Adapting Australia's water resources to a changing climate

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1 Introduction

Over the course of this century, climate change is expected to alter the hydrological cycle, changing factors such as rainfall, runoff, evaporation, water supply and water demand. This will be imposed on a background of high variability. Australian streamflow variability is amongst the highest in the world, and we have adapted to this in many ways. Per capita storage is the highest of any country, large irrigation systems provide about half our agricultural wealth and, until recently, urban populations could rely on largely unrestricted water supplies.

Historically, hydrological science has aimed to quantify the mean and variability of climatic and hydrological phenomena from climate observations. The major assumption has been that climate is stationary. This assumption has two aspects: 1) the statistical relationships between major climatic variables such as temperature and rainfall remain constant, and 2) the relationship between mean rainfall and aspects of its variability also remain constant. The magnitude and frequency of extreme events are then estimated using statistical methods. Most water infrastructure is designed and operated on this principle. However, because the relatively short instrumental record does not represent the full range of extremes that could occur, water is managed and allocated using fairly conservative rules (Long and McMahon 1996).

Water supply and distribution systems were developed to provide security of supply for irrigation, industry and urban centres. Because much of this activity occurred during the latter half of the 20th century, a period of generally favourable rainfall, Australian water supply systems have been very successful in fulfilling their aims, leading many water managers and users to believe that their systems are largely “climate proof” except during the most severe floods and droughts.

Since the 1980s it has been suggested that climate change could have significant impacts on water supply. However, low confidence in model projections of rainfall and impact assessments showing the possibility of increasing or decreasing supply has led to climate change having a low priority in the list of water managers’ concerns.

Three lines of evidence have acted to change this:

1. Regional climate projections and hydrological assessments based on those projections showing the full range of potential runoff changes have been dominated by decreases in water availability, particularly in southern Australia.
2. Evidence of past climate indicates that climate is influenced by a number of quasi-cyclic phenomena ranging from the El Niño–Southern Oscillation (ENSO) phenomena with a periodicity of 3–7 years, to multi-decadal cycles affecting rainfall, storm tracks and storm frequency, and centennial and millennial processes. The dynamics of most of these longer-term phenomena are poorly understood but regime changes can produce substantial hydrological responses.
3. Recent sustained reductions in rainfall in southwestern (mid 1970s) and southeastern Australia (mid 1990s) and a severe drought in 2002–3, have led to extended water restrictions in urban centres and reduced water allocations for irrigation.

These changes have increased the awareness of potential climate change risks on water resources. It is no longer assumed that climate will remain stationary, or that ongoing water reform will adequately manage the potential risks arising from climate. However, each system and activity will have a different exposure to climate hazards now and in the future. Adaptation to climate change will need to become a normal part of the sustainable management of water resources but at present both the information and methods to apply that information are uncertain and require development.

This guide summarises the latest information about climate change and how it may affect water resources, and has two aims: 1. To inform water managers and users on the latest information about climate change and water resources in Australia, and 2. To provide this information in such a way to allow managers and planners to begin adapting to climate change.

1.1 The global context

Concerns about climate change and water resources have arisen against a backdrop of rapid and unsustainable changes in freshwater demand and supply. Humans have appropriated almost half the volume of accessible global runoff through dam construction, water diversion, exploitation of groundwater aquifers, stream channelisation and inter-catchment water transfers (Rosenberg *et al.* 2000). These actions have altered continental water balances, affected aquatic environments, changed river and coastal zone biogeochemistry and contributed to sea level rise (Vorosmarty and Sahagian 2000). During the 20th century, global population tripled, but human water use multiplied six times, leaving millions of people without adequate water supply and basic sanitation (Cosgrove and Rijsberman 2000).

Various international initiatives have responded to the challenges facing global water supply and management, including the International Conference on Water and Sustainable Development (1998), the International Conference on Freshwater (2001), the World Water Forums (1997, 2000, 2003) and the UN Millennium Declaration (2000). The UN World Water Assessment Programme produced the first UN Water Development Report describing the state of the world's water resources (World Water Assessment Programme 2003).

Scenarios have been developed to explore changes in future demand and how they may be managed. Rosegrant and Cai (2002) found that under a business as usual scenario (BAU), total global water withdrawals increased by 22% over 1995 levels, and consumption for all non-irrigation uses rose 62% in the period 1995–2025. Their 'water crisis' scenario assumed a moderate worsening of current trends in water and food policy and in investment, and under this set of assumptions water consumption was 35% higher than BAU. For the 'sustainable water' future, where water consumption is 20% less than BAU by 2025, agricultural water prices would need to triple in developed countries and double in developing countries. The World Commission for Water's *Vision for a Water Secure World* (Cosgrove and Rijsberman 2000) produced a normative 'vision' scenario for water policy and management by 2025. The key elements required to achieve this vision of sustainability are awareness of the crisis; stakeholder representation in integrated water management; full cost pricing of water services; more public funding for research and innovation; and increased international cooperation. It is therefore essential to take an expanded view of climate change and water resources that explicitly recognises the dimensions and implications of water policy and human choice.

Australian activities contributing to these global efforts include making the Murrumbidgee catchment a focus catchment of UNESCO's Hydrology for the Environment, Life and Policy (HELP) Initiative; and participation in the Dialogue on Water and Climate with the aim of uniting the science and management of water. Nationally, the Wentworth Group addressed the sustainable management of water resources, but the issue of climate change remains to be incorporated into this agenda. While Australia is well-advanced in some areas of water reform and sustainable water management, there are some significant risks that need to be addressed.

1.2 Climate change and water

Climate change will increase temperatures in most regions but impacts on precipitation are much less certain and more regionally specific. A warmer world is expected to have a more intense hydrological cycle, with increased global mean precipitation, precipitation intensity and evaporation. Models suggest increasing river discharge in Arctic regions, and increased freshwater delivery to the northern hemisphere in particular, with subsequent impacts on salinity and ocean circulation (Stocker 2005; Wu *et al.* 2005). Various studies support the hypothesis of more extreme events with global warming (e.g. Hennessy *et al.* 1997; Palmer and Ralsanen 2002), thereby increasing flood risk in many places. Increased water vapour in the atmosphere can produce more intense precipitation events even when total precipitation remains constant (Karl and Trenberth 2003). However, changes to the intensity, frequency and duration of precipitation events are not often analysed in observations or models (Trenberth *et al.* 2003) and precipitation processes occur on scales not adequately resolved by models and have large essentially random components (Trenberth 1998). Changes in rainfall distributions or seasonality could have far greater impact than changes in average amounts (Allen and Ingram 2002).

Other possible impacts of climate change on water resources include water quality decline; changes in peak streamflow timing; glacier retreat; and changes in irrigation demand (Arnell and Lui 2001). Irrigation is the sector that is most likely to suffer negative effects. Globally there are now an estimated 250 million hectares under irrigation, which is nearly five times the amount at the beginning of the 20th century (Rosegrant *et al.* 2002). Increased temperature and changes in potential evapotranspiration may lead to shifts in optimal growing periods, regional suitability or per hectare irrigation requirements (Doll 2002). Naturally occurring droughts are likely to be exacerbated by enhanced potential evapotranspiration (Trenberth 1998; Dai *et al.* 2004). Clearly there is the potential for significant social, economic and environmental impacts on water supply and demand as a consequence of climate change.

2 Australian water resources

2.1 Snapshot of the resource

In Australia approximately 12% of rainfall (380,000 GL) ends up as runoff, and potential annual groundwater supplies are in the order of 15,000 GL (Dunlop *et al.* 2001b). Australia has one of the highest per capita consumption rates in the world (1.31 ML/person/year) (NLWRA unpublished). During 2000–01, 72,431 GL of water was extracted from the environment and used within the Australian economy (ABS 2004). Agriculture consumed the largest volume of water with 16,660 GL, representing 67% of water consumption (ABS 2004). Of other uses, the electricity and gas supply industry consumed 7%, manufacturing 4%, mining 2%, other industries 3% and the household sector 9% (ABS 2004). The use of reuse water has increased dramatically from 134,424 ML in 1996–97 to 516,563 ML in 2000–01 but is still only 2% of the total amount consumed (ABS 2004). Irrigated agriculture is the largest overall user of water and accounts for approximately 29% of the total gross value of production from agriculture (NLWRA unpublished). Between 1985 and 1996/97, irrigation usage increased by 76% (NLWRA unpublished).

Over thousands of years, Australia's environment has evolved to cope with climate variability to the point where much of the flora and fauna has become dependent on it. On the other hand, agricultural, domestic and industrial uses require a constant water supply so that activity and income can be maintained on a regular basis. This has created a conflict between environmental and human uses in water management, where one requires an environmentally-driven and variable supply and the other requires supplies when demands are greatest – at the opposite time of the year when water would be naturally available. This success in the ability to harness water for humanly productive purposes has come at some cost. Australian hydrological regimes have changed dramatically in the past 200 years. Between 1857 and 2003 Australians constructed thousands of weirs and locks (3,600 in the Murray Darling Basin alone), thousands of kilometres of levee banks, 446 large dams and over 50 inter- and intra-basin water transfer schemes (Arthington and Pusey 2003). The National Water Resources Assessment (2001) found that 26% of surface water management areas and 30% of groundwater management units are either fully or over-allocated. The ecological effects of over-allocated water resources are significant and include loss of wetlands, decline of riparian forests, altered aquatic plant community structure, biodiversity decline, blooms of toxic cyanobacteria, and exotic plants and animal invasions (Arthington and Pusey 2003).

Although recent water reforms have led to increases in the cost of water, some commentators maintain that the full cost (environment and infrastructure) is not being paid. Urban users pay 10 times the amount and use 10% of the volume used by agriculture, a price estimated to be about half that needed to cover the resource rent to pay for environmental externalities (Dunlop and Foran 2001). Dunlop *et al.* (2001a) identify the main drivers of change in Australian water use as domestic and export market-driven growth in commodity production, social attitudes towards water use and reuse and the environment, government policy, and global climate change.

2.2 Institutional background

Over the last decade the institutional foundations of water resource management in Australia have undergone major changes. In 1994 the Council of Australian Governments (COAG) introduced a strategic framework for national water reform. The central elements of this ongoing reform include adoption of consumption based pricing and water trading; separation of water property rights from land title; and recognition of the environment as a legitimate user of water.

The reforms are overseen by the National Competition Council (NCC), with the initial target completion date of 2001 now extended to 2005. In August 2003 COAG announced the National Water Initiative (NWI) to stimulate further progress in the national water policy agenda. Its goals include the expansion of permanent trade; quickly addressing over-allocated systems; recovery of water to achieve environmental outcomes; more secure water access entitlements; better monitoring and accounting of water use; more transparent and effective water planning and management; and improved public access to water information. Key elements are outlined in Box 2.1. Implementation of the NWI will be overseen by the Natural Resource Management Ministerial Council.

The National Water Initiative also specifies the use of a risk management framework, with provision for different risk structures to be implemented if key stakeholders agree. Under the suggested framework, reductions from climate change, droughts or bushfires are to be borne by water users. Reductions from improvements in knowledge about the water system's capacity to sustain particular extraction levels are to be borne by water users up to 2014. After 2014, water users bear the risk for the first 3% reduction in allocations, and the States and Commonwealth share the risk above 3%. Reductions arising from changes in government policy not previously provided for would be borne by governments. Crase *et al.* (2004) suggest two potential problems with this approach to risk: the challenge of defining the dichotomy between the two genres of risk, and the possibility that public intervention to ensure the environmental health of rivers may become less steadfast.

Water policy is rapidly evolving at both Commonwealth and State level. National level initiatives are summarised in Annex 1.

Key elements of the National Water Initiative

- Water access entitlements to grant perpetual access to a share of the resource;
- Improved specification of environmental outcomes, and statutory provision for water that is provided to ensure these outcomes;
- Substantial progress in returning over-allocated systems to sustainable levels to be made by 2010;
- More efficient administrative arrangements to facilitate trade, and removal of institutional barriers;
- Regional assessment of the level of water intercepted by land use change activates and potential regulation of these activities;
- Full cost recovery pricing for water in both urban and rural sectors;
- Demand management in urban areas;
- National standards for water accounting, reporting and metering;
- Establishment of a National Water Commission (NWC) to assess progress in implementing the NWI.

Box 2.1 Key elements of the National Water Initiative.

3 Climate and water

The main task in relating climate change to water management is to link the different aspects of climate to planning horizons that range from short-term tactical through to long-term strategic. Decision-making, ideally made within a risk management framework or regular review process, assesses whether and how these aspects are to be managed and they are then implemented, monitored and reviewed to determine whether they are producing desirable outcomes. Table 3.1 summarises many of these links. This chapter summarises what is known about each of these aspects of climate and how they may affect the hydrological cycle.

Decision Type	Time Horizon	Climate Aspects	Concern	Who
Day to day management (Tactical)	Intraseasonal	Seasonal availability of water, short-term rainfall events, short-term evaporation rates	Delivery of orders and allocations, flow regulation, flood control, maintenance of water quality, irrigation, drainage	Water operators and users at enterprise level (e.g. farmers, engineers)
Seasonal management (Tactical)	Seasonal	Interannual rainfall variability, seasonal moisture balance	Allocations, seasonal planning, cropping and stock returns, drought control	Water authority, farmers, regulatory bodies
Mid-term planning (Strategic)	Multiseasonal (2–15 years)	Frequency of dry & wet years, decadal variability	Policy (e.g. NAPs for dryland and irrigation salinity), economic reform, whole farm planning, catchment strategies, Landcare	Catchment managers, legislators, public service, individual farmers, enterprise bodies (e.g. NFF, RDCs), NGOs
Long-term planning (Strategic)	Decades	Decadal variability, climate change	Infrastructure planning, sustainability	Planning bodies, whole of government approach, visionaries

Table 3.1 Management and planning undertakings in the water sector as they relate to climate over different time horizons.

3.1 Patterns of climate variability

3.1.1 Short-term variability

Short-term climate variability includes rainfall intensity, extreme temperatures, high levels of evaporation and storm events. Rainfall intensity is expected to increase in most areas due to increased moisture capacity of the atmosphere. These increases will not be spatially uniform but dynamic modelling indicates that the increases will favour areas where convective activity is currently most intense (e.g. where convection is influenced by topography). Days of light rainfall and the number of raindays will decrease in many cases – this will tend to increase the length of dry-day sequences. High-temperature events, especially those extending over several days, place a high demand on water in both irrigation systems and also increase external use of domestic water. Delivery of supply then becomes an issue, particularly when it is needed to avoid crop damage.

