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**Climate change, uncertainty and adaptation:
the case of irrigated agriculture in the
Murray–Darling Basin in Australia**

by

**John Quiggin,
David Adamson,
Sarah Chambers,
and
Peggy Schrobback**

Schools of Economics and Political Science
University of Queensland
Brisbane, 4072
rsmg@uq.edu.au
<http://www.uq.edu.au/economics/rsmg>



**THE UNIVERSITY
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AUSTRALIA

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**John Quiggin, David Adamson, Sarah Chambers, and
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Risk and Sustainable Management Group

**School of Economics and School of Political Science and International
Studies**

University of Queensland

EMAIL j.quiggin@uq.edu.au

PHONE + 61 7 3346 9646

FAX +61 7 3365 7299

<http://www.uq.edu.au/economics/johnquiggin>

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Abstract

Climate change is likely to have substantial effects on irrigated agriculture. Extreme climate events such as droughts are likely to become more common. These patterns are evident in median projections of climate change for the Murray–Darling Basin in Australia.

Understanding climate change effects on returns from irrigation involves explicit representation of spatial changes in natural stocks (i.e. water supply) and their temporal variability (i.e. frequency of drought states of nature) and the active management responses to capital stocks represented by mitigation and alternative adaptation strategies by state of nature . A change in the frequency of drought will induce a change in the allocation of land and water between productive activities. In this paper, a simulation model of state-contingent production is used to analyze the effects of climate change adaptation and mitigation. In the absence of mitigation, climate change will have severe adverse effects on irrigated agriculture in the Basin. However, a combination of climate mitigation and adaptation through changes in land and water use will allow the maintenance of agricultural water use and environmental flows.

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 Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) (IPCC 2007a,b,c) states that it is very likely (more than 90 per cent) that human action is the primary contributor to changes in the global climate, and that these changes will continue throughout the 21st century. Attention has therefore turned to assessment of the possible effects of climate change, and to the options for mitigation and adaptation.

Garnaut (2008) suggests that lower rainfall and higher evaporation will probably (that is, with probability between 50 and 90 per cent) be the norm in Australia's Murray–Darling Basin under climate change. The frequency of droughts is also likely to increase. Climate change is likely to exacerbate existing conflicts between competing agricultural, urban and environmental demands for water.

The prevalence of severe drought conditions in the Murray-Darling 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.

Other evidence suggests that climate change may already be a major factor in reducing rainfall (South-Eastern Australia Climate Initiative 2008).

Responses to climate change have focused on options for mitigation and adaptation. Mitigation and adaptation have frequently been presented as substitutes, 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 et al. 2009).

Even if atmospheric concentrations of CO₂ are stabilized at or near current levels, climate change will continue for some decades and adaptation will therefore be necessary. Conversely, the feasibility of adaptation strategies depends on the capacity of mitigation to limit the rate and extent of climate change. In the case study considered here, the reduction in streamflows associated with ‘business as usual’ projections of climate change would end irrigated agriculture in large parts of the Murray-Darling Basin, and thereby preclude most adaptation options.

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

The analysis follows the state-contingent modelling approach presented by Adamson et al. (2007) and previously applied to medium term modelling of climate change by Quiggin et al. (2008) and Adamson et al. (2009). This analysis extends previous applications by examining the interaction between adaptation and mitigation. To undertake this, a comparison between two forecasted long run climate scenarios ‘with’ (450ppm) and ‘without’ (550ppm) climate change policy mitigation is presented against historical climatic data (i.e. baseline). This data is then compared to three time periods 2000 (baseline), 2050 and 2100 which allows us to investigate the implications of producer adaption strategies under policy mitigation of both climate response and reallocation of water rights to the environment.

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 Murray-Darling 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. Concluding 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. The IPCC provides an extensive discussion of the uncertainties surrounding these projections.

Most attention in the Fourth Assessment Report and in public discussion of climate change 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 average global warming over the next century will be at least 2 degrees Celsius (°C) relative to the 20th century average (IPCC 2007c).

Thus, for the purposes of policy analysis, the relevant comparison is between warming of 2°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°C to 6.4°C, with a midpoint of around 4°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.

