AP-R243

IMPACT OF CLIMATE CHANGE ON ROAD INFRASTRUCTURE

AUSTROADS

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Sydney 2004

Impact of Climate Change on Road Infrastructure
First Published 2004

National Library of Australia
Cataloguing-in-Publication data:

Impact of Climate Change on Road Infrastructure
ISBN 0 85588 692 7

Austroads Project No. RSM.S.N.503

Austroads Publication No. AP–R243/04

Project Manager

Mr Gary Norwell, MR WA

Published by Austroads Incorporated
Level 9, Robell House
287 Elizabeth Street
Sydney NSW 2000 Australia
Phone: +61 2 9264 7088
Fax: +61 2 9264 1657
Email: austroads@austroads.com.au
www.austroads.com.au

AUSTROADS PROFILE

Austroads is the association of Australian and New Zealand road transport and traffic authorities whose purpose is to contribute to the achievement of improved Australian and New Zealand transport related outcomes by:

- developing and promoting best practice for the safe and effective management and use of the road system
- providing professional support and advice to member organisations and national and international bodies
- acting as a common vehicle for national and international action
- fulfilling the role of the Australian Transport Council's Road Modal Group
- undertaking performance assessment and development of Australian and New Zealand standards
- developing and managing the National Strategic Research Program for roads and their use.

Within this ambit, Austroads aims to provide strategic direction for the integrated development, management and operation of the Australian and New Zealand road system — through the promotion of national uniformity and harmony, elimination of unnecessary duplication, and the identification and application of world best practice.

AUSTROADS MEMBERSHIP

Austroads membership comprises the six State and two Territory road transport and traffic authorities and the Commonwealth Department of Transport and Regional Services in Australia, the Australian Local Government Association and Transit New Zealand. It is governed by a council consisting of the chief executive officer (or an alternative senior executive officer) of each of its eleven member organisations:

- Roads and Traffic Authority New South Wales
- Roads Corporation Victoria
- Department of Main Roads Queensland
- Main Roads Western Australia
- Department of Transport and Urban Planning South Australia
- Department of Infrastructure, Energy and Resources Tasmania
- Department of Infrastructure, Planning and Environment Northern Territory
- Department of Urban Services Australian Capital Territory
- Commonwealth Department of Transport and Regional Services
- Australian Local Government Association
- Transit New Zealand

The success of Austroads is derived from the synergies of interest and participation of member organisations and others in the road industry.

ACKNOWLEDGEMENTS

This project was funded jointly by Austroads and the Commonwealth Department of Transport and Regional Services.

The project was coordinated by Dr Mark Harvey of the Bureau of Transport and Regional Economics. Dr Harvey authored the Executive Summary. Climate change modelling was undertaken by a team consisting of Dr Peter Whetton, Dr Kathy McInnes, Bob Cechet, Dr John McGregor and Dr Kim Nguyen of the CSIRO Division of Atmospheric Research. Bob Cechet authored the report. Traffic forecasting and pavement modelling was undertaken by a team consisting of Neil Houghton, Craig Lester, Evan Styles, Norbert Michel and Tim Martin of ARRB Transport Research. This team co-authored the report. The section on the impacts of climate change on population was prepared by Dr Bob Birrell of the Centre for Population and Urban Research at Monash University. Anna Heaney and Stephen Beare of ABARE produced the report on the effects of climate change on salinity. The Austroads Project manager was Mr Gary Norwell of Main Roads Western Australia.

EXECUTIVE SUMMARY

There is an increasing body of evidence that the earth's climate is changing with some of the changes attributable to human activities. Climate change can have direct and indirect impacts on road infrastructure.

The direct impacts are due to the effects of the environment. Rainfall changes can alter moisture balances and influence pavement deterioration. In addition, temperature can affect the aging of bitumen resulting in an increase in embrittlement of the surface chip seals that represent more than 90% of the rural sealed roads in Australia. Embrittlement of the bitumen causes the surface to crack, with a consequent loss of waterproofing of the surface seal. The result is that surface water can enter the pavement causing potholing and fairly rapid loss of surface condition. More frequent reseal treatments will ameliorate the problem, but at a cost to road agencies. Changes in temperature and rainfall patterns can interact where higher temperatures increase cracking, which compounds the effects of increased rainfall. This study examines changes in road agency costs as a result of projected climate changes, both temperature and rainfall.

Flood heights and frequencies are important considerations for the location and design of roads and bridges. Sea level rise and increased occurrence of storm surges will affect roads in coastal areas.

Large parts of Australia are affected by salinity, which affects roads in two ways. High water tables reduce the structural strength of pavements, and salt rusts the reinforcement in concrete structures. Climate change will have an impact on salinity because precipitation and evapotranspiration are the main determinants of surface and ground-water flows, which in turn affects salinity levels.

The indirect impacts of climate change on roads are due to the effects on the location of population and human activity altering the demand for roads.

Road infrastructure is a long-lived investment. Roads typically have design lives of 20 to 40 years and bridges of 100 years. An understanding of the expected impacts of future climate change by road planners, designers and asset managers could engender considerable cost savings in the long term. At the broad strategic level, if road providers are forewarned of any costly future effects on existing infrastructure, they can better prepare to deal with them.

The project aims to:

- provide an assessment of likely local effects of climate change for all Australia for the next 100 years, based on the best scientific assessment currently available;
- assess the likely impacts on patterns of demography and industry, and hence on the demand for road infrastructure;
- identify the likely effects on existing road infrastructure and potential adaptation measures in road construction and maintenance; and
- report on policy implications arising from the findings of the project.

The project is the result of collaboration by a number of organisations with expertise in different areas.

- The CSIRO Division of Atmospheric Research produced detailed Australia-wide projections of climate for the next 100 years. These were passed on to three consultants to assess the implications.
- The Monash University Centre for Population and Urban Research investigated the likely effects on population settlement patterns and demographics.
- ARRB Transport Research examined the implications for roads in the National Highway System;
- The Australian Bureau of Agricultural and Resource Economics (ABARE) forecast changes to salinity and agricultural production in the Murray-Darling basin, with the likely effects on road infrastructure;
- The Bureau of Transport and Regional Economics (BTRE) coordinated the project and authored the Executive Summary, Introduction and the Policy Implications chapter.

Climate change forecasts

Methodology

In 2000, the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) produced 40 future emissions scenarios for greenhouse gases and sulfate aerosols based on population, energy and economic models.[1] With current computer resources it is not feasible to run an atmospheric-ocean global climate model (AOGCM) on each scenario. So the IPCC used a highly simplified climate model to develop a range of global warming scenarios.

CSIRO chose one of the higher emissions scenarios, 'A2', in its AOGCM, in order to provide for a significant increase in greenhouse gas emissions during the 21st century and a strong contrast with current conditions. This scenario is predicated on a global population of around 15 billion in 2100 and has no special status as a likely future. Under the A2 scenario, the *rate* at which carbon dioxide is released into the atmosphere grows steadily over the next 100 years, increasing nearly fourfold. These emissions in turn provide a strong radiative forcing signal for the establishment of regional climate change patterns over the Australian continent.

CSIRO's AOGCM is a comprehensive general circulation model that contains atmospheric, oceanic, sea-ice, and biospheric submodels. For the atmospheric model, the globe is divided up into a grid comprised of squares about 300 kilometres wide. For each square there are nine layers extending up into the atmosphere. For each rectangular block, there is a suite of parameters such as temperature, air pressure, wind velocity, water vapour content and so on. The oceanic model has 12 vertical layers. With a time step of 30 minutes, the AOGCM required three months to run on a supercomputer from the period 1870 to 2100. For each block, pressure, temperature, and moisture, plus a suite of surface properties were saved at 6-hourly intervals over the 230 year period.

Results from the AOGCM were used to 'nudge' CSIRO's atmospheric Conformal-Cubic General Circulation Model (GCM). In this model, the grid is stretched to provide high resolution over Australia (squares of about 50 kilometres), but lower resolution for the rest of the world (squares of around 800 kilometres on the far side of the globe). To avoid errors introduced by the lack of detail over the rest of the world, winds outside of Australia were 'nudged' to make them consistent with winds in the AOGCM.

Outputs were monthly means of average, maximum and minimum temperature, precipitation, solar radiation, and potential and actual evaporation for each grid point. These were expressed in terms of local temperature change or percent for rainfall/radiation/evaporation change *per degree of global warming*. Expressing them per degree of global warming means that, for any IPCC scenario, a forecast can be derived for any grid point over the next 100 years. Also, from the upper and lower limits and average of the envelope of IPCC global warming scenarios, one can obtain ranges and mid-points of changes over time.

Key findings

Overall, Australia is expected to become hotter and drier. The key results for temperature and rainfall are presented in map form in figures 1 and 2. The simulation employed in this study forecasts that average annual temperatures will increase by 2º to 6ºC by 2100. Warming will not be uniform with Tasmania and coastal zones least affected and inland areas most affected. This compares with the results of an earlier study over the Australian continent examining many scenarios and many general circulation models (CSIRO 2001) which indicated that annual average temperatures were predicted to increase by 1.0 to 6.0ºC over most of Australia by 2070.[2] More extremely hot days and few cold days are expected. For example, the average number of summer days over 35°C in Melbourne is likely to increase from 8 at present to 10–20 by 2070.

[1] The IPCC methodology has been criticised as being based on unrealistically high assumptions for long-term economic growth, particularly for developing countries. See Castles and Henderson (2003), The IPCC Emission Scenarios: An Economic-Statistical Critique, *Energy & Environment*, Vol. 14, Nos. 2 & 3, pp. 159-185. Also see the IPCC response to these criticisms, Nakicenovic, N. et al. (2003), IPCC SRES Revisited: A Response, *Energy & Environment*, Vol. 14, Nos. 2 & 3, pp.187-214."

[2] CSIRO 2001, *Climate projections for Australia*. Climate Impact Group, CSIRO Atmospheric Research, Melbourne, 8 pp. http://www.dar.csiro.au/publications/projections2001.pdf.

The average number of winter days below 0°C in Canberra is likely to drop from 44 at present to 6–38 by 2070.

There is forecast to be a general reduction in rainfall over most of the continent, except for the far north where there will be significant increases. These results may be compared to those obtained with other, less detailed, climate models for the Australian region. Rainfall decreases for Australia are predicted in most models, although some models show extensive areas of increase in northern areas.

In places where average rainfall increases, there will be more extremely wet years. There are also likely to be tropical cyclones of greater intensity, leading to an increase in the number of severe oceanic storm surges in the north. There will be more frequent, or heavier, downpours. Conversely, there will be a higher frequency of droughts in regions where average rainfall decreases.

Evaporation is projected to increase over most of the country, adding to moisture stress on plants, and to drought.

Sea level rise and storm surges

Although not directly simulated in the CSIRO simulations, the findings of the IPCC indicate that sea level is projected to rise by 9 to 88 cm by 2100, or 0.8 to 8.0 cm per decade. These projections take into account the range of emission scenarios as well as model uncertainties.

Tropical cyclones are associated with the occurrence of oceanic storm surges, gales and flooding rains in northern Australia. Projecting future tropical cyclone behaviour is difficult since these systems are not well resolved by global or regional climate models. Present indications are:

- regions of origin are likely to remain unchanged;
- maximum wind-speeds may increase by 5–20 per cent in some parts of the globe by the end of the century; and
- preferred paths and poleward extent may alter, but changes remain uncertain.

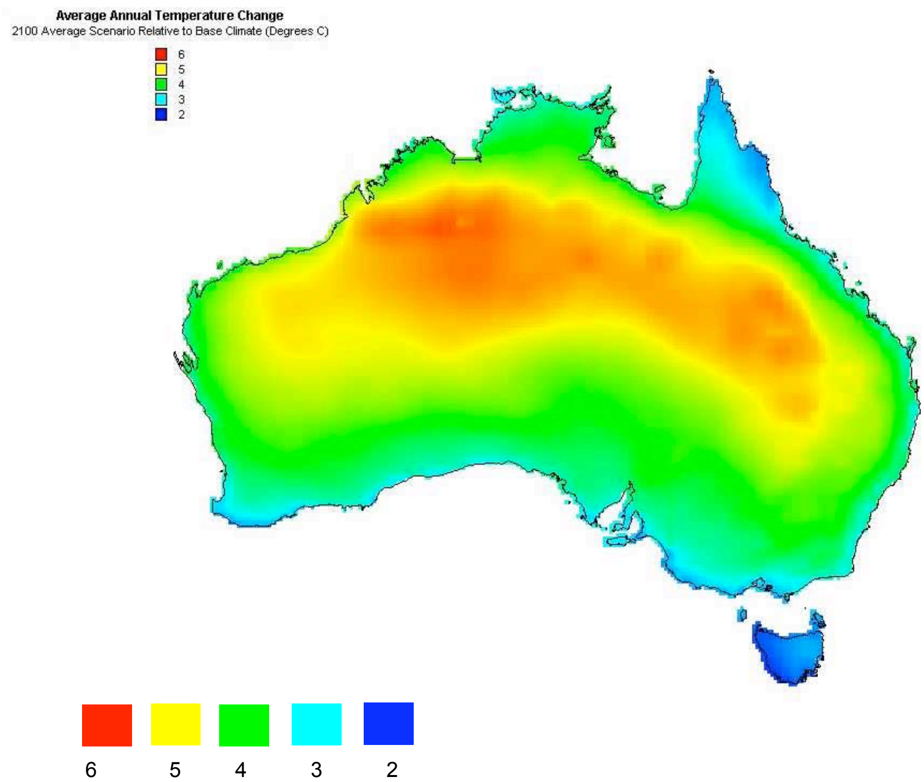

Figure 1 Temperature Changes (Year 2100 relative to base climate) under the A2 scenario

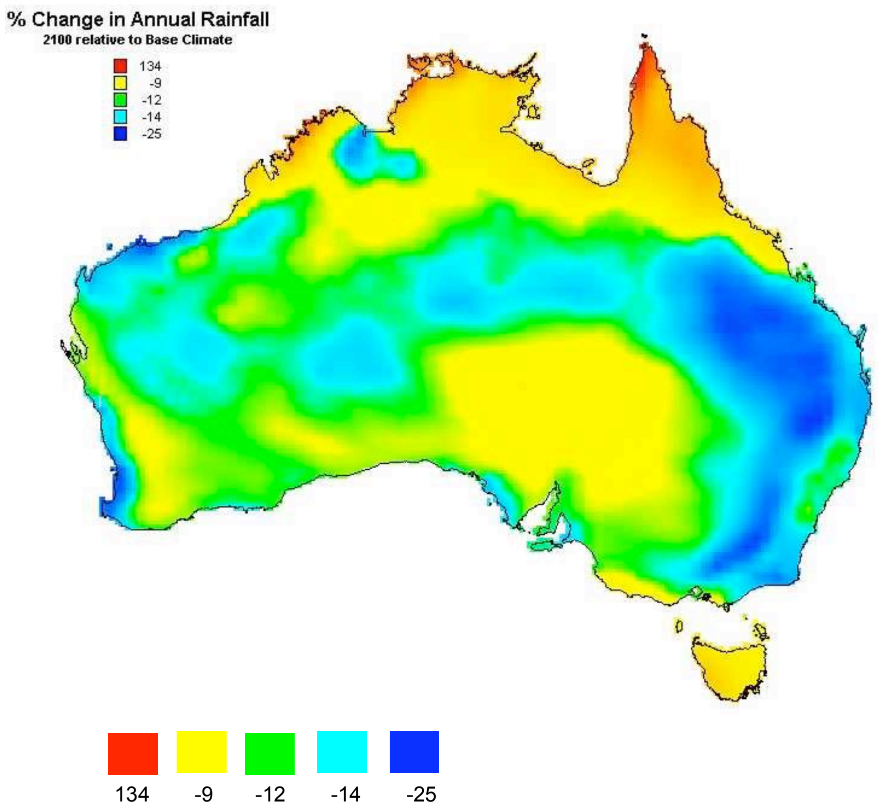

Figure 2 Percentage changes in average annual rainfall 2000–2100 under the A2 scenario

Impacts on population and settlement patterns

Methodology

The Monash University Centre for Population and Urban Research reviewed the factors shaping Australia's population outlook and settlement patterns: fertility, mortality, and international and internal migration movements. Population projection scenarios (based partly on ABS projections and supplemented by the ANU demographic projection software) were developed for Australia as a whole, States and major metropolises. Adjustments were made to the projections for eight major metropolitan regions to reflect the impact of forecast climate change. The adjustments were based on expert judgement supported by a comfort index ('relative strain index'), which is a function of temperature and humidity. The underlying theory is that a comfortable climate is a major driver of internal migration. For example, part of the current attraction of Cairns, the Gold and Sunshine coasts is their life-style promise, of which the climate is a major factor.

Key findings

The analysis in this report builds on a central projection for Australia's population, which assumes that the Total Fertility Rate will fall to 1.6 and stabilise at that level and that net overseas migration will be 90,000 per year over the 21st century. The population projected on these assumptions grew throughout the 21st century from 19.1 million in 2000 to 27.3 million in 2100. Industry restructuring trends in Australia strongly favour further metropolitan population concentration, so there will be a greater concentration of Australia's population in the four major metropolises (Sydney, Melbourne, Brisbane and Perth). There will be a significant increase in the share of Australia's population living in Queensland. To the extent that population growth occurs outside the four major metropolises, the location is mainly in non-metropolitan Queensland and to a lesser extent in non-metropolitan Western Australia. Projections were prepared for each of Australia's metropolises, which assessed the demographic implications of these assumptions.

With Australia generally becoming hotter and drier, total net migration from overseas is forecast to be lower, and hence the total population will be lower. No estimate was made of this for Australia as a whole.

Table 1 shows the adjustments made to 2100 population forecasts to account for climate change.

Table 1 Population (with and without Climate Change effects)

Selected Statistical Division	2100 Population as a percentage of 2000 population (no climate change)	Year 2100 population adjustment factor (with climate change)	Climate change factors driving population change
Sydney	159%	1.00	Temps higher but not expected to affect population growth
Melbourne	125%	1.15	Temperatures higher resulting in more attractive climate
Brisbane	211%	0.96	Temperatures higher resulting in less attractive climate
Moreton	305%	0.98	Temperatures higher resulting in less attractive climate
Adelaide	63%	0.79	Restricted water supply, especially in Spring
Perth	195%	0.88	Less attractive climate; restricted water supply
Darwin	275%	1.34	Temps high but heavy rainfall drives increased agriculture
ACT	93%	1.00	Temps higher but not expected to affect population growth
Cairns	279%	0.83	Temperatures higher resulting in less attractive climate

Of the eight metropolitan regions assessed, only Darwin and Melbourne gain population as a result of climate change. Coastal areas to the south, including the mid to north NSW coast, southern NSW coast and Victorian coast are all likely to become more attractive. Their climates are expected to become more like that in south-east Queensland today.

Hotter and wetter conditions will make Darwin less attractive for human settlement. However, the higher rainfall in the northern Australia combined with less rainfall in much of central and southern Australia should promote agricultural production in the north, enhancing Darwin's role as an administrative and service centre. Hence a 34 per cent upward adjustment was made to the Darwin population forecast for climate change.

Climate change in Melbourne and its hinterland will make it a more attractive area in which to live and thus is likely to favour population growth. The suburban frontier of Melbourne can be extended to the east towards the LaTrobe Valley on largely pastoral land suitable for urban development. This will require changes in existing land use zonings. Assuming this occurs, Melbourne is likely to lose less people per annum to other states than in the stable climate scenario.

Sydney and ACT population projections are not expected to be affected.

The 16 per cent (medium projection) forecast decline in annual rainfall for Adelaide will add to its water supply problems causing an even greater projected population loss.

A relatively high increase in average temperature from 17.0° to 21.1° by 2100 for Perth, combined with sharply lower annual rainfall will mean pressure on the already limited water supply. Consequently, slightly lower overseas and interstate migration is expected.

In the absence of any climate change, south-east Queensland is forecast to be the fastest growing region of Australia. As south-east Queensland warms, the coastal areas of Moreton will become more attractive. At the same time, the ample land for development to the west of Brisbane will become hotter and drier and hence less attractive. The consequence will be increased development pressures along the Gold Coast and Sunshine Coast over the first half of the 21st century. With land limited, there will be pressures for more high rise units, and settlement in north and mid-NSW. There is projected to be little change in the comfort index. With warmer conditions forecast for coastal regions of south-east Australia, there will be less incentive to move north. Small negative adjustments have therefore been made to the population projections for the Moreton region as a whole and for Brisbane.

Anticipated temperature increases, sharp increases in summer rainfall and associated likelihood of flooding will diminish the attractiveness of Cairns for permanent settlement.

The climate projections show sharply increased temperatures and lower rainfall levels for inland southern Australia, which includes the main 'wheat-sheep' productive zone. Since large areas of this zone are already at the current climatic margin for cereal production, it is likely that a further trend towards a warmer, drier climate will lead to lower production. This will exacerbate the tendency towards concentration in metropolitan areas. The ABARE study in this report confirms this conclusion.

In summary, the Monash University Centre for Population and Urban Research advises that the areas expected to gain population as a result of climate change are NSW and Victorian coastal regions, and the northern part of Northern Territory. Areas expected to lose population are Perth, Adelaide, Queensland and inland southern and central Australia in general. It should be noted that the adjustments made are, for the most part, small in relation to increases predicted to take place in the absence of climate change.

Impacts on road transport demand

Methodology

ARRB Transport Research estimated the impact of the climate-adjusted population projections on the demand for road use. Origin–destination population factors were developed between the eight metropolitan areas assessed following a gravity model approach. If one population A increases by ΔA and another population B increases by ΔB, then the passenger traffic between the two centres increases by $(A+\Delta A)*(B+\Delta B)/(A*B)$.

Passenger and freight tasks were considered separately. Car ownership per capita was forecast to reach saturation point of 550 cars per 1000 persons around 2030. Adjusting for changes in per capita ownership, car travel increases could be forecast from population growth figures.

The freight task was estimated using the same origin–destination population factors combined with a predicted increase in freight per capita. Road freight *per capita* is forecast to continue rising until 2060 and thereafter to stabilise. It was assumed that, in the future, fewer vehicles would be needed to transport the same volume of freight, compared to the number required in the year 2000. This is due to a combination of larger vehicles in the future, higher utilisation rates, and higher mass limits. The proportions of B-doubles in the truck fleet and mass limits are rising, but these trends were not assumed to continue beyond 2020. This approach did not consider changes in freight movement as a result of changes in primary production that may arise as a result of climate changes.

Key findings

The future of road freight demand is the single most significant variable in assessing the future of road maintenance costs. Projecting road freight demand to 2100 is highly speculative and ARRB TR warns that actual outcomes in 2100 could vary substantially.

Generalising across the National Highway System, this report assumes, conservatively, that:

- demand will increase most in Queensland and moderately in the Melbourne–Sydney corridor, decline around Adelaide, and increase only slightly on the inter-capital routes from Perth;
- the proportion of heavy freight vehicles will rise slightly, from 12.1 to 13.9 per cent;
- average freight payload will rise by about 25 per cent from 2000 to 2100, with most of this gain occurring in the next decade; and
- average 'Equivalent Standard Axles' (ESAs) per articulated truck will double due to higher axle mass limits.

Impact on pavement performance

Methodology

A wetter climate leads to a higher rate of pavement deterioration, both as function of time and as a function of the load in equivalent standard axles (ESAs). For modelling purposes, climate is represented by the 'Thornthwaite moisture index', which is a function of precipitation, temperature and potential evapo-transpiration. The latter depends on a range of factors including temperature and length of daylight hours. Across Australia, the index varies from +100 on Cape Yorke Peninsula to –50 in central Australia. ARRB TR used the CSIRO data to adjust values of index for climate change. Index values were interpolated for locations on the National Highway System. Roads in areas with higher value for the Thornthwaite index will deteriorate faster than those with a lower value for the same traffic loading.

The pavement modelling was undertaken using two approaches. The first was the ARRB TR pavement life-cycle costing (PLCC) model and the second using the Highway Development and Management 4 (HDM4) model. The former was used to assess pavement performance at a network level and the latter to assess selected road lengths at a more detailed level.

The PLCC model estimates life-cycle road agency costs (maintenance and rehabilitation) and road-user costs (travel time and vehicle operation) based on roughness predictions for a set of defined road categories. The present value of combined road agency and user costs is calculated for a 60-year analysis period assuming a 7 per cent real discount rate. The model selects treatment options and timings to minimise the present value of costs subject to any specified constraints on maximum roughness or annual agency budget limits. To analyse the entire National Highway System, the network was split into 60 different road 'sections', each section having similar climate characteristics, traffic levels, vehicle mix and pavement characteristics.

The HDM4 analysis was also undertaken on the basis of minimising the present value of the sum of road agency and user costs. The main difference between the PLCC and HDM4 approaches to maintenance is that the latter employs a much more detailed pavement deterioration algorithm. HDM4 uses a set of interdependent algorithms covering roughness, rutting, cracking, potholing, ravelling, strength and so on, and consequently has much more detailed data requirements. By contrast, the deterioration algorithm in the PLCC model has roughness as a function of pavement age, cumulative ESAs, the Thornthwaite index and annual average maintenance expenditure as a surrogate for agency maintenance treatments. Eight road segments, one from each state and territory, located in or near a metropolitan area, were analysed in detail using the HDM4 model. Site-specific predicted changes in Thornthwaite index, AADT and per cent heavy vehicles were used in the model.

As pavement deterioration in the models depends on both the Thornthwaite index and ESAs, both the direct and indirect effects of climate change on pavements come into play. Although trucks and not cars add to ESAs and so contribute to pavement deterioration, car traffic has an impact on the timing and types of maintenance treatments where the model is set up to minimise the present value of the sum of road agency and road user costs. Since increased roughness adds to road user costs for cars, higher volumes of car traffic will justify maintaining the road at a higher standard leading to greater agency costs.

Limitations of the analysis of impacts on pavement performance include that:

- effects of weather extremes such as severe storms and flooding have not been taken into account;
- road agencies may not develop maintenance programs to minimise the present value of costs. Budget constraints may lead to short-term underspending on maintenance at the expense of higher costs in the long term, while social and equity considerations may lead to less trafficked parts of the National Highway System being maintained at higher standards than can be economically justified;
- reliable and accurate calibration of the pavement deterioration algorithm for conditions in each state has not yet been completed;
- design pavement strengths have been assumed to remain unchanged. Where forecast pavement deterioration is expected to be higher due to truck traffic or the environment, road agencies would be expected to build stronger pavements, substituting capital for maintenance costs. The assumption of constant pavement strengths implies that if heavy vehicle traffic changes in response to climate change (for example through changes in population settlement patterns), then existing pavements will reach the end of their useful lives earlier requiring rehabilitation, also increasing costs to road agencies; and

- no allowance has been made of expansion of the number of lane-kilometres to cater for increased demand for road capacity. A greater surface area of pavement will add to maintenance costs, but spreading the truck traffic over a greater surface area should counteract this effect.

Key findings

The drier climate leads to negative changes in Thornthwaite index values over most of the continent. Areas of greatest negative change include the south-west of WA, north-east Victoria, and southern NSW. The greatest positive changes occur in south-west Tasmania and the top end of Queensland. The index in the central area of Australia is projected to change little.

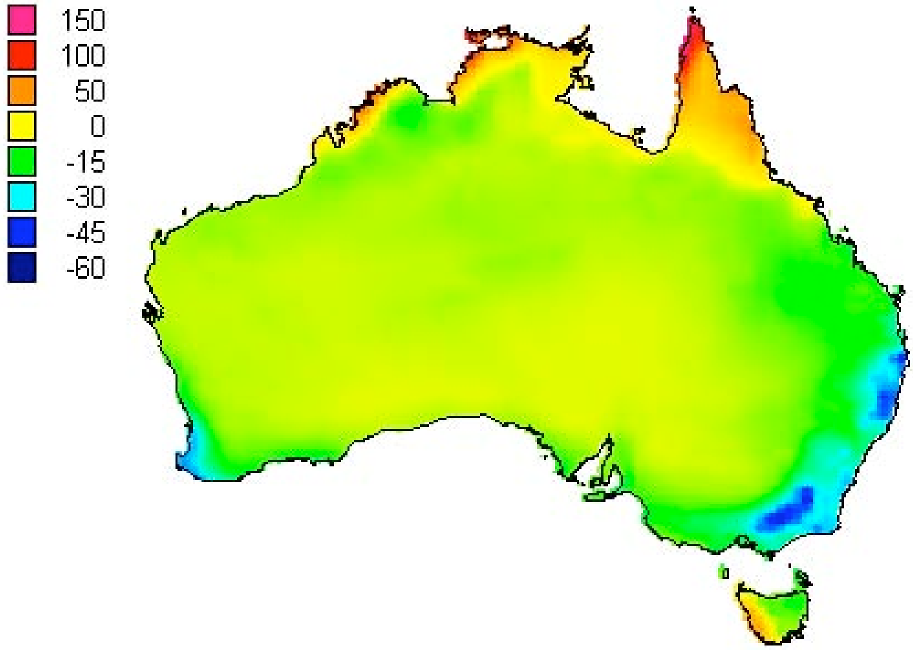

Figure 3 Changes in Thornthwaite Index (2000 to 2100) under the A2 scenario

Table 2 below shows optimal agency costs in each State/Territory for 2000 climate and population levels compared with 2100 climate with adjusted 2100 population levels, as estimated from the PLCC model. It should be noted that these results do *not* compare scenarios with and without climate change. They compare 2000 traffic volumes and climate with 2100 climate-adjusted traffic volumes and climate.

Table 2 Optimal agency costs (PLCC model)

State	Optimal Agency Cost ($million)		Change
	Base Climate	2100 Climate	
NSW	72.3	90.1	25%
VIC	32	37.6	18%
QLD	82	124.2	51%
WA	48.3	56.1	16%
SA	27.6	23.4	-15%
TAS	6.5	6.8	5%
NT	17.9	37.3	108%
ACT	0.6	0.7	17%
Total	287.3	376.1	31%

The Northern Territory and Queensland experience large increases, primarily driven by population growth, though the forecast wetter climate in the far north also plays a role. The decline in South Australia reflects the smaller population and drier climate.

The PLCC model produces separate results for both maintenance and rehabilitation of pavements. The maintenance expenditures refer to pavement-related expenditure on routine and periodic maintenance activities, such as pothole patching, kerb and channel cleaning, patching, surface correction and resealing. Rehabilitation refers to chipseal resheeting and asphalt overlays, depending upon the pavement type. For Australia as a whole, there is not predicted to be any change in the split between maintenance and rehabilitation funding (35:65) arising as a result of climate change and traffic growth. However, the picture is different for individual states. The rehabilitation proportion is forecast to rise (maintenance proportion to fall) significantly for Tasmania and conversely for Western Australia. This is largely a reflection of differences in the pavement age distribution and life times of pavements.

Results from the HDM4 analysis are presented in table 3. Road agency costs are presented as undiscounted total costs (expressed in $'000 per kilometre) for a 20 year analysis period. The results show that road agency costs can change considerably under the 2100 traffic and climate scenario, as shown by the NSW segment for which costs are 57 per cent higher. The Northern Territory cost is virtually unchanged, despite a fourfold increase in traffic. This may be due to pavements in the Northern Territory having adequate capacity for the projected increased traffic. It might also be noted that changes in passenger car traffic have no effect on pavement deterioration rates. Most of the change in road user costs is associated with increases in traffic, as these are total costs not costs per vehicle.

Parts C and D of table 3 show the results with the Thornthwaite index held constant. They show that the environmental effects of climate change on agency and road user costs are minuscule. Virtually all of the changes come about from population growth leading to traffic increases.

Table 3 Results of HDM4 analysis

A. Road Agency Costs

	Total Road Agency Costs ($ '000)		
	Base Climate	2100 Climate & Traffic Changes	
	Base Alternative	Base Alternative	Change
ACT_04	97.8	97.8	0%
NSW_03	46.2	72.8	57%
NT_01	176.6	177.1	0%
QLD_15	83.6	106.1	27%
SA_29	99.0	96.8	-2%
TAS_05	140.2	159.4	14%
VIC_14	128.7	177.3	38%
WA_01	205.9	244.1	19%

B. Road User Costs

	Total Road User Costs ($m)		
	Base Climate	2100 Climate & Traffic Changes	
	Base Alternative	Base Alternative	Change
ACT_04	33.0	33.8	2.53%
NSW_03	32.5	60.2	85.28%
NT_01	19.6	87.2	344.22%
QLD_15	43.8	131.7	200.48%
SA_29	56.1	30.9	-45.01%
TAS_05	18.0	20.3	13.23%
VIC_14	41.6	72.0	73.03%
WA_01	36.4	50.1	37.57%

C. RA Costs (Traffic Changes Only)

	Total Road Agency Costs ($ '000)		
	Base Climate	2100 Traffic Changes Only	
	Base Alternative	Base Alternative	Change
ACT_04	97.8	97.8	0%
NSW_03	46.2	72.7	57%
NT_01	176.6	176.9	0%
QLD_15	83.6	103.1	23%
SA_29	99.0	96.8	-2%
TAS_05	140.2	159.5	14%
VIC_14	128.7	175.5	36%
WA_01	205.9	244.5	19%

D. RUC Costs (Traffic Changes only)

	Total Road User Costs ($m)		
	Base Climate	2100 Traffic Changes Only	
	Base Alternative	Base Alternative	Change
ACT_04	33.0	34.1	4%
NSW_03	32.5	60.8	87%
NT_01	19.6	87.0	343%
QLD_15	43.8	123.4	182%
SA_29	56.1	31.3	-44%
TAS_05	18.0	20.3	13%
VIC_14	41.6	74.2	78%
WA_01	36.4	50.5	39%

Impact on salinity in the Murray–Darling Basin

Methodology

To forecast effects of climate change, ABARE incorporated the CSIRO forecasts into its Salinity and Landuse Simulation Analysis (SALSA) model of the Murray–Darling basin. The area covered by the model extends across four states from the Condamine–Culgoa catchment in southern Queensland clockwise around the eastern edge of the basin to the Avoca catchment in Victoria. Irrigation areas within each of these catchments are also represented. The SALSA model also includes the Victorian Mallee and South Australian Riverland irrigation areas immediately adjacent to the Murray River that extend from Nyah downstream to

Morgan. The area covered represents a substantial part of the Australian landmass and the methodology could be employed for other catchments.

The model consists of a network of land management units linked through overland and ground water flows. The hydrological component incorporates relationships between rainfall, evapotranspiration, surface water run-off, irrigation, the effects of landuse change on ground water recharge and discharge rates, and the processes governing salt accumulation in streams and soil. The climate projections were incorporated into the model via two variables: rainfall and evapotranspiration. The excess of precipitation over evapo-transpiration is split between surface water flows and groundwater recharge, depending on the land type and slope profile of each land management unit. The rate of flow of groundwater depends on hydraulic gradients, which can be very flat in the lower parts of the catchment, requiring perhaps several hundred years to come into equilibrium (recharge equal to discharge) following a change in recharge.

The hydrological processes in the model are integrated with economic models of landuse. Landuse is allocated to maximise economic return from the use of agricultural land and water for irrigation. Each land management unit is managed independently to maximise returns given the level of salinity of available land and water resources, subject to any landuse constraints. Incorporated into this component is a relationship between yield loss and salinity for each agricultural activity. Thus, landuse can shift with changes in the availability and quality of both land and water resources. The cost of salinity is measured as the reduction in economic returns from agricultural activities from those that are currently earned.

The model was run twice to enable comparisons to be made: a baseline simulation with precipitation and climate held constant, and a climate change simulation.

Key findings

In the baseline scenario, net production revenue in present value terms is forecast to fall by almost 3 per cent between 2000 and 2100. High water tables reduce agricultural yields in both irrigation and dryland regions. Increasing salt concentration of surface water flows reduces yields from irrigation, also leading to a reduction in economic returns. In response to the increase in soil salinisation and instream salinity, there is expected to be a gradual switch out of pasture into cropping activities as they offer a higher marginal return under these conditions. This change in land use is likely to occur in both irrigated and dryland parts of the basin.

Under the climate change scenario, the present value of net production revenue falls by 11 per cent between 2000 and 2100. The effects of climate change vary considerably across catchments, with the loss in agricultural revenue being generally higher in the Darling River tributaries. A reduction in available surface water flows results in a proportional reduction in the volume of water available for irrigation. Land engaged in the lowest returning irrigated activity in each catchment would be switched into lower returning dryland activities. Catchments predominantly engaged in high value cropping, such as cotton production or horticulture would be particularly affected by reductions in available water.

The effects of climate change on salt concentration of river flows are mixed. There is less surface water to dilute existing salt loads leading to increased salt concentration in both the Darling and Murray Rivers in comparison to the baseline. In addition to reducing yields from irrigated production, increased salt concentration of surface water flows will also have an impact on infrastructure (eg. bridges) and the riverine environment.[3]

However, changes in precipitation and evapotranspiration reduce the volume of ground water recharge and, over time, the volume of ground water discharge. A reduction in the volume of ground water discharge generates salinity benefits. Ground water discharge transports salt to the river by direct seepage or by surface discharge that eventually reaches the river system. In the model, salt loads in the Murray River began declining between 2050 and 2100, relative to the baseline, as decreases in recharge were gradually reflected

[3] Other studies have examined the effects of rising water tables and dryland salinity on major infrastructure including roads. The interested reader is referred to the work of the National Land and Water Resources Audit (www.nlwra.gov.au).

in decreases in discharge. However, as there is less surface water available to dilute the salt, the reduction in salt load is not sufficient to improve the water quality of the Murray River, even in the longer term.

A reduction in recharge also means that water tables will be lower, which lessens the accession of saline ground water into the landscape. There is little difference in the area affected by high water tables between the baseline and climate change scenarios over the first 50 years, but by 2100, the area affected by high water tables under changed climate conditions is predicted to be almost 20 per cent lower than the baseline. There is, however, considerable variation in the reduction in the area of high water tables between catchments.

The compounding effects of the long response times and uncertainty in climate change science are likely to make any policy responses to declining water availability and quality difficult to design and implement.

Policy implications

Uncertainty

Any set of forecasts is subject to uncertainty in varying degrees. This report is no exception. There are considerable uncertainties throughout the whole process described, and these uncertainties are compounded as outputs from one model become inputs to other models and so on. The first level of uncertainty comes about from the choice of emissions scenario. The Intergovernmental Panel on Climate Change has published a wide range of scenarios, but only one could be used as the basis for modelling. The particular scenario chosen is one of the highest with an almost fourfold increase in the rate of emissions between now and 2100. Under the lowest scenarios, emissions in 2100 fall to below the current level. A second level of uncertainties relates to the climate forecasts from the CSIRO model. Further levels of uncertainty are introduced by the modeling processes that take the CSIRO forecasts as inputs to estimate impacts on road pavements and salinity. The population forecasts represent one particular Australian Bureau of Statistics scenario, modified by ‘expert judgement’ to take account of climate change. The traffic forecasts used for the pavement modelling were developed from the population projections introducing a further level of modelling uncertainties.

The numerical results in the report should therefore be regarded as broad indications only, and even the qualitative conclusions should be treated with caution. All things considered, the study should be regarded as telling a story about a possible future, from which can be gleaned some indications of likely directions over the coming 100 years.

Demand for road use

The main driver of road investment and maintenance needs is population growth and freight generated by new developments and productivity. The associated greater levels of car and truck traffic give rise to needs for investment in road capacity expansion and stronger pavements, and for higher standards of maintenance. ABS Population projections have the south-east Queensland, Cairns and Darwin regions expected to grow most over the next 100 years. There will be increasing concentration of population in the four major metropolises of Brisbane, Sydney, Melbourne and Perth, and a decline for Adelaide and inland areas in general.

When climate change is overlaid on this scenario, population forecasts for Darwin and Melbourne are adjusted significantly upward and those for Adelaide, Perth and Cairns, downward. The largest adjustments for climate change are Darwin with plus 34 per cent, and minus 21 per cent for Adelaide. To put these adjustments into perspective, unadjusted 2100 population forecasts for the eight metropolitan areas as a percent of 2000 levels, range from 63 per cent for Adelaide to 305 per cent for Moreton. After adjusting for climate change, the range becomes 50 per cent for Adelaide to 369 per cent for Darwin. This shows that climate change is by no means the most important factor influencing future population levels.

With the north of Australia expected to become wetter, the northern part of the Northern Territory could become an important agricultural centre. The hotter, drier climate will have an adverse impact on agriculture in general, which is likely to reduce road demand in inland areas. However, use of drought resistant, higher yielding strains of grain could be a mitigating factor.

Road design and maintenance

Theoretically, rates of pavement deterioration should slow as rainfall decreases, saving on maintenance costs. In the long term, design thicknesses for new pavements could possibly be reduced. However, these effects over the next 100 years are expected to be so small as to have negligible impact on the costs of road provision.

An exception is those areas forecast to become wetter, the far northern parts of Australia. Here, costs of pavement maintenance and construction may increase. Also in these areas, the capacity of existing culverts and waterways may prove inadequate.

The life of bituminous surface treatments is affected by ambient temperature. An increase in temperature will accelerate the rate of deterioration of seal binders and require earlier surface dressings/reseals, which will lead to higher maintenance costs.

Sea level rise could be a concern for low-lying roads in coastal areas, particularly if the rise by 2100 is towards the upper end of the projected range of 9 to 88 cm. The problem may be worse in northern Australia if wind speeds become higher during storm surges. Planners and designers of roads and causeways in low-lying coastal areas can take account of projected rises in sea level over the lives of assets. The impact on existing roads and causeways can be taken into account at the time they require rehabilitation or improvement. Clearances for new bridges over tidal water should take into account the potential rise in sea level over the life of the bridge, usually 100 years.

In the absence of climate change, ABARE modelling forecasts that the area affected by high water tables in the Murray–Darling catchment will rise from 1.1 million hectares to 5.3 million hectares by 2100, almost a fivefold increase. The expected effect of a hotter, drier climate is to reduce the forecast 2100 amount to 4.4 million hectares (almost a fourfold increase compared with the year 2000 amount). Thus, while climate change may mitigate salinity problems, the effect is nowhere near sufficient to reverse the rising trend.

Higher water tables can accelerate the rate of pavement deterioration due to capillary action increasing the moisture content of pavements. Road agencies may need to raise the levels of existing embankments when pavements reach the ends of their useful lives. The design of new roads should provide for anticipated rises in water tables in susceptible areas. This will increase construction costs.

Another manifestation of the salinity problem is increased salt concentrations in rivers. Climate change may exacerbate this problem because, with less rain to dilute surface salt, surface water flows are predicted to become saltier. Steel reinforcing in concrete structures in riverine environments may therefore be more prone to corrosion. Road agencies might consider ways to better protect reinforcing in saline environments.

Further research

If further research into the effect of climate change on roads is to take place, the most worthwhile area appears to be the impact on flooding. Bridges, causeways and alignments are the most long-lived features of road infrastructure, and knowledge of future changes in flood heights and frequencies will be valuable information for planners.

TABLE OF CONTENTS

1. INTRODUCTION

There is an increasing body of evidence suggesting that the earth's climate is changing with some of the changes attributable to human activities. The concentration of carbon dioxide in the atmosphere today is likely to be higher than it has been for the past 20 million years and the current rate of increase of carbon dioxide is greater than at any time in the past 20,000 years. Climate models predict that increasing atmospheric concentrations of greenhouse gases will lead not only to global warming, but also to changes in climatic variability and the frequency, intensity and duration of extreme events such as hot days, heat waves, and heavy storms.

Climate change can have direct and indirect impacts on road infrastructure. The direct impacts are due to the effects of the environment, primarily moisture, which weakens flexible pavements, rendering them more susceptible to damage by heavy vehicles and shortening their lives. There are other effects as well. Temperature affects aging of bitumen through oxidisation and embrittlement. Flood heights and frequencies are important considerations for the location and design of roads and bridges. Large parts of Australia are affected by salinity, which affects roads in two ways: high water tables reduce the structural strength of pavements and salt rusts the reinforcing in concrete structures.

The indirect impacts of climate change on roads are due to the effects on the location of population and human activity altering the demand for roads.

Road infrastructure is a long-lived investment. Roads typically have design lives of 20 to 40 years and bridges of 100 years. An understanding of the expected impacts of future climate change by road planners, designers and asset managers could engender considerable cost savings in the long term. At the broad strategic level, if road providers are forewarned of any costly future effects on existing infrastructure, they can better prepare to deal with them.

1.1 Objectives of the project

The project aims to:

- provide an assessment of likely local effects of climate change for Australia for the next 100 years, based on the best scientific assessment currently available;
- assess the likely impacts on patterns of demography and industry, and hence on the demand for road infrastructure;
- identify the likely effects on existing road infrastructure and potential adaptation measures in road construction and maintenance; and
- report on policy implications arising from the findings of the project.

Only the roads included in the National Highway System were modelled; however, the general findings are applicable to the rest of the road network.

1.2 Structure of the project

This project is the result of collaboration by a number of different organisations with expertise in different areas:

- The CSIRO Division of Atmospheric Research ran its global climate change models to produce forecasts of climate on a grid of about 50 kilometres up to 2100. The resultant data was passed on to three consultants to assess its implications.
- The Monash University Centre for Population and Urban Research investigated the likely effects on population settlement patterns and demographics.
- ARRB Transport Research used these population projections to forecast changes in road transport demand. It also calculated changes to an index of climate from the CSIRO data. The road demand and climatic indexes were together used in pavement deterioration models to predict the implications for pavement deterioration and maintenance expenditure needs.

- The Australian Bureau of Agricultural and Resource Economics (ABARE) employed its hydrological–economic model of the Murray-Darling basin to forecast implications of climate change for salinity and agricultural production in the region, and related this to road infrastructure.
- The Bureau of Transport and Regional Economics (BTRE) coordinated the project and authored the Executive Summary, Introduction and the Policy Implications chapters.

Figure 1.1 is a digramatic representation of the project's structure.

There are other potential impacts of climate change on roads not investigated by this project:
- The data could be used to examine the implications for flooding in particular areas. This requires first a hydrological model of the catchment to predict flooding heights, durations and water velocities, and second, a model of the topology of the area that relates flood heights to local road infrastructure.
- The Murray-Darling basin covers a large proportion of the Australian land-mass, but there many areas outside that Murray-Darling basin affected by salinity.
- Effects of climate change on agricultural industries outside the Murray-Darling Basin and implications for the demand for road use could be investigated in much more detail.
- The CSIRO models do not provide forecasts for sea level rises expected to result from climate change, nor for the likelihood of changes in storm activity, though CSIRO has provided information on these based on current scientific views.

Individuals or organisations wishing to make use of the CSIRO data for research purposes may obtain a copy by email at no charge by contacting either the Austroads head office or the BTRE.

1.3 Structure of the report

This report is a compilation of the reports of the different consultants in the order: CSIRO (section E), ARRB Transport Research (sections A to D) and ABARE (section F). The report from Monash University Centre for Population and Urban Research appears as section B of ARRB TR's report, because Monash University was subcontracted by ARRB TR. Being a compilation of consultants' reports, each report commences with its own executive summary. The BTRE's 'Policy Implications' chapter concludes the report.

A summary of the findings regarding future climate change arising from the CSIRO data appears as section 3.4 of this report (section A of ARRB TR's report).

The consultants generated a large volume of appendices, containing many pages of diagrams and tables. Only one appendix has been published in this report: section 3.5.4 (appendix B1). The appendices not included in this volume may be downloaded from the Austroads internet site: www.austroads.com.au.

