

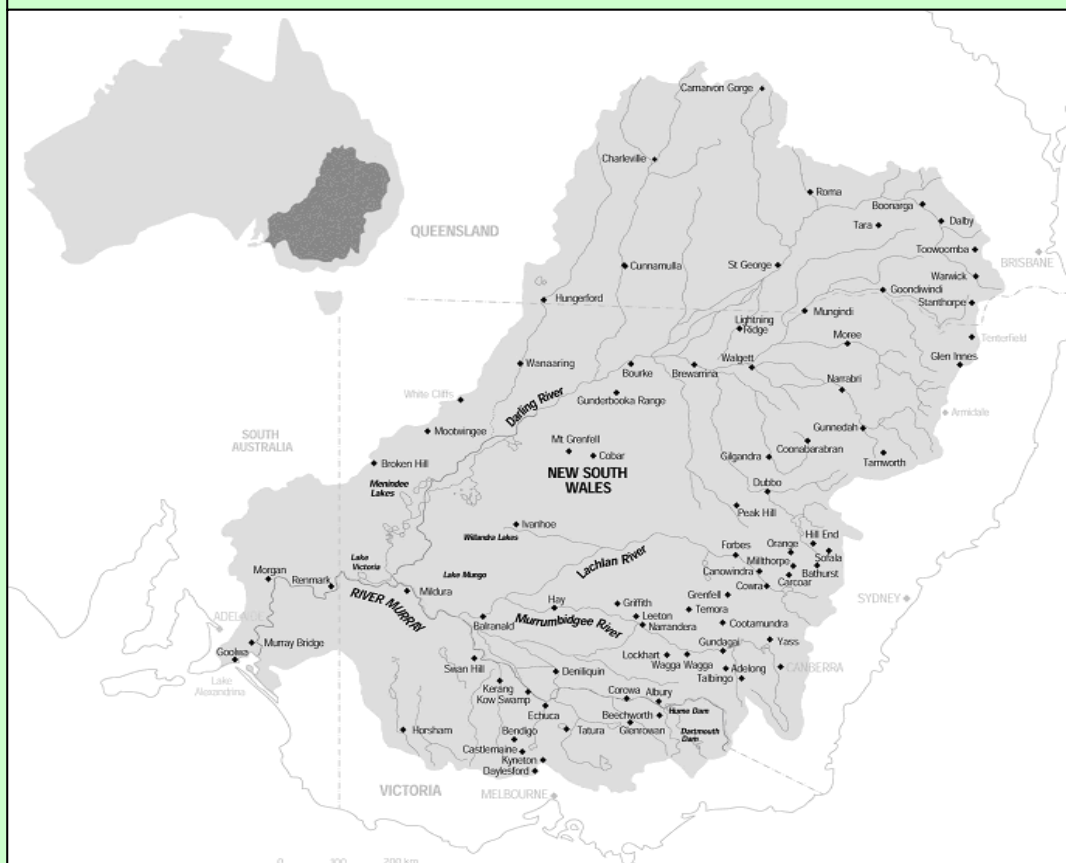
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Climate change, mitigation and adaptation: the case of the Murray–Darling Basin in Australia

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Abstract

Climate change is likely to have substantial effects on irrigated agriculture. It is anticipated that many areas that are already dry will become drier, while areas that already receive high rainfall may experience further increases. Extreme climate events such as droughts are likely to become more common. These patterns are evident in projections of climate change for the Murray–Darling Basin in Australia.

To understand the effects of climate change, as modified by mitigation and adaptation, active management responses designed to improve returns in particular states of nature, such as in the case of drought must be considered. A change in the frequency of drought will induce a change in the allocation of land and water between productive activities. Even with action to stabilize atmospheric concentrations of CO₂ at or near current levels, climate change will continue for some decades and adaptation will therefore be necessary. Conversely, most adaptation strategies are feasible only if the rate and extent of climate change is limited by mitigation. In this paper, a simulation model of state-contingent production is used to analyze these issues.

Key words: Irrigation, Uncertainty, Climate Change

JEL Codes: Q25, Q54

Climate change and irrigated agriculture: the case of the Murray–Darling Basin in Australia

The analysis undertaken by climate scientists and summarized in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) (IPCC 2007a,b,c) leaves little doubt that human action is causing changes in the global climate, and that these changes will continue throughout the 21st century. Attention has therefore turned to assessment of the likely effects of climate change, and to the options for mitigation and adaptation.

Projections of climate change for the Murray–Darling Basin in Australia suggest that climate change is likely to result in lower rainfall and higher evaporation (Garnaut 2008). The frequency of droughts is also likely to increase. Climate change will exacerbate existing problems arising from the excessive expansion of irrigated agriculture.

The prevalence of severe drought conditions in the Basin since 2002 has been interpreted as evidence that climate change is already under way, although it is not clear to what extent this change is driven by anthropogenic global warming. The Wentworth Group of Concerned Scientists (2006) states:

Our continent is getting hotter, and rainfall patterns have changed significantly ... And science is warning us of further uncertainty as a result of climate change. This change in climate may be part of a natural cycle or it might be caused by climate change or it might be a combination of both.