Water

Water, derived from natural precipitation, from irrigation or from groundwater, is a crucial input to agricultural production. The IPCC (2007b, Chapter 3, p. 175) concludes, that, for the world as a whole, 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, and projections are subject to substantial uncertainty, as discussed below.

Climate change is projected to increase the variability of precipitation over both space and time. In general, areas that are already wet are likely¹ 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 et al. 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 et al. 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).

¹ The IPCC states that the term ‘likely’ refers to a probability of greater than 66 per cent, but below 90 per cent. Except where noted, we will adhere to this usage in the present paper.

Uncertainty

Projections of the likely impact of climate change are subject to considerable uncertainty. The most significant areas of uncertainty regarding global climate projections include: the future time path of greenhouse gas emissions; the proportion of emissions that remain in the atmosphere; and the sensitivity of climatic variables such as global mean temperatures.

Another set of problems arise in deriving projections for the catchments that make up the Murray–Darling Basin. There is a large literature on the problem of ‘downscaling’ global model projections to local scales. Flowerdew and Green (1992) and others have developed techniques for downscaling projections of spatially-linked variables, such as precipitation. Despite significant progress (Charles et al. 2003; Pitman and Perkins 2007), considerable uncertainty remains.

These issues are discussed in more detail by Adamson et al. (2009), who conclude (p. 349).

Although many issues remain unresolved, there has been considerable progress in improving projections of the mean values of climatic variables. Rather less progress has been made in projecting changes in the probability distribution of climatic variables over time and within given regions. In particular, while it is generally expected that the frequency of droughts will increase, there are few estimates of associated changes in the temporal distribution of inflows.

Adamson et al. (2009) argue that these problems are best addressed using an explicit state-contingent representation of irrigation technology.

2. The Murray–Darling Basin

The Murray-Darling Basin (hereafter 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

