south. The combined impacts of this when assessing the relative shock level is to moderate the overall State assessment.

- The certainty of climate change being the driver of reduced rainfall in the capital cities in the southern part of Australia is higher than for eastern Australia and/or for increased rainfall in northern Australia.

Port infrastructure and operations

The following information was reviewed as background and informed the assumptions made in developing the port infrastructure and operations storyline and determining the magnitude of the potential climate change impacts and calibrating them in the shock matrix.

Port operation and infrastructure

- 95% of the time Port operations occur, 24 hours, seven days a week; therefore operates 346 days a year.

- Shipping and port operations in Australia are projected to increase at the same rate as Australian GDP (Port of Melbourne Corporation, 2007).

- The ratio for reduction of infrastructure life to depreciation is 1:1.

- The number of ports is not likely to change substantially over time however infrastructure at current ports will be augmented to increase export capability.

- Assumed no seasonal change in import/export throughput and value of ports.

Transitions over time

- Port infrastructure life is expected to decrease by 10% leading in a 10% increase in depreciation. The main contributors to this are rising sea levels and elevated temperatures producing accelerated corrosion rates. This will lead to increase expenditure on maintenance i.e. increase in operational expenditure, until such time as more resilient materials are introduced. It is expected that design, construction and maintenance standards will improve over time.

- Frequency and intensity of extreme events such as cyclones and severe storms will generally increase over time.

Adaptation over time

- In order to reduce productivity loss associated with downtime the following adaptations may occur:
  - installation of seawall protection
  - increased size of ships and number of voyagers to maximise productivity during good weather conditions
  - increased number of cranes and berths to increase productivity during good weather conditions.

- In order to reduce deterioration of infrastructure construction and design techniques will be modified to address increased corrosion due to increased sea level, ocean acidification and increased temperatures.
State based considerations

Key ports for each state were chosen based on the current value of through-put. Table 13 provides the bulk and container through-put in mass tonnes and value for selected key ports used in the assessment for the impacts of climate change on port infrastructure.

Table 13  Key ports selected for assessment of the impacts of climate change on port infrastructure

<table>
<thead>
<tr>
<th>State</th>
<th>Port</th>
<th>Bulk 2005/2006* (tonnes)</th>
<th>Container 2005/2006* (tonnes)</th>
<th>Total value of Throughput (exports + imports, including bulk and non bulk) based on 04/05 data*</th>
</tr>
</thead>
<tbody>
<tr>
<td>VIC</td>
<td>Melbourne</td>
<td>7,065,033</td>
<td>18,552,270</td>
<td>$53,650,106</td>
</tr>
<tr>
<td></td>
<td>Geelong</td>
<td>10,875,028</td>
<td>–</td>
<td>$3,291,872</td>
</tr>
<tr>
<td>NSW</td>
<td>Sydney</td>
<td>14,648,977</td>
<td>11,255,778</td>
<td>$45,773,666</td>
</tr>
<tr>
<td></td>
<td>Newcastle</td>
<td>84,916,237</td>
<td>191,782</td>
<td>$6,593,981</td>
</tr>
<tr>
<td>WA</td>
<td>Fremantle</td>
<td>19,257,361</td>
<td>4,862,296</td>
<td>$18,112,430</td>
</tr>
<tr>
<td></td>
<td>Dampier</td>
<td>109,557,053</td>
<td>–</td>
<td>$12,565,709</td>
</tr>
<tr>
<td></td>
<td>Bunbury</td>
<td>12,192,307</td>
<td>3,435</td>
<td>$2,768,597</td>
</tr>
<tr>
<td></td>
<td>Port Hedland</td>
<td>110,551,624</td>
<td>6,152</td>
<td>$3,936,918</td>
</tr>
<tr>
<td>TAS</td>
<td>Launceston</td>
<td>3,529,786</td>
<td>1,511,705</td>
<td>$1,376,147</td>
</tr>
<tr>
<td>NT</td>
<td>Darwin</td>
<td>780,212</td>
<td>76,702</td>
<td>$1,982,453</td>
</tr>
<tr>
<td>QLD</td>
<td>Brisbane</td>
<td>19,148,772</td>
<td>6,667,025</td>
<td>$24,500,572</td>
</tr>
<tr>
<td></td>
<td>Townsville</td>
<td>9,703,518</td>
<td>234,153</td>
<td>$3,841,598</td>
</tr>
<tr>
<td>SA</td>
<td>Adelaide</td>
<td>7,273,123</td>
<td>2,220,098</td>
<td>$7,012,163</td>
</tr>
</tbody>
</table>

Source: Department of Transport and Regional Economics, Bureau of Transport and Regional Economics, (2007)

East coast ports

- The east coast container ports (Melbourne, Sydney, Adelaide, Brisbane and the South East coast bulk ports) are in sheltered harbours. Downtime due to weather is currently minimal except in exceptional circumstances such as cyclone events.
- North coast ports are affected by cyclones.