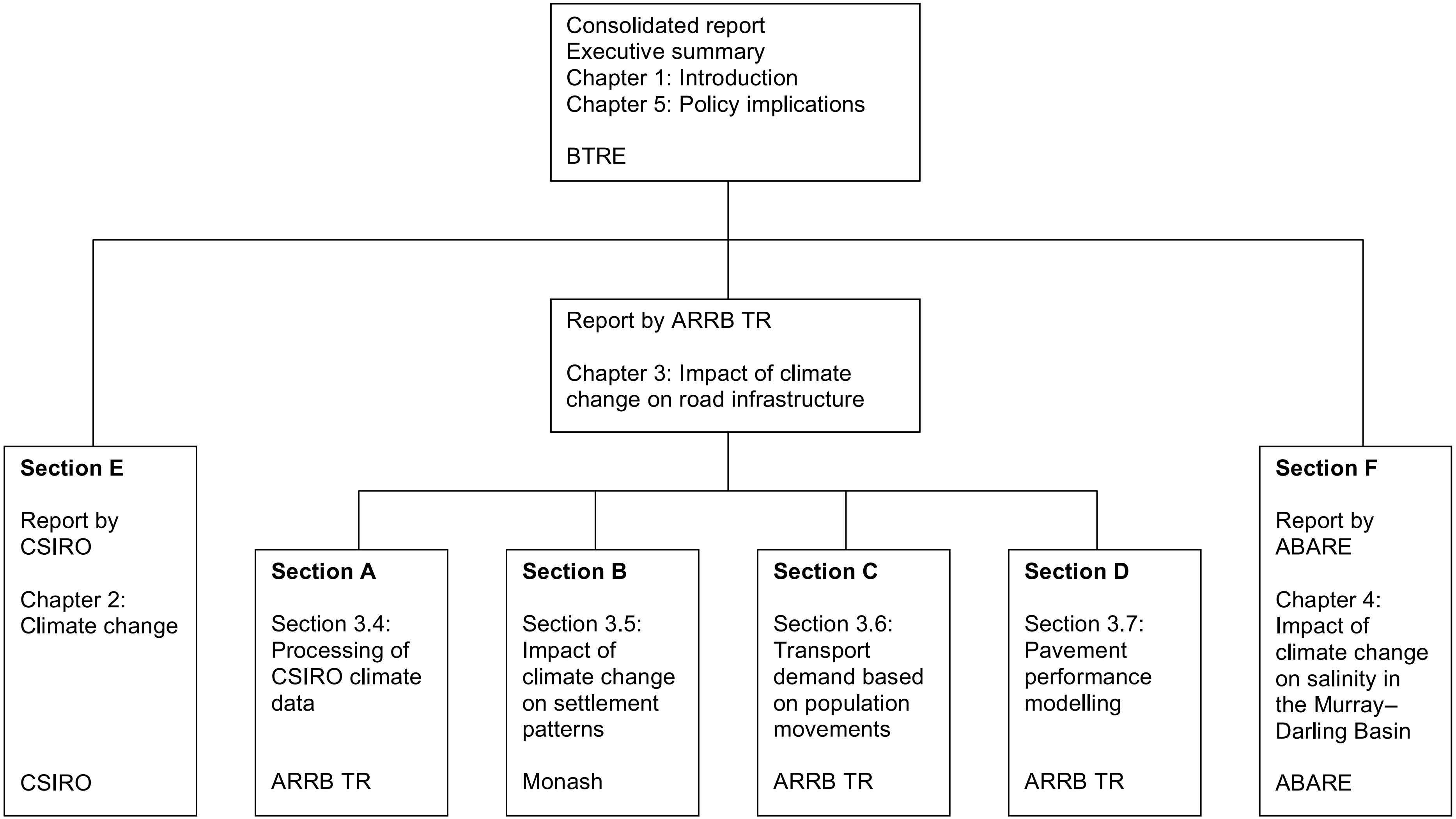

Figure 1.1 Structure of the report

2. CLIMATE CHANGE (SECTION E)

This chapter provides background for addressing the climate change issue, and outlines the methodology adopted for the provision of climate and climate change data provided by CSIRO Atmospheric Research for use by ARRB in road pavement deterioration models.

2.1 Outline and summary

2.1.1 Observational Evidence of Climate Change

Over many 1000's of years, fluctuations in climate have been relatively common and have had significant impacts on the Earth-Atmosphere system. The associated temperature changes were triggered by variations in the orbit of the earth, which changed the distribution of solar radiation received on the earth. Over recent decades, scientists have begun to consider the possibility of rapid climate change brought about by human activities caused by a global population in excess of 6 billion people. Appendix E1 "Evidence of Climate Change" (available on Austroads website: www.austroads.com.au) provides observations that show the global climate is changing, and has changed significantly since the industrial revolution.

The main findings are:

- An increasing body of observations gives a collective picture of a warming world and other associated changes in the climate system.
- Surface observations show that during the 20th century a warming of about 0.6°C in the global average temperature and a sea-level rise of about 15 centimeters has occurred. Since 1950, night-time daily minimum air temperatures over the land increased at about twice the rate of daytime daily maximum air temperatures. The increase in sea surface temperature over this period is about half that of the mean land surface air temperature.
- Global average surface temperatures have been warmer for most years of the 1990's than at any time in the 20th century. The warmest year in the instrumental record was 1998.
- Australia's continental-average temperature has risen by 0.7°C from 1910-1999, with most of this increase occurring after 1950 (see Figure E.1).
- A wide range of global and local evidence supports the above statements, ranging from balloon measurements, snow, ice and glacier extent and also oceanic profile measurements.
- Climatologists no longer have confidence that climatic statistics of the recent past can predict the climate of the future.

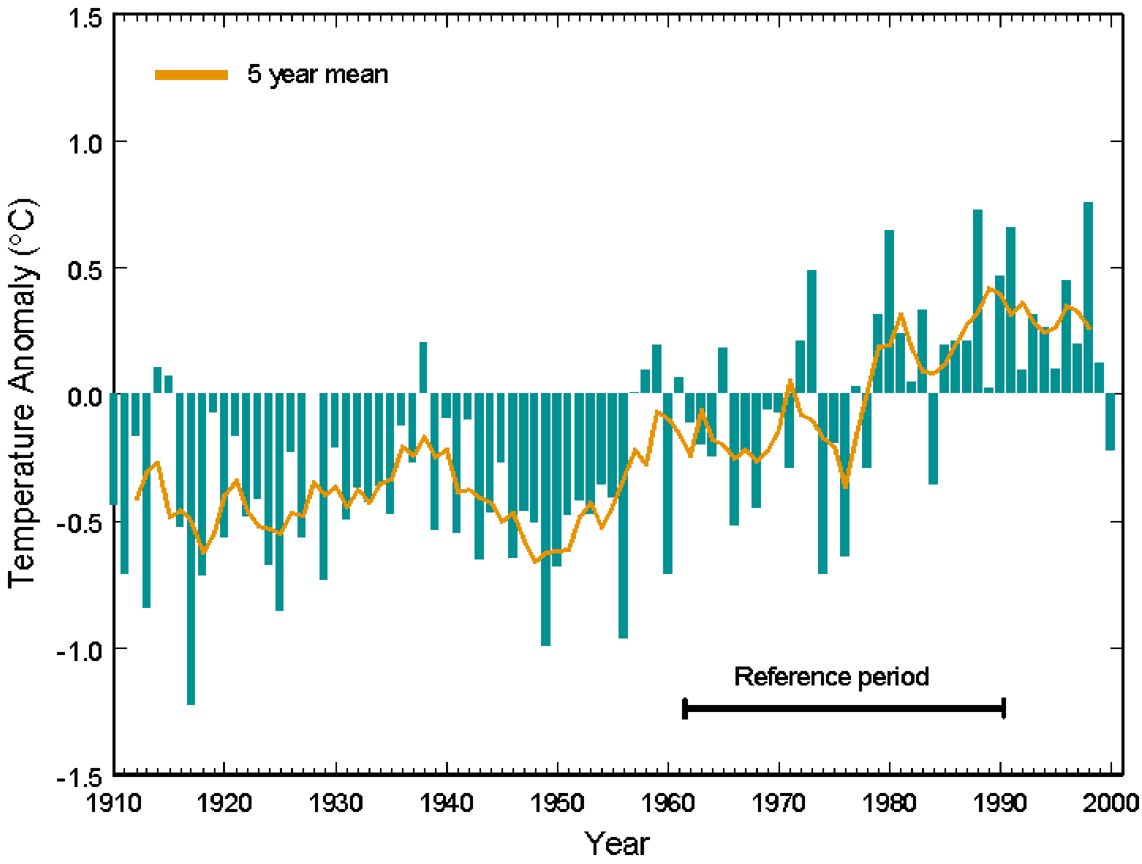

Figure E.1 Annual mean temperature anomalies for Australia based on the 1961-1990 normal reference period.

Source: Australian Bureau of Meteorology

2.1.2 Atmospheric Composition Change and Emission Scenarios

Current population projections show the world's population may exceed 15 billion by the end of the century. The consequent demands on the production and consumption of goods and services and for land, energy and materials will greatly intensify pressure on the environment and living resources; not just of developing countries but throughout the world. These pressures will be felt acutely in Australia because of its uniquely fragile environment.

The presence of greenhouse gases in the Earth's atmosphere has the effect of making global surface temperatures higher than they may otherwise be. The earth naturally absorbs and reflects incoming solar radiation and emits longer wavelength terrestrial (thermal) radiation back into space. On average, the absorbed solar radiation is balanced by the outgoing terrestrial radiation emitted to space. A portion of this terrestrial radiation is itself absorbed by gases in the atmosphere. The energy from this absorbed terrestrial radiation warms the Earth's surface and atmosphere, creating what is known as the "natural greenhouse effect". Monitoring of the concentration of these gases in the later part of the 20th century and over recent centuries and millennia by extracting air from ice-cores (IPCC 2001), indicates that concentrations are increasing. Appendix E2 "Atmospheric composition change and emission scenarios" (available on Austroads website: www.austroads.com.au) considers observations of the key greenhouse gases in the atmosphere that produce the "greenhouse effect". The "enhanced greenhouse effect" and future scenarios for greenhouse gas emissions are also considered.

The main findings are:

- Most of the observed global warming over the last 50 years can be attributed to increased greenhouse gas concentrations, due to human activities.
- Concentrations of some greenhouse gases are continuing to increase to levels not previously measured.
- Concentrations of most of the greenhouse gases will increase during the 21st century under all Intergovernmental Panel on Climate Change (IPCC) emissions scenarios considered.
- Analysis of air bubbles in Antarctic ice shows that carbon dioxide concentrations are now higher than at any time in the past 420,000 years.
- It is likely that carbon dioxide concentrations today are higher than they have been for 20 million years.

2.1.3 Intergovernmental Panel on Climate Change (IPCC)

The IPCC was established in 1988 to investigate the problem of potential global climate change. Its assessment is based mainly on published and peer reviewed scientific technical literature. The IPCC provides the overall policy framework for addressing the climate change issue, and scientific, technical and socio-economic advice to the world community including state of knowledge of causes of climate change, its potential impacts and options for response strategies.

The IPCC Third Assessment Report (TAR) "Climate Change 2001" provides a comprehensive and up-to-date assessment of the policy-relevant scientific, technical, and socio-economic dimensions of climate change, and draws on new findings since 1995 when the Second Assessment Report (SAR) was finalized. The Second Assessment Report concluded that: "Human activities are changing the atmospheric concentrations and distributions of greenhouse gases and aerosols. These changes can produce a radiative forcing by changing either the reflection or absorption of solar radiation, or the emission and absorption of terrestrial radiation" (IPCC 1996). Building on the conclusion, the more recent IPCC Third Assessment Report (TAP) (IPCC 2001) asserts that "concentrations of atmospheric greenhouse gases and their radiative forcing have continued to increase as a result of human activities". The IPCC also reported that the global average surface temperature of the Earth has increased by between 0.6 ± 0.2 °C over the 20th century. The main messages from the IPCC TAR of interest to the authorities providing major road system infrastructure are discussed in Appendix E3 "Intergovernmental Panel on Climate Change (IPCC), Third Assessment Report (TAR), Climate Change 2001" (available on Austroads website: www.austroads.com.au).

2.1.4 Climate Change Projections for Australia

In May 2001, CSIRO Atmospheric Research released a climate change projections brochure (CSIRO, 2001), providing a brief summary of regional climate projections for Australia. These projections were based on poorer horizontal resolution global climate model information (only one regional model was considered: 125 km horizontal resolution) than utilized for this study. Impacts and Adaptation are discussed in a companion brochure (IAWG, 2001), prepared by the CSIRO Impacts and Adaptation Working Group (IAWG). Climate change has social, economic and ecological impacts. Impacts to Australian water resources, urban and coastal communities, agriculture and human health, among others, are detailed.

The main findings from these publications are:

- Australia will be generally hotter and drier. Over most of the continent, annual average temperatures are projected to be 0.4 to 2°C greater than 1990 by 2030. By 2070, average annual temperatures are likely to increase by 1 to 6°C.
- Most parts of Australia are likely to experience more frequent, or heavier, downpours. In places where average rainfall increases, there will be more extreme wet years. Conversely, there will be more droughts in regions where average rainfall decreases.
- Warming will not be uniform. Slightly less warming is expected in some coastal areas, and slightly more warming in the northwest and interior. More extremely hot days and fewer cold days are expected. For example, the average number of summer days over 35°C in Melbourne

are likely to increase from 8 at present to 10-20 by 2070. The average number of winter days below 0°C in Canberra is likely to drop from 44 at present to 6-38 by 2070.

- Decreases in rainfall are likely in South-western Australia, as well as in parts of south-eastern Australia and Queensland. These decreases are likely to be most pronounced in winter and spring. There are also likely to be more intense tropical cyclones, leading to an increase in the number of severe oceanic storm surges in the north.
- Evaporation is projected to increase over most of the country, adding to moisture stress on plants, and to drought.

At present, projections of regional climate change are considered by many policymakers as being too broad for decision-making. The CSIRO Climate Change Research Program (CCRP) is working towards reducing uncertainties in projections of future climate change in the Australian region, so as to increase the opportunity for effective adaptation and mitigation actions (see Section 2.6, "Climate Change Modeling: Future enhancements"). The scientific research is ongoing, and requires constant updating so that society at large can assess the risk associated with climate change.

2.1.5 Using computer models to understand Climate Change in the Australian Region

Assessing how much global warming may be induced by a given increase in greenhouse gases, and the resulting regional effects, is not a straightforward undertaking. There are many feedback processes in the global climate system which may amplify or suppress any external influences on climate (such as increased radiative forcing from increased concentrations of greenhouse gases). Assessing the climate impact of increased greenhouse gas concentrations and the feedbacks requires a model of the global climate system which includes all of the relevant physical processes.

Two major scientific developments have enabled the scientific community to confirm the global warming hypothesis. The first development is the rapid improvement in our knowledge of the way earth's climate system operates. Major advances in the field of paleoclimatology (the study of climate prior to the widespread availability of records of temperature, precipitation and other instrumental data) has given scientists new insights into the dynamics of the climate system. Paleoclimates use environmental recorders to estimate past climatic conditions and thus extend our understanding far beyond the 100+ year instrumental record. "Proxy" records of climate have been preserved in tree rings, locked in the skeletons of tropical coral reefs, extracted as ice cores from glaciers and ice caps, and buried in laminated sediments from lakes and the ocean. Data from new studies of current and paleoclimates, improved analysis of data sets, more rigorous evaluation of their quality, and comparisons amongst data from different sources have led to greater understanding of climate change. Discussion and disagreement regarding the use of paleoclimate proxies as a historic temperature record are considered in Bradley et al. (2000).

The second development is the rapid advancement of global climate modelling. Over the last decade or so, a number of research centres around the world have developed highly complex global climate models in response to the significant scientific interest in climate change. Barnett et al. (1999) provide an excellent review of progress in model-based detection and attribution of climate change. These models are structured with the laws of physics and contain our best understanding of climate system dynamics and chemistry. They simulate meteorological variables such as temperature, humidity, precipitations and wind speed and direction on a network of grid points covering the Earth's surface and through the depth of both the atmosphere and oceans. Appendix E4, "CSIRO Climate Models" (available on Austroads website: www.austroads.com.au) details the computer models developed and employed in this study by CSIRO Atmospheric Research.

Global climate models have shortcomings which may significantly limit their ability to reliably simulate future climate. For example, current global climate models do not adequately simulate El Nino – Southern Oscillation behaviour, which is a very important source of year-to-year climate variability in the Australian region. There are also large uncertainties associated with simulating the behaviour of the ocean under future climate change. Global climate models have a horizontal resolution of 200 – 400 km which is not fine enough to adequately represent the effects/impacts on the regional pattern of climate change of for example, mountain ranges, large lakes or wetland systems. This problem is addressed for specific regions by using a higher resolution regional climate model embedded in the coarse resolution global model. Section 2.4, "CSIRO Climate Model Output (regional patterns of change)" details the methodology used to determine the future regional patterns of climate change, as well as the sources for the "base climatologies" utilised by ARRB in this study.

Regional patterns of change for a range of climate variables have been prepared, utilizing a combination of both CSIRO global and regional climate models for the period 1960 to 2100, using a single future greenhouse gas emissions scenario (IPCC "A2" greenhouse gas emissions scenario). The patterns have been scaled so they represent the regional sensitivities to the global warming observed from employing the climate model simulation. They are supplied as an absolute change in temperature per degree of global warming for maximum and minimum temperature, and as a percentage change per degree of global warming for rainfall, solar radiation, potential evaporation and actual evaporation.

We also compare the climate model *average monthly climate* for the reference period (30-year period 1961 – 1990) with the observational record to determine the relationship between model outputs and real-world location-specific data. We have assumed that during this period, Australia experienced a "stationary climate" with little or no global warming. This assumption is common in the evaluation of the output of climate models, although from Figure E.1 (reference period); it can be seen that this is not in fact accurate. It does consider a period in time when instrumental records first achieved a level of both spatial density and accuracy required for an examination of this kind, and the climate change signal during this 30-year period is an order of magnitude smaller than that projected during the 21st century.

In sections 2.5 and 2.6, we consider the uncertainties in the methodology adopted for this study, and discuss possible further enhancements with regard to climate change computer modelling. Finally, we also provide contacts, references and further reading with regard to climate change information.

2.2 Simulating the Impacts of Climate Change

The purpose of this section is to describe the methodology used to construct the climatic information provided to ARRB. Figure E.2 depicts the progression of stages required to provide climate change scenarios for assessing the impacts of climate change. Changes in future Australian climate are derived from many climate model simulations, utilising a range of emission scenarios. Spatial results are generally represented by a grid of cells, with cell size varying from 200 by 200 km to 400 km by 400 km, depending on the model. This study concentrated on obtaining a "best estimate" of the regional climate change pattern (0.5 degree or about 50 kilometre horizontal resolution) using a single climate model realisation.

This single realisation of the regional pattern of future climate is based on the IPCC A2 greenhouse gas emissions scenario (see Section 2.3). The A2 scenario is one of the higher greenhouse gas emitting scenarios (see Figure E.3). Current computing resources and cost allowed the use of only one emissions scenario for this study. Each realisation employing a different emissions scenario requires about 14 weeks computer time on a NEC SX-5 supercomputer. The A2 scenario was chosen for this study because it provides a significant increase in greenhouse gas emissions during the 21st century. These emissions in turn provide a strong radiative forcing signal for the establishment of regional climate change patterns over the Australian continent.

CSIRO Atmospheric Research has provided ARRB information describing how the Australian climate may change during the next 100 years. This has been achieved by combining the full range of projected global warming as given by IPCC (2001) with projected regional climate changes obtained from a single CSIRO regional climate model (see Section 2.4). This is currently the highest horizontal resolution (50 km) regional climate change simulation available over the Australian continent.

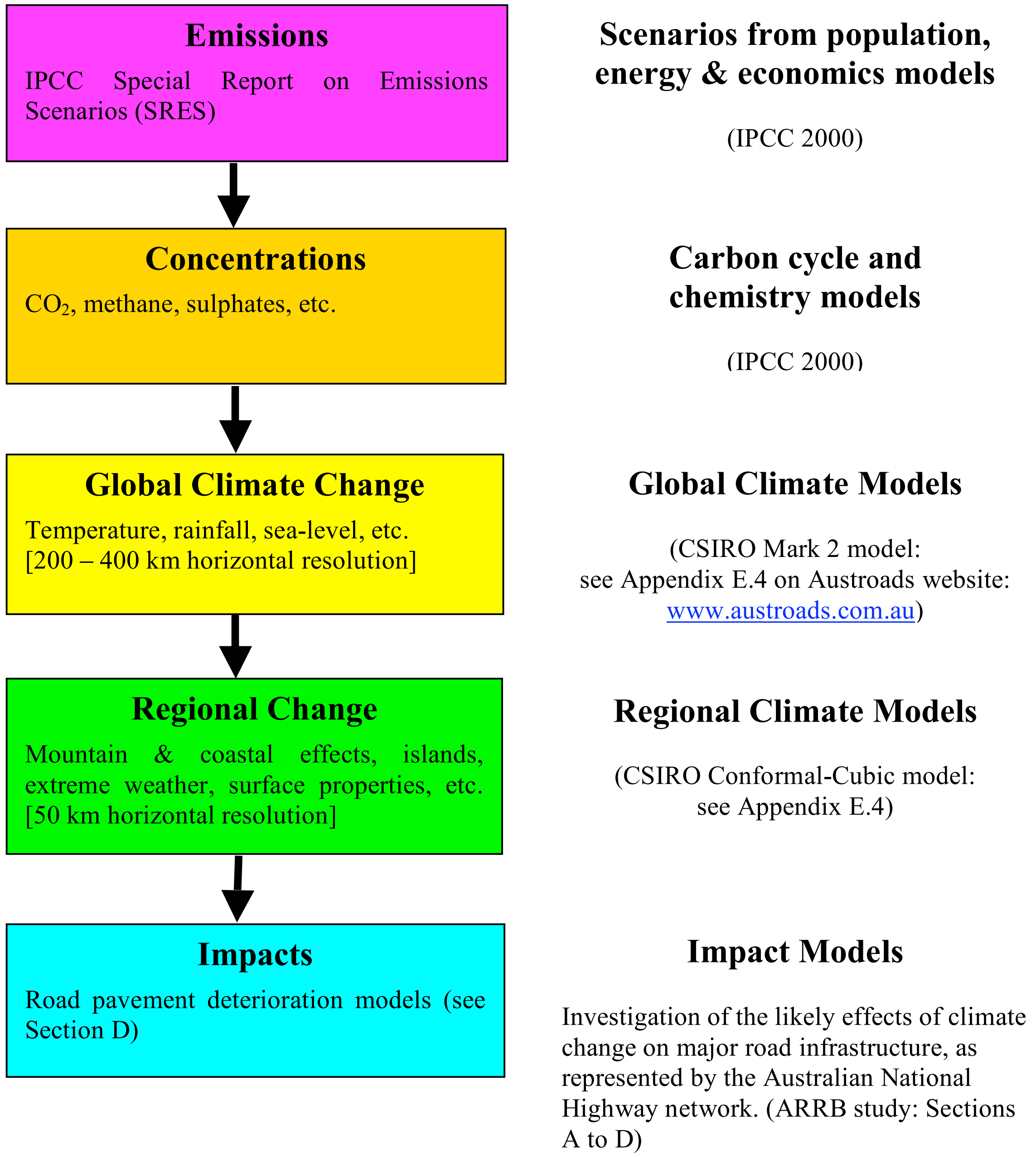

Figure E.2 Main stages required to provide climate change scenarios for assessing the impacts of climate change.

This approach is similar to that used in previous climate change assessments (CSIRO 1992, 1996, and Whetton et al. 1996). The steps involved in the methodology are to:

1. utilise ranges of projected global warming from IPCC (2001);
2. extract the regional climate change patterns using CSIRO Conformal-Cubic (C-C) computer model "nudged" by the CSIRO Mark 2 Coupled Atmospheric-Ocean General Circulation Model (AOGCM) [utilising IPCC A2 emissions scenario]; and
3. combine the regional information obtained from the regional climate model with the range of IPCC global warming projections.

This methodology allows the full range of projected global warming as given by IPCC (2001) to be combined with the projected regional climate change patterns obtained from the CSIRO modelling. The aim is to quantify ranges of uncertainty where possible.

The technique for determining the range of projected global warming utilised by the IPCC is described in Section 2.3. The CSIRO computer models employed are described in Appendix E4 (available on Austroads website: www.austroads.com.au). In addition, a format specification for the data files, and the shell of a simple FORTRAN program (reads the data from the 12 monthly files) are also included in Appendix E4. The utilisation of the final computer model data products (climate change patterns for a range of geophysical parameters) is described fully in Section 2.4.

2.3 Greenhouse Gas emission scenarios and Global Warming Projections

Projecting how climate may change for any given region or time in the future is complex and difficult. Estimating how rapidly greenhouse gas concentrations in the Earth's atmosphere will increase over the next 100 years is problematic. For example, emissions of carbon dioxide (CO_2) due to burning of fossil fuel will depend on future rates of population and economic growth, and the relative use of fossil and non-fossil fuel sources.

The IPCC (2000) Special Report on Emission Scenarios (SRES) produced 40 future emission scenarios for greenhouse gases and sulfate aerosols based on population, energy and economic models. Scenarios A1B, A1T, A1F1, A2, B1 and B2 represent four families of technology-population-economy futures identified by the IPCC (Figure E.3). The scenario employed in this study (A2) is described as follows:

> "The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing population. Economic development is primarily regionally oriented and per capita economic growth and technological change more fragmented and slower than other storylines." (IPCC 2000)

The A2 scenario is one of the higher greenhouse gas emitting scenarios (see Figure E.3). The A2 scenario was chosen for this study because it provides a significant increase in greenhouse gas emissions during the 21st century. These emissions in turn provide a strong radiative forcing signal for the establishment of regional climate change patterns over the Australian continent.

By contrast, the lower greenhouse gas emitting scenario B1 is described as follows:

> "The B1 storyline and scenario family describes a convergent world with the same global population that peaks in the mid-21st century and declines thereafter. There is rapid change in economic structures towards a services and information economy, with reduction in material intensity and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social and environmental sustainability including improved equity, but without additional climate initiatives." (IPCC 2000)

Greenhouse gas emissions scenarios are then converted to atmospheric concentrations using carbon cycle and chemistry models (IPCC, 2000). These concentrations can be used as input parameters to radiation calculations within a computer climate model. For example, carbon dioxide concentrations increase from about 370 parts per million (ppm) in the year 2000 to 550 ppm by 2100 for the B1 scenario, and to 970 ppm for the A2 scenario. Concentrations of other greenhouse gases also increase. The atmospheric cooling effects of sulfate aerosols are considered by the models. Direct aerosol effects (scattering and absorption of sunlight and heat) are included but indirect aerosol effects (cloud lifetime and optical properties) are excluded due to high uncertainty.

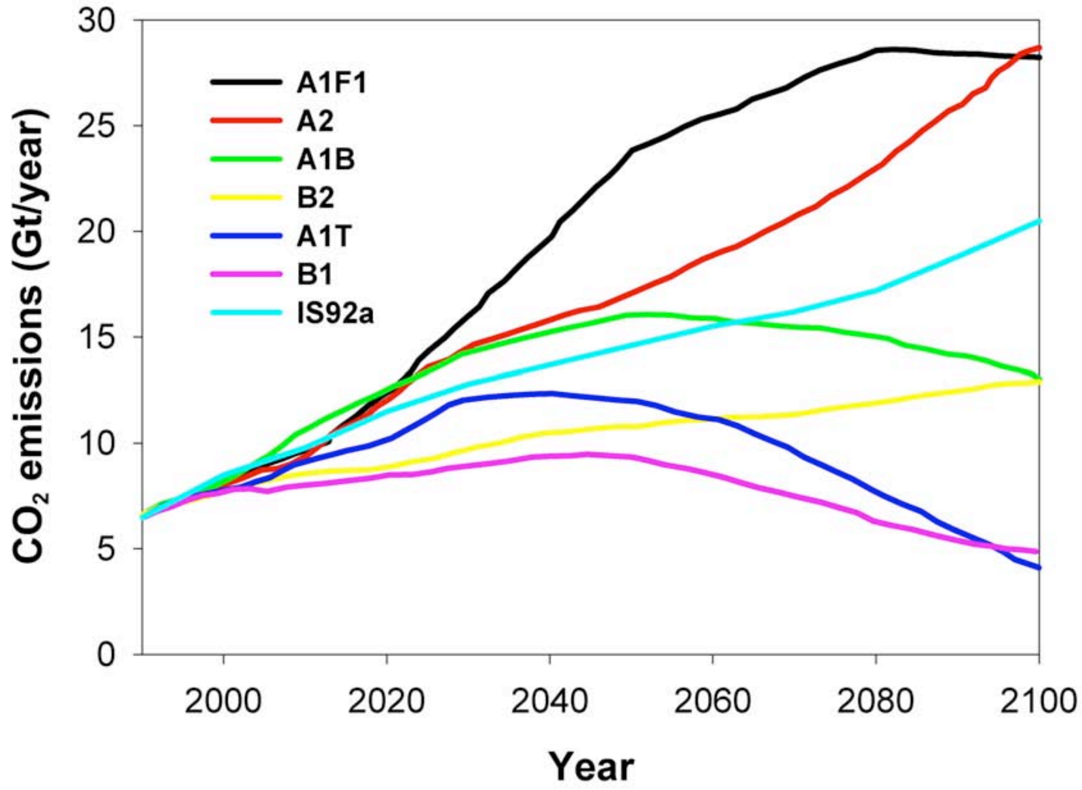

Figure E.3 SRES emission scenarios [6] (Giga-tonnes per year) for carbon dioxide (CO2), and the IS92a mid-case scenario used by the IPCC in 1996. (IPCC, 2000).

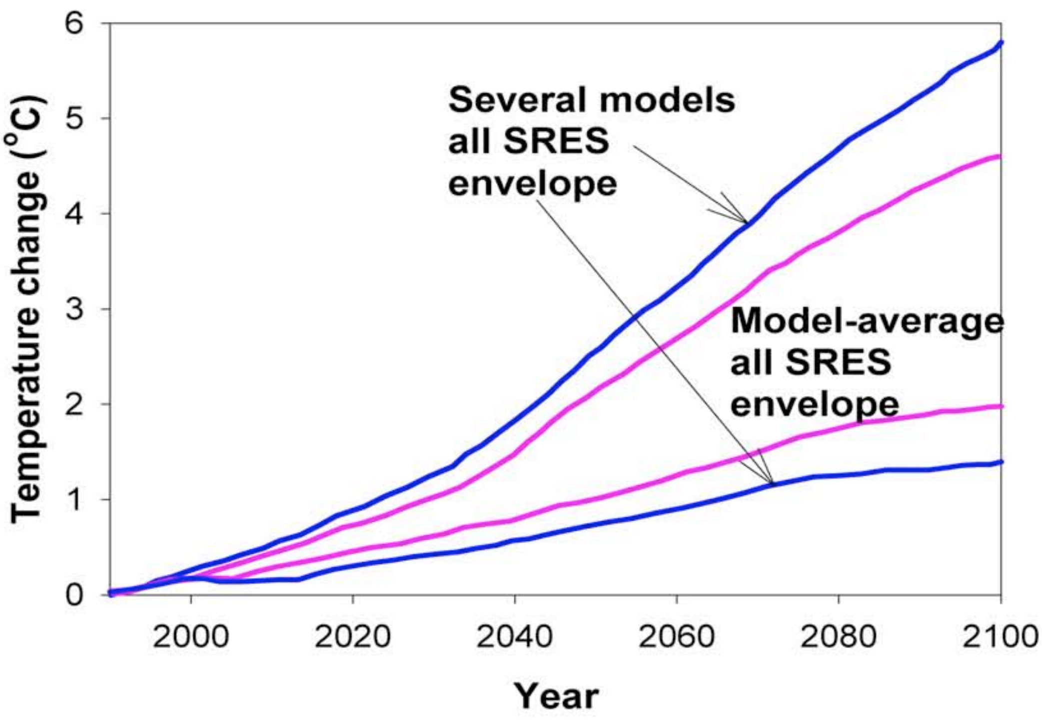

Figure E.4 Projections for global-average warming relative to 1990 for a range of SRES greenhouse gas and sulfate aerosol emission scenarios. (IPCC, 2000).

The IPCC Working Group 1 Summary for Policymakers (IPCC, 2001) provides estimates of global-average warming based on 35 of the 40 SRES emission scenarios (Figure E.4). These estimates were determined using simple models tuned to match the global performance of general circulation models. The pink lines represents the variation in results according to emission scenarios averaged across all models, while the blue lines also allow for model to model variation. Global mean warming ranges are tabulated by decade in Table E.1. Relative to 1990, global mean warming ranges from 1.4 to 5.8°C by the year 2100, which is a warming rate of 0.1 to 0.5°C per decade. The observed warming rate since the 1970s has been 0.15°C per decade.

These global warming projections are the basis for the regional projections. The range of warming for 1990-2100 allow for the full range of the latest IPCC greenhouse gas and sulfate aerosol emission scenarios (SRES scenarios) plus variations across a range of climate models in their global average response to enhanced greenhouse conditions.

Our experience with dealing with climate change information suggests that it is of greatest benefit to present ranges of change that incorporate quantifiable uncertainties associated with estimating climate change, namely the

- range of future emission scenarios
- range of climate model responses
- model to model differences in the regional pattern of climate change.

These ranges are normally provided by using a large number of climate model global warming projections which provide information on the magnitude of the global climate response over time, and also the regional response in terms of local change per degree of global warming. For this study, we use estimates of global-average warming based on 35 of the 40 SRES emission scenarios shown in Table E.1. In addition, we have utilised outputs from the CSIRO modeling to provide high-resolution regional patterns of change for a single IPCC A2 emissions scenario.

The IPCC projected warmings were not based directly on the output of atmosphere-ocean global climate models (AOGCMs). Instead, they were obtained from the output of a highly simplified climate model tuned to mimic the behaviour (in global-average terms) of the more complex AOGCMs. Using current computing resources it is not feasible to run AOGCMs over the full range of SRES scenarios, but this can be done with the simplified model. For further information on the IPCC global warming scenarios see IPCC (2001).

Table E.1 Projections for global-average warming (°C) relative to 1990 for 35 of the 40 SRES greenhouse gas and sulfate aerosol emission scenarios. (IPCC, 2000).

Year	High warming	Mid-high warming	Mid-low warming	Low warming
1990	0.00	0.00	0.00	0.00
2000	0.26	0.21	0.14	0.09
2010	0.52	0.45	0.28	0.17
2020	0.87	0.73	0.46	0.31
2030	1.27	1.03	0.62	0.43
2040	1.84	1.48	0.79	0.57
2050	2.56	2.14	1.01	0.74
2060	3.24	2.69	1.25	0.91
2070	3.97	3.31	1.51	1.14
2080	4.69	3.82	1.75	1.25
2090	5.24	4.27	1.88	1.31
2100	5.80	4.60	1.98	1.40

2.4 CSIRO Climate Model Output (regional patterns of change)

2.4.1 Australian climate data

Geophysical parameter data describing the present Australian climate, in grided form at 0.5 degree by 0.5 degree horizontal resolution, has been assembled from the following sources (Table E.2). These data form the "base climatology" (representing the average conditions experienced from 1961-1990) for the ARRB pavement deterioration modelling study.

Table E.2 Sources of "present Australian climate" data (0.5-degree horizontal resolution)

Parameter	Source of data
Rainfall	Australian Bureau of Meteorology
Maximum & minimum temperature	Australian Bureau of Meteorology
Mean temperature	CSIRO (base data: Aust. Bureau of Meteorology)
Solar radiation	Climate Research Unit, Uni. of East Anglia, U.K.
Potential & actual evaporation	CRC for Catchment Hydrology (Uni.of Melbourne)

Appendix E4 provides a format specification for the above data files and also the model derived regional climate change patterns. In addition, the shell of a simple FORTRAN program that reads the data from the 12 monthly files is detailed and provided with the data.

2.4.2 Evaluation of the region climate simulation for the CSIRO C-C model

Patterns of climate change for the Australian region are readily obtainable from global and regional climate model simulations (see Appendix E4 available on Austroads website: www.austroads.com.au). Typically, there are significant differences between models with regard to climate change simulated at the regional scale, particularly for precipitation. Thus, to represent this uncertainty a range of model results should be used in preparing regional projections. This was not possible in this study due to the high horizontal resolution required and the associated cost and time constraints. Instead we selected what may be considered a 'state-of-the-science' climate model and assessed its ability to simulate the present Australian climate. Monthly mean temperature, precipitation and mean sea level pressure averaged over the period 1961-1990 were considered. The C-C model output was assessed against observations by comparing plots (maps) of surface geophysical parameters (ie. surface pressure, surface temperature & rainfall) and examining differences.

Although deficiencies are present, the large-scale features of Australian climate (i.e. latitudinal temperature gradients, seasonality of precipitation and major circulation features such as the high pressure belt and the trade-winds) are all well simulated. Monthly averaged mean sea-level pressure was very well simulated in all months. Results for monthly averaged rainfall were better than any previous model results over the Australian region. Monthly rainfall averages for most of the continent were very good, except for the extreme northern tropics where summer totals were too high (by up to 20%). In addition, the monsoon onset was too early (occurring in November) and the cessation was also slightly early compared to climatological averages. Monthly averaged maximum temperatures in summer were a few degrees too high over the southwest and southeast parts of the continent. Winter monthly averaged maximum temperatures were a few degrees too low (up to 5 degrees over small areas) over the arid interior regions of the continent. Monthly averaged minimum temperatures in winter/spring were a few degrees too high over the extreme northern parts of the continent.

Note that the model evaluation undertaken was with respect to average climatic conditions. In principle, models could also be assessed with respect to how they simulate the evolution of regional climate over the instrumental period (primarily the 20th century). However, there are practical difficulties with this. The observed climatic evolution is a combination of trends forced by anthropogenic increases in concentrations of greenhouse gases and sulfate aerosols, variations due to changes in natural climate forcing (such as solar variations and volcanic eruptions) and changes forced by natural internal variations in climate. For this simulation, and for any GCM simulation, the effect of changes in other forcings are not fully represented, and the sequence of natural internal climatic fluctuations as observed cannot be represented. This is important because, at the regional scale, greenhouse related climate changes to date are likely to be weak relative to natural internal variability. This means that to draw useful conclusions from a comparison of model and simulated climatic evolution over the twentieth century, powerful statistical techniques are required. These are being developed for application at the global scale, and the extension of this to application at the regional scale is a research priority.

2.4.3 Extracting the regional climate change pattern from the C-C model output

The CSIRO Conformal-Cubic simulation was analysed to extract Australian region patterns of change for

- Monthly means of average, maximum and minimum temperature
- Monthly means of precipitation, solar radiation and potential and actual evaporation.

The climate response was calculated at each grid point in terms of local temperature change (or percent for rainfall/radiation/evaporation change) per degree of global warming using the full simulation period available (1990-2100). This is undertaken by linearly regressing the local monthly mean value for each parameter (temperature/rainfall/radiation/evaporation) against the global average temperature and taking the slope of the relationship at each grid point as the estimated response (linear least-squares regression). The grid point values were then mapped to obtain the pattern of model response. It should be noted that the regional response pattern was not found to vary systematically with the emission scenario in the CSIRO model simulations run at coarse horizontal resolution. This indicates that the limitation of using only one emission scenario (A2) to develop the regional response is not likely to be a limitation of this study.

2.4.4 Combining the regional climate change patterns & IPCC global warming projections

We have obtained regional patterns of climate change from the CSIRO Conformal-Cubic model. The derivation of these regional climate change sensitivities has been detailed above. These regional changes have been scaled so they represent the regional sensitivities to the global warming observed employing the CSIRO Conformal-Cubic model. A regional change per degree of global warming may be multiplied by the global warming for a given date to obtain the projected regional climate for that date. The global warming projection may be different to the one that originally applied in the simulation from which the regional change was obtained. Such rescaling of model results to a given global warming scenario has been commonly used in climate scenario formation to assist with the representation of uncertainty (CSIRO 1992, 1996; Hulme and Sheard, 1999).

ARRB have utilised this information by determining the appropriate global warming from Figure E.4, and then multiplying the regional climate change sensitivity for each parameter by the global warming to vary the data provided that represents the present climate. Using this method, the ranges of change per degree of global warming prepared here are combined with the IPCC (2001) global warming scenarios to obtain regional ranges of change at a given point in time.

For example considering the year 2050 and utilising Figure E.4 as a nomogram, draw a vertical line up from 2050 until it intersects the four lines shown. Then draw horizontal lines to the left until they intersect the y-axis (global warming). The inner two horizontal lines represent the range of global warming for 2050 when considering 35 emission scenarios averaged across all models employed. The outer two horizontal lines represent the range of global warming for 2050 when also considering the "model to model" variations.

Table E.3 Year 2050 global warming projection (utilising Figure E4 as a nomogram)

2050 global warming	Temperature (deg. C)
Mid-point [average] value	1.6
Range considering 35 emission scenarios [average response of all models]	1.0 – 2.2
Range considering model-to-model variability & 35 emission scenarios	0.8 – 2.7

The global warming ranges and also a mid-point global warming projection (as shown in Table E.3 for Year 2050) can be applied to the modelled climate change sensitivities to determine climate change biases from the present climate. Adding the climate change biases to the base climatology provides estimates of the average and range of conditions expected in 2050 for each of the five geophysical parameters supplied.

Geophysical parameter sensitivities are supplied as an absolute change in temperature per degree of global warming for maximum, minimum, and mean temperature, and as a percentage change per degree of global warming for rainfall, solar radiation, potential evaporation and actual evaporation. For a parameter sensitivity (%sens) provided as the percentage change per degree of global warming (GW), Equation (1) is used for determining the future climatology:

$$\textbf{2050 climatology} = \textbf{bc} + (\textbf{bc} \times [\%\textbf{sens}] \times \textbf{GW}\{\textbf{2050}\}) \qquad \textbf{(1)}$$

where bc = base climatology (average 1961–1990)

[%sens] = parameter sensitivity (% change per deg C. of GW)

GW{2050} = Global Warming for 2050 (in degrees Celsius)

For a parameter sensitivity (t_sens) provided as the temperature change per degree of global warming (GW), Equation (2) is used for determining the future climatology:

$$\textbf{2050 climatology} = \textbf{bc} + (\textbf{t\_sens} \times \textbf{GW}\{\textbf{2050}\}) \qquad \textbf{(2)}$$

where [t_sens] = parameter sensitivity (deg C. per deg C. of GW)

The predicted 2050 global warming range (derived from a range of general circulation models utilising 35 emission scenarios) allows ARRB to conduct sensitivity studies that include a range of possible global warming projections with the high horizontal resolution regional climate change patterns (sensitivities) based on a single emission scenario realisation (high emissions IPCC A2 scenario) for the Australian region.

2.5 Climate change modelling: Uncertainties

This document is intended to provide a brief summary of the latest science behind regional climate projections for Australia, and the attached data is intended to provide broad-scale information suitable for a study of the climate sensitivity of the long-term provision of major road system infrastructure. Climate change projections from a range of greenhouse gas emissions scenarios provide a range of possible global warming. Due to uncertainty about future human behaviour and some aspects of climate science, precise predictions of climate change cannot be made.

Where possible these uncertainties have been quantified. However, changes outside the ranges given here cannot be ruled out, nor can confidence levels be reliably quantified. Hence, these projections should be used with caution.

Where possible, we have estimated a range of possibilities, taking into account:

- uncertainty in the emissions scenarios for greenhouse gases and sulfate aerosols
- variations in the global-average and regional climatic responses between models.

There are additional uncertainties which are difficult to quantify, such as:
- biological feedbacks, e.g. enhanced plant growth due to higher carbon dioxide levels
- future changes in climate due to natural forces such as changes in solar radiation and volcanic eruptions,

but these are considered small compared to greenhouse gas effects (see Figure E.5).

The CSIRO Climate Change Research Program (CCRP) is working towards reducing uncertainties in projections of future climate change in the Australian region, so as to increase the opportunity for effective adaptation and mitigation actions. CCRP aims to provide better insight into the probable nature and rate of climate change over Australia. In this instance, this knowledge is needed to enable transport engineers and road planners to understand the national vulnerability to climate change of pavement deterioration, in an effort to adapt to climate change and to provide the basis for determining the potential costs of climate change.

2.6 Climate change modelling: Future enhancements

Models of the climate system provide the only viable way of evaluating future climate changes that result from industrial and land-use emissions of greenhouse gases. Over the past few years CSIRO has been developing its Mark 3 climate model, which includes many of the processes important in the simulation of climate. One notable advance is that the CSIRO Mark 3 model does not require flux adjustment (systematic ‘corrections’ applied to the interface between the atmosphere and oceans). One major caveat to all simulations of climate change is that even the most advanced climate models are incomplete.

The best estimates for all processes exerting a radiative forcing on the climate system and also their uncertainty estimates (depicted as error bars) are also shown in Figure E.5. The climate models considered in this study incorporate three of the four left-most processes shown in Figure E5. These are the climate change radiative forcing (left to right) due to greenhouse gases, stratospheric ozone, and sulphate aerosols. The remaining eight processes identified as influencing climate change are currently not understood well enough to include in climate models.

Recent investigations into the effect of aerosols on cloud formation have revealed a cooling effect, previously unaccounted for in climate models, which may partly explain their tendency to overestimate global warming (based on simulations undertaken for the warming experienced over the later part of the 20th century). The role of the “indirect aerosol effect” is of major importance due to its radiative cooling effect (negative feedback; see Figure E5). The burning of fossil fuels — as well as creating greenhouse gases — produces small pollution particles called aerosols, which seem to exert a cooling effect on climate. This effect is largely restricted to the more polluted areas (ie. only a regional effect), whereas greenhouse gases are well mixed throughout the entire atmosphere.

The most extensively studied impact of aerosols is their so-called ‘direct’ effect: the white haze of pollution that hovers over industrial areas of the northern hemisphere, and sometimes over Melbourne and Sydney. This haze of small particles reflects some incoming sunlight back to space, and can have a significant cooling effect on climate. In addition to this direct effect, however, aerosols can also influence the properties of clouds (called the ‘indirect’ aerosol effect). Pollution also suppresses rain formation and causes the clouds to persist for longer, thereby further increasing the amount of sunlight reflected back to space (called the “cloud-lifetime” effect). The indirect aerosol and cloud-lifetime effects may be strong enough to substantially offset the warming due to the enhanced greenhouse effect over heavy polluted regions. The sum of the two effects may even give a net cooling in some regions.

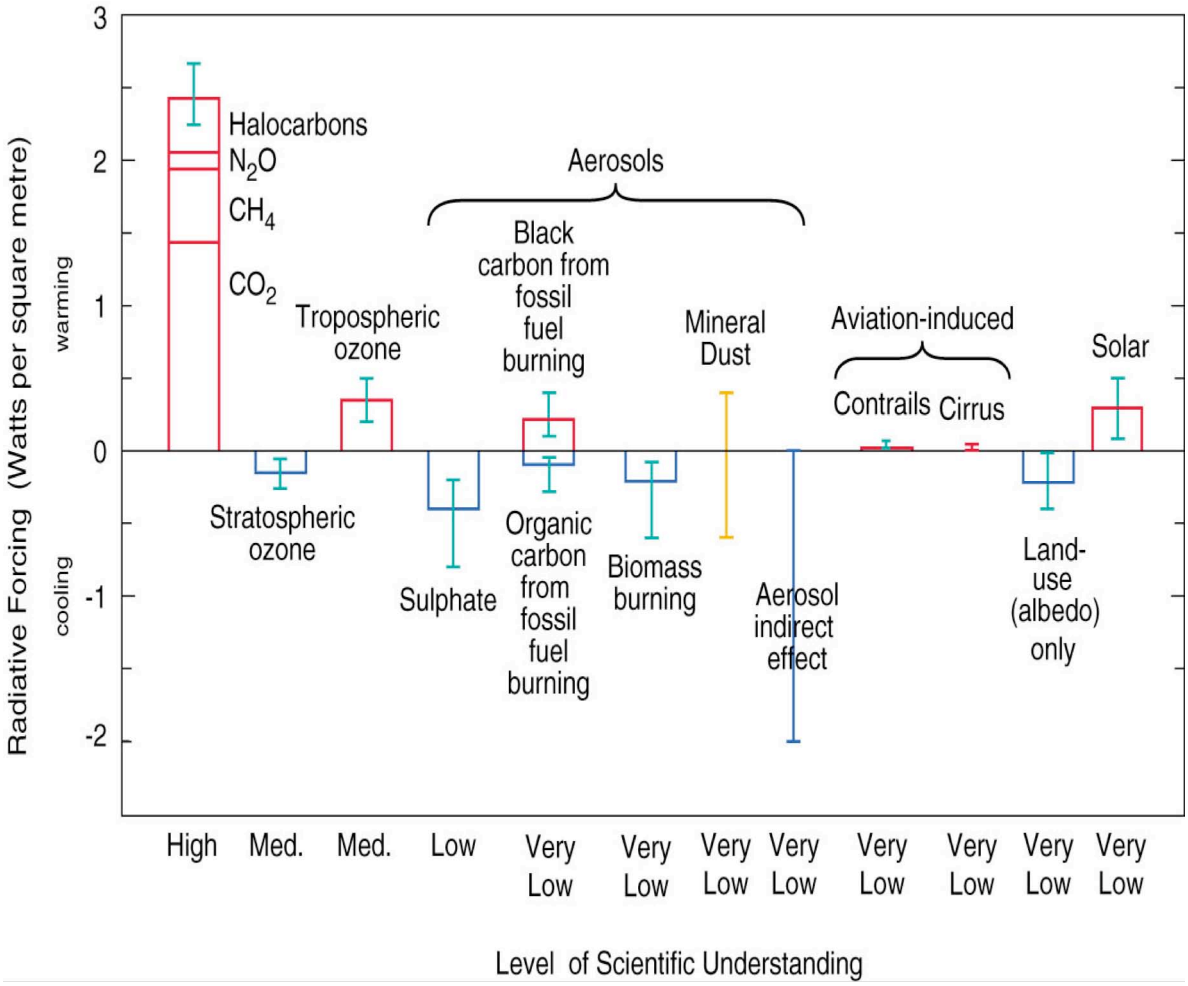

Figure E.5 The global mean radiative forcing of the climate system for the year 2000, relative to 1750. (IPCC, 2001).