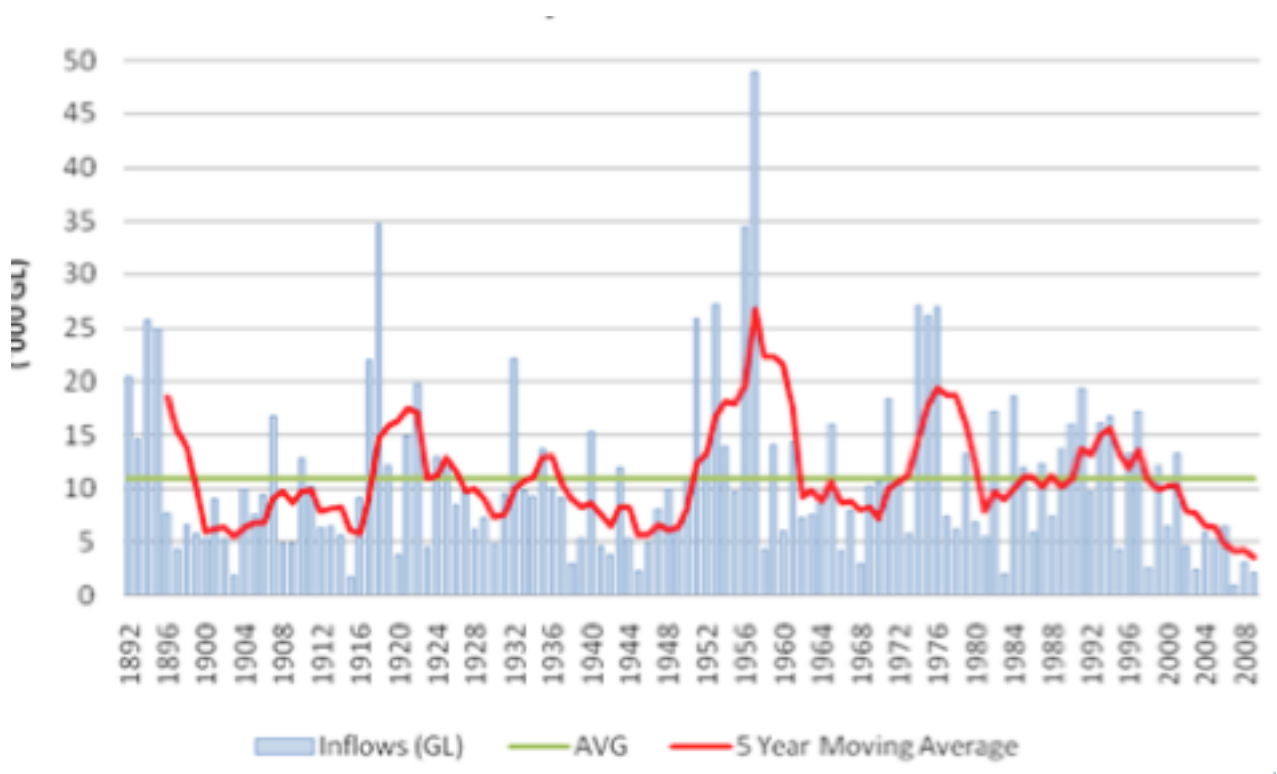


Annual inflows into the Basin since the 1890s have averaged 27 000 GL, of which runoff into streams contributed about 25 000 GL, accessions to groundwater

systems about 1000 GL and transfers into the Basin as a result of the Snowy River scheme about 1000 GL.²

Figure 2 illustrates the variation in inflows of water to the Murray river system³, and the prolonged period of low inflows beginning in 2002.

Figure 2: Inflows to the Murray River system 1892-2008



Within the Basin, 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

² The Snowy River project, undertaken from 1950 to the early 1970s, diverted water from the Snowy River into the Murray and Murrumbidgee rivers for the purposes of irrigation and hydroelectricity generation.

³ Historical data on the Darling River is limited. The Murray River accounts for around 70 per cent of inflows to the Basin.

agricultural commodities produced in Australia (Australian Bureau of Statistics 2008).

The 2.1 million people living in the Basin (Murray Darling Basin Authority 2009) depend on water flowing in the Basin as a source of potable drinking water, for household and industrial uses, for recreation activities and for environmental services. A further 1.3 million people, mainly in Adelaide rely on the Basin for urban water supplies (Australian Bureau of Statistics et al 2009).

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. The Coorong lagoon ecosystem at the mouth of the Murray is of particular scientific, environmental and cultural significance. By 2002-03 the majority of the Basin was officially declared in drought (Australian Bureau of Statistics, 2008) and many southern regions are still receiving exceptional circumstances drought (DAFF 2010). Consequently upstream water flows to the Coorong and the lower lakes stopped which has raised grave social concerns about the continued viability of these water bodies and the associated ecosystems up and down the Basin (Commonwealth Scientific and Industrial Research Organization (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 of inflows. To manage the uncertainty associated with water availability, the rivers of the Basin have been regulated by large dams (Khan 2008). Around 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. Water quality problems, most notably salinity, were becoming more severe (Quiggin 2001).

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 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 (Murray–Darling Basin Commission 2003), the National Water Initiative (Council of Australian Governments 2004), the National Plan for Water Security (Howard 2007) and the Water for the Future Plan (Wong 2008).

Climate change projections

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 that it is likely (above 50 per cent, but below 90 per cent), that precipitation in the Murray–Darling Basin will decline as a result of climate change.

Further, increased temperatures and evaporation will reduce inflows for any given level of precipitation. After accounting for interdependencies, such as the effect of rainfall and clouds on minimum temperatures, Cai and Cowan (2008) conclude that a 1°C increase in maximum temperature results in a 15 per cent decrease in streamflow in the Murray–Darling Basin.

Uncertainty surrounds the likely impact of climate change on the Murray–Darling Basin.

Jones et al. (2001) gave an overview of modelling research, concluding (p. 3):

Recent projections of rainfall change for the MDB suggest a decline in winter and spring rainfall by the year 2030. In summer, rainfall may either decrease or increase, with increases slightly more likely, while in autumn the direction of rainfall change is uncertain. Possible rainfall increases are largest towards the north of the MDB and decreases are largest to the south. Temperature is expected to increase in all areas. Potential evaporation is also highly likely to increase in all areas due to higher temperatures. These increases will be larger in regions and seasons in which rainfall decreases. Increases in open water evaporation will affect wetlands and water storages.

The combination of generally declining rainfall and increased evaporation implies that the availability of water would, in general, be reduced. However, this outcome is not certain.