West coast ports

- North west coast ports are affected by cyclones
  - For harbour sheltered ports the Indian Ocean Swell does not infiltrate harbours therefore increase in swell is not a likely threat to productivity for these ports.
  - If a cyclone comes within a 300 km radius of port, port shuts down. This radius is different for different ports (e.g. Dampier—harbour location, relies on tides for access, 400 km radius for cyclone shut down), however 300 km radius is a good rule of thumb. Actions in the event of a cyclone are governed by Emergency Response Plans for each port.
  - North west shelf is protected from Trade winds while the far north (e.g. Timor Sea area) is affected by trade winds.
  - Southwest region (includes Fremantle and Bunbury) ports are limited by swell (outside harbour) and wind (inside harbour).
Tasmania

- Key ports are Launceston and Hobart. These ports deal with dry bulk, liquid bulk, containers and gas.

- An additional issue for Tasmania not found for other states is the impact on ferries. E.g. Bass Strait coastal trade. Tasmania is dependent on this.

- Increase wind and storm events will reduce the number of sailings that can be made by existing system.

Figure 37  Average annual number of tropical cyclones—all years

![Image of average annual number of tropical cyclones](source)

Source: BOM, 2008
Appendix B  Percentage shocks

The percentage shock impacts for the Garnaut Climate Change Review (GCCR) infrastructure stories for Buildings in Coastal Settlements, Electricity Transmission and Distribution Networks, Water Supply Infrastructure in Capital Cities and Port Infrastructure and Operations are provided from Subsection 6.2.1 to Subsection 6.2.4 as a percentage shock matrix for each state and each climate change scenario (namely U1, U2, U3, M1, M2, M3 ad M4). No step change in sea level rise has been included in any of the percentage shock matrices.

The net magnitude shock matrices indicating the impact scale of the infrastructure stories were used to generate an estimated percentage change impact to feed into the CGE modelling process. These estimated percentage changes were initially guided by and then reviewed by infrastructure technical specialists to shape and refine the percentage estimates based on industry experience and publicly available information. Additional information used to determine the percentage shocks are provided before each matrix.

The percentage changes for each story are an average change over each time scale (2008–2030, 2031–2070 and 2071–2100) and the relative differences in the timescale sizes (22 years, 39 years and 29 years) has been considered in the initial net magnitude assessment and also transferred to the percentage shock assessments. The percentage shocks are not cumulative over each time scale.

Buildings in coastal settlements

Coastal zone

The shocks outlined in the Buildings Story are to be applied to 80% of the total buildings within each state, this represents the buildings which are within the coastal zone (50km from the coast). It was assumed that the 80% average was the same for each state, even though it is expected that WA and Tasmania may have a greater proportion of their population and therefore buildings within 50 km of the coast.

The percentage shocks for buildings in the coastal settlements include the following:

**Capital expenditure**

- **New Buildings:** The additional cost for new residential buildings in response to climate change. This shock is based on the likely cost of increasing the insulation of new homes as well as installing double glazed windows for new houses in warmer climate zones (i.e. NSW, WA, QLD, SA, QLD). For cooler climate zones (i.e. Victoria and Tasmania) the shock estimates only the inclusion of insulation not double glazing, as the latter is not considered cost effective (DEWR, 2007). The actual impact may be greater than the shocks estimated in this report as insufficient information was available on the likely costs on new building design in preparation for bushfire and extreme wind events. This shock does not include commercial and industrial buildings.

- **Existing Buildings:** The cost to upgrade existing residential buildings in response to climate change. This shock is based on the likely cost of upgrading or retrofitting insulation and double glazing windows for existing houses in warmer climate zones (i.e. NSW, WA, QLD, SA, QLD). For cooler climate zones (i.e. Victoria and Tasmania) the shock estimates only the inclusion of insulation not double glazing, as the latter is not considered cost effective (DEWR, 2007). The actual impact may be greater than the shocks estimated in this report as insufficient information was available on the likely costs on retrofitting existing buildings in preparation for bushfire and extreme wind events. This shock does not include commercial and industrial buildings.

