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Climate change and water resources in the Murray Darling Basin, Australia

Impacts and possible adaptation

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In Australia, changes to the hydrological cycle under conditions of enhanced global warming are likely to be complex and spatially diverse. While a number of emission scenarios have been developed to explore the key drivers of global warming, the capacity to adapt to climate change has not received the same level of attention.

A simulation model was used to examine the potential impact of changes in precipitation and evaporation for two scenarios developed by the Intergovernmental Panel on Climate Change. In the scenarios considered, precipitation is expected to decrease and evaporation to increase over much of the Murray Darling Basin in the present century. The consequent reduction in surface water flows over a relatively short time frame, coupled with the delayed effects of a reduction in ground water recharge, generates both positive and negative economic and environmental impacts.

Improved water use efficiency and the existence of an operational water market were explored as possible means of adapting to the decreasing availability of surface water resources and were found to significantly mitigate the effects of a drier climate. However, both will require well defined and secure property rights to achieve the maximum economic benefit.

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Introduction

Climate change is expected to have significant impacts on the hydrological cycle at both a global and regional scale. This will in turn, affect the availability of, and demand for, water resources and the way the resources are most effectively managed. The Intergovernmental Panel on Climate Change (IPCC) was formed in 1988 to assess the nature and extent of global warming as well as options for mitigating and adapting to climate change. To date, the assessments have focused on establishing the historical relationship between greenhouse gas emissions and global warming and projecting the impact of past and future emissions on the earth's climate, and consequently on the marine and terrestrial environment.

A number of future emission scenarios have been developed to explore the links between global warming and economic development, population growth and technological progress. While none of these scenarios is linked to specific policies to reduce emissions, they have provided a range of possible outcomes against which the benefits at a global and regional level of mitigating climate change can be assessed. However, the capacity to adapt to climate change has not received the same level of attention.

This may, in part, reflect the fact that assessing the potential and incentives to adjust to changes in climatic conditions requires the explicit consideration of the links between biophysical changes in the environment, productivity and economic returns. In the contribution of Working Group II to the Third Assessment Report of the IPCC, Arnell and Chunzhen (2001) reiterate this point, concluding that there have been relatively few published studies on the impact of climate change on real world water resource systems and that most of these studies ignore the potential for adaptation.

The objective in this paper is to examine the impacts of climate change on the hydrological cycle, particularly stream and ground water flows, water quality and irrigated agriculture in Australia's Murray Darling Basin. The intent is not to project the likely extent or range of possible climate outcomes but, first, to compare how different trends in global warming may affect economic and environmental outcomes in the basin and, second, to examine the extent to which market based options, such as investments to increase water use efficiency and water trading, can be used to offset or enhance the economic impacts of climate change. These market based adaptations may, in turn, have positive or negative external effects on water flows and water quality that may warrant further consideration.

The approach taken was to, first, select a pair of contrasting global warming scenarios from the Special Report on Emissions Scenarios (SRES) that reflected a plausible range of greenhouse gas emissions by the year 2100 (IPCC 2000). The Atmospheric Research Division of Australia's Commonwealth Scientific and Industrial Research Organisation (CSIRO) has run global and regional climate models to develop long term projections for a variety of climatic variables such as precipitation, temperature and potential evaporation. Changes in these variables have been derived using climate model simulations to provide information on the magnitude of regional responses in terms of local change per degree of global warming on a 120 square kilometre grid for the Murray Darling Basin. These climatic changes were incorporated into the Salinity and Landuse Simulation Analysis (SALSA) model, developed at the Australian Bureau of Agricultural and Resource Economics (ABARE) (Bell and Heaney 2001). This model combines simulation and optimisation techniques to represent the relationships between agricultural production systems and the hydrological cycle of river catchments.

Key biophysical and economic results are presented for each scenario. The biophysical variables considered include river flows, salt loads and salt concentration at several locations on the Murray River. The economic variables under consideration include changes in net agricultural returns and the opportunity cost of irrigation water.

The Murray Darling Basin

The Murray Darling Basin covers more than one million square kilometres in south east Australia and accounts for around 14 per cent of Australia's total landmass (map 1). The basin catchment contains Australia's three largest rivers — the Darling, Murray and

Map 1: Major rivers in the Murray Darling Basin

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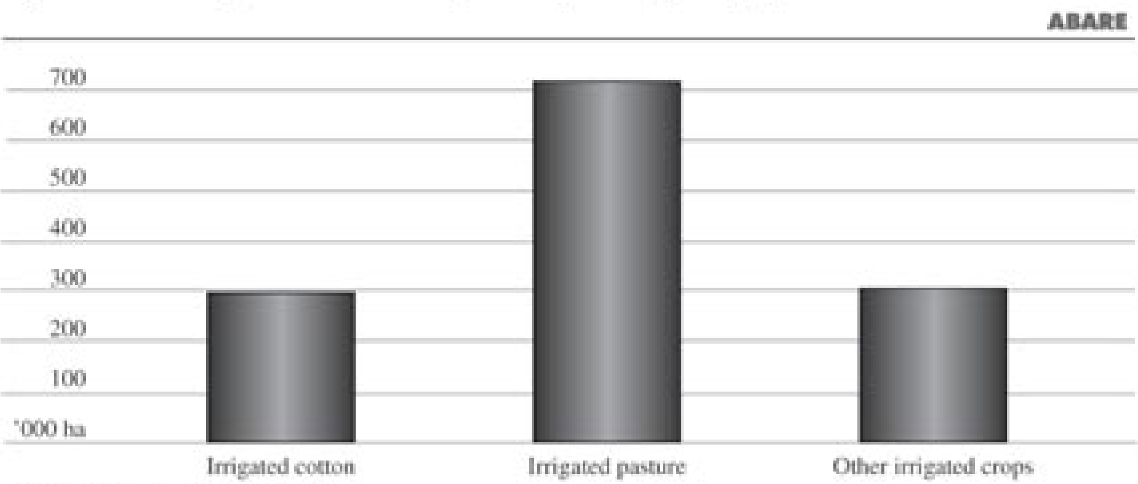
Murrumbidgee — that collectively stretch for almost 7000 kilometres. Much of the basin is extensive plains and low undulating areas, mostly below 200 metres above sea level. An important consequence of the extent of the Murray Darling Basin is the great range of climatic conditions and natural environments including rainforests in the cool and humid eastern uplands, the temperate mallee country of the south east, the subtropical areas of the north east as well as the semiarid and arid lands of the far western plains.

While the Murray Darling river system is large in terms of its catchment area and length, it is small in terms of surface water runoff. Almost 90 per cent of the basin contributes virtually no runoff to the river systems, except at times of flooding. The catchments draining the Great Dividing Range — the Murrumbidgee, Murray and Goulburn–Broken — contribute almost half of the mean annual runoff while occupying only 11 per cent of the area of the basin. The variability of rainfall in the basin means that the river systems are subject to considerable variability of flows. Because of this large variation in stream flows, storage dams are needed to provide continuity of water supplies for urban, industrial and agricultural uses. At the same time, the Murray Darling Basin provides unique aquatic, terrestrial and wetland habitats for native plants and animals.

The Murray Darling Basin accounts for more than 40 per cent of agricultural production in Australia. Valued at an estimated A$34 billion, broadacre properties grazed around 5.9 million beef cattle and 51 million sheep in 1999-2000. Wheat production exceeded 12 million tonnes in the same year. While the Murray Darling Basin is dominated by extensive dryland agriculture, irrigated agriculture in the basin accounts for around 70 per cent of all water used in Australia (Crabb 1997). An estimated 1.3 million hectares was irrigated in 1996-97 with irrigated pasture accounting for more than 50 per cent of the total area irrigated (figure 1). River systems within the Murray Darling Basin provide domestic water supplies to more than 10 per cent of the Australian population and support a range of industries.

Figure 1: Area irrigated in the Murray Darling Basin, by crop type



Source: ABS Agricultural Census 1996-97

Demand for water is high in the Murray Darling Basin and an audit of water use in 1995 showed that if the volume of water diversions continued to increase, river health problems would be exacerbated, the security of water supply for existing users would be diminished, and the reliability of water supply during long droughts would be reduced. Consequently, a cap was imposed on the volume of water that could be diverted from the rivers for consumptive uses. The cap limits further increases in water diversion but does not constrain new developments provided their water requirements are met by using current allocations more efficiently or by purchasing water from existing developments.

Global climate change – the SRES scenarios

The IPCC developed a series of greenhouse gas emission scenarios to reflect the current understanding of the likely trends in future emissions and the uncertainties that surround these trends. The differences in the scenarios are intended to represent the range of uncertainty associated with the paths that the key drivers of emissions — population growth, economic growth and technological change — may take over the next century. There are four basic SRES storylines. At one extreme, high levels of both economic and population growth coupled with slow and limited adoption of clean, resource efficient technologies lead to the largest increase in emissions. At the other extreme is a scenario with low population growth and a fairly rapid shift into resource efficient technologies and a reduction in the material intensity with the use of pollution enhancing processes and materials.