More recent evidence suggests that climate change is already a major factor in reducing rainfall (South-Eastern Australia Climate Initiative 2008).

Discussion of responses to climate change has focused on the options of mitigation and adaptation. These have frequently been presented as polar alternatives, with some opponents of action to stabilize the global climate arguing that it would be more cost-effective to focus on adaptation. However, mitigation and adaptation are not exclusive alternatives, and will, in many cases be strategic complements (Bosello, Carraro and de Cian 2009).

Even with action to stabilize atmospheric concentrations of CO₂ at or near current levels, climate change will continue for some decades and adaptation will therefore be necessary. Conversely, as will be shown in this paper, most adaptation strategies are feasible only if the rate and extent of climate change is limited by mitigation.

In this paper, we will discuss the problems of modelling and responding to climate change in irrigation systems, using the Murray–Darling Basin as an example. We will examine the role of uncertainty in detail. Finally, we will consider how responses to climate change interact with water policy.

The analysis follows the state-contingent modelling approach presented by Adamson, Mallawaarachchi and Quiggin (2007) and previously applied to medium term modelling of climate change by Adamson, Mallawaarachchi and Quiggin (2009). It extends previous work by examining the interaction between adaptation and mitigation, a task which requires the use of a range of long run climate projections for the period 2010 to 2100.

The paper is organized as follows. The implications of global climate change for water resources and their management are outlined in Section 1. The economic, social and environmental significance of the Murray–Darling Basin is described in Section 2, and the effects of climate change on the already highly variable rainfall patterns of the Basin are discussed. Section 3 deals with the modelling of water allocation, using a state-contingent approach to risk and uncertainty, in which irrigators may respond flexibly to changes in the stochastic distribution of

water prices and availability. The results of simulation modelling of adaptation to climate change with and without global mitigation policies are presented in Section 4. Final comments are presented in Section 5.

1. Global Climate Change

In its Fourth Assessment Report, the IPCC (2007a,b,c) summarizes a wide range of projections of climate change, encompassing different climatic variables, time and spatial scales, models and scenarios. Most attention is focused on projections of changes in global mean temperatures. However, analysis of the impact of climate change on agriculture requires consideration of regionally specific changes in a range of variables including temperature, rainfall and the effects of CO₂ concentrations on crop growth.

Even with aggressive strategies to stabilize atmospheric CO₂ concentrations at levels between 400 and 500 parts per million (ppm), it seems inevitable that warming over the next century will be at least 2 degrees Celsius (C) relative to the 20th century average.

Thus, for the purposes of policy analysis, the relevant comparison is between warming of 2 degrees C over the 21st century and the more rapid warming that may be expected under 'business as usual' projections, in which there is no policy response to climate change. The IPCC (2007a) presents a range of 'adaptation only' projections, in which estimates of warming over the period to 2100 range from 2 degrees C to 6.4 degrees C, with a midpoint of around 4 degrees C.

The term 'business as usual' is somewhat misleading since it implies that farmers and others will not change their strategies as a result of climate change. In fact, even if there are no changes in public policy, changes in climate will lead farmers to adapt, by changing their production plans, or perhaps by leaving agriculture. For this reason, the term 'adaptation only' will be used in preference

to 'business as usual' to describe projections in which carbon emissions are not constrained by mitigation policies.

As shown by Quiggin and Horowitz (2003), the main costs of climate change for agricultural producers are costs of adaptation and adjustment. It follows that the rate of change of warming is at least as important as the equilibrium change in temperature levels. Recent observed warming has been at a rate of around 0.2 degrees per decade (Hansen et al. 2006). 'Adaptation only' projections imply an increase in the rate of warming over coming decades.

Water

Water, derived from natural precipitation, from irrigation or from groundwater, is a crucial input to agricultural production. IPCC (2007b, Chapter 3, p. 175) concludes, with high confidence, that the negative effects of climate change on freshwater systems outweigh its benefits. In addition to raising average global temperatures, climate change will affect the global water cycle. Globally, mean precipitation (rainfall and snowfall) is projected to increase due to climate change. However, this change will not be uniform.

Climate change is projected to increase the variability of precipitation over both space and time. Areas that are already wet are likely to become wetter, while those that are already dry will in many cases become drier, with average precipitation increasing in high rainfall areas such as the wet tropics, and decreasing in most arid and semi-arid areas (Milly, Dunne and Vecchia 2005). Where precipitation increases there are likely to be more frequent events involving very high rainfall, such as monsoon rain associated with tropical cyclones (IPCC 2007a).