- **Reduced Life Expectancy of Buildings:** The percentage reduction of the expected life of buildings, residential, commercial or industrial. The percentage reduction is from the current estimated 40 year life of assets. For example, a five per cent (5%) shock means that buildings will only last 38 years rather than the typical 40 years. This shock has been reduced over the ‘2031–2070’ and ‘2071–2100’ timeframes through improved design standards (reflected in the New
Building and Existing Building shocks) extending the life expectancy of buildings (i.e. limiting the reduction in life span expected from climate change impacts had there been no change to building designs).

Operational expenditure

- **Operational expenditure** from additional maintenance and repair costs primarily caused by a combination of accelerated degradation of materials and increased extreme events. This shock purely relates to coastal residential, commercial and industrial buildings and is not related to infrastructure such as drainage, coastal protection and road access. It is anticipated that for U1, U3 and U2 climate scenarios there will be a willingness to accept greater maintenance costs rather than high preventative capital investment between 2071 and 2100.

Sea level rise

Consideration of gradual sea level rise has been included in the reduced life expectancy and operational expenditure shocks. A step change in sea level rise has not been included in any of the economic shocks.

Based on the authors' understanding of climate change impacts on buildings, less than 20% of the likely impacts on buildings have been analysed for economic input into the CGE modelling.

The full shock matrix for buildings in coastal settlements is provided in Figure 38 and Figure 39.
### Figure 38  Buildings in coastal settlements—Shock Matrix for Business as Usual Scenarios

**Timeframe 2008 - 2030**

<table>
<thead>
<tr>
<th>Climate Scenario</th>
<th>U1</th>
<th>U2</th>
<th>U3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shocks</td>
<td>NB   EB  RL  OP</td>
<td>NB   EB  RL  OP</td>
<td>NB   EB  RL  OP</td>
</tr>
<tr>
<td>VIC</td>
<td>0.8% 0% 2% 9%</td>
<td>0.8% 0% 2% 9%</td>
<td>0.8% 0% 2% 8%</td>
</tr>
<tr>
<td>NSW</td>
<td>1.4% 0% 2% 9%</td>
<td>1.4% 0% 2% 9%</td>
<td>1.4% 0% 2% 12%</td>
</tr>
<tr>
<td>WA</td>
<td>1.5% 0% 2% 4%</td>
<td>1.5% 0% 2% 4%</td>
<td>1.5% 0% 2% 6%</td>
</tr>
<tr>
<td>NT</td>
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**Timeframe 2031 - 2070**

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**Timeframe 2071 - 2100**

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**Legend**

- **NB** New Buildings
- **EB** Existing Buildings
- **RL** Reduced Life Expectancy of Buildings
- **OP** Operational Expenditure

Additional climate change related costs for new building design.
Climate change adaptation cost to retrofit existing buildings.
Percentage reduction of building life (i.e. 5% = buildings only last 38 years versus expected 40 year life of assets).
Percentage increase in the repair and maintenance of buildings.
### Figures 39-40

#### Buildings in coastal settlements—Shock Matrix for Strong Mitigation Scenarios

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**Legend**

- **NB** New Buildings
- **EB** Existing Buildings
- **RL** Reduced Life Expectancy of Buildings
- **OP** Operational Expenditure

### Electricity transmission and distribution networks

The percentage shocks for electricity transmission and distribution networks includes the following:

- **Capital expenditure** impacts from additional changes in design and early renewal/replacement of transmission and distribution infrastructure from accelerated degradation and damage from extreme events, including impacts from gradual sea level rise. Capital expenditure does not include demand side impacts on increased generation capital expenditure. This shock applies to the total of each state’s transmission and distribution infrastructure; and

- **Operational expenditure** from additional maintenance and repair costs for transmission and distribution infrastructure from accelerated degradation and damage from extreme events, including impacts from gradual sea level rise. This applies to the total of each state’s transmission and distribution infrastructure.

Based on the authors’ understanding of climate change impacts on electricity transmission and distribution, approximately 80% of the climate change impacts on electricity transmission and distribution have been analysed for economic input into the CGE modelling. The full shock matrix for electricity transmission and distribution networks is provided in Figure 40.
**Water supply infrastructure in major cities**

This study focuses on capital cites, as regional centres have a different supply profile and constraints. The percentage shocks for water supply infrastructure in capital cities includes the following:

- **Capital expenditure—Supply** impacts from additional capital costs to provide alternative water supply (i.e. desalination plants). This shock excludes impacts from sea level rise. In estimating the shock consideration was given to capital cities. For this study the same percentage shock is assumed to be applied to the whole state. However, it is noted that the true shock may be higher for the total water supply infrastructure in each state as it is believed that the cost for regional areas will be greater per capita than in major cities;

