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Declining inflows and more frequent droughts in the Murray–Darling Basin: climate change, impacts and adaptation*

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It is likely that climate change will be associated with reductions in inflows of water to the Murray–Darling Basin. In this study, we analyse the effects of climate change in the Murray–Darling Basin using a simulation model that incorporates a state-contingent representation of uncertainty. The severity of the impact depends, in large measure, on the extent to which climate change is manifested as an increase in the frequency of drought conditions. Adaptation will partially offset the adverse impact of climate change.

Key words: drought, Murray–Darling Basin, state-contingent production.

Severe drought conditions in 2006 and 2007 have reduced inflows of water to the Murray–Darling river system to the lowest levels on record. A number of commentators have expressed the view that the severity of the drought is related, at least in part, to climate change caused by human activity (Murray Darling Basin Ministerial Council 2007). Regardless of the attribution of causes for the current drought, 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 of Concerned Scientists 2006).

Analysis of the effects of climate change is complicated by high levels of variability and uncertainty with respect to natural inflows to, and outflows from, the system. Among the world's major river systems, the Murray–Darling has both the lowest average inflow and the greatest proportional variability of inflows (Murray Darling Basin Commission 2006).

Analysis of the impact of climate change on the Murray–Darling Basin must, therefore take account of uncertainty. A state-contingent representation of production under uncertainty (Chambers and Quiggin 2000) is well-suited to this task, since different states of nature (droughts, normal rainfall

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and flood events) are represented explicitly, as are the responses of water users to the uncertainty they face. Property rights may also be modelled as bundles of state-contingent claims.

Climate models suggest that precipitation¹ in the Murray–Darling Basin will decline as a result of climate change, and that, as a result, inflows to the system will also be reduced. To analyse the effects of such reductions, it is necessary to model the resulting change in the state-contingent probability distribution for inflows to the system.

A reduction in inflows might take the form of a proportional reduction in inflows for all states of nature, that is, a uniform downward shift in the distribution. Alternatively, the probability distribution of inflows might change, with droughts becoming more frequent. In this study, we model and compare the effects, for the Murray–Darling Basin, of proportional reductions in inflows and of an increase in the frequency of drought.

The study is organised as follows. Section 1 deals with climate change and uncertainty, and introduces a number of distinctions that are important in understanding the issues. Climate change scenarios for the Murray–Darling Basin are described, along with the relationship between precipitation, evaporation and inflows. Section 2 summarises the state-contingent model of land and water allocation in the Murray–Darling Basin developed by Adamson *et al.* (2007). We show how climate change may be incorporated in the model, either as a proportional reduction in inflows to the Basin or as an increased frequency of drought. In Section 3, estimates of the impact of climate change are presented. It is shown the adverse impacts of climate change are significantly greater if change takes the form of more frequent droughts, rather than a uniform reduction in inflows across all states of nature. However, these adverse impacts may be partially offset by adaptation. In Sections 4 and 5, some suggestions for further research and some concluding comments are offered.

1. Climate change and uncertainty

Variability and uncertainty regarding natural flows is central to the analysis of irrigated agriculture. When considering climate change, it is useful to distinguish between predictable variation (for example, seasonal patterns) and uncertainty, and to further distinguish two kinds of uncertainty: risk and ambiguity. Risk arises when the probability distribution of a given variable is known. Ambiguity, also sometimes referred to as Knightian uncertainty (Knight 1921; Ellsberg 1961), arises when probabilities are unknown, or when it is not possible to describe all possible outcomes in advance.

The simplest case is that of predictable seasonal variability. In the Murray River, the natural pattern is one of high flows in spring, caused by the melting of snow in the Snowy Mountains, followed by low flows in summer and autumn. Dams allow water to be captured when it is readily available, and

¹ The term ‘precipitation’ will be used to encompass both rainfall and snowfall.

used when it would otherwise be scarce, and therefore provide a useful tool for managing seasonal variability.

Management of the Murray has produced a more even seasonal pattern with peak flows in summer, when demand for irrigation water is highest, rather than in spring. This change has potential adverse effects on environmental flows, since the natural pattern of occasional flooding is disrupted (Scott 1997).

Even under stable long-term climatic conditions, the probability distribution of inflows to the Murray–Darling Basin displays high levels of risk compared with other major river systems. Farmers and other water users do not respond passively to risk, but choose production strategies to manage risk. To represent this appropriately, it is necessary to analyse production under uncertainty in state-contingent terms. A general theory of state-contingent production is developed by Chambers and Quiggin (2000) and applied to the modelling of the Murray–Darling Basin by Adamson *et al.* (2007).