A variety of projections of rainfall, temperature, humidity and evaporation for each catchment in Basin 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 climate variants for each projection emission trajectory. The assumptions used for each projection are described in Garnaut (2008, Table 6.2, p. 124). In this study, we have considered the implications for agricultural land and water use of Medium projections for two emissions trajectories. Implications of a number of other scenarios are modelled in Quiggin et al (2008).

This first of these projections is the Medium climate variant for the 'adaptation only' trajectory, in which mean global temperature increases by about 4.5°C in 2100. The second is the Medium climate variant for the 'mitigation' trajectory, which involves stabilization of atmospheric concentrations at 450 ppm CO₂ equivalents with the result that mean global temperature increases by about 1.5°C by 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 (percentage reduction from historical in parentheses)

Catchment	Historical average ^a	Adaptation only		Mitigation	
		2050	2100	2050	2100
Condamine	803	586 (27)	257 (68)	634 (21)	626 (22)
Border Rivers, Qld	735	537 (27)	235 (70)	588 (21)	573 (22)
Warrego–Paroo	419	302 (28)	126 (70)	331 (21)	327 (22)
Namoi	1,076	839 (22)	484 (55)	893 (17)	882 (18)
Central West	1,748	1 363 (22)	804 (54)	1 468 (16)	1 451 (17)
Maranoa–Balonne	1,328	956 (28)	398 (70)	1 049 (21)	1 036 (22)
Border Rivers–Gwydir	1,652	1 289 (22)	760 (54)	1 388 (16)	1 371 (17)
Lachlan	1,186	925 (22)	534 (55)	984 (17)	973 (18)
Murrumbidgee	4,958	3 888 (22)	2 296 (54)	4 175 (16)	4 083 (18)
North East	4,796	3 842 (20)	2 417 (50)	4 079 (15)	4 032 (16)
Murray 1	1,784	1 372 (23)	746 (58)	1 474 (17)	1 442 (19)
Goulburn-Broken	3,877	2 830 (27)	1 279 (67)	3 102 (20)	3 024 (22)
Murray 2	530	403 (24)	207 (61)	435 (18)	424 (20)
North Central	736	530 (28)	213 (71)	581 (21)	567 (23)
Murray 3	162	123 (24)	63 (61)	133 (18)	130 (20)
Mallee	13	9 (31)	4 (69)	10 (23)	10 (23)
Lower Murray Darling	115	85 (26)	41 (64)	93 (19)	91 (21)
SA MDB	162	105 (35)	21 (87)	120 (26)	117 (28)
Snowy River	1,118	913 (18)	635 (43)	960 (14)	953 (15)
Total	27,198	20 897 (23)	11 845 (56)	22 172 (18)	22 112 (19)

a Average 1891-2000

Under the Medium projection, inflows are projected 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.

It is important to remember that the changes in inflows described in Table 1 are projections based on scenarios, which in turn are conditional on global emissions trajectories. They are not predictions. The use of Medium projections means that, based on current understanding of the climate, and if global emissions follow the assumed trajectories, average future rainfall is equally likely to be higher or lower than in the reported projections.

3 Modelling

The model results presented here are derived from an updated version of the state-contingent Murray–Darling Basin Model described in Adamson, et al. (2007).⁴ The river systems in the Basin are represented as a network of catchments, with water use in upstream catchments determining the volume of water available to downstream catchments. Natural inflows of salt and reflow of saline water resulting from irrigation interact to determine salinity levels.

⁴ Detailed documentation is available at http://www.uq.edu.au/rsmg/docs/RSMG_MDB_Model_Documentation_010610.docx

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, such as the Coorong, at the mouth of the Murray in South Australia.

The model captures uncertainty in the availability of water inflow to the Basin using the general 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.

The state of nature determines the inflow of water to the system in a given year. This is consistent with the fact that most productive activities take place on an annual cycle and that allocations of water are made on an annual basis. The model solution represents the expected returns to a long-term allocation of land between productive activities, for a given probability distribution over states of nature. The baseline probability distribution is derived from observed inflows over the period of historical records from the 1890s to the early 2000s. This distribution is then adjusted to incorporate the projected effects of climate change in 2050 and 2100.