- **Capital expenditure—Distribution** impacts from additional capital costs related to water supply infrastructure (i.e. pipes). This shock excludes impacts from sea level rise. In estimating the shock consideration was given to capital cities. For this study the same percentage shock is assumed to be applied to the whole state. However, it is noted that the true shock may be higher for the total water supply infrastructure in each state as it is believed that the cost for regional areas will be greater per capita than in capital cities; and

- **Operational expenditure** from additional maintenance and repair costs due to increased damage to supply and distribution assets. Consideration has not been given to the effects of increases in

---

**Legend**

- C Capital expenditure
- O Operational expenditure
- Additional capital costs due to changes in design and damage.
- Additional maintenance and repair costs.

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**Table: Electricity transmission and distribution networks—Shock Matrix**

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**Timeframe 2008 - 2030**

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**Timeframe 2071 - 2100**

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the cost of electricity consumption per unit of water supplied. However some information on the relative electricity consumption for a range of water supply options is provided. This shock excludes impacts from sea level rise. This shock has been extrapolated to the total water supply operational expenditure in each state.

**Productivity**

Productivity shocks were not developed into economic percentage shocks due to the complexity of the supply and demand impacts on productivity. Examples of productivity shocks include increased losses of water through leaks or evaporation from distribution pipes and channels and the loss of productivity due to manufacturing down time related to the temporary reduction or lack of water supply.

**Electricity consumption per unit of water for current supply versus desalination plants**

Little published and peer reviewed information exists on the comparative amount of energy used to produce a unit of potable water. The available information suggests that desalination is the least energy efficient of the water supply options. It is assumed that desalination uses at least double the electricity of current water supply but could in a worst case scenario use 20 times as much electricity.

Knights et al. (2007) have concluded that desalination uses significantly more energy than our traditional storage and pipe network systems and more energy than is required to recycle wastewater to a level fit for reuse. Their analysis of operational energy usage for a range of New South Wales water treatment technologies highlights the following energy usage rates:

- Warragamba and other water storages 0.25 kWh/kL
- access ‘deep storage’ 0.4 kWh/kL
- Shoalhaven inter-basin transfer 2.4 kWh/kL
- residential wastewater reuse (greenfields) 1.2 kWh/kL
- large scale indirect potable wastewater recycling 2.8–3.8 kWh/kL
- desalination 5.4 kWh/kL
- residential indoor retrofit (that reduces hot water use) −32.6 kWh/kL.

Knights et al. (2007) have concluded that the information above is broadly applicable to other Australian cities.

However, it should be noted that energy use is system-specific and so water supply options will use different amounts of energy in different locations. Further, water efficiency options save both energy and water and will thus affect the comparative rates of energy use for different treatment technologies. It should also be noted that the figures above only consider operational energy and embodied energy within the distribution and treatment processes can also be significant.

It can also be expected that with technological research and development the differential between desalination and other water treatment options will narrow over time.

The electricity consumption is generally less than 1% of current operating expenditure for water companies (Pamminger, 2007).

Based on the authors’ understanding of climate change impacts on water supply, approximately 80% of the climate change impacts on water supply have been analysed for economic input into the CGE modelling.

The full shock matrix for water supply infrastructure in major cities is provided in Figure 41.
### Figure 41  Water supply infrastructure in major cities—Shock Matrix

#### Timeframe 2008 - 2030

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#### Legend
- **CS**: Capital expenditure—Supply
- **CD**: Capital expenditure—Distribution
- **O**: Operational costs

Additional capital costs to provide alternative water supply (i.e. desalination plant).
Additional capital costs to replace distribution assets (i.e. pipes).
Additional maintenance and repair costs due to increased damage.
Port infrastructure and operations

The percentage shocks for port infrastructure and operations includes the following:

- **Productivity** from additional climate change related port downtime including gradual sea level rise and cyclones. This shock applies to the total port productivity for each state;

- **Capital expenditure** impacts from additional capital costs due to changes in design, protection and damage to port infrastructure including gradual sea level rise and cyclones. This shock applies to the total port capital expenditure for each state; and

- **Operational expenditure** from additional maintenance and repair costs due to increased damage to port infrastructure, including impacts from gradual sea level rise and cyclones. This shock applies to the total port operational expenditure for each state.

The analysis of the impact of climate change on port infrastructure and operations takes into account a number of climatic variables including cyclones. Port operations are affected by extreme climatic events such as cyclones and to a lesser extent ocean swell, extreme wind and increased temperature. Extreme weather events lead to port downtime causing loss in productivity and increases in operational expenditure. There are a number of reasons why cyclones should be part of the assessment.