Storm events effect stormwater and sewer management and can also cause localised flooding. Based on limited dynamic modelling, it appears that if mean rainfall decreases, only the rarer, more extreme events may increase (e.g. those >5 to 10-year return period) but those increases may be dramatic. Localised flooding is also affected by catchment modification, so will increase with urbanisation and will need to be managed. Such changes are also closely linked to water quality. Northern Australia may experience increases in tropical cyclone and storm intensities (Henderson-Sellers *et al.* 1998; Walsh *et al.* 2004).

3.1.2 Seasonal and annual variability

Australian annual rainfall variability is dominated by ENSO, which is largely generated from ocean-atmosphere interactions in the Pacific. Regional rainfall is also influenced by conditions in the Indian and Southern Oceans. ENSO is linked to dry conditions over much of Australia and the link between rainfall, streamflow and ENSO is statistically significant (Chiew *et al.* 1998). The northern Australian monsoon is influenced by events in the Indonesian archipelago and the South China Sea. How these phenomena may change under climate change remains unclear. Although coupled ocean-atmosphere models reproduce many of the phenomena associated with interannual variability, long-term changes have low predictability. The Pacific Ocean will become more ENSO-like and ENSO continues to oscillate in the higher-resolution models indicating that interannual climate variability is likely to remain high.

When mean rainfall decreases analyses show that prolonged and more intense periods of drought are likely under enhanced greenhouse conditions (Kothavala 1999). Nicholls (2004) examined the 2002 drought in its historical context and concluded that higher temperatures and increased evaporation contributed to its severity.

Two lines of research are involved in developing tools to manage seasonal and interannual variability. Although these tools have been used fairly widely in dryland agriculture, they have less often been used for managing water resources on a seasonal basis. The first is work in seasonal climate forecasting based on both statistical and dynamic methods. Statistical methods assess relationships between spatial and temporal data, taking advantage of teleconnections between the ocean and the atmosphere to assess changing patterns of variability. The challenge for statistical methods is to incorporate non-stationarity as the climate changes and old relationships may no longer hold. Dynamic methods involve running climate models to the present time with observed data, then allowing them to run forward with the memory of ongoing processes in the ocean and atmosphere. Hybrid methods involve the combination of dynamic and statistical methods. One key linkage particularly relevant to water resource management is that between ENSO-related indices and streamflow rather than between ENSO and rainfall. This integrates a great deal of potential uncertainty between rainfall and streamflow for a relationship that has about the same level of predictability (Khan *et al.* 2004).

The second line of research is through an understanding of the relationship between interannual variability and decadal climate regimes, and how the likelihood of a given outcome changes as a property of a specific decadal regime (see below).

3.1.3 Decadal variability

There is a long but sporadic history of research on the influence of decadal variability on Australia's climate, but it is only now being taken seriously in terms of its impact on water resources. This was in part due to inappropriate statistical tools (e.g. those used for the linear analysis of stationary time series) being used to assess non-linear behaviour. Phenomena that are influenced by decadal variability include mean rainfall, rainfall intensity, ENSO variability, cyclone frequency and the latitudinal position of weather patterns.

Two key aspects of rainfall variability are influenced on decadal time scales: the modulation of ENSO affecting interannual variability and phases of decadal mean rainfall. The Inter-Decadal Pacific Oscillation (IPO) modulates ENSO variability producing La Niña and El Niño-dominated phases (Allan *et al.* 1996; Power *et al.* 1999). ENSO events have a stronger impact during negative phases of the

IPO (Power *et al.* 1999; Kiem and Franks 2004). Kiem and Franks (2004) found that IPO negative phases show a statistically significant increase in La Niňa events, a finding that has implications for water planning.

The other form of decadal variability sees alternating wet, dry and normal periods lasting for a number of decades, which then change rapidly into another phase. A history of such phases labelled drought-dominated and flood-dominated regimes was constructed for NSW from the early 19th century by Warner (1987). Vivès and Jones (2003) investigated this phenomenon for all Australian rainfall stations with more than 60 years of record in the period 1890–1989 using the bivariate test to determine if, and when, a statistically significant step change occurred for each station. Step changes were clustered around the mid 1890s, the late 1940s, and the late 1960s and early 1970s. Each of these events is associated with historical events where large changes in rainfall were noted.

The 1890s change occurred in eastern Australia and was associated with the collapse of the grazing industry in western NSW, the retreat of wheat growing from central SA and large changes in flow patterns in the Darling River. This change is contemporaneous with reductions in river flows in north Africa and China (Whetton *et al.* 1990). The late 1940s signalled an increase in rainfall across this region, and a possible decrease in south-west WA, although the records are scant. The change in the late 1960s was associated with a decrease in southwestern WA followed by an increase in eastern Australia in the mid 1970s. The timing of these changes show some relationship with reconstructed La Niña and El Niño-dominated phases, with dates of 1946/48 and 1976 being prominent, but they do not coincide exactly.

These changes are part of an emerging pattern of decadal variability being reconstructed for different parts of the world where step changes in mean rainfall creates oscillating cycles of dry, wet and “normal” periods on a multi-decadal time scale. Larger departures in these sequences are possible, creating megadroughts, such as the one in southwestern USA several centuries ago (Gray *et al.* 2003).

Model-based studies are now analysing model output, searching for these characteristics. The recent generation of coupled climate models do show considerable decadal rainfall variability. A better understanding of both decadal forms of rainfall variability would allow one to know what regime the rainfall of a place may be in, the pattern of risks associated with that regime and when a regime change has occurred. Two examples are relevant: 1) the step change in SW WA took some time to recognise but did alter the pattern of risks facing water supply and 2) it is not clear whether the change in SE Australia since the 1990s is a similar type of change, whether the change is permanent, is likely to be sustained for some decades, or whether rainfall will shortly return to previously higher values. Clearly, different forms of decadal rainfall variability will need to be managed in the future.

Case study: Water storage in the Williams river catchment, NSW

Kiem and Franks (2004) used a stochastic modelling approach based on Monte Carlo sampling to analyse the performance of the Grahamstown reservoir in the Williams river catchment of NSW during 3 climate epochs. Williams river streamflow is highly correlated with ENSO and is also highly variable on multidecadal timescales. Three different management scenarios were considered: 1) increasing the storage level at which the various restriction stages are introduced if an El Niňo event is forecast or being experienced; 2) increasing the amount of water pumped into the reservoir, if an El Niño event is forecast or being experienced, by relaxing water quality constraints; or 3) increasing the amount of water pumped into the reservoir by increasing the maximum pumping capacity of the pumping station.

A critical threshold was crossed when reservoir capacity dropped below 30%. The results showed that the risk of exceeding this threshold was almost 20 times higher when the Inter-decadal Pacific Oscillation was positive than when it was negative, and adaptive reservoir management techniques had the greatest impact on improving drought security when drought risk was highest.

Case study: SW Western Australia

Variability is an inherent element of Australia's climate. In southwestern Western Australia, early winter rainfall decreased by 15–20% in the mid 1970s. A concerted research effort has found that this regime shift is associated with large scale global atmospheric circulation changes, and is likely to be caused by a combination of climate change and natural climatic variability (IOCI 2002).

Such an abrupt change in rainfall and streamflows led to adaptive responses by regional water decision-makers, outlined in IOCI (2002) and Sadler (2003). In the mid 1980s, water resource managers became concerned with decreased inflows to Perth's reservoirs. In 1987 the WA Water Authority decided to make incremental adjustments based on the prevailing CSIRO rainfall scenarios that predicted a 20% decrease in rainfall and a resultant 40% decline in streamflows by 2040. With no sign of a return to "normal" rainfall levels, adjustments were made to the timing of new water sources in the early 1990s. The 1995 strategic plan *Perth's Water Future* was based on streamflow averages weighted towards the recent past, but still regarded the experience as an extreme run. In 1996, a regional climate variability and water resources workshop brought relevant stakeholders together and discussed the possibility of non-linear jumps in decadal climate variability. This led to a changed decision paradigm, with adjustments in the design basis for surface water sources, initiatives to reduce demand, and an accelerated development of new water sources at a cost of $500 million. The Indian Ocean Climate Initiative (IOCI), a collaborative research programme, was launched in 1998.

One of the primary roles of IOCI, supporting informed adaptation, is complicated by the fact that the information needs of sectoral decision-makers, and their critical thresholds, vary widely (Sadler 2003). IOCI (2002) accepts that no single approach to adaptation will cover all circumstances, due to different risk structures and decision time-frames within different industry sectors. However, their experience is that leadership in good adaptive planning by institutions with the resources and sophistication to make informed and considered responses is potentially catalytic in effect, with water management decisions impacting on other sectors such as urban planning and environmental management (Sadler 2003).

3.2 Mean climate change

CSIRO has periodically produced projections of mean climate change for temperature and rainfall for Australia over the past 15 years. The latest projections present a range of potential changes in temperature, rainfall and potential evaporation. These encompass uncertainties associated with different emissions scenarios and climate model sensitivities, and differences between models in forecasting regional mean climate change (CSIRO 2001).

3.2.1 Temperature

Australia warmed by 0.7°C from 1910–1999, with most of this occurring after 1950. By 2030, temperatures are expected to be 0.4 to 2.0°C higher over most of Australia, with slightly less warming in some coastal areas and Tasmania and the potential for greater warming in the Northwest. By 2070 this range is 1.0 to 6.0°C. There is a progressive increase in the number of extreme summer days over 35°C and a decrease in the number of winter days below 0°C.

3.2.2 Rainfall

Average annual rainfall tends towards decrease in the Southwest and in parts of the Southeast and Queensland. Other areas, such as much of eastern Australia and the tropical north, show little change on an annual basis. Some inland and eastern coastal areas could experience an increase in summer rainfall, and some inland areas become wetter in Autumn. For the far Southeast and Tasmania, projected rainfall decreases in both seasons. Most locations show a trend towards reduced rainfall or are seasonally dry in winter and spring, with the greatest seasonal reduction in the Southwest. Tasmania tends towards winter increases (Figures 3.1, 3.2).

Decreases in winter and spring in southern Australia, and increases over Tasmania, are consistent with a strengthening of the westerly frontal system and its movement southward. One of the key research questions concerning the current run of dry years in south-western and south-eastern Australia is whether this process has already commenced. Drying in western Victoria in the mid 19th century (Jones *et al.* 2001) and long-term warming of ocean temperatures south of Tasmania, attributed to an extension of East Australia Current (Thresher *et al.* 2004), suggests this may be a climatic trend that is pre-greenhouse, but one which is projected to continue under greenhouse.

The Northern Australian wet season (Nov–Apr) is strongly influenced by the summer monsoon. The behaviour of the monsoon and the frequency of cyclones are affected by ENSO. How ENSO may respond to climate change is still unclear, and therefore the direction and timing of the northern Australian Monsoon remains uncertain.

Box 3.1 presents a summary of expected impacts on rainfall by 2030. More specific impacts by State are provided in Annex 2.

Probable climate change impacts on Australian rainfall by 2030

- up to 15% less rainfall year round in the Southeast and in spring in Queensland
- up to 20% less rainfall year round in the Southwest
- More years with serious rainfall deficiencies
- Up to 15% more summer rainfall on the east coast
- Up to 15 % more autumn rainfall inland
- Heavier daily rainfall where average rainfall increases, or decreases slightly, leading to more flooding
- A tendency for decreases in winter-spring (June-Nov) rainfall over the southern half of the continent and increased summer-autumn rainfall (Dec-May) in the north

Box 3.1 Summary of Climate change implications for Australian rainfall by 2030 (Hennessy 2003).

Rainfall Summer -2070

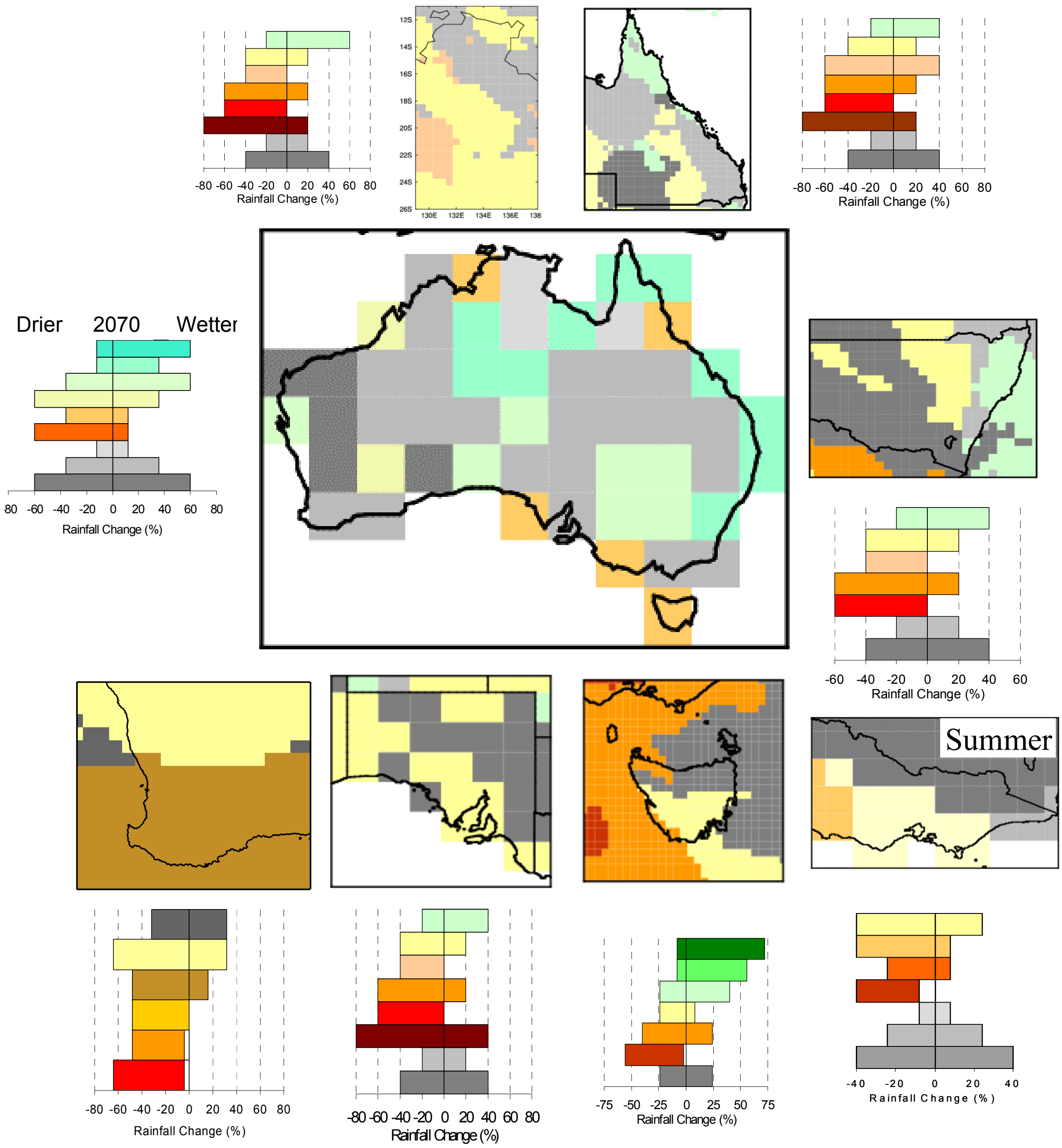


Figure 3.1 Expected summer precipitation ranges (%) in 2070 compared to 1990 (McInnes in press).