CSIRO are working towards incorporating a number of additional elements of the earth system into their climate model:

- cycling of carbon within the terrestrial biosphere and between the biosphere and the atmosphere;
- indirect radiative effects of aerosols, and better treatment of the direct radiative effects; and
- cycling of carbon within the oceans, and improvements to the way mixing is represented within ocean models (not included in Figure E.5 but considered to be poorly understood).

These development activities ensure that CSIRO's contribution to the climate modelling within the scientific community remains internationally competitive and credible, and that climate impact support to the Australian community will be maintained in the future. What is needed is a means of understanding the complex interactions within natural systems and their intersection with human society so that the effects of manipulating these systems can be predicted with confidence. The field of research that aims to supply this knowledge is called *Earth System Science*. CSIRO is an active part of developments in this area, which is one of the most rapidly growing areas of research worldwide. They are assembling the scientific tools and knowledge required to embrace and implement the idea of *sustainable development,* whereby the people living on earth over the next half century meet their needs while nurturing and restoring the planet's life support systems.

The overarching national need for this research in this particular study, relates to the ability of Australia's road planning specialists to understand and plan for the changes in climate that will occur throughout this century as a result of increases in the concentrations of greenhouse gases in the atmosphere. National, regional and local planning for climate change is compromised by significant scientific uncertainties, particularly at regional and local scales, associated with the magnitude and rate of future climate change. The scientific research is ongoing, and improved computer models including high regional resolution realisations employing a range of emissions scenarios are planned. Results for these future studies will be available to the major road system infrastructure providers for future investigations.

2.7 Contacts for Climate change information

The first point of contact for new information regarding Australia's future change is the CSIRO Atmospheric Research, Climate Impact Group. Their web site is located at http://www.dar.csiro.au/impacts/index.html

The CSIRO Impact and Adaptation Working Group (IAWG) has been formed to act as a "shop front" for external clients to come to interact with CSIRO (all parts of the organisation) regarding Climate Change Impact and Adaptation activities. Their web site is located at http://www.marine.csiro.au/iawg/

CSIRO conducts a major multidisciplinary research program into climate change and the greenhouse effect. Six CSIRO Divisions and two Working Groups are involved in the Climate Change Research Program (CCRP). Their web site is located at http://www.dar.csiro.au/ccrp/

OzClim is a regional climate change scenario generator and impacts software package for Australia. Included are a wider range of variables than summarised here. Climate change projections for the south Pacific and parts of Asia are also available. http://www.dar.csiro.au/publications/ozclim.htm

2.8 Sea-level rise projections for Australia

The material in this section on sea level rise projections and in the next on extreme weather events was not derived from the modelling undertaken as part of this study. It is sourced from published literature and has been included because it is of relevance to infrastructure planning.

Sea level rise has a number of potential effects on coastal urban infrastructure, including accelerated erosion and increased incidence of coastal flooding. This is a relevant planning issue because the effects of sea level rise are likely to be noticeable within the design lifetime of infrastructure such as buildings and roads. The current state of the science was recently reviewed in Church et al. (2001), as part of the IPCC Third Assessment Report. The overarching conclusion of this work is that predictions of global sea level rise remain relatively confident, although there is a wide range of possible outcomes.

Some progress has been made on the incorporation of these results into practical planning recommendations for urban infrastructure (for a recent summary, see Walsh et al. 2002).

In assessing the likelihood of possible sea level rise, a necessary first step is to understand sea level rise over the 20th century, the period for which the data is best and during which warming due to the enhanced greenhouse effect should be noticeable in the observed record. While much progress has been made to unravel the causes of the observed sea level rise over the 20th century, there remain significant obstacles to the complete understanding of this issue.

2.8.1 Sea Level Rise in the 20th century

The best current estimate of observed global average sea level rise in the 20th century is contained in Table E.4. Total sea level rise in the 20th century has several components:

- the warming and thereby expansion of the oceans;
- the melting of glaciers;
- the s`torage of water in surface reservoirs;
- the release of groundwater;
- the melting or growth of the large ice sheets; and
- a slow continuing adjustment of the ice sheets since the height of the last Ice Age.

An important distinction is between *steric* effects (ones that change the volume of the ocean without changing its mass, such as ocean warming) and *eustatic* effects (additions to the mass of the ocean, for instance from melting glaciers). The sum of the best estimates of these components is compared with the observations derived largely from tide gauge records. The total observed rise over the 20th century is 10-20 cm. Tide gauges represent the most accurate current record of sea level rise, but they must be corrected for geological movement of the land on which they sit and the geographical spread of gauges is not uniform. The comparison in Table E.4 suggests either that the sum of the estimated components is too low or that the observations are too high (or possibly the large error bars mask any differences).

New estimates of these quantities have been made even since the recent publication of the IPCC TAR. The non-uniform nature of the location of the tide gauges has led to suggestions that this data record is geographically biased. Cabanes et al. (2001) conclude that the gauges are mostly located in areas that have experienced recent warming and that the gauge record overestimates actual 20th century warming as a result. They suggest that this sea level rise over this period was almost entirely due to steric effects. Nevertheless, there is strong evidence of a substantial eustatic component from glacier melting. Arendt et al. (2002) report that Alaskan glaciers have been recently been melting at a rate of 0.27 mm yr^{-1}, a higher rate than assumed by Church et al. (2001). Meier and Wahr (2002) estimate that the contribution by glaciers since 1988 is 5 cm per century, higher than the upper limit of the IPCC TAR estimate in Table E.4. Thus it seems very unlikely that sea level rise in the 20th century could have been entirely due to the expansion of the oceans. These issues are far from resolved and does highlight the considerable uncertainty in our current knowledge.

Table E.4 Estimated contributions to sea level rise in the 20th century* (centimetres)

Component	Low	Middle	High
Thermal expansion	3	5	7
Glaciers/small ice caps	2	3	4
Surface water and ground water (terrestrial) storage (not climate change)	-11	-3.5	4
Greenland ice sheet (20th century)	0	0.5	1
Antarctic ice sheet (20th century)	-2	-1	0
Ice sheets – adjustment since last Ice Age	0	2.5	5
Other	0	0.3	0.5
TOTAL	-8	7	22
OBSERVED	10	15	20

* Low and high values refer to the estimated upper and lower limits.
Source: Church et al. 2001

2.8.2 Future Sea Level Rise and Planning

Given current controversy regarding observed sea level rise in the 20th century, it is not surprising that there is a wide range of predictions of sea level rise for the 21st century. Table E.5 shows the estimates compiled by Church et al. (2001) as incorporated in the IPCC TAR. Future sea level rise consists of contributions from continued warming of the ocean as well as melting of glaciers, small ice sheets and Greenland.

While Table E.5 does represent the best scientific estimate of future sea level rise, these figures are not really adequate for planning purposes. Apart from the fact that there is a wide range of estimates, planners would like a particular value of sea level rise to be associated with a specific probability of occurrence. Some methods have been suggested to do this, based on risk assessment methodologies (e.g. Abbs et al. 2000; Jones, 2001), but to our knowledge application of these techniques to specific planning in Australia has not yet occurred. It is important to note that the main cause of uncertainty prior to about 2050 is caused by our lack of complete understanding of the processes that cause sea level rise. Because of the thermal inertia of the oceans, there is little difference in the various sea level rise projections before about 2050, after which different rates of warming due to different projections of future greenhouse concentrations cause large differences in sea level rise.

Table E.5 Predicted global mean sea level rise for 2040 and 2100 (centimetres)

	Low	Mid	High
2040	3	12	30
2100	9	48	88

Source: Church et al. (2001).

Management options for sea level rise in urban areas are restricted by the cost of the infrastructure required to be protected. Therefore, abandonment is not usually an option. Protection options for urban or resort-area beaches may include a sea wall behind an artificially nourished beach. In tourism areas, aesthetic considerations may dictate careful design of such infrastructure to preserve the attractiveness of the location, which may tend to increase the cost. Towards the end of the century, managed retreat may need to be considered in some locations, as other options become expensive. In some locations, new development may need to be restricted. Setbacks are appropriate in these cases and are incorporated in many planning schemes. Alternatively, rolling easements may be employed, where development is progressively prohibited further inland as the sea level rises. Approval for development in vulnerable locations may have considerable future costs, as protection may become prohibitively expensive. Planning decisions made now may be particularly cost-effective in this regard.

Recently, planning for sea level rise has been incorporated into various State strategic planning documents. In Queensland, a new State Coastal Management Plan prescribes the inclusion of climate change issues, including sea level rise, into local planning. In New South Wales, a project is currently under way to identify future development options along the coast. Future coastal hazards will be identified and development may be restricted in those locations. Guidelines for sea level rise planning are already incorporated in the plans of virtually all local councils in New South Wales. Other States also have various planning approaches to this issue (Walsh et al. 2002).

2.9 Tropical Cyclones, Storm Surges and extreme sea levels

Storm surges are meteorologically forced long wave motions that produce temporary elevations or depressions in sea surface height. They are driven primarily by surface wind stress and to a lesser extent by falling barometric pressure. Wind stresses induce ocean currents which, if blocked by a coastal barrier, pile up against the coast to produce elevated sea levels or wind set-up. Alternatively, wind stresses acting in the longshore direction with sufficient fetch and duration produce longshore currents that eventually become deflected by Coriolis effects. If a coastal barrier lies in the path of the deflected flow, elevated sea levels can also occur due to a process referred to as current set-up or Ekman drift.

The structure of the coastal terrain plays an important role in determining the storm surge impact. Shallow coastal bathymetry tends to amplify the storm surge, and topographic features can channel the coastal currents. Hence, the width of the continental shelf and the presence of headlands, offshore reefs and islands are all contributing factors. The orientation of the coastline to the prevailing weather systems determines whether the region is vulnerable to storm surges and the height of the coastal topography determines how much coastal flooding is likely.

In addition to storm surges, coastal sea levels are influenced by tides and waves. Tidal currents interact non-linearly with storm surge currents to produce sea level peaks that are smaller than the sum of the parts. This is due to the quadratic relationship between currents and friction of the ocean floor. The cumulative effect of wave breaking in the surf zone can cause a temporary elevation in mean sea level known as wave setup. Wave setup at the coast is generally considered to reach between 15 and 20% of the incident Root Mean Square (RMS) wave height (WMO, 1988).

Wave set-up also interacts non-linearly with the storm surge, although Mastenbroek et al. (1993) have found that this effect is usually small. Surface waves increase the roughness of the ocean surface, thereby enhancing the surface wind stress. They also contribute to bottom currents and therefore can enhance the bottom friction, particularly in shallower water where the relative wave height is larger.

A further consequence of breaking waves is wave run-up, which causes overtopping of levees or dunes. Its magnitude is dependent on the shape and slope of the local terrain. Finally, storm water run-off due to rainfall may have a positive impact on sea levels at the point of discharge, although this is likely to be significant only within estuaries and tidal inlets.

Much of the coastline of Australia experiences extreme sea level events comprising contributions from storm surge waves and tides. However, the meteorological conditions that cause them and the relative importance of the resulting storm surge, tide and wave components varies from place to place. Potentially the largest storm surges occur in tropical Australia. This is mainly due to the potential severity of tropical cyclones in this region which are the main generation mechanism for oceanic storm surges, gale force winds and flooding rains in northern Australia. Projecting future tropical cyclone behaviour is difficult since these systems are not well resolved by global or regional climate models. Present indications are:

- regions of origin are likely to remain unchanged;
- maximum wind-speeds may increase by 5–20% in some parts of the globe by the end of the century; and
- preferred paths and poleward extent may alter, but changes remain uncertain.

The relatively wide and shallow continental shelf which extends around much of northern Australia from the Great Barrier Reef on the east coast to the northwest shelf on the west coast also contributes to the storm surge severity in this region. Empirical studies carried out on cyclone-induced storm tides in this region have indicated that wave setup is likely to be only a small component (about 10% of the storm surge height) (e.g. Hubbert and McInnes, 1999).

The southeast coast of Australia from southern Queensland to the NSW/Victorian border with its narrow continental shelf is not conducive to severe storm surges and extreme sea-levels that occur in this region are typically less than a metre in height. On the other hand, this region of coast experiences large waves and swell from the Tasman Sea. McInnes and Hubbert (2001) have shown that mid-latitude lows are a major cause of extreme sea levels along this stretch of coastline. They use numerical models to show that wave setup is likely to be as important as storm surge to contributing to extreme sea levels in this region.

Along the southern Australian coast, storm surges of at least half a metre in height occur year round with the greatest frequency of events occurring during the winter and spring months. They are caused by the westerlies or southwesterlies following the passage of cold fronts and have been modelled by Hubbert and McInnes (1999) both along the south coast and within Port Phillip Bay. The interaction of the storm surges with tides in Bass Strait has also been modelled by McInnes and Hubbert (2003).

2.10 Acknowledgements

In the setup, running and evaluation of the CSIRO climate models, the assistance and advice of Drs. John McGregor, Jack Katzfey, Ramasamy Suppiah and Kim Nguyen was invaluable. The advice of Drs. Peter Whetton, Kathy McInnes in the preparation of the manuscript, and the assistance of Janice Bathols in the preparation of the projections, was also greatly appreciated.

2.11 Disclaimer

The scenario for future emissions used in this report (SRES A2) was chosen to provide a standard case for the determination of the regional sensitivity of the global climate change. This case should not be treated as having any special status as a likely future. In particular, it should be noted that the SRES A2-marker case is predicated on a global population of around 15 billion in 2100.

Predicted likely changes in global climate are based on best current scientific understanding. The range of values depicting likely changes is due to an allowance for uncertainty in future emissions of greenhouse gases and the response of the climate system. Emission scenarios are based on estimates of population, energy consumption, energy efficiency, gross world product, energy resources and reserves.

The climate change parameter projections utilised in this study are based on results from computer models that involve simplifications of real physical processes that are not fully understood. Accordingly, no responsibility will be accepted by CSIRO for the accuracy of the projections inferred from this study or for any person's interpretations, deductions, conclusions or actions in reliance on this information.

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E.1 Evidence of Climate Change

E.2 Atmospheric composition change and emission scenarios

E.3 Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report (TAR) "Climate Change 2001"

E.4 CSIRO Climate Models

3. IMPACT OF CLIMATE CHANGE ON ROAD INFRASTRUCTURE

Executive Summary

Austroads and the Department of Transport and Regional Services engaged ARRB Transport Research and CSIRO Division of Atmospheric Research to undertake a project to examine likely future climate scenarios for the whole of Australia during the 21st Century, and investigate the likely effects of this climate change on major road infrastructure, as represented by the Australian National Highway network.

This Report details work undertaken by ARRB Transport Research (and Monash University Centre for Population and Urban Research as a sub-consultant). This work examined future population settlement patterns, transport demand and road pavement performance modeling. The CSIRO work is separately reported.

Looking into the future (especially out to the year 2100) is extremely difficult. Therefore, the reader is cautioned that the results in this Report are based on a particular set of scenario assumptions used in the analysis, and limited by a number of methodological uncertainties inherent in the approach used.

For example, there are uncertainties in the levels of future greenhouse gas emissions, uncertainties in the climate responses to these greenhouse gas concentrations, as well as differences between the range of climate change models available. Typically, a range of emission scenarios are used to describe these alternative futures and global warming temperature changes are presented within envelopes containing ‘low’, ‘mid’ and ‘high’ estimates. A further limitation that needs to be emphasised, is that the project budget and resources available did not allow for investigation of extremes in climate change (that may influence the intensity and frequency of floods or storm events). These climate extremes that may have significant implications for road infrastructure.

The other tasks undertaken in the project involve similar levels of uncertainty. For example, projecting population changes to the year 2100, estimating how these these population settlement patterns may change in response to climate change, projecting transport demand out to the year 2100, and the limitations inherent in the road pavement models all combine to introduce critical uncertainties into the results.

This report has four main sections.

Climate Data Processing

Regional climate modeling was undertaken by CSIRO Division of Atmospheric Research to generate future climates out to the year 2100. The modeling produced a variety of climatic variables relevant to road pavement deterioration (in particular, precipitation and temperature) for a 0.5 degree geographical grid (latitude/longitude) across the Australian continent. As noted above, this work has been separately reported.

Section 3.4 details the steps required to process the climate data into appropriate parameters required by the pavement deterioration models. The parameters of interest (rainfall, temperature and Thornthwaite index) are presented graphically and discussed for both the base climate and the future predicted climate. Section 3.4 provides details of the changes in climate (specifically temperature and rainfall) including detailed analysis of selected capital cities.

Overall, the results indicate a future climate that is characterised as ‘drier and hotter’ although there are regional variations.

Population Demographics

The Monash University Centre for Population and Urban Research was subcontracted by ARRB Transport Research to quantify how Australian population demographics are likely to be effected by

climate change. Projected changes in regional population distribution patterns as a result of climate change are presented for each of the major cities.

Section 3.5 provides a discussion of the 'shaping factors' that will influence population settlement patterns in Australia. Australia's population is projected to increase to around 25.4 million by 2050 and remain stable after that (based on ABS Series 2 projections). The major metropolises absorb over 75 per cent of the 6.4 million total population growth over the period.

The population projections are modified in response to the climate changes noted in selected major locations.

Transport Demand

Section 3.6 translates the population projections (with climate change) into projected changes in road transport demand. Three parameters (used later in the pavement deterioration models) are used to express the growth in road transport demand. They are:

- Annual Average Daily Traffic (AADT);
- Percent Heavy Vehicles (%HV); and
- Average Equivalent Standard Axle (ESA) per Heavy Vehicle.

Pavement Deterioration

Section 3.7 documents the inputs and outputs from two pavement deterioration models used to examine the effect of climate change on the long term provision of road infrastructure. Appendices to Section 3.7 (appendices D1 and D2 available on Austroads website: www.austroads.com.au) provide detailed model information.

The Pavement Life Cycle Costing (PLCC) model is used to evaluate the effect of climate and travel demand change on the maintenance and rehabilitation expenditure requirements for the Australian National Highway System. This is done using current and predicted future climate data (from Section 3.4) and transport demand data (from Section 3.6).

The Highway Development and Management Version 4 (HDM-4) software system uses the same data to examine, in greater detail, the effect of climate change and associated changes in transport demand on certain sections of road in each state. These sections have been chosen to represent areas of the National Highway network that experience the greatest change in climate.

3.1 Introduction

Austroads initiated this project to examine the effects of climate change on long term provision of major road system infrastructure. Climate change has the potential to affect roads (for example, through changes in pavement moisture conditions) which may have implications for road pavement performance and rehabilitation and maintenance costs.

The project scope includes only the sealed National Highway System and does not include the arterial road network, local roads or unsealed roads.

The project has been undertaken through the capabilities of a number of organisations including ARRB Transport Research, CSIRO Division of Atmospheric Research, Monash University Centre for Population and Urban Research and the Bureau of Transport Economics.

This Report details work undertaken by ARRB Transport Reearch and Monash University. The climate modeling work undertaken by CSIRO is separately reported.

The objectives of the project were to:

- Undertake climate modeling. This was carried out by CSIRO Division of Atmospheric Research using the CSIRO Conformal-Cubic (atmosphere-only) General Circulation Model. The modeling results are separately reported.
- Examine the implications for major road infrastructure (National Highway System). This was carried out by ARRB Transport Research and Monash University (as a sub-consultant). The CSIRO climate modeling provided a set of data outputs including climatic variables relevant to road pavement deterioration modeling. (This data and the processing undertaken by ARRB Transport Research is described in Section 3.4).

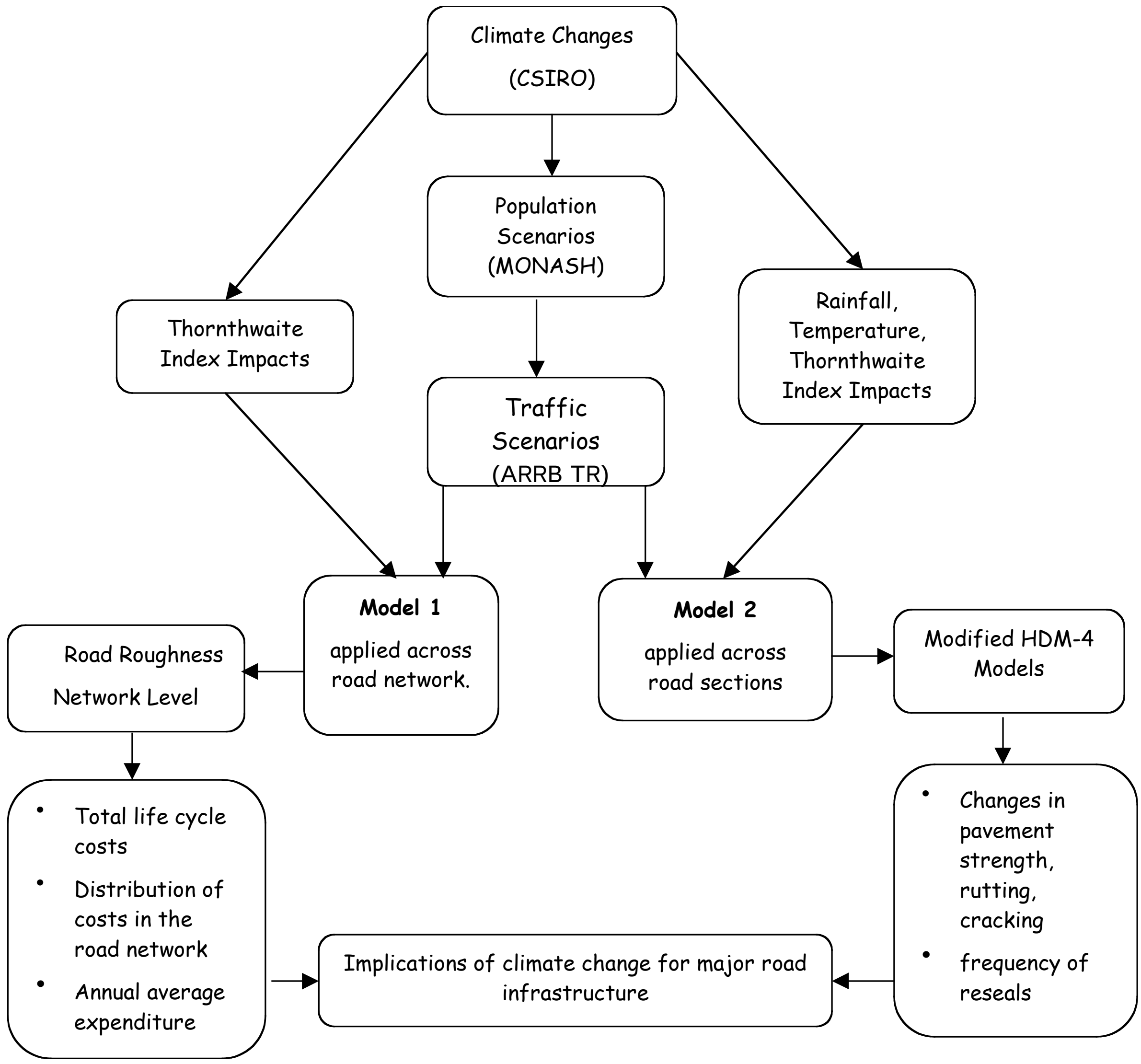


Figure 3.1: Project Structure

3.2 Structure of Report

The Project Report is divided into different in Sections that examine different aspects of the Project.

- Section 3.4 of the Report documents the data processing tasks required to transform the raw CSIRO Division of Atmospheric Research climate data into parameters required by the pavement deterioration models used later in the project. The climate modeling undertaken bu CSIRO is separately reported.
- Section 3.5 of the Report documents the work undertaken by the Monash University Centre for Population and Urban Research in relation to likely changes in population settlement patterns and

demographics as a result of predicted climate change. Projected changes in regional population distribution patterns as a result of climate change are presented for each of the major cities.
- Section 3.6 of the report documents the work undertaken by ARRB Transport Research to use the population projections and estimate changes in road transport demand. Three parameters (used in the pavement deterioration models) are used to express the growth in road transport demand. These are AADT, % Heavy Vehicles and Average ESAs per Heavy Vehicle.
- Section 3.7 of the report documents the inputs and outputs from the two pavement deterioration models used to examine the effects of climate change on the long term provision of road infrastructure. These models (HDM-4 and PLCC) are described in detail.

3.3 Introduction to Pavement Deterioration Modeling

Moisture and temperature are major influences on road deterioration: moisture affects pavement structural performance; and temperature affects surfacing performance (through bitumen aging effects which include oxidation and embrittlement).

Other factors, such as traffic volumes, pavement type, pavement history (previous maintenance, rehabilitation and construction works) and other road variables (such as road geometry, pavement structural characteristics and material properties) influence pavement deterioration.

Pavement deterioration is also influenced by the standards of maintenance applied. The road authorities undertake road maintenance and investment to deliver a road system with defined levels of performance. In addition to these agency costs (capital costs of road construction and maintenance) there are road user costs (vehicle operating costs, travel time and social costs – eg. accident costs, pollution, noise) that must also be considered. In this project, the focus is on the road agency costs.

Due to project constraints, it has not been possible to examine the impacts of extreme weather events such as extreme rainfall, extreme temperature or flood frequencies which will also impact on road design, road condition and operation.

As shown in Figure 3.1, two road deterioration models were used to assess pavement performance. They included the ARRB Transport Research Pavement Life Cycle Costing (PLCC) model and Highway Development and Management (HDM-4).

The PLCC model is developed in Delphi. Input data files may be imported from Excel and outputfiles may be exported to Excel. The PLCC model uses optimisation routines (Evolver genetic algorithm) to determine the minimum total cost subject constraints including budget constraints or minimum roughness constraints.In the PLCC model, the road network is divided into a small number of categories or road types which have similar attributes such as traffic flow and climate. This is done since the optimisation for a large number of road types can take a lot of processing time. The modeling asumes a pavement age profile of 15 years, and applies the same pavement model to all road categories (again for reasons of limited project budget). The PLCC output includes total costs (agency costs and road user costs) on a life cycle basis (eg 60 years), the distribution of costs in the road network and annual average expenditure.

The user provides data relating to analysis period (for example, 60 years), discount rate and costs functions (including fixed and variable costs). A typical input file has following fields:
- Road description (eg chainage data for network under consideration)
- Category (eg 1 = National Highway, 2 = Rural)
- Rehabilitation type (eg Granular, …)
- Deterioration factor
- Length (km)
- Average age of pavement
- Pavement strength (SNC)
- Roughness (minimum NRM count)

- Average Thornthwaite Index value
- AADT (vehicles per day)
- % heavy vehicles
- ESA's per vehicle

The HDM-4 road deterioration model has been enhanced by ARRB TR including modified calibration factors. HDM-4 can be applied across specific road sections at a time and provides more detailed information (for example, changes in pavement strength, rutting and cracking) than the PLCC model.

The data input requirements include road inventory data, climate variables (temperature, rainfall and Thornthwaite index), traffic information (AADT, vehicle mix, Equivalent Standard Axles per heavy vehicle), pavement type (materials, strength, thickness), pavement condition (age, initial pavement roughness) and works programs.

In each of the models, the future transport demand is required as a data input. Future transport demand is described in Section 3.6 and is based on selected scenarios relating to the level of traffic and growth rates. These scenarios also inlcude a likely vehicle mix over time (eg. mix of cars, light and heavy vehicles).

3.4 Processing of CSIRO Climate Change Data (section A)

The purpose of this Section is to outline the data processing undertaken on the climate change data provided by CSIRO Division of Atmospheric Research in preparation for input into the road pavement deterioration models (see Section 3.7).

3.4.1 Climate Modelling Data

The CSIRO Division of Atmospheric Research was contracted by Austroads to run its global and regional climate models for the period 1960 to 2100, producing results for a variety of climatic variables relevant to road pavement deterioration (precipitation, temperature, etc) on a 0.5 degree geographical (latitude/longitude) grid across the entire Australian continent.

The climate data was used in the following project tasks:

- Road deterioration modeling undertaken by ARRB Transport Research.
- Assessment of the implications of climate change for demographic, social and industrial trends and hence on the demand for transport infrastructure (jointly undertaken by ARRB Transport Research and the Centre for Population and Urban Research at Monash University).

Details of the climate modeling work undertaken by CSIRO is separately reported. The CSIRO base climate and climate change data was delivered to ARRB Transport Research on a CD-ROM containing 12 monthly space delimited ASCII files. These ASCII files were read directly into a series of Excel worksheets for further processing. Each file contained 5,865 data records representing 5,865 locations contained within the 0.5° latitude/longitude grid across the continent (roughly extending from 112° Longitude:- 44° Latitude, to 154° Longitude: -10° Latitude).

Table A.1 details the data record fields of the climate data provided from CSIRO. A number of data fields (such as monthly averaged maximum and minimum temperatures, and monthly average downwelling solar radiation) are provided in the CSIRO data set, but have not been used in the analyses undertaken in this Project. Only those data fields in Table A1 that have been underlined were required as input into the road deterioration models; these include the following:

- Data ID (grid location identifier)
- Longitude
- Latitude
- Mask (indicating if the grid cell is located over land or sea)
- Tmean (monthly averaged temperature in deg.C)

- Rainfall (monthly averaged rainfall in mm)
- Tmean_sc (degree C change per degree C of global warming)
- Rainfall_sc (Percent change per degree C of global warming)

Table A.1 Climate Data Fields

Parameter	Description
Data ID	Record counter (1 -> 5865)
Longitude	Longitude of data grid-point [112 -> 154; 85 x ? degree intervals]
Latitude	Latitude of data grid-point [-44 -> -10; 69 x ? degree intervals]
Mask	Identifies if grid cell occurs over land or sea (sea = 0, land = 1)
Tmax	Monthly averaged maximum screen level (2 metre) temperature
Tmin	Monthly averaged minimum screen level (2 metre) temperature
Tmean	Monthly averaged mean screen level (2 metre) temperature
Rainfall	Monthly averaged rainfall
Solar_rad	Monthly averaged downwelling solar radiation
Pot.evap	Monthly averaged potential evaporation
Act.evap	Average monthly actual evaporation
Tmax_sc	Deg.C change per deg.C of GW ("global warming")
Tmin_sc	Deg.C change per deg.C of GW
Tmean_sc	Deg.C change per deg.C of GW
Rainfall_sc	% change per deg.C of GW
Solar_rad_sc	% change per deg.C of GW
Pot.evap_sc	% change per deg.C of GW
Act.evap_sc	% change per deg.C of GW

The International Panel on Climate Change (IPCC) Special Report on Emission Scenarios (SRES) describes a number of emission scenarios for greenhouse gases (measured in Gt CO_2 emissions per year). These emissions are converted into atmospheric concentrations which are used to estimate global-average warming (temperature deg.C change over time) relative to 1990 for each scenario.

The global warming temperature change is usefully described in terms of an 'envelope' which represents variations within a scenario (each scenario results in a low, mid and high global warming temperature change over time), as well as variations within the different climate models used. This 'envelope' indicates that global average warming ranges from 1.4 to 5.8 deg.C by the year 2100 relative to 1990 (or a warming rate of 0.1 to 0.5 deg.C per decade).

The CSIRO data set provides 'low', 'mid' and 'high' estimates of global warming for a selected set of SRES scenarios (specifically A1, A2, A1F, B1, B2, and A1T). Figure A.1 illustrates the 'envelope' based on the mid-range global warming temperature changes for the above set of SRES scenarios.

These six scenario estimates have been averaged to produce what is called the "AVERAGE" scenario. The mid-range global warming temperature change for this "AVERAGE" scenario is shown in Figure A.2

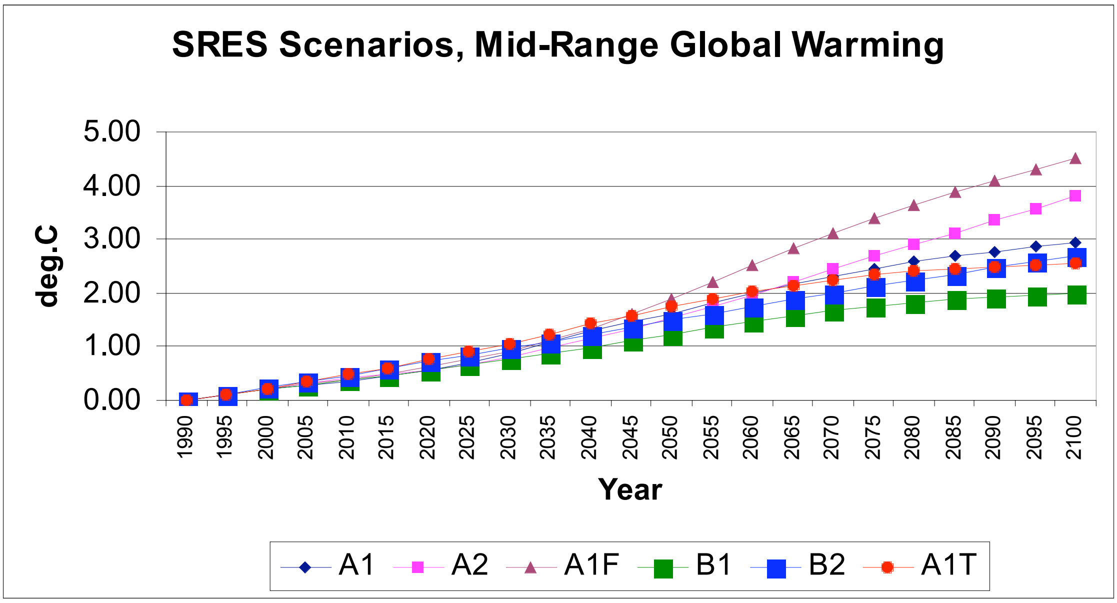


Figure A.1 SRES Mid-Range Global Warming Envelope

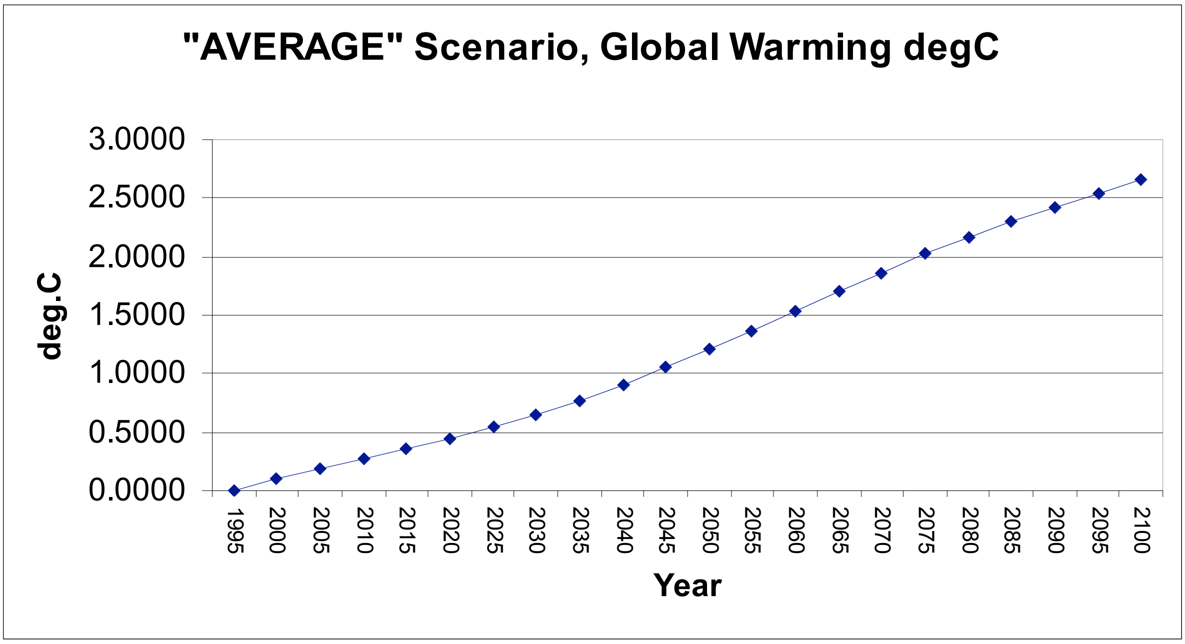


Figure A.2 "AVERAGE" Global Warming

3.4.2 Data Processing

Figure A.3 outlines the data processing paths used to translate the CSIRO data sets into data inputs for the pavement deterioration models. The key elements of this processing included:

- Extraction of the Base Climate, 2020 Climate, 2040 Climate, 2060 Climate, 2080 Climate and 2100 Climate data sets. The technique used to extract these climate data sets will be explained below but is based on the "AVERAGE" climate scenario described in Figure A.2 above. This approach also allows for some sensitivity analysis to be undertaken using different climate scenarios.
- Calculation of the Thornthwaite Moisture Index based on the climate data. As described below, the Thornthwaite Index is a climate classification scheme and is used as a parameter in the road deterioration models. An Excel based 'Thornthwaite Calculation Engine' was built to automate the Index calculations.
- Data interpolation. Interpolation was required to enable determination of a the appropriate climate parameters for a location on the National Highway System (which may not necessarily coincide with the spatial scale of the climate data (based on a 0.5 longitude/latitude grid).

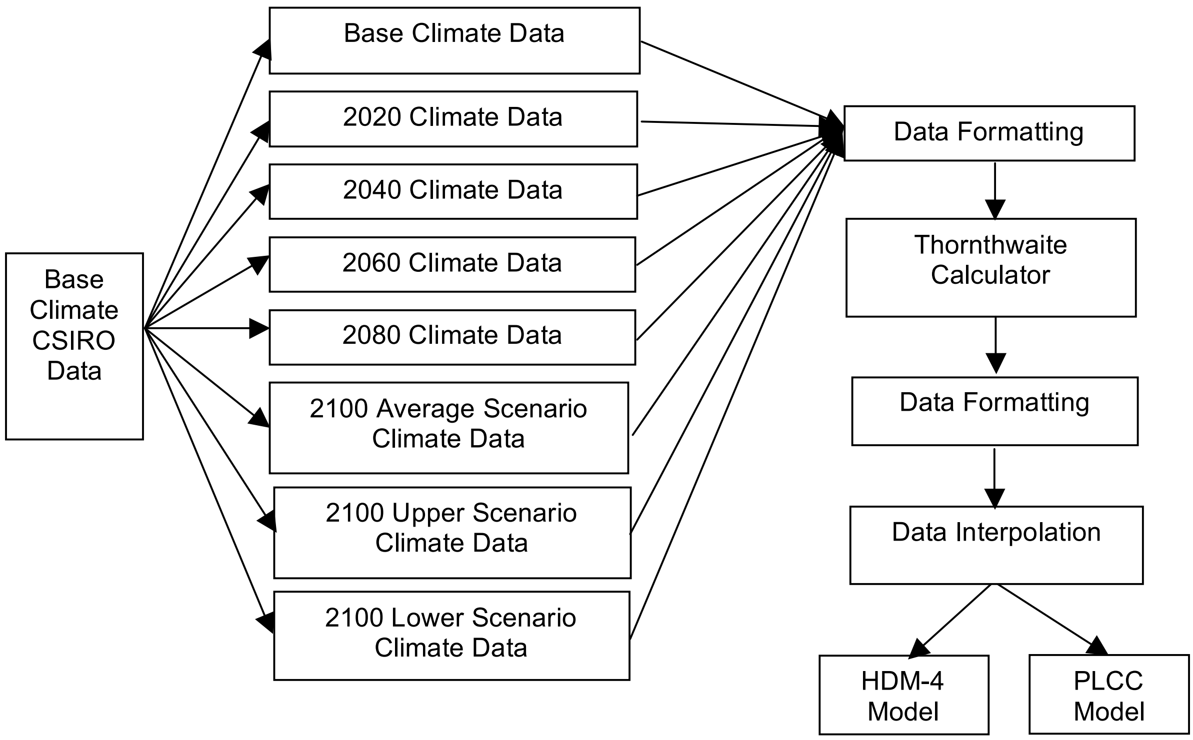


Figure A.3: Data Processing Pathway

Future Climates

The CSIRO data sets included in-built climate sensitivities. For example, changes in temperature (for future climatologies) are expressed as a degree C change per degree of global warming; changes in rainfall are expressed as a percentage change per degree of global warming.

The global warming (GW) parameter is the primary climate change parameter that is applied to each of the parameter sensitivities to calculate regional climate changes. The GW value used for the various time periods was arrived at by taking an average of the estimated average global warming (on a global level) based on 6 of the IPCC SRES emission scenarios. (As noted above, this is called the "AVERAGE" scenario).

Hence, future climatologies are easily determined using the following steps:

- Determine the appropriate global warming value (for example, read directly from Figure A.2 for the "AVERAGE" scenario).
- Multiply the regional parameter sensitivity by the global warming value. This parameter sensitivity is provided in the CSIRO data set. For example, the rainfall sensitivity is expressed as a percentage change per degree of global warming (that value of which is contained within the 'Rainfall_sc' data field of the input data files – refer to Table A.1). Similarly, the temperature sensitivity is expressed as a temperature change per degree of global warming and is found in the 'Tmean_sc' data field.
- Add to the base climate.

In summary, future climatologies were are calculated by applying the parameter sensitivities (provided by CSIRO) to each of the parameters of interest, along with the level of global warming associated with the scenario being analysed, as shown in Box A.1 below:

Box A.1

Future rainfall = bc + (bc x [%sens] x GW)

Where:

bc	=	base climate rainfall in mm
%sens	=	% change in rainfall per degree change in global warming (a data field provided by CSIRO)
GW	=	average predicted global warming (°C) on a global scale

Future temperature = bc + (t_sens x GW)

Where:

bc	=	base climate mean temperature (°C)
t_sens	=	temperature change per degree of global warming (a data field provided by CSIRO)
GW	=	average predicted global warming (°C) on a global scale

In addition to the "AVERAGE" scenario constructed, two further scenarios were considered.
The "UPPER" scenario was based on the A1F SRES scenario (the worst case global warming scenario as indicated in Figure A.1 above) and the 'mid' temperature change (which represents the average global warming value from all models applied to the A1F scenario).

The "LOWER" scenario was based on the B1 SRES scenario (the most optimistic global warming scenario as shown in Figure A.1 above) and the 'mid' temperature change (which represents the average global warming value from all models applied to the B1 scenario).

Sensitivity to the emissions scenarios has been analysed using the worst case ("UPPER") emission scenario (A1F) and the best case ("LOWER") scenario (B1). These global warming temperature changes under these scenarios is:

- 2.0 °C Global warming by 2100 ("LOWER" scenario)

- 3.08 °C Global warming by 2100 (“AVERAGE” scenario)
- 4.5 °C Global warming by 2100 (“UPPER” scenario)

Appendix A2 (available on Austroads website: www.austroads.com.au) shows the GW value for 5 year steps from 1990 to 2100 for each of the 6 IPCC SRES emission scenarios included in the analysis, along with the average. Values that were used in ARRB TR analysis have been highlighted.

The following section summarizes the climate results for rainfall and temperature. Sensitivity results

3.4.3 Results

Rainfall

This section summarizes the results of the data processing for the base climate and the future (year 2100) climate calculations. Data is presented in GIS format for the whole of the continent.

Data has also been extracted for the Major Capital Cities with climate sensitivity illustrated using the AVERAGE, UPPER and LOWER scenarios as described above. This disaggregation of data was used to assist in the population settlement changes as a result of future climate change. (Refer to Appendix A3 available on Austroads website: www.austroads.com.au for the capital city results). The road deterioration modeling, discussed in Section 3.7, has only been undertaken for the AVERAGE scenario due to project budget constraints.

Figure A.4 shows the average annual rainfall, in millimetres per month, for the Australian continent. It shows a concentration of rainfall extending around the northern and eastern coasts down to southern Victoria and Tasmania. There is also a patch of high rainfall area in south west WA. The interior of the continent is typically dry (less than 50mm per month), with decreasing rainfall towards the centre.

Figure A.5 shows the average annual rainfall for the year 2100 climate (based on the “AVERAGE” scenario described above). An overall trend to a drier climate is apparent with increases in rainfall evident only in the far north.

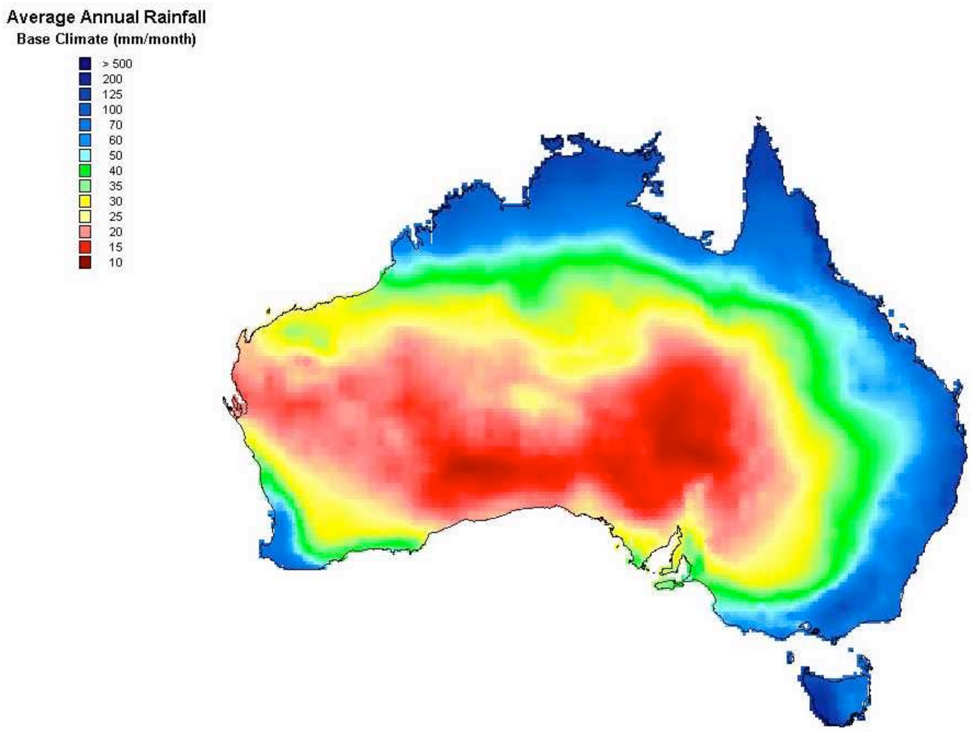


Figure A.4 Average Annual Rainfall for the Base Climate

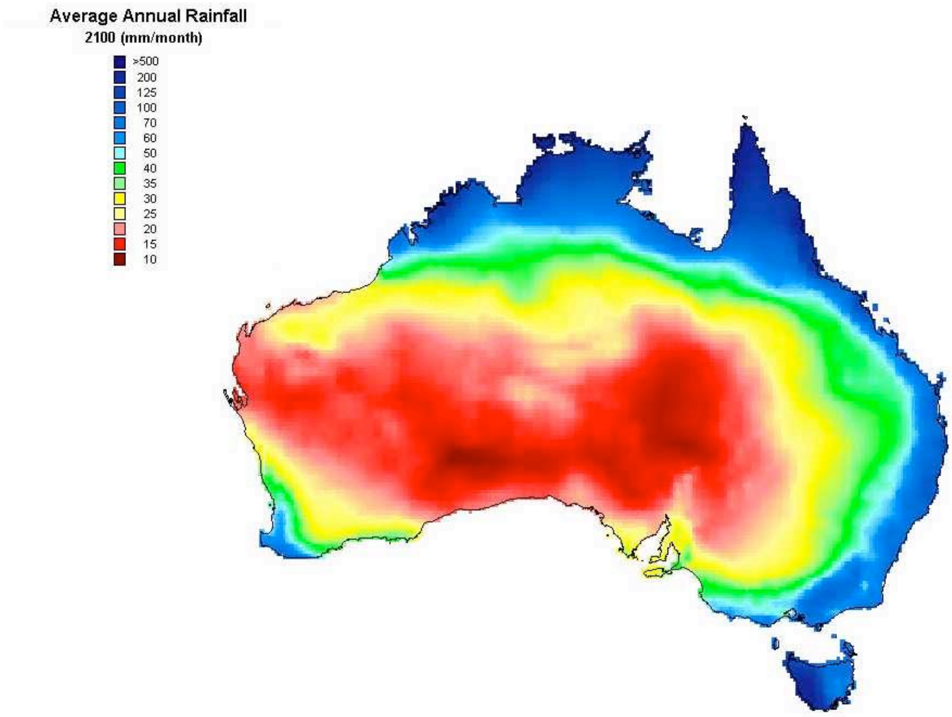


Figure A.5 Average Annual Rainfall for the 2100 Climate

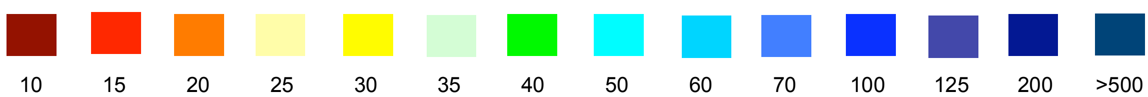


Figure A.6 shows the percentage change in annual rainfall over the period 2000 to 2100. Generally, there is a reduction in rainfall over much of the continent with significant increases in the north.