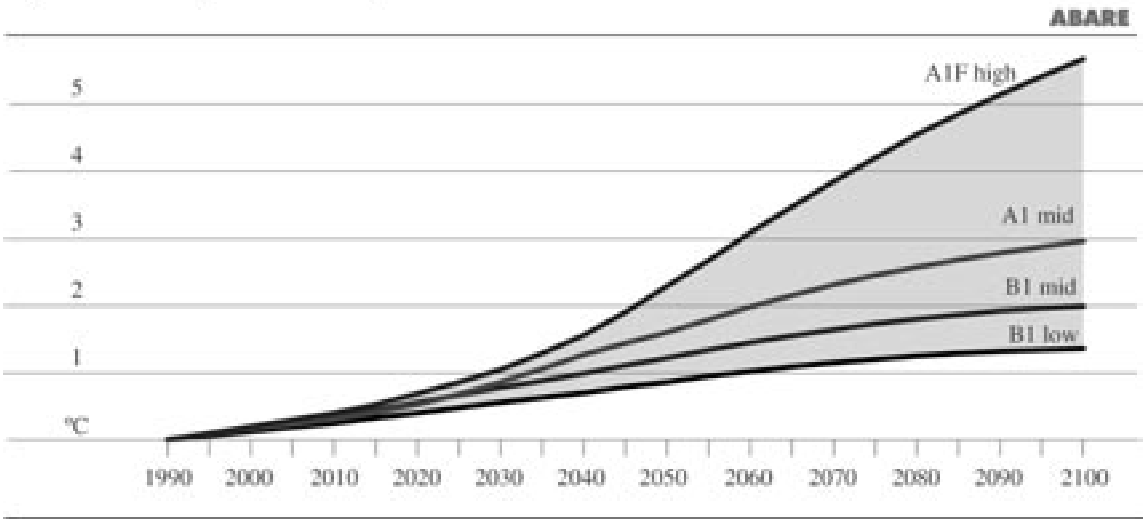
At the same time there is considerable uncertainty about the extent of global warming associated with a given trend in emissions, and the sensitivity of the climate to greenhouse trends. For each of the four SRES storylines, a set of global climate change models was used to generate potential levels of global warming to the year 2100 for each scenario. The different models were used to establish high, medium and low levels of climate sensitivity for each scenario. The advantage of using several models was that the scenarios together encompass the current range of uncertainties about future greenhouse gas emissions, in addition to the current knowledge of, and uncertainties associated with, the driving forces underlying the scenarios.

Over the full set of SRES scenarios and model projections, the level of global warming in 2100 ranges from 1.4 to 5.8°C relative to 1990. Figure 2 shows the envelope for projections in temperature rise under the SRES scenarios, with scenario A1F high generating the largest increases in temperature, and B1 low the smallest increases. The projections indicate that warming will vary by region and, while overall precipitation is expected to increase over the coming century, there are projected regional increases and decreases in average rainfall over land masses. Larger year to year variations in precipitation are very likely. The intensity and frequency of extreme weather events is also expected to increase (IPCC 2001).

The focus in this study is to examine how different global warming trends may affect the hydrological cycle and agricultural production in the Murray Darling Basin. It is not specifically concerned with the assumptions of economic, technological, demographic or other forces that underlie a specific emissions scenario. At the same time, it is useful to contrast a scenario that reflects an extension of the current trend in emissions to one in which there has been a significant reduction in emissions.

Two global warming curves were selected from within the SRES envelope shown in figure 2. The ***A1 scenario*** corresponds to a story line of high economic growth but with limited population growth, and the rapid introduction of new and more efficient energy technologies. The ***B1 scenario*** corresponds to low population growth coupled with the adoption of clean and resource efficient energy technologies. Estimates of temperature rise under both scenarios selected for this study are relatively conservative in comparison

Figure 2: SRES global warming curves



with some of the more fossil fuel intensive scenarios, with temperature predicted to increase by 2.95°C by 2100 under scenario A1, and 1.98°C under scenario B1. The global warming curves selected for each scenario reflect a moderate level of sensitivity to changes in the level of greenhouse gas emissions. The shape of the global warming curves suggests that much of the temperature increase under scenario A1 happens in the latter half of the century whereas under scenario B1, temperature increases steadily over the coming 100 years.

The shape of the curves, and hence the timing of the climate impacts, has important implications for both the biophysical and economic consequences of climate change in the Murray Darling Basin.

Climate change in the Murray Darling Basin

Regional projections of climate change in Australia under the scenarios have been conducted by CSIRO. These studies use regional climate models, on either a 125 kilometre or 60 square kilometre grid that have been nested within the CSIRO Mark II global climate model. Changes in average annual precipitation and potential evaporation are calculated using OZCLIM, a climate change scenario generator developed at CSIRO (Walsh et al. 2001). The impacts of global warming on average annual precipitation in the Murray Darling Basin for years 2050 and 2100 are shown for each scenario in maps 2 to 5. For the Murray Darling Basin, the midrange of these projections indicates that there will be a general decline in precipitation and an increase in potential evaporation. However, the extent and timing of the decline in these parameters varies across the basin in line with the differences between the global warming curves.

In scenario SRES A1, the decline in precipitation is projected to be less than 5 per cent in 2050 for almost all catchments except in those feeding the Victorian tributaries of the Murray River where the decline is expected to be between 5 and 10 per cent. Projected declines in precipitation under the SRES B1 scenario are less severe. By 2100, precipitation declines by between 5 and 10 per cent for most of the basin and by up to 20 per cent in the Victorian tributaries of the Murray River under the A1 scenario. In contrast, many of the Murray River tributaries are projected to experience a decline in precipitation of less than 10 per cent by 2100 under the SRES B1 scenario, and by less than 5 per cent in almost all of the Darling River tributaries.

Rainfall distribution is also likely to vary under climate change. Summer rainfall is expected to decline under both scenarios, particularly in the southern reaches of the basin. Reductions in summer rainfall for the Darling River tributaries are expected to be between 1 and 7 per cent under the A1 scenario and between 2 and 6 per cent for the B1 scenario in 2100. Victorian tributaries of the Murray River are expected to experience a decline in summer rainfall under both scenarios by 2100. While climate change projections based on the SRES scenarios do not yield conclusive results on the frequency of La Niña and El Niño events, the severity of both flood and droughts is expected to increase.

In addition to precipitation, climate change has an impact on temperature, humidity and wind speed, all of which have an impact potential evaporation. An increase in annual average potential evaporation is expected over the whole basin under both global warming scenarios by 2100, particularly in the Murray River tributary catchments. The impacts are greater under the A1 scenario, with increases in potential evaporation of almost 20 per cent in many of the southern reaches. On balance, the projections for the Murray Darling Basin are for slight to moderate reductions in water availability for dryland agriculture and moderate to substantial reductions in surface water flows. Increases in open water evaporation will also affect effluent stream systems, water storages and wetlands.

Map 2: **Projected decline in precipitation in the Murray Darling Basin under SRES scenario A1, 2050**

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Map 3: **Projected decline in precipitation in the Murray Darling Basin under SRES scenario A1, 2100**

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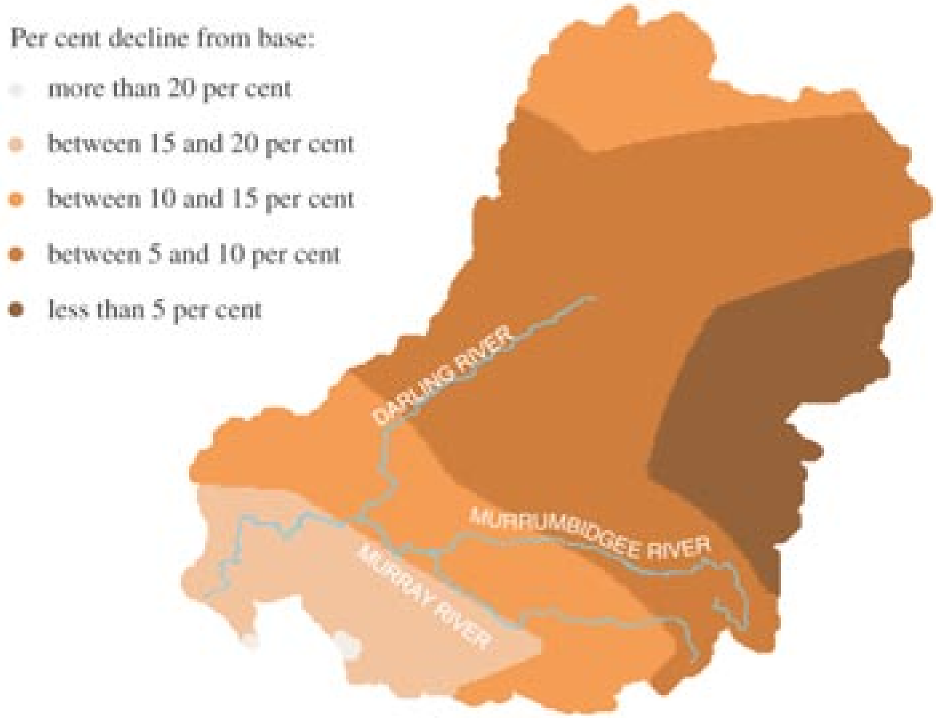