Climate change will increase climatic risk, by raising the probability of extreme events and introduce ambiguity arising from the fact that our understanding of changes in climatic patterns remains limited, particularly at regional and catchment levels. Thus, while we know that the probability distribution of climatic variables will change from the historically observed values, we cannot yet determine the probability distribution that will be applicable in the future. This is a classic case of ambiguity (Ellsberg 1961).

Most discussion of ambiguity in economic choice under uncertainty has focused on the case of an unknown probability distribution over a known set of possible outcomes. Increasingly, however, attention has focused on the more fundamental problem that some relevant future events are not foreseen adequately in advance.

Climate change itself provides an illustration. When concern about the sustainability of irrigation policy in Australia first emerged in the 1980s, the possibility of climate change was not seriously considered in this or other discussions of public policy. Even as late as 1994, the water reform programme agreed by the Council of Australian Governments (1994) took little account of climate change.

Although a good deal of attention has now been paid to climate change, new and unexpected implications of climate change continue to emerge. For example, the likelihood of more frequent and severe bushfires came to prominence following the fires of January 2003 which caused severe damage and loss of life in the Australian Capital Territory and New South Wales.

1.2 Climate change scenarios

Considerable uncertainty surrounds the likely impact of climate change on the Murray–Darling Basin. At the global level, considerable uncertainty remains with respect to both the future path of greenhouse gas emissions and the sensitivity of the global climate to atmospheric concentrations of greenhouse gases.

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.

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

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 will, in general, be reduced. However, this outcome is not certain.

Jones *et al.* (2001) present a number of possible scenarios for the regional impacts of climate change. As noted above, all simulations include an increase in mean temperatures and evaporation, and most include a reduction in mean rainfall.

Jones *et al.* use a simple model relating proportional changes in mean annual inflows to proportional changes in mean annual precipitation and potential evapotranspiration (the sum of evaporation and plant transpiration). When applied to the Macquarie catchment in the Murray–Darling Basin, this model yielded an elasticity of inflows with respect to precipitation in excess of 3.5, indicating that a 10 per cent reduction in precipitation will generate a reduction in inflows of at least 35 per cent. A 10 per cent increase in evaporation will reduce inflows by around 8 per cent. Thus, quite modest changes in precipitation and evaporation could reduce inflows substantially. Similar results are derived for Victoria by Jones and Durack (2005).

Jones *et al.* (2007) apply the methods of Jones and Page (2001) and Jones and Durack (2005) to derive inflow projections for the Murray–Darling Basin from regional projections of precipitation and temperature derived from various climate models (include models developed in Australia and overseas) and scenarios. The inflow projections of Jones *et al.* (2007) are used as the basis of the modelling undertaken in this study.

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.

Such projections involve a complex set of processes operating at very different temporal and geographical scales, from the large-scale El Nino/Southern Oscillation cycle to short-term changes in local microclimates. Fundamental issues, such as whether, and how, climate change will affect the El Nino cycle remain unresolved.

It seems likely, however, that climate change will be associated with an increase in the frequency of extreme events. Alexander *et al.* (2007) provide evidence for Australia, showing that higher mean temperatures are associated with more frequent extreme events.

In this study, we will consider two alternative hypothesis regarding changes in the state-contingent distribution of inflows. In the first, changes in inflows are proportional across states of nature, so that a reduction in mean inflows implies an equiproportional reduction in the standard deviation. In the second, changes in inflows are driven primarily by changes in the frequency of drought.

2. Model

The model is based on that presented in Adamson *et al.* (2007), with a number of subsequent developments. Most importantly, the range of irrigation activities has been expanded to include wheat production, and the modelling of salt and water flows has been updated with assistance from the Murray–Darling Basin Commission. The result of these changes is to generate model outputs including total water use, salinity levels and environmental flows that are closer to the currently observed outcomes.

The river system is divided into catchments $k = 1 \dots K$. The system is modelled as a directed network. The catchments are linked by endogenously determined, state-contingent, flows of salt and water. Water flows out of a given catchment are equal to inflows (net of evaporation and seepage) less extractions (net of return flows). Extractions are determined endogenously by land use decisions as described above, subject to limits imposed by the availability of both surface and ground water.

Agricultural land and water use in each region is modelled by a representative farmer with agricultural land area L_k . The model includes 18 catchments corresponding to Catchment Management Authority regions within the Basin and one urban region, Adelaide. The regions are linked sequentially on the basis of existing flow patterns. The network captures the cumulative water volume and salt loads from the Condamine–Balonne catchment of southern

Queensland to the Lower Murray–Darling Catchment that encompasses the South Australian portion of the Basin where the river system joins the sea.

There are S possible states of nature corresponding to different levels of inflows and other climatic conditions. In the present simulations, $S = 3$. That is, there are three states of nature: Drought (low precipitation and inflows), Normal (normal precipitation and inflows) and Wet (high precipitation and inflows).