Rainfall Winter -2070

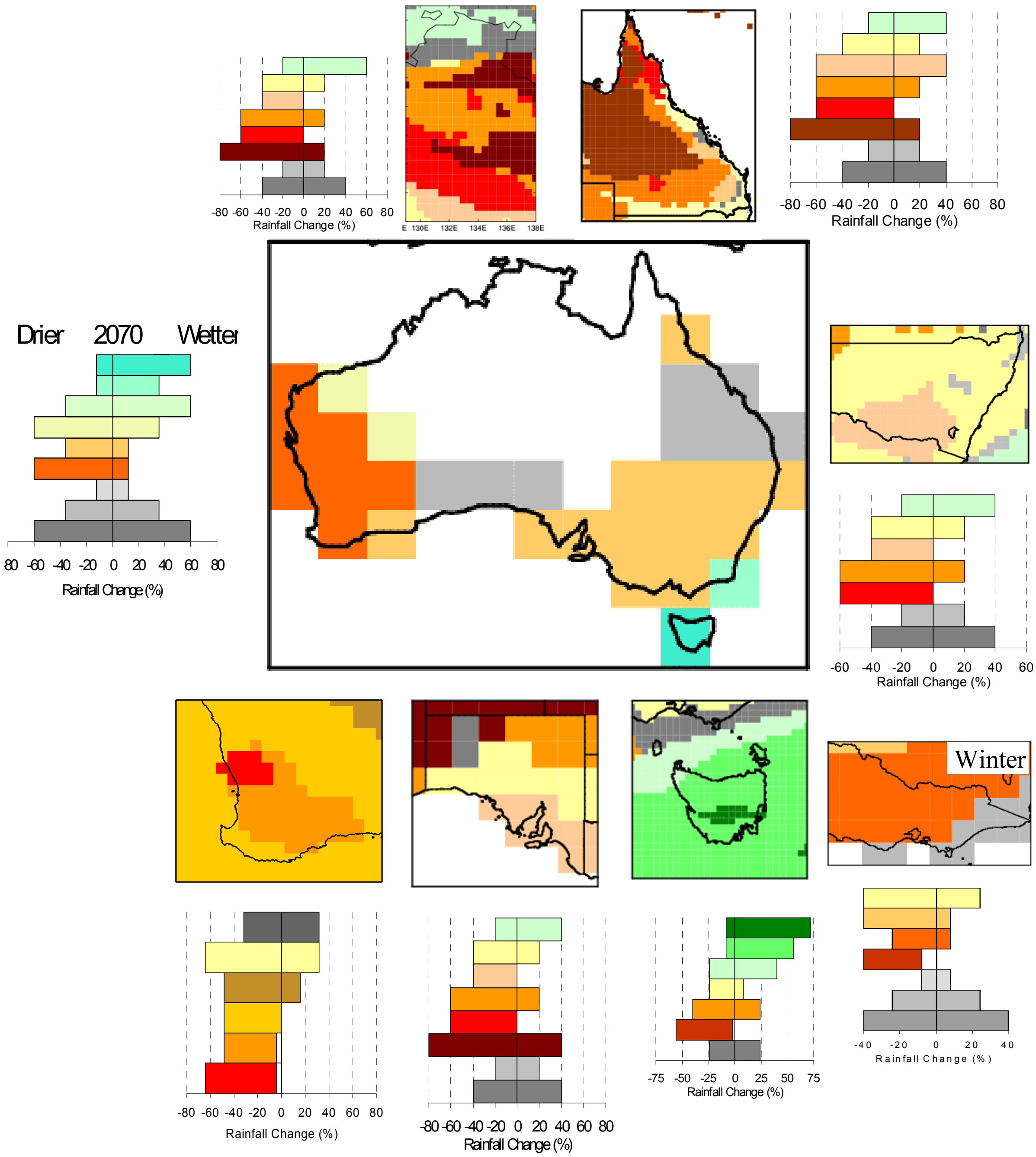


Figure 3.2 Expected winter precipitation ranges (%) in 2070 compared to 1990 (McInnes in press).

3.2.3 Potential Evaporation

There have been a number of observations of decreasing pan evaporation (E_{pa}) in areas of the northern hemisphere over the last 50 years (Peterson *et al.* 1995; Chattopadhyay and Hulme 1997; Thomas 2000), and this has been largely attributed to decreases in solar irradiance and changes in the diurnal temperature range and vapour pressure deficit (Roderick and Farquhar 2002). Roderick and Farquhar (2004) analyse pan evaporation data from Australia and conclude that the terrestrial surface has become less arid over the past 30 years as potential evaporation (E_0) has decreased.

CSIRO model projections (CSIRO 2001) show point potential evaporation increases in all seasons, with an average range of 0 to 8% per degree of global warming. Decreases in the annual atmospheric moisture balance (rainfall minus potential evaporation) range from 15 to 160mm by 2030 and 40 to 500mm by 2070. Increases in areal potential evaporation are about ⅔ of that. Changes in actual evaporation are dependent on the interaction between rainfall and potential evaporation and will tend towards increase if rainfall increases and decrease if rainfall decreases. During wetter periods of the year when soil moisture is high, actual evaporation will increase.

Observations of decreasing pan evaporation are not necessarily at odds with expectations of increasing potential evaporation due to climate change. Evaporation from a pan is and indicator of evaporation from the surrounding environment, E, only when water is not limited: $E = E_0 = aE_{pa}$ (where a is a pan coefficient). When moisture is limiting, E and E_{pa} show complementary rather than proportional behaviour (Brutsaert and Parlange 1998). Golubev *et al.* (2001) provide an update on an earlier paper where they concluded that evaporation was losing its strength (Peterson *et al.* 1995) and report an increasing trend in actual evaporation over the contiguous US and former USSR. Results by Dai *et al.* (2004) indicate that the proportion of the globe experiencing dry conditions rose from approximately 12 to 30% since the 1970s. A primary cause for this widespread drying is surface area temperature increases over land, which increases the water holding capacity of the air and thus the demand for moisture. This is consistent with expectations of increased evaporation under greenhouse warming.

3.2.4 Runoff

Simple methods for estimating the range of potential runoff changes for catchments are useful for translating changes in climatic variables such as rainfall and potential evaporation into quantities that are more useful for water managers. These estimates, while not particularly accurate, are valuable at the project scoping stage, when preliminary estimates of change can help determine what may be needed in a more detailed assessment

Jones and Page (2001) found that a simple relationship could be used to estimate mean changes in runoff from a rainfall-runoff model across a wide range of climate changes. They applied 56 climate scenarios to a rainfall-runoff model for the Macquarie River in NSW, producing changes in mean annual streamflow, environmental flows and bulk irrigation allocations. A simple linear regression relationship relating climate change inputs to these outputs was produced: one linear and one non-linear. The results showed that annual mean changes in Precipitation (P) and potential evapotranspiration (Ep) could be related to changes in mean annual flow with surprising accuracy (with a standard error of ~2% for a given climate input).

The linear regression took the form:

$$\partial F = \partial P \times A + \partial Ep \times B$$

where ∂F is change in mean annual flow in percent, ∂P is change in mean annual rainfall in percent, ∂Ep is change in mean annual potential evaporation in percent and A and B are constants. Factor A is a measure of catchment sensitivity to rainfall changes, and factor B is a measure of catchment sensitivity to changes in potential evaporation.

Further work has investigated whether this relationship can be used across a wide range of catchments. Jones *et al*. (submitted) and Chiew *et al*. (2005) measured the sensitivity of three hydrological models for 22 catchments over Australia ranging from cool temperate to tropical and moist to arid. These catchments are unimpaired so represent a fairly natural hydrological cycle. The results showed that the hydrological models produced different sensitivities for A and B factors across the range of catchments and were highly correlated in their responses for several catchment characteristics. The most significant relationship between the A and B factors was percent change in annual average catchment runoff. Sensitivity, shown by the magnitude of both A and B, decreased with increasing runoff. The results suggested that a simple relationship can be used to give an approximate estimate of changes in runoff.

This relationship model takes the form:

$$\delta Q = C \times Q/P \times \delta P + D \times Q/P \times Ep$$

where Q/P is measured in percent runoff as proportion of rainfall and C and D are constants.

Figure 3.3 shows the range of changes for the major catchments of the Murray Darling Basin (MDB).

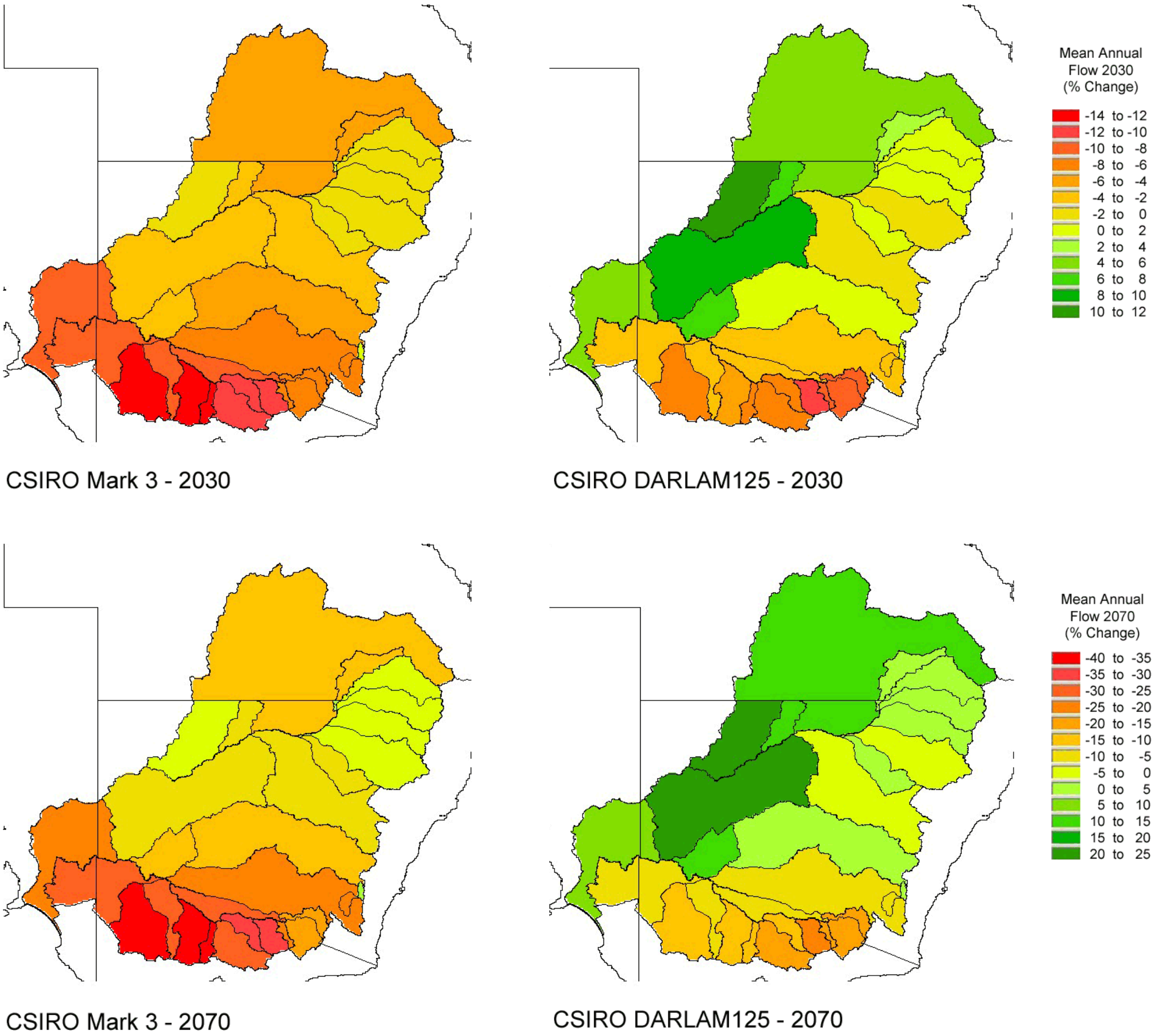


Figure 3.3 Changes in mean annual flow for 2030 and 2070 for the Murray Darling Basin.

3.3 Preparing climate scenarios for impact assessment

Most numerical estimates of climate change are restricted to representing changes in climate averages. However, this does not imply that climate change only affects climate means or that change will be gradual, as represented by climate model output. Future climates will be the product of prevailing climate variability interacting with the enhanced greenhouse effect and scenarios need to take a whole-of-climate approach.

Climate scenarios need to represent the climatic variables and range of variability that adequately describes the activity being assessed. For example, if flood risk is to be investigated, daily rainfall data from climate models should not be used directly but should be downscaled to represent site data through dynamic or statistical methods, or alternatively, existing daily data can be scaled up to represent changes mirroring those observed in climate model studies. The continuity of existing statistical relationships between different variables (e.g. rainfall, humidity, temperature and potential evaporation) should not be assumed to be represented by physically consistent changes derived from climate models. Depending on the needs of an assessment the representation of daily change, decadal variability, or ENSO relationships may require data on scales ranging from a single estimate of mean change to time series on a sub-daily time scale.