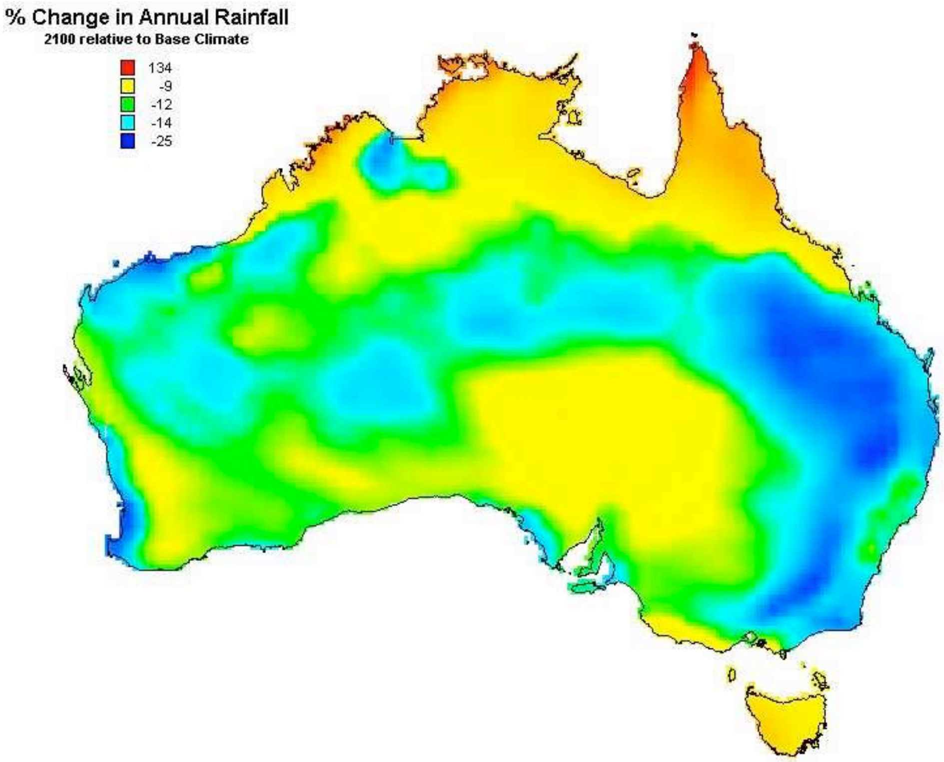


Figure A.6 Percent Change in Average Annual Rainfall 2000 - 2100

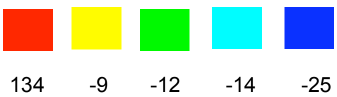


Figure A.7 shows the seasonal variations in rainfall for the base climate. It shows that rainfall patterns in Australia are high variable throughout the seasons. The tropical parts in the north of the continent experience a ‘wet season’ with high rainfall in Summer and Autumn and a ‘dry season’ with minimal rainfall in Spring and Winter. The southern parts of the continent experience more consistent rainfall throughout the year with central areas remaining dry throughout the year.

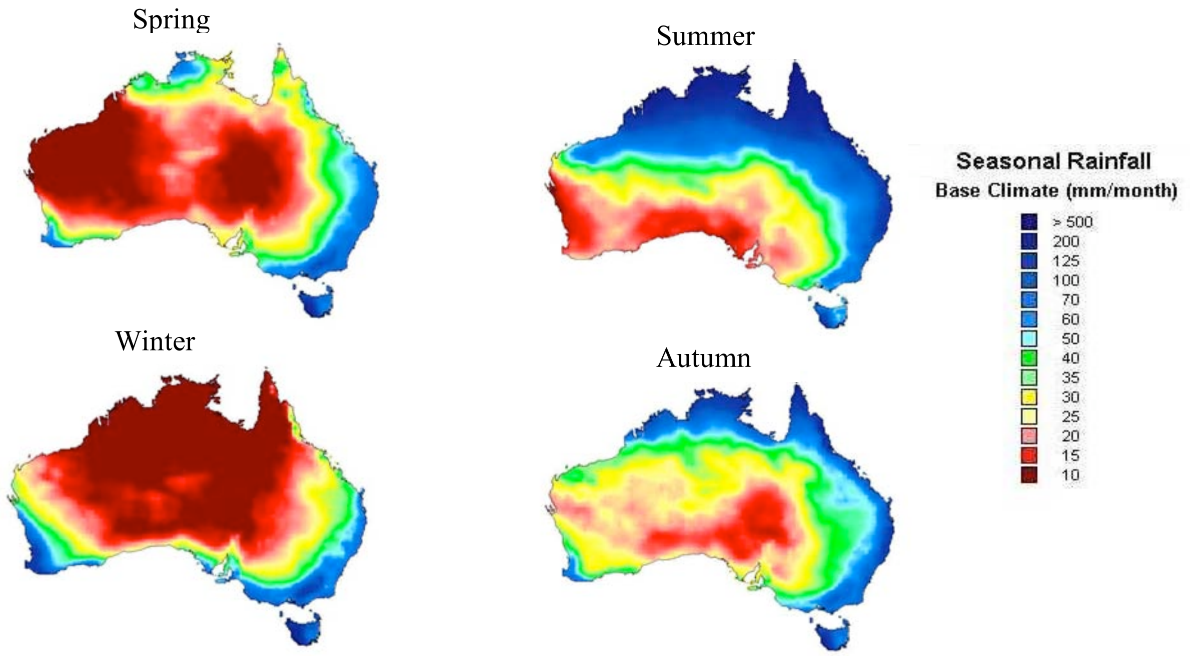


Figure A.7 Seasonal Rainfall for Base (2000) Climate

Figure A.8 shows the seasonal variations in rainfall for the 2100 climate. It shows that the same general trends (highly seasonal in the north, more consistent in the south) continue with an overall decrease in rainfall evident in all seasons.

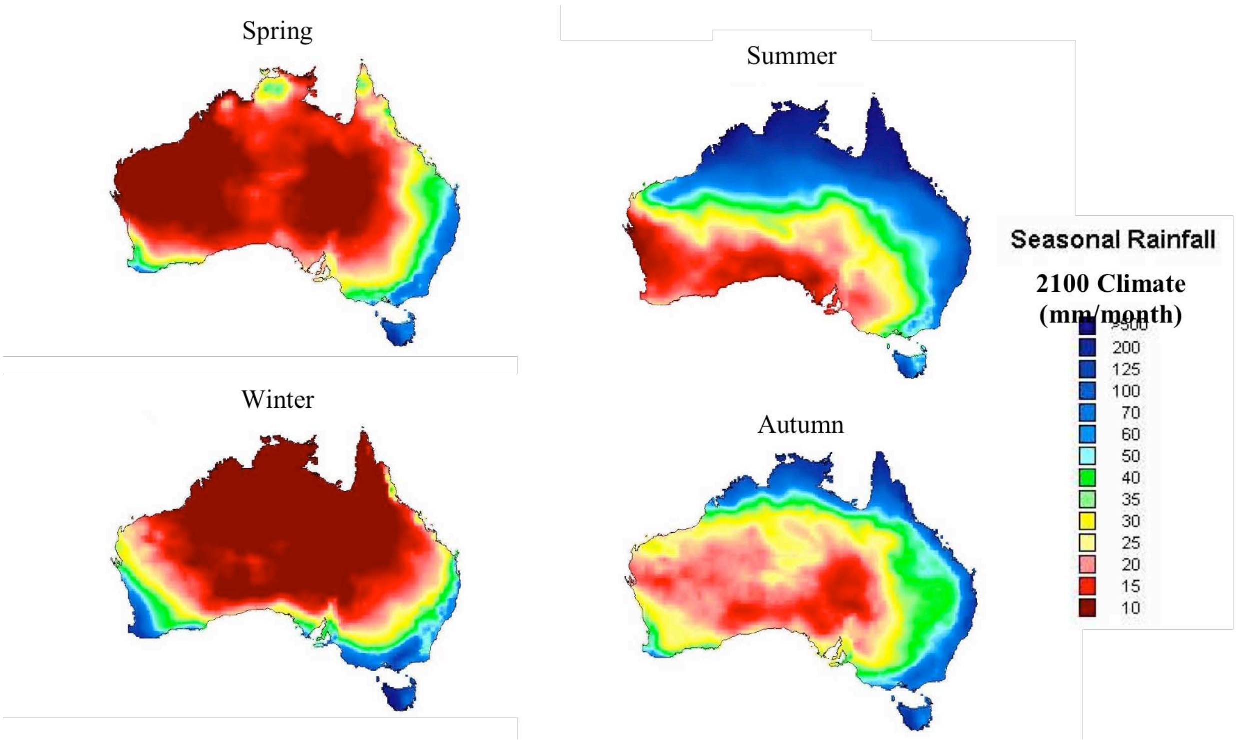
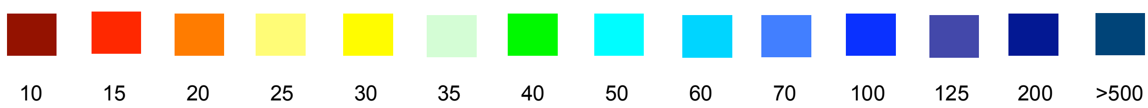


Figure A.8 Seasonal Rainfall for 2100 Climate



Temperature

Figure A9 show the average annual temperature for the base climate. It shows a gradient from temperatures in the region of 10 - 15 °C in Tasmania and along the southern coast up to 25 – 28 °C along the north coast of the continent

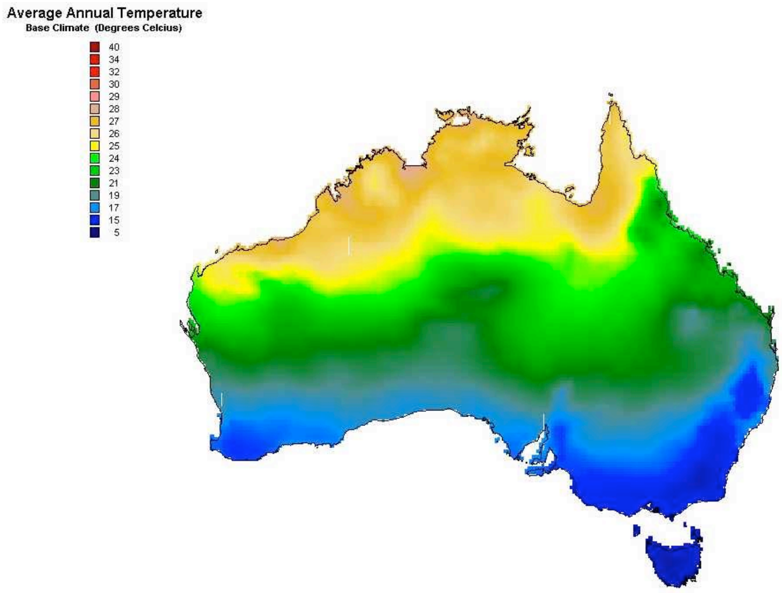


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Figure A9 Average Annual Temperature for the Base Climate

Figure A10 show the average annual temperature for the 2100 climate. It shows a gradient from temperatures in the region of 10 - 20 °C in Tasmania and along the southern coast up to 32 – 34 °C along the north coast of the continent. It is clear that average temperatures have increased significantly throughout the continent.

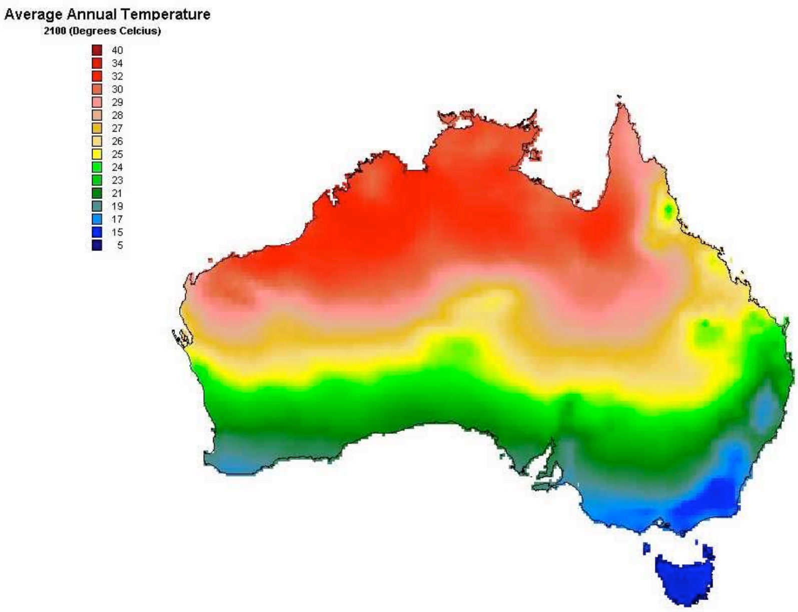


Figure A10 Average Annual Temperature for the 2100 Climate

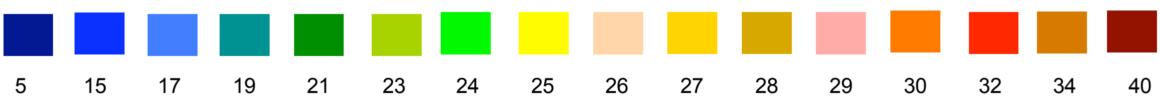


Figure A11 shows the maximum temperature ranges throughout the continent for the base climate. This is the maximum difference between minimum and maximum daily temperatures, this is an input parameter into the pavement deterioration models used later in the analysis. The figure shows that maximum temperature variation occurs in the central region with the most consistent temperatures occurring in far north Queensland and the Northern Territory.

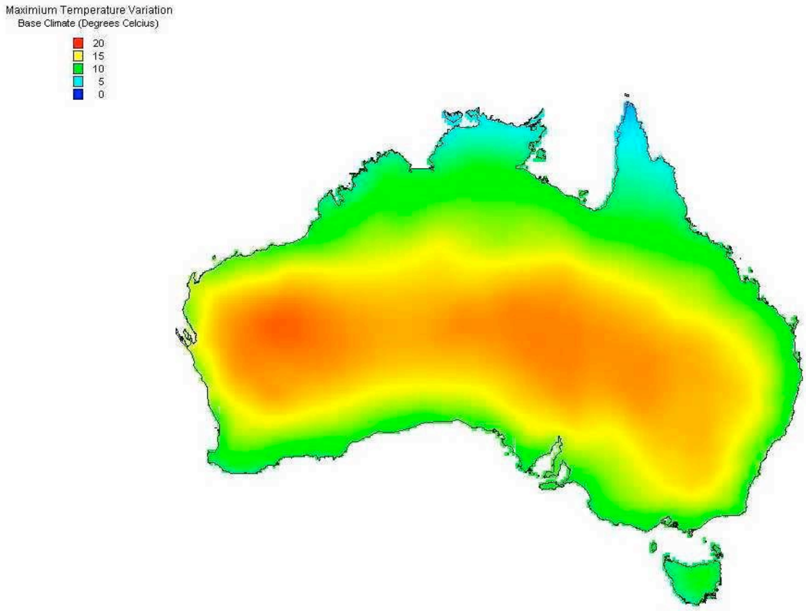


Figure A11 Maximum Temperature Range for the Base Climate

Figure A12 shows the maximum temperature variation for the 2100 climate. The basic pattern of more extreme temperature ranges towards the centre of the continent persists, while a general increase in temperature range, indicated by the more prominent red and yellow patches, can be discerned.

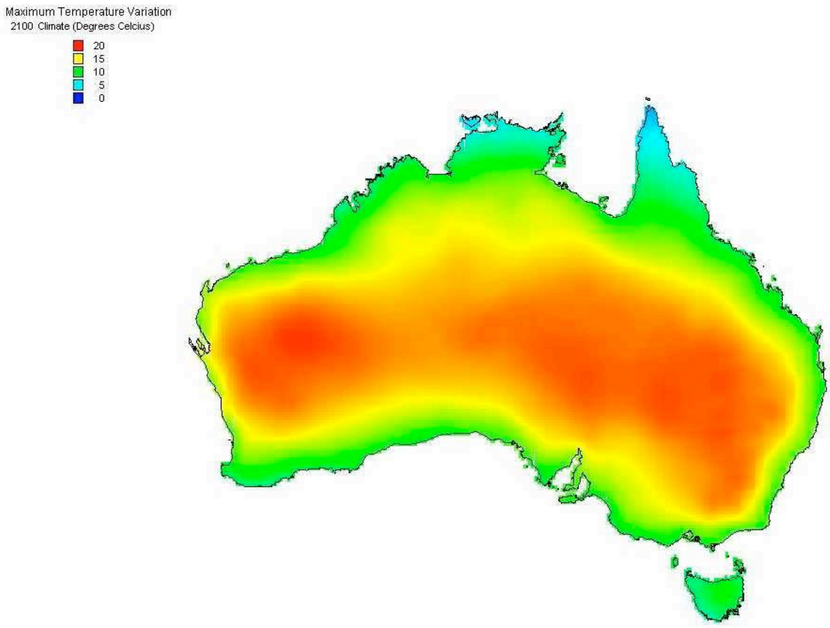


Figure A12 Maximum Temperature Range for the 2100 Climate

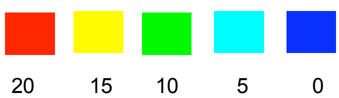


Figure A13 shows the changes in temperature for the 2100 climate relative to the base climate. It shows that average annual temperatures around the continent increase by 2 – 6 °C over this period. Temperature increases are greatest in the northern central region (indicated by the red patches) and least in coastal areas, far north Queensland, and Tasmania (indicated by the blue).

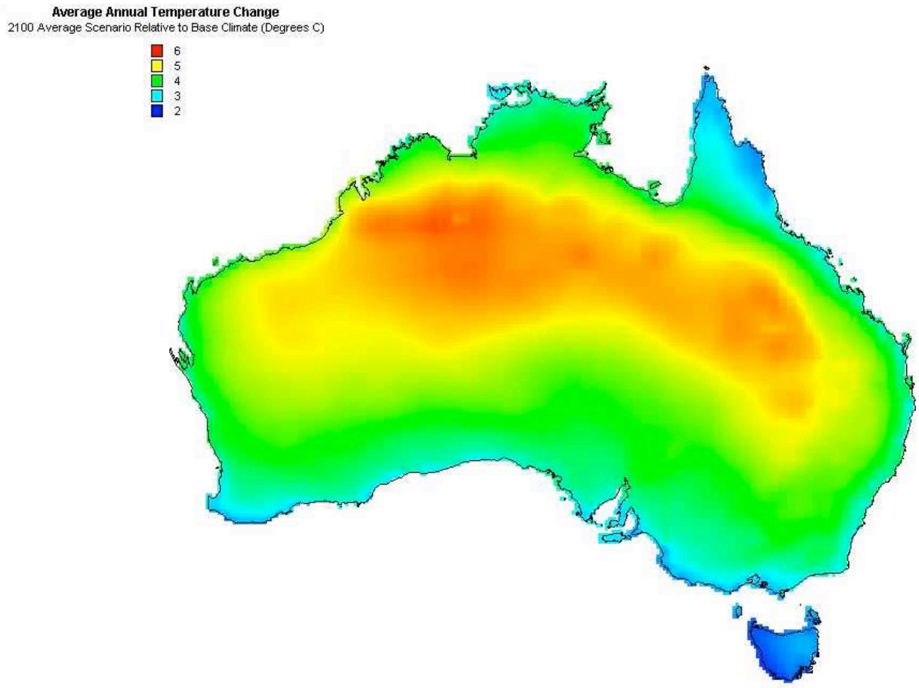
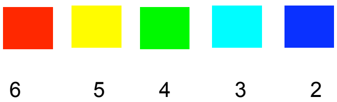


Figure A13 Temperature Changes (Year 2100 relative to base climate)



3.4.4 Thornthwaite Moisture Index

Method

Thornthwaite (1931) described a method of climate classification based on observed climatic data. The method determines the precipitation-evaporation ratio (called the P-Eratio) for any given month. Thornthwaite provided an empirical relationship between the P-Eratio, and measured monthly data for precipitation (P) and temperature (T) as shown in Equation 1.

Equation 1

$$P - Eratio = 11.5 * \{P/(T - 10)\}^{10/9}$$

where P is monthly precipitation in inches, T is mean monthly temperature in degF.

Thornthwaite defined the Precipitation-Evaporation Index (I) as the sum of the twelve monthly P-E ratios with a factor of 10 introduced for numerical convenience. See Equation 2.

Equation 2

$$P - EIndex(I) = \sum_{n=1}^{12} 10 * 11.5\{P/(T - 10)\}_n^{10/9}$$

After converting to SI units this gives (see Gentilli, 1972):

Equation 3

$$P - EIndex(I) = \sum_{n=1}^{12} 1.65\{Pmm/(Tc + 12.2)\}_n^{10/9}$$

Where *Pmm* is precipitation in mm and *Tc* is mean monthly temperature in deg C.

This method provided the following broad climate classifications:

Climate	**P-E Index**
Super humid	P-E >128
Humid	64 to 128
Sub humid	32 to 64
Semi arid	16 to 32
Arid	P-E < 16

This method was modified by Thornthwaite in 1947 to incorporate a moisture index which relies on a water balance approach. The modified approach is described below.

Thornthwaite's 1947 Method

In 1947 Thornthwaite (1947) described a method for climate classification based on an index called the Thornthwaite Moisture Index. This approach uses precipitation (P), temperature (T) and potential evapotranspiration (PET) as the key variables. Potential evapotranspiration will depend on a range of factors including temperature and length of daylight hours.

Thornthwaite provided a method to calculate the potential evapotranspiration (PET) of a location given latitude and temperature data. The general form of the equation provided is:

Equation 4 $$PET(um) = 1.6 * (10t/I)\}^a$$

where PET(um) is the unadjusted monthly potential evapotranspiration in cm, t is the mean monthly temperatures in deg C, I is an annual Heat Index (Equation 5 and Equation 6) and a is a coefficient provided by Equation 7.

Equation 5 Monthly Heat Index $(i) = (t/5)^{1.514}$

Equation 6 Annual Heat Index (I) = Sum of monthly head index values

Equation 7 $$a = 0.000000675 \times I^3 - 0.0000771 \times I^2 + 0.01792 \times I + 0.49239$$

Equation 4 provides an 'unadjusted rate of potential evapotranspiration' that can be adjusted to account for the differences in the length of daylight hours which varies with season and latitude. Adding the correction factors to Equation 4 gives:

Equation 8 $$PET(m) = f1 \times f2 \times 1.6 \times (10t/I)^a$$

where $f1$ is the fraction of the number of days in the month i divided by the average days in a month, 30; and $f2 = (Ni/12)$ is the fraction of the number of the hours in a day divided by the base of 12 hours in a day.

Annual potential evapotranspiration is given by:

Equation 9 $$PET(annual) = \sum_{n=1}^{12} \{PET(m)\}_n$$

Mather (1978) provides the original form of the definition of a Moisture Index (Im) as:

Equation 10 $$\mathrm{Im} = Ih - Ia$$

where Ih = humidity index (Ih = 100S/PET), S = moisture surplus from the water budget and PET is the potential evapotranspiration; and Ia = aridity index (Ia = 100D/PET) where D is the moisture deficiency from the water budget.

On an annual basis, Surplus S= P-AE (Precipitation minus Actual Evapotranspiration) and Deficit D = PET-AE (Potential Evapotranspiration minus Actual Evapotranspiration). Substituting for Ih - Ia in Equation 10 gives:

Equation 11 $$\mathrm{Im} = 100 \times (\frac{P}{PET} - 1)$$

However, water surplus means seasonal additions to subsoil moisture and ground water. Deeply rooted perennials may make partial use of subsoil moisture and thus minimise the effects of drought. Transpiration proceeds, but at reduced rates. For this reason, a surplus of only 60mm in one season will counteract a deficiency of 100mm in another. Thus in an over-all moisture index the humidity index has more weight than the aridity index: the latter has only six tenths the value of the former. (Thornthwaite, 1948)

Equation 12 $$\mathrm{Im} = Ih - (0.6 \times Ia)$$

Equation 13 $$\mathrm{Im} = \frac{100S - 60D}{PET}$$

In order to calculate Im from Equation 13 it is necessary to determine moisture surplus and deficit. This will involve assumptions relating to the soil moisture content. Richards et. al. (1983) provide a Climatic Map of Australia based on the Thornthwaite Moisture Index using a hypothetical soil profile with a water storage of 4inches (100 mm). Refer to Figure A14. A more detailed version is provided in Figure A15 (developed in GIS format by ARRB Transport Research).

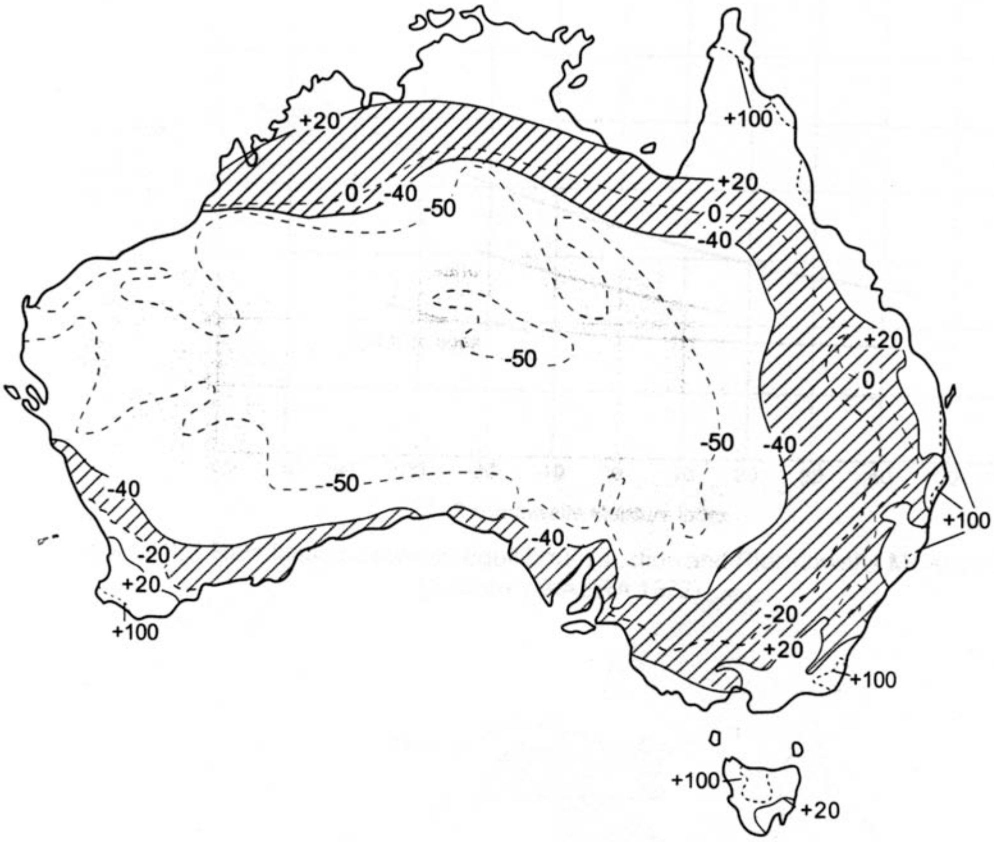


Figure A14 Thornthwaite Moisture Index Map

Contours show Thornthwaite Index values. Shaded range is +20 to –40.

+20 to -40

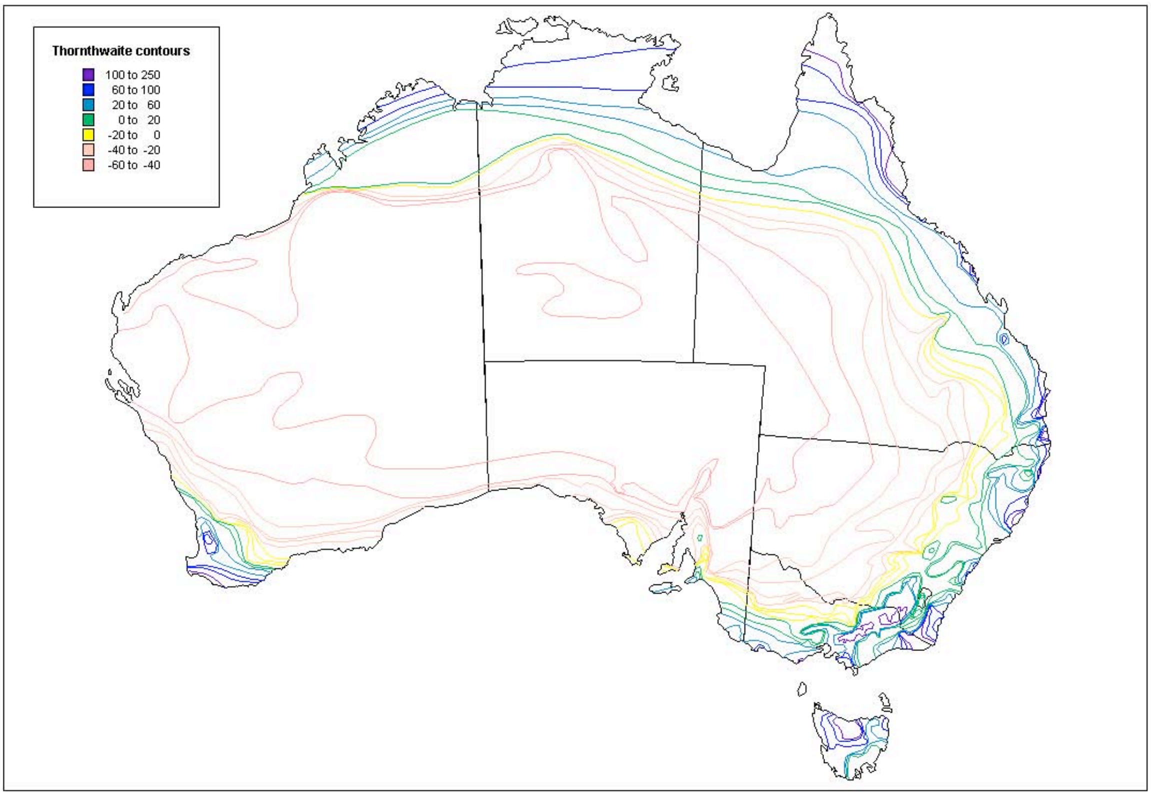
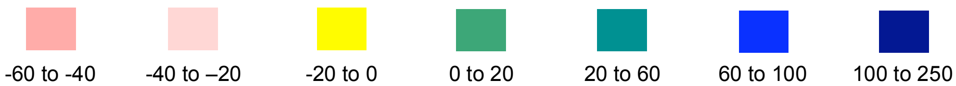


Figure A15 Detailed Thornthwaite Moisture Index Contours



Calculating the Thornthwaite Index

A Visual Basic Application (VBA) for the Thornthwaite Moisture Index Calculator has been developed to assist in calculating I_m values using equation 10. A screen capture of the calculation sheet is shown in Appendix A1 (available on Austroads website: www.austroads.com.au).

The key steps and assumptions of the calculation approach are:

1. Assume initial soil moisture content of 100mm (refer Richards et al, 1983)

2. Assume an Average Soil Moisture Capacity (AWC) of 100mm. (refer Thompson, 1999)

3. Runoff (RO) is not included in the calculation. Hence the general water balance equation:
   Input = Output + Change in Storage becomes
   $P = PET + \Delta S + RO$
   Where P is precipitation, PET is Potential Evapotranspiration, ΔS is the change in soil moisture storage and RO is runoff (ignored)

4. Calculate PET using Thornthwaite's equation (Equation 6). The correction factor is obtained using the latitude of the site being evaluated.

5. Calculate P – PET. This can be positive or negative. Positive values indicate water is available to recharge soil moisture and/or runoff. Negative values indicate the amount by which precipitation fails to supply the PET requirement (PET is also called the Water Need)

6. Calculate Accumulated Potential Water Loss (AccPotWL). This is the accumulated sum of the negative P – PET values and is used in determining the current level of soil moisture storage. The value here will depend on the assumed AWC. (See Point 1 above). (refer Thompson, 1999)

7. Calculate soil moisture storage. Soil Moisture Storage is less than or equal to AWC (a maximum value). When P – PET is positive and soil moisture is less than the capacity (AWC), then the positive value is added to the previous months soil moisture. Positive P-PET values when the soil moisture is at AWC represent excess rainfall available for runoff.

8. Calculate change in Soil Moisture (ΔS). This is positive or negative but is only recorded when the soil moisture is less than AWC.

9. Actual evapotranspiration (AE) is calculated as follows
   $AEi = PETi$ if Precipitation $Pi + \Delta S$ is greater than or equal to PETi. Or
   $AEi = Pi + \Delta S$ where $\Delta S = Si\text{-}1 - Si$ if precipitation $Pi + \Delta S$ is less than PETi

10. Calculate Moisture Surplus. If Precipitation P is greater than Actual Evapotranspiration, then
    Surplus $S = Pi - AEi$
    Pi is precipitation for month i
    AEi is the actual evapotranspiration for month I

11. Calculate Moisture Deficit. Deficit is the difference between PET and AE.
    Deficit $D = PETi - AEi$
    PETi is the potential evapotranspiration for month i
    AEi is the actual evapotranspiration for month i

12. Calculate Thornthwaite Moisture Index Im (Equation 10).

Two Thornthwaite Index maps were generated based on current and future climate data provided by CSIRO. A Base Climate (2000) is shown in Figure A16 and a Future Climate (2100) is shown in Figure A17.

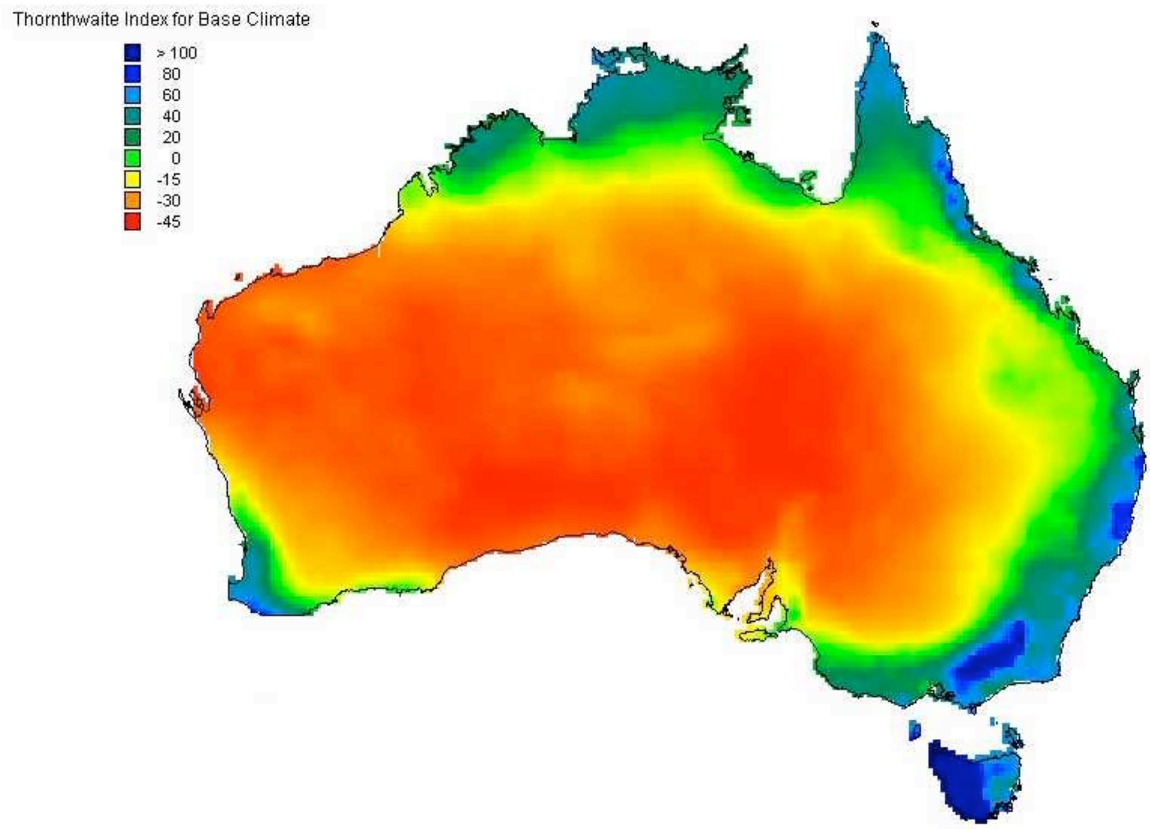


Figure A16 Base Climate (2000) Thornthwaite Index Map

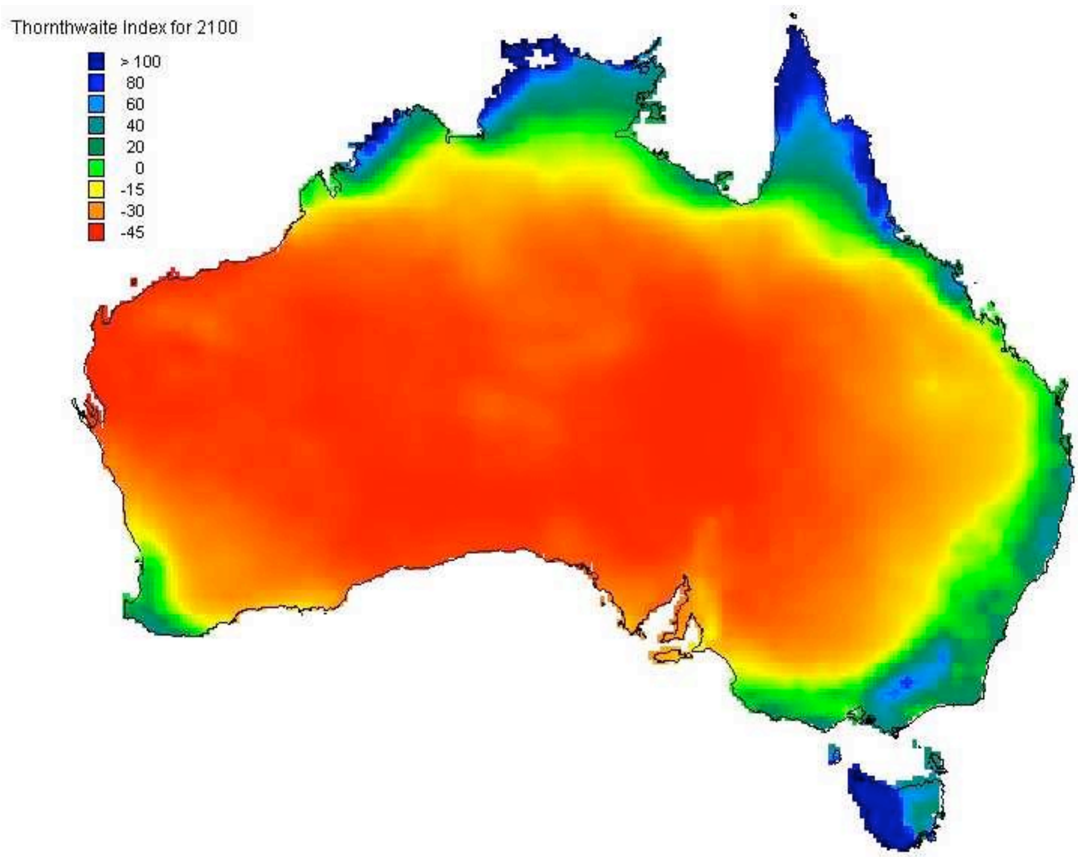
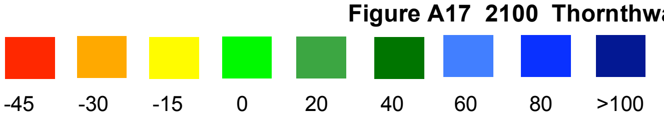


Figure A17 2100 Thornthwaite Index Map



As shown in Figures A16 and A17 the changes in Thornthwaite Index are not very pronounced. Figure A18 illustrates the extent of the change based on differences between the 2000 base climate and the 2100 future climate.

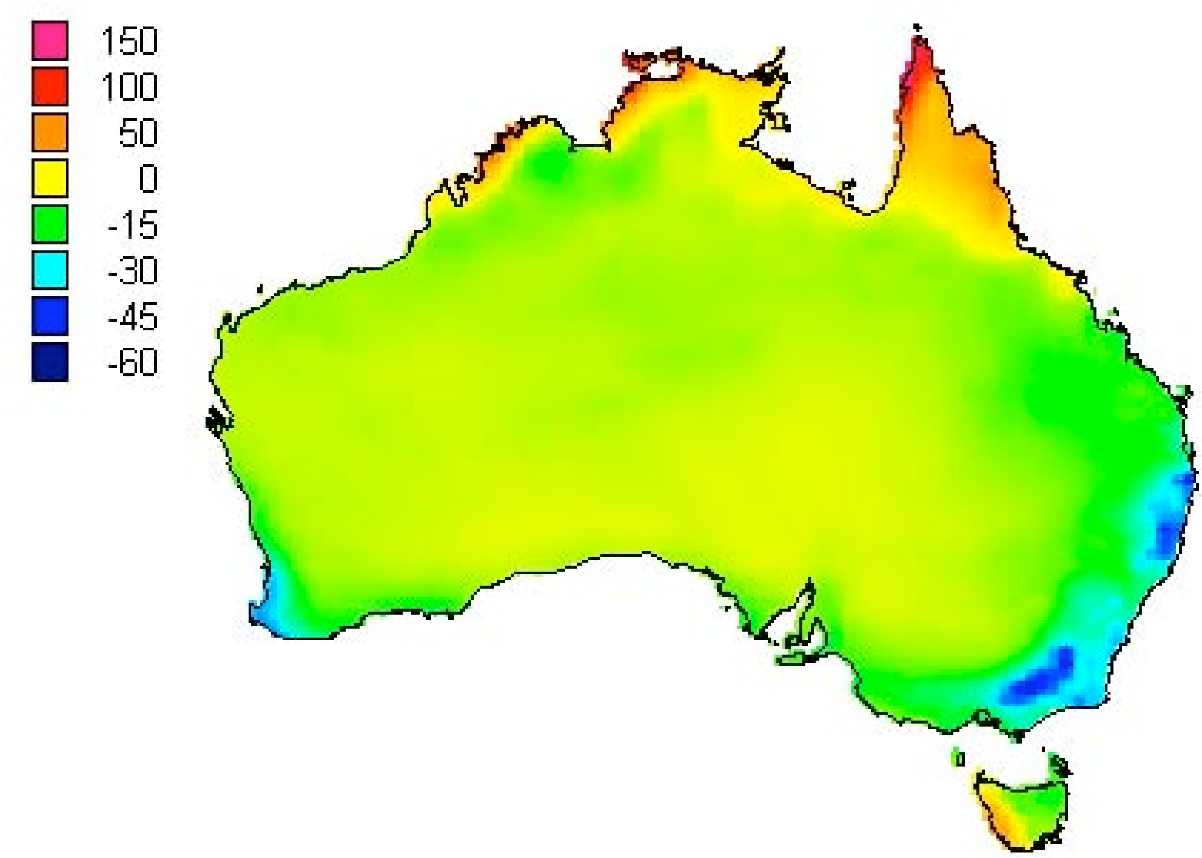


Figure A18 Changes in Thornthwaite Index (2000 to 2100)

With reference to Figure A18 the following key points may be discerned from the maps:

- There is a tendency to a drier climate overall (indicated by the negative change in Thornthwaite Index)
- The central area of Australia is relatively unchanged
- There are localised areas where the changes to the Thornthwaite Index is greatest including
  - ⇒ South-West of Western Australia,
  - ⇒ North-East Victoria and Southern NSW,
  - ⇒ South-West Tasmania,
  - ⇒ Top-End Queensland.

Data Interpolation

It is necessary to generate a sub-set of data that represents key variables (Thornthwaite index, temperature, rainfall etc.) for ordinates on the existing National Highway System. The standard procedure generates a Thornthwaite Index (Im) based on input data for a 50km grid. In order to determine the Im index value for a specific location (based on Longitude and Latitude) such as a National Highway Chainage point, an interpolation routine is used.

The routine is based on Lagrangian polynomial curve fitting, whereby a point can be found to fit any {X,Y} data set. Any odd number of data pairs can be used to generate the polynomial, with accuracy increasing with the number of points. For this exercise, a 5 x 5 coordinate grid was used to interpolate data values for a specific longitude/latitude. Where there were insufficient data points surrounding the ordinates being interpolated for (e.g. coastal areas), the interpolation was reduced to a 3 x 3 grid, or if again not possible, the nearest data point.

In calculating a value of Thornthwaite Index for coordinates (116.43,-35.17) for example, the subroutine finds the closest coordinates as the basis for interpolation, shown boxed in the table below as the centre of the interpolation grid. A Thornthwaite value is then interpolated for each of the five rows of data corresponding to the longitude, 116.43.

	115.5	116.0	116.5	117.0	117.5
-36.00	107	110	108	101	89
-35.50	97	101	100	90	74
-35.00	82	90	89	72	51
-34.50	64	81	51	27	9
-34.00	56	53	20	3	-8

e.g. First interpolation X = {115.5, 116, 116.5, 117, 117.5}, Y = {107, 110, 108, 101, 89}

X_{in1} = 116.43, find solution Y_{out1}

Second interpolation X = {115.5, 116, 116.5, 117, 117.5}, Y = {97, 101,100, 90, 74)

X_{in2} = 116.43, find solution Y_{out2}

Repeat for each of 5 rows of Thornthwaite data.

The 5 values corresponding to longitude 116.4 are then used to interpolate a Thornthwaite value corresponding specifically to latitude –35.1.

e.g. X={-36.0, -35.5, -35.0, -34.5, -34.0} Y={ Y_{out1} , Y_{out2}, Y_{out3}, Y_{out4}, Y_{out5}}

X_{in} = -35.17, find solution Y_{out} specific to longitude, latitude {116.43, -35.17}

Using the basic subroutine, loops are then overlaid to calculate values for multiple long/lat pairs and multiple data sheets (Thornthwaite, temp, rainfall, etc) as required.

The methodology was validated by interpolating values from data tables generated using complex trigonometric functions with small to high differential values between ordinates, and the values obtained were in agreement to 7 or 8 decimal places.

3.4.5 References

Thornthwaite, C.W., (1931). The Climates of North America According to a New Classification, *The Geographical Review*, Vol 21(1), pp.633-654.

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Thornthwaite, C.W. (1948). An Approach Toward a Rational Classification of Climate, *The Geographical Review*, pp.55-94.

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Richards, B.G., Peter, P., and Emerson, W.W. (1983). The effects of vegetation on the swelling and shrinking of soils in Australia. *Geotechnique*, Vol 33, No 2, pp.127-139, Institution of Civil Engineers, London.

Thompson, S.A. (1999). *Hydrology for Water Management*. Rotterdam Books.

3.4.6 List of appendices on Austroads website: www.austroads.com.au

A1 Screen Capture of Thornthwaite Calculator Calculation Sheet

A2 Table of GW (degC predicted increase) for different SRES Scenarios

A3 Rainfall and temperature charts

3.5 Impact of Climate Change on Settlement Patterns (section B)

The purpose of this Section is to outline the shaping factors that will influence Australia's population during the 21st century and to assess the differential regional impact climate change could have on the settlement patterns.

3.5.1 Introduction

This Section was prepared by the Monash University Centre for Population and Urban Research. It presents the results of the demographic analysis tasks associated with the Climate Change project. This work was undertaken in two phases:

Phase 1 examined 'shaping' factors affecting fertility, mortality, international and internal migration movements that influence population settlement patterns. Population projections scenarios (based partly on the ABS projections and supplement by the ANU demographic projection software) were developed for Australia, States and major metropolises.

Phase 2 examined the differential regional impact climate change could have on the settlement patterns projected in Phase 1. This phase considered the effects of 'push' factors in migrant source countries that may alter population flows to Australia as well as the affects on the life-style appeal and suitability for settlement.

3.5.2 Phase 1 — Overview of Shaping Factors

This phase deals with the demographic outlook for Australia during the 21st Century, including likely population distribution patterns. No account is taken of the implications of possible climate change in Australia or elsewhere in the world. Such influences will be considered later in the light of the CSIRO's estimates of the regional impact of climate change in Australia.