In the baseline version of the model, the Normal state of nature occurs with probability 0.5 and is characterised by aggregate inflows of 24050 GL (1 Gigalitre (GL) = 1 billion litres). In the Drought state of nature, which occurs with probability 0.2, inflows are reduced by 40 per cent in all catchments relative to the Normal state. In the Wet state of nature, which occurs with probability 0.3, inflows are increased by 20 per cent in all catchments relative to the Normal state. With these parametric values, the distribution of inflows has a mean of 23 600 GL and a standard deviation of 5 300 GL.

The mean value is comparable to that observed historically (Murray–Darling Basin Commission, pers. comm., July 2007). The standard deviation is lower than the historically observed standard deviation for natural inflows. This is because management of the system using dams and controlled releases of water means that the annual variability of inflows of water available for irrigation is less than the variability of natural inflows.

The status of the river in each catchment and state of nature is measured by a flow variable and Q water quality variables. The $(Q + 1) \times K \times S$ vector of status variables is determined endogenously by water use decisions. In the present simulations, the only water quality variable is salinity. The interaction between producers arises from the fact that changes in salinity levels, arising from the decisions of upstream water users, affect crop yields for downstream irrigators. The model therefore incorporates the adverse effects of salinity on yields, derived from agronomic data.

There are M distinct agricultural commodities, as well as water supplied for urban use in Adelaide and therefore $(M + 1) \times S$ distinct state-contingent commodities. In the present simulations, $M = 10$. The commodities are listed in the first column of Table 1.

Some commodities are produced using more than one technology. The second column of Table 1 shows commodities produced using a single technology. The third column of Table 1 shows commodities for which two technologies are modelled, one requiring high water inputs and one in which an increased capital input (such as investment in micro-irrigation technology) is used to reduce the water input requirements. The final column of Table 1 shows commodities for which two rotations are available. In the fixed rotation, the proportions of irrigated and dryland fallow land are the same in all states of nature. In the flexible rotation, which may be described as ‘opportunity cropping’, irrigation is used in Wet (high inflow) states of nature, and dryland production in Drought (low inflow) states.

There are N inputs, committed before the state of nature is known. In the present version, $N = 5$. The model inputs are water, land, labour, capital and a

Table 1 Commodities represented in the model

Commodity	Technology		
	Single technology*	High and low water use†	Flexible and fixed rotations‡
Citrus	—	Yes	—
Cotton	—	—	Yes
Grains	Yes	—	—
Grapes	Yes	—	—
Dairy	—	Yes	—
Rice	—	—	Yes
Sheep/Wheat	—	—	Yes
Stone Fruit	—	Yes	—
Vegetables	Yes	—	—
Dryland (default)	Yes	—	—

*Commodities produced using only one technology.

†Commodities produced with high and low water use technologies.

‡Commodities produced using flexible and fixed rotations.

generic cash input. A variety of constraints on input use are imposed. Land is constrained by total area, and by soil type for particular commodities. In addition, constraints may be imposed on changes in the total area under irrigation and on the total volume of irrigation consistent with the Cap on extractions imposed by the Council of Australian Governments (1994). The supply of operator and household labour is assumed to be constrained in short run versions of the model, but contract labour is incorporated in the generic cash input.

In general, input and output prices are assumed to be the same in all regions. However, the model allows for different rules for setting water prices.

2.1 Activities

In each region, land is allocated across A_k different activities. For 1 ha of land an activity is represented by: (i) state-contingent outputs of a single commodity (dimension S); (ii) water use in each state of nature (dimension S) and (iii) other inputs (dimension N). Hence, for each region k , the matrix of activity coefficients has dimensions $A_k \times (N + 2S)$. As in Quiggin (1988), there may be more than one technology used to produce a given commodity.

Productivity in a given state of nature will depend on salinity, which in turn will be determined by upstream water use. Constraints on water availability will be determined by the interaction between upstream water use, institutional arrangements and policy variables.

The extended model uses region-specific gross margin budgets, reflecting differences in production conditions between regions. In addition, information on soil type is used to constrain production areas for specific commodities within regions. In this and other respects, geographical information system (GIS) technology has proved valuable in integrating data from

different sources, based on inconsistent and overlapping divisions of the study area, into consistent data units.

Because the model is solved on an annual basis, the process of capital investment is modelled as an annuity representing the amortised value of the capital costs over the lifespan of the development activity. This provides the flexibility to permit the modelling of a range of pricing rules for capital, and to allow the imposition of appropriate constraints on adjustment, to derive both short run and long run solutions.

2.2 Solution concepts

The model allows a variety of solution concepts. Two broad classes of solution may be considered.