Most studies utilise scenarios developed from several different data sources to adequately represent the input variables at the scale required. Scenarios should be capable of investigating the questions at hand, represent the major uncertainties affecting the outcomes and contain clearly stated underlying assumptions. Both uncertainties and likelihoods should be communicated effectively with the results. On the other hand, scenarios should not be more complex than they need to be.

Although assessments may investigate events far into the future, if adaptations are warranted, those adaptations are likely to be implemented in the short- to medium- term. Many adaptations to climate change will combine the management of current climate risks within a strategic framework aiming towards sustainable natural resource management (i.e. a strategy that acts now but takes a long-term view). For that reason, if it is possible to adapt current management and decision-support tools to assess adaptations to climate change, water managers would prefer to do so, rather than to build a new system just for climate change. This will influence scenario development, because they need to be compatible with the tools at hand. However, some new tools will also need to be developed. One key capacity is the ability to simulate changes in both water supply and demand under changing climates, a capacity that is currently only available in a limited number of systems.

3.4 Water resource impact assessments

Most water resource assessments carried out during the 1990s were based on CSIRO (1996) regional climate scenarios. These scenarios were constructed using output from simple ocean global climate models (GCMs) and the more advanced coupled atmosphere-ocean GCMs which produced scenarios showing both substantial increases and decreases in rainfall. For example, Chiew *et al.* (1995) simulated large increases and decreases in runoff and streamflow over most of Australia, with increases dominating in northern Australia and Tasmania. They found that although changes in 2030 and 2070 were uncertain, those changes could be large enough to warrant a significant planning response.

Schreider *et al*. (1996; Schreider *et al.* 1997) investigated changes in the Goulburn, Ovens, Mitta Mitta and Kiewa catchments using “most wet” (+1.5°C, +20% summer, +10% winter) and “most dry” (+2°C, 0% summer, -10% winter) scenarios for 2030 from CSIRO (1992). These scenarios produced neutral to negative changes in streamflow of much greater variability in the snow-free catchments, and slightly positive to negative changes in the snow-affected catchments. Despite using similar climate scenarios to Chiew *et al*. (1995), these results produced much less runoff.

A number of single model studies have simulated reduced runoff and streamflow and examined their impacts on irrigation supply. Wang *et al*. (1999) investigated the Campaspe River water supply using a scenario from the CSIRO regional climate model, in which rainfall decreases in the first half of the year and increases in the second half for a net annual decrease. Irrigation allocations are based on a water right with up to a further 120% of sales water in years when supply is available. The security of the basic water right was reduced by 1% in 2030 (0.8°C global warming), 4% in 2070 (1.8°C global warming) and 16% at $2{\times}CO_2$ (4.1°C global warming). However, irrigation security was maintained at the expense of downstream environmental flows. Utilising the same climate model, a study of the Macquarie River basin in NSW estimated reduced inflows into the Burrendong Dam of 10–30% by 2030 with reduced irrigation allocations and environmental flows (Hassall and Associates 1998). Based on these changes, possible economic losses of up to several hundred million dollars were estimated (Hassall and Associates 1998).

Using the U.S. National Center for Atmospheric Research GCM, Kothavala (1999) found that changes in the Palmer Drought Index produced longer and more severe drought in northeastern and southeastern Australia. Based on output from the U.K. HadCM2 and HadCM3 models, Arnell (2001) found marked decreases in runoff over most of mainland Australia but some increases over Tasmania. For the Murray-Darling Basin (MDB), decreases in mean flow ranged from about 12 to 35% by the 2050s, decreasing the magnitude of 10-year maximum and minimum monthly runoff.

The CSIRO (2001) scenarios of rainfall and potential evaporation were used to develop a risk assessment approach for the Macquarie catchment in New South Wales (Jones and Page 2001; Jones and Pittock 2002). Jones and Page (2001) performed repeated random sampling of the IPCC (2001) ranges of projected global warming, and of seasonal ranges of change in rainfall and potential evaporation from nine climate models. They calculated changes in inflow into the Burrendong Dam, in irrigation allocations under the present management rules, and in environmental flows into the Macquarie Marshes. While the full range of possible changes in flow in 2030 was +10% to -30%, the most likely range (covering 90% of all possible outcomes) was approximately 0% to -15%. In 2070, the full range was about -20% to +60% but the most likely range was +5% to -35% (all figures rounded to the closest 5%).

The impact of climate change on salinity problems affecting agriculture has been investigated in two studies. In a further development of the Macquarie study, Herron *et al*. (2002) examined the effects of climate change, inter-decadal variability and afforestation on water supply. Widespread afforestation has been suggested as a means of addressing the problems of dryland and stream salinity and for sequestering carbon. A 10% increase in tree cover in the headwaters of the Macquarie catchment, reduced inflows into the Burrendong Dam by 17%. A mid-case scenario of global warming by 2030 caused an additional 5% reduction in flow; if this occurred during a drought-dominated period of rainfall such as occurred in 1895–1948, flows would reduce by another 20%. Current water use in the basin is largely adapted to the wetter conditions of the post 1949 epoch.

Beare and Heaney (2002) examined changes in river flow and salinity levels (along with economic consequences) for two mid-range IPCC SRES scenarios (A1 mid, and B1 mid) by altering evapotranspiration rates in line with expected changes in rainfall. They found substantial reductions in flow under both scenarios. In the SRES A1 mid-range scenario, flow reductions across the whole MDB catchments were 16 to 25% in 2050 and between 24 and 48% in 2100. Flow reductions were 12 to 19% under the B1 mid-range scenario in 2050, and 16 to 30% in 2100. Salt concentrations tended to increase in the tributary rivers above irrigation areas because surface water runoff declined by a greater proportion than salt loads. Salinity increases in the Goulburn-Broken River system (Victoria) and the Gwydir River (NSW) were in the range 13 to 19% by 2050 and 21 to 72% in 2100. Salinity levels below irrigation areas were simulated to remain stable or fall due to reduced recharge of, and discharge from, saline aquifers. However, lower water tables may have both benefits and costs to agriculture (Beare and Heaney 2002).

Two studies have examined the consequences of increases in extreme daily rainfall. In the Bass catchment in Victoria, high flows were increased relative to changes in mean flow (Chiew and McMahon 2002). Chiew *et al*. (2003) examined changes in rainfall and runoff in six small catchments around Australia, using an ensemble of five simulations generated by the CSIRO Mark2 model. This study took account of the changes in daily rainfall distributions generated by the GCM, rather than simply perturbing historical daily rainfall by the change in mean monthly rainfall. The results showed a decrease in mean annual rainfall and runoff in eastern Australia of 3-6% and southwest Australia of 7% in 2021–2050 relative to 1961–1990, but these decreases are less than those simulated using simple perturbation methods.

In southwestern Western Australia, mean rainfall has declined dramatically from the late 1960s. An average rainfall decline of 10–20% caused a 40–50% decline in dam inflow (ATSE 2002; IOCI 2002; Sadler 2003). This is roughly what the first Australian scenario for enhanced greenhouse conditions suggested, with low confidence, might occur by 2030 (Pittock 1988). The IOCI (2002) report summarises climate change simulations with the CSIRO Mark2 model. Multiple simulations suggest annual rainfall decreases of about 10% by 2100, and soil moisture decreases of about 15%. A simulation with the CSIRO Mark3 model results in similar estimates.

4 Adapting to climate change

As mentioned in the last chapter, adaptation to climate change is ideally carried out as part of strategic planning and management. In the past, infrastructure was built to last, but usually not with climate change in mind. Some very strategic individual decisions have been made, for example the setting aside of protected catchments for urban water supply and the development of large integrated irrigation and power developments such as the Snowy River Scheme. However, these developments have not totally fulfilled the requirements of integrated catchment management. Inadequate environmental flows, losses in water quality and land degradation have often followed, perhaps not directly due to the development of the infrastructure itself but certainly to the accompanying land and water use within the catchment. The strategic component of integrated catchment management needs to take account of processes and events that involve long-term changes. These include climate change, land-use change, rehabilitation of land and water resources, and wildfire and post fire regrowth. In this chapter we describe how climate change can be introduced into this process.

There are two components to adapting to climate change. One is the development of adaptive capacity – this is a piece of climate change jargon that refers to the ability of society to adapt to climate change. It refers to the institutions, knowledge, intention and ability to manage change. The other is the process of adapting to climate change itself through the implementation of specific actions and monitoring of those actions. This chapter describes methods for adaptation compatible with the AS/NZS 4360:2004 Risk Management Standard. Chapters Five and Six deal with urban and rural catchments, respectively.

4.1 Building the capacity to adapt

The first generation of climate impact studies compared the impacts of climate change with the current baseline, and then suggested adaptation measures to manage that change. Adaptation was therefore the end point in a sequence that began with climate scenarios. More recent approaches see adaptation as an ongoing process that takes account of how society copes with current climate risks (Burton *et al.* 2002). Assessments begin with an understanding of how a society manages current climate-related risks, then introduce climate change. The UNEP-GEF *Adaptation Policy Framework* (Burton and Lim, in press; http://www.undp.org/cc/whatsnew.htm) is a useful reference for current thinking on adaptation.

Climate change should also seen in the multi-stress context of sustainable development (Downing *et al.* 2003). 'Mainstreaming' adaptation integrates climate change concerns into ongoing development processes. For Australian water resources, this means building climate change into the water reform agenda and integrated catchment management. In this context, adaptive capacity refers to the ability of existing social structures, through communities, institutions and policy processes, to identify, analyse, prioritise and treat climate risk (Adger *et al.* in press). The Intergovernmental Panel on Climate Change's Third Assessment Report's chapter on water resources describes adaptive capacity as:

- The capacity of water related institutions, incorporating the authority to act, skilled personnel, and capability to consider a wide variety of alternatives;
- The capability to use multi-objective planning and evaluation procedures in assessment of policy alternatives, and incentives to undertake ex-post evaluation;
- The legal framework for water administration;
- Wealth, including natural resources, human-made capital, and the ability and willingness to transfer wealth among regions and groups;
- State of technology and the framework for dissemination;
- Mobility of human populations;
- The speed of climate change;
- The complexity of management arrangements (e.g. number of stakeholders); and
- The ability of managers to assess current resources and project future resources (Arnell and Lui 2001).

In Australia, this process is taking place through catchment management authorities (CMAs) and water corporations with the involvement of multiple levels of government through the provisions of policy, regulations and research application; research providers and consultants who provide and integrate knowledge; and community-based organisations and industry as stakeholders who explore, prioritise and implement adaptation measures. One key development is the integration of climate change into strategic development plans: CMAs produce plans on a five-yearly basis. In addition, a number of water corporations and state governments are sponsoring integrated assessments, which aim to build climate change into management strategies. The CMA structure has not yet been implemented Australia-wide but most states have formalised bodies working at the catchment level.

4.2 Risk management and critical thresholds

Here, we approach climate change through the AS/NZS 4360:2004 risk management standard because of its compatibility with recent developments of risk assessment methods for climate change (e.g. Burton and Lim in press). Simply put, risk management involves assessing the likelihood of a specific event, deciding whether the outcome requires management, either by reducing the likelihood of the event, and/or its consequences, evaluating treatment options, then implementing and monitoring those options.

The AS/NZS 4360:2004 standard process involves the following steps, adapted here for assessing water resources under climate change:

Communicate and consult
Communicate and consult with internal and external stakeholders and appropriate at each stage of the risk management process and concerning the process as a whole.

Establish the context
Develop the aims, desired outcomes, process and criteria for the assessment. For water resources, criteria can be organisational performance goals, levels of security, water quality, water supply, and thresholds where critical levels of harm are set so that they can be assessed for likelihood of exceedance (Pittock and Jones 2000). Critical thresholds include flood magnitude and frequency, loss of life, financial losses, water quality criteria and critical levels of restrictions. The scoping stage will also involve the briefing of stakeholders on climate change issues, the choice of assessment team and familiarisation of team members with the different aspects of the issues at hand.

There are two major structures one can apply to the analysis. The first is the natural hazards approach, where hazards are identified and climate scenarios (and other stress factors) are applied to an assessment system to analyse the outcomes. The second is the vulnerability approach where a desirable or undesirable future state is identified, then assessed for its likelihood under a range of future conditions (Jones and Boer in press; Jones and Mearns in press). It is possible to apply either or both to an assessment. A third is the policy approach where a current policy or policies is/are analysed for how they cope under climate change (Burton and Lim in press). Figure 4.1 shows how climate change may interact with the coping range in terms of exceeding a given threshold.

The next three stages (identify, analyse and evaluate risks) can be assessed in several ways. The approach recommended by the Adaptation Policy Framework (Burton and Lim in press) is to assess current climate risks followed by future climate risks. If current climate risks are well understood, then an assessment would proceed straight to future climate risks. If not, or a reappraisal was required, then it would be possible to identify, analyse and evaluate risks for current climate, then for future climate in sequence. Another way is to complete each of the following steps for current climate, then future climate, in turn.

Identify risks
Identify how climate change may pose risks or opportunities for the system under investigation. This may be a specific investigation (e.g. flood risk) or involve an assessment of the system (e.g. a water supply and distribution network) undertaken with internal and external stakeholders.

Analyse risks

Investigate the likelihood of specific outcomes either by projecting a set of changes through a system to determine the outcomes (natural hazards-based approach) or to determine the likelihood of threshold exceedance (vulnerability-based or goal-oriented approach). These methods are outlined in greater detail in Jones and Boer (in press), and Jones and Mearns (in press) and in the following case study.

Evaluate risks
Compare the estimated level of risk against the original criteria to determine the balance between benefit and losses and whether it needs to be treated. This step involves the use of decision criteria to determine whether to act and how to act. Although there are a number of case studies which can show how this has been addressed, this technique requires more work to provide guidelines that can fit a range of situations. Tools for assessment include cost-benefit analysis, multi-criteria analysis and the assessment of stakeholder perception of risk based on the analysis.

Treat risks
Develop and implement specific cost-effective strategies and action plans. One avenue is within formal strategic plans implemented at the corporate or authority level. These should treat both the upside and downside of risk.