Map 4: **Projected decline in precipitation in the Murray Darling Basin under SRES scenario B1, 2050**

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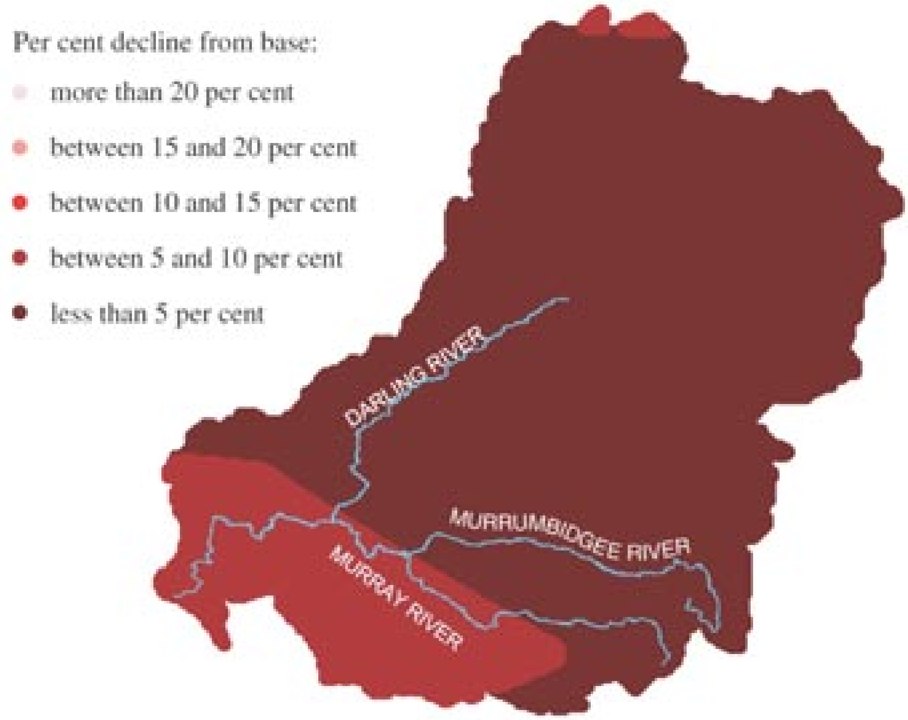

Map 5: **Projected decline in precipitation in the Murray Darling Basin under SRES scenario B1, 2100**

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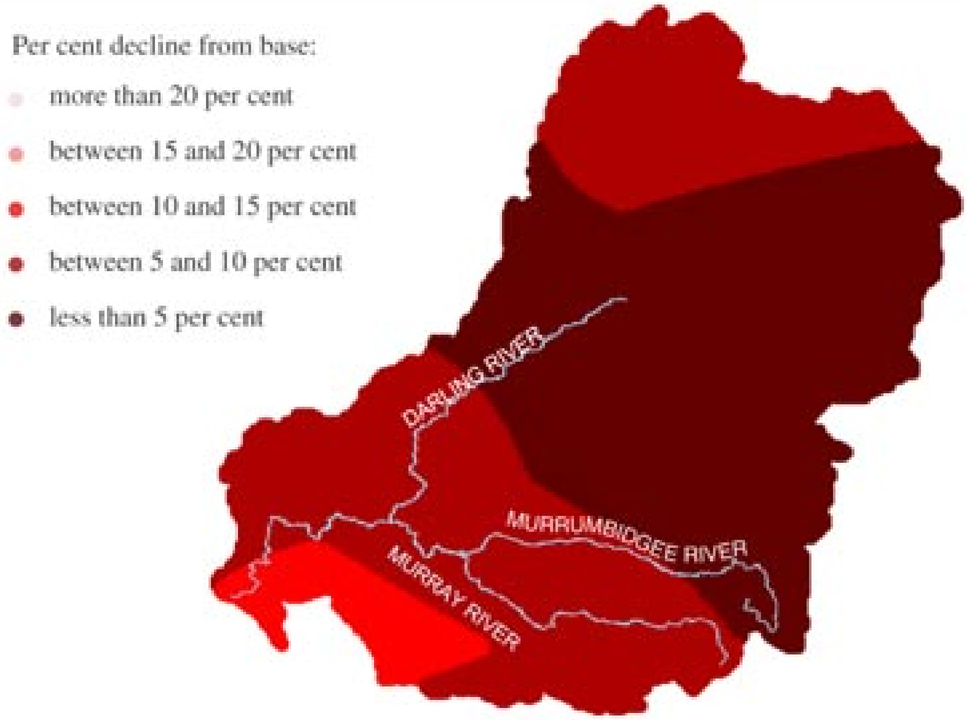

Climate change and water resources

Changes in precipitation are the prime driver of change in the availability of both surface and ground water resources. However, there are a number of other factors that can significantly affect regional water balances that are likely to be influenced by climate change. Within a simple water balance model, the volume of water available as surface water and ground water resources are the excess of precipitation over evapotranspiration. Climatic factors have a direct effect on evapotranspiration through changes in potential evaporation that occur with changes in solar radiation, humidity, temperature and wind speed at ground level.

Vegetation cover has a significant influence on evapotranspiration, with deep rooted trees and perennial species generally returning more water to the atmosphere than annual grasses and other shallow rooted species. However, the influence of vegetation cover on transpiration increases with higher precipitation (Zhang, Dawes and Walker 1999) and this may moderate the direct impacts of climate change. In low rainfall areas (less than 500 millimetres a year), different vegetation covers transpire about the same volume of water. In areas with rainfall above 500 millimetres a year, deep-rooted plants transpire an increasingly larger volume of water when compared with shallow rooted grasses. Changes in climatic conditions can, in turn, have an impact on ground cover and evapotranspiration. While the physiological response of vegetation to increased concentrations of atmospheric carbon dioxide is uncertain, higher levels of carbon dioxide can result in greater levels of water use efficiency by plants, resulting in reduced transpiration. At the same time, associated climatic effects such as higher temperatures, changes in rainfall and soil moisture could either enhance or negate potentially beneficial effects of higher carbon dioxide concentrations on plant physiology. Significant changes in temperature and precipitation may alter the species composition of ground cover and, hence, evapotranspiration also.

Precipitation that is not returned to the atmosphere (excess) is either transported as surface water runoff or enters the ground water system (ground water recharge). The fraction of this excess water that enters the ground water system depends on the rate of infiltration, the rate at which water can penetrate the soil surface and percolation through the soil profile. The rate of penetration depends on several factors including the slope or gradient of the land, size, texture and structure of the soil particles and the level of soil moisture. On more steeply sloped land there tends to be fewer and smaller local depressions to store water that can then infiltrate the soil. Clay soils have finer soil particles creating smaller gaps through which water can enter and move through the soil profile. Under these conditions most of the excess enters the river system as surface runoff. Sandy and less compacted soils have larger gaps allowing water to enter and move through the soil profile more easily than in heavier soils. Catchment runoff can be insignificant on flat terrain with sandy soils. The intensity, frequency and duration of rainfall events affect soil moisture, and the likelihood of and extent to which the soil will become saturated.

Water demand

Irrigated agriculture generates the largest consumptive demand for surface and ground water resources in the Murray Darling Basin. Around 10 000 gigalitres of surface water is diverted for irrigation in the Murray Darling Basin each year (MDBC 2002). While the availability of water for irrigation is likely to decrease under conditions of reduced precipitation and increased evapotranspiration, it is uncertain how sensitive agricultural water demands will be under enhanced greenhouse conditions. There are competing effects. First, decreased precipitation may lead to lower soil moisture profiles during the irrigation season, depending on the timing of the rainfall and the water holding capacity of the soil. Second, increases in potential evaporation through, for example, increased temperature or reduced humidity, is likely to increase losses from irrigation storages and channels. However, as noted previously, increased atmospheric concentrations of carbon dioxide can lead to higher efficiency of plant water use, reducing the level of irrigation required to obtain a given yield.

Case studies in the United States have produced some conflicting results. In a climate change scenario investigated by Hatch et al. (1999), irrigation requirements were estimated to fall by as much as 30 per cent for corn in the south east United States. However, Ritschard et al. (1999) explored the same scenario and estimated that irrigation water requirements would increase. These studies indicate the considerable uncertainty about future demand for irrigation water and, hence, irrigation abstractions under conditions of enhanced global warming (Arnell and Chunzhen 2001).

Water quality

Climate change has the potential to make a significant impact on water quality in the Murray Darling Basin. As much of the continent was covered by an inland sea several millions of years ago, saline ground water systems are part of Australia's geological legacy. Consequently, more than 25 per cent of Australia's accessible ground water is above 1500 milligrams of salt per litre (mg/L) and more than 10 per cent is in excess of 5000 mg/L (National Land and Water Resources Audit 2000). In irrigation areas along the south west reaches of the Murray River, ground water salinity levels are in excess of 30 000 mg/L, close to the salt concentration of seawater.