Firstly, it is important to point out that the analysis does not assume that cyclones only affect ports when they directly ‘hit’ port infrastructure. Port closure due to cyclones can also occur due to a ‘near miss’ event in which the cyclone passes through an area designated in a specific port’s emergency management plan calling for a shut down. For example, some ports require closure should a cyclone occur within a 300 km radius of the port. Secondly, ports located in cyclone prone areas, such as northwest Western Australia, the coast of the Northern Territory and the Queensland coast are already affected by downtime associated with cyclones. As a result, excluding the impact of cyclones on port infrastructure and operations would result in an underestimation of the productivity shocks. Thirdly, our results are based on the information provided during two workshops involving a range of experts (including port infrastructure experts). As the analysis included all factors affecting port operations, the impact of cyclone ‘hits’ and ‘near-misses’ can not be disentangled without re-visiting all results. In discussions with Geoscience Australia, their cyclone assessments for the GCCR have excluded impacts on ports, so it is acceptable to apply cyclone impact to ports and not double count cyclone impacts.

Based on the authors’ understanding of climate change impacts on port infrastructure and operations, approximately 80% of the climate change impacts on port infrastructure and operations have been analysed for economic input into the CGE modelling.

The full shock matrix for port infrastructure and operations is provided in Figure 42 over the page.
## Figure 42  
Port infrastructure and operations—Shock Matrix

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**Legend**

- **P** Productivity  
- **C** Capital expenditure  
- **O** Operational expenditure

Additional climate change related port downtime including gradual sea level rise and cyclones.  
Additional costs due to changes in design, protection and damage to port infrastructure including gradual sea level rise and cyclones.  
Additional maintenance and repair costs for port infrastructure including gradual sea level rise and cyclones.
Appendix C  Climate scenario data

The following climate graphs were developed by Maunsell using climate data provided by CMAR.

Global warming scenario

Figure 43  A1FI Global warming trend compared to mitigation scenarios
Temperature, rainfall, humidity and evaporation by climate scenario

Temperature

Figure 44  Annual temperature change for the U1 Climate Scenario

Unmitigated Scenario 1 (U1) - Annual Temperature
90th percentile change per degree of global warming

Figure 45  Annual temperature change for the U2 Climate Scenario

Unmitigated Scenario 2 (U2) - Annual Temperature
50th percentile change per degree of global warming
Figure 46  Annual temperature change for the U3 Climate Scenario

Unmitigated Scenario 3 (U3) - Annual Temperature
50th percentile change per degree of global warming

- Sydney
- Melbourne
- Adelaide
- Perth
- Greater Hobart
- Darwin
- Canberra
- Brisbane

Figure 47  Annual temperature change for the M1 Climate Scenario

Mitigation Scenario 1 (M1) - Annual Temperature
90th percentile change per degree of global warming

- Sydney
- Melbourne
- Adelaide
- Perth
- Greater Hobart
- Darwin
- Canberra
- Brisbane
Figure 48 Annual temperature change for the M2 Climate Scenario

**Mitigation Scenario 2 (M2) - Annual Temperature**
50th percentile change per degree of global warming

Year

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Figure 49 Annual temperature change for the M3 Climate Scenario

**Mitigation Scenario 3 (M3) - Annual Temperature**
50th percentile change per degree of global warming

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Figure 50  Annual temperature change for the M4 Climate Scenario

Mitigation Scenario 4 (M4) - Annual Temperature
50th percentile change per degree of global warming

Year

-0.20
0.00
0.20
0.40
0.60
0.80
1.00
1.20
1.40
1.60
1.80

Temperature - Degrees Celsius

1990 2000 2010 2020 2030 2040 2050 2060 2070 2080 2090 2100

Sydney
Melbourne
Adelaide
Perth
Greater Hobart
Darwin
Canberra
Brisbane

Figure 51  Annual rainfall change for the U1 Climate Scenario

Rainfall

Unmitigated Scenario 1 (U1) - Annual Rainfall
10th percentile change per degree of global warming

Year

Rainfall - % Change

1990 2000 2010 2020 2030 2040 2050 2060 2070 2080 2090 2100

Sydney
Melbourne
Adelaide
Perth
Greater Hobart
Darwin
Canberra
Brisbane
Figure 52  Annual rainfall change for the U2 Climate Scenario

Figure 53  Annual rainfall change for the U3 Climate Scenario
Figure 54  Annual rainfall change for the M1 Climate Scenario

Figure 55  Annual rainfall change for the M2 Climate Scenario
Figure 56  Annual rainfall change for the M3 Climate Scenario