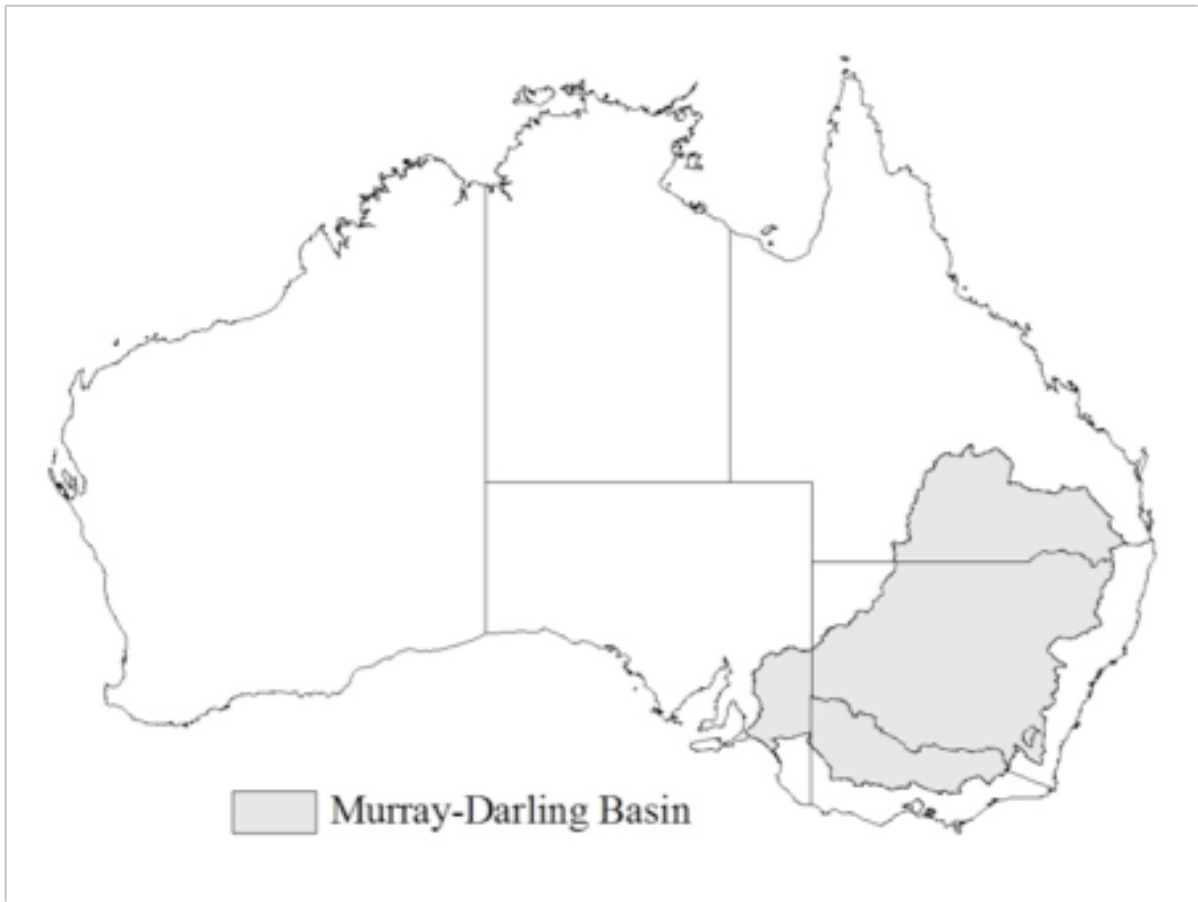
Severe droughts are also likely to increase by multiples ranging from two to ten, depending on the measure (Burke, Brown, and Nikolaos 2006) particularly in the temperate zone between 30 and 60 degrees latitude.

In addition, higher temperatures will lead to higher rates of evaporation and evapotranspiration, and therefore to increased demand for water for given levels of crop production (Döll 2002). Water stress (the ratio of irrigation withdrawals to renewable water resources) is likely to increase in many parts of the world (Arnell 2004).

2. The Murray–Darling Basin

The Murray–Darling Basin is an area of national significance in Australia. The Basin covers over 1 million km² or 14 per cent of Australia’s land area (Australian Bureau of Statistics 2008). The Basin contains the catchments of two major rivers: the Darling and the Murray, along with many tributaries of which the most significant is the Murrumbidgee. Most of the Basin is naturally semi-arid (variable rainfall with average annual rainfall between 250 and 300 millimetres). Irrigation has played a major role in the expansion of agriculture in the Basin since the late 19th century (Quiggin 2001).