Rising river salinity is a major water quality issue in the Murray Darling Basin. Land clearing and irrigation have increased ground water recharge, which over time has led to rising water tables and increased discharge of saline ground water into rivers and streams. Consequently, the deterioration of river health owing to increasing salinity has been a concern to state and federal governments over recent years.

A salinity audit, released by the Murray Darling Basin Ministerial Council in 1999, projected that salt mobilisation in the basin would double from 5 million tonnes a year in 1998 to 10 million tonnes in 2100. Much of this increase is likely to be mobilised from the irrigation areas that were developed within 10 kilometres of the river in the south west reaches of the Murray River. This area, known as the Victorian Mallee and South Australian Riverland, is characterised by extensive horticultural production. While these regions often practise highly efficient irrigation using sophisticated irrigation scheduling and delivery technology, they overlay highly saline ground water aquifers and any ground water leakage results in large volumes of salt being mobilised to the Murray River. The audit also reported that the average salinity of the Murray River at Morgan, upstream of the major offtakes of water supplies to Adelaide, a city of more than one million people in South Australia, will exceed the 800 EC[1] World Health Organisation threshold for desirable drinking water quality in the next fifty to one hundred years (MDBMC 1999).

Changes in climatic conditions will have both short and longer term impacts on river and stream salinity. If, for example, there is a reduction in precipitation, there will be an immediate reduction in surface water runoff and less water available to dilute existing levels of saline ground water discharge. The decline in water quality will affect agriculture as the productivity of water used for irrigation is reduced. It will also affect the riverine environment as well as urban and industrial water users.

However, reductions in precipitation and increases in evapotranspiration lead to reduced recharge that, over time, is reflected in a reduction in saline ground water discharge and lower ground water tables. The length of the delay could range from a few years to several hundred years depending on the hydrological characteristics of the ground water flow system. The reduction in ground water discharge leads to benefits that are twofold. Salinity benefits are derived from the reduction in the discharge of saline water directly into rivers and streams. Depending on the hydrological characteristics of the catchment, reductions in salt mobilisation may translate into lower salt concentrations even under conditions of reduced surface water flows. Salinity benefits are also derived if the reduction in discharge reduces the mobilisation of saline ground water into the landscape.

Reductions in the area affected by dryland salinity are likely to vary across the basin, with the timing and extent dependent on the net effect of changes in the hydrological cycle, the response time of the ground water flow system and the rate of recharge in each catchment. The impact of global warming on surface water and ground water flows, salt concentration and the area of high water tables under the SRES A1 and B1 scenarios are examined using the SALSA model, described in the following section.

[1] The most widely used method of estimating the salinity concentration of water is by electrical conductivity. To convert EC units to mg/L total dissolved salts, multiplication by a conversion factor of 0.6 generally applies.

The SALSA model

The SALSA modeling framework was developed at ABARE, in cooperation with the Murray Darling Basin Commission and CSIRO Land and Water Division. The model was developed using the user interface and simulation facilities of Extend (v4) (Imagine That Inc. 1997). The model incorporates the relationships between land use, vegetation cover, surface and ground water hydrology and agricultural returns. The basin scale model consists of a network of land management units linked through overland and ground water flows. The geographic area under consideration is shown in map 6.

The spatial coverage of the SALSA model includes the predominantly dryland regions of the Murray Darling Basin spanning from the Condamine–Culgoa catchment in southern Queensland clockwise around the eastern edge of the basin to the Avoca catchment in Victoria. Irrigation within each of these catchments is also represented. The SALSA model also includes the Victorian Mallee and South Australian Riverland irrigation areas immediately adjacent to the Murray River that extend from Nyah downstream to Morgan[2]. In

Map 6: Cachments in the Murray Darling Basin covered by the SALSA model

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[2] All data presented for the Victorian Mallee and South Australian Riverland refer to irrigation areas within 10 kilometres of the Murray River. It is assumed that dryland agriculture more than 10 kilometres from the Murray River will not contribute salt loads to the river system.

the analysis presented here, 78 individual land management units are defined according to the characteristics of the ground water system — that is, they are classified according to whether they are local, intermediate or regional flow systems.

Within each land management unit, economic models that optimise land use are integrated with a representation of hydrological processes in each catchment. The hydrological component incorporates the relationships between irrigation, rainfall, evapotranspiration and surface water runoff, the effect of land use change on ground water recharge and discharge rates, and the processes governing salt accumulation in streams and soil. The interactions between precipitation, vegetation cover, surface water flows, ground water processes and agricultural production are modeled at a river reach scale. In turn, these reaches are linked through a network of surface and ground water flows.

In the agroeconomic component of the model, land is allocated to maximise economic return from the combined use of agricultural land and irrigation water. Each land management unit is managed independently to maximise returns given the level of salinity of available land and surface and ground water resources, subject to any land use constraints. Incorporated in this component is the relationship between salinity and yield loss for each agricultural activity. Thus, land use can shift with changes in the availability and quality of both land and water resources. The cost of salinity is measured as the reduction in economic returns from agricultural activities from those that are currently earned. Some key features of the model are described briefly below. A full description is given in Bell and Heaney (2001).

Hydrological component

The hydrological component of the model consists of three parts. The first determines the distribution of precipitation and irrigation water between evaporation and transpiration, surface water runoff and ground water recharge. Within this component of the model there are two climatic drivers that are specified uniquely for each hydrologically defined land management unit — average annual rainfall and evapotranspiration — specified as a function of rainfall and land cover.

In the initial specification of the SALSA model, the Holmes–Sinclair relationship was used to specify the link between ground cover and evapotranspiration. For a given ground cover, the Holmes–Sinclair relationship (estimated by Zhang et al. 1999) relates evapotranspiration to precipitation. The relationship does not include variation in potential evaporation, as it was not found to be a significant discriminator. However, in the climate change scenarios that were evaluated, projected changes in potential evaporation were large in comparison with projected changes in precipitation using the Holmes–Sinclair relationship.

A study conducted by Hassel and Associates (1998) estimated the impact of high and low climate change scenarios on surface water runoff in the Macquarie–Bogan catchment of New South Wales. The study used a Sacramento model (Burnash, Ferral and McGuire 1984) that incorporates changes in potential evaporation to estimate catchment runoff. Runoff was then used to generate stream flows that were calibrated using the IQQM daily flow model (New South Wales Department of Land and Water Conservation 1995). The Sacramento model generated changes in stream flows that were approximately three times greater that would be predicted using the Holmes–Sinclair relationship.

Given the likely sensitivity of the analysis to the incorporation of potential evaporation, the Holmes–Sinclair evapotranspiration relationship used in the SALSA model was modified to account for changes in potential evaporation. The relationships for tree and grass covered catchments provided the envelope for all other groundcovers used in the SALSA model. (The relationship between precipitation and evapotranspiration for all other groundcovers was specified as a linear combination of the relationships for trees and grass.)

The relationship for tree cover was specified as:

(1) $$ET_{Trees} = ppt\left(1+\frac{\Delta 2800}{ppt}\right)\left(1+\frac{\Delta 2800}{ppt}+\frac{ppt}{\Delta 400}\right)^{-1}$$

where

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

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

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

An α of 0 gives the original Holmes–Sinclair specification and a value of 1.0 provided a reasonable fit to the runoff relationships generated by the IQQM model in the Macquarie–Bogan catchment. An α value of 1.0 was used for the simulations conducted and reported here. A simulation using the original Holmes–Sinclair specification is reported in appendix A for comparison.

The second hydrological component of the model determines surface water runoff and ground water recharge. The distribution of the excess between surface and ground water recharge is assumed to be a constant proportion. For example, on heavier, less permeable soils on the steeper terrain of the upland catchment areas, ground water recharge fractions range from 10 to 30 per cent. On the sandier, more permeable soils on flat terrain in the low lying catchment areas, recharge fractions were between 80 and 100 per cent.

The third part of the hydrology component determines ground water discharge into streams and into the landscape in the form of high water tables. The equilibrium response time of a ground water flow system is the time it takes for a change in the rate of recharge to be fully reflected in a change in the rate of discharge. The equilibrium response time does not reflect the actual flow of water through the ground water system but the transmission of water pressure.

Assuming the contributions of recharge are additive and uncorrelated over time, it is possible to model gross discharge directly, thereby avoiding the need to explicitly model ground water levels. In the approach adopted here, total discharge rate D in year t is a logistic function of a moving average of recharge rates in the current and earlier years according to:

(3) $$D(t) = R(0) + \sum_{i=t-m}^{t} \frac{R(i) - R(i-1)}{1 + \exp\left[\left(v_{half} - i\right) / v_{slope}\right]}$$

where $R(0)$ is the initial equilibrium recharge rate, m is the number of terms included in the moving average calculation, and v_{half} and v_{slope} are the time response parameters. The moving average formulation allows the accumulated impacts of past land use change to be incorporated, as well as to model prospective changes.