The state-contingent approach allows the representation of producers managing risk by varying their allocation of land between activities. Each activity produces a vector of state-contingent outputs, one for each state of nature. Expected returns for a land allocation therefore depend on output prices and on the probabilities with which each state of nature occurs. These probabilities may be based on historical experience, as in the baseline simulations presented here, or on projections of the possible effects of climate change.

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 through

stochastic variation in the outputs of each commodity. This idea allows for producers to adopt alternative state-contingent plans, and reduces the risk of ‘hardwiring’ sub-optimal adaptations to uncertainty.

In the model presented here, for example, cotton is produced using two different state-contingent production activities. ‘Cotton Fixed’ produces the same output, and requires the same input of irrigation water, in all states of nature. ‘Cotton Wet’ uses irrigation to produce cotton in ‘Wet’ states of Nature, when the shadow price of water is low. In other states of Nature, no irrigation is undertaken and dryland crops are produced. This activity is an example of opportunity cropping.

The model also allows producers to produce some commodities, using alternative technologies, in which yield is traded off against water-intensity. An increase in the shadow price of water encourages a shift to less water-intensive technologies (Adamson et al 2007).

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 et al (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.

The model may be solved in one of two ways. In the ‘sequential’ solution, land and water allocations are chosen in each catchment to maximize expected returns in that catchment subject to constraints imposed by the availability of water rights, and to constraints on the availability of water, determined by the decisions of water users in upstream catchments. Adamson et al (2007) have

shown that the land allocation derived from the sequential solution is fairly close to that observed in the Basin under the current policy regime.

In the ‘global’ solution, land and water allocations are chosen to maximize expected returns for the Basin as a whole, subject to a constraint on aggregate water use for irrigation, and a constraint requiring that the salinity of water supplied to the city of Adelaide should be below a target level of 800 EC units.⁵ The global solution represents the long-run outcome in the absence of barriers to trade in water entitlements.

State-contingent and discrete stochastic programming approaches

Choices under uncertainty can 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 et al. (1993). It may therefore be useful to compare state-contingent and discrete programming approaches.

For the DSP approach, Consider a production system in which an objective function over n commodities is maximised subject to m constraints. Using the notation of Cocks

$$\max z = c'x$$

subject to

$$Ax \leq b$$

and

$$x \geq 0$$

where c and x are $n \times 1$, A is $m \times n$ and b is $m \times 1$

⁵ An EC (electrical conductivity) unit is a measure of salinity. 800 EC units is considered the upper limit for good quality potable water.

Cocks considers the case where the pair (A,c) is state-contingent, taking each of k possible values with probability p_k (he notes that the framework does not allow a sensible interpretation of stochastic constraints b , since these may be violated)

Cocks first shows that, using a diagonalization procedure, the original non-stochastic problem may be converted into a maximization problem with a scalar objective function, subject to a set of constraints of dimension $(2*m*n + m) \times (2*m*n+n)$.

The same diagonalization procedure may be applied to each of the K state-contingent pairs (A_k,c_k) while holding b constant. The result is again a problem of maximizing a scalar objective function. The constraint matrix now has dimension $((K+1)*m*n + m) \times (K+1)*m*n+K*n$.

Most interest with the DSP approach arises in applications allowing ‘recourse’, that is, the choice of some inputs after the state of nature has been partially or fully revealed. Cocks considers an example where land and capital are allocated between crops with no information about the state of nature. Labour is allocated after information on labour productivity is revealed. Finally, prices are revealed, but no further decisions may be made on the basis of this information.

The state-contingent production representation suggests an alternative to the diagonalization procedures suggested by Cocks. The commodities in the deterministic model are replaced by state-contingent commodities. That is ‘cotton in a wet state’ is treated in the model as being a different commodity from ‘cotton in a dry state’, just as ‘wheat in a dry state’ is different from ‘cotton in a dry state’ or ‘grapes in a normal state’. In this setting, we may refer to the class of state-contingent commodities producing cotton as a ‘commodity type’. In general resource constraints may also be state-contingent.

The state-contingent approach is consistent with modern production theory, and allows for a straightforward application of such duality-based concepts as input and output distance functions (Chambers and Quiggin 2000). The DSP approach

also allows for the application of duality theory, and for the derivation of shadow prices, but the economic interpretation is not as immediate.