Mitigation Scenario 3 (M3) - Annual Rainfall
90th percentile change per degree of global warming

Figure 57  Annual rainfall change for the M4 Climate Scenario

Mitigation Scenario 4 (M4) - Annual Rainfall
50th percentile change per degree of global warming
Relative humidity

Figure 58  Annual relative humidity change for the U1 Climate Scenario

Figure 59  Annual relative humidity change for the U2 Climate Scenario
Figure 60  Annual relative humidity change for the U3 Climate Scenario

Unmitigated Scenario 3 (U3) - Annual Relative Humidity
90th percentile change per degree of global warming

Figure 61  Annual relative humidity change for the M1 Climate Scenario

Mitigation Scenario 1 (M1) - Relative Humidity
10th percentile change per degree of global warming
Figure 62  Annual relative humidity change for the M2 Climate Scenario

Mitigation Scenario 2 (M2) - Relative Humidity
50th percentile change per degree of global warming

Figure 63  Annual relative humidity change for the M3 Climate Scenario

Mitigation Scenario 3 (M3) - Relative Humidity
90th percentile change per degree of global warming
Mitigation Scenario 4 (M4) - Relative Humidity
50th percentile change per degree of global warming

Evaporation

Unmitigated Scenario 1 (U1) - Annual Potential Evaporation
90th percentile change per degree of global warming
Impact of climate change on infrastructure in Australia and CGE model inputs

Figure 68 Annual Potential Evaporation for the M1 Climate Scenario

Mitigation Scenario 1 (M1) - Evaporation
90th percentile change per degree of global warming

Figure 69 Annual Potential Evaporation for the M2 Climate Scenario

Mitigation Scenario 2 (M2) - Evaporation
50th percentile change per degree of global warming
Figure 70  Annual Potential Evaporation for the M3 Climate Scenario

Mitigation Scenario 3 (M3) - Evaporation
50th percentile change per degree of global warming

-1.00 0.00 1.00 2.00 3.00 4.00 5.00 6.00 7.00 8.00

Evaporation - % Change

Sydney
Melbourne
Adelaide
Perth
Greater Hobart
Darwin
Canberra
Brisbane

1990 2000 2010 2020 2030 2040 2050 2060 2070 2080 2090 2100
Year

Figure 71  Annual Potential Evaporation for the M4 Climate Scenario

Mitigation Scenario 4 (M4) - Evaporation
50th percentile change per degree of global warming

-1.00 0.00 1.00 2.00 3.00 4.00 5.00 6.00

Evaporation - % Change

Sydney
Melbourne
Adelaide
Perth
Greater Hobart
Darwin
Canberra
Brisbane

1990 2000 2010 2020 2030 2040 2050 2060 2070 2080 2090 2100
Year
Temperature and rainfall by capital city

Sydney

Figure 72  Annual temperature change per degree of global warming for all climate scenarios for Sydney

![Sydney - Annual Temperature 1990-2100](image)

Figure 73  Annual rainfall change per degree of global warming for all climate scenarios for Sydney

![Sydney - Annual Rainfall 1990-2100](image)
Figure 74  Annual temperature change per degree of global warming for all climate scenarios for Melbourne

Figure 75  Annual rainfall change per degree of global warming for all climate scenarios for Melbourne
Adelaide

Figure 76 Annual temperature change per degree of global warming for all climate scenarios for Adelaide

Adelaide - Annual Temperature 1990-2100

Figure 77 Annual rainfall change per degree of global warming for all climate scenarios for Adelaide

Adelaide - Annual Rainfall 1990-2100
Perth

Figure 78  Annual temperature change per degree of global warming for all climate scenarios for Perth

![Perth - Annual Temperature 1990-2100](image)

Figure 79  Annual rainfall change per degree of global warming for all climate scenarios for Perth

![Perth - Annual Rainfall 1990-2100](image)
Greater Hobart

Figure 80   Annual temperature change per degree of global warming for all climate scenarios for Greater Hobart

Hobart - Annual Temperature 1990-2100

Year

Temperature - degrees calcius

U1
U2
U3
M1
M2
M3
M4

Figure 81   Annual rainfall change per degree of global warming for all climate scenarios for Greater Hobart

Hobart - Annual Rainfall 1990-2100

Year

Rainfall - % Change

U1
U2
U3
M1
M2
M3
M4
Darwin

Figure 82  Annual temperature change per degree of global warming for all climate scenarios for Darwin

![Darwin - Annual Temperature 1990-2100](image)

Figure 83  Annual rainfall change per degree of global warming for all climate scenarios for Darwin