Monitor and review
Ongoing assessment of both the process and of treatment measures is necessary. Often several passes through the risk assessment process may be needed: the first time climate may be assessed on its own, and the second time investigated with related environmental and human-induced stresses, investigating the feedbacks between climate and those other stresses.

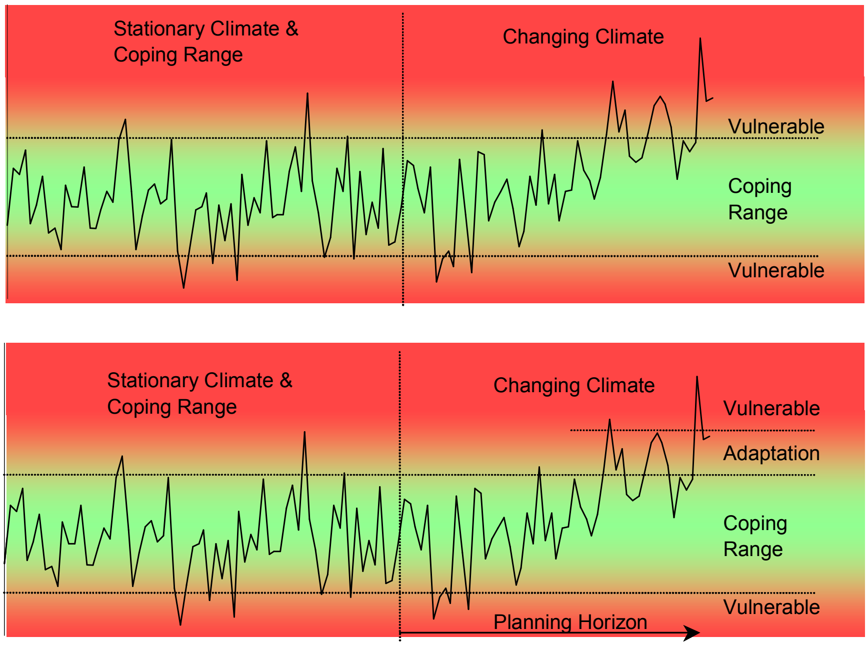


Figure 4.1. Stationary climate, climate change and the coping range (Jones and Mearns in press).

Case study: Irrigation allowances and environmental flows in the Macquarie catchment, NSW

Jones and Page (2001) applied the two pathways of risk analysis discussed in Section 4.2: the natural-hazards approach where climate changes are projected through a system to investigate the outcomes, and the vulnerability (or performance) based approach where criteria in the forms of thresholds are proposed and their probability of exceedance assessed. They used CSIRO's climate scenario generator OzClim (Page and Jones 2001) and The NSW department of Industry, Planning and Natural Resources' Integrated Quality Quantity Model, a rainfall-runoff and river management model, to analyse the risk of climate change on water resources in the Macquarie catchment.

Monthly changes in precipitation and potential evaporation were applied to a historical daily climate record dating from 1890–1996. Applying the full range of changes from the IPCC range of global warming in 2030 and 2070 and regional changes from a suite of climate models, combined with Monte Carlo sampling of those uncertainties, they produced a full range of change in mean annual water storage, irrigation supply and environmental flows of +10 to -30% in 2030 with the most likely 90% of outcomes falling in the 0 to -15% range. For 2070, the full range was +20 to -60% with the most likely 90% of outcomes in the 0 to -35% range (Figure 4.2). Flows were allocated to irrigation and environmental flows using the 1996 management rules.

In the vulnerability-based approach, two critical thresholds were chosen: environmental flows to the waterbird nesting area of the Macquarie marshes falling below 350GL for 10 consecutive years; and irrigation allowances falling below a level of 50% allocation for 5 consecutive years. These thresholds allowed for coping capacity by using measures of accumulated stress. The first critical threshold would lead to no major breeding event during a bird life-cycle and the second would likely lead to widespread economic failure for farmers. The analysis also considered distinct modes of decadal climatic variability in the historical record, a drought-dominated (1890–1947) and a flood-dominated period (1948–1996). Sensitivity analysis show that both critical thresholds would be exceeded with mean changes in flow of -10% in a drought dominated regime (DDR), -20% in a normal climate and -30% in a flood dominated climate (FDR).

Assessing risk as a function of change in average climate and inter-decadal rainfall variability, by 2030 both thresholds had a 20–30% likelihood of being exceeded in a drought-dominated climate, less than 1% in a normal climate, and much less than 1% in a flood-dominated climate. By 2070 these risks were found to be 70–80%, 35–50% and 10–20%, respectively. This work has contributed to policy surrounding environmental flow regimes and investigations are underway to ascertain if the decadal shifts in climate are similar to those experienced in southwestern Western Australia. Further work is aiming to explore how rule changes in allocations can share the risks between different activities, analyse changes in flow variability and integrate salt transport models to investigate the interaction between climate and salinity on water quality. The authors suggest hedging risk through adaptation and monitoring climate to determine whether ongoing changes are likely to exceed critical thresholds.

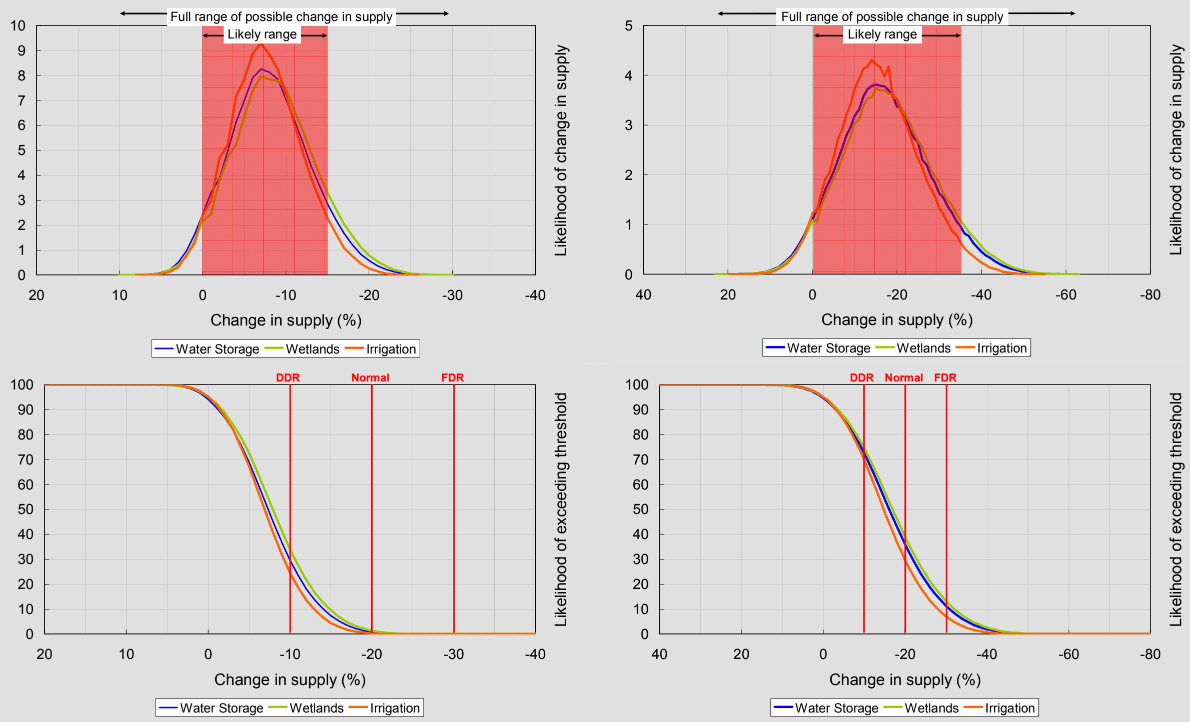


Figure 4.2 Change in mean annual water storage, wetland environmental flows and irrigation allocations for the Macquarie catchment in 2030 (upper left) and 2070 (upper right). The shaded area covers the most likely 90% of outcomes. The likelihood of exceeding critical thresholds for irrigation allocations and environmental flows is presented as a function of the decadal rainfall regime in 2030 (lower left) and 2070 (lower right).

4.3 Decision criteria

The evaluation stage of the process is probably the least understood and the most critical; partly because of the large uncertainties associated with long-run environmental outcomes like climate change and salinity. Given the uncertainty associated with climate change and the fact that non-climatic stresses may be of more pressing concern to water managers, when should climate change be incorporated into planning? A key criterion is the ease of implementation. Effecting adaptation measures also requires political, technical and financial support from senior government agencies, and buy-in from the community (De Loe *et al.* 2001; Ivey *et al.* 2004).

Ideally, climate change plans should be comprehensive, flexible and easy to use. Hamlet *et al*. (2001) suggest the following decision criteria for use in water resource planning:

- *Piggybacking* – planning is in progress or is required for other reasons;
- *Rare opportunity* – the planning arena is unlikely to be revisited in the next several decades due to cost or other considerations;
- *Sensitivity* – the water system in question is highly sensitive to reductions in storage filling events, or to other changes in streamflow timing;
- *Durability* – high costs and/or long economic life span are associated with decisions addressed by a particular planning process;
- *Irreversibility* – planning decisions made now may irreversibly increase future vulnerability; and/or

- *Inflexibility* – there is a limited ability to respond to rapid changes in climate without long-term planning.

These decisions probably have more to do with whether an assessment proceeds in the first place. They will also influence the project scoping phase in terms of project design and goals. Further work needs to be carried out on the evaluation process, which will also draw from other areas of natural resource management and learning-by-doing.

5 Urban water

Climate change may result in a number of potentially negative effects on urban water systems. These include reduction in supply or changes in peak streamflow timing; reduced water quality; increased salinity or pollutant loads; increased evaporation; changed catchment hydrology; and increased frequency or severity of extreme rainfall, floods and droughts. Not all of these problems will eventuate in all regions, but those problems that occur will do so in the context of rapid institutional changes in water management. Much current planning is based on statistical analysis of historic records, but the preceding sections have illustrated that responding to climate change requires a more sophisticated assessment of the interactions between climate change and climate variability.

Climate is not the only dynamic component of urban water planning. Demographic and social changes have major implications for water demand. There is also evidence that our vulnerability to natural hazards such as floods has increased over the past decades. The number of people affected by natural disasters has risen from 197 million per year in 1981–1990 to 211 million in 1991–2000 (World Water Assessment Programme 2003). Economic losses from the great floods of the 1990s were ten times those of the 1960s in real terms (Cosgrove and Rijsberman 2000). Global climate change will eventuate in the context of increased urban development pressures and vulnerability.

Various climate change adaptation measures have been covered in the literature (Table 5.1), but it is the institutional context rather than the measure itself that is critical. Water reforms and the evolution of maturing water economies has led to a broadening role for water authorities, who must now deal with the social , economic and hydrological dimensions of catchment management (Tisdell and Ward 2003). Hamlet *et al.* (2001) describe the key elements of the adaptation process as problem assessment and determination of regional vulnerabilities; long term planning efforts resulting in the creation and refinement of specific adaptation strategies; and incorporation of these preferred adaptation strategies into regional water policy and water law.

Management and planning	Supply	Demand
Improve seasonal forecasting	Increase usable storage	Provide incentives for purchase and use of efficient technology
Improve monitoring to validate climate scenarios and/or trigger contingency plans	Diversify sources of water supply	Promote public education
Improve the efficiency of delivery systems	Connect regional water systems	Introduce market forces, water banks
Introduce advanced waste water treatment		

Table 5.1 Examples of climate change adaptation measures for urban water (Arnell and Lui 2001; Hamlet *et al.* 2001).

One tool to examine how adaptation may take place in urban systems is the use of analogy, which considers the institutional actions and changes as a response to past climatic events or variability (Glantz 1991). As with any discussion of adaptation, the regional context is paramount. The following case studies illustrate the importance of ongoing processes of dialogue and social learning.

Case study: UK water management

Subak (2000) discusses the experience of UK water managers with climate change planning. In England and Wales 1995 was the driest year since records began in 1766, leading to water shortages that were particularly apparent in the higher rainfall Northern Regions. Yorkshire water, for instance, resorted to trucking water to customers at a cost of £45 million.

In 1996 the UK Department of Environment and Heritage coordinated a meeting of all water companies and produced an action plan: *Water resources and supply: agenda for action*. This called upon companies to produce plans incorporating climate change into supply and demand projections up until the year 2025. These plans were based on 4 regionally-specific scenarios developed by the UK Hadley Centre. Based on a series of interviews, Subak determined most of the companies had reservations about the usefulness of the scenarios for planning, and relied on historical data. A number of companies credited a degree of resilience in the 1995 drought to their responses to the dry period of 1975/76. During this event, 8 out of 10 major water authorities experienced difficulty delivering enough water, prompting decisions to increase water storage capacity.

Water companies pledged to implement a range of demand side management measures at a national water summit in 1997. This was the first time many of them had made a concerted effort to reduce water consumption. Therefore for many of the companies, supply adaptations to climate change were made during the 1970s and early 1980s and demand adaptations during the mid-1990s.

Case study: Melbourne Water

TBC

6 Agriculture and land management

6.1 Future challenges

In 2000–2001, agriculture was responsible for 67% of Australian water consumption, with a total area of about 2 million hectares under irrigation (Dunlop 2001). The nexus between water use and agriculture will change in the future as a consequence of political, social and technological choices (Dunlop *et al.* 2001b). For instance:

- land area under crop production could continue to expand;
- area cropped could be held constant, increasing production solely from changing technology and management;
- area cropped could contract significantly with an accompanying reduction in grain exports;
- irrigation could grow through increased diversions and expansion into new areas; or
- water use could be reduced through intensification, innovation or shifts to higher value forms of agriculture

According to the same study, the irrigation sector faces a number of significant challenges, including how to facilitate continued growth of the industry through restructuring; reduced streamflows from the expansion of the plantation industry at the heads of catchments; managing the development of large areas of intensive agriculture in northern Australia; managing the legacy of past over-clearing and continued clearing of native vegetation; and how to respond to biodiversity concerns in agricultural lands, rivers and wetlands.