The state-contingent approach may also be adapted to model learning over the course of the production season, using intermediate ‘event-contingent’ commodities, which are contingent on the realization of some event (an element of a partition of the state space) and are used as inputs to the production of the final vector of state-contingent commodities. In the present application, however, explicit representation of this process for a large number of regions with a wide range of commodities would produce a problem of unmanageable complexity. Rather, the specification of state-contingent inputs and outputs is taken to include optimal intra-seasonal adjustments. Alternative adaptations within a production system are modelled as different activities producing different proportions of the same state-contingent outputs.

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 the salinity of water 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 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. As described above, the producer irrigates their cotton crop only in the 'Wet' state of nature.

Representing climate change

As noted above, climate change is modelled using the Medium climate variant projections produced for the Garnaut Review. These models represent long run changes in average climate, but do not encompass the uncertainty about annual flows represented by the RSMG model.

In particular, the scenarios for climate change include projected reductions in mean inflows, but do not include projections of changes in the probability distribution of rainfall and inflows, as required for the model presented here. Hence, it is necessary to adopt assumptions about the probability distribution consistent with our (limited) available knowledge.

The simplest approach would be to represent the reduction in mean inflow 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 from modelling of global climate change suggest that the variance of rainfall is likely to increase even where mean values decrease (Burke, et al. 2006). There is considerable uncertainty about these predictions, so that it is possible that the variance of rainfall may in fact decline. On the other hand, from the subjective viewpoint of decision makers, uncertainty about the projected impacts of climate change is itself a source of additional variance.

To avoid incorporating a reduction in variance into the analysis, 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 0.5.⁶ 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.

⁶ This should not be taken as a prediction that there will be literally no wet seasons, or occasional floods, in a future of climate change. All that is necessary is that wet seasons should be so infrequent as not to form a significant factor in the production plans of farmers.

First, the salinity of water supplied to Adelaide is constrained not to exceed 800 EC. This constraint is not imposed 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.

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.

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 (\$billion)	Salinity (EC)	Water use ('000 GL)	Environmental flow ('000 GL)
Baseline	2000	2.7	460	11.9	4.8
Adaptation only	2050	2.0 (-27%)	555 (+21%)	7.4 (-38%)	1.9 (-60%)
	2100	1.0 (-62%)	NA*	2.9 (-76%)	0.7 (-86%)
Mitigation and adaptation (Environment residual)	2050	2.7 (-2%)	688 (+50%)	11.2 (-6%)	3.0 (-38%)
	2100	2.7 (-3%)	698 (+52%)	11.0 (-7%)	2.9 (-40%)
Mitigation and adaptation (Environment priority)	2050	2.4 (-11%)	359 (-22%)	8.4 (-29%)	4.9 (+2%)
	2100	2.4 (-12%)	350 (-24%)	8.1 (-32%)	4.9 (+2%)

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

A number of features of these results are noteworthy.

First, the volume of water available for use and environmental flows falls significantly in all projections. The beneficial effects of mitigation become evident mostly after 2050.⁷

Second, assuming the validity of the median projections used here, mitigation leading to stabilization of global CO₂ at 450 ppm is sufficient, in combination

⁷ 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. By contrast, in 'warm wet' variants, inflows are largely unchanged throughout the simulation period.

with adaptation, to reduce economic damage from climate change to modest levels (i.e. difference between environmental priority and environmental residual is 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.

The projections imply that the Darling River, under certain scenarios, may become a closed system with no net outflow. This implication reflects the modelling assumption that the probability of Wet years (those with rainfall substantially above the 20th century average) will decline to zero. In reality it is likely that occasional flood events would produce flows from the Darling in the Murray. However, such low-probability events would have little economic significance, since they would not justify maintenance of irrigated agriculture.

Similarly, the projections for 2100 imply that in Drought states, the Murray and Murrumbidgee would 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.

These projections are subject to the uncertainty noted above with respect to climate projections as well as the obvious uncertainties involved with such a long period, during which new agricultural technologies may be developed that permit exploitation of intermittent flows.

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, in terms of foregone net returns to agriculture, of around \$250 million/year, assuming global mitigation policies are successful.