![Darwin - Annual Rainfall 1990-2100](image)
Canberra

Figure 84  Annual temperature change per degree of global warming for all climate scenarios for Canberra

Canberra - Annual Temperature 1990-2100

Figure 85  Annual rainfall change per degree of global warming for all climate scenarios for Canberra

Canberra - Annual Rainfall 1990-2100
Brisbane

Figure 86  Annual temperature change per degree of global warming for all climate scenarios for Brisbane

Figure 87  Annual rainfall change per degree of global warming for all climate scenarios for Brisbane
Maximum temperature by capital city

Figure 88  Maximum temperature days over 35°C for Sydney for all climate scenarios

![Sydney Maximum Temperature Graph](image)

Figure 89  Maximum temperature days over 35°C for Melbourne for all climate scenarios

![Melbourne - Maximum Temperature Graph](image)
Figure 90  Maximum temperature days over 35°C for Adelaide for all climate scenarios

Figure 91  Maximum temperature days over 35°C for Perth for all climate scenarios
Figure 92  Maximum temperature days over 35°C for Greater Hobart for all climate scenarios

![Greater Hobart - Maximum Temperature](image1)

Figure 93  Maximum temperature days over 35°C for Darwin for all climate scenarios

![Darwin - Maximum Temperature](image2)
Figure 94  Maximum temperature days over 35°C for Canberra for all climate scenarios

Figure 95  Maximum temperature days over 35°C for Brisbane for all climate scenarios
Figure 96  Projected change in annual average tropical cyclone occurrence in the Australian region for 40-year time slices centred on 2030 and 2070

Blue regions indicate a decrease in tropical cyclone occurrence and red regions indicate an increase in occurrence. Results are from the CCAM Mark3 simulations forced with the SRES A2 scenario presented in Abbs et al (2006).

Source: CSIRO (2007)
Figure 97  Averaged pH (a) and aragonite saturation (b) observed for the 1990s and projected values for the 2070s for pH (c) and aragonite (d) using the CSIRO Mark 3.5 model under the A2 scenario


Figure 98  Best estimate projected wind speed change by 2030 for the A1B emission scenario

Source: CSIRO (2007)
### Figure 99

Average number of days per year with Fire Danger Rating of ‘very high’ or greater and the per cent change from the current value

<table>
<thead>
<tr>
<th>site</th>
<th>now</th>
<th>Low mk2</th>
<th>Low mk3</th>
<th>High mk2</th>
<th>High mk3</th>
<th>Low mk2</th>
<th>Low mk3</th>
<th>High mk2</th>
<th>High mk3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2020</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Adelaide**: 18.3
  - now: 19.2
  - low mk2: 19.8
  - low mk3: 20.8
  - high mk2: 22.3
  - high mk3: 19.9
  - 20.8
  - 26.1
  - 30.2

- **Amberley**: 13.3
  - now: 14.5
  - low mk2: 14.2
  - low mk3: 16.4
  - high mk2: 15.7
  - high mk3: 15.3
  - 14.8
  - 22.7
  - 20.9

- **Bendigo**: 13.9
  - now: 15.6
  - low mk2: 16.1
  - low mk3: 17.5
  - high mk2: 18.4
  - high mk3: 16.6
  - 17.1
  - 25.2
  - 28.6

- **Bourke**: 57.2
  - now: 62.3
  - low mk2: 61.4
  - low mk3: 71.3
  - high mk2: 68.6
  - high mk3: 66.4
  - 64.5
  - 103.7
  - 91.5

- **Brisbane AP**: 5.2
  - now: 5.4
  - low mk2: 5.3
  - low mk3: 5.9
  - high mk2: 5.8
  - high mk3: 5.7
  - 5.6
  - 8.5
  - 7.3

- **Canberra**: 16.8
  - now: 18.3
  - low mk2: 18.9
  - low mk3: 21.5
  - high mk2: 22.8
  - high mk3: 20.0
  - 20.6
  - 29.9
  - 33.4

- **Ceduna**: 46.4
  - now: 47.7
  - low mk2: 48.0
  - low mk3: 49.4
  - high mk2: 50.5
  - high mk3: 48.5
  - 49.0
  - 56.5
  - 58.6

- **Charleville**: 89.0
  - now: 95.6
  - low mk2: 93.6
  - low mk3: 108.3
  - high mk2: 102.0
  - high mk3: 101.5
  - 97.2
  - 147.5
  - 126.7