Climate change will occur in this dynamic context. Changes in temperature, rainfall and/or potential evaporation may lead to shifts in optimal growing periods or irrigation requirements and could worsen droughts (Trenberth 1999; Doll 2002). The impact of a combination of enhanced carbon dioxide (CO_2) and temperature is often species specific, and not additive, meaning that the combined influence of the changes cannot be predicted from knowledge of their individual effects (Polley 2002). Increasing CO_2 increases plant water use efficiency, but the individual effects of CO_2 enrichment are subject to complex internal interactions (Drake and Gonzalez-Meler 1997). An enriched level of CO_2 in plants leads to increased growth, although this effect tends to decrease after extended exposure and varies widely between species (Graves and Reavey 1996; Mooney *et al.* 1999). Broader environmental changes can affect terrestrial productivity. For instance there has been an observed reduction in solar radiation over the past 50 years, or 'global dimming' (Stanhill and Cohen 2001), thought to be due to increases in human-generated aerosols, and changing optical properties of the atmosphere and clouds. In water limited environments, a decrease in solar radiation, especially when combined with an increase in diffuse radiation, can act to increase productivity (Stanhill and Cohen 2001).

Assessments for dryland cropping systems shows that CO_2 fertilisation can compensate for losses due to climate change alone (Howden *et al.* 1999), but to date there has been little assessment on this effect for irrigation systems facing potential losses in water supply. In one study, Hassall and Associates *et al.* (2002) showed that despite reductions for irrigation allocations in the northern rivers of the MDB overall increases in cotton production more than compensated for losses in irrigation supply. In another study, changes were positive for crops but negative for livestock (Hassall and Associates 1998). Although the vigour of pasture may increase, both forage quality and water supply could decrease, with increasing heat stress decreasing milk yields (Jones and Hennessy 2000), indicating potential risks for the irrigated dairy industry. A number of poorly understood factors, such as pests, changes to landscape hydrology or climatic regimes such as ENSO, could influence impacts on farming systems.

Land degradation caused by dryland and irrigation salinity poses a threat to both water supply and quality. Like climate change, salinity is a long-term issue that will interact with climate change, as will the solutions to addressing salinity, such as reafforestation and management of "leaky" agricultural systems. Rising saline watertables also threaten wetlands in both eastern and western Australia. Land degradation issues such as salinity, erosion, soil acidification and habitat loss will all interact with climate change and the hydrological cycle, so will need to be managed at the landscape scale.

An investigation of a number of processes affecting runoff and water supply in the MDB such as climate change, farm dams, revegetation, urban growth, and reduced allocations from the Snowy River, found that flows to the Murray River may decrease by over 2,000 GL by 2020 (Earth Tech 2003). This exceeds the amount planned in the Living Murray Initiative, which promises 500 GL in the short term. Dunlop *et al.* (2001a) considered a national scenario that assessed climate change in conjunction with increasing demand. They found that early investment in adaptation measures such as water conservative irrigation and urban developments would see greater adoption and fewer shortages under climate change. In addition, institutional elements of current national water reforms, such as the ability to transfer water between regions, and guaranteeing and increasing environmental flows, were important to successful adaptation.

Case study: The Murray Darling Basin

Beare and Heaney (2002) investigated the joint impacts of climate change and salinity on the hydrological cycle of the MDB, considering how different trends may effect economic and environmental outcomes. The research looked at the extent to which market-based options could offset or enhance economic impacts. Using the SRES A1 and B1 emissions scenarios (Nakicenovic *et al.* 2000) and CSIRO's OzClim model (Page and Jones 2001), the study applied precipitation decreases and increases in evapotranspiration rates, which reduced surface water flows and groundwater recharge. There were slight to moderate reductions in water availability for dryland agriculture, moderate to substantial reductions in surface water flows (16–25% by 2050, 24–48% by 2100) and increases in open water evaporation. This led to an associated increase in the opportunity cost of water (i.e. a 60% increase in the Goulburn-Broken catchment under the A1 scenario). Climate change could help ameliorate salinity in the long term if a drier climate and improvements in water use efficiency reduced groundwater recharge. However decreases in the volume of runoff and a delay in the impact of reduced recharge in discharge rates, means that salts in streamflow will increase in the short-term before decreasing over the long term.

The economic analysis showed costs to agriculture of $1.2 billion under the A1 scenario and $0.8 billion under the B1 scenario, principally caused by reduction in surface water flows, increased river salinity and a reduction in irrigated agricultural production. Adaptation, such as improvements in water use efficiency or water trading, has the potential to create significant reductions in the agricultural costs of climate change. Improvements in water use efficiency could reduce the costs associated with the SRES A1 by almost 60%. Building the capacity to adapt would involve adoption of more flexible institutional arrangements to facilitate efficient reallocation of resources, and investment in options such as increased conservation of ground water and other resources. Beare and Heaney conclude that the impetus created by the potential impacts of climate change may simply reinforce a broad set of incentives to expand the capacity to adapt to a changing environment (Beare and Heaney 2002, pg. 29).

Recent scientific studies have provided the impetus for climate change to be incorporated into natural resource management within the MDB. A study extending the results from the Macquarie catchment to the southern MDB concluded that reductions in flow due to climate change were highly likely and consequently increases were unlikely (Jones *et al*., 2002). Artificial scenarios provided to the MDB Commission were used in scoping the likely impacts through the MDBC's water management model, showing that, on the basis of current formulas, reductions in flow were shared between environment and irrigation supply in the proportions 83% and 17%, respectively (Close, pers comm.) This study, Beare and Heaney (2002) and Herron *et al.* (2002) led to the incorporation of climate change into planning for the MDB. This work is still in its very early stages.

6.2 Environmental flows and ecosystem services

The life cycle of many riparian, wetland and aquatic species is dependent on interannual variation in hydrologic conditions (Richter *et al.* 1996). Environmental flows describe water levels and volumes in streams and wetlands required for the maintenance of these ecological needs. Factors responsible for the decline of aquatic biodiversity in regulated rivers include salinity, habitat destruction and modification, disruption of life history processes, loss of connectivity and increased susceptibility to invasions by exotic species (Arthington and Pusey 2003). Alterations to flow regimes in many rivers are considerable; for instance the median flow of the River Murray to the sea is 27% of natural flow (Goss 2003).

Provision of water for environmental flows is an important element of current policy initiatives. For instance the Murray Darling Basin Water Agreement was signed in June 2004 by the Commonwealth, NSW, Vic, SA, and Act governments. It provides $500 million over 5 years to reduce the level of water over-allocation and achieve specific environmental outcomes in the MDB under the Living Murray Initiative. Watery recovery measures include investment in water infrastructure and behavioural change and purchase of water on the market. Environmental priorities are the following: the Barmah-Millewa Forest, Gunbower and Koondrook-Perricoota Forests, Hattah Lakes, Chowilla floodplain (including Lindsay-Wallpolla), the Murray mouth, Coorong and Lower Lakes, and the River Murray Channel.

Despite the existence of numerous methodologies (see Tharme 2003), defining ecosystem needs clearly enough to guide policy remains a significant challenge and improvements are needed in the science, the decision-making process, or both (Poff *et al.* 2003). There is currently a limited recognition of the potential impact of climate change and variability on environmental flow allocations (Schofield and Burt 2003). Doubts about the science of environmental flows have already led to litigation in the MDB, and ecologists are ill-equipped scientifically to deal with such conflicts (Arthington and Pusey 2003). Experiences with environmental water allocation indicate that open processes with community input are complicated, but generate ownership of outcomes, and that close collaboration is needed between biophysical and social research that includes an appreciation of local knowledge (Schofield and Burt 2003).

6.3 Integrated Catchment Management

Recent decades have witnessed a shift in natural resource management towards the broader perspective of ecosystems, multiple spatial and temporal scales and the use of collaborative decision-making (Cortner and Moote 1994; Clark *et al.* 1999; Imperial 1999). Since its evolution in the 1980s, Integrated Catchment Management has become the dominant land management paradigm in Australia. The House of Representatives' Standing Committee on Environment and Heritage conducted an enquiry into catchment management and its report contains a discussion of the institutional barriers facing effective catchment management nationally. The Committee goes so far as to claim that ecologically sustainable use of Australia's catchment systems is the most pressing contemporary public policy issue facing the community (2000, pg. 1). Issues uncovered in the enquiry include lack of continuity of expertise due to loss of agricultural extension officers, lack of continuity within institutions due to short term funding arrangements, problems obtaining and utilising data, and serious communication difficulties within and between government departments. The report recommends trusted institutions with access to stable sources of funding and suggests a National Catchment Management Authority (NCMA) be established to oversee the recommended institution-building efforts.

Institutional structures are fundamentally important to the ability to adapt to climate change. A large body of theory suggests that adaptive environmental management should have elements of institutional flexibility, holism, experimentation, dialogue and stakeholder inclusion (e.g. Holling 1973; Walters 1986; Lee 1993). Uncertainty should be incorporated into landscape-scale management by considering a range of acceptable outcomes, avoiding irreversible negative effects, and setting measurable objectives in terms of ecosystem function and social desires (Vogt *et al.* 1997). Folke *et al.* (2002) nominate several key areas for policy in order to build resilience in social-ecological systems: developing indicators of change and early warning; recognizing the existence of ecological thresholds and the possibility of surprise; and creating arenas for stakeholder collaboration. Factors that can enhance resilience include local ecological knowledge, an understanding of cycles of natural events, a diversity of dynamic institutions, and intergenerational transmission of knowledge (Folke *et al.* 1998).

Despite this large body of theory on ideal structures for natural resource and catchment management, implementation on the ground remains a serious challenge. Based on work in the Herbert river catchment, Bellamy and Johnson (2000, pg. 278-9) suggest that the following barriers that make it difficult to implement ICM in a strategic, integrated and equitable way:

- Effects of change in resource use or management take time to become apparent;
- Ignorance as well as lack of access to information on the long-term effects of agricultural practices on the environment leads to continuation of unsustainable activities;
- Current agricultural technology is problem-oriented and does not lend itself easily to a systems focus;
- There exist disparities in power and resources at the local level;
- Capacity is limited and funding is declining- government rhetoric is often not matched by resources;
- Long term environmental solutions do not fit in with the short-term business and political time frames of agricultural and government decision-making;
- The goals of ICM are unclear, multiple, and often contested by different stakeholder groups; and
- Despite various conceptualisations in the literature there is a lack of practical guiding principles to guide communities in implementing a systems-based approach to ICM.

Managing catchments in a complex and dynamic environment is undoubtedly a difficult task. However over the last decade or so there have been significant steps forward in our understanding of key issues, and in policy process for reform at Commonwealth, State and Local levels.

7 Conclusion

The justification for considering climate change as an integral component of water resources planning is that despite the uncertainties many models are pointing to a decrease of water availability in key regions of Australia. Many of our surface and groundwater areas are already over-allocated, and alterations to hydrological regimes have resulted in problems such as habitat loss and salinisation. Increasing pressure on the resource and the cascading effects of management decisions on water users and the environment mean that adaptation is important. The indications are that early adoption of adaptation will reduce the costs and impacts of climate change.

Many of the pre-existing management structures for water resource planning were developed during a period of generally favourable rainfall. However, real-world examples of adaptation show that using the past as a guide to the future is not good policy. Climatic events such as the step change in rainfall in southwestern WA in the 1970s, reductions in rainfall in the Southeast in the 1990s and the extreme drought of 2002-3, have illustrated how the assumption of a stationary climate is no longer a valid one for water managers. Various forms of climate variability- seasonal, inter-annual and decadal- need to be considered in adaptation planning. Our knowledge of these various aspects of climate has improved, but the climate change signal and natural variability will interact in complex and possibly unpredictable ways. It is important to mesh these different scales of adaptation with different planning horizons. Stakeholders will differ not only in their scales of interest, but also in their information needs, and risk structures. Case studies of adaptation by urban water managers highlight the importance of information sharing and dialogue, and that good adaptation planning by key institutions can be catalytic and lead to social learning.

The foundation for coping with future climate risk is an understanding of a given region of interest and its current climate risks. This is one aspect of the current prevailing methodological approach to adaptation. However this clearly implies a place-based assessment, which paints a broad picture of the region of interest, its environmental history and specific vulnerabilities. The ability to cope with different aspects of climate change varies according to region and sector, and even between social groups. This makes it difficult for scientists to propose a specific ‘how to’ template for adaptation. A few studies have begun to approach adaptation by determining critical thresholds particular to a region and its stakeholders, and quantifying the risks of climate change. These show the importance of a) understanding the prevailing regional climatic regime and b) stakeholder-defined critical thresholds to focus research and strategic management.

If an understanding of risk and regional vulnerability is one aspect of adaptation, the other is building the capacity for flexibility and adaptive management. In discussing adaptation in the water resources sector, one thing that becomes apparent is the key role played by institutional structures and policy decisions. Globally, there is an impending water resources crisis, but scenario exercises show that the choice of policy pathways could do much to ameliorate it, independently of changes in climate. In Australia the institutional landscape for water resources has shifted substantially over the last couple of decades with ongoing reforms including changes to water rights, trading, provision for environmental flows, and improved accounting and monitoring of use. A vast body of social science research tells us that adaptable institutions require factors such as open and collaborative management structures, cross-scale linkages, learning by doing, information generation and transmission and monitoring. Integrated catchment management, the prevailing natural resource management paradigm in Australia, aims to achieve many of these things, but is still in the relatively early stages of institutional development. Reviews of ICM in Australia have uncovered weaknesses and made suggestions for improvement. To a large extent adaptation to climate change will be facilitated by our success or otherwise in manifesting these new institutional structures.

Annex 1: Key national water policy initiatives

COAG Strategic Framework
In 1994 the Council of Australian Governments (COAG) introduced a strategic framework for national water reform. The key elements of this reform included consumption based pricing and the development of water trading, changes to the institutional basis for water allocations, and recognition of the need to maintain flows to the environment.

National Action Plan for Salinity and Water Quality.
Endorsed by COAG in 2000, this plan targets 20 priority regions where salinity and water quality problems are a major concern. With a joint government commitment of $1.4 billion over 7 years the goal of the plan is to motivate and enable regional communities to use coordinated and targeted action to prevent, stabilise and reverse trends in dryland salinity.
Key points of the plan include:

- Targets for improving water quality and salinity;
- Clarification of water rights and water pricing;
- Integrated catchment management plans and community capacity building;
- An improved governance framework, including property rights, pricing, and regulatory reforms for water and land use; and
- Clearly articulated roles for the Commonwealth, State and local governments and the community.