Parameters shaping Australia's population outlook

There is reasonable agreement among population experts about the major parameters shaping Australia's population outlook. The Total Fertility Rate (TFR) which is a measure of the number of children women will have (on average) have over their child bearing lives, is likely to fall somewhat from the present level of 1.75. The current Australian level is higher than that in the (non-Catholic) Western European nations Australia has most in common with, including the UK and Sweden. The social and economic circumstances which appear to have contributed to the low fertility levels in these societies, are also evident in Australia.[4] They include an increasing proportion of women who achieve post school qualifications and take up occupations commensurate with these qualifications. Such women have more to lose by leaving paid employment in order to raise children. Another common circumstance is the longer period facing young men and women before they can be secure in their employment outlook. Without such security men and women are unlikely to establish long-term coupling relationships. These are usually a prerequisite before a couple will consider raising a family. Thus there is a trend towards later marriage and age of first birth (which tends to translate into fewer births for the women in question than would otherwise be the case).

The projections developed below incorporated an assumption consistent with these ideas. It is assumed that the TFR will fall to 1.6. by 2008 and remain at this level thereafter. If this is the case it will have a profound impact on Australia's population size and structure during the 21st Century. Successive generations will fall well short of replacing their predecessors. (A TFR of 2.1 is required for generation replacement rather than 2.0 because some women die during the reproductive life span. Thus those that complete this span have to have slightly more than two children during the period. Also, because there is always around four per cent more male live births than females, and because the

4 D. A. Coleman, 'Reproduction and survival in a an unknown world', *People and Place*, vol 8, no 2, 2000, pp 1-5; Peter McDonald, 'Low fertility in Australia: evidence, causes and policy responses,' *People and Place*, vol 8, no 2, 2000, pp. 6-20

TFR refers to the number of births a woman would have over her child bearing life, the replacement level TFR must be a little higher than 2.0 in order to adjust for this lower ratio of female to male births).The inevitable consequence is that if the TFR falls as projected to 1.6, Australia's population will fall (in the absence of immigration) quite sharply, especially in the second half of the Century. It also means that there will be a steep increase in the proportion of the population aged 65 or over.

The immigration assumption employed is that of a sustained annual net inflow of 90,000 per annum. This is about the same the actual average net annual inflow in the second half of the 1`990s. Needless to say it is very difficult to anticipate the level of immigration, because it is subject to so many influences, including the state of the economy (and particularly the level of unemployment in Australia) and the various 'push' pressures from the main immigration source countries. In Australia's case the largest current source country is New Zealand, but the largest aggregate of source countries are located in Asia.

There will be pressure for higher immigration intakes as Australia's population ages and the rate of growth of the population slows. However, there are grounds for doubting whether such higher intakes will occur. It has proved politically difficult for most Western societies to respond to incipient population ageing and population decline by resorting to high migration intakes, especially where the migrants in question come from 'different' cultural or racial backgrounds. This is evident in Western Europe where low fertility has already contributed to a significant ageing problem. For example, in Germany, the proportion of the population aged 65 plus was 15.5 per cent in 1995.[5] By comparison, the parallel figure for Australian in 2000 was 12.3 per cent. Several Western European countries also face excesses for deaths over births over the next decade, including Italy, Spain, Germany and Sweden. As a consequence, even with some immigration many of these countries will experience sharp population declines over the period 2000 to 2050. In Germany, the fall is likely to be from 82 million to somewhere between 65 and 73 million over this period.[6]

Despite these circumstances, no Western European country has initiated a compensating immigration program. The only response has been to facilitate the inflow of highly skilled migrants (especially IT professionals), usually on a temporary visa basis. This policy stance may change as the populations of the European countries in question begin to shrink.

As recent experience with the politics of migration in Australia has shown, any sharp increase in migration to Australia is also likely to be controversial. In addition any expansion of the migration program during the first half of the 21st Century, is likely to occur in a context where other developed nations (including Japan) will be looking for high quality migrants as well. The competition for such migrants will be stiff. On the other hand, given that the global population is likely to reach at least 8 billion by mid-Century, there will be no shortage of low skilled persons ready to move to Australia, Europe or North America. There is little prospect however, that such persons will be wanted in the 'knowledge economies' certain to prevail in the mid-21st Century developed world.

The mortality assumption is that there will be a continued gradual improvement in life expectancy at birth, from (currently) 75.9 for males and 81.5 for females to 83.3 years for men and 86.6 years for females by 2051.

The projection detailed below has been built around the assumptions outlined above, that is a TFR of 1.6 after 2008, net annual migration of 90,000 and a gradual improvement in mortality. The projection resulting corresponds to the 'Series 2' projection drawn from the latest Australian Bureau of Statistics (ABS) report on population projections for Australia.

Under this projection Australia's population will increase from 18.9 million in mid-1999 to 25.4 million in 2051.[7] The population will subsequently peak at 25.5 million in 2063, and thereafter decline

5 United Nations Population Division, *Replacement Migration*, 2000, p. 37

6 Geoffrey McNicoll, 'Reflections on 'Replacement Migration', *People and Place*, vol 8, no. 4, 2000, pp 1-2

7 Projections derived from 'Series 2' drawn from Australian Bureau of Statistics, *Population Projections Australia, 1999-2101*, Cat. no. 3222.0, August 2000.

slightly to 25.3 million by 2101. It is not until the decade between 2030 and 2040 that deaths exceed births. However, thereafter the gap widens, such that by 2051 deaths exceed births by 62,000. After 2051 there is a further gradual widening of this gap. By 2101 deaths exceed births by 95,000. Nevertheless, as Table B.1 shows, under the 'Series 2' assumptions, Australia's population stabilises during the second half of the 21st Century, because the projected net intake of 90,000 migrants per annum roughly matches the projected excess of deaths over births.

Table B.1 provides an indication of what Australia's population would look like under plausible assumptions which would give significantly higher and lower outcomes than those of the 'Series 2' projection. On the high side, it is assumed that fertility is the same as with 'Series 2' but net migration is sustained at 150,000 per annum over the 21st Century. The effect is that Australia's population continues to grow in the second half of the Century to reach 33.1 million. On the low side, a TFR of 1.3 is employed (about the level current in Germany, Spain and Italy). In such a scenario, it is highly unlikely that net immigration would drop below 90,000 level because of the resulting pressure for more migrants in such a low fertility situation. Under these assumptions Australia's population would increase marginally to 2051 then fall during the second half of the 21st Century to about the level reached in 1999.

Table B.1: Population projections for Australia, 1999-2101 (millions)

	Low	Series 2	High
Year ending 30 June	**Population (millions)**		
1999	19.0	19.0	19.0
2021	22.2	22.9	24.4
2051	22.9	25.4	29.5
2101	19.0	25.3	33.1
Period	**Annual growth rates (%)**		
1999 to 2021	0.76	0.93	1.29
2021 to 2051	0.11	0.36	0.70
2051 to 2101	-0.34	-0.01	0.24

Source: ABS, Population Projections, Australia, 1999-2101
Assumptions:
Low: TFR=1.3, Net annual migration=90,000
High: TFR=1.6, Net annual migration=150,000
Series 2: TFR=1.6, Net annual migration=90,000

The subsequent analysis builds around the 'Series 2' projection. This is partly to simplify discussion of distribution patterns. Nevertheless it is evident that a number of plausible alternative population scenarios could be constructed. There are a host of unknowns over the horizon on this front. One to be discussed in the course of this project is the implication for Australia's environmental setting of climate change. This may have implications for judgements about Australia's capacity to carry large numbers of additional residents.

The three scenarios shown in Table B.1 give an indication of the range of 'realistic' demographic prospects for Australia. They have in common however that most of the growth of Australia's population will occur in the early years of the 21st Century.

This means that major infrastructure investments will have to be made to accommodate the extra people regardless of any climate change impacts. Under the 'Series 2' assumptions, Australia's population grows by 6.5 million between 1999 and 2051. But some 2.4 million, or 36 per cent of this expansion will occur in the first 12 years of the period, that is from 1999 to 2011. Thereafter, the rate of growth of the population slows. Given the 'Series 2' assumptions, Australia can look forward to an unprecedented period of population stability, at least during the last two thirds of the 21st Century.

Table B.2 provides a projection of the regional distribution of Australia's population. It is based on the 'Series 2' assumptions outlined above and a set of assumptions about the internal movement of Australians, which are examined and justified in the discussion below. The State and regional projections do not extend beyond the mid-21st Century because the ABS does not provide such projections beyond this date.

Three major regional outcomes are evident for the period to 2051. One is greater concentration of Australia's population in the four major metropolises (Sydney, Melbourne, Brisbane and Perth). The second is the significant increase in the share of Australia's population living in Queensland. The third outcome is that to the extent that population growth occurs outside the four major metropolises, the location is mainly in non-metropolitan Queensland and to a lesser extent in non-metropolitan Western Australia.

Metropolitan dominance

The number of people resident in the four major metropolises is projected to increase from 10.4 million in 1999 to 15.3 million in 2051. They absorb 76.5 per cent of Australia's total 6.4 million total population growth over the period. During the same period, their share of Australia's total population increases from 54.9 per cent to 60.3 per cent. The main loss of population share occurs in the rest of NSW, the rest of Victoria and South Australia.

Table B.2: Projected population growth in Australia by region, 1999 to 2051

Location	Population 1999 ('000)	Population 2051 ('000)	Increase 1999 to 2051 ('000)	Share of Australia's population 1999 (%)	Share of Australia's population 2051 (%)	Share of Australia's projected increase 1999-2051 (%)
Sydney	4,041	5,857	1,816	21.3	23.0	28.2
Rest of NSW	2,370	2,390	20	12.5	9.4	0.3
Melbourne	3,417	4,393	976	18.0	17.2	15.1
Rest of Victoria	1,295	1,154	-141	6.8	4.5	-2.1
Brisbane	1,601	2,864	1,263	8.4	11.3	19.6
Rest of Qld	1,911	3,237	1,326	10.1	12.7	20.6
Adelaide	1,093	1,102	9	5.8	4.3	0.1
Rest of SA	400	308	-92	2.1	1.2	-1.4
Perth	1,364	2,231	867	7.2	8.8	13.5
Rest of WA	497	806	309	2.6	3.2	4.8
Hobart	194	146	-48	1.0	0.6	-0.7
Rest of Tasmania	276	173	-103	1.4	0.7	-1.6
Darwin	88	192	104	0.5	0.8	1.6
Rest of NT	105	177	72	0.5	0.7	1.1
ACT	310	372	62	1.6	1.5	0.9
Australia	18,987	25,408	6,441	100	100	100

Assumptions:
TFR 1.6
Net overseas migration 90,000 per annum
Source: ABS, Population Projections Australia, 1999-2101, 2000

There are two sets of demographic assumptions which bring about these outcomes. The first is the expectation that (as in the 1990s) the majority (around 72 per cent) of Australia's overseas migrants will settle in Sydney, Melbourne and Perth. The reason for this confidence is that migrants from non-English-Speaking-Background countries (currently, the majority of Australia's migrants) overwhelmingly locate in areas where co-ethnic communities and family are already resident. These are mainly in Melbourne and Sydney. Another important motive is that, as argued below, these locations are likely to exhibit the best job prospects.

The second set of assumptions relate to internal migration movements. The context here is that there is a long history of metropolitan population concentration in Australia. This continued after World War Two until the 1970s. However, in the 1970s and 1980s there was some evidence of 'counter urbanisation'.[8] During these decades, Melbourne and Sydney grew at a slower rate than did their 'rest of state' hinterlands. This was partly attributable to net population losses to these hinterlands.

Opinion differs amongst demographers about whether this 'counter urbanisation' will continue. The view of the Monash University Centre for Population and Urban Research is that it will not continue. During the 1990s there were much smaller losses of persons moving from Sydney and Melbourne to their rest of state areas or to interstate locations than was the case in the 1980s. This turnabout was particularly striking for Melbourne. By the end of the 1990s,Victoria was gaining people from interstate after decades of sustained losses. Most of this gain was attributable to net movements of people to Melbourne. The net effect of the high concentration of overseas migrants in Sydney and Melbourne and the reduction in net intra and inter-state migration losses from these two cities was that during the 1990s their share of their respective states' populations expanded.

The projections shown in Table B.2 indicate that the recent pattern will continue during the first half of the 21st Century. This is despite the fact that the ABS has incorporated into its internal migration assumptions for the 'Series 2' projection a moderate reversion towards the earlier pattern of metropolitan losses. Sydney is projected to experience net internal migration losses of 15,000 per annum and Melbourne 7,000 per annum. Even with these assumptions, Sydney's share of the New South Wales population increases from 63 per cent in 1999 to 71 per cent in 2051 and Melbourne's share of Victoria from 72.5 per cent to 79.2 per cent. This may seem an unlikely outcome, especially given concerns about Sydney's congested state. Nevertheless, it is argued below that industry restructuring trends in Australia strongly favour further metropolitan population concentration.

The swing to the north

The projections summarised in Table B.2 indicate an increase in the proportion of Australia's population located in Queensland. Queensland is projected to receive 40.2 per cent of Australia's population growth between 1999 and 2051. As a result Queensland grows from 3.5 million in 1999 to 6.1 million in 2051, and its share of Australia's population over the same period increases from 18.5 per cent to 24.0 per cent. By this time Queensland will have overtaken Victoria to become Australia's second most populous state.

The Table shows that Queensland's growth is projected to be shared equally by Brisbane and the 'rest of Queensland'. Queensland government planners expect most of this rest of Queensland growth will occur in the Moreton Statistical Division surrounding Brisbane, mainly in the Gold Coast and Sunshine Coast. Their latest projection anticipates that over the period to 2035, 77 per cent of all Queensland's population growth will occur in the Brisbane and Moreton Statistical Divisions.[9] The other major Queensland locations likely to experience significant population growth are the coastal settlements of Wide Bay/Burnett and the Far North (particularly Cairns).

The increase in the share of Australia's population located in Queensland has been going on for decades. The assumption incorporated into Table B.2 (and which is the main factor contributing to the continuation of this pattern) is that Queensland will gain 25,000 persons (net) per annum from interstate migration. This is well down from the actual levels of 30-40,000 per annum that Queensland experienced in the late 1980s and the first half of the 1990s. Most of this interstate migration has been locating in South East Queensland, mainly the Gold Coast and Sunshine Coast, but also increasingly in Brisbane.

8 Martin Bell and Graeme Hugh, *Internal Migration in Australia 1991-1996*, Joint Commonwealth, State, Territory Population, Migration and Multicultural Research Program, March 2000, p. 92

9 Department of communication and Information, Local Government and Planning, *Population Projections for Queensland, 1998 Edition*, 1998, p. 17

Coastal development

One significant issue relevant to the implications of climate change for population movement is the extent to which Australian location patterns are being shaped by the attractions of a coastal lifestyle. If this lifestyle is linked to weather patterns then any changes in climate could have important ramifications for population movements.

There was a phase in Australian demographic analysis when the idea that Australia was experiencing a 'population turnabout' or 'counter urbanisation' (as noted above) was in vogue. Demographers attracted to this notion thought that Australia was entering a new phase involving greater dispersal of the population, particularly to coastal locations. Various factors, including the impending ageing of the population, the increased proportion of the population dependent on social security benefits (most of whom could move to wherever they wanted with their benefit intact), and anti-metropolitan lifestyle fashions of the 'sea-change' variety, were suggested as motivating this trend.[10]

Table B.3 shows the pattern of non-metropolitan coastal settlement over the period 1991-1996 and 1996-1999. For this purpose all Australian Statistical Local Areas (SLAs) which were located on the coast were identified. It is difficult to show earlier SLA patterns because of changes to SLA boundaries. On this definition, it is the case that Australia's non metropolitan coastal areas have experienced high rates of growth relative to their population base, particularly in Queensland and northern NSW. It is plausible that the salubrious weather patterns of the coast in question was an important factor in this growth. There was no parallel expansion in the cooler coastal settlements of Victoria.

Table B.3: Australia's non-metropolitan coastal population, 1991 to 1999

	Population (millions)	Share of Australia's population (per cent)	Population growth (millions)		Share of Australia's growth (per cent)	
	1991	1991	1991-1996	1996-1999	1991-1996	1996-1999
Gold Coast area (incl. Tweed (S) Pt A)	279,443	1.6	74,667	37,126	7.3	5.7
Sunshine Coast area	164,938	1.0	50,099	21,520	4.9	3.3
Other Qld	657,822	3.8	81,343	32,873	7.9	5.0
NSW North Coast (excl. Tweed (S) Pt A)	325,856	1.9	35,990	16,883	3.5	2.6
NSW South Coast	123,814	0.7	13,955	5,332	1.4	0.8
Newcastle SSD	444,932	2.6	18,456	15,920	1.8	2.4
Wollongong SSD	244,935	1.4	10,809	6,902	1.1	1.1
Vic Gippsland	64,282	0.4	473	939	0.0	0.1
Greater Geelong SSD	151,907	0.9	338	3,898	0.0	0.6
Other Vic	116,961	0.7	4,552	2,754	0.4	0.4
SA non metropolitan	166,721	1.0	338	1,149	0.0	0.2
WA non metropolitan	279,672	1.6	21,746	22,112	2.1	3.4
TOTAL	3,021,283	17.5	312,766	167,408	30.5	25.5

Source: Centre for Population and Urban Research, Monash University, unpublished

The Table shows that movement to these coastal locations has slowed. It also indicates that the Gold Coast and Sunshine Coast are the main locations for non-metropolitan coastal growth. It is questionable whether these locations should, given their current level of development, be interpreted primarily as retirement or life style alternative locations. The Gold Coast and Sunshine Coast are becoming increasingly integrated into a South East Queensland mega-urban zone. The implication is that the attractions of South East Queensland may have more to do with job prospects and other aspects of the increasingly metropolitan orientation of the area than lifestyle factors.

10 Martin Bell and Graeme Hugh, op cit, pp 92-95

Also the scale of the 'turnabout' at least as it has affected metropolitan areas has contracted since the 1980s. As indicated, the net losses from Melbourne and Sydney (mostly to northern coastal areas) have contracted during the 1990s. Much of the gains from internal migration currently being experienced in the northern NSW and Queensland coastal areas are from the 'rest of state' hinterlands of NSW and Queensland.

Social and Economic Changes which may affect population numbers and distribution
Climatic changes such as decreased precipitation and increased evapotranspiration will, in general, lead to a decrease in surface water flows. The reduction in fresh water will mean increased instream salinities and a decline in water quality. This will affect agricultural production where this water is used for irrigation (for example, in high value horticultural regions in the South Australian Riverland and the Victorian Mallee). The climate projections show sharply increased temperatures and lower rainfall levels for inland southern Australia, which cover the main 'wheat-sheep' productive zone. Since large areas of this zone are already close to the current climatic margin (particularly in terms of rainfall) for cereal production it was assumed that a further trend towards a warmer, drier setting would lead to lower production.

A major change affecting employment prospects in Australia is the flourishing of industries identified as part of the 'new economy'. The growth of this sector is the dominant outcome of industry restructuring. It reflects a combination of outsourcing of business and financial services and a sharp expansion in demand for these services. Over the past couple of decades, the sharpest growth in service industries in Australia has been in the services to finance and insurance sector (which includes investment fund operation and financial advice) in property services and in the business services sector (which includes computing, marketing, legal, consulting and related services as well as scientific and technical services). Jobs in this sector generally demand high skills and are well paid. [11]

The crucial point from the point of view of population trends is that there is a clear pattern of concentration of these jobs in the major metropolitan locations.[12] Table B.4 shows the most recent trends for the business services sector. Sydney and Melbourne's supremacy as locations for this rapidly growing employment sector is clear. The reasons for this concentration have to do with the 'agglomeration' advantages, that is, the competitive advantage gained by service firms located in centres where there is a high density of clients, competitors and related service providers. The high paid (and sometimes scarce) staff involved are also attracted to the cultural, consumption and recreational offerings provided by metropolitan locations.

Table B.4: Business services employment by major locations in Australia, May 1996 and May 2000

Location	May 1996		May 2000	
	Numbers employed	Per cent share of Australia	Numbers employed	Per cent share of Australia
Sydney	191,125	27.1	265,465	29.7
Melbourne	160,682	22.8	210,733	23.5
Brisbane	68,917	9.8	89,061	9.9
Other Capitals	111,514	15.9	136,784	15.3
Rest of Australia	170,830	24.3	192,167	21.5
Australia	703,068	100.0	894,210	100.0

Source: ABS Labour Force, May 1996 and May 2000, unpublished

There has been speculation that 'new economy' jobs can be dispersed to regional locations because of the relative ease of providing the required telecommunications infrastructure. However there is little

11 B. Dyster and D. Meredith, *Australia in the International Economy in the Twlentieth Centry*, Sydney, Cambridge University Press, 1990; Mark Cully, 'The Cleaner, the Waiter , the Computer Operatio: Job Change, 1986-2001. *Australian Bulletin of Labour*, vol. 28, no 3, September 2002, pp. 142-162

12 Bob Birrell and Kevin O'Connor, 'Regional Australia and the 'new economy', *People and Place*, December 2000

evidence to support this speculation, at least in relation to Australia. Regional centres, including those located along the coast show quite low concentrations of 'new economy' employment.[13] The one area where such centres do offer substantial employment, that is in the provision of direct customer banking and insurance services there has been a contraction in employment in regional locations.

There has also been a parallel restructuring of Australia's manufacturing and agricultural industries. The industries in these two sectors which have survived are those capable of rapid improvements in output and productivity. This has often meant limited employment growth or sometimes a contraction in employment levels. To the extent that there are positive spin-offs from this productivity, they tend to be garnered in the metropolises by the firms providing the business and financial services to the industries in question, or by metropolitan consumers who benefit from lower real prices.

This structural change is making the metropolises magnets for people. The main determinant of where overseas migrant and internal movers locate is employment opportunities. This point holds for coastal communities as well. Persons reaching retirement age constitute a small minority of those moving to the Gold Coast, the Sunshine coast or other non metropolitan locations. When movement patterns are compared by age it is found that the lowest net rate of movement out of Australia's metropolises to other locations in Australia is amongst persons in their retirement ages.[14] Only 5.9 per cent of Queensland's net gain from interstate migration during the 1991-1996 period was from persons aged 65 plus and just 11 per cent from those aged 55 plus.[15]

Most movers to the coast are working aged persons and their families, who appear to be attracted by the prospect of employment opportunities in the 'sunbelt'. Once located in these communities they find that the main employment opportunities are in providing 'people services' for both long term residents and tourists (including retail and accommodation services). The work is often casual and low paid. Data on income levels in these coastal communities show a very low income pattern.[16] Growing awareness of this situation helps explain the slow down in movement to the coast shown in Table B.3. There is also a strong pattern of out movement of young people in their late teens and early twenties propelled by the search for better work and education opportunities.[17]

Population Ageing

On the face of it, the impending ageing of Australia's population could suggest counter trends to those pointing towards increased metropolitan concentration. The extent of the change in Australia's age structure under the Series 2 projection is shown in Table B.5. The share of Australians aged 65 plus increases from 12.2 per cent in 1999 to 26.1 per cent in 2051. The number of persons in this age group is projected to grow from 2.3 million in 1999 to 4.2 million in 2021 and 6.6 million in 2051.

Table B.5: Share of Australia's population aged 65+ 'series 2' assumptions

Year	Proportion aged 65+ (per cent)	Number aged 65+, ('000)
1999	12.2	2,322.1
2011	14.3	3,036.0
2021	18.4	4,220.3
2031	22.3	5,405.1
2041	24.8	6,213.2
2051	26.1	6,628.3
2101	27.0	6,817.9

Source: ABS, Population Projections Australia, 1999-2101, p. 75

13 Ibid, p. 59
14 Martin Bell and Graeme Hugh, op cit, p. 38
15 Ibid, p. 83
16 Bob Birrell, 'Residential relocation in Sydney and the NSW coast over the period 1991-1996', *People and Place*, June 1999, pp. 40-42
17 Shane Nugent, 'Why Sydney keeps growing – Trends in population distribution in New South Wales, 1991 to 1966', *People and Place*, December 1998, pp 24-32

The inevitable growth in the numbers and proportion of Australia's population aged 65 plus implies a sharp growth in retirement linked services. Because older people require high levels of heath, hostel, nursing home and related services there will be a parallel growth in employment associated with these services. The mobility levels of old people are relatively low. Nevertheless, because there will be so many more of them during the 21st century, even a small out migration to coastal centres will boost their populations. Climate change could be influential in the choice of these locations.

A more profound implication of population ageing is the impact it will have on the size of the Australian workforce. The effect of reduced numbers of births at the same time as relatively large numbers of baby boomers move into retirement will be to significantly reduce the size of the working age population. The ABS projects that the annual rate of labour growth will decline sharply over the next decade or so, from around 1.6 per cent currently to 0.4 per cent per annum growth by 2015-16.[18] By the decade of the 2020s Australia's working age population (15-64) will have almost stabilised. By contrast it has been growing by 100,000-200,000 per annum during the 1980s and 1990s.[19]

The implications for the size and distribution of Australia's population could be significant. There will be intensified pressure to expand the overseas migration intake to make up for the 'disappearing worker' in Australia. If this does not occur (for reasons suggested earlier) employers will have to pay more attention to attracting, training and keeping workers, including the older workers that in recent years have been 'dispensable'. It was argued earlier that the main reason why the alleged 'population turnabout' subsided during the 1990s was the increased prosperity of Australia's metropolitan centres. The effect of reduced workforce growth, especially in these metropolises, will be to reinforce this development.

Phase 1 — Conclusion

This analysis points to the consolidation of recent trends towards greater metropolitan concentration of Australia's population. The implications for infrastructure are significant. The extent of building and rebuilding required in already densely settled locations is much greater than it is for greenfields sites. Issues related to the quality and costs of urban life will become more prominent particularly in Sydney as that city approaches 6 million. These issues are likely to come to a head quickly because much of the growth towards this figure for Sydney, and the 4.4 million projected for Melbourne by 2051 will occur in the next two decades. Sydney is likely to add 500,000 over the decade to 2011 and 400,000 over the decade to 2021. Melbourne will add around 300,000 to 2011 and 250,00 to 2021.

3.5.3 Phase 2 — Climate Scenarios and Population Movement

Population projections under climate change conditions were prepared for Cairns, Moreton Statistical Division (SD), Brisbane, Sydney, Melbourne, Adelaide and Perth. Except for Cairns, these locations were chosen by the project team because they are the main metropolitan areas of Australia. Cairns was of particular interest because of its current rapid growth and because of the possibility this growth could be particularly affected by climate change. The projections were based on recent data covering fertility, mortality, overseas migration and internal migration for each area. However the assumptions concerning overseas migration and internal migration were modified where it was considered that the climate changes projected by the CSIRO would impact on each location's settlement attractions.

Judgements as to these impacts were made as to how these climate changes would effect the level of movement within Australia to and from these areas and their appeal to overseas migrants. The basis of these judgements is outlined below. We have erred on the side of caution given the uncertainty about how future residents will react to climate changes which will take decades to evolve. The main focus was on the ways climate change would affect the lifestyle attractions of locations, particularly though

18 Ernest Healy, 'Australia's ageing labour force: how should government respond?', *People and Place*, vol 9, no. 1, March 2001, p. 38

19 Access Economics, *Population Ageing and the Economy*, Commonwealth Department of Health and Aged Care, Canberra, 2001, pp. 26-27

greater extremes of summer heat and humidity. Likely changes to geographical conditions brought about by climate change were also considered, including effects on storm surges and coastal erosion.

The judgements about the human impact of projected climate change were based on the projections CSIRO provided for climate projections. No account was taken of any possible changes in these projections due to modifications of greenhouse gas emission levels flowing from current interventions.

It would have been possible to prepare population projections under climate change conditions for each Australian SD, since data was gathered on fertility, mortality, internal migration and overseas migration for each SD and climate change projections were available for each SD. There is little doubt that the projected climate changes will affect population numbers in Australia's regional areas. Especially in the south, agricultural yields are likely to suffer because of the projected hotter and drier conditions. These climatic conditions will also reduce the attractions of some regional urban areas relative to metropolitan and regional centres located along the coast. However, the brief for this work was limited to the metropolitan areas described above, partly because of the costs of providing projections for each SD under climate change conditions, and partly because Australia's population is largely concentrated in these metropolitan areas. As a consequence they will be main drivers of road transport movements for the rest of this century.

Temporary movements, including tourists, working holiday makers, students and business visitors are growing rapidly. As of September 2001, unpublished data from the Department of Immigration, Multicultural and Indigenous Affairs indicates that there was a stock of 572,291 temporary residents in Australia. This figure does not include New Zealanders citizens, who do not need visas to visit Australia. It would be appropriate to include the growing numbers of these visitors to the projected impact of population growth on traffic movements. However such movements were not included in the brief for this project.

The following comments relate to the eight selected metropolitan regions for which population projections Mark II were prepared on the assumption of no climate change.

Cairns: Climate projections suggest that population movement to the area will decline because the anticipated temperature increases, sharply increased summer rainfall and the associated likelihood of flooding will diminish the area's attraction for permanent settlement. Coastal areas to the south, including the Mid to North NSW coast, southern NSW coast and Victorian coast, are all likely to become relatively more attractive. Their climates are expected to become more like current coastal SE Queensland today.

Tourism associated with the Great Barrier Reef is likely to be a continuing attraction but its outlook is clouded by limited information of the impact of climate change on the Barrier Reef and on the hinterland rainforest. The projected decline in rainfall in Spring, Winter and Autumn implies the area will remain attractive for tourists in these seasons.

On balance it is expected that there will be a decline in the flow permanent residents to the area during the 21st century.

Cairns (Mk I data)	Stable climate	Climate change adjustment 2040
Annual net overseas migration	543	450
Annual net internal migration	1,063	500

Moreton SD: as SE Queensland warms, the coastal areas of Moreton will become more attractive for intrastate Queensland movement (including from Brisbane). By contrast, the ample land for development to the west of Brisbane City will become hotter and drier and so will become less attractive. The consequence will be increased development pressures along Gold Coast and Sunshine Coast over the first half of 21st Century. However, limited green-fields development space is available, with resultant pressure for redevelopment of existing low density development, including a higher proportion of high rise units.

The implication is that people looking for living space in coastal areas are likely to look to alternative locations particularly to the mid to north NSW. This argument implies that population movement to Moreton will be maintained at current rates over the first half of the century. However, by the second half of the 21st century as temperature rise, proximity to the coast is likely to be valued especially highly. However, there will only be limited room for further development. It is questionable whether life style retirees will be attracted to permanent high rise living.

Climate change also promises challenges to the physical environment of the coastal areas in Moreton. The developed zone already encroaches on foreshore dunes. Much of the area is low lying and possibly threatened by rising sea levels, storm surges and associated sand movements. Major storm wall construction likely to be needed. Our interpretation of comfort factors as they relate to the region's projected warming are that no significant change will occur. According to current calculations of the 'relative strain' index[20], the region is relatively favoured. Projections of relative humidity to the end of the 21st century (prepared by CSIRO) suggest there will be little deterioration in this situation.

Regardless of the physical and climatic outlook for the Moreton region, the prospect of warmer conditions in coastal regions of SE Australia implies that there will be less motive to move north in search of more salubrious environments. The combination of these developments by mid century is likely to diminish the region's attraction for many interstate movers. These include persons who in the past have been attracted to the small business and employment opportunities flowing from the region's rapid urban and tourist development.

Moreton SD	Stable climate	Climate change adjustment 2040
Annual net overseas migration	3,193	2,500
Annual net internal migration	12,000	10,000

Brisbane SD: The projection for Brisbane (without climate change) already incorporates an expected slowdown in internal migration gains over the current levels. This is because of the likely continuing concentration of new economy employment in Melbourne and Sydney. However, Brisbane is likely to remain the key administrative and service centre for the north.

As indicated above, climate change will increase the proportion of those employed in the Brisbane SD who will reside in adjacent Gold Coast and Sunshine Coast locations. For this reason we have a projected a further decline in the numbers of migrants locating in Brisbane in the second half of this century.

Brisbane SD	Stable climate	Climate change adjustment 2040
Annual net overseas migration	8,717	8,000
Annual net internal migration	8,000	7,000

Sydney: is expected to remain the main urban interface between Australia and the global economy and therefore likely to remain the main locus of overseas migrants. It also is likely to continue to draw younger people and highly skilled persons from elsewhere in Australia. Sydney expected to continue

[20] The 'relative strain index' is based on the formula RSI= (T-21)/58-e, where T=air temperature and e= air's water-vapour pressure (mb). Values of RSI above 0.3 represent discomfort. For this project, the CSIRO projected RSI values under the climate change scenario which described the number of days when the RSI at 3 pm indicated 'discomfort'.

to lose modest numbers due to overspill as city expands and to the high price of housing for less affluent and retired persons.

Sydney's economic role is unlikely to be affected by climate change. Sydney, being Australia's wealthiest city, should be able to afford any required technological/engineering accommodations to climate change. CSIRO projections show Sydney's average temperature in 2101 will be the same as Brisbane's now and thus there is no reason to believe climate change could prompt an increase in outflow.

Sydney	Stable climate	Climate change adjustment 2040
Annual net overseas migration	34,475	34,475
Annual net internal migration	-13,800	-13,800

Melbourne: Climate projections indicate Melbourne is likely to be the least affected of the eight metropolitan areas by changes in temperature and rainfall. However, to the extent climate change affects population movements, it is likely to be in Melbourne and its hinterland's favour. Melbourne is projected to become warmer (similar to Adelaide today) and almost as dry as Adelaide at present. It is likely that Victorian coastal areas including the Mornington and Bellarine Peninsulas will become more favoured tourist/retirement locations. The projected climate change is unlikely to affect Melbourne's status as the number two urban interface with the global economy. Our conclusion is that, given relatively ample land for suburban development, Melbourne, not only will be able to accommodate extra numbers without running out of space, is probably likely to lose less people per annum than projected in the standard projections.

Melbourne	Stable climate	Climate change adjustment 2040
Annual net overseas migration	19,126	19,126
Annual net internal migration	-6,000	-3,000

Perth: The projections indicate a relatively high increase in average temperature from 17.9 degrees to 21.1 by 2100, which will make Perth hotter than Brisbane at present. Perth already experiences a high incidence of summer days over 35 degrees. The CSIRO provided no seasonal temperatures in its projections. However, assuming summer temperatures rise, residents will have to endure more extreme temperature events. This, combined with the projected sharply lower annual rainfall, particularly in the winter, will mean pressure on the already limited water supply. As a consequence, slightly lower interstate and overseas migration is projected.

Perth	Stable climate	Climate change adjustment 2040
Annual net overseas migration	11,078	9,000
Annual net internal migration	1,500	750

Adelaide: The stable climate projections already show Adelaide losing people on account of its difficult economic situation. The climate change projections, particularly the 16% decline in annual rainfall (medium projection), will add to the city's water supply problems. The projected hotter and drier climate is not likely to have much bearing on the choice of Adelaide as a settlement location one way or the other.

Adelaide	Stable climate	Climate change adjustment 2040
Annual net overseas migration	2,892	2,600
Annual net internal migration	-2,000	-2,500

Darwin: Like Cairns, the hotter and wetter conditions projected will make the area less attractive for human settlement. On the other hand, the great increase in rainfall, combined with the reduction in rainfall in much of central and southern Australia, will favour investment in agriculture in the north so Darwin's role as an administrative and service centre is likely to be enhanced by this outlook.

Darwin	Stable climate	Climate change adjustment 2040
Annual net overseas migration	332	600
Annual net internal migration	500	1,000

3.5.4 Appendix B1

Figure B1.1 illustrates the changes in population in selected major locations based on the work of Monash University Centre for Population and Urban Research including adjustments using predicted future climates.

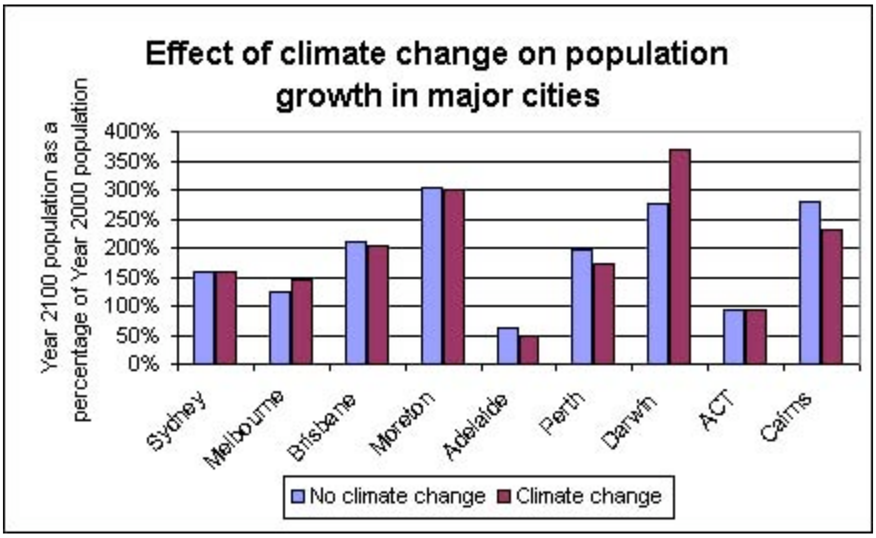

Figure B1.1 Effect of Climate change on Population Growth

3.6 Transport Demand Based on Population Movements (section C)

The purpose of this Section is to summarise the results of the transport demand projections based on the population movement projections described in Section 3.5

Forecasting road transport demand is a difficult task which few have attempted beyond 2015[21]. There are a multitude of variables to be considered – economic, social, environmental. This Section attempts an estimate of the most probable future for road transport in Australia, in light of demographic projections prepared in Section 3.5 (which have similar degrees of uncertainty). No attempt has been made to quantify the statistical variation of transport demand.

There are three main areas of road transport demand to be considered - passenger, light commercial (LCV) and heavy freight. Freight traffic comprises 12% of vehicles on the national highway system, varying from 38% on some sections of the Hume Highway to 5% on urban freeways. Pavement deterioration models used in this analysis are based solely on heavy vehicle traffic, therefore assumptions regarding freight are the most critical determinant of road maintenance cost predictions.

LCV traffic is growing quite strongly, partly in response to growth in the services sector of the Australian economy and partly due to changing freight distribution patterns. As most LCV traffic is urban and this analysis relates to the national highway system, the influence of LCV growth is not considered. Passenger vehicle volumes on the national highway have been estimated to give an indication of the future adequacy of road capacity.

In this analysis we assume for the sake of expediency that there are no new highways or increased capacity, so we are measuring the impact of increased traffic on the existing national highway network. In reality there will be upgrading and widening of existing routes, including progression to dual carriageway and provision of additional passing lanes. Predicting when and where this might occur and how much it would cost is outside the scope of this analysis.

3.6.1 Methodology Overview

This project is concerned with the interactions between climate change, population distribution patterns, transport demand and the impacts of passenger and freight demand on the life cycle performance of the road asset.

To undertake the analysis, likely future climate scenarios for the whole of Australia during the 21st Century were developed by CSRIO Division of Atmospheric Research. This work has been separately reported. Data from the CSIRO modeling were processed to obtain suitable inputs to the ARRB TR pavement deterioration models, which included a Pavement Life Cycle Costing (PLCC) model and HDM-4. In addition to this, projected changes in regional population distribution patterns as a result of climate change were developed by Monash University. These population shifts were used as factors in forecasting the future road transport task (passenger and freight movements).

The population projections under future climate conditions are discussed in Section 3.5 and are based on a ‘population adjustment’ factor determined by Monash University as summarised in Table C.1.

21 Current BTRE projections extend to 2020 (BTRE 2002).

Table C.1 Population (with and without Climate Change effects)

Selected Statistical Division	2100 Population as a percentage of 2000 population (no climate change)	Year 2100 population adjustment factor (with climate change)	Climate change factors driving population change
Sydney	159%	1.00	Temps higher but not expected to affect population growth
Melbourne	125%	1.15	Temperatures higher resulting in more attractive climate
Brisbane	211%	0.96	Temperatures higher resulting in less attractive climate
Moreton	305%	0.98	Temperatures higher resulting in less attractive climate
Adelaide	63%	0.79	Restricted water supply, especially in Spring
Perth	195%	0.88	Less attractive climate; restricted water supply
Darwin	275%	1.34	Temps high but heavy rainfall drives increased agriculture
ACT	93%	1.00	Temps higher but not expected to affect population growth
Cairns	279%	0.83	Temperatures higher resulting in less attractive climate

In order to examine the road pavement effects of future traffic flows, both the passenger and freight tasks must be considered. A demand forecast calculator was developed in Excel which used the climate adjusted population distributions above as a key driver of transport demand out to the year 2100. Baseline AADT values for the National Highway system were sourced from Austroads.

Based on the modified population projections a set of Origin-Destination Population Factors was developed that were used in the travel demand analysis. These are shown in Table C.2.

Table C.2 Origin-Destination Population Factors (Climate Adjusted)

Origin-destination pair	2000	2020	2040	2060	2080	2100
Sydney-Melbourne	1.00	1.19	1.33	1.41	1.46	1.52
Sydney-(Brisbane/Morton)	1.00	1.27	1.51	1.68	1.79	1.85
Sydney-ACT	1.00	1.21	1.38	1.47	1.52	1.54
(Brisbane/Morton)-Cairns	1.00	1.38	1.73	2.00	2.19	2.31
Melbourne-Adelaide	1.00	1.12	1.19	1.20	1.19	1.22
Adelaide-Perth	1.00	1.18	1.30	1.31	1.26	1.17
Perth-Darwin	1.00	1.30	1.56	1.72	1.80	1.83
(Brisbane/Morton)-Darwin	1.00	1.38	1.73	2.01	2.22	2.36
Brisbane-Morton	1.00	1.37	1.72	1.99	2.19	2.31
Adelaide-Darwin	1.00	1.07	1.06	0.98	0.87	0.74
ACT -(Brisbane/Morton)	1.00	1.35	1.65	1.89	2.05	2.15
ACT –Adelaide	1.00	1.06	1.03	0.92	0.76	0.59

For the passenger transport task, the simple approach illustrated in Equation 1 was used.

Equation 1 Future Passenger Car Travel =
Baseline AADT * (1-%HV) * Population Factor * Cars per Capita

For the freight transport task, a similar approach was used as illustrated in Equations 2 and 3.

Equation 2 Future Heavy Vehicle Travel = Baseline AADT * %HV * Population Multiplier * Freight per Capita Factor / Payload Factor

Equation 3 Future Heavy Vehicle Average ESAs[22] = Baseline Avg ESAs * ESA Factor

For the freight task, a number of additional issues were also considered. These included the future makeup of the heavy freight vehicle fleet (with a particular emphasis on the B-double share of articulated truck freight), changes to axle mass limits, and growth in the freight task (forecast using a logistic-curve relationship between road freight and population, which assumes that current levels of road freight growth are not sustainable in the long term) (see Section 3.6.3).

A combination of the assumptions relating to these factors results in the factors shown in TableC.3 for freight transport in 2100 relative to 2000.

Table C.3 Estimated freight related parameters for the year 2100 relative to 2000

Freight per capita factor	Urban[23] payload per heavy vehicle factor	Urban ESAs per heavy vehicle factor	Change in urban ESAs per tonne payload[24]	Rural payload per heavy vehicle factor	Rural ESAs per heavy vehicle factor	Change in rural ESAs per tonne payload
1.49	1.19	1.45	22.3%	1.26	1.66	31.9%

The baseline average ESA figure for each national highway section was used and factored up accordingly using the values in Table C.3.

3.6.2 Passenger vehicle traffic

Car ownership per head of population follows an S-shaped logistic curve, that while still rising is flattening out. The Bureau of Transport Economics CARMOD circa 1996 suggested a peak at around 516 cars/ 1000 persons, but current data suggests a figure of about 550, in line with levels in the USA which have reached a plateau[25]. The trend in Australia is illustrated in Figure C.1.

Travel per passenger vehicle has remained fairly constant over the last decade, and is not projected to change in the future, therefore passenger vehicle kilometres is proportional to passenger vehicles numbers.

In this analysis light vehicle traffic[26] has been forecast using the relationship:
$L_f = L_b * (P_f / P_b) * (C_f / C_b)$
where:

- Subscript *f* refers to the forecast year and subscript *b* the base year
- L = Light Vehicle Travel between any Origin - Destination pair
- P = combined population of the origin-destination pair
- C = Car Ownership per Capita.

Sample calculation:

Year 2000 total Melbourne/Sydney population 7,551,603; 507.6 cars/1000 persons
Year 2100 estimated total Melbourne/Sydney population 10,825,726; 550.0 cars/1000 persons
Melbourne-Sydney light vehicle traffic multiplier
= (10,825,726 / 7,551,603)* (550 / 507.6) = 1.553

22 Equivalent Standard Axles
23 Rural/ urban usage as distinguished by the ABS in the Survey of Motor Vehicle Usage (SMVU).
24 Different to rural areas because of the higher fraction of rigid trucks.
25 BTRE projects plateauing at above 560 cars/ 1000 persons after 2010 (BTRE 2002:119).
26 Light vehicles are defined as passenger cars and light commercial vehicles (under 3.5 tonnes).

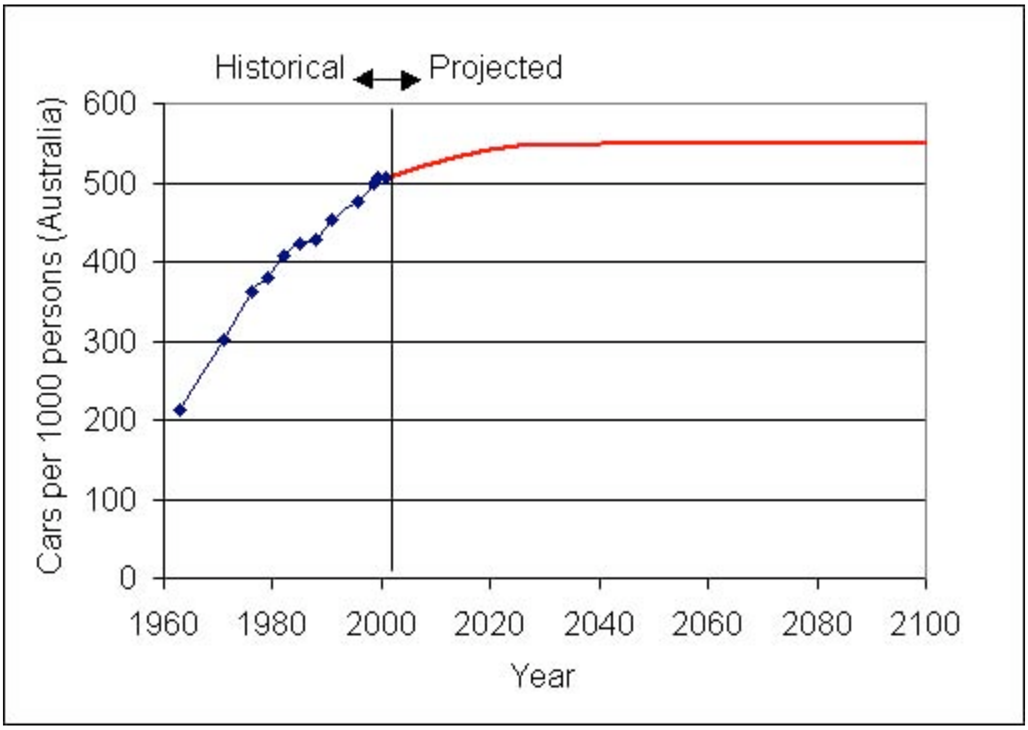

Figure C.1: National Average Passenger Cars per 1000 Persons – Historical and Projected

Projection curve based on the logistic equation Cars per Capita = $k/(1 + ae^{-bt})$ where k=550, a=12, b=0.087

3.6.3 Freight traffic

There are a number of factors to be considered when measuring the influence of growing freight traffic on our roads. These are discussed below.

Make-up of the vehicle fleet

Legislative changes since the mid 1990's have led to the widespread use of large road freight vehicles including B-double trucks, rigid trucks with dog trailers and road trains. This migration to larger vehicles has to some extend absorbed the impact of the increasing freight task, in terms of both road wear and road space.

The 'Survey of Motor Vehicle Usage' (SMVU) published by the Australian Bureau of Statistics may be used to look at trends and develop assumptions on the future makeup of the freight vehicle fleet. Projections have been made based on the following data and assumptions:

- Rigid trucks currently carry 37% of heavy freight in urban areas and 11.5% in rural areas. These percentages have been stable over the last decade and are therefore assumed to remain static.
- Of articulated truck freight, 22% will be carried by road trains (remaining static), 35% by B-doubles by 2020 (up from 22% currently, as illustrated in Figure C.2) and the remainder will be 6-axle single trailer.