- **Cobar**: 56.0
  - now: 61.4
  - low mk2: 60.8
  - low mk3: 69.9
  - high mk2: 67.9
  - high mk3: 65.2
  - 64.0
  - 99.5
  - 91.8

- **Coffs Harbour**: 1.5
  - now: 1.6
  - low mk2: 1.6
  - low mk3: 1.8
  - high mk2: 1.8
  - high mk3: 1.8
  - 1.8
  - 2.3
  - 2.5

- **Dubbo**: 23.0
  - now: 25.6
  - low mk2: 25.3
  - low mk3: 30.0
  - high mk2: 29.2
  - high mk3: 27.4
  - 27.1
  - 45.9
  - 43.8

- **Hobart**: 2.0
  - now: 2.0
  - low mk2: 2.0
  - low mk3: 2.0
  - high mk2: 2.1
  - high mk3: 2.0
  - 2.1
  - 2.0
  - 2.2

- **Launceston**: 1.0
  - now: 1.0
  - low mk2: 1.2
  - low mk3: 1.1
  - high mk2: 1.2
  - high mk3: 1.0
  - 1.2
  - 1.2
  - 2.2

- **Laverton**: 11.8
  - now: 12.0
  - low mk2: 12.3
  - low mk3: 12.8
  - high mk2: 13.6
  - high mk3: 12.4
  - 12.8
  - 16.7
  - 19.2

- **Melbourne AP**: 14.8
  - now: 15.7
  - low mk2: 15.9
  - low mk3: 17.0
  - high mk2: 17.6
  - high mk3: 16.2
  - 16.5
  - 21.2
  - 23.6

- **Mildura**: 56.6
  - now: 59.5
  - low mk2: 60.3
  - low mk3: 65.5
  - high mk2: 66.9
  - high mk3: 62.3
  - 63.7
  - 84.7
  - 90.5

- **Mt Gambier**: 11.5
  - now: 11.6
  - low mk2: 11.8
  - low mk3: 12.3
  - high mk2: 12.8
  - high mk3: 12.0
  - 12.3
  - 14.0
  - 15.4

- **Moree**: 30.5
  - now: 34.5
  - low mk2: 33.7
  - low mk3: 41.1
  - high mk2: 38.9
  - high mk3: 37.6
  - 36.4
  - 62.8
  - 55.8

- **Nowra**: 8.8
  - now: 8.7
  - low mk2: 9.1
  - low mk3: 9.2
  - high mk2: 10.3
  - high mk3: 8.9
  - 9.6
  - 10.8
  - 14.7

- **Richmond**: 13.3
  - now: 13.8
  - low mk2: 14.2
  - low mk3: 15.2
  - high mk2: 16.3
  - high mk3: 14.5
  - 15.1
  - 20.3
  - 23.6

- **Rockhampton**: 11.2
  - now: 12.0
  - low mk2: 11.9
  - low mk3: 13.2
  - high mk2: 13.5
  - high mk3: 12.4
  - 12.8
  - 18.6
  - 19.4

- **Sale**: 5.4
  - now: 5.4
  - low mk2: 5.7
  - low mk3: 5.9
  - high mk2: 7.1
  - high mk3: 5.7
  - 6.3
  - 8.1
  - 11.1

- **Sydney AP**: 7.6
  - now: 7.8
  - low mk2: 8.1
  - low mk3: 8.3
  - high mk2: 9.4
  - high mk3: 8.0
  - 8.7
  - 9.8
  - 14.2

- **Wagga**: 32.6
  - now: 34.8
  - low mk2: 35.0
  - low mk3: 39.7
  - high mk2: 40.3
  - high mk3: 37.1
  - 37.2
  - 56.3
  - 57.6

- **Willamtown**: 10.3
  - now: 10.8
  - low mk2: 11.2
  - low mk3: 11.5
  - high mk2: 12.8
  - high mk3: 11.3
  - 11.9
  - 13.9
  - 17.8

- **Woomera**: 109.1
  - now: 112.3
  - low mk2: 112.8
  - low mk3: 118.1
  - high mk2: 119.4
  - high mk3: 115.2
  - 115.9
  - 135.4
  - 139.1

- **Per cent change**:
  - now: 196.9
  - low mk2: 205.8
  - low mk3: 260.7
  - high mk2: 306.5
  - high mk3: 306.5

Values for ‘present’ are for 1973–2007. The CCAM (Mark2) results are denoted ‘mk2’ and CCAM (Mark3) results are denoted ‘mk3’. CCAM (Mark2) refers to a high global warming scenario and is most closely related to the U1 scenario in this report. CCAM (Mark3) is a low global warming scenario and is most closely related to the U2 scenario in this report.