The plan is overseen by the Natural Resource Management Council, which was established in 2001 to develop a coordinated approach to natural resource management.

The National Water Quality Management Strategy (NWQMS)
A joint initiative under the Natural Resource Management Ministerial Council. The strategy consists of a set of policies, a process and a series of national guidelines on all aspects of water quality management.

The Natural Heritage Trust
The Natural Heritage Trust was set up by the federal Government in 1997 to help restore and conserve Australia's environment and natural resources.
In the 2001 Federal Budget, the Government announced an additional $1 billion for the Trust, extending the funding for five more years (from 2002-03 to 2006-07). Of this additional $1 billion, the Government expects to spend at least $350 million on measures to improve Australia's water quality. The Natural Heritage Trust is administered by a Ministerial Board comprising the Minister for the Environment and Heritage and the Minister for Agriculture, Fisheries and Forestry.

National Water Initiative
In August 2003 COAG announced the National Water Initiative to stimulate further progress in the national water policy agenda. Implementation of the NWI will be overseen by the Natural Resource Management Ministerial Council. Key elements of the initiative include:

- Water access entitlements to grant perpetual access to a share of the resource;
- Improved specification of environmental outcomes, and statutory provision for water that is provided to ensure these outcomes;
- Substantial progress in returning over-allocated systems to sustainable levels to be made by 2010;
- More efficient administrative arrangements to facilitate trade, and removal of institutional barriers;
- Regional assessment of the level of water intercepted by land use change activates and potential regulation of these activities;
- Full cost recovery pricing for water in both urban and rural sectors;
- National standards for water accounting, reporting and metering;
- Demand management in urban areas;
- Establishment of a National Water Commission (NWC) to assess progress in implementing the NWI; and
- A risk allocation framework, with users to bear the risk of reductions from climate change, droughts or bushfires.

Murray Darling Basin Water Agreement.
The MDB Water Agreement was signed in June 2004 by the Commonwealth, NSW, Vic, SA, and Act governments. It sets aside $500 million over 5 years to reduce the level of water over-allocation and achieve specific environmental outcomes in the MDB under the Living Murray Initiative. Watery recovery measures include investment in water infrastructure and behavioural change and purchase of water on the market. Environmental priorities are the following: the Barmah-Millewa Forest, Gunbower and Koondrook-Perricoota Forests, Hattah Lakes, Chowilla floodplain (including Lindsay-Wallpolla), the Murray mouth, Coorong and Lower Lakes, and the River Murray Channel.

Annex 2: Climate change and water by State: Summary impacts and references for further information

New South Wales (Hennessy *et al.* 2004b)
There is a tendency for decreasing annual average rainfall over NSW, mainly in winter and spring. Autumn rainfall could decrease in the North and increase in the far West. Summer rainfall is projected to increase along the coast and in the Northeast and decrease in the northwest. Annual average potential evaporation increases (1.5 to 13% west of the highlands and 1 to 8% along the coast by 2030, increasing to 4 to 40% and 2 to 24% respectively by 2070). Changes are largest in winter and least in summer. Decreases in the moisture balance are expected (0 to 195mm along the coast and 20 to 325mm in North by 2030, rising to 0 to 600 mm and 55 to 1000mm by 2070).

Northern Territory (Hennessy *et al.* 2004a)
Much of the Northern Territory becomes drier in both the wet and dry seasons, however there is a large degree of uncertainty in rainfall projections. Most models simulate drier conditions, especially from July to October, and some indicate the possibility of a delayed start to the wet season. Potential evaporation increases by 2-5% in 2030 and 4-20% in 2070, with smaller increases in the North and large increases in the central West (November-April) and in the South (May-October). The moisture balance is expected to decline by up to 30-130mm by 2030 and 90-400 mm by 2070, with smaller decreases in the North.

Queensland (Walsh *et al.* 2002) (Updated projections currently in prep.)
There is a significant amount of regional uncertainty in the Queensland rainfall scenarios. Summer rainfall tends to increase along the coast (-5 to +15% by 2030), except in the Townsville region. In the far North there is a tendency for rainfall reductions in autumn. Increases in rainfall may predominate in the far interior. There is the possibility of more frequent heavy rainfall events. Despite possible rainfall increases in some locations the moisture balance is expected to decrease, particularly in the far interior.

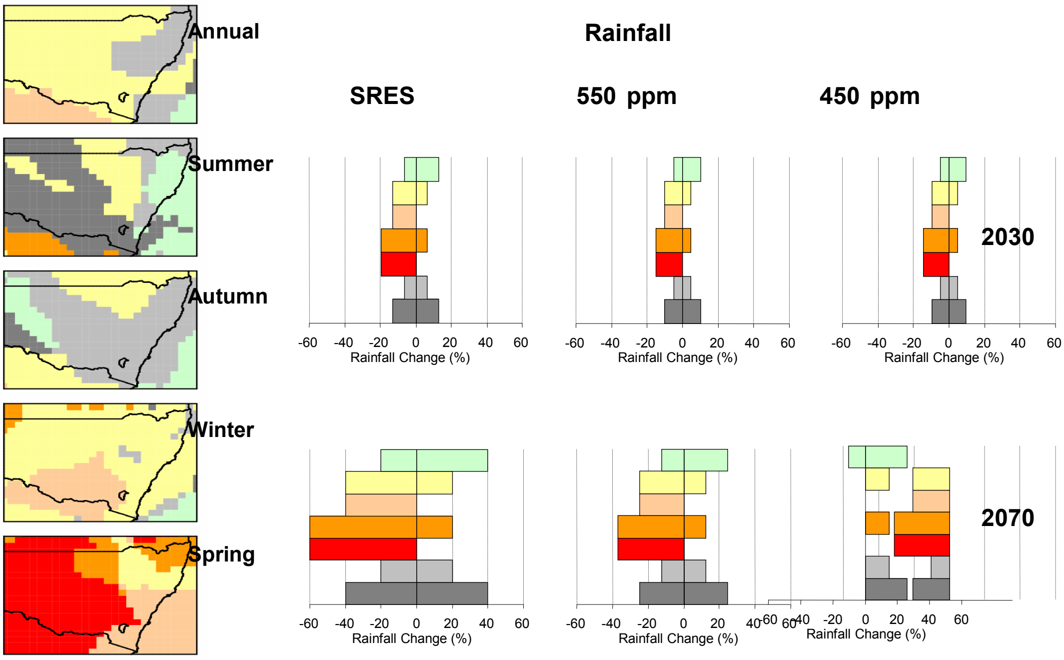
South Australia (McInnes *et al.* 2002)
Projected annual rainfall averages are expected to decrease over most of South Australia (-3% to +6% by 2030 and -40 to +20% by 2070). There are stronger decreases in the far Southeast and increases and decreases are equally likely in the Northeast. Potential evaporation shows the largest increases in the east and northwest of the state (2 to 9% by 2030 and 6 to 24% by 2070 in winter and spring). Moisture balance deficits are stronger in summer and increase towards the northeast of the state (10 to 110 mm by 2030 and 50 to 320 mm by 2070). Changes in extreme rainfall events by the year 2030 are substantial in most seasons and regions.

Tasmania (McInnes *et al.* 2004)
There is uncertainty and disagreement between models on Tasmanian projections, however there is a general tendency toward drier conditions in the Northwest and wetter conditions in the Southeast. Annual average rainfall could increase by up to 13% across much of the state although decreases of up to 8% also possible. In the far East, the range includes possible increases of up to 25% by 2030. Annual average potential evaporation increases are in the range of 1 to 7% by 2030 and 3 to 24% by 2070. There is an expected increase in mean rainfall events even when mean rainfall decreases.

Victoria (Whetton *et al.* 2002)
Scenarios indicate decreasing annual averages over much of Victoria (-9% to +3% in 2030 and -25 to +9% in 2070). These decreases are stronger in the far Northwest, whereas increases and decreases are equally likely in the far East. Summer rainfall may be reduced in southern and southwestern Victoria. In autumn, there is a tendency for decreased rainfall over most of the state, except for the far North and East. Winter rainfall could decrease, except in the South and East. Spring rainfall looks likely to decrease throughout the state. Possible increases in extreme daily rainfall may lead to more frequent heavy events, even where average rainfall decreases.

Western Australia
South Western WA has already experienced significant reductions in winter rainfall and streamflow and model results suggest a decline of autumn and winter rainfall under enhanced greenhouse conditions (IOCI 2002). Evans and Schreider (2002) used a stochastic weather generator and earlier GCM (CSIRO9) to model rainfall and runoff in 6 catchments that supply 90% or Perth's water. Mean streamflow entering the Swan river declines by 12 to 24% under 1.5x CO_2 and 2x CO_2 scenarios respectively. Precipitation would have to increase substantially to account for the expected increases in evaporative demand. However the authors note that mean values must be considered alongside changes in the nature of precipitation and the individual characteristics of catchments.

NEW SOUTH WALES

a) 

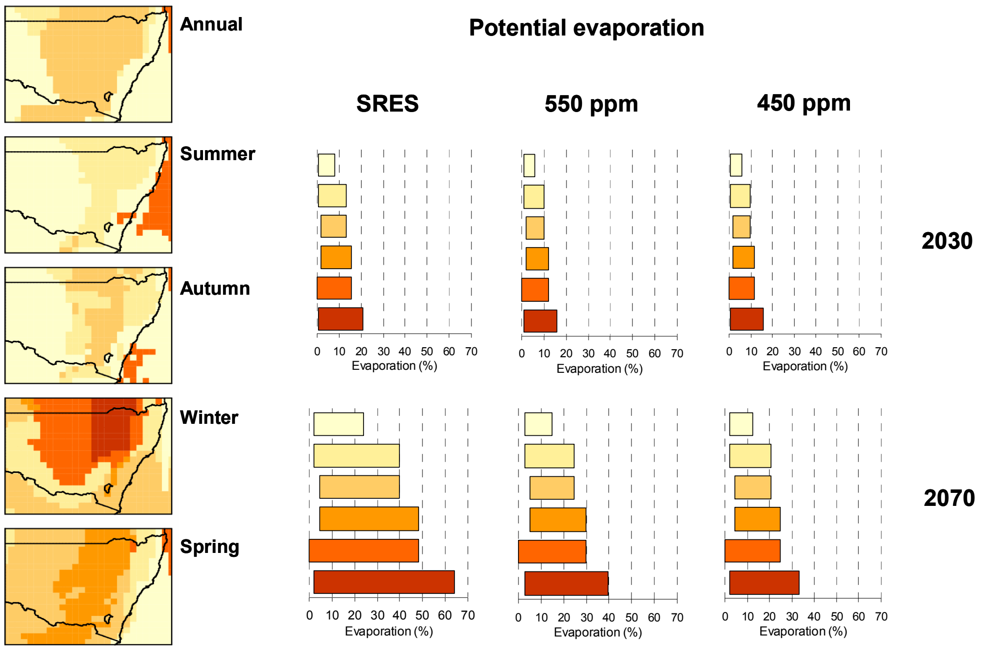
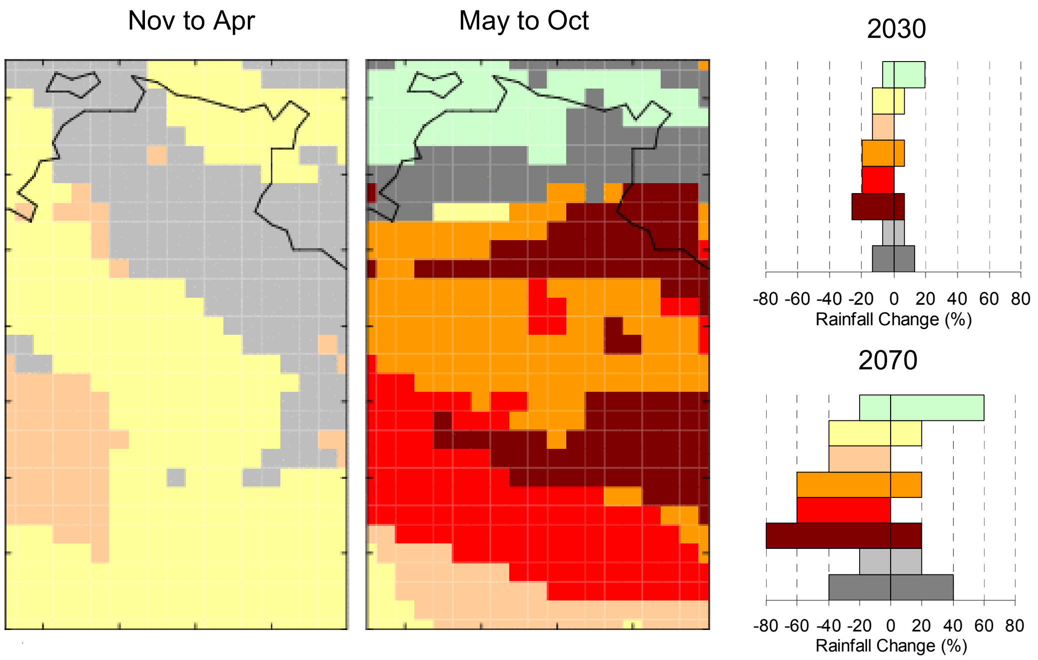
b) 

Figure 1: (a) Ranges of change in average rainfall % for the years 2030 and 2070 relative to 1990. Also shown are impacts under the IPCC's 550ppm and 450ppm CO2 stabilisation scenarios. (b) Ranges of change in point potential evaporation % for the years 2030 and 2070 relative to 1990 (Hennessy *et al.* 2004b, pg. 35, 37).