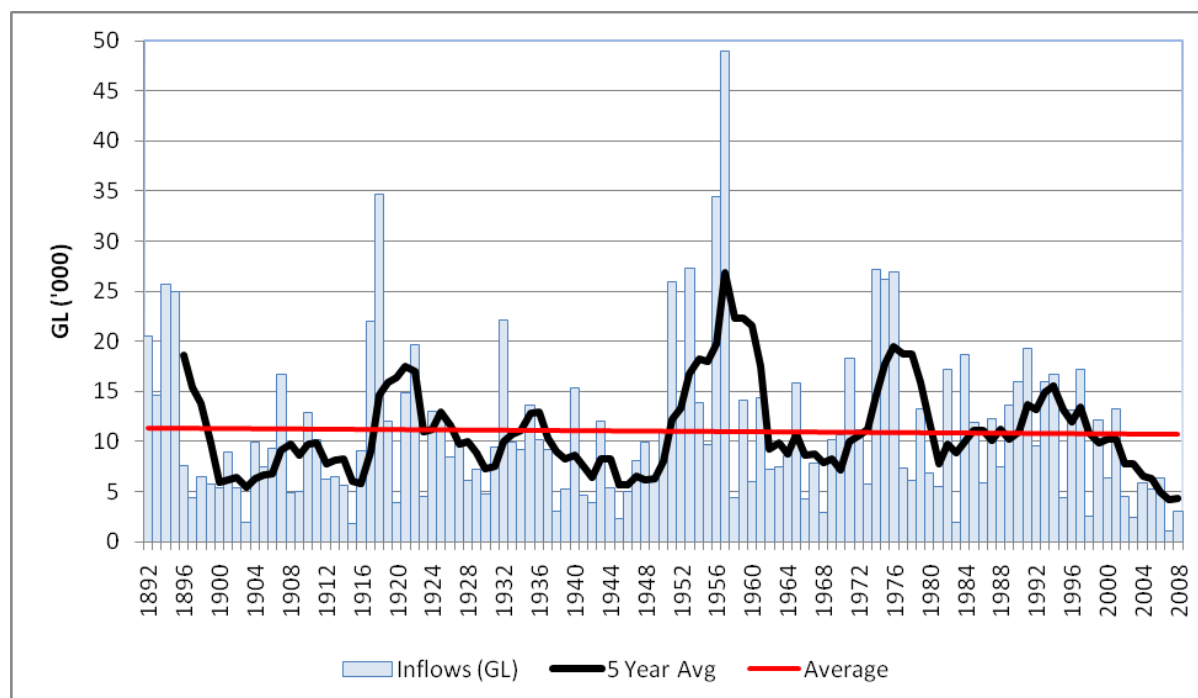
Figure 1: Murray–Darling Basin, Australia



Annual inflows into the Basin since the 1890s have averaged 26,000 GL, of which runoff into streams contributed about 24 000 GL, accessions to groundwater systems about 1000 GL and transfers into the Basin as a result of the Snowy River scheme about 1000 GL.

Figure 2 illustrates variation in the availability of water and the prolonged period of low inflows beginning in 2002.

Figure 2: Inflows to the Murray–Darling Basin 1892-2008



Within the Basin, an irrigated area of 1.7 million hectares of irrigated crops and pastures produces output with a gross value of \$4.6 billion. Dryland agriculture in the Basin contributes \$10.4 billion. The Basin accounts for 39 per cent of the total value of agricultural commodities produced in Australia (Australian Bureau of Statistics 2008).

There are over 2.7 million people living in the Basin (Murray Darling Basin Commission 2006) all of whom are in some way dependent on water flowing in the Basin as a source of potable drinking water, for the industry they work in (primary or secondary), for recreation activities and for community networks. A further 1.1 million people in Adelaide rely on the Basin to provide drinking water (Australian Bureau of Statistics 2006).

The Basin includes over 1.9 million hectares of important wetlands. Ten of these wetlands have been recognized under the Ramsar convention for their high ecological significance as essential breeding grounds for diverse water bird and fish species. Among numerous areas of importance, the Coorong lagoon

ecosystem at the mouth of the Murray is of particular scientific and cultural significance. During the drought, natural flows of water to the Coorong and the lakes immediately upstream stopped, raising grave concerns about the continued viability of these water bodies and the associated ecosystems (CSIRO 2008).

Irrigation and policy

Among the world's major river systems the Murray–Darling has both the lowest average rainfall and the greatest proportional variability. In order to manage the uncertainty associated with water availability, the rivers of the Basin have been regulated by large dams in an attempt to 'drought-proof' supplies (Khan 2008). Close to 50 percent of average annual surface water flows are diverted for consumptive use, most of which is used by agriculture.

The history of irrigated agriculture in the Murray–Darling Basin has been dominated by government or government-sponsored development initiatives. Unlike the situation in many countries with riparian or appropriation rights, state governments claimed ownership of all water flowing in streams. Water use, either through direct extraction from streams, or from irrigation systems was allowed under licenses that were fixed in duration and tied to specific pieces of land (Quiggin 2001).

Until the 1980s, Australian irrigation policy was in the expansion phase characteristic of water systems where resource constraints are not immediately binding (Randall 1981). Policy was guided by a developmentalist, 'nation-building' framework, in which public investment was directed towards objectives of growth in production and regional population, with no expectation of a return on publicly invested capital (Davidson 1969).

By the late 1980s the capacity of the Basin to support additional diversions was almost exhausted. In 1992, the Murray–Darling Basin Agreement was signed, replacing the 1915 River Murray Waters Agreement. The central idea was to

replace bureaucratic systems of water allocation based on licenses with a unified market system based on tradeable water rights to ensure that water was allocated to its most socially valuable use.