The Australian government has committed \$10 billion over 10 years to the National Water Plan, in which the Murray Darling Basin plays a central role. Around \$3 billion has been allocated to the repurchase of excess water rights, an amount comparable in magnitude to the present value of the foregone net returns to agriculture estimated here. If this amount is used efficiently, it should, therefore, be sufficient to maintain existing environmental flows.

The simulations undertaken in this study have a number of further implications for the pattern of adaptation of land use in response to climate change and for the substitution and complementarity relationships between adaptation and mitigation. Detailed results on the allocation of land and water between crops and regions are available as an Appendix from the authors.

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 water becomes more scarce, the proportion of water allocated to horticultural crops should increase, since these are the crops which yield the highest ratio of output value to water input.

A state-contingent analysis yields the opposite conclusion. Horticultural crops generally require a consistent supply of water. Climate change is associated with an increase in the frequency of droughts, when the shadow price of water is very high. The result is that the cost of securing a stable water supply for horticultural crops increases.

The increased frequency of droughts leads to an expansion of 'opportunity cropping' activities, in which irrigation is used in years of high water availability and is replaced by dryland production activities in years of low water availability. In the model described here, opportunity cropping activities that use

irrigation water in Wet and Normal states, but not in Drought states, tend to expand as a result of climate change.

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.⁸ This model finding is consistent with empirical studies of adaptation to water scarcity in the recent drought (Sanders et al 2010).

⁸ Failure of the Wet state may lead to water requirements for horticultural production that are 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.

Table 3: State-contingent water use in the Murray–Darling Basin (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	1.5	0.0	7.3	2.1	0.8
Adaptation only	2050	1.1	0.3	2.8	3.0	0.0
	2100	0.0	0.8	0.0	2.1	0.0
Mitigation and adaptation (Environment residual)	2050	1.5	0.0	6.7	1.9	0.9
	2100	1.5	0.0	6.6	1.9	0.9
Mitigation and adaptation (Environment priority)	2050	1.5	0.0	4.8	1.3	0.5
	2100	1.5	0.0	4.6	1.3	0.5

Results available in the Appendix 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.

The results may also be used to examine the interaction between adaptation and mitigation. Adamson et al. (2009) show that the state-contingent modelling framework yields simple linear 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 proportion to the availability of water, 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 potentially applicable to 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 be unsustainable. 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, the effects of reduced water availability in all states of nature are less severe and leave open a wide range of adaptation opportunities.

Table 4: Estimated effects of climate change on economic value (\$billion) before and after adaptation (percentage of baseline economic value in parentheses)

Simulation	Year	Before adaptation	After adaptation	Benefit of adaptation
Adaptation only	2050	1.8 (-36%)	2.0 (-27%)	0.2 (9%)
	2100	1.0 (-65%)	1.0 (-62%)	0.1 (3%)
Mitigation and adaptation (Environment residual)	2050	2.3 (-17%)	2.7 (-2%)	0.4 (15%)
	2100	2.2 (-19%)	2.7 (-3%)	0.4 (16%)
Mitigation and adaptation (Environment priority)	2050	2.0 (-25%)	2.4 (-11%)	0.4 (14%)
	2100	2.0 (-27%)	2.4 (-12%)	0.4 (15%)

5. Concluding comments

The effects of, and the nature of adaptation to, climate change cannot be modelled accurately without taking appropriate account of uncertainty. Uncertainty affects all aspects of analysis of climate change, from projections of emissions paths, to global and local impacts on climatic variables to economic and social outcome. In this paper, we have focused on impact of climate change on the uncertainty associated with agricultural production, represented by state-contingent production technologies.

As is shown by the results presented here, the results of a deterministic analysis of the impacts of climate change may be seriously misleading. In particular, whereas intuition derived from a non-stochastic analysis implies that an increase in the scarcity of water should imply an increased allocation to high-value horticultural crops, a state-contingent stochastic analysis yields the opposite result.

The modelling presented here illustrates the complexity of the relationship between adaptation and mitigation. For small and moderate changes in climatic conditions, adaptation and mitigation are substitutes. However, in the absence of mitigation, severe reductions in inflows are expected to occur between 2050 and 2100. Under such conditions, there are no feasible adaptation options in many catchments other than the abandonment of irrigated agriculture. In general the more extensive the climate change in the absence of mitigation, the more likely it is that adaptation and mitigation are complements rather than substitutes.

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.

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