In sequential solutions, water users at each stage of the system maximise private returns from water use, subject to constraints arising from regulation or the allocation of water rights, including the salinity of incoming water, but without taking direct account of the effects of their actions on downstream water users.

In global solutions, the allocation of water is chosen to maximise the social value of the Basin as a whole, possibly subject to institutional constraints. Social value encompasses the economic return to agriculture in the Basin, the value of urban water use in Adelaide, and the environmental value imputed to flows remaining in the river system, measured by flows to the sea. The solution procedure, analogous to dynamic programming, involves determining the value of water at the final stage of the system and determining optimal upstream allocations by a recursive backward induction.

In the present study, all solutions are derived subject to constraints on water use chosen to match the Cap on extractions imposed in 1995. For regions in Queensland, where individual caps have not yet been agreed, water use is constrained not to exceed average levels for 2000.

2.3 Modelling climate change

In the present study, climate change is modelled as a change in inflows of water to the catchments in the Murray–Darling Basin, using inflow projections made by Jones *et al.* (2007), described above. These projections are presented in the form of a probability distribution of changes in inflows for 2030 in which the 5th, 50th and 95th percentiles are reported.

In this study, attention is focused on the 95th percentile projection, which implies the largest reductions in inflows. There are a number of reasons for this modelling choice.

First, the policy interest in the effects of climate change in the Murray–Darling arises primarily from the risk of a substantial reduction in inflows. Hence, it is desirable to model the economic impact of such a reduction, and the extent to which the impact of reduced inflows may be offset by adaptation.

Second, the very low levels of inflows experienced in recent years, with the lowest inflows on record occurring in 2006 suggests that the probability distribution derived from climate models may be overly conservative, or that the effects of climate change associated with anthropogenic global warming are being amplified by naturally occurring reductions in rainfall (Wentworth Group of Concerned Scientists 2006).

Finally, given a projection of the impact of a large reduction in inflows, an upper bound estimate for the likely cost of a smaller reduction can be obtained by linear interpolation. A lower bound estimate can be obtained using shadow prices and probabilities for the initial solution, as discussed below. Hence, the analysis undertaken here provides upper and lower bounds for the likely economic costs of inflow reductions lying within the range considered plausible by Jones *et al.* (2007).

Jones *et al.* produced estimates of changes in inflow for each Surface Water Management Area (SWMA) in the Basin. SWMAs are areas defined by the State and Territory water management agencies for the purposes of reporting on surface water resources. The boundaries of the reporting units commonly coincide with the Australian Water Resources Council river basins. In a number of cases the reporting units represent subdivisions of these river basins.

The model used here is specified over 18 Catchment Management Areas (CMAs). Catchment Management Areas included multiple SWMAs, often with overlapping boundaries. A simple area-weighted aggregation method was applied to aggregate the changes in inflows estimated by Jones *et al.* (2007) at the SWMA level over each of the CMAs.

In area-weighted aggregation, implemented in ArcInfo GIS, a set of incompatible zones describing a given region are superimposed and intersected, to create a set of intersection zones (Flowerdew and Green 1992; Walker and Mallawaarachchi 1998). A three-step clip-dissolve-compute operation produced a spatially weighted aggregate of the changes in inflows over each of the CMAs based on the data for the subcatchments partly or wholly contained in that CMA.

The results of this process are described in Table 2. For each catchment listed in Column 1, Column 2 gives the reduction, by 2030, in mean inflows associated with the 95th percentile of the distribution of climate changes modelled by Jones *et al.* (2007).

The projections presented in Table 2 describe changes in mean inflows, but not the change in the probability distribution of inflows used in the state-contingent model described above. To simulate climate change, it is necessary to specify a change in the probability distribution of inflows, subject to the constraint that the reduction in mean inflows should be equal to that projected by Jones *et al.* (2007).

Two approaches are considered. The simpler of the two approaches, referred to as the ‘proportional reduction approach’, requires, for each catchment, the application of the percentage reduction in inflows given in Table 2

Table 2 Projected reductions in mean inflows by 2030, by catchment

Catchment	Reduction in mean inflows (per cent)
Condamine	27
Border Rivers, Queensland	24
Warrego–Paroo	22
Namoi	25
Central West	19
Maranoa–Balonne	13
Border Rivers–Gwydir	14
Western	13
Lachlan	12
Murrumbidgee	9
North East	11
Goulburn–Broken	12
Wimmera	10
North Central	12
Murray	13
Mallee	13
Lower Murray Darling	12
South Australia Murray Basin	13

Source: Derived from Jones *et al.* (2007) Surface Water Management Area.

to the modelled inflows in each of the three states of nature. In the proportional reduction approach, the probabilities of Wet, Normal and