By the early 2000s, it was apparent that policy had failed to generate sustainable allocations of water. These problems were exacerbated by years of severe drought. The severity of the drought is related, at least in part, to climate change caused by human activity (Murray–Darling Basin Ministerial Council 2007). Climate models suggest, on the balance of probabilities, that precipitation in the Murray–Darling Basin will decline as a result of climate change, and, with high probabilities, that increased temperatures and evaporation will reduce inflows for any given level of precipitation.

However, given the high levels of natural variability in precipitation, and the apparent presence of multi-decade cycles, attribution of causes for the current drought is subject to high uncertainty. Nevertheless, the balance of evidence suggests that climate change will be associated with reductions in rainfall in the Murray–Darling Basin, and with more frequent and severe drought conditions in the future (Wentworth Group 2006).

The failure of existing management policies in the Murray-Darling Basin has produced a series of responses, each responding to the actual or perceived deficiencies of its predecessors : the Living Murray Program (2002), the National Water Initiative (2004), the National Plan for Water Security (2007) and the Water for the Future Plan (Wong 2008).

Climate change projections

A variety of projections of rainfall, temperature, humidity and evaporation for each catchment in the model were produced for the Garnaut Review of Climate Change (Garnaut 2008). Since there remains considerable uncertainty about the impact of climate change on rainfall patterns, the Garnaut Review presented

Wet, Dry and Medium variants for each emission trajectory. In this study, we have considered the implications of Medium projections for two emissions trajectories.

This first is the Medium projection for the adaptation only trajectory, in which mean global temperature increases by about 4.5°C in 2100. The second is the Medium projection for the ‘mitigation’ trajectory, which involves stabilization of atmospheric concentrations at 450 ppm CO₂ equivalents with the result that global temperature increases by about 1.5°C in 2100.

These projections were coupled with the results of modelling by Jones et al. (2007) to derive inflow projections for the Basin at a catchment level for the period from 2010 to 2100. Projections for 2050 and 2100 are presented in Table 1.

Table 1 Projected mean inflows (per cent of baseline value)

Catchment	Adaptation only		Mitigation	
	2050	2100	2050	2100
Condamine	72.6	31.8	79.4	78.0
Border Rivers, Qld	72.9	32.4	79.6	78.2
Warrego–Paroo	72.0	30.2	78.9	77.5
Namoi	77.8	44.7	83.3	82.2
Central West	78.3	46.0	83.7	82.6
Maranoa–Balonne	72.0	30.2	78.9	77.5
Border Rivers–Gwydir	78.1	45.6	83.5	82.5
Western	76.0	40.1	81.9	80.7
Lachlan	77.8	44.6	83.3	82.1
Murrumbidgee	78.1	45.4	83.5	82.4
North East	79.8	49.8	84.8	83.8
Murray 1	75.6	39.2	81.6	80.4
Goulburn-Broken	72.9	32.6	79.6	78.3
Murray 2	75.6	39.2	81.6	80.4
North Central	71.6	29.4	78.7	77.2
Murray 3	75.6	39.2	81.6	80.4
Mallee	70.8	27.3	78.0	76.6
Lower Murray Darling	74.4	36.2	80.7	79.4
SA MDB	65.0	12.9	73.7	71.9
Snowy River	81.7	56.8	85.9	85.2
Total	76.6	41.7	82.6	81.1

Inflows are expected to decline in all catchments as a result of climate change. The smallest reductions are those for the Snowy River. The decline is greatest for catchments in parts of the Basin that are already relatively dry, most notably the South Australian section of the Basin.

The ‘adaptation only’ scenario implies a substantial reduction in inflows over the period to 2100. In drought states, the projections imply that flows will cease altogether in the downstream sections of the Murray and in most of the Darling.

3 Modelling

The model results presented here are derived from an updated version of the state-contingent Murray–Darling Basin Model documented in Adamson,

Mallawaarachchi, and Quiggin (2007). The model simulates the allocation of land and water to agricultural activities as the result of constrained optimization by representative farmers in each catchment in the Basin, as well as flows of water for urban use and residual 'environmental flows' in the main stream and a number of sensitive 'icon' sites.

The model captures uncertainty in the availability of water inflow to the system using the theory of state-contingent production developed by Chambers and Quiggin (2000). Each activity produces a bundle of state-contingent outputs, one for each state of nature. An activity may produce net profits in some states of nature, and net losses in others.¹

The idea that multiple state-contingent activities may be available for the production of a single commodity is what distinguishes the approach put forward here from most previous simulation models that incorporate uncertainty. The standard approach has been to introduce stochastic variation into the outputs of each commodity. This approach allows producers to manage risk by varying their allocation of land between commodities, in the same way as investors can diversify portfolios.

Dichotomous choices can also be modelled using the tools of discrete stochastic programming (Cocks 1968). Important applications of discrete stochastic programming to Australian agriculture include Brown and Drynan (1986), Kingwell (1994) and Kingwell, Pannell and Robinson (1993).