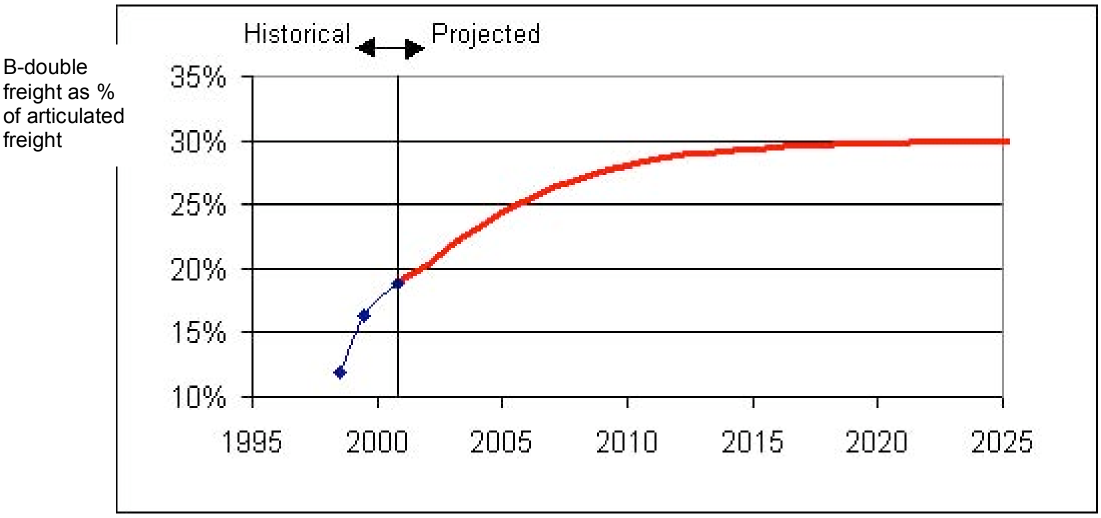

Figure C.2: Estimate of B-doubles as a fraction of articulated truck freight

Axle mass Limits

The 1999 'Mass Limits Review' (MLR, yet to be implemented as of 2001), represents the latest increment in increased length and mass limits for trucks and combination vehicles. The BTE has postulated (in Working Paper 35) two possible increases in mass limits beyond the MLR. Table shows calculations of Equivalent Standard Axles (ESAs) for a B-double truck under different load scenarios:

- Current mass limits
- Mass limits defined by the Mass Limits Review (1999) soon to come into force
- Scenario 2 and Scenario 3 hypothesised by the BTE for future increases in mass limits

ESAs are used as an input to the pavement deterioration models used in this report (refer to Section 3.7). As an approximate rule of thumb, road maintenance costs are proportional to the ESA loading (ESAs per lane per annum) on the road surface (Rosalion and Martin 1999)[27].

ESAs increase dramatically with load due to the '4th power law':

- ESAs = (axle load/ reference load)^4
  - ⇒ where the reference load is determined from the load that causes the same damage for each axle configuration as a standard single axle (Austroads 1992, Table 7.1)[28]
  - ⇒ The above exponent of four is typical for most flexible pavements, however, higher exponents are used for stiffer pavements.

Hence gains in payload and the profitability of road freight are offset by increased road wear and maintenance costs.

[27] Rosalion, N. and Martin, T. (1999). Analysis of Historical Data on Pavement Performance, ARRB Transport Research Contract Report RE7134 (ARRB TR: Vermont South, Victoria).
[28] Austroads (1992). Pavement Design (Austroads: Sydney).

Table C.4 – Payload and Equivalent Standard Axle (ESA) Calculations for a fully laden 9-axle B-double Truck

Current Limits (2001)					
Axle	Axle load	Ref load	ESA	Avg tare	Max Payload
ss	6	5.3	1.64	21.00	41.5
td	16.5	13.5	2.23		
trd	20	18.1	1.49		
trd	20	18.1	1.49		
Totals	62.5	55	6.86		62.5
Payload / ESA's = 6.05					

MLR Limits (2002)					
Axle	Axle load	Ref load	ESA	Avg tare	Max Payload
ss	6	5.3	1.64	21.00	47.0
td	17	13.5	2.51		(+3)
trd	22.5	18.1	2.39		
trd	22.5	18.1	2.39		
Totals	68.0	55	8.93		68.0
Payload / ESA's = 5.26					

BTE Scenario 2 (2010?)					
Axle	Axle load	Ref load	ESA	Avg tare	Max Payload
ss	6	5.3	1.64	21.50	56.5
td	19	13.5	3.92		(+8)
trd	26.5	18.1	4.59		
trd	26.5	18.1	4.59		
Totals	78	55	14.76		78.0
Payload / ESA's = 3.83					

BTE Scenario 3 (2020?)					
Axle	Axle load	Ref load	ESA	Avg tare	Max Payload
ss	6	5.3	1.64	22.00	66.5
td	20.5	13.5	5.32		(+16)
trd	31	18.1	8.60		
trd	31	18.1	8.60		
Totals	88.5	55	24.17		88.5
Payload / ESA's = 2.75					

ss = single steer axle; td = tandem axle group; trd = tri axle group; ( ) indicates additional mass with 'road-friendly suspension'

For a given freight task, the use of vehicles with more axles reduces road wear, measured as 'Equivalent Standard Axles' or ESA's. Hence gains in payload and the profitability of road freight are offset by increased road wear and maintenance costs.

Table C.4 and Figure C.3 illustrate how for a given vehicle, increasing payload causes a deterioration in the ratio of payload to ESA's. In other words, as mass limits are increased, the number of ESA's rises faster than the payload, reflecting the fourth power relationship between ESA's and axle loads.

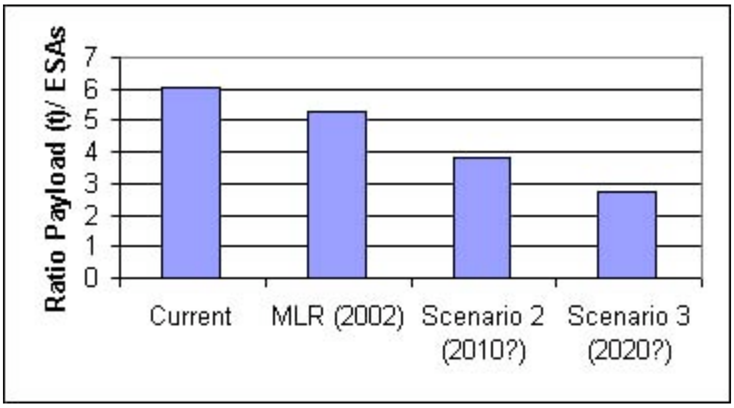

Figure C.3: Ratio of Payload to ESA's for a fully laden 9-axle B-double truck under different axle limit scenarios

From a road maintenance perspective, 'Scenario 2' seems a likely maximum and is assumed in this analysis. Australia makes widespread use of low cost 'spray seals' in its road infrastructure, which is necessary in order to economically link our widespread population. Whilst cheaper, spray seals are also more susceptible to damage from heavy vehicles and increasing axle loads above levels set in the 1999 MLR would necessitate a massive upgrading of the surfacings of our road pavements to gain more durability.

Growth in the total freight task

Growth in the freight task is modelled by the BTE as a function of GDP and freight rates[29]. On the basis of a constant 3.2% growth per annum in GDP, total road freight (measured in tonne-km) is projected to rise by 4.1% per annum through to 2015, with an 80 per cent increase between 2000 and 2015 (BTE 1999).

Extending projections over the very long term is a precarious task. If we assume 3.2% growth in GDP to 2100, this represents a 23 fold growth in the economy with population growth of 42% over the same 100 year period - a 16 fold increase in GDP per capita. If we apply 4.1% growth to the freight task to 2100, this would represent a 56 fold increase in road freight over current levels(!). An alternative set of assumptions or scenarios is clearly required.

Freight activity in some proportion to GDP

Whereas TRUCKMOD assumes freight growth exceeds GDP growth by some 30% based on historical trends, this model would assume freight growth slowing in relation to GDP growth in the very long term. [30]

[29] BTE TRUCKMOD formula for road freight: $\ln(TOTFRT) = -16.443 + 1.573 \ln(RGDP) + 0.166 \ln(RROADLH)$

[30] BTRE comment: While the raw ABS Survey of Motor Usage data support the view that recent freight growth has equalled GDP growth in recent years, these data are not reliable. A revised ABS time series is in progress at the time of writing. Raw data for 1997-98 to 2000-01 are not directly comparable to earlier year data, due to a change in ABS survey methodology. In light of comparison with diesel fuel sales data and other considerations, BTRE regards them as underestimates, while 1994-95 numbers are overestimates (Mitchell and Cosgrove 2001). Based on the ABS's 2001 SMVU (ABS 2003) revisions, as well as BTRE revisions to earlier SMVU figures, the ratio of tonne-kilometres per dollar of real GDP increased by about 16 per cent over the 1990s, from 0.19 to over 0.21. For illustrative purposes, continuation of current trends would result in a freight level of 13,000 tonne-kilometres per person by 2020, notwithstanding any subsequent saturating trend in respect of population.

	NSW	VIC	QLD	WA	SA	TAS	ACT	NT	AUST
90/91	0.137	0.189	0.246	0.215	0.229	0.250	0.073	0.487	0.187
94/95	0.148	0.231	0.307	0.251	0.342	0.264	0.077	0.589	0.224
97/98	0.126	0.195	0.239	0.208	0.325	0.200	0.064	0.449	0.188
98/99	0.146	0.207	0.264	0.220	0.287	0.192	0.076	0.468	0.201
99/00	0.134	0.212	0.247	0.203	0.339	0.206	0.074	0.340	0.196
00/01	0.129	0.228	0.264	0.171	0.345	0.228	0.047	0.322	0.198

Figure C.4: Trends in road freight t-km per dollar of Gross State Product

Source: Austroads National Performance Indicators 2000. Based on ABS Survey of Motor Vehicle Usage data and National Accounts Gross State Product Chain Volume (real) measures, reference year 1998-99.

But whatever relationship between GDP and freight activity we assume, we must then consider an appropriate very long term scenario for GDP growth.

Over the last 30 years there has been:

- a rise of 70% in population (average 1.44% per annum)
- a rise of 300% in real GDP (average 3.8% per annum)
- a rise of 128% in real GDP per capita (average 2.3% per annum)

There are many reasons behind increased real GDP per capita in Australia over recent decades – globalisation, automation and increased resource consumption, to name a few. The outlook for real GDP has been projected as 3.8% per annum to 2005-2006 *(IBISWorld, 2001)* and 3.3% p.a. from 1997-98 to 2014-15 *(BIS Shrapnel long-term forecast, 1993)*. It is not within the scope of this particular project to speculate on economic growth to 2100, other than to highlight that sustained growth in real GDP per capita over a 100 year period is highly improbable.

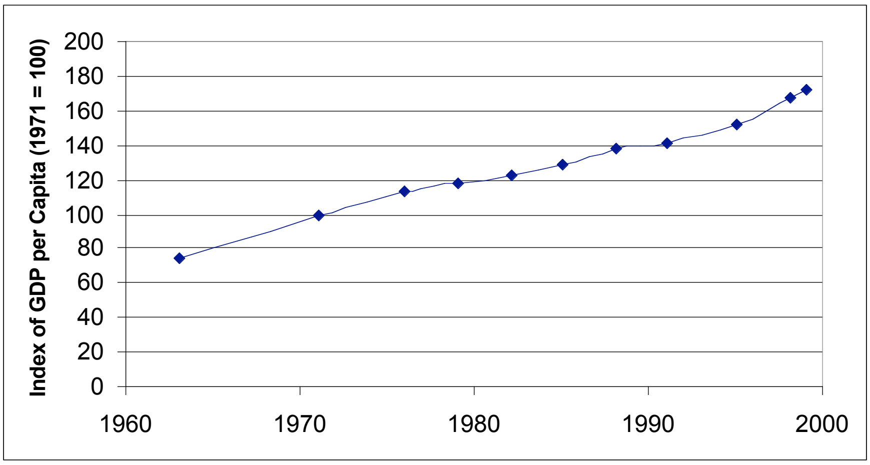

Figure C.5 – Trend in GDP per Capita

Source: ABS

A logistic-curve relationship between road freight and population

Another possibility is a logistic-curve relationship between road freight and population, whereby we see continued growth in road freight t-km per capita which plateaus at some time in the future through a combination of factors (alternative transport technologies, declining growth, logistic efficiency etc.). The curve below (which is assumed in the analysis undertaken in this Report) is based on a plateau of 10,000 t-km per annum around year 2060, up from the 2000-01 figure of 6,700. This approach assumes a link between population and road freight consumption, and that current levels of road freight growth are not sustainable either economically or physically (in terms of road infrastructure).

This future scenario for road freight is only one of a myriad of possibilities. It is a conservative approach that allows for some productivity gains but not for continued high growth.

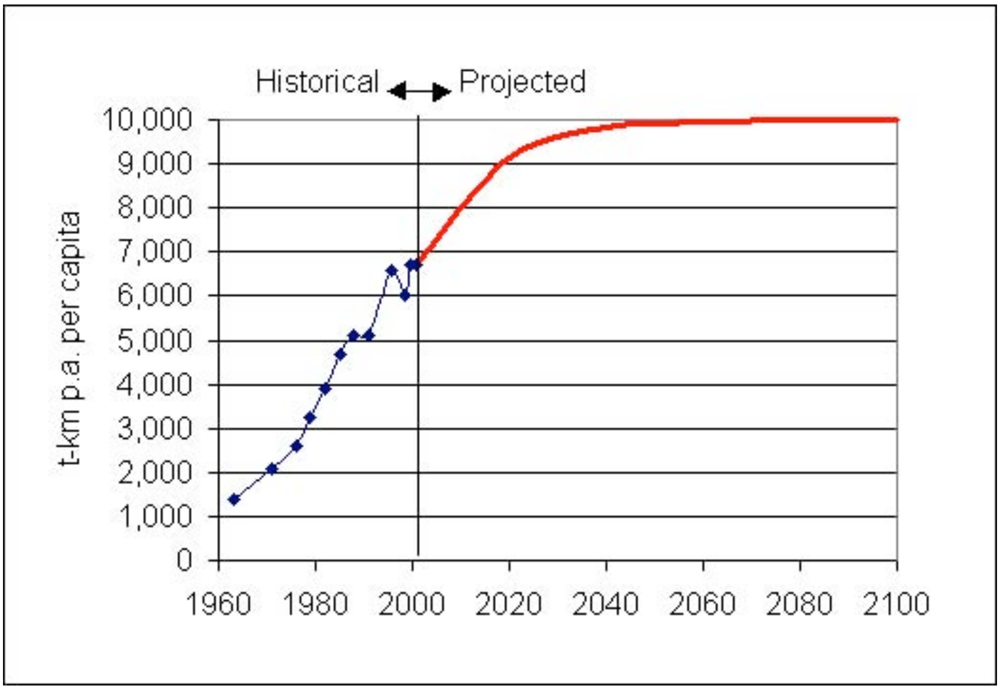

Figure C.6 – Proposed logistic curve for road freight per capita

Projection curve based on the logistic curve t-km per capita = k/(1 + ae-bt) where k=10000, a=42, b=0.08

Distribution of the freight task

Freight flows across the national highway network are influenced by the location of areas of supply (production), demand, and international transport hubs (air and sea ports). It is assumed in forecasts that existing freight flows are an indicator of future freight demand. As with light vehicle movements, it will be assumed that the freight task increases in proportion to population increases for city pairs, being an indicator of both demand and supply.

Competing modes

There is significant potential for a revitalised rail system to take some market share from road freight. This will be immediately evident in 2002 due to the Toll/Lang acquisition of National Rail. Coastal shipping and particularly air freight are growing markets, however, they are usually complementary rather than competitive with road freight. The siting of sea and airports will influence the nature of the land freight leg of freight movements. State governments are also setting targets to increase the rail share of containerised freight flows into and out of the ports. The Victorian government, for example, has set a target of 30% of container movements into and out of the Port of Melbourne are to be undertaken by rail by the year 2030. However, the forecast grow in container traffic will still see a significant increase in container movements by road.

The other potential factor is innovation in land freight movement, which is almost to be expected given the history of infrastructure. Over the last century we have seen the rise of various infrastructures, including canals, railways, roads and airlines. The future of freight is likely to include a mixture of both old and new technologies, and most importantly, multi-modal solutions.

Due to the complexities of the modal interactions, these factors are not considered within the demand analysis undertaken in this Report.

3.6.4 Summary of Road Transport Demand

Methodology

Changes to vehicle mass limits and the make-up of the vehicle fleet are forecast to stabilise prior to 2020. Road freight per capita is forecast to continue rising until 2060, and total road freight will continue to rise in proportion to population.

Estimates of road vehicle payload capacities and ESAs were calculated as shown in table C.5. This methodology was applied for 20 year intervals over the next century, and for both rural and urban scenarios (for urban scenario, figures of 37% rigid and 63% articulated trucks are assumed at lines *a* and *b*). A matrix of derived road transport factors is shown in Table C.6.

Table C.5 – Sample calculation of freight vehicle payloads and average ESAs

ROW	DESCRIPTION	Derivation	2000 data	2100 data	Ratio 2100/ 2000
a	rural heavy freight by rigid truck	Survey of Motor Vehicle Usage	11.5%	11.5%	
b	rural heavy freight by articulated truck	Survey of Motor Vehicle Usage	88.5%	88.5%	
c	Rigid truck average payload capacity (t)	Travel weighted average of Austroads class 2 to 5 vehicles	8.50	8.65	1.02
d	Articulated truck average payload capacity (BTE scenario 2) (t)	Travel weighted average of Austroads class 6 to 11 vehicles	32.99	44.58	1.35
e	% rural heavy freight rigid truck, by vehicle kilometres	$= \dfrac{(a \div c)}{(a \div c + b \div d)}$	33.5%	33.5%	
f	% rural heavy freight articulated truck, by vehicle kilometres	$= \dfrac{(b \div d)}{(a \div c + b \div d)}$	66.5%	66.5%	
g	Rural average payload (rigid + articulated) (t)	$= c \times e + d \times f$	21.55	26.85	1.25
h	Average ESAs - rigid	Travel weighted average of Austroads class 2 to 5 vehicles	1.68	1.73	1.03
i	Average ESAs – articulated	Travel weighted average of Austroads class 6 to 11 vehicles	6.18	12.9	2.09
j	Rural average ESAs (rigid + articulated)	$= h \times e + i \times f$	4.67	9.16	1.96

Table C.6 – Matrix of Road Transport Factors to 2100

Year	Freight per capita factor	Urban payload factor	Urban ESA factor	Rural payload factor (line *g* in Table above)	Rural ESA factor (line *j* in Table above)	Cars per capita factor	Population factor *(route & area dependent – national average shown)*
2000	1.000	1.000	1.000	1.000	1.000	1.000	1.00
2020	1.358	1.228	1.682	1.313	1.960	1.066	1.18
2040	1.460	1.228	1.682	1.313	1.960	1.081	1.31
2060	1.483	1.228	1.682	1.313	1.960	1.083	1.38
2080	1.487	1.228	1.682	1.313	1.960	1.083	1.41
2100	1.488	1.228	1.682	1.313	1.960	1.084	1.42

The calculation shown in Box C.1 was applied to 60 sections of the National Highway to prepare input for the analysis of road costs.

Box C.1 – Sample traffic calculation

Section of the Hume Highway from 68 to 190 km south of Sydney.

Baseline 2000 data

AADT 14,069

% Heavy Vehicles 28.9%

Light vehicle AADT 10,010

Heavy vehicle AADT 4,059

Average ESAs per heavy vehicle 3.65

Area classification Rural

Year 2100 data

Sydney-Melbourne population factor relative to 2000 (with climate change) = 1.52

Estimated light vehicle AADT = Population factor * Cars per capita factor * Base Light vehicle AADT
= 1.52 * 1.084 * 10,010
= 16,503

Estimated heavy vehicle AADT = Population factor * Freight per capita factor / Rural payload factor *
Baseline Heavy Vehicle AADT
= 1.52 * 1.488 / 1.313 * 4,059
= 6,992

Revised total AADT = 16,503 + 6,992
= 23,495

% Heavy Vehicles = 6,992 / 23,495
= 29.8%

Revised average ESAs = Baseline ESAs x Rural ESA Factor
= 3.45 * 1.96 = 6.76

It was assumed that national average truck fleet characteristics apply for all road sections; the only distinction being made between rural and urban averages. For example, Perth to Adelaide traffic currently has quite low average ESAs due to rail freight carrying most heavy cargo; roads in outback Queensland have high average ESAs due to the prevalence of mining trucks. The nationally averaged trend in payloads and ESAs is applied equally to both these cases. Ideally consideration would be given to the current and future make-up of the vehicle fleet on each road section before applying adjustments.

Road Demand Conclusions

The future of road freight demand is the single most significant variable in assessing the future of road infrastructure maintenance costs. A scenario for road freight demand has been proposed and traffic data has been generated on that basis – the actual outcomes in the year 2100 could different by a factor of two in either direction.

Generalising across the National Highway:

- There will be about 60% additional traffic, by count of total vehicles (passenger and freight).
- Demand will increase dramatically in Queensland, moderately in the Melbourne/Sydney corridor, and decline around Adelaide. Perth urban traffic will increase but intercapital traffic from Perth will rise only slightly.
- The proportion of heavy freight vehicles will rise slightly, from 12.1 to 13.9%
- The total amount of road freight carried will rise by 112% from 2000 to 2100
- Average freight payload will rise by about 25% from 2000 to 2100, with most of this gain occurring in the next decade.
- Average 'Equivalent Standard Axles' per articulated truck will double due to higher axle mass limits.
- Total ESA-kms on the National Highway will rise by around 230% through a combination of freight growth, increased mass limits and a higher ratio of ESAs to payload.

3.7 Pavement Performance Modelling (section D)

The purpose of this Section is to summarise the results of the pavement performance modeling undertaken for the Climate Change Project.

3.7.1 Introduction

This Section presents the results of the pavement performance modeling task undertaken by ARRB Transport Research (ARRB TR) for the 'Effects of Climate Change on the Long Term Provision of Major Road Infrastructure' project.

As noted in the Project Introduction, the focus of the pavement performance modeling was confined to Australia's sealed National Highway road network under selected climate change scenarios. The location of maximum change in magnitude of Thornthwaite index does not necessarily correspond with the location of the existing National Highway System.

The forecasts of future maintenance expenditures in this section assume that the National Highway System stays in its current form although the paved area of roads is likely to increase over time to accommodate demands for greater capacity. It is possible, therefore, that extensions to the National Highway System, or existing arterial or local road networks, may traverse areas of significant change in Thornthwaite Index..

Concrete pavements in the National Highway (NH) in NSW represent around 17% of the NSW lane km. However, concrete pavements represent around 3% of the total NH network across Australia. On a network wide basis (all arterials) concrete roads would represent much less than 3%. On this basis, concrete pavements have been treated the same as flexible pavements, with a much greater pavement/subgrade strength, which results in a much lower rate of deterioration than flexible pavements as expected.

Further research is needed to investigate and quantify the impacts of climate change (and resultant changes in transport demand) on roads other than the National Highway System. This is a significant gap that requires further targeted research as a matter of urgency.

The pavement modeling was undertaken using two modeling approaches. The first was the ARRB TR pavement life-cycle costing model (PLCC) and the second was the Highway Development and Management 4 (HDM-4) model. The PLCC model was used to assess pavement performance at the network level, while the HDM-4 model was used to assess selected road lengths at a more 'detailed' level. The reader is referred to the Section 3.7 appendices (D1 and D2 available on Austroads website: www.austroads.com.au) which provide further information on the two modeling approaches.

Both modeling approaches were used to examine how future maintenance and rehabilitation cost budgets for the National Highway System are likely to change under different climate scenarios.

3.7.2 Overview of Results

A brief summary of the key pavement performance results is provided below. The Reader can find additional information in the body of the Section 3.7 report which follows.

The project scope has not allowed detailed sensitivity analysis under different IPCC climate change scenarios to be undertaken. Therefore, the results presented need to be considered in the light of the specific scenario assumptions used in the climate modelling and the population and transport demand projections that formed the basis of the pavement model input data.

The estimates of annual road agency expenditure on the National Highway road network, using the PLCC and HDM-4 analysis tools, are highly sensitive to the predicted rates of pavement deterioration (which in turn are driven by assumptions relating to traffic growth, heavy vehicle composition, vehicle loading and climatic variables).

It is important to note also, that the climate change projections have not included any analysis of weather extremes (such as flooding) that may impact upon road infrastructure and the resulting maintenance and rehabilitation requirements. Such extremes may be important in areas such as the Northern Territory and North Queensland, where the likelihood of total road destruction as a result of these weather extremes is greater.

With these constraints, the pavement modeling indicates that for the sealed National Highway road network in year 2100:

- The average annual pavement maintenance and rehabilitation budget is estimated to increase by around 30% (taking into account both the influences of climate change and transport demand changes). This represents a change of just under $90m pa in the annual maintenance and rehabilitation budget - increasing from $287.3m pa (base climate) to $376.1m pa (in the year 2100 climate).
- There are significant state variations in the change of pavement maintenance and rehabilitation costs as a result of climate variation and population and transport demand levels. For example, increases of over 100% and 50% are projected for Northern Territory and Queensland respectively (primarily due to the larger population increases expected within these states).
- There is a small decrease (between 0% and -3%) in the required pavement maintenance and rehabilitation budget based solely on change in climate factors. This result reflects the generally warmer and drier Australian climate which reduces the rate of pavement deterioration.

3.7.3 Network Pavement Life-Cycle Costing Analysis

The ARRB TR network pavement life-cycle costing (PLCC) model (Linard *et al*. 1996) was used to estimate the annual pavement related maintenance and rehabilitation costs for the sealed National Highway road network under a base climate (year 2000) and a future climate scenario (year 2100).

The PLCC model determines life cycle agency and road user costs based on the roughness predictions for a set of defined road categories. The road user costs (travel time plus vehicle operating costs) as well as the road agency costs of pavement related maintenance and rehabilitation are included in a present value (PV) discounted cash flow analysis over a given analysis period. The PV sum of the road user costs and road agency costs are the total life cycle costs. A 60 year analysis period was used with the predicted rates of pavement deterioration on the road network to ensure that pavement rehabilitation occurred at least once within the analysis period on all road types.

The PLCC model estimates the minimum possible (or optimum) total life cycle cost (LCC) for the unconstrained annual agency budgets based on achieving the minimum present value (PV) sum of road agency and road user costs, over a 60 year analysis period using a real discount rate of 7%. The model used a genetic algorithm (Evolver 1995) to achieve optimisation of a very large number of options, subject to any specified constraints on maximum network roughness and annual agency budget limits.

The pavement performance predictions are based on an ARRB TR calibrated model (Martin and Roberts 1998) which predicts pavement deterioration, in terms of the change in road roughness for the defined road categories. The improvement in both roughness and strength as a result of pavement rehabilitation is predicted using other models developed by ARRB TR (Martin 1994; Martin and Ramsay 1996) based on Australian pavement performance data.

The project timeframe and computer processing constraints prevented separate optimisation of the National Highway System within each state, instead the optimisation has been performed on the National Highway System at a national level, while still distinguishing between sections occurring in each state. In order to undertake the analysis at the National level, the National Highway System within the PLCC model was defined in terms of a maximum of 60 different road 'sections' for the whole of the country. The road sections were determined based on similar climate characteristics, traffic levels, vehicle mix and pavement characteristics. This provided life cycle costing data for the whole of the National Highway System. State level data was derived from this aggregated data on a lane-km basis. This approach averages out many of the variations in the estimated levels of funding between the States, but was required due to the time and processing constraints mentioned.

The 60 road sections referred to are based on similar climate characteristics and traffic levels which means that each of these sections was based on the assumed homogeneity of each section, that is, each section had its unique traffic levels (AADT, %HVs). These sections are an aggregation of a number of smaller road segments which have similar climate and traffic features, rather than the sections having these features.

These road 'sections' encompassed defined lane lengths of the following pavement types:

- Asphalt Pavements (predominantly in urban areas); and,
- Chip Sealed Granular Pavements (in rural areas).

Lane lengths for each road 'section' that comprises each States' road network are defined by the following parameters:

- annual average daily traffic (AADT)
- percentage heavy vehicles (%HV)
- pavement/subgrade strength.
- pavement age
- roughness
- climate classification index

Because some of these parameters were not provided in the original database for each State road network, they were estimated as shown below.

- average pavement/subgrade strength, defined in terms of a modified structural number, *SNC* (Paterson 1987) was assigned to each of the road 'section' based upon ARRB TR research (Roberts *et al*. 1997).
- average pavement age (years since last rehabilitation or construction) was derived from the updated data supplied by the representative of each State Road Agency. For those 'sections' where adequate data could not be provided, an estimate was obtained by using a historical relationship between current roughness and pavement age (Martin 1996b) that has been established for arterial roads.

PLCC Outputs

The ARRB TR network pavement deterioration model predicted rates of pavement deterioration ranging from 1.4 to 2.5 NRM/year for the National Highway road network. This was considered reasonable as these roads are generally kept in very good condition as depicted by the pavement's current age and roughness.

The PLCC model generates road agency costs and road user costs. Typically, the road user costs are significantly larger than the road agency costs. Table D.1 shows the (undiscounted) optimal road agency costs and the road user costs under the base climate and the year 2100 changed climate.

Based on the current base climate, the road agency costs are in the range of 1.5% to 2.5% of the road user costs. As a rough 'rule of thumb', using the entire National Highway System road network (around 18,600 km) the average annual road agency costs per kilometre are of the order of $15,500 per km.

Table D.1 Optimal Road Agency and Road User Costs

	2000 Base Climate	2100 Average Scenario Climate
Road User Costs (RUC) ($million)	11,660	22,247
Road Agency Costs (RA) ($million)	287	376
Total Costs ($million)	11.947	22,623
RA as % of Total Costs	**2.5%**	**1.7%**

Detailed results from the PLCC analysis are summarised graphically and in tabular form in Appendix D3 (available on Austroads website: www.austroads.com.au). The following section examines the road agency cost component in further detail.

Agency Costs

Table D.2 below outlines the agency costs of maintenance and rehabilitation required on a State by State basis for each of the climate scenarios run using the PLCC model. These results are representative of the expected expenditure splits under unconstrained conditions. These figures are representative of the order-of-magnitude change in funding that is expected as a result of changes in climate and traffic.

Although separate analyses were not undertaken for each state (due to project budget and processing constraints) the 60 defined road sections enabled each State NH network to be represented by its own unique number of sections. Theses state representations were combined to represent the whole NH network. This allowed data within Table D.2 to be determined by undertaking an analysis based on the 60 sections for a total network optimisation. The analysis was not conducted on each state separately.

The results show that agency costs increase by an average of 31% nationally. Increases at the state level range from a 15% *decrease* in agency costs for South Australia up to a 108% *increase* in agency costs for the Northern Territory.

The data in Table D.2 is shown graphically in Figure D.1.

Table D.2 Summary Table of Optimal Agency Costs

State	Optimal Agency Cost ($million)		Change
	Base Climate	2100 Climate	
NSW	72.3	90.1	25%
VIC	32	37.6	18%
QLD	82	124.2	51%
WA	48.3	56.1	16%
SA	27.6	23.4	-15%
TAS	6.5	6.8	5%
NT	17.9	37.3	108%
ACT	0.6	0.7	17%
Total	**287.3**	**376.1**	**31%**

Figure D.1 depicts the results of the annual agency cost (maintenance and rehabilitation costs) for each State over the 60 year analysis period for the PLCC analyses. These funding levels were obtained by allowing the model to determine the lowest total life cycle costs under unconstrained conditions.

Figures D.2 and D.3 show the funding splits between the various States for the 2000 base climate and 2100 climate scenario respectively.

Comparison of Figures D.2 and D.3 highlights subtle changes in funding allocation between various States. The proportion of funding required by South Australia, New South Wales, Victoria and Western Australia are predicted to decrease in the range 1-4% while the proportion of funding required by Queensland and the Northern Territory are likely to increase, primarily due to the population growth in these northern states. The proportion of funding required by Tasmania and the ACT is predicted to not change significantly. The decline in the levels of maintenance funding in SA reflects the combination of a drier climate and the effects of a relative reduction in population and associated lower traffic levels.

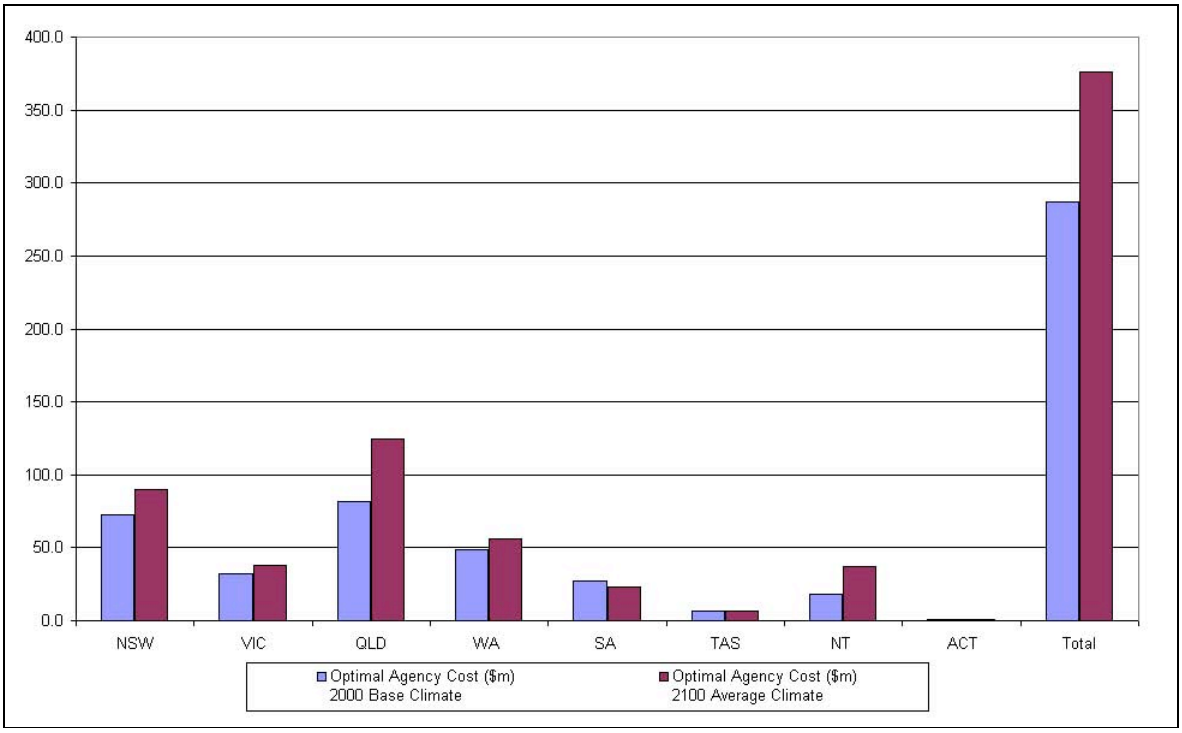

Figure D.1: Optimal Agency Cost

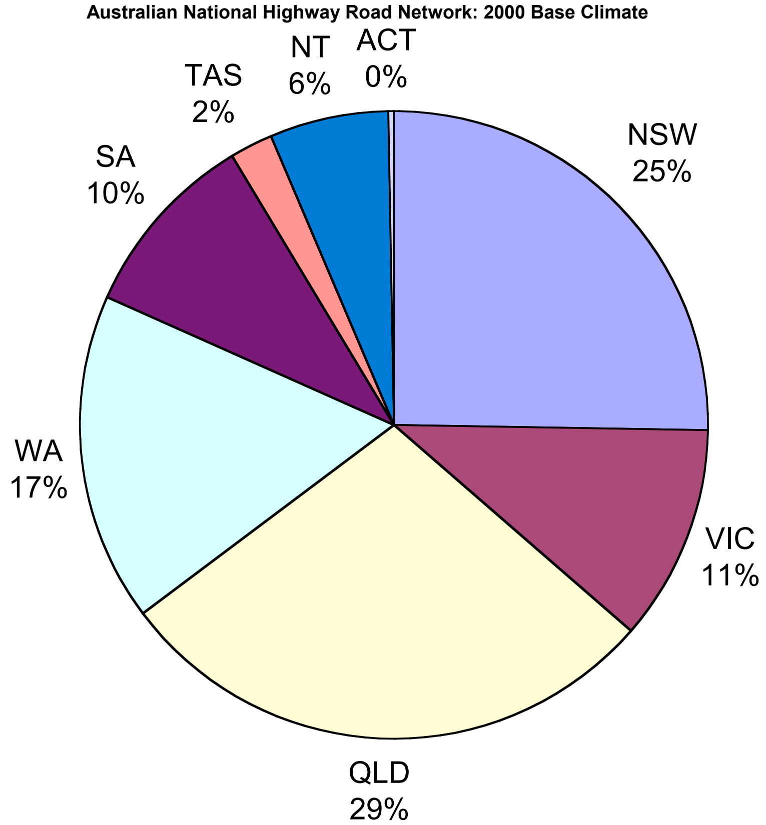

Figure D.2: Estimated Agency Costs variation by each of the States (2000 Base Climate)

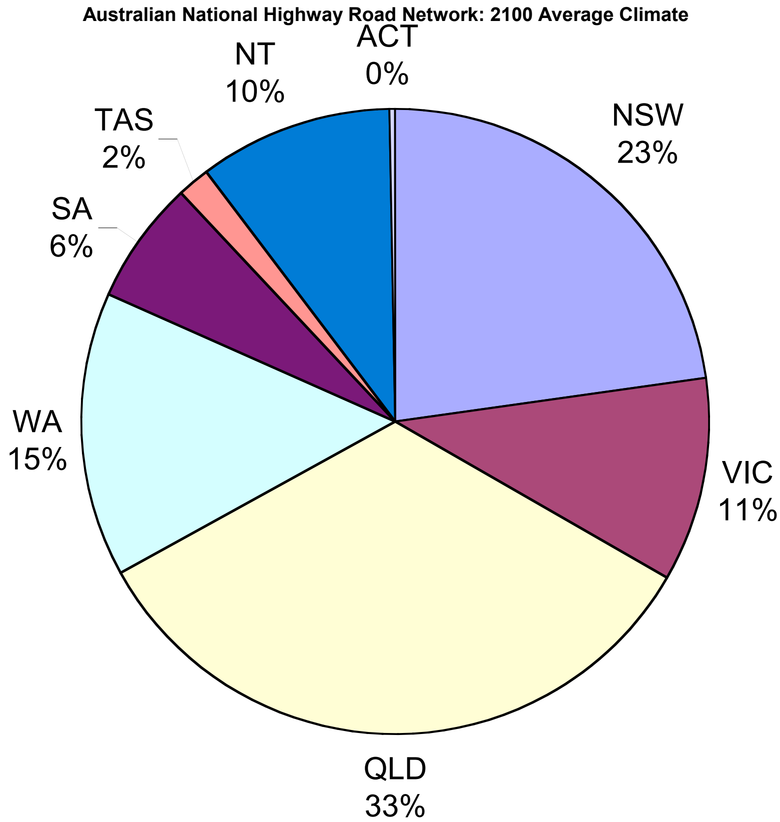

Figure D.3: Estimated Agency Cost variations for each of the States (2100 Climate)

As noted above, the analysis based on the change in climate classification (characterised by a change in the Thornthwaite Index) does not include other climate changes such as severe storm events or flooding, which add a new level of uncertainty to the modeling process. Road maintenance and rehabilitation costs may change dramatically due to the need to rebuild roads as a result of unpredictable severe weather events.

The prediction of pavement deterioration by the current ARRB TR network pavement deterioration model (Martin and Roberts 1998) is partly based on road samples with a maximum continuous deterioration of around 10 years. The influence of annual maintenance expenditure on pavement deterioration has not yet been completely quantified because of the data correlation problems with these samples (Robinson 1994). Recent research is focussed on quantifying the influence of maintenance on pavement performance to improve the modeling, as well as the calibration.

However, the rates of deterioration used, in terms of roughness increase, are based on calibration factors for roughness deterioration derived for each of the 60 sections based on available roughness progression information. The rates are similar to those experienced by each of the relevant State road authorities. It would not be appropriate to simply use one factor for all roads.

In summary, a reliable and accurate calibration of the current ARRB TR network pavement deterioration model to each States conditions has not yet been completed. Therefore, the estimation of the annual budget for the Australian National Highway road network is subject to some uncertainty.

If the actual deterioration of the road network is less than that predicted by the ARRB TR deterioration model, then the annual budget estimates given by the PLCC analyses in this report are likely to be too high. The converse is also true, that is, higher rates of actual deterioration than those predicted means the annual budget estimates given by the PLCC analyses are likely to be too low.

The results produced show an optimised level of funding. Road agencies may not necessarily optimize their maintenance expenditures due to budget constraints (which mat result in under maintenance). Alternatively, the selection of maintenance standards (or levels of service) that are not appropriate for the given levels of traffic will produce more than desirable maintenance funding and also a sub-optimal result. Therefore, this study does not consider whether the road agencies are applying inappropriate standards for the given levels of traffic.

Distribution of Annual Agency Costs

PLCC produces separate results for both maintenance and rehabilitation of pavements. The maintenance expenditures refer to pavement related expenditure on routine and periodic maintenance activities, such as pothole patching, kerb and channel cleaning, patching, surface correction and resealing. Rehabilitation refers to chipseal resheeting and asphalt overlays, depending upon the pavement type.

Table D.3 below outlines the splits in the maintenance and rehabilitation expenditures required to maintain the National Highway road network for baseline and 2100 climate scenarios. These results are based purely on an unconstrained network analysis.

Table D.3: Summary Table of Maintenance and Rehabilitation Expenditure Splits

States	2000 Base Climate	
	Maintenance Expenditure ($m)	Rehabilitation Expenditure ($m)
NSW	26.7	45.6
VIC	11.4	20.7
QLD	31.3	50.7
WA	8.6	39.7
SA	12.7	15.0
TAS	3.4	3.1
NT	6.7	11.3
ACT	0.3	0.4
Total	101.0	186.3
	287.3	

States	2100 Average Scenario Climate	
	Maintenance Expenditure ($m)	Rehabilitation Expenditure ($m)
NSW	32.8	57.3
VIC	13.8	23.7
QLD	45.1	79.1
WA	13.9	42.2
SA	9.8	13.6
TAS	2.6	4.1
NT	13.1	24.2
ACT	0.3	0.4
Total	131.4	224.7
	376.1	

States	% Change	
	Maintenance	Rehabilitation
NSW	23%	26%
VIC	21%	15%
QLD	44%	56%
WA	61%	6%
SA	-23%	-9%
TAS	-21%	34%
NT	96%	114%
ACT	-1%	10%
Total	30%	31%
	31%	

The PLCC analyses indicate that the split in the maintenance and rehabilitation expenditure for the year 2000 base climate is around 35% for maintenance and 65% for rehabilitation works (expressed as a percentage of the total Australian National Highway road network budget). The analysis also shows that there is no significant change in the split between maintenance and rehabilitation funding arising as a result of climate change and traffic growth (ie. year 2100 climate scenario).

State Distribution: Maintenance Costs

A summary of annual maintenance cost outcomes from the PLCC analyses is shown in Figures D.4 and D.5, where the annual maintenance expenditure for each State is expressed as a percentage of the annual budget for the Australian road network.

It should be noted that no assumptions are made concerning the non-pavement related portion of maintenance/rehabilitation funding because the PLCC network analysis only estimates pavement related expenditures. Therefore, any changes in total expenditures that may result from climate effects, beyond the pavement related expenditures, have not been included.

Noting the previous paragraph, the following variations in maintenance expenditure on the road categories were observed with the expected change in climate from 2000 to 2100:

- there are variations in the maintenance expenditure portion (expressed as a percentage of annual budget) distributed to most States with changes in climate;
- the southern States experience a decrease in their maintenance expenditure portion (as a percentage of annual budget) from 13% to 7% in the case of South Australia and 3% to 2% in Tasmania and 26% to 25% in New South Wales, while Victoria remains unchanged.
- Western Australia experiences an increase in the maintenance expenditure portion (as a percentage of annual budget) from 9% to 11%, due to the rehabilitation budget being reduced, due to the highways being lightly trafficked and located in relatively stable climate. Northern Territory increased from 7% to 10% while Queensland shows the greatest increase in maintenance expenditure rising from 31% to 34%.

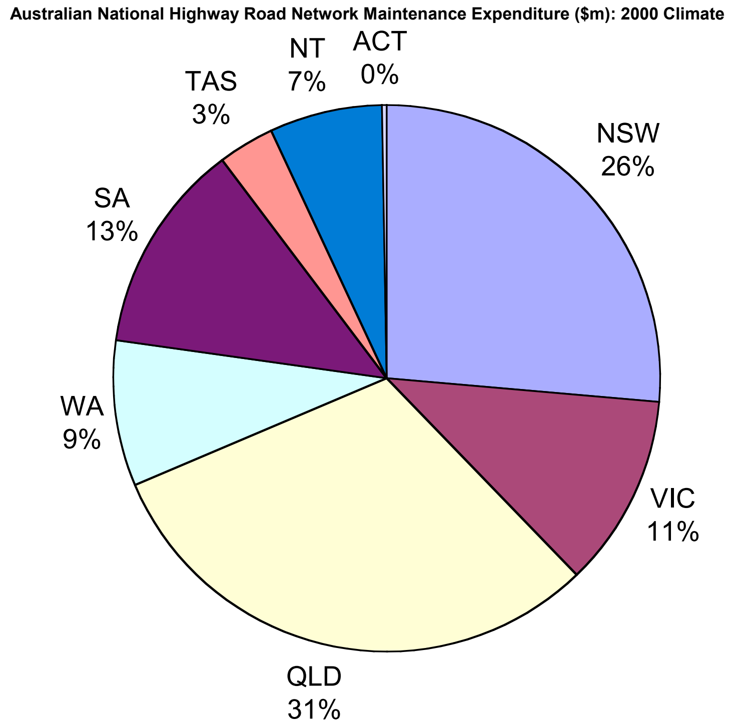

Figure D.4: Estimated State Maintenance Costs Distribution (2000 Base Climate)

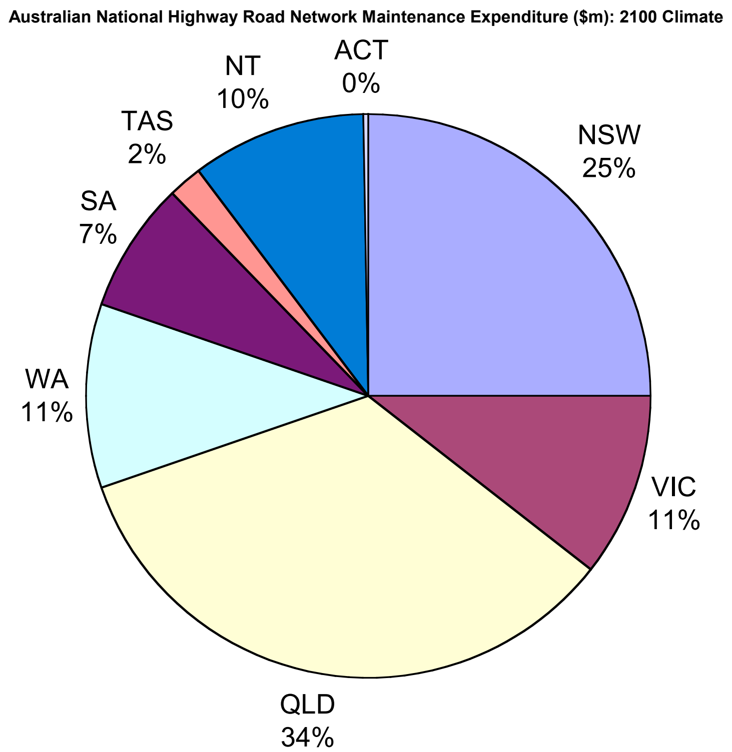

Figure D.5: Estimated State Maintenance Cost Distribution (2100 Climate)

State Distribution: Rehabilitation Costs

A summary of the annual rehabilitation expenditure outcomes from the PLCC analyses is shown in Figures D.6 and D.7, where the annual rehabilitation expenditure for each State is expressed as a percentage of the annual budget for the entire Australian National Highway road network.

The PLCC analyses predict that the rehabilitation portion of annual agency varies significantly with the change in climate (as seen by the percentages in Figures D.6 and D.7). The predicted rehabilitation expenditure is the usually larger portion of an annual budget because major reductions in roughness occur through rehabilitation when minimising total Life Cycle Costs.