Ground water response times within the Murray Darling Basin vary substantially. In the upland areas, there tends to be greater hydraulic head and shorter lateral flow distances to the point of discharge, predominantly into small streams. Average equilibrium response times in these areas range between 60 and 120 years. In the low lying catchment areas, where there is very little hydraulic head and lateral flow distances are long, equilibrium response times can be well in excess of 1000 years. In established irrigation areas the soil can be saturated and the ground water system nearly pressurised. Equilibrium response times under these conditions are much faster, of the order of twenty to forty years.

Agroeconomic component

Changes in water availability, quality and the emergence of high water tables all have an impact on agricultural productivity. The agroeconomic component of the model seeks to maximise the returns to agriculture under the current conditions of the resource base. The management problem considered in the agroeconomic component of the model is that of maximising the economic return from the use of agricultural land by choosing between alternative steady state land use activities in each year. Five land use activities are considered — irrigated crops, irrigated pasture, irrigated horticulture, dryland crops and dryland pasture.

Each land management unit is assumed to allocate its available land each year between the above activities to maximise the net return from the use of the land in production, subject to constraints on the overall availability of irrigation water from rivers, sw^*, and from ground water sources, gw^*, and suitable land, L^*:

(4) $$\max \frac{1}{r}\sum_j p_j x_j\left(L_j, sw_j, gw_j\right) - csw\sum_j sw_j - cgw\sum_j gw_j$$

subject to

(5) $$\sum_j sw_j \leq sw^*, \sum_j gw_j \leq gw^* \text{ and} \sum_j L_l \leq L^*$$

where x_j is output of activity j, L_j is land used in activity j, sw_j is surface water and gw_j is ground water used for irrigation of activity j, r is the discount rate, and ***csw*** is the unit cost of surface water used for irrigation and cgw is the unit cost of ground water used for irrigation. The net return to output for each activity is given by p_j and is defined as the revenue from output less the cost of inputs, other than land and water, per unit of output.

For each activity, the volume of output depends on land and water use (or on a subset of these inputs) according to a Cobb-Douglas production function:

(6) $$x_j = \begin{cases} A_j L_j^{\alpha_{Lj}} sw_j^{\alpha_{swj}(t)} gw_j^{\alpha_{gwj}} & 0 < \alpha_{Lj} + \alpha_{swj} + \alpha_{gwj} < 1 \text{ for } j = 1,2,3 \\ A_j L_j^{\alpha_{Lj}} & 0 < \alpha_{Lj} < 1 \qquad \text{for } j = 4,5 \end{cases}$$

where A_j, α_{Lj}, α_{swj} and α_{gwj} are technical coefficients in the production function. Note, the technical coefficients on surface irrigation water are time dependent, to capture the impact of changes in salt concentration in the Murray River.

The costs to irrigated agriculture and horticulture resulting from yield reductions caused by increased river salinity are modeled explicitly. The impact of saline water on the productivity of plants is assumed to occur as plants extract saline water from the soil. The electro-conductivity, EC, of the soil reflects the concentration of salt in the soil water and reduces the level of output per unit of land input (land yield) and per unit of water input (water yield). This is represented by modifying the appropriate technical coefficients, α_{swj}, in the production function for each activity from the level of those coefficients in the absence of salinity impacts. That is:

(7) $$\alpha_{swj}(t) = \frac{\alpha_{swj}^{\max}}{1 + \exp\left(\mu_{0j} + \mu_{1j} EC\right)}$$

where μ_{0j} and μ_{1j} are productivity impact coefficients determined for each activity and α_{swj}^{max} is the level of the technical coefficient in the absence of salinity.

Model calibration

The data required to calibrate the model are extensive. The calibration procedure is given in Bell and Heaney (2001). The key physical data were historical rainfall, stream flow and salt load, and projected salt loads and areas of high water tables. Historical flows and salt loads were obtained from Jolly et al. (1997). Projected salt loads were obtained from the national salinity audit (MDBMC 1999), Barnett et al. (2000) and Queensland Department of Natural Resources (2001). These data, in combination with the expertise of consulting ground water hydrologists, were used to determine the hydrological parameters of the model.

Agroeconomic data were obtained from a wide range of sources. Land and water use data were obtained from many sources including ABARE farm survey data, Australian Bureau of Statistics Agricultural Census data and regional water authorities. Farm survey data were the primary source of the data used to estimate the fully capitalised returns to various land use activities in the model. These returns were then used to calibrate the production functions.

To calculate initial values for the production function parameters in (6), the total rent at full equity accruing to each activity was first calculated as the summation of rent associated with the use of land and other fixed inputs to production and surface and ground water. That is:

(8) $$RentTotal_j = RentL_j + RentSW_j + RentGW_j + RentOther_j$$

where

(9) $$\begin{aligned} RentL_j &= L_j(0)p_{\min} \\ RentSW_j &= sw_j(0)c\tilde{s}w \\ RentGW_j &= gw_j(0)c\tilde{g}w \\ RentOther_j &= L_j(0)\left(p_j - p_{\min}\right) \end{aligned}$$

where p_{min} is the net return to land and other fixed capital structures in their marginal use and $c\tilde{s}w$ is the opportunity cost of surface water used for irrigation and $c\tilde{g}w$ is the opportunity cost of ground water used for irrigation in the initial period. Data on the marginal value of agricultural land in Australia are not generally available; hence it was simply assumed that the marginal value was 50 per cent of the average return from the lowest returning activity. Trade prices for permanent water entitlements are a potential source of information on the opportunity costs of irrigation water. However, there are significant physical and institutional constraints on water trade between catchments in the Murray Darling Basin and trade, to date, has been limited. In regions where there are large volumes of water used to produce irrigated pasture and cereal crops, the annual opportunity cost of water was assumed to be in the range $20–30 a megalitre. In cotton and horticultural areas the opportunity cost of water was assumed to be considerably higher at $70 and $150 a megalitre respectively.

Initial values for the production function coefficients for each activity were then determined as:

(10)
$$\alpha_{Lj}(0) = \frac{RentL_j}{RentTotal_j}$$
$$\alpha_{swj}(0) = \frac{RentSW_j}{RentTotal_j}$$
$$\alpha_{gwj}(0) = \frac{RentGW_j}{RentTotal_j}$$
$$A_j = L_j(0)^{1-\alpha_{Lj}(0)} sw_j(0)^{-\alpha_{swj}(0)} gw_j(0)^{-\alpha_{gwj}(0)}$$

Within a simulation, these coefficients are adjusted from the initial values according to equation (6). The coefficients in equation (6) were derived from estimated yield losses caused by irrigation salinity (MDBC 1999).

The Murray Darling Basin Commission has linked its hydrological modeling to estimates of cost impacts based on incremental increases in salinity. Costs downstream of Morgan are imputed as a function of EC changes in salt concentration at Morgan. The analysis considers agricultural, domestic and industrial water uses. Using the cost functions derived in this model, each unit increase in EC at Morgan is imputed to have a downstream cost of $173 450 (Doug Young, Primary Resources South Australia, personal communication, January 2002). This cost is included in the analysis presented here.

Changes in annual average precipitation and potential evaporation were estimated for the SRES climate change scenarios using the scenario generator OZCLIM version 2.0.1. Changes in these variables were estimated as percentage changes from the base year 1995 for the years 2020, 2050 and 2100. The intervening years were linearly interpolated. The output generated by OZCLIM was then translated into a GIS point coverage using ArcInfo. Precipitation and potential evaporation data were extracted for each the land management unit in the SALSA model using ArcView3.1. These data were incorporated into the hydrological component of the modeling framework described previously.

Reductions in precipitation are projection for both the A1 and B1 scenarios. In isolation, this would be expected to increase irrigation water requirements and reduce dryland yield. At the same time, increased concentrations of atmospheric carbon dioxide, are likely to result in greater water use efficiency by plants. The extent to which one of these offsetting factors will dominate is highly uncertain. In the analysis presented here it was assumed that dryland crop yields are unaffected by global warming.

Simulation design

To create a reference point, a 100 year simulation under constant climatic conditions was run. Two simulations were undertaken to compare climate change impacts under the SRES A1 and B1 global warming scenarios. Two further simulations were undertaken for each of the global warming scenarios to assess the capacity of improved irrigation water use efficiency and water trading as means of adapting to the impacts of climate change.

The purpose of conducting the reference simulation was to allow the isolation of the impacts associated with projected climatic changes from those impacts associated with increasing salinity of soil and water resources. Within the SALSA model, past changes in land use impact significantly on future river flows and salt concentrations, regardless of future climatic conditions. These, in turn, affect future economic returns. The reference simulation was used as a base from which to measure changes in biophysical and economic outcomes due to changing climatic conditions and any adjustments made in response to those conditions.