The approach adopted here, using the notion of state-contingent commodities, does not require the introduction of explicit stochastic elements, and permits the derivation of standard outputs of programming models such as shadow prices, which have a direct economic interpretation. More generally, as discussed in

¹ Egan and Hammer (1996) determined that, in dryland production systems, between 70 and 80 per cent of total income over a ten year period is earned in the best three years and a net loss is made in another three.

Chambers and Quiggin (2000), the tools of duality theory are fully applicable in a state-contingent setting. The modelling approach used here allows use of the standard duality concepts associated with linear and nonlinear programming.

These advantages of the state-contingent approach are particularly relevant in relation to the modelling of climate change. Climate change is expected to produce an increase in mean temperatures and a reduction in mean precipitation in the Murray–Darling Basin. However, as shown by Adamson, Mallawaarachchi and Quiggin (2009) the effects of changes in mean values are modest in comparison with those of changes in the stochastic distribution of inflows to the system and, in particular, with increases in the frequency of drought.

Using a state-contingent production representation of uncertainty, climate change may be represented as a change in the probability distribution of states of nature, with hotter, drier states becoming more probable.

General specifications

The Basin is simulated at a Catchment Management Authority scale for 19 catchment regions, along with Adelaide and the Coorong. The Adelaide and Coorong catchments allow for the representation of water quality arriving in Adelaide and a proxy value for environmental flows represented by water reaching the Coorong.

The model contains three states of nature, corresponding to Normal, Wet (20 per cent above normal inflows) and Drought (40 per cent below normal inflows) conditions. The probabilities of the the three states (Normal: 0.5, Wet: 0.3, Drought: 0.2) and the associated inflow levels are calibrated to match the observed historical mean and variance of inflow levels.

An activity in the model is specified by inputs and outputs in each state of nature. A given activity may produce the same commodity in each state, or

different commodities in different states. Three examples of state contingent productions systems included within the model are:

- **Vegetables:** In the Normal state, the vegetable production activity is represented by an average return from a range of alternative irrigated vegetable crops. In the Drought state, water resources are conserved by planting only a dryland rockmelon crop. In the Wet state, all resources are transferred to producing tomatoes for the fresh market.
- **Sheep/Wheat:** This production activity represents a state-contingent production plan where producers allocate resources between sheep and wheat production in response to climatic conditions and market forces. The production mix between the two outputs is 50 per cent wheat, 50 per cent sheep in the Normal state, 90 per cent sheep and 10 per cent wheat in the Drought state and 30 per cent sheep and 70 per cent wheat in the wet state. Effort is placed in keeping the breeding stock alive during the Drought state while in Wet states there is plenty of fodder available on the non-irrigated pasture, and irrigated land can be allocated to wheat production.
- **Wet Cotton.** The producer irrigates their cotton crop only in the 'Wet' state of nature. This activity is an example of opportunity cropping.

Representing climate change

The scenarios for climate change imply a reduction in mean inflows. This could be represented by an equiproportional reduction in inflows for each of the three states. However this would imply a similar, equiproportional reduction in variance. Although the catchment-level climate projections used here do not include projections of variance, the results for global climate change suggest that the variance of rainfall is likely to increase even where mean values decrease.

For this reason, the reduction in inflows associated with climate change in the ‘adaptation only’ case is modelled partly as a change in the probability distribution, which is changed so that only Normal and Drought states occur, each with probability 0.5. To match the reduction in mean inflows for each catchment, the change in probability distribution is combined with a proportional adjustment in flows in each state.

In the ‘mitigation’ case, the probability distribution of states of nature is assumed unchanged. The reduction in inflows, as shown in Table 1, is modelled as an equiproportional reduction in each state of nature.

Policy responses

The model is solved to determine the allocation of land and water that yields the maximum expected return for the Basin as a whole subject to a number of policy constraints. Some constraints are applied in all runs.

First, the salinity of water supplied to Adelaide is constrained not to exceed 800 EC. This constraint is not feasible in the ‘adaptation only’ projection for 2100 as there is no flow in drought states.

Second, for each catchment, there is a constraint limiting total use of water for irrigation. This constraint reflects the existing policy regime, which has included such restrictions since the imposition, in 1994, of a cap on aggregate water use.

In addition, we consider two water allocation rules that might be adopted in the ‘mitigation’ scenario. Under the first allocation rule, referred to as ‘environment as residual claimant’, existing constraints on water use are left unchanged. As a result, changes in land and water use in irrigation are fairly modest, and the main effect of reduced inflows is to reduce the flow of water through natural environments in the system, measured here by the outflow at the Coorong. Under the second allocation rule, referred to as ‘environmental flows take priority’, constraints are imposed to ensure that environmental flows, as

measured by the average outflow at the Coorong are maintained. Under this policy, adjustment to reduced inflows is achieved primarily through reduced water use in agriculture.