The following variations in rehabilitation expenditure on the road categories were observed with the expected change in climate from 2000 to 2100:

- there are variations in the rehabilitation expenditure portion (expressed as a percentage of annual budget) distributed to most States with changes in climate;
- the northern states experience an increase in rehabilitation expenditure proportion with the Northern Territory increasing from 6% to 10% and Queensland increasing from 28% to 32%;
- the southern States experience a decrease in their rehabilitation expenditure portion (as a percentage of annual budget) from 8% to 6% in the case of South Australia, from 24% to 23% for New South Wales, and from 11% to 10% in Victoria. Tasmania and the ACT remain unchanged. Western Australia experiences a decrease in the rehabilitation expenditure portion from 21% to 17%.

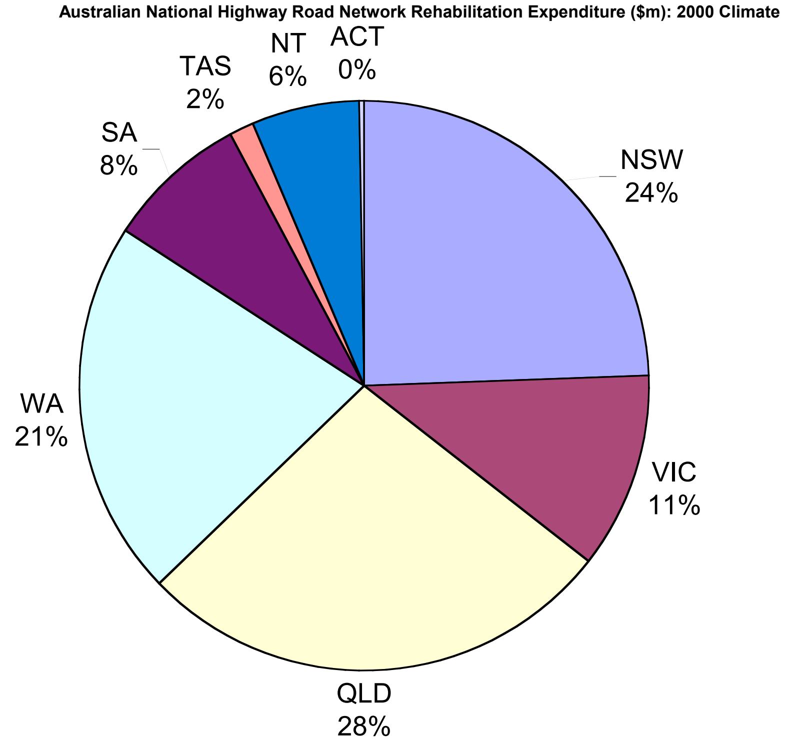

Figure D.6: Estimated State Rehabilitation Costs Distribution (2000 Base Climate)

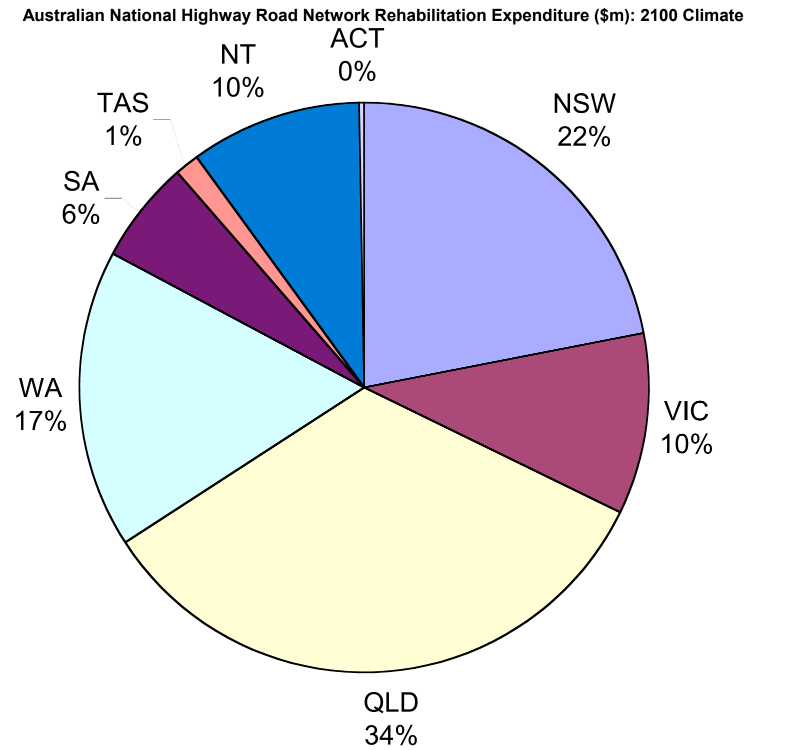

Figure D.7: Estimated State Rehabilitation Cost Distribution (2100 Climate)

3.7.4 Highway Development And Management – 4 (HDM-4)

Aims and General Approach

The Highway Development and Management (HDM-4) software (ISOHDM, 2000a) can be used to carry out detailed pavement performance analyses (for example using a more detailed set of pavement performance parameters such as roughness progression, rutting and cracking), works scheduling, and other analytical tasks (such as environmental performance relating to Greenhouse gas emissions).

This section describes the results of the HDM-4 detailed analysis of selected road segments under the same climate change (and transport demand) scenarios as used in the network PLCC model. HDM-4 uses road deterioration algorithms that are interdependent (roughness, rutting, cracking, potholing, ravelling, strength, etc.) and which have detailed data requirements. The algorithms are similar to the algorithms used in HDM-III and originate from Paterson's work in the early 1980s on deterioration (see Paterson, 1987). Because of the data requirements, HDM-4 was used in this study, to review the expected changes to pavement performance and maintenance funding at a more detailed level using small road lengths of 1 to 2 km.

The HDM4 analysis assumes a minimum periodic maintenance case (the base case), which is essentially an estimation of the routine maintenance costs required to keep the pavement in sound operational condition. The HDM4 analysis was undertaken at a strategic level (for the selected short road lengths) to estimate total life-cycle costs that include road user costs and agency costs. Treatments, in this case routine maintenance options, (in response to predicted road deterioration) are selected based on producing the minimum Present Value of the total life-cycle cost, subject to any constraints imposed. (In the analysis undertaken no constraints were included). That is essentially the same approach that is used in the PLCC analysis which minimizes the present value of both road-user and agency costs, but uses the annual average maintenance expenditure, ME, as a surrogate for agency maintenance treatments.

No interventions for roughness etc. were assumed so the analysis estimates changes in the routine maintenance costs with the predicted changes in traffic and climate. The project budget did not allow for additional analyses using maintenance strategies other than routine maintenance as the base case.

The PLCC network model uses an aggregate roughness relationship (described in Martin, 1994 and updated in Martin,1998). In contrast to HDM-4 (which uses specific treatments for maintenance in its life-cycle costing analysis), the ARRB roughness model uses maintenance expenditure as the direct variable (endogenous) influencing pavement performance and allowing a continuous optimisation to occur at a network level. This approach is in contrast to the step change analysis of HDM-4 in the optimization process.

The analysis undertaken by the PLCC model provided a network level assessment of changes in agency maintenance and rehabilitation costs at a broad spatial scale. The total network level costs were disaggregated (on a lane-km basis) to reflect State level costs. As noted previously, the generally hotter and drier climate experienced over much of Australia in the future has a beneficial effect in terms of pavement performance. However, there are significant regional variations in the extent of climate change and the HDM-4 software was used to examine specific locations based on the magnitude of the climate change effect (measured by the change in Thornthwaite Index) indicated the need for more detailed analysis.

The road segments selected for detailed HDM-4 analysis are summarised in Table D.4. As shown these segments include road sections where the climate change is consistent with the trend over the whole continent (ie. hotter and drier) and sections where the climate change includes an increase in rainfall (for example, the NT_01 and QLD_15 road sections).

Table D.4 Road Segments used in HDM-4 Analysis

Site	State	Long	Lat	Change in Thornthwaite Index	Change in Temperature (degC)	Change in Rainfall (Mean Monthly Precipitation mm)
ACT_04	Australian Capital Territory	149.14	-35.24	-25.31	4.18	-10.55
NSW_03	New South Wales	150.52	-34.38	-26.04	4.73	-10.15
NT_01	Northern Territory	131.07	-12.57	58.45	5.40	64.12
QLD_15	Queensland	145.74	-17.02	45.65	5.36	46.85
SA_29	South Australia	138.61	-34.92	-15.24	4.38	-6.47
TAS_05	Tasmania	147.25	-41.66	-15.35	2.72	-2.98
VIC_14	Victoria	145.06	-37.22	-26.64	3.06	-10.40
WA_01	Western Australia	116.03	-31.90	-31.34	5.55	-17.98

The locations of the selected road segments are also shown in GIS format in Figure D.8

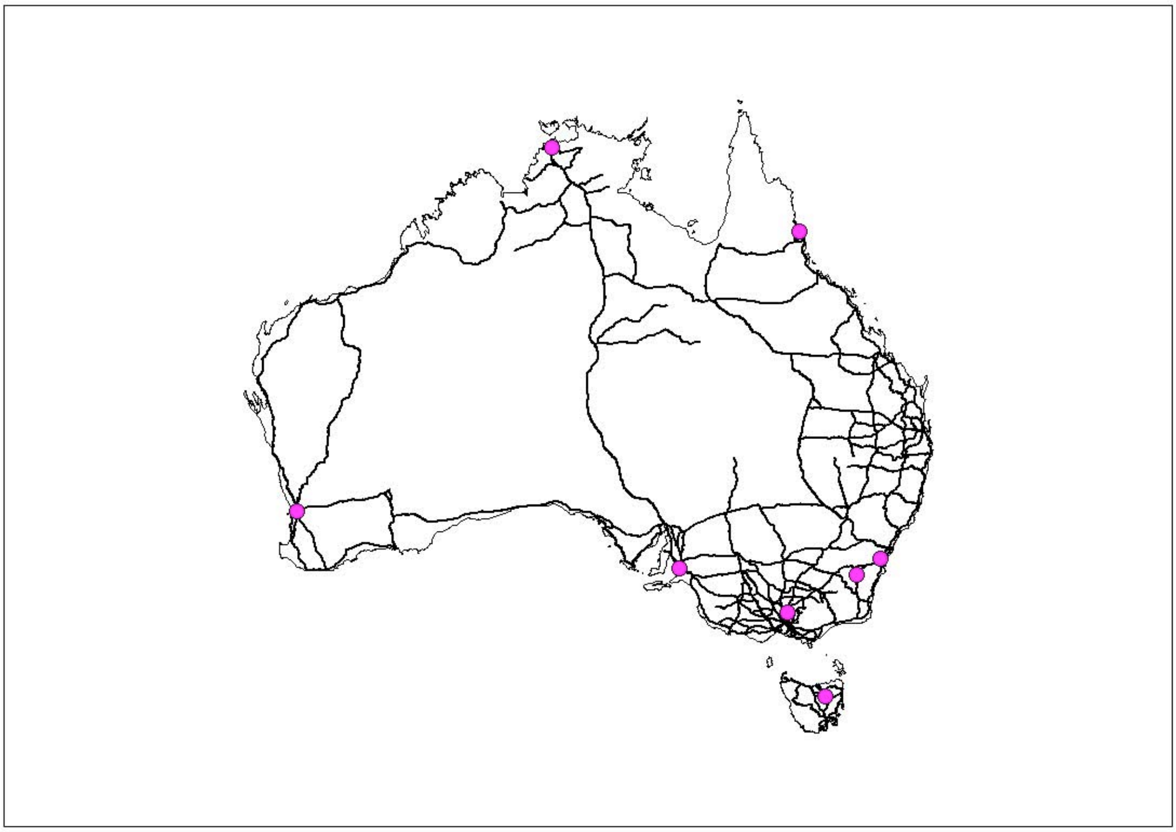

Figure D.8 Location of Road Segments selected for HDM-4 Analysis

Data Requirements and Highway Definition

HDM-4 requires additional data input compared with the PLCC network model. The data requirements included:

- Road category (highway, urban, rural, unsealed). Sine this project examined the National Highway System only the 'highway' category was used in the modeling.
- Rehabilitation type (granular, asphalt)
- Deterioration calibration factor
- Average AADT
- Percent heavy vehicles
- Average ESAs per heavy vehicle
- Average age of pavement
- Pavement strength (average SNC)
- Average initial roughness (NRM)
- Minimum roughness after reconstruction (set at a default value of 45 NRM)
- Climate (temperature and rainfall)
- Average Thornthwaite Index
- Road length
- Lane kilometres
- Lane area
- Rise and fall
- Curvature

Where specific data was not available, default values (based on practitioner best estimates) were used during the modeling. In all cases, distinctions were made for road segments in different States to ensure consistency with actual conditions within each State. Further description the detailed inputs to the HDM-4 model are described in Appendix D2 (available on Austroads website: www.austroads.com.au).

Tables D.5 and D.6 summarise the HDM-4 data inputs for each of the selected road segments. These road segments are identified by their chainage and road name.

Table D.5: Base Climate National Highway Network Definitions as input into HDM-4

ROAD NAME	ID	Rehab. Type 1=Granular 2=Asphalt	Road length	Lane kms	Lane Area	Average Age of Pavement	Average SNCo	Average Initial Roughness	Min. Roughness post re-const.	Av Thorn-thwaite	Rise & Fall	Curvature	Average AADT	% Heavy Vehicles	Average ESA's per Heavy Vehicle
			(km)	(km)	('000 m^2)	(years)		(NRM)	(NRM)		(m/km)	(deg/km)	(veh/day)	(%)	(ESA/veh)
NORTHBOURNE AVE: (0 - 1.8)	ACT_04	2	1.8	7.2	25.0	25	3.5	53	45	38	12	10	21600	3	3.0
HUME HWY: (91.8 - 189.56)	NSW_03	2	97.8	391.0	1368.6	8	10.0	43	40	57	14	14	9597	34.7	3.6
Stuart Hwy : (0 - 34.58)	NT_01	2	34.6	137.6	545.7	14	3.6	46	40	45	14	14	8951	13.6	3.0
10P: (1667.067 - 1676.122)	QLD_15	2	9.1	31.7	114.1	11	3.5	59	40	59	13	12	23752	7	2.0
Adelaide Urban: (0 - 18.7)	SA_29	2	18.7	75.7	302.9	32	3.7	88	40	-7	12	10	28186	7.1	1.9
MIDLAND HWY: (165.32 - 175.96)	TAS_05	1	10.6	42.6	153.2	14	3.2	48	45	69	13	12	10166	6.1	1.8
Hume Hwy : (62.4 - 94.5)	VIC_14	1	32.1	128.4	474.4	15	4.3	43	35	24	13	12	14994	24	2.9
Perth to Adelaide: (0 - 22.79)	WA_01	1	22.8	52.4	440.3	29	3.6	66	45	35	13	12	16793	10.6	0.2

Table D.6 2100 Climate National Highway Network Definitions as input into HDM-4

ROAD NAME	ID	Rehab. Type 1=Granular 2=Asphalt	Road length	Lane kms	Lane Area	Average Age of Pavement	Average SNCo	Average Initial Roughness	Min. Roughness post re-const.	Av Thorn-thwaite	Rise & Fall	Curvature	Average AADT	% Heavy Vehicles	Average ESA's per Heavy Vehicle
			(km)	(km)	('000 m^2)	(years)		(NRM)	(NRM)		(m/km)	(deg/km)	(veh/day)	(%)	(ESA/veh)
NORTHBOURNE AVE: (0 - 1.8)	ACT_04	2	1.8	7.2	25.0	25	3.5	53	45	13	12	10	21892	3.5	4.4
HUME HWY: (91.8 - 189.56)	NSW_03	2	97.8	391.0	1368.6	8	10.0	43	40	27	14	14	16690	38.1	5.3
Stuart Hwy : (0 - 34.58)	NT_01	2	34.6	137.6	545.7	14	3.6	46	40	103	14	14	36625	15.4	4.4
10P: (1667.067 - 1676.122)	QLD_15	2	9.1	31.7	114.1	11	3.5	59	40	105	13	12	52554	8.0	2.9
Adelaide Urban: (0 - 18.7)	SA_29	2	18.7	75.7	302.9	32	3.7	88	40	-22	12	10	15408	8.1	2.8
MIDLAND HWY: (165.32 - 175.96)	TAS_05	1	10.6	42.6	153.2	14	3.2	48	45	54	13	12	11121	7.0	2.6
Hume Hwy : (62.4 - 94.5)	VIC_14	1	32.1	128.4	474.4	15	4.3	43	35	-3	13	12	24393	26.8	4.2
Perth to Adelaide: (0 - 22.79)	WA_01	1	22.8	52.4	440.3	29	3.6	66	45	4	13	12	21716	12.1	0.3

HDM-4 Road Segment Analysis Results

HDM4 was used to examine maintenance costs for selected road sections. Although HDM4 allows for different works programs to be included in the analysis, the results are presented for a 'base alternative'. The 'base alternative' is a minimum periodic maintenance program considering routine maintenance only. The output maintenance costs from HDM-4 are presented as a works program over a 20 year period. Hence, depending on the starting condition of the pavement under analysis different levels of capital expenditure and recurrent expenditure may be required over the 20 year work program to meet the desired pavement condition.

Road Expenditure

HDM-4 produces both road agency and road user cost projections as well as the costs of alternative treatment interventions (such as asphalt or granular surfaces at different roughness levels). The road user cost projections can also include the effects of congestion on urban arterial roads. In this project, however, we are primarily concerned with road agency costs for the National Highway System (and so a 'free flow' traffic flow pattern was used within HDM-4). Table D.7 shows the results of the HDM-4 analyses for the selected road segments including both climate change effects and the transport demand effects for the 'base alternative' maintenance program. The road agency costs are presented as undiscounted total costs (expressed as $ '000 per kilometre) for the 20 year analysis period, based on a 'free flow' traffic pattern and unconstrained routine maintenance only program.

Table D.7 HDM-4 Analysis results

A. Road Agency Costs

	Total Road Agency Costs ($ '000)		
	Base Climate	2100 Climate & Traffic Changes	
	Base Alternative	Base Alternative	Change
ACT_04	97.8	97.8	0%
NSW_03	46.2	72.8	57%
NT_01	176.6	177.1	0%
QLD_15	83.6	106.1	27%
SA_29	99.0	96.8	-2%
TAS_05	140.2	159.4	14%
VIC_14	128.7	177.3	38%
WA_01	205.9	244.1	19%

B. Road User Costs

	Total Road User Costs ($m)		
	Base Climate	2100 Climate & Traffic Changes	
	Base Alternative	Base Alternative	Change
ACT_04	33.0	33.8	2.53%
NSW_03	32.5	60.2	85.28%
NT_01	19.6	87.2	344.22%
QLD_15	43.8	131.7	200.48%
SA_29	56.1	30.9	-45.01%
TAS_05	18.0	20.3	13.23%
VIC_14	41.6	72.0	73.03%
WA_01	36.4	50.1	37.57%

C. RA Costs (Traffic Changes Only)

	Total Road Agency Costs ($ '000)		
	Base Climate	2100 Traffic Changes Only	
	Base Alternative	Base Alternative	Change
ACT_04	97.8	97.8	0%
NSW_03	46.2	72.7	57%
NT_01	176.6	176.9	0%
QLD_15	83.6	103.1	23%
SA_29	99.0	96.8	-2%
TAS_05	140.2	159.5	14%
VIC_14	128.7	175.5	36%
WA_01	205.9	244.5	19%

D. RUC Costs (Traffic Changes only)

	Total Road User Costs ($m)		
	Base Climate	2100 Traffic Changes Only	
	Base Alternative	Base Alternative	Change
ACT_04	33.0	34.1	4%
NSW_03	32.5	60.8	87%
NT_01	19.6	87.0	343%
QLD_15	43.8	123.4	182%
SA_29	56.1	31.3	-44%
TAS_05	18.0	20.3	13%
VIC_14	41.6	74.2	78%
WA_01	36.4	50.5	39%

Table D.7A and D.7B indicate the changes in Road Agency Costs and Road User Costs in the year 2100 based on projected transport demand and future climate. Since HDM4 is also able to include the effects of different works programs, the results are presented for the 'Base Alternative' (unconstrained routine maintenance only). As indicated in the discussion of the PLCC model results, the Road User Costs are significantly greater than the Road Agency costs. The Road Agency costs (expressed in $'000 per kilometre) may change considerably under the 2100 traffic & climate change scenario. As an example, the Road Agency costs for the road segment NSW03 increase by over 50%.

Table D.7C and D.7D indicate that the traffic change effects are significantly greater than climate change effects. Again, it needs to be emphasised that the effects of weather extremes have not been considered in this analysis.

The changes in road user costs are primarily due to the significant increase in transport demand (driven by changes in population settlement patterns). The decrease in road user costs in the South Australian road segment (SA_29) reflects the decreased population and therefore transport demand of Adelaide.

Using the results of the PLCC and the HDM4 analyses, the effects of climate change (on road maintenance) are small compared to the effects of increased traffic. The PLCC analyses indicated a small decrease in road agency costs (of the order of –3%) based on the whole National Highway network. The HDM4 analyses suggest that the regional variation in climate change may lead to changes in road agency costs in the range from –2% to +2%.

Pavement Performance

HDM4 is able to provide detailed pavement performance projections over time. Changes in parameters such as average roughness, structural cracking, ravelling and the number of potholes can be determined over time. For example, Tables D.8 and D.9 below indicate changes in the pavement roughness over time, for each State, under a base treatment alternative, including the combined effects of changed climate and changes in traffic loading resulting from the projected transport demand in year 2100.

These results indicate a marked increase in roughness over time (compared with the year 2000 climate and traffic parameters) for the road segment located in Queensland (QLD_15). Figures D.9 and D.10 illustrate the changes in road roughness and pothole formation for this road segment. (Detailed results for the road segments in other States may be found in Appendix D4 available on the Austroads website: www.austroads.com.au).

Figures D.9 – D.13 below (along with Figures D45 – D92 in Appendix D4 (available on Austroads website: www.austroads.com.au) show a hypothetical situation in which 2100 data is substituted into a 2001 analysis. The road deterioration figures are intended as representative examples of the types of analyses available within HDM-4. The figures are based on routine maintenance only and will not therefore represent typical situations in the road network. As an example, Figure D.9 illustrates roughness increasing towards an IRI count of 12 which would not usually be tolerated in the road network.

Increased traffic levels in 2100 may result in the following possibilities: (i) higher maintenance costs (in the short term); (ii) reduced pavement rehabilitation interval; and, (iii) pavement reconstruction to cope with the higher traffic levels. It is more likely that option (ii) would be used so that the pavements would be strengthened as part of the rehabilitation process to match the expected traffic demand. Rehabilitation would not occur unless surface and structural conditions demanded it, so the approach of using increased maintenance costs as a surrogate for increased construction costs is a reasonable approximation in this context.

Table D.8: Average Roughness (IRI) estimates by year for the 2000 climate under the base case alternative.

Year	ACT_04	NSW_03	NT_01	QLD_15	SA_29	TAS_05	VIC_14	WA_01
	Base Alternative							
2001	2.05	1.68	1.79	2.30	3.43	1.86	1.68	2.56
2002	2.12	1.74	1.84	2.37	3.55	1.93	1.75	2.60
2003	2.19	1.81	1.90	2.45	3.67	1.99	1.81	2.65
2004	2.27	1.88	1.97	2.55	3.81	2.07	1.88	2.76
2005	2.34	1.95	2.03	2.63	3.94	2.16	1.95	2.97
2006	2.42	2.02	2.09	2.72	4.08	2.27	2.05	3.24
2007	2.50	2.10	2.16	2.82	4.22	2.41	2.17	3.50
2008	2.58	2.17	2.24	2.93	4.38	2.54	2.33	3.74
2009	2.67	2.25	2.33	3.05	4.54	2.70	2.50	3.97
2010	2.77	2.33	2.43	3.17	4.73	2.88	2.67	4.18
2011	2.89	2.41	2.53	3.31	4.93	3.07	2.84	4.35
2012	2.99	2.50	2.63	3.44	5.12	3.24	3.04	4.48
2013	3.10	2.61	2.72	3.57	5.31	3.40	3.25	4.58
2014	3.22	2.72	2.81	3.69	5.48	3.55	3.46	4.67
2015	3.34	2.83	2.88	3.81	5.65	3.69	3.66	4.76
2016	3.48	2.94	2.96	3.92	5.82	3.82	3.84	4.84
2017	3.63	3.05	3.03	4.03	5.99	3.94	4.00	4.91
2018	3.79	3.18	3.10	4.13	6.16	4.07	4.16	4.98
2019	3.96	3.32	3.16	4.23	6.33	4.20	4.31	5.05
2020	4.14	3.47	3.22	4.33	6.49	4.33	4.46	5.12

Table D.9: Average Roughness (IRI) values by year for the 2100 Climate under the base case alternative.

Year	ACT_04	NSW_03	NT_01	QLD_15	SA_29	TAS_05	VIC_14	WA_01
	Base Alternative							
2101	2.05	1.68	1.82	2.34	3.42	1.86	1.68	2.57
2102	2.10	1.76	1.93	2.49	3.51	1.94	1.75	2.65
2103	2.15	1.84	2.05	2.65	3.61	2.01	1.82	2.74
2104	2.21	1.92	2.19	3.11	3.72	2.11	1.95	2.90
2105	2.26	2.01	2.31	4.04	3.82	2.23	2.15	3.20
2106	2.32	2.09	2.44	5.16	3.92	2.35	2.40	3.55
2107	2.38	2.18	2.59	6.18	4.03	2.49	2.63	3.86
2108	2.44	2.27	2.74	7.09	4.16	2.65	2.87	4.14
2109	2.51	2.38	2.90	7.88	4.29	2.84	3.07	4.35
2110	2.59	2.50	3.08	8.55	4.43	3.03	3.24	4.51
2111	2.68	2.60	3.26	9.10	4.58	3.21	3.37	4.63
2112	2.76	2.71	3.44	9.55	4.72	3.38	3.49	4.73
2113	2.85	2.83	3.62	9.93	4.85	3.53	3.59	4.83
2114	2.94	2.95	3.80	10.24	4.98	3.67	3.68	4.92
2115	3.04	3.09	3.98	10.53	5.11	3.81	3.77	5.01
2116	3.15	3.23	4.15	10.81	5.23	3.95	3.86	5.09
2117	3.27	3.38	4.32	11.09	5.35	4.08	3.95	5.17
2118	3.40	3.55	4.49	11.38	5.46	4.21	4.03	5.25
2119	3.53	3.71	4.67	11.67	5.58	4.35	4.12	5.34
2120	3.67	3.88	4.84	11.96	5.69	4.49	4.20	5.42

Figure D.9 shows the change in pavement roughness over time for the road segment QLD_16 located in Queensland. It is clear that the roughness progresses much more rapidly under the future (year 2100) climate and traffic scenario than under the base conditions.

Refer to Figures D45 – D52 in Appendix D4 (available on Austroads website: www.austroads.com.au) for average roughness graphs for each of the road segments.

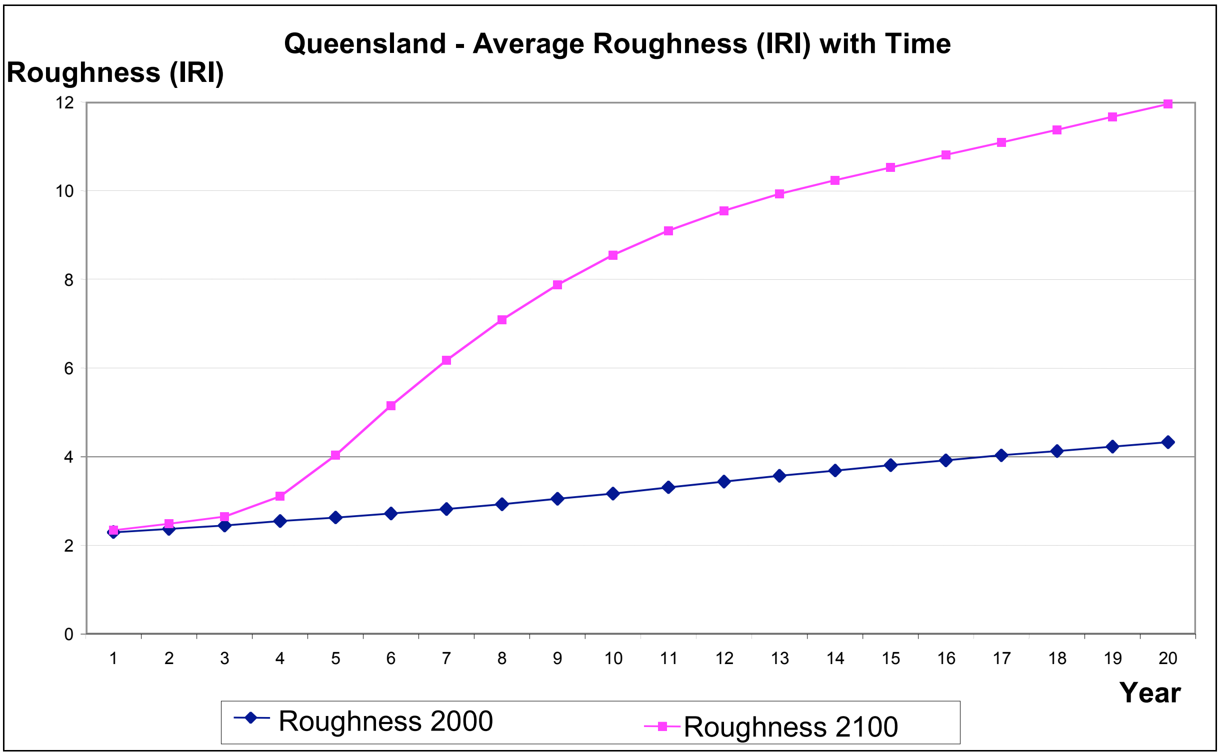

Figure D.9: Average roughness (IRI) with time for a road segment in Queensland.

Figure D.10 illustrates changes in pavement performance in terms of the formation of potholes. Because the HDM4 analysis was not constrained, it is expected that all potholes formed within any year are repaired as part of routine maintenance each year. (It is possible to enforce constraints such as the maximum area of repair, or a budget constraint which prevents all potholes formed in any year from being repaired).

Therefore, the 'saw tooth' behaviour in Figure D10 is expected since it reflects the development of potholes (through the processes of cracking and ravelling) and their repair, in any one year. The pothole formation algorithm in HDM4 is based on the level of ravelling and structural cracking in any one year. These deterioration measures are shown in Figure D.11 and Figure D.12 respectively.

Refer to Figures D69 – D76 in Appendix D4 (available on Austroads website: www.austroads.com.au) for number of pothole graphs for each of the road segments.

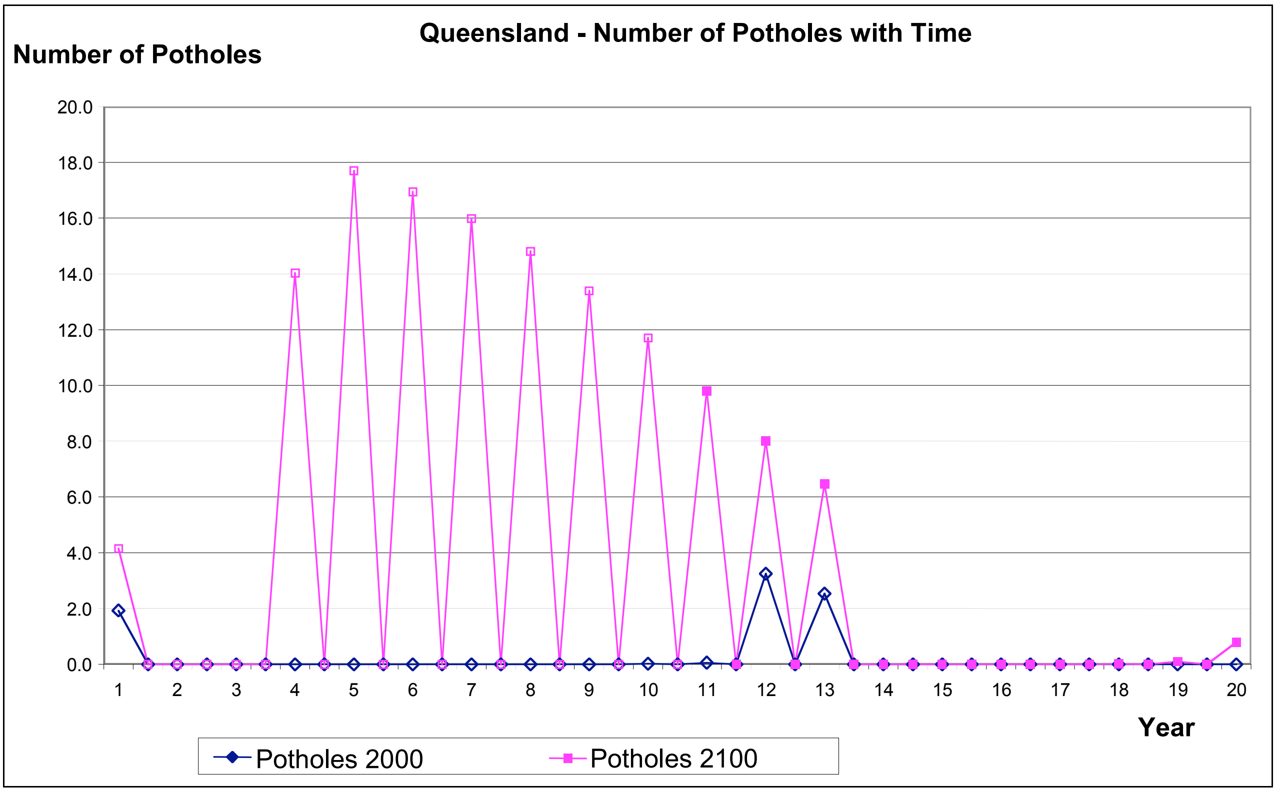

Figure D.10 Number of Potholes Forming with time for Queensland.

Figure D.11 shows the % of road surface that is ravelled in each year. The reduction in ravelling that is shown to occur after the fourth year of analysis does not reflect repairs but appears to be an artifact of the algorithm used by HDM-4 to calculate ravelling. HDM-4 places a higher priority on cracking than ravelling, which means that areas reported as cracked are not reported as ravelled. As the % road surface effected by cracking grows (refer Figure D.12 the % that is ravelled is constrained. Refer to Figures D61 – D68 in Appendix D4 (available on Austroads website: www.austroads.com.au) for ravelling graphs for each of the road segments.

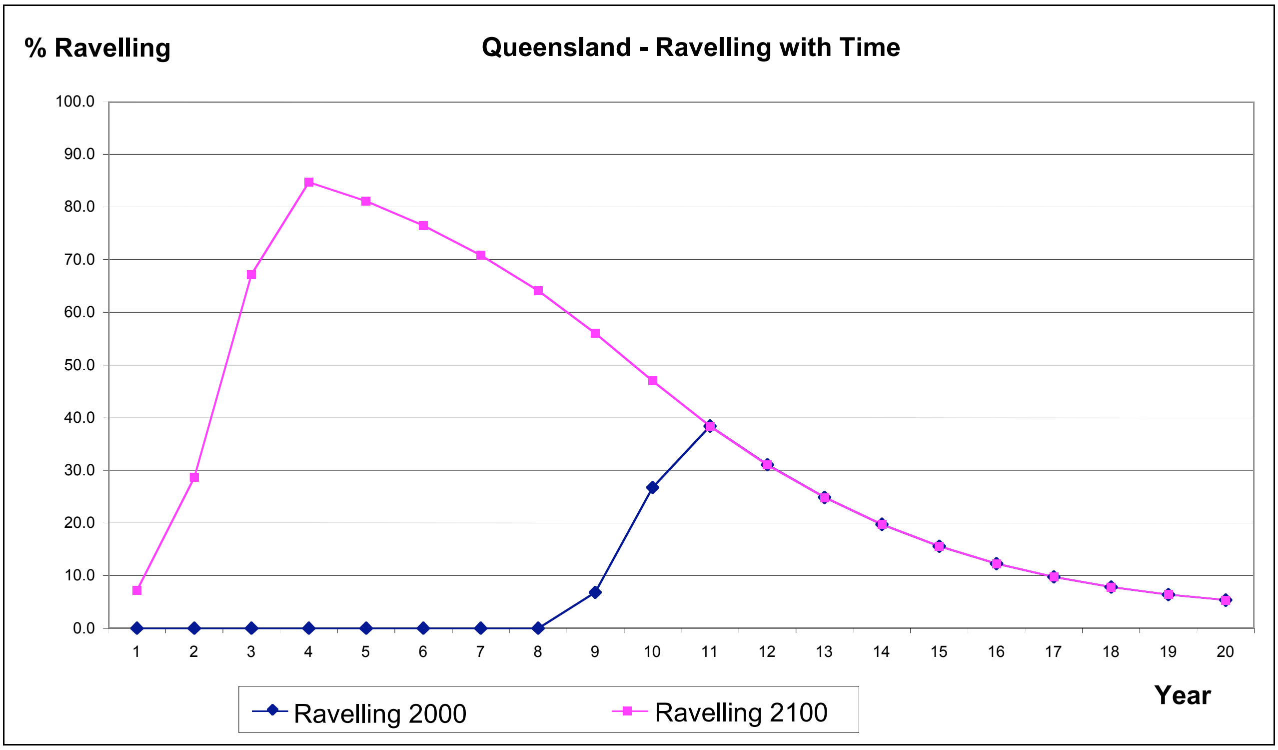

Figure D.11 Ravelling with time for Queensland.

Figure D.12 shows the % of road surface effected by cracking. The sawtooth shape, as with potholing, is a result of the cracking being repaired annually as part of routine maintenance. As the pavement ages the onset of cracking becomes more rapid to the point where over 90% of the road becomes cracked in a single year.

Refer to Figures D53 – D60 in Appendix D4 (available on Austroads website: www.austroads.com.au) for structural cracking graphs for each of the road segments.

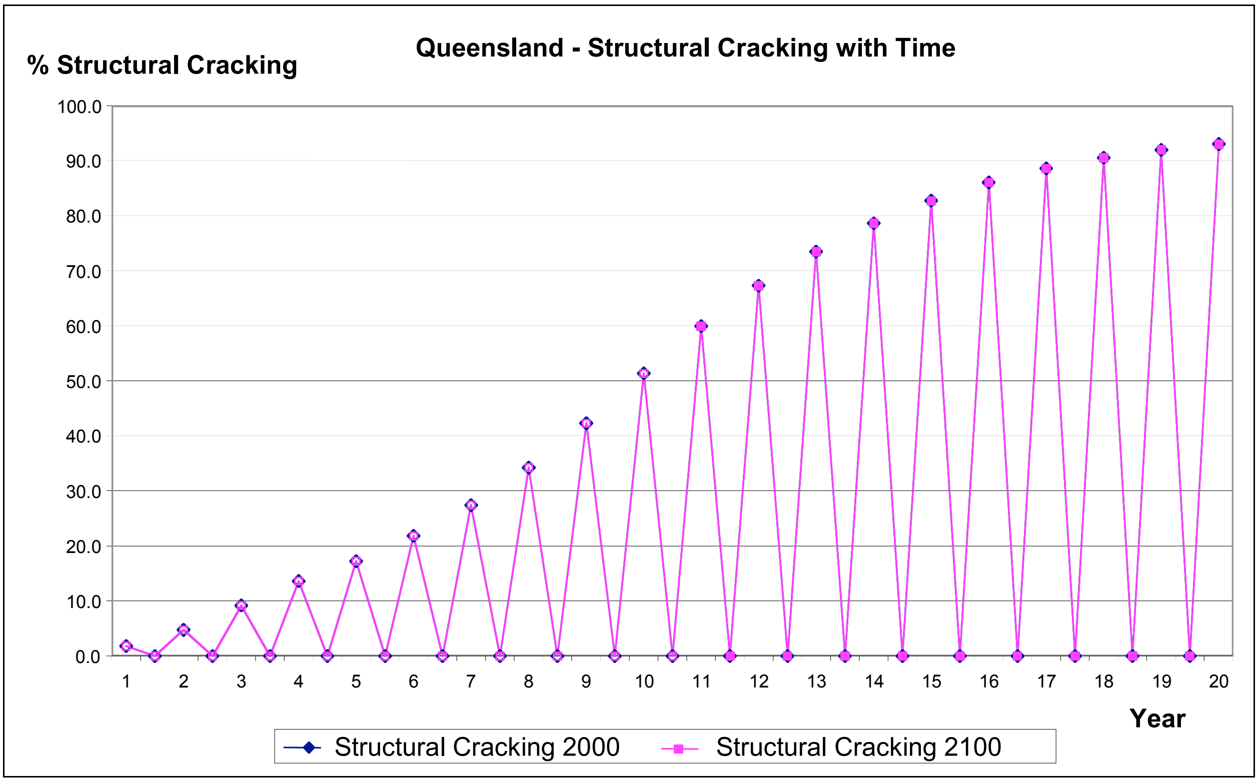

Figure D.12: Structural Cracking forming with time for Queensland.

Environmental Performance

HDM-4 also provides a capability for estimating environmental conditions as a result of changes in traffic composition and growth. Parameters such as emissions of carbon can be determined. There is, however, a need to review the environmental models within HDM4 and their calibration factors to check such estimates under Australian road conditions.

Figure D.13 shows the rise in the Carbon Dioxide emissions associated with the growth in traffic and heavy vehicle composition. The 2100 curve is much higher than the 2000 climate curve primarily due to the increased traffic load on this section of road. The upwards slope of the curves is tied to the increasing roughness of the surface over the period. This is much more pronounced in the 2100 climate as roughness increases at a faster rate (see Figure D.9).

Refer to Figures D77 – D84 in Appendix D4 (available on Austroads website: www.austroads.com.au) for Carbon Dioxide emissions graphs for each of the road segments.

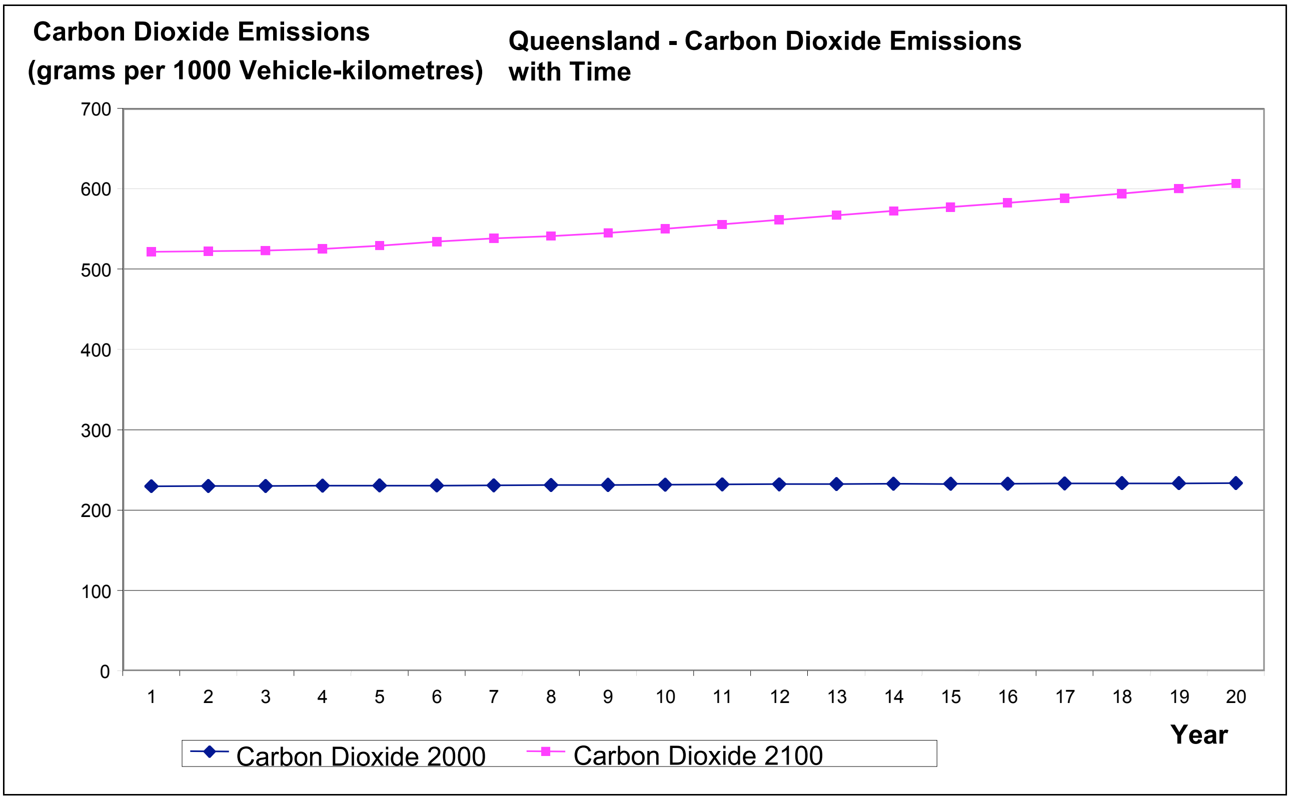

Figure D.13: Carbon Dioxide levels with time for Queensland.

3.7.5 References

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3.7.6 List of appendices on Austroads website: www.austroads.com.au

D1 PLCC Model Technical Details and Road Network Definition

D2 HDM-4 Model Technical Details and Road Network Definition

D3 PLCC Road Network Results

D4 HDM-4 Road Network Results

4. IMPACT OF CLIMATE CHANGE ON SALINITY IN THE MURRAY–DARLING BASIN (SECTION F)

Summary

Changes in the hydrological cycle under conditions of enhanced global warming are likely to be complex and spatially diverse. In the report presented here, a simulation model was developed to examine the potential impact of changes in precipitation and evaporation in the Murray Darling Basin under a climate change scenario developed for the Bureau of Transport and Regional Economics by CSIRO Atmospheric Research Division.

These climatic changes were incorporated into the Salinity and Landuse Simulation Analysis (SALSA) model developed at ABARE. This model combines simulation and optimisation techniques to represent relationships between agricultural production systems and the hydrological cycle of river catchments. Using the SALSA model, the impacts of climate change on surface water flows, water tables, ground water discharge and salt mobilisation into streams and the landscape were evaluated.

The SALSA model was run to establish a baseline scenario under the assumption of no change in long term climatic conditions. The CSIRO climate change projections were used to develop an alternative scenario. In the scenario considered, precipitation is predicted to decrease and evapotranspiration to increase in all catchments, leading to a concurrent reduction in surface water flows. Reductions in stream flow have a significant impact on irrigated agriculture. The high value horticultural regions in the South Australian Riverland and Victorian Mallee and cotton production in the northern catchments will be affected, particularly if they are unable to source additional entitlements through water trade. In addition, there is less fresh water to dilute existing salt loads, leading to a gradual increase in salt concentration in the Murray River relative to a baseline in which climate remains constant. This concurrent decline in water quality affects agriculture as the productivity of water used for irrigation is reduced, as well as urban and industrial water users and the riverine environment.

There are also longer term or delayed impacts. Changes in precipitation and evapotranspiration lead to reduced recharge that, over time, is reflected in a reduction in ground water discharge. The length of the delay can range from a few years to several hundred years, depending on the physical characteristics of the ground water flow system. The reduction in ground water discharge leads to benefits that are derived in two ways. First, salinity benefits are derived from the reduction in the discharge of saline water, and hence reduced salt loads, directly into rivers and streams. The effect of reduced discharge may be even greater in irrigation areas if reduced water availability leads to a reduction in leakage into ground water systems, either as a result of less irrigation or an improvement in water use efficiency. Even under conditions of reduced surface water flows, the reduction in salt loads may translate into lower salt concentrations depending on the salinity of the underlying ground water system. Reductions in saline discharge to the river system from irrigation areas will be greatest in the South Australian Riverland and Victorian Mallee, where ground water salinity approaches that of sea water.

Second, salinity benefits are also derived if the reduction in discharge lessens the accession of saline ground water into the landscape. Reductions in the area affected by dryland salinity vary across the basin, with the timing and extent dependent on the net effect of changes in the hydrological cycle, the response time of the ground water flow system and the rate of recharge in each land management unit. While reductions in precipitation and increased evapotranspiration are predicted to lessen ground water recharge, the delayed response of ground water discharge is such that the area of high water tables is expected to continue to rise over coming decades. The increase in the area affected by high water tables is, however, smaller than what would have occurred under constant climatic conditions.

Over the longer term, revenue decreases for both dryland and irrigated agriculture. Under changing climatic conditions, dryland cropping and pasture yield less output, leading to reduced returns, despite reductions in the area affected by high water tables. While improvements in water quality lead to improvements in irrigated productivity, this is more than offset by the reductions in the availability of surface water for

irrigation. Irrigation regions on the tributaries of Darling River are particularly affected as high value cotton production is reduced.