It was assumed that the existing cap on current extractions for consumptive use in the Murray Darling Basin would be maintained in volumetric terms for all simulation runs. As a consequence, any increases in river flows above current levels are implicitly allocated to the environment. Current estimates of average annual water use were used to determine shares of entitlements to surface water flows. These shares were then used to adjust volumetric allocations given any reductions in river flows due to climate change. Within an irrigation region, water trade is implicit in that water is sourced from the lowest returning activity in the event of a reduction in water availability. Trade between catchments has been very limited in the Murray Darling Basin due mainly to institutional impediments and has not been incorporated into the SALSA model.

Input and output prices, irrigation water use efficiency and, with the exception of salinity induced changes in yield, productivity were held constant in the reference simulation. A real discount rate of 3 per cent was used to calculate net present values.

The impact of climate change on the use of ground water resources for irrigation was not modeled. In general, ground water is an important source of irrigation water in the northern catchments of the Murray Darling Basin where the underlying aquifers are large. In some irrigation regions, for example those along the Namoi River, there is significant ground water extraction from shallow river aquifers and the impact of climate change on this resource could be significant.

Water use efficiency scenario

The extent to which irrigators respond to reduced allocations or higher water prices by investing in delivery infrastructure or altering management practices to increase water use efficiency in the Murray Darling Basin remains largely unknown. Prior to the cap being placed on diversions in 1995, there was little incentive for irrigators to increase water use efficiency and hence there is likely to be considerable room to adopt water saving technologies and practices in many areas. Hafi, Kemp and Alexander (2001) reports that total system losses could be reduced by around 50 per cent with the refurbishment of channels, increased use of drip irrigation and reuse systems in two irrigation areas in the Murrumbidgee catchment. In the horticultural areas of South Australia, water use efficiency is relatively high, of the order of 75–80 per cent, because closed delivery systems are used. However, improved management techniques, such as the use of moisture probes to improve scheduling and reduce irrigation depths, have the potential to substantially increase water use efficiency on-farm (Anthony Meisner, Department of Environment, Heritage and Aboriginal Affairs, South Australia, personal communication, November 2000 and April 2002).

In the water use efficiency scenario, irrigation losses through ground water leakage, drainage and overland return flows were reduced by 50 per cent over the 100 year simulation. For example, in a region with a base level of water use efficiency of 60 per cent, an additional 20 per cent was phased in to increase efficiency by 80 per cent by 2100. It is likely that improvements would occur in response to the decreased availability of water for irrigation. Therefore, the rate at which efficiency gains were introduced was scaled to match the rate of change in precipitation under the different global warming scenarios. The change in precipitation to 2100 was used as a base. For example, if precipitation falls by 3 per cent in 2050 and by 10 per cent in 2100, the reduction in irrigation losses in 2050 would be 15 per cent; three-tenths of the maximum savings of 50 per cent. The capital cost of undertaking the efficiency improvements was not included in the analysis.

After increasing irrigation efficiency, less water is needed to maintain the same level of crop production, leading to water savings. Under the current property rights structure in the Murray Darling Basin, irrigators have the implicit right to retain the water saved. In the simulations presented here, irrigators retain these savings and use them to expand irrigated production. Alternatives not considered include leaving the savings in the river as a dilution flow or trading them if an operational water market exists. The results of the water use efficiency simulations are presented as changes in regional agricultural returns.

Water trade scenario

Water trading between irrigation areas has the potential to allow irrigators flexibility to adapt to climate change if water can be purchased to meet any shortfall in crop requirements. Even with appropriate property rights and institutional arrangements, the potential to trade water from outside the catchment does not exist in all regions. In the northern catchments of the Murray Darling Basin, irrigation takes place on tributary rivers and there is little or no potential for water to be traded between catchments. However, in the southern part of the basin, the majority of irrigation water is sourced from the main stem of the Murray River and the potential for water trade is extensive.

Trade was emulated by first calculating the reduction in allocation associated with a decline in surface water availability. It was assumed that the high value production regions in the South Australian Riverland and Victorian Mallee would maintain current levels of water use through trade. The required volumes were calculated and sourced from irrigation areas in catchments upstream of the confluence of the Murray and Murrumbidgee rivers, excluding the Avoca. These upland catchments tend to have large irrigation areas under lower value cropping or pasture activities. As in the water use efficiency simulations, the results of the trade simulations are presented as changes in regional agricultural returns. The value of the water traded was not included in the analysis.

Results

The key variables reported for each simulation are changes in the net present value of agricultural production, and river flows and salt concentration for selected tributary rivers and points along the Murray River. The tributary rivers selected were the Gwydir, a tributary of the Darling River in the north of the Murray Darling Basin, and the Goulburn–Broken, a tributary of the Murray River, in the uplands of Victoria. The reported river flows and salt concentrations are for points above irrigation offtakes and are intended to show the impact of climate change on catchment runoff. The points along the Murray River include the confluences of the Murrumbidgee and the Darling Rivers and at the last lock along the Murray River at Morgan. The salt load in the Murray River is heavily influenced by irrigation. Salinity levels and flows at Morgan have traditionally been used as standards for water quality in the Murray River. Downstream of Morgan, the major source of consumptive water demand is from industrial and urban use in Adelaide.

As noted, changes in land use in the Murray Darling Basin over the past century are expected to have a substantial impact on water availability and quality, with consequent effects on agricultural returns over the next 100 years. This reflects the delay between increases in ground water recharge, caused by the clearing of native vegetation for pasture and crop production, and its eventual discharge into the river system. This is reflected in the constant climate reference simulation. In the reference simulation, salinity at Morgan increases from 307 mg/L in 2000 to 454 mg/L in 2100 (512 EC to 757 EC). The area subject to high water tables increases nearly threefold, from around one million hectares to almost three million hectares. The net present value of agricultural returns is projected to fall by more than $660 million and costs to urban and industrial users below Morgan are projected to be around $525 million.

The result from the SRES A1 and B1 scenarios, without trade or water use efficiency adaptation, are presented in tables 1 and 2. In the SRES A1 scenario, climate change imposes costs to agriculture of almost $1.2 billion in net present value terms. This falls to about $0.8 billion under the SRES B1 scenario. As it was assumed that dryland agricultural yields are unaffected by the combination of declining precipitation and increased atmospheric concentrations of carbon dioxide, these declines are principally caused by the reduction in surface water flows and consequent reduction in irrigated agricultural production. Increased river salinity also reduces irrigation yields and imposes additional costs on urban and industrial users below Morgan but the order of magnitude of these impacts is considerably lower.

There are substantial reductions in flow under both scenarios. In the SRES A1 scenario, flow reductions range across the catchments from 16 to 25 per cent in 2050 and between 24 and 48 per cent by 2100. The reductions in precipitation and increases in potential evaporation are lower in the SRES B1 scenario generating smaller reductions in stream flows. The difference in flows between the scenarios escalates over time. Flows are between 4

Table 1: **Changes in economic returns for the SRES climate scenarios, compared with the reference case**

Region	**SRES A1 No trade**	**SRES B1 No trade**	**Difference between scenarios**
	$m, npv	$m, npv	%
Northern catchments	–480	–326	32
Southern catchments	–442	–287	35
Victorian Mallee and South Australian Riverland	–256	–177	31
Adelaide	–50	–36	28
Total	–1 228	–826	33

Table 2: **Flows and salt concentrations at selected locations**

	Reference scenario			**Change to 2050**		**Change to 2100**	
Location	**2000**	**2050**	**2100**	**A1**	**B1**	**A1**	**B1**
Flows	GL	GL	GL	%	%	%	%
Goulburn–Broken River	2 397	2 475	2 481	–19	–15	–35	–23
Gwydir River	587	619	679	–25	–19	–48	–30
Murrumbidgee River **a**	7 453	7 691	7 863	–14	–10	–24	–16
Darling River **a**	8 237	8 583	8 851	–16	–12	–29	–20
Morgan	6 898	7 210	7 451	–16	–12	–29	–20
Salinity	Mg/L	Mg/L	Mg/L	%	%	%	%
Goulburn–Broken River	52	60	62	15	13	40	21
Gwydir River	123	145	182	19	16	72	35
Murrumbidgee River **a**	138	153	177	–8	–6	–25	–16
Darling River **a**	222	269	302	2	1	–12	–8
Morgan	307	397	454	4	2	–10	–6

a At the confluence of the Murray River.

and 6 per cent higher in the SRES A1 scenario than under the SRES B1 scenario in 2050, and between 8 and 18 per cent higher in 2100.