Results

Simulation results for the expected values of four key variables are presented in Table 2. These variables are: “Economic return”, that is, the total economic return to agricultural and urban water use; ‘Salinity’ measured in EC units for water supplied to Adelaide; ‘Water use’, measured in gigalitres (GL) and including water used for irrigation and urban water supply; and ‘Environmental flow’, measured in gigalitres as the outflow at the Coorong.

Table 2: Projections of key model variables

Simulation	Year	Economic return (\$m)	Salinity (EC)	Water use (GL)	Environmental flow (GL)
Baseline	2000	2,739.3	460.0	11,869.9	4,774.5
Adaptation only	2050	2,004.7	554.9	7,360.2	1,923.8
	2100	1,042.0	NA*	2,861.2	682.4
Mitigation and adaptation (Environment residual)	2050	2,678.4	688.3	11,201.1	2,954.8
	2100	2,663.5	698.4	11,035.7	2,861.7
Mitigation and adaptation (Environment priority)	2050	2,443.8	359.2	8,378.2	4,864.0
	2100	2,413.6	349.9	8,070.8	4,869.5

* No meaningful average as there is zero flow in drought state

A number of features of these results are noteworthy.

First, although the volume of water available for use and environmental flows falls significantly in all projections, the change in economic value from the baseline simulation is similar, and relatively modest, for all the 2050

projections.² This is because the effects of mitigation become evident mostly after 2050.

Second, assuming the validity of the median projections used here, mitigation leading to stabilization of global CO₂ at 450 ppm is sufficient, in combination with adaptation, to reduce economic damage from climate change to modest levels (less than \$400 million year). By contrast, while adaptation alone is a reasonably effective response for the period from now until 2050, it becomes ineffectual when inflows fall sharply as projected for the second half of this century.

Third, salinity can be managed to achieve the current policy target of a maximum of 800 EC for Adelaide water supply in all simulations except the ‘adaptation only’ simulation for 2100. For this simulation, the failure of runoff in the drought state of nature makes the hydrological component of the model unreliable by 2100. Subject to the obvious uncertainties involved with such a long period, the projections imply that the Darling river will become a closed system with no net outflow. In Drought states, the Murray and Murrumbidgee become a series of ponds, and no longer provide sufficient water for Adelaide potable drinking supplies. With the exception of some upstream catchments, the modelling results reported for this case involve the replacement of irrigation by dryland agriculture.

Finally, comparison of the baseline simulation with the ‘mitigation and adaptation (environment has priority)’ simulation shows that it is possible to maintain existing environmental flows at a cost of around \$250 million/year, assuming global mitigation policies are successful. Given that the Australian government has committed \$10 billion over 10 years to the National Water Plan,

² These results are derived from median projections of climate change. Within the range of model projections consistent with our current knowledge, ‘hot dry’ variants show substantial effects on flows, outputs and economic returns before 2050.

in which the Murray Darling Basin plays a central role, this cost seems reasonable.

The simulations undertaken in this study have a number of further implications for the pattern of adaptation to climate change and for the substitution and complementarity relationships between adaptation and mitigation. One change in land use patterns is of particular interest, since it is the opposite of what would be expected on the basis of a deterministic analysis. Deterministic analysis suggests that, as scarcity leads to an increase in the shadow price of water, allocations should shift to horticultural crops, where the average ratio of output value to water input is higher.

A state-contingent analysis yields the opposite conclusion. Horticultural crops generally require a consistent supply of water, regardless of seasonal conditions. Climate change is associated with an increase the frequency of droughts, when the shadow price of water is very high. This price change favors ‘opportunity cropping’ activities, in which irrigation is used in years of high water availability (Wet states in the model used here), and is replaced by dryland production activities in years of low water availability (Drought states in the model used here). In the present model, some opportunity cropping activities use irrigation water only in the Wet state. Others use irrigation water in Wet and Normal states, but not in Drought states.

Table 3 provides estimates of the amount of water used in horticultural and broadacre production activities and the states of nature in which such production activities require use of irrigation. As water becomes scarce, producers adapt by reducing the area allocated to production activities that require irrigation in all states of nature, and increasing allocations to activities with flexible state-contingent water use. This adjustment is particularly important in the ‘adaptation only’ case.³

³ Failure of the Wet state may lead to water requirements for horticultural production that are

Table 3: State-contingent water use (GL)

Simulation	Year	Horticulture		Broadacre		
		Irrigation in all states	Irrigation in Wet and Normal states	Irrigation in all states	Irrigation in Wet and Normal states	Irrigation in Wet state only
Baseline	2000	1,507	0	7,302	2,089	766
Adaptation only	2050	1,101	259	2,788	3,007	0
	2100	0	811	0	2,050	0
Mitigation and adaptation (Environment residual)	2050	1,504	0	6,693	1,872	926
	2100	1,504	0	6,565	1,897	864
Mitigation and adaptation (Environment priority)	2050	1,504	0	4,845	1,317	507
	2100	1,504	0	4,571	1,303	488

More detailed results on the allocation of land and water between crops and regions are available as an Appendix from the authors. These results show that, in the ‘adaptation only’ scenario, the focus of horticultural production shifts from citrus and grapes (high value commodities that require irrigation in all states) to a vegetable production activity using irrigation to produce tomatoes in Normal and Wet states and producing rockmelons without irrigation in Drought states.

higher than modelled here, as additional irrigation is needed to flush the salt away from the root zones. This extra water requirement may lead to further adjustment towards opportunity cropping.