The hydrological interactions under enhanced global warming are complex, involving both temporal and spatial tradeoffs. Of particular significance is the reduction in surface water flows over a relatively short time frame, coupled with the delayed effects of the reduction in ground water discharge. This may impose significant economic and environmental costs as salt concentration increases. The more immediate effect of increased stream and river salinity may have an adverse impact on transport infrastructure. Reductions in ground water recharge will, in the long term, result in lower water tables that may reduce damage to both road and rail infrastructure. However, structures such as drainage lines and culverts may be affected by the deposition of sediment stemming from the increased erosion from bare saline land. The compounding effects of the long response times and uncertainty in climate change science are likely to make any policy responses to declining water availability and quality difficult to design and implement.

4.1 Introduction

The CSIRO Division of Atmospheric Research has run global and regional climate models to develop long term projections for a variety of climatic variables such as precipitation, temperature and potential evaporation. Changes in these variables have been derived using climate model simulations to provide information on the magnitude of regional responses in terms of local change per degree of global warming. In the scenario considered here, precipitation is expected to decline over all of the Murray Darling Basin, particularly in the northern areas over the next 100 years. Global warming is also likely to affect evaporation, with an increase in annual average potential evaporation, particularly in the northern catchments. On balance, the projections are for slight to moderate reductions in water availability for dryland agriculture and moderate to substantial reductions in surface water flows.

While it is recognised that a reduction in the volume of surface water flows is likely to have significant implications for both consumptive and nonconsumptive water uses in the basin, the effects of changes in precipitation and evapotranspiration on dryland and instream salinity are less well known. The increased mobilisation of salt into the landscape and streams is a significant problem in the Murray Darling Basin. It occurs when the replacement of native vegetation with crops and pasture and inefficient irrigation practices cause more water to enter a ground water system (recharge) than can be discharged. This results in rising water tables and, over time, saline ground water being discharged into soil (dryland salinity) and water (instream salinity) resources, causing damage to infrastructure such as roads and bridges, and agricultural yield losses, and threatening the riverine environment.

The hydrological processes that mobilise salt will shift with changes in precipitation and evapotranspiration under enhanced greenhouse conditions that will, in turn, have implications for dryland and instream salinity in the Murray Darling Basin. The objective in this consultancy is to use the climate change projections developed for the Bureau of Transport and Regional Economics (BTRE) by CSIRO Atmospheric Research Division to assess the implications for the future extent of salinity in the Murray Darling Basin.

4.2 Tradeoffs in the hydrological cycle under global warming

4.2.1 Key components of the hydrological cycle

The SALSA modeling framework incorporates a representation of both surface and ground water processes, the relationship between these hydrological processes and dryland and instream salinity, and the impact of salinity in soil and water resources on agricultural productivity. The surface and ground water components of the SALSA model explicitly incorporate the impacts of predicted changes in precipitation and evapotranspiration on salt mobilisation under enhanced greenhouse conditions through changes in ground water recharge and in the volume of surface water runoff. The impacts are highly dependent on the physical characteristics of each subcatchment and, as a consequence, changes in catchment hydrology under global warming will generate a range of location specific impacts. There are a number of variables that determine ground water flows, surface water yields and the mobilisation of salt within, and from, a catchment area. These variables include:

- precipitation;
- rates of evaporation and transpiration;
- ground water response times;
- soil types;
- ground water salinity; and
- the morphology of the catchment.

Changes in precipitation and rates of evaporation and transpiration are directly affected under global warming. In turn, these changes will determine the volume of surface water flows and changes in ground water recharge.

Precipitation may be returned to the atmosphere as evapotranspiration from the vegetation cover, flow over land into surface water bodies or enter the ground water system. On average, evaporation and transpiration increase with higher levels of precipitation. However, for any given increase in precipitation, evapotranspiration will not increase by the same amount; hence, the proportion of precipitation that will either flow over land or into the ground water system (ground water recharge) increases with precipitation.

The volume of precipitation that is not returned to the atmosphere through evapotranspiration will either flow overland or recharge the ground water. The fraction of this excess water that enters the ground water system depends on the rate of infiltration, the rate at which water can penetrate the soil surface, and percolation through the soil profile. The rate of penetration depends on several factors including the slope or gradient of the land, size and structure of the soil and the level of soil moisture. On more steeply sloped land there tends to be fewer and smaller local depressions to store water that can then infiltrate the soil. Clay soils have finer soil particles, creating smaller gaps through which water can enter and move through the soil profile. Sandy and less compacted soils have larger gaps allowing water to enter and move through the soil profile more easily than in heavier soils.

The equilibrium response time of a ground water flow system is the time it takes for a change in the rate of recharge to be fully reflected in a change in the rate of discharge. One of the most important factors is the lateral distance of ground water flows – that is the distance between recharge and discharge. The greater the lateral distance that the ground water flows, the slower the response time. Hence, the distance between where recharge and discharge is occurring will have a substantial impact on the timing of costs or benefits of climate change.

A catchment can contain a number of component flow systems. In a regional flow system, hydraulic gradients can be very flat; hence for a given lateral distance, a long period of time is required for the system to come to equilibrium. Over the flow system as a whole, however, the impact of changes in recharge on discharge may not be seen for several hundred years.

Generally, the upper reaches of the catchment are more steeply sloped and these areas are characterised by local flow systems. In these local systems, ground water pressure pulses move through the flow system rapidly and the delay between a change in the rate of recharge and the volume of discharge from the aquifer over a given distance may be fast in comparison to a regional flow system. Over the flow system as a whole, the balance between recharge and discharge may be restored within 100 to 200 years.

4.2.2 Impact of changes in precipitation and evapotranspiration on catchment salinity

The hydrological characteristics of the flow system determine the tradeoffs associated with changes in precipitation and evapotranspiration and in the lagged effects of changes in ground water recharge. In all catchments, decreased precipitation and increased evapotranspiration leads to a reduction in surface water flows. The more immediate effects of this are twofold. First, the reductions in stream flow have significant effects on irrigated agriculture. The impact is most severe in high value horticultural regions, particularly if they are unable to source additional entitlements through water trade. Second, there is less fresh water to dilute existing salt loads, which leads to a gradual increase in salt concentration in the Murray River. The decline in water quality affects agriculture, because the water used for irrigation is less productive. This also applies to urban and industrial water users.

There are longer term impacts also. Reduced precipitation and increased evapo-transpiration lead to a reduction in recharge that, over time, is reflected in a reduction in ground water discharge. The length of the delay can range from a few years to several hundred years depending on the physical characteristics of the ground water flow system. The reduction in ground water discharge leads to benefits that are derived in two ways. First, salinity benefits are derived from the reduction in the discharge of saline water directly into rivers and streams. The effect of reduced discharge may be even greater in irrigation areas if reduced water availability leads to a reduction in leakage into ground water systems, either as a result of less irrigation or an improvement in water use efficiency. Even under conditions of reduced surface water flows, reduced salt loads may translate into lower salt concentrations depending on the salinity of the underlying ground water system.

Second, salinity benefits are derived if the reduction in discharge stops the accession of saline ground water into the landscape. Reductions in the area affected by dryland salinity are likely to vary across the basin, with the timing and extent dependent on the net effect of changes in the hydrological cycle, the response time of the flow system, and the rate of recharge in each land management unit.

Changes in the area affected by dryland salinity, reduced surface water availability and increases in salt concentration of irrigation water drawn from rivers imposes an associated cost on agriculture as a result of the loss in agricultural productivity.

Using the SALSA model, the impacts of climate change on surface water flows, water tables, ground water discharge and salt mobilisation into streams and the landscape were evaluated. In addition, the cost to agriculture as a result of climate change is estimated. These impacts are estimated under the assumption that there is no policy intervention to manage salinity.

4.3 Methodology

4.3.1 Model specification

The Salinity and Landuse Simulation Analysis (SALSA) modeling framework was developed at ABARE, in cooperation with the Murray Darling Basin Commission (MDBC) and CSIRO Land and Water Division. It incorporates the relationships between land use, vegetation cover, surface and ground water hydrology and agricultural returns. The basin scale model consists of a network of land management units linked through overland and ground water flows. The spatial coverage of the SALSA model includes the predominantly dryland regions of the Murray Darling Basin spanning from the Condamine–Culgoa catchment in southern Queensland clockwise around the eastern edge of the basin to the Avoca catchment in Victoria. The catchments considered in this study are labeled in map 1. Catchments within the Murray Darling Basin shown in map 1 that are shaded in grey are not considered to contribute surface or ground water flows to either the Murray or Darling Rivers and are not included in the analysis.

In the analysis presented here, each catchment is split into between two and six land management units. The land management units are defined according to the characteristics of the ground water systems within each catchment – that is, they are classified according to whether they are local, intermediate or regional flow systems. The model consists of a network of land management units linked through overland and ground water flows.

As noted in the previous section, hydraulic gradients can be very low in regional and intermediate flow systems and a long period of time, perhaps several hundred years, is required for the system to come into equilibrium following a change in recharge. Conversely, in local systems, the delay between a change in the rate of recharge and a change in the volume of discharge may be relatively short, within 100 to 200 years.

Irrigation areas within each of these catchments are also represented. The SALSA model also includes the Victorian Mallee and South Australian Riverland irrigation areas immediately adjacent to the Murray River that extend from Nyah downstream to Morgan. To allow for a range of hydrological response times, related to the distance of irrigation development from the river valley, the land management units in the Victorian Mallee and South Australian Riverland irrigation areas were split into three bands – within 2.5 kilometres from the Murray River, between 2.5 and 5 kilometres from the river and between 5 and 10 kilometres from the river. A similar methodology was used in the other irrigation regions although response times were assumed to be longer in the larger regions.

Map 1: Catchments in the Murray Darling Basin covered by the SALSA model

As lateral distances to the river system are short in irrigation regions and the soil profile often pressurised, a reduction in irrigation recharge can have an almost immediate effect on saline discharge to the river. These differences in response times between irrigation regions and between local, intermediate and regional ground water flow systems are a major driver of the hydrological and economic impacts of changes in recharge under climate change.

Within the modeling framework, economic models of land use are integrated with a representation of hydrological processes in each land management unit. The hydrological component incorporates the relationships between irrigation, rainfall, evapotranspiration and surface water runoff, the effect of land use change on ground water recharge and discharge rates, and the processes governing salt accumulation in streams and soil.

In the agroeconomic component of the model, land use is allocated to maximise economic return, or production revenue, from the use of agricultural land and irrigation water. Each land management unit is managed independently to maximise returns given the level of salinity of available land and water resources, subject to any land use constraints. Incorporated in this component is the relationship between yield loss and salinity for each agricultural activity. Thus, land use can shift with changes in the availability and quality of both land and water resources. The cost of salinity is measured as the reduction in economic returns from agricultural activities from those that are currently earned. The modeling approach is described in more detail in Bell and Heaney (2001).

4.3.2 Incorporating climate change into the SALSA model

The focus in this study is to examine how the climate change scenario developed for BTRE may affect changes in the hydrological cycle, and to provide an assessment of the likely local effects of climate change for the Murray Darling Basin for the next 100 years. Regional projections of climate change in Australia under this scenario were conducted by CSIRO Atmospheric Research. These climate change projections were incorporated into the SALSA model using two climatic drivers. The first driver, average annual rainfall, was specified uniquely for each hydrologically defined land management unit. The second driver, evapotranspiration was specified as a function of rainfall and land cover in each land management unit. The excess of precipitation over evapotranspiration is split between surface water flows and groundwater recharge, depending on the land type and slope profile of each land management unit.

The specification of evapotranspiration as a function of rainfall and land cover alone was viewed as a major limitation of the SALSA model with respect to projecting the impacts of climate change. A study conducted using the Integrated Quality Quantity Model (IQQM) in the Macquarie–Bogan catchment indicated that the climatic factors that determine change in evapotranspiration are change in both rainfall and potential evaporation (Herron, Davis and Jones, unpublished). In initial trials with the SALSA model in the Macquarie–Bogan catchment, the SALSA model significantly understated changes in surface water runoff when only changes in rainfall were incorporated.

To address this problem the Holmes–Sinclair evapotranspiration relationship used in the SALSA model was modified to account for changes in potential evaporation. The relationship for tree cover was specified as:

$$ET_{Trees} = ppt\left(1 + \frac{\Delta 2800}{ppt}\right)\left(1 + \frac{\Delta 2800}{ppt} + \frac{ppt}{\Delta 1400}\right)^{-1}$$

where
$$\Delta = 1 + \alpha \frac{PE_t}{PE_{t=0}}$$

and *ppt* is annual precipitation in millimetres, α is a parameter, *PE* is potential evaporation, and *t* denotes time in years. The relationship for grass cover was specified as:

$$ET_{Grass} = ppt\left(1 + \frac{\Delta 2200}{ppt}\right)\left(1 + \frac{\Delta 2200}{ppt} + \frac{ppt}{\Delta 1100}\right)^{-1}$$

A range of values for α was explored and a value of 1.0 provided a reasonable fit to the runoff relationships generated by IQQM model (New South Wales Department of Land and Water Conservation 1995).

4.3.3 Projections methods

Changes in annual average precipitation and potential evaporation were estimated for the climate change scenario using OZCLIM, a climate change scenario generator developed by CSIRO Atmospheric Research. Climate projections were extracted from OZCLIM for the years 2020, 2050 and 2100; intervening years were linearly interpolated. These data were calculated as percentage change from the base, where the base year was 1990. The output generated by OZCLIM for 2020, 2050 and 2100 was then translated into a GIS point coverage using ArcInfo. Changes in annual average precipitation and potential evaporation were extracted for each land management unit in the SALSA model using ArcView3.1 and were incorporated into the hydrological component of the modeling framework using the methodology explained above.

The distances for the main roads were derived from the transport layer of AUSLIG's Global Map Data Australia 1M 2001. The roads were categorised as primary routes, secondary routes, and limited access routes that were both paved and operational were allocated to a subcatchment. The total distances were calculated in ArcView3.1.

4.4 Key findings

Summary tables for key results under both the baseline and climate change scenarios are presented in tables F.1 and F.2. The results for the baseline in which both precipitation and climate are held constant are presented in appendix tables A1–A16 (available on Austroads website: www.austroads.com.au). The baseline simulation adopted is one of 'business as usual' in agricultural production. In the simulation period, the impact of land cover on surface water flows, ground water flow systems and dryland salinity was estimated. Agricultural producers are able to alter their use of land and irrigation water in response to changes in the salinity of these resources but there is assumed to be no policy intervention to manage salinity in this scenario. The cost of salinity in the baseline scenario is measured as the reduction in economic returns from agricultural activities from those that are currently earned.

The total estimated cost of lost production revenue is approximately $662 million, over the 100-year period in net present value (NPV) terms. Costs are incurred as high water tables reduce agricultural yields in both irrigated and dryland regions. Increasing salt concentration of surface water flows reduces yields from irrigation, also leading to a reduction in economic returns. This cost does not include damage to roads and other infrastructure due to high water tables and environmental damage.

Table F.1: Summary results for the baseline scenario

		2000	2025	2050	2100
Net production revenue	$m, npv	3 827	3 794	3 776	3 718
Area of high water tables	'000 ha	1 137	2 177	2 957	5 341
Salt concentration					
Darling – below the Macquarie	mg/L	152	193	218	277
Murray – below the Murrumbidgee	mg/L	141	150	156	181
Murray – below the Darling	mg/L	226	255	271	301
Murray – at Morgan	mg/L	313	368	396	445
Surface water flows		1 434	1 563	1 662	1 905
Darling – below the Macquarie confluence	GL	7 345	7 483	7 608	7 784
Murray – below the Murrumbidgee confluence	GL	8 128	8 396	8 620	9 040
Murray – below the Darling	GL	6 789	7 065	7 293	7 720
Murray – at Morgan	GL	3 827	3 794	3 776	3 718

Table F.2: Summary results for the climate change scenario

		2000	2025	2050	2100
Net production revenue	$m, npv	3 827	3 738	3 654	3 400
Area of high water tables	'000 ha	1 137	2 144	2 801	4 404
Salt concentration					
Darling – below the Macquarie	mg/L	152	212	268	483
Murray – below the Murrumbidgee	mg/L	141	155	165	198
Murray – below the Darling	mg/L	226	270	300	343
Murray –at Morgan	mg/L	313	395	450	548
Surface water flows		1 434	1 221	914	172
Darling – below the Macquarie confluence	GL	7 345	7 106	6 834	6 060
Murray – below the Murrumbidgee confluence	GL	8 128	7 683	7 132	5 259
Murray – below the Darling	GL	6 789	6 373	5 845	4 435
Murray –at Morgan	GL	3 827	3 738	3 654	3 400

Five catchments – the Loddon, Murrumbidgee, Macquarie–Bogan, Condamine–Culgoa and Campaspe – account for around 60 per cent of the total costs in the baseline scenario. There is a substantial increase in the area affected by high water tables with relatively high groundwater salinity levels in the Murrumbidgee and Loddon catchments. In the Goulburn–Broken, Macquarie–Bogan and Campaspe catchments most of the costs are also caused by high water tables. However, in the Condamine–Culgoa catchment there is a substantial increase in river salinity that affects cotton yields in the second half of the simulation. Furthermore, the collective impact of increased river salinity in the Victorian Mallee and South Australian Riverland is more than $60 million.

In response to the increase in soil salinisation and instream salinity, there is expected to be a gradual switch out of pasture into cropping activities as they offer a higher marginal return under these conditions. This change in land use is likely to occur in both irrigated and dryland parts of the basin.

The impacts of changes in climate under the climate change scenario considered in this report vary considerably across catchments. Catchment profiles under climate change are given at the subcatchment level in appendix tables B1-B16. The impacts of climate change, net of the baseline, are given in appendix tables C1-C16. Results for key model outputs under climate change are given in appendix tables D1-D8. (These appendices are available on the Austroads website: www.austroads.com.au.)

Compared with the baseline, the loss in agricultural revenue is generally higher in the Darling River tributaries as reductions in available surface water and increases in salt concentration impact heavily on irrigated production. As the volume of surface water available decreases, there may be a reduction in the volume of water available for irrigation depending on the institutional arrangements in place. In the analysis presented here, a reduction in available surface water flows results in a proportional reduction in the volume for water available for irrigation. Land engaged in the lowest returning irrigated activity in each catchment would be switched into lower returning dryland activities, imposing a cost to agriculture. Catchments predominantly engaged in high value cropping, such as cotton production, or horticulture would therefore be particularly affected by reductions in available water. It is important to note that some regions, such as the Victorian Mallee and South Australian Riverland may be able to trade water from regions engaged in lower returning irrigated activities, such as pasture, to offset reductions in agricultural revenue, depending on the water property rights and trading institutions in operation. The capacity for irrigation regions to trade to mitigate the reduction in irrigation entitlements has not been included in this analysis.

Under this climate change scenario, lower volumes of surface water are available to dilute existing salt loads leading to increased salt concentration in both the Darling and Murray Rivers in comparison to the baseline. Under the climate change scenario considered, salt concentration in the Murray River was simulated to increase steadily over the next 100 years from around 520 EC in 2000 to more than 913 EC in 2100. In addition to reducing yields from irrigated production, increased salt concentration of surface water flows will also have an impact on infrastructure and the riverine environment.

However, changes in precipitation and evapotranspiration reduce the volume of ground water recharge and, over time, the volume of ground water discharge. Reductions in recharge under climate change are gradual and the lagged effect on ground water discharge may occur over several decades or longer. The timing of the reduction in ground water discharge is highly location specific and dependent on the equilibrium response time of the ground water flow system.

A reduction in the volume of ground water discharge generates salinity benefits. Ground water discharge transports salt to the river by direct seepage or by surface discharge that eventually reaches the river system. The volume of salt transported to the river depends to a large extent on the salinity of the ground water. The salinity of ground water discharge in the Murray River and its tributaries is generally low in the upland catchments. Ground water salinity levels tend to increase moving downstream and reach levels approaching seawater in low lying regions of Victoria and South Australia.

The volume of salt mobilised to streams and rivers was simulated to increase over the coming 50 years. Salt loads in the Murray River began declining between 2050 and 2100 relative to the baseline as decreases in recharge were gradually reflected in decreases in discharge. By 2100, salt loads at Morgan were around one third lower under the climate change scenario as the volume of salt exported from each catchment declined. However, surface water flows were also reduced under climate change. The decrease in precipitation and increase in evaporation lead to a 40 per cent reduction in surface water flows at Morgan in 2100. As there is less surface water available for dilution flows, the reduction in salt load is not sufficient to improve water quality in the Murray River, even in the longer term.

A reduction in the volume of surface water may also lead to reduction in the volume of salt mobilised as ground water recharge, and over time, discharge will be reduced if less water is applied for irrigation or irrigation efficiency is improved. The reductions in the volume of salt mobilised will be greatest if this occurred in highly saline irrigated regions such as the Victorian Mallee and the South Australian Riverland.

A reduction in discharge also lessens the accession of saline ground water into the landscape. The impact of the reduction in recharge on high water tables under climate change is presented in figure F.1. The area affected by high water tables over the entire Murray Darling Basin under the climate change scenario is simulated to increase from more than 1.14 million hectares in 2000 to almost 2.80 million hectares in 2050. The area of high water tables in 2100 was simulated to be around 4.40 million hectares. The progression of the area affected by high water tables under climate change is shown in maps 2-5.

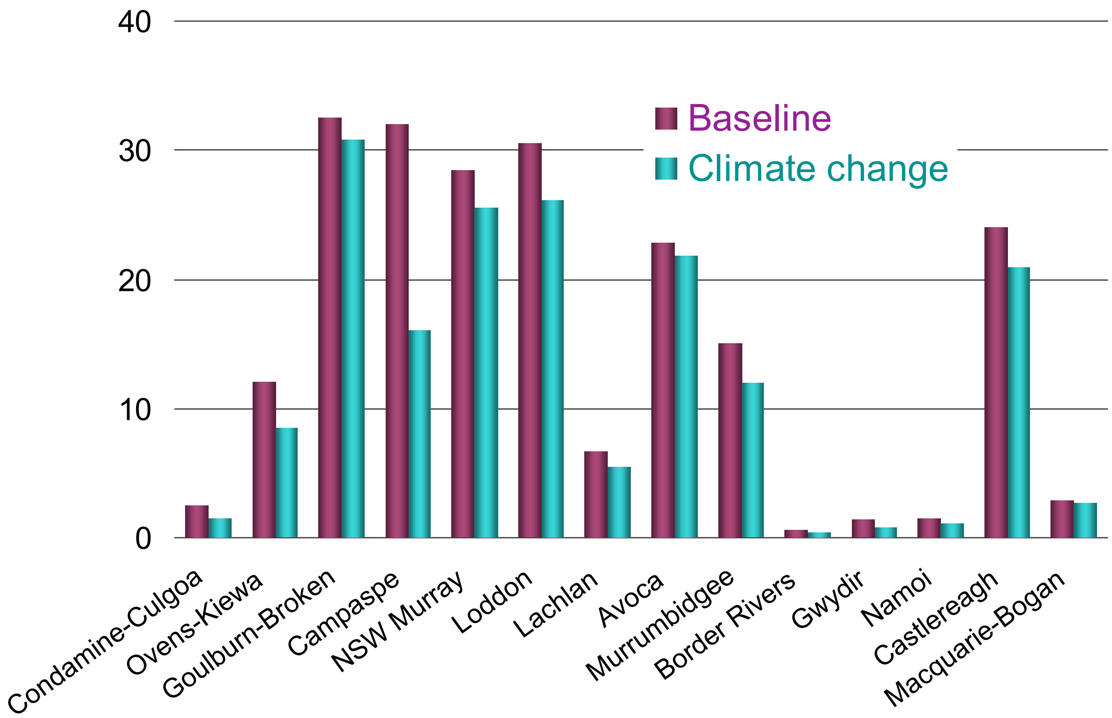
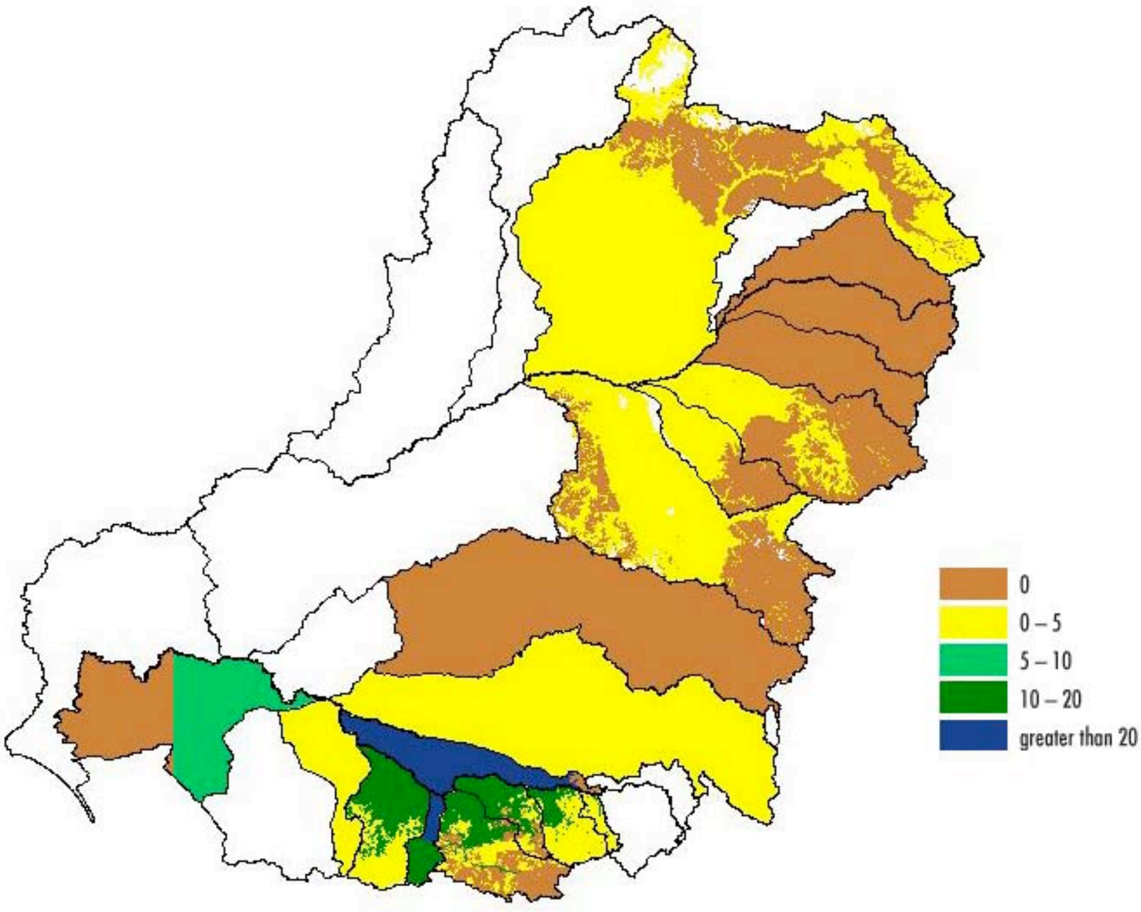
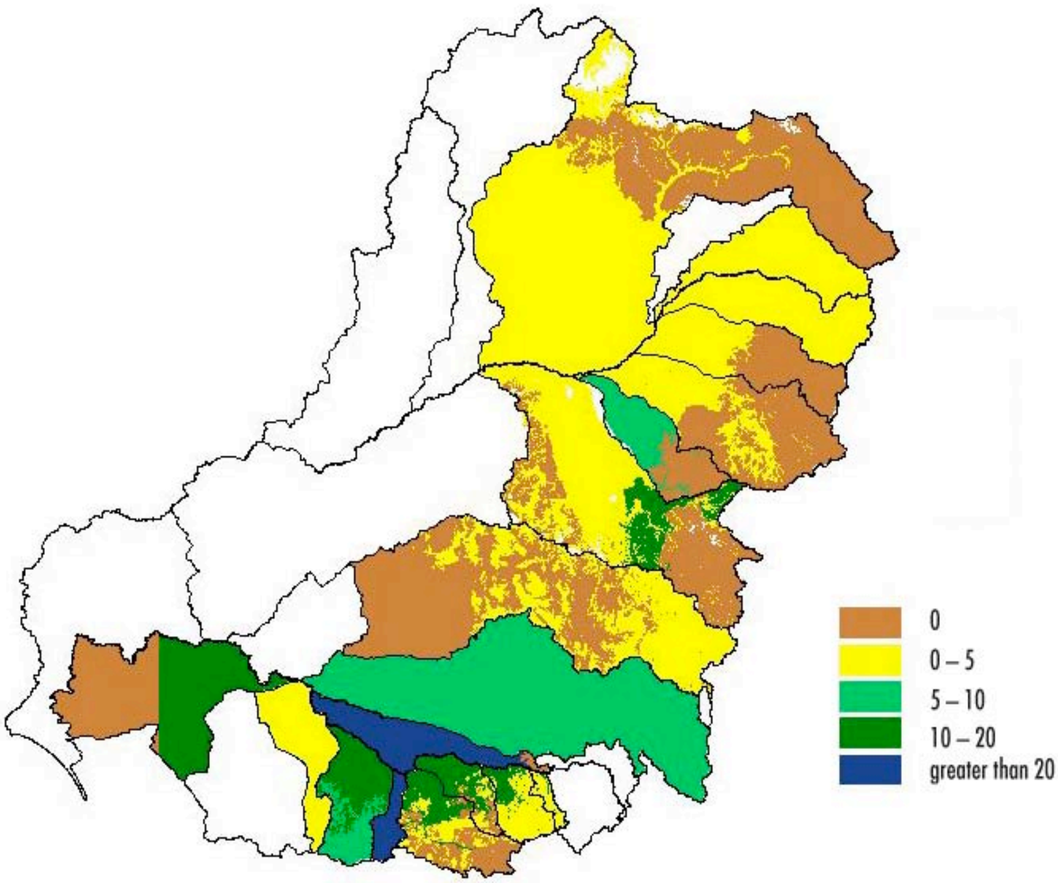


Figure F.1: Proportion of catchment affected by high water tables, 2100

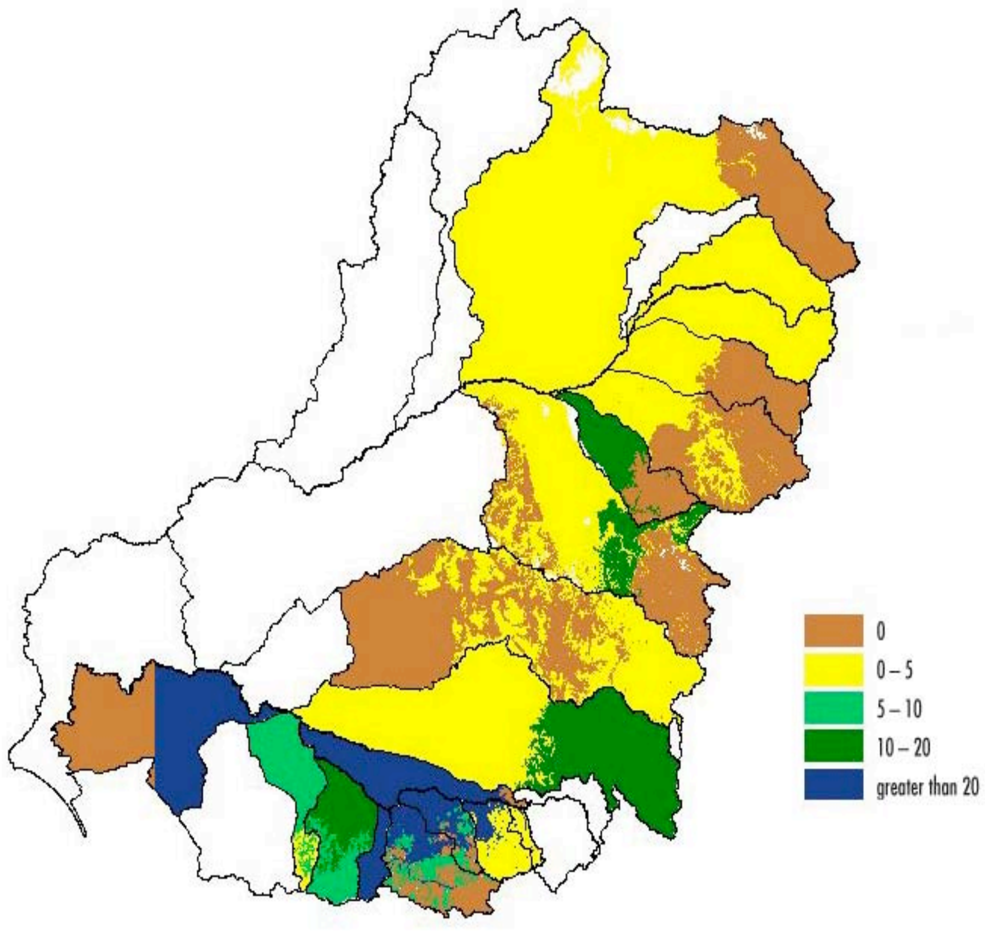
The total area affected by high water tables under the baseline scenario was simulated to be around 2.96 million hectares in 2050 and around 5.34 million hectares in 2100. The area affected by high water tables was lower in 2100 under the climate change scenario than the baseline. While there was little difference between the two scenarios to 2050, between 2050 and 2100 lower volumes of recharge under the climate change scenario were slowly reflected in reductions in saline discharge into the landscape. As a result, the area affected by high water tables in 2100 under changed climate conditions was almost 20 per cent lower than the baseline. There was, however, considerable variation in the reduction in the area of high water tables between catchments (figure F.1). This variation is driven by differences in recharge rates and the response times of the ground water flow systems. Even after 100 years, many subcatchments would not have reached a new equilibrium, so further reductions in the area affected by high water tables are likely.



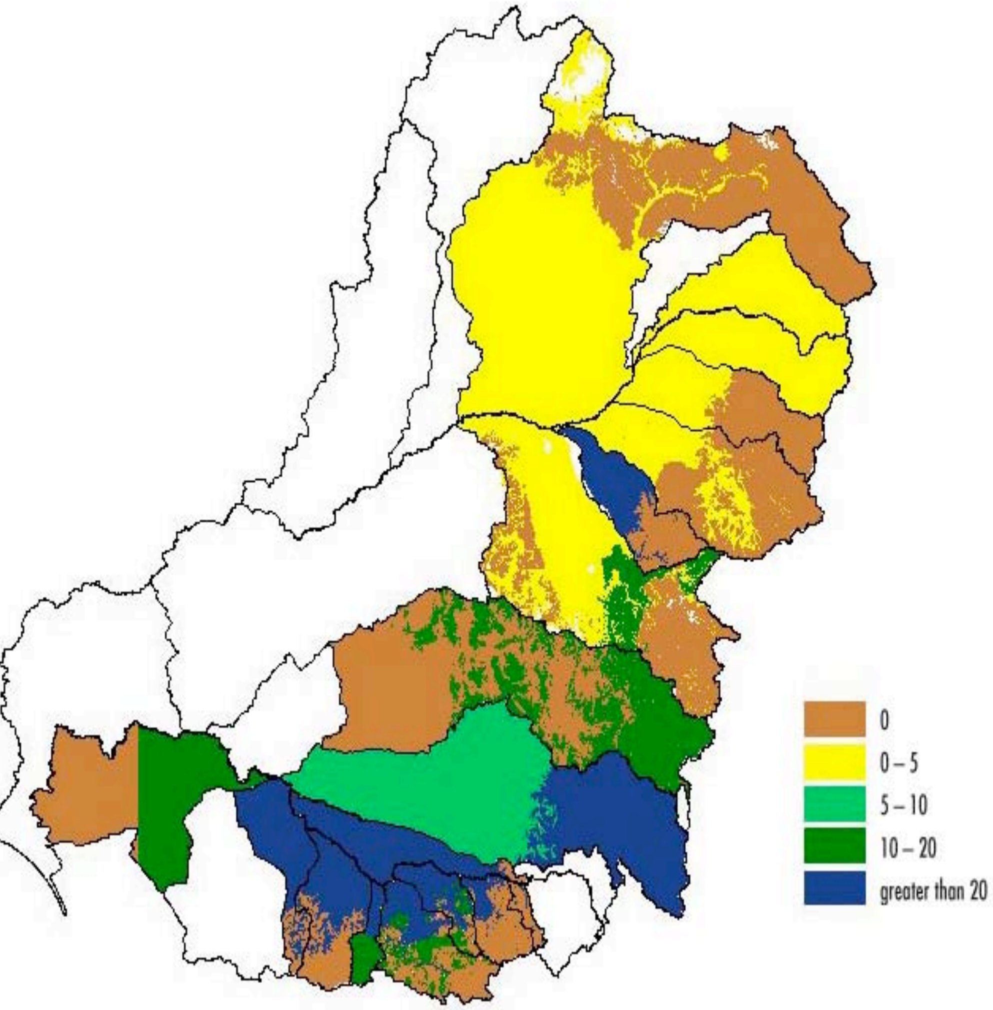
Map 2: Proportion of catchment affected by high water tables, 2000



Map 3: Proportion of catchment affected by high water tables, 2025

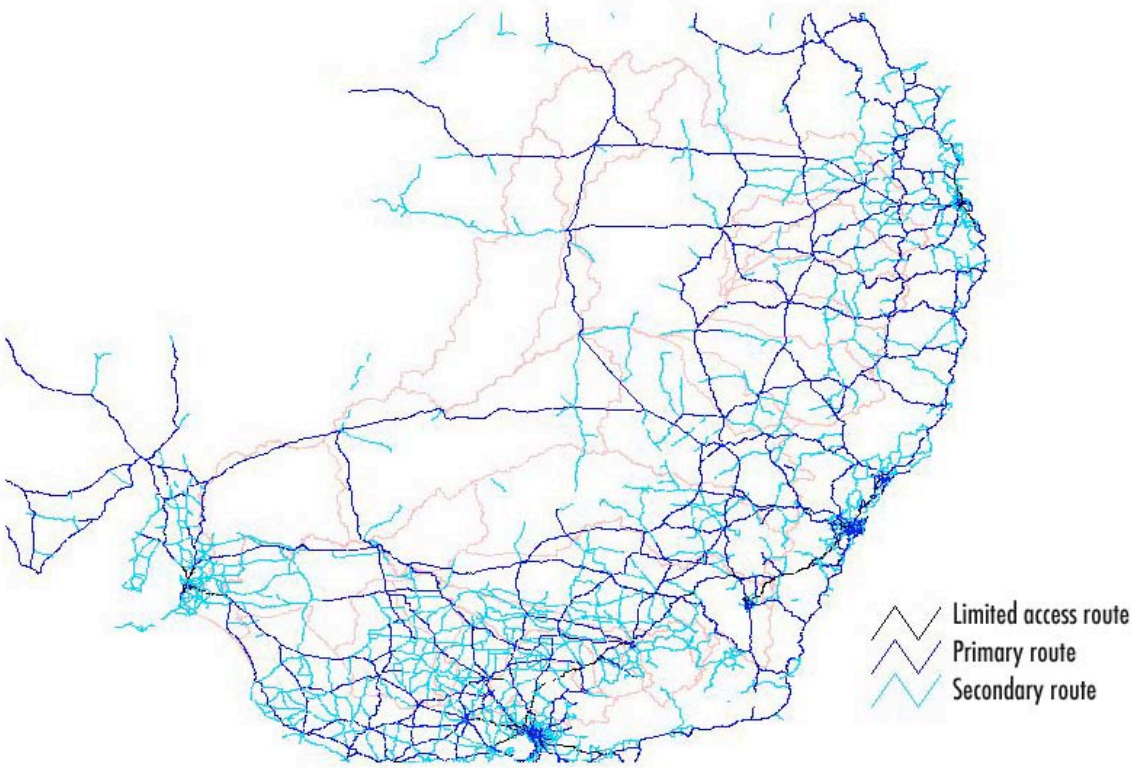


Map 4: Proportion of catchment affected by high water tables, 2050



Map 5: Proportion of catchment affected by high water tables, 2100

The road system throughout the Murray Darling Basin is extensive (map 6). It is not possible to identify specific road assets that are likely to be adversely affected by saline high water tables. It was possible to determine the length of road, by route type, within each subcatchment (appendix table E1 available on Austroads website: www.austroads.com.au). By comparing these data with the area of high water tables within each subcatchment, it is possible make a qualitative assessment of the road assets that are at risk under climate change. For example, in the lower local and regional subcatchments of the Macquarie–Bogan, there are over 300 kilometres of primary road routes. These regions have moderately high stream salinity and areas affected by water tables that are likely to expand. The problem is potentially greater in the Avoca catchment where almost 250 kilometres of primary road routes are in an area with high levels of instream salinity and a significant expansion in the area of high water tables is predicted. Substantial increases in high water tables are likely in the Goulburn–Broken and Murrumbidgee catchments. While groundwater, and hence stream salinity, is generally low in these catchments, the presence of high water tables is likely to be the primary cause of road damage through base failure. Secondary damage to sprayed road seal is more likely to occur where ground water salinities are high. There are likely to be isolated areas throughout the basin where high ground water salinities may affect road pavements. It is, however, generally more expensive to rehabilitate the road base after water damage than to replace deteriorating seal.



Map 6: Roads in the Murray Darling Basin, by route type

Source: AUSLIG

Changes in the intensity and frequency of rainfall events in the Murray Darling Basin are also expected to increase under conditions of enhanced global warming (IPCC 2001). The impacts of changes in extreme weather events were not examined in this report but it is likely that they will lead to increased probability of flooding, leading to damage of transport infrastructure.

4.5 References

Bell, R. and Heaney, A. 2001, *A Basin Scale Model for Assessing Salinity Management Options: Model Documentation*, ABARE technical working paper 2000.1 (www.abareconomics.com), Canberra, August.

IPCC (Intergovernmental Panel on Climate Change) 2001, *Climate Change in 2001: The Scientific Basis*, Houghton, J., Ding, Y., Griggs, D. Noguer, M., van der Linden, P., Dai, X., Maskell, K. and Johnson, C. (eds), Cambridge University Press, Massachusetts.

New South Wales Department of Land and Water Conservation 1995, *Integrated Quality Quantity Model (IQQM) Reference Manual*, Sydney.

5. POLICY IMPLICATIONS

5.1 Uncertainty

Any set of forecasts is subject to uncertainty in varying degrees. This report is no exception. There are considerable uncertainties throughout the whole process described, and these uncertainties are compounded as outputs from one model become inputs to other models and so on. The first level of uncertainty comes about from the choice of emissions scenario. The Intergovernmental Panel on Climate Change has published a wide range of scenarios, but only one could be used as the basis for modelling. The particular scenario chosen is one of the highest with an almost fourfold increase in the rate of emissions between now and 2100. Under the lowest scenarios, emissions in 2100 fall to below the current level. A second level of uncertainties relates to the climate forecasts from the CSIRO model. Further levels of uncertainty are introduced by the modeling processes that take the CSIRO forecasts as inputs to estimate impacts on road pavements and salinity. The population forecasts represent one particular Australian Bureau of Statistics scenario, modified by ‘expert judgement’ to take account of climate change. The traffic forecasts used for the pavement modelling were developed from the population projections introducing a further level of modelling uncertainties.

The numerical results in the report should therefore be regarded as broad indications only, and even the qualitative conclusions should be treated with caution. All things considered, the study should be regarded as telling a story about a possible future, from which can be gleaned some indications of likely directions over the coming 100 years.

5.2 Demand for road use

The main driver of road investment and maintenance needs is population growth and freight generated by new developments and productivity. The associated greater levels of car and truck traffic give rise to needs for investment in road capacity expansion and stronger pavements, and for higher standards of maintenance. ABS Population projections have the south-east Queensland, Cairns and Darwin regions expected to grow most over the next 100 years. There will be increasing concentration of population in the four major metropolises of Brisbane, Sydney, Melbourne and Perth, and a decline for Adelaide and inland areas in general.

When climate change is overlaid on this scenario, population forecasts for Darwin and Melbourne are adjusted significantly upward and those for Adelaide, Perth and Cairns, downward. The largest adjustments for climate change are Darwin with plus 34 per cent, and minus 21 per cent for Adelaide. To put these adjustments into perspective, unadjusted 2100 population forecasts for the eight metropolitan areas as a percent of 2000 levels, range from 63 per cent for Adelaide to 305 per cent for Moreton. After adjusting for climate change, the range becomes 50 per cent for Adelaide to 369 per cent for Darwin. This shows that climate change is by no means the most important factor influencing future population levels.

With the north of Australia expected to become wetter, the northern part of the Northern Territory could become an important agricultural centre. The hotter, drier climate will have an adverse impact on agriculture in general, which is likely to reduce road demand in inland areas. However, use of drought resistant, higher yielding strains of grain could be a mitigating factor.

5.3 Road design and maintenance

Theoretically, rates of pavement deterioration should slow as rainfall decreases, saving on maintenance costs. In the long term, design thicknesses for new pavements could possibly be reduced. However, these effects over the next 100 years are expected to be so small as to have negligible impact on the costs of road provision.

An exception is those areas forecast to become wetter, the far northern parts of Australia. Here, costs of pavement maintenance and construction may increase. Also in these areas, the capacity of existing culverts and waterways may prove inadequate.

The life of bituminous surface treatments is affected by ambient temperature. An increase in temperature will accelerate the rate of deterioration of seal binders and require earlier surface dressings/reseals, which will lead to higher maintenance costs.

Sea level rise could be a concern for low-lying roads in coastal areas, particularly if the rise by 2100 is towards the upper end of the projected range of 9 to 88 cm. The problem may be worse in northern Australia if wind speeds become higher during storm surges. Planners and designers of roads and causeways in low-lying coastal areas can take account of projected rises in sea level over the lives of assets. The impact on existing roads and causeways can be taken into account at the time they require rehabilitation or improvement. Clearances for new bridges over tidal water should take into account the potential rise in sea level over the life of the bridge, usually 100 years.

In the absence of climate change, ABARE modelling forecasts that the area affected by high water tables in the Murray–Darling catchment will rise from 1.1 million hectares to 5.3 million hectares by 2100, almost a fivefold increase. The expected effect of a hotter, drier climate is to reduce the forecast 2100 amount to 4.4 million hectares (almost a fourfold increase compared with the year 2000 amount). Thus, while climate change may mitigate salinity problems, the effect is nowhere near sufficient to reverse the rising trend.

Higher water tables can accelerate the rate of pavement deterioration due to capillary action increasing the moisture content of pavements. Road agencies may need to raise the levels of existing embankments when pavements reach the ends of their useful lives. The design of new roads should provide for anticipated rises in water tables in susceptible areas. This will increase construction costs.

Another manifestation of the salinity problem is increased salt concentrations in rivers. Climate change may exacerbate this problem because, with less rain to dilute surface salt, surface waters flows are predicted to become saltier. Steel reinforcing in concrete structures in riverine environments may therefore be more prone to corrosion. Road agencies might consider ways to better protect reinforcing in saline environments.

5.4 Further research

If further research into the effect of climate change on roads is to take place, the most worthwhile area appears to be the impact on flooding. Bridges, causeways and alignments are the most long-lived features of road infrastructure, and knowledge of future changes in flood heights and frequencies will be valuable information for planners.

INFORMATION RETRIEVAL

Austroads (2004), **Impact of Climate Change on Road Infrastructure**, Sydney, 148pp, AP-R243/04

KEYWORDS:

climate change, road infrastructure provision, environment, salinity, ground-water, temperature, road planning, asset management, road design, bridge design

ABSTRACT

There is an increasing body of evidence that the earth's climate is changing with some of the changes attributable to human activities. Climate change can have direct and indirect impacts on road infrastructure. The direct impacts are due to the effects of the environment. Rainfall changes can alter moisture balances and influence pavement deterioration and temperature can affect the aging of bitumen. Flood heights and frequencies are important considerations for the location and design of roads and bridges. Sea level rise and increased occurrence of storm surges will affect roads in coastal areas. Climate change will have an impact on salinity, which leads to high water tables that in turn reduce the structural strength of pavements. The indirect impacts of climate change on roads are due to the effects on the location of population and human activity altering the demand for roads.

Road infrastructure is a long-lived investment. Roads typically have design lives of 20 to 40 years and bridges of 100 years. An understanding of the expected impacts of future climate change by road planners, designers and asset managers could engender considerable cost savings in the long term. At the broad strategic level, if road providers are forewarned of any costly future effects on existing infrastructure, they can better prepare to deal with them

This report:

- Provides an assessment of likely local effects of climate change for all Australia for the next 100 years, based on the best scientific assessment currently available
- assesses likely impacts on patterns of demography and industry, and hence on the demand for road infrastructure
- identifies likely effects on existing road infrastructure and potential adaptation measures in road construction and maintenance; and
- reports on policy implications arising from the findings of the project.

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