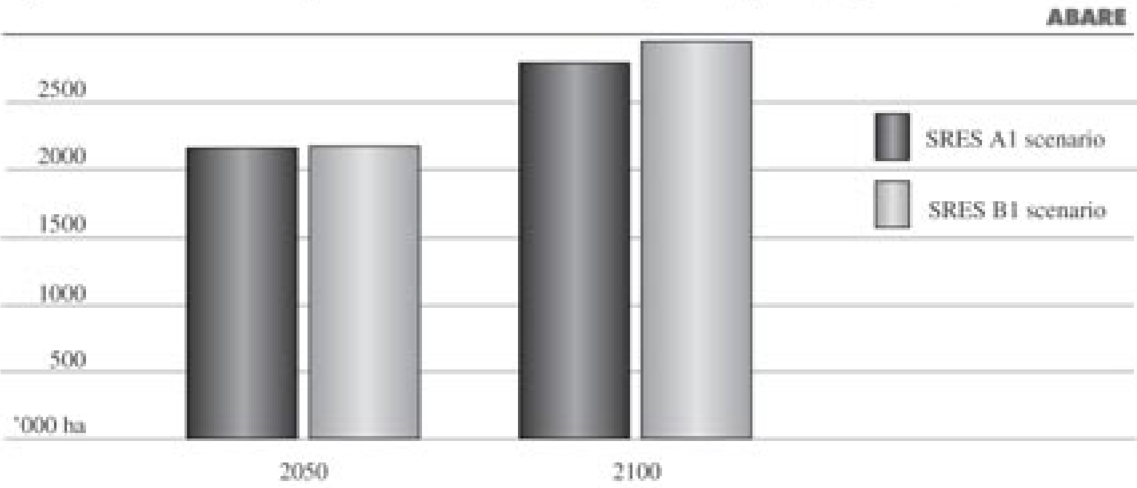
The impact of the two climate change scenarios on water quality varies over time and location, reflecting differences in both land use and the underlying hydrology of each land management unit. Salt concentration tends to increase in the tributary rivers above irrigation areas as surface water runoff declines by a greater proportion than salt loads, particularly in the shorter term. There are increases in river salinity in both the Goulburn–Broken and Gwydir Rivers under both climate change scenarios, with the more severe impacts under the SRES A1 scenario.

Increasing river salinity is caused by two factors. First, there is an immediate reduction in both surface runoff and ground water recharge. However, there is a substantial delay before a reduction in recharge is fully reflected in a reduction in ground water discharge and a corresponding reduction in salt loads mobilised into the river system. Initially, the decrease in saline discharge from the ground water system is more than offset by the reduced dilution effect of lower river flows leading to increased river salinity. Second, the excess precipitation over evapotranspiration that enters the river system as runoff tends to be large relative to that which enters the ground water system. As a result, the salinity benefits from the eventual reduction in ground water discharge can be more than offset by the reduction in surface water flows available to dilute existing salt loads, even in the longer term. However, the benefits from reduced recharge may outweigh the costs associated with reductions in surface water flows if ground water salinities are quite high.

While irrigation areas are generally significant exporters of salt to the river system, they also tend to have saturated soil profiles, meaning that a change in recharge leads to a reduction in discharge relatively quickly. Consequently, the impact of climatically induced changes to precipitation and evaporation below irrigation areas is quite different. Salinity levels tend to increase only marginally or even decline as the volume of irrigation water applied falls and this reduction is quickly translated into a reduction in ground water discharge. As a result, water quality in the Murray River is higher under the SRES A1 scenario even though it tends to generate more adverse impacts on catchment runoff than the SRES B1 scenario. In this instance, the benefits of reduced recharge under the SRES A1 scenario offsets the reduction in surface water flows generating water quality benefits in the Murray River.

The fact that increased global warming may generate both positive and negative environmental impacts is further illustrated in figure 3, which shows the areas affected by high water tables in the two scenarios. High water tables reduce agricultural yields, damages transport, communication and other infrastructure though water logging and by depositing salt into the landscape (dryland salinity). The extent of the damage that occurs as a result of high water tables is highly dependent on the salinity of ground water being

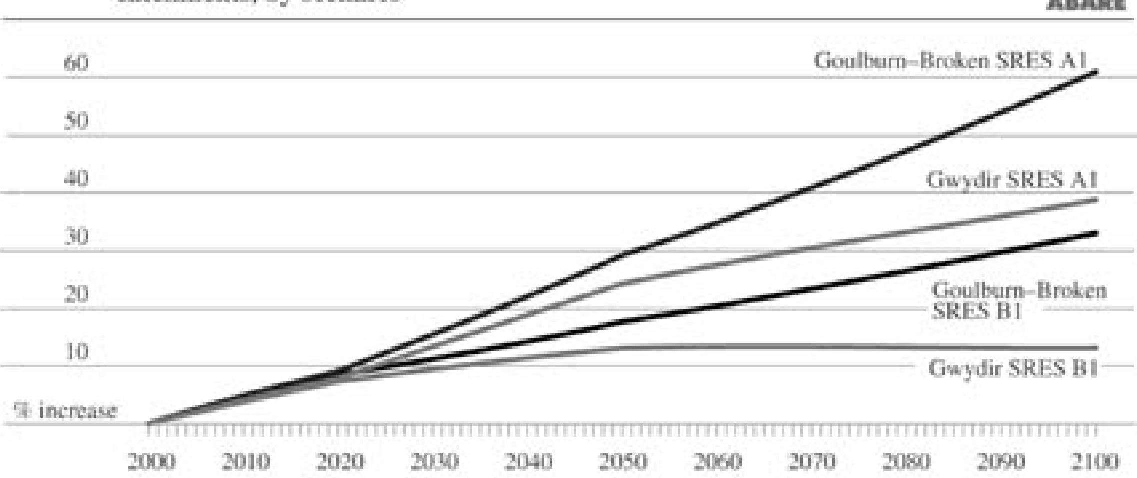
Figure 3: Total area of high water tables in the Murray Darling basin, by SRES scenario



mobilised into the landscape. Production losses are higher with higher ground water salinity. The areas affected by high water tables under the two scenarios do not begin to diverge until after 2050 because of the delayed response of the ground water system. By 2100, however, the area affected by high water tables is lower under the SRES A1 scenario. This is because the reduction in precipitation leads to a larger reduction in recharge. It is important to note that while reductions in ground water recharge tend to have benefits in saline ground water systems, it can also impose costs though reduced ground water availability for irrigation and higher pumping costs in fresh ground water systems.

The evaluation of these scenarios did not take into account any economic incentives to adapt to climate change. These economic incentives are potentially quite large as the opportunity cost of water increases with decreasing availability. The opportunity cost of water in the irrigation areas of the Goulburn–Broken and Gwydir catchments is shown in figure 4.

Figure 4: The opportunity costs of irrigation water in the Goulburn–Broken and Gwydir catchments, by scenario



Under the SRES A1 scenario, the opportunity cost of water increases by 60 per cent in the Goulburn–Broken catchment and by almost 40 per cent in the Gwydir catchment without water trade. Under the SRES B1 scenario, it increases by 35 per cent and 12 per cent respectively. The larger percentage increase in the Goulburn–Broken reflects the greater range of irrigated activities undertaken in this region.

As the volume of surface water available for irrigation use decreases, agricultural producers are likely to adapt to the scarcity, and hence increasing water prices, by improving their water use efficiency through either better delivery systems or improved irrigation management practices. The adoption of more efficient irrigation practices is likely to be widespread as demands for water from competing consumptive and nonconsumptive uses increase. In addition, water trading will give producers more flexibility to adapt to the impacts of climate change by allowing water to be transferred to the highest value uses.

The impacts of climate change with improved water use efficiency and an operational water trading market on economic returns are reported in table 3. Improvements in water use efficiency have the potential to generate significant reductions in the agricultural costs of climate change. The hypothetical improvement in water use efficiency modeled here reduces the costs of climate change under the SRES A1 scenario by almost 60 per cent. Water use efficiency improvements generate agricultural benefits, as irrigators are able to maintain, or in some instances expand, irrigated production. The agricultural returns generated more than offset the cost of climate change under the SRES B1 scenario. It should be noted that the incentive to increase water use efficiency would be lower under the SRES

Table 3: **Change in economic returns, net of the reference simulation, for the SRES climate scenarios with water trading and improved water use efficiency**

Location	**No adaptation**	**Trade**	**Difference between no adaptation and trade**	**Water use efficiency (WUE)**	**Difference between no adaptation and WUE**
	$m, npv	$m, npv	%	$m, npv	%
SRES A1					
Northern catchments	–480	–480	0	–275	43
Southern catchments	–442	–470	–7	6	101
Victorian Mallee and South Australian Riverland	–256	3	101	–73	71
Adelaide	–50	–55	–11	118	340
Total	–1 228	–1 002	18	–224	82
SRES B1					
Northern catchments	–326	–326	0	–25	92
Southern catchments	–287	–306	–7	524	282
Victorian Mallee and South Australian Riverland	–177	3	102	–8	95
Adelaide	–36	–42	–16	173	583
Total	–826	–671	19	663	180

B1 scenario as the reduction in water availability is smaller than under the SRES A1 scenario.

There are, however, significant biophysical outcomes associated with the different scenarios (table 4). These occur for two reasons. First, improved water use efficiency leads to a reduction in return flows through reductions in surface water runoff, ground water discharge and drainage that reach the river system. This results in reduced water availability for downstream users if efficiency is improved in areas with relatively low base levels of irrigation efficiency and hence high levels of surface water runoff. As consumptive water use from the Murray River is capped, the reduction in return flows may generate a cost borne by downstream water users if reduced availability leads to reduced allocations. Flow levels at different points along the Murray River for improvements in efficiency under both SRES scenarios are shown in table 4. Decreases in flows occur under both scenarios as crops transpire a greater proportion of the irrigation water applied. The changes are larger in 2100 than in 2050 because the rate of increase in water use efficiency was aligned to declines in precipitation.

Second, reduced ground water discharge reduces the level of salt mobilised into the river system. If efficiency improvements are undertaken in areas with highly saline ground water, water quality benefits resulting from the reduction in the volume of saline discharge to the river system may more than offset the reduction in available surface water flows, generating downstream benefits. The water quality impacts of an improvement in water use efficiency are shown in table 4. Despite the reduction in flows, reduced leakage into the ground water system results in a much greater proportionate reduction in saline ground water discharge generating substantial improvements in water quality. The improvement in water quality in the longer term is greatest under the SRES A1 scenario as the combination

Table 4: **Changes in flows and salt concentrations from the reference scenario, at selected locations with adaptation**

	Water use efficiency				Trade			
Location	**Change to 2050**		**Change to 2100**		**Change to 2050**		**Change to 2100**	
	A1	**B1**	**A1**	**B1**	**A1**	**B1**	**A1**	**B1**
	%	%	%	%	%	%	%	%
Flows								
Murrumbidgee River **a**	–16	–12	–27	–20	–13	–10	–23	–16
Darling River **a**	–18	–14	–32	–23	–16	–12	–28	–19
Morgan	–18	–14	–33	–24	–16	–12	–28	–19
Salinity								
Murrumbidgee River **a**	–27	–46	–64	–57	–9	–6	–26	–17
Darling River **a**	–9	–27	–47	–42	1	0	–12	–8
Morgan	–7	–31	–48	–45	4	3	–5	–3

a Below the confluence of the Murray River.

of a drier climate and the improvement in water use efficiency leads to a greater reduction in recharge than under SRES scenario B1. It is important to note, however, that while improved water use efficiency may mitigate the effects of climate change, it is not a costless offset as it can require a substantial capital investment.

The economic and biophysical impacts of water trade under climate change conditions are shown in tables 3 and 4 respectively. Water trade from the upland catchments in the southern part of the basin to horticultural areas in the Victorian Mallee and South Australian Riverland offsets about 13 per cent of the costs imposed by climate change under the SRES A1 scenario and around 19 per cent under the SRES B1 scenario. As the traded water is moving to areas dominated by high value horticultural production, the economic benefits generated in these areas more than offset the costs incurred in the regions where water is traded. However, there are still substantial losses in the northern catchments that are dominated by high valued cotton production, as there is no capacity to trade water between catchments.

In contrast to the water use efficiency scenario, trade does not have a significant impact on flows. However, there is an effect on salt loads discharged from different locations along the Murray River system. Salt loads and concentrations are reduced above the horticultural areas in the Victorian Mallee and South Australian Riverland. This occurs for two reasons. First, the water that is being traded down the river system acts as a dilution flow between the source and the destination of the trade. Second, as irrigation has decreased in the upstream irrigation areas, decreased recharge reduces the volume of salt mobilised to the river system leading to water quality improvements. However, water quality below the destination areas declines with trade under both SRES scenarios. In the no trade scenario, salinity levels fall 10 per cent and 6 per cent, respectively, for the SRES A1 and B1 scenario (table 2). With trade, the corresponding reductions in salinity are lower, at 5 per cent and 3 per cent respectively. This is because trade maintains the level of irrigation, and therefore, the highly saline ground water discharge in the horticultural regions. This results in higher salt load and higher salt concentrations when compared to the simulation without trade.

Conclusions

The SRES scenarios have been designed to highlight the uncertainty associated with future trends in emissions and the level of global warming and other climatic changes that may occur in response to those trends. The two SRES scenarios that were compared in this study are fairly conservative within the envelope of modeled global warming outcomes for the scenarios developed by the IPCC. The projected impacts of these two scenarios on river flows, water quality and economic returns in the Murray Darling Basin vary considerably.

A moderate increase in the rate of global warming was projected to result in a substantial decline in river flows and economic returns. River flows were between 8 and 18 per cent lower under the SRES A1 scenario in comparison with the SRES B1 scenario, and overall economic returns were 33 per cent lower. However, an increased rate of global warming under the SRES A1 scenario did not result in uniformly worse environmental outcomes. The drier climate under the SRES A1 scenario resulted in a greater decrease in irrigation that led to a larger reduction in recharge than the SRES B1 scenario. This resulted in a larger improvement in water quality in the Murray River even though it tended to generate more adverse affects on catchment runoff. The area affected by high water tables was lower in the drier climate simulated under the SRES A1 scenario.

When the uncertainty inherent in the SRES scenarios is coupled with the unknowns associated with regional climate projections, changes in surface water yields, ground water systems and crop yields, any direct concern about the specific range of outcomes appears unwarranted. The fact that climate change can generate significant changes in both economic and environmental outcomes at a regional scale adds to the risk associated with longer term public and private investments. At the same time, it increases the value associated with the capacity to adapt to changes in the physical environment.

Building the capacity to adapt may take the form of more flexible institutional arrangements to facilitate the efficient reallocation of resources, investing in options such as increased conservation of ground water and other resources. Any potential adaptations will need to be supported by research in both hydrological and agronomic responses to enhanced greenhouse conditions. Capacity building is not costless. However, the impetus created by the potential impacts of climate change may simply reinforce a broad set of incentives to expand our capacity to adapt to a changing environment and social concerns for that environment.

The adaptation simulations that were explored within this study suggest that water trade and the capacity to increase water use efficiency can significantly mitigate the effects of a drier climate. Both water trade and the incentive for investing in the infrastructure required to improve the efficiency of water use require well defined and secure property rights to achieve the maximum economic benefit. Further, water trade has the capacity to generate both positive and negative downstream benefits to both consumptive water users and the environment. Institutional arrangements that govern trade will need to take these externalities into account. Property rights have been the central issue in the water reform debate in Australia, and with increasing concern for river and stream health, the debate is likely to intensify.

Appendix A: Incorporating climate change into the SALSA model

In the climate change projections for the Murray Darling Basin, changes in potential evaporation are large relative to changes in precipitation. At the same time, the influence of potential evaporation on the relationship between ground cover and evapotranspiration is uncertain. The Holmes–Sinclair relationships estimated by Zhang et al. (1999) that were initially used in the SALSA model did not incorporate potential evaporation as an explanatory variable. As discussed in the main text, this relationship was modified to align surface runoff estimates with previous work using the Sacramento Model. The sensitivity of the results to this modification is presented here.

Differences in economic returns for the SRES A1 scenario with no response to potential evaporation (**NR**) and modified Holmes–Sinclair relationships (**MR**) are presented in table 5. Differences in flows and salt concentrations at selected locations are given in table 6.

Table 5: **Changes in economic returns for SRES A1 scenario with and without a response to changes in potential evaporation**

Region	**MR**	**NR**	**Change**
	$m	$m	%
Northern catchments	–480	–118	75
Southern catchments	–442	–168	62
Victorian Mallee and South Australian Riverland	–256	–120	53
Adelaide	–50	–23	55
Total	–1 228	–429	65

Table 6: **Flows and salt concentrations at selected locations for SRES A1 scenario with and without a response to changes in potential evaporation**

Location	**Reference scenario**			**Change to 2050**		**Change to 2100**	
	2000	**2050**	**2100**	**MR**	**NR**	**MR**	**NR**
Flows	GL	GL	GL	%	%	%	%
Goulburn-Broken River	2 397	2 475	2 481	–19	–12	–35	–24
Gwydir River	587	619	679	–25	–8	–42	–16
Murrumbidgee River **a**	7 453	7 691	7 863	–14	–9	–24	–16
Darling River **a**	8 237	8 583	8 851	–16	–10	–29	–18
Morgan	6 898	7 210	7 451	–13	–10	–29	–18
Salinity	Mg/L	Mg/L	Mg/L	%	%	%	%
Goulburn-Broken River	52	60	62	15	8	40	23
Gwydir River	123	145	182	19	2	72	15
Murrumbidgee River **a**	138	153	177	–8	–5	–25	–16
Darling River **a**	222	269	302	2	0	–12	–8
Morgan	307	397	454	4	2	–10	–6

a At the confluence of the Murray River.

The sensitivity of the result to the effect of potential evaporation is large. If the level of evapotranspiration is not increased to reflect increased potential evaporation, river flows are between 8 and 28 per cent higher by 2100. Economic costs are reduced by around 65 per cent. The impacts are greater in the northern part of the basin, as the increases in potential evaporation are greater.

The impacts on water quality are mixed. The salt concentration of surface runoff above the irrigation areas is lower when evapotranspiration is not affected by potential evaporation because the increase in surface water runoff more than offsets the increase in groundwater discharge. However, higher runoff leads to increases in water availability for irrigation. This leads to higher levels of groundwater discharge from the irrigation areas and a reduction in water quality in the main stem of the Murray River.

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