The results may also be used to examine the interaction between adaptation and mitigation. Adamson, Mallawaarachchi, and Quiggin (2009) show that the state-contingent modelling framework yields simple first-order approximations for the impact of climate change in the absence of adaptation.

The impact of an equiproportional reduction in the availability of water in all states of nature may be approximated on the assumption that the allocation of land to all irrigated agriculture activities is reduced in the same proportion, with the land so released being converted to dryland production. The impact of a change in the probability distribution of states of nature may be modelled by holding state-contingent returns constant and calculating the change in expected return associated with the given change in probabilities.

In Table 4, we report the results of estimates of the impact of climate change on the value of water used in irrigation, in the absence of adaptation, and compare these to the simulated values reported in Table 2. The difference, reported in the final column of Table 4, is an estimate of the benefits of adaptation. Adaptation is beneficial in every case. For the simulations presented here, adaptation and mitigation are complements. That is, the benefits of adaptation are higher in the simulations with mitigation than in the ‘adaptation only’ simulation.

The complementarity relationship between mitigation and adaptation reflects several features of the projections and simulations considered here. First, in the absence of mitigation, the supply of water is so limited by 2100 that there is little scope for adaptation. This point is true for a wide range of ecological and agricultural systems affected by climate change. Adaptation is a useful response to moderate rates of climate change. However, where climate change produces a rapid and radical change in conditions, adaptation of existing ecosystems and human activities may not be feasible. Instead, the systems in question will undergo collapse. New systems will ultimately emerge, but stable adaptation may not be feasible until the climate itself has stabilized at a new equilibrium.

For the more moderate climate changes projected for 2050, the complementarity between adaptation and mitigation reflects more specific features of the projections. In the ‘adaptation only’ simulation, the increased frequency of drought reduces the set of adaptation options, and precludes most high-value horticultural activities and opportunity cropping based on irrigation in Wet states only. By contrast, in the simulations where both adaptation and mitigation take place, reduced water availability in all states of nature leaves open a wide range of adaptation opportunities.

Table 4: Estimated effects of climate change on economic value (\$m) before and after adaptation

Simulation	Year	Before adaptation	After adaptation	Benefit of adaptation
Adaptation only	2050	1766	2004	238
	2100	962	1042	80
Mitigation and adaptation (Environment residual)	2050	2263	2678	416
	2100	2222	2664	442
Mitigation and adaptation (Environment priority)	2050	2049	2444	395
	2100	2003	2414	410

5. Concluding comments

First, the effects of, and the nature of adaptation to, climate change cannot be modelled accurately without taking appropriate account of uncertainty. The analysis presented here shows that an increase in the frequency of droughts will result in economic losses and environmental damage substantially greater than would be expected from a similar reduction in average inflows modelled in a non-stochastic framework. Moreover, whereas a non-stochastic analysis implies that an increase in the scarcity of water should imply an increased allocation to high-value horticultural crops, a stochastic analysis yields the opposite result.

Second, the modelling presented here illustrates the complexity of the relationship between adaptation and mitigation. For low and moderate rates of climate change, adaptation and mitigation are substitutes, with adaptation likely to be a lower cost alternative if the rate of change of climatic conditions is low. However, given the severe reductions in inflows expected in the absence of mitigation, there are no feasible adaptation options in many catchments other than the abandonment of irrigated agriculture. In general the higher the rate of climate change in the absence of mitigation, the more likely it is that adaptation and mitigation are complements rather than substitutes.

Third, even with strong mitigation, maintenance of existing allocations of water to irrigated agriculture implies a reduction in environmental flows, from levels that are already considered unsustainably low. The analysis presented above shows that, given stabilization of atmospheric concentrations of CO₂ at 450 ppm, environmental flows could be maintained or increased at relatively modest economic cost.

The simulations reported here are based on the assumption of constant relative prices. A more complete treatment would require a general equilibrium analysis

taking account of impacts on product and factor prices. In most problems of this kind, general equilibrium effects are of relatively minor importance, since changes in supply from one region have only a modest impact on the prices of goods traded in national and world markets.

In the case of climate change, however, the effects modelled here will be part of a global change. In the ‘adaptation only’ projection, global reductions in agricultural productivity are likely to drive an increase in the prices of agricultural commodities (IPCC 2007b; Quiggin 2008). This will attract more resources to agriculture. The implication is that reductions in agricultural output will be smaller than modelled here, but, given the greater economic value of agricultural products, the welfare loss will be greater than in the case of a local climate change, specific to the Murray–Darling Basin.

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