NORTHERN TERRITORY

a) 

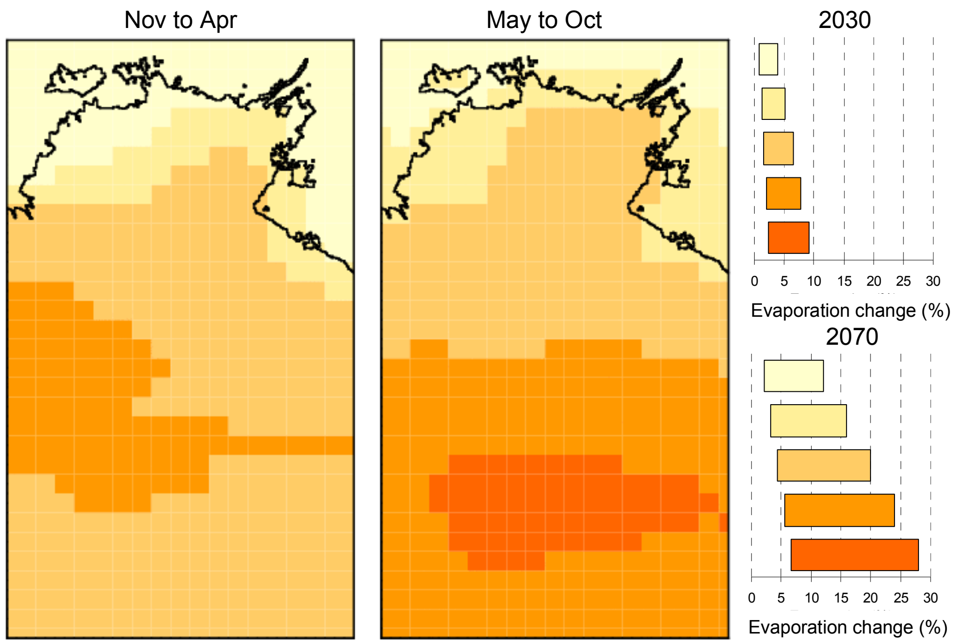
b) 

Figure 2: (a) Average November to April and May to October changes in rainfall (%) for 2030 and 2070, relative to 1990. (b) Patterns of change in potential evaporation for November to April and May to October in 2030 and 2070, relative to 1990 (Hennessy *et al.* 2004a, pg. 32, 33).

SOUTH AUSTRALIA

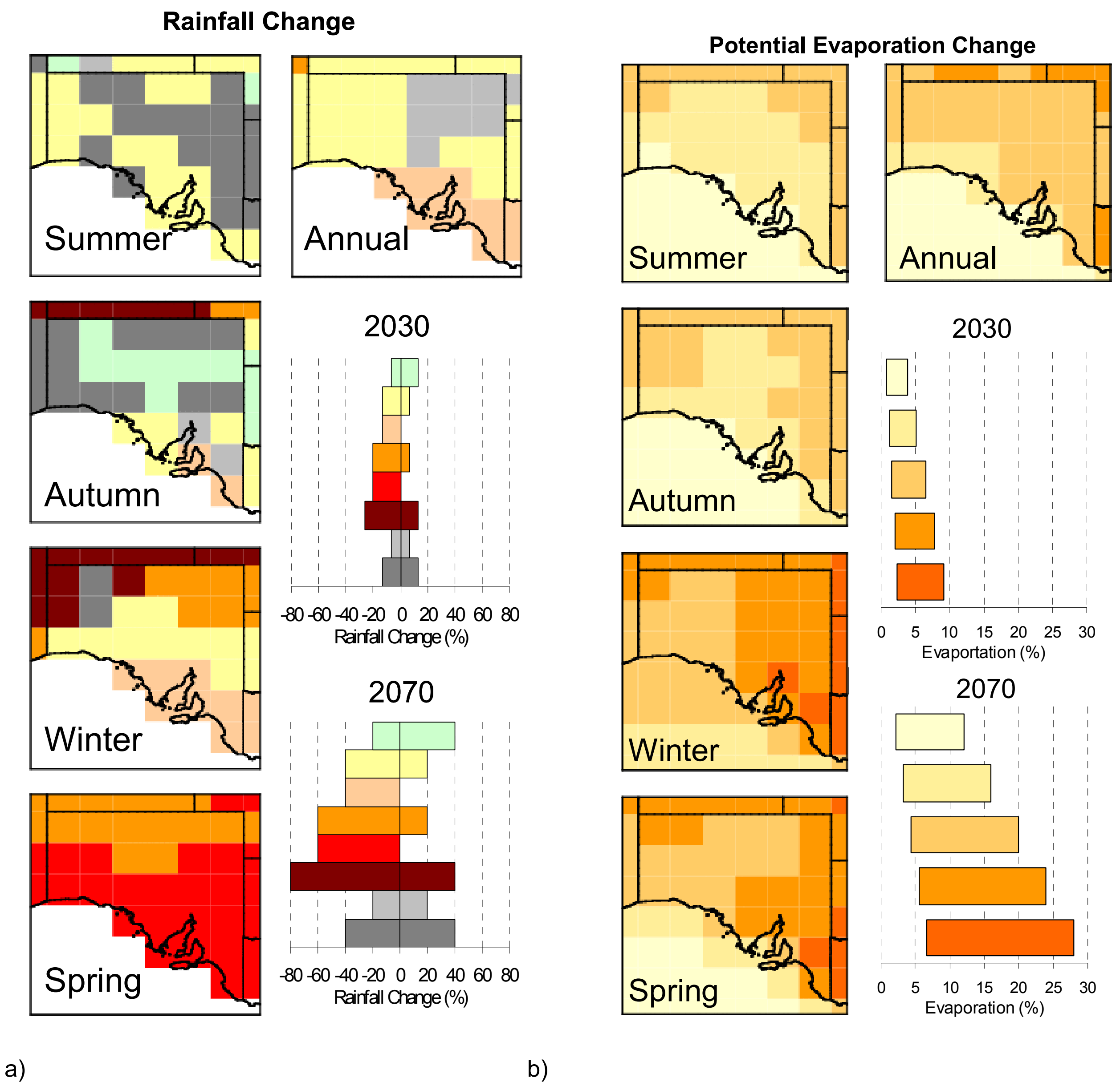


Figure 3: (a) Average seasonal and annual rainfall change (%) for 2030 and 2070 relative to 1990. (b) Patterns of seasonal and annual change presented as ranges of change across five GCMs and two RCMs for potential evaporation (% per °C of global warming) (McInnes *et al.* 2002, pg.27,30).

TASMANIA

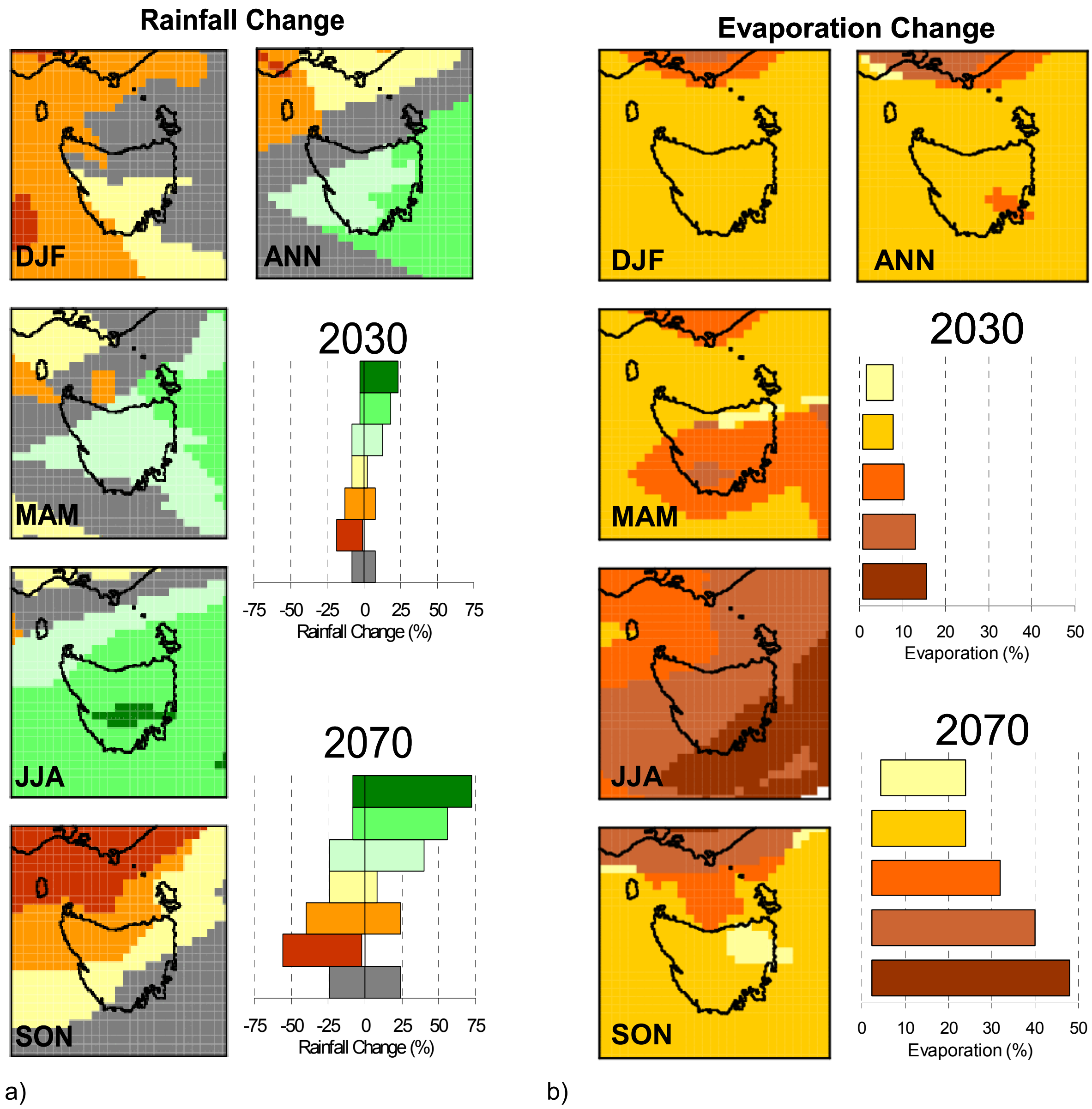


Figure 4: (a) average seasonal and annual rainfall change (%) for 2030 and 2070 relative to 1990. (b) Average seasonal and annual potential evaporation change (% per °C of global warming) for 2030 and 2070 relative to 1990 (McInnes *et al.* 2004, pg. 32, 35).

VICTORIA

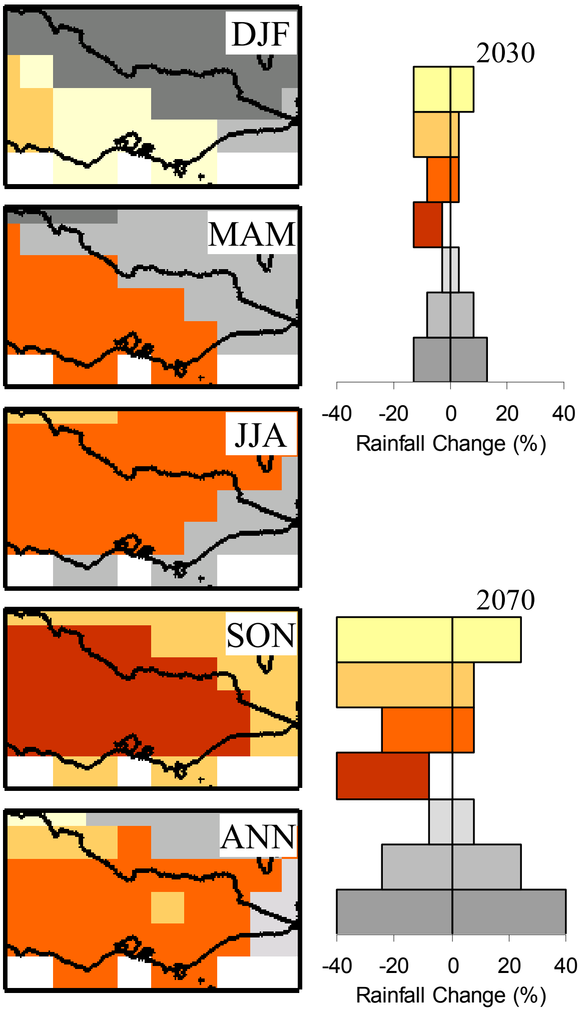


Figure 5: Ranges of average seasonal and annual rainfall change (%) for around 2030 and 2070 relative to 1990 (Whetton *et al.* 2002, pg. 41).

WESTERN AUSTRALIA

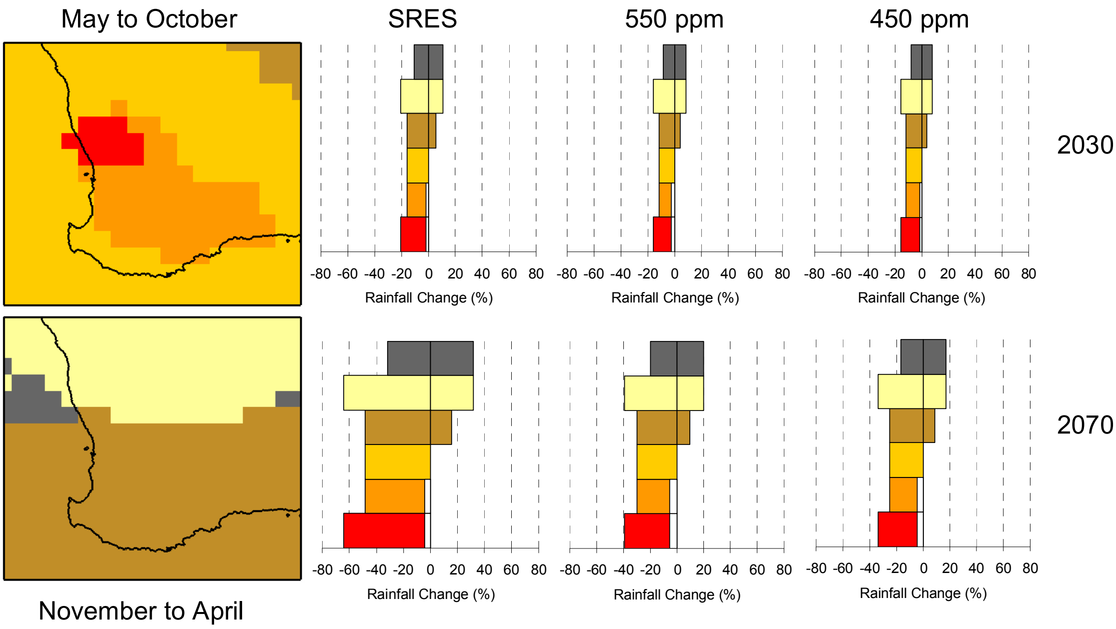


Figure 6: Ranges of change in rainfall for the southwestern Western Australia by 2030 and 2070 (Suppiah and Durack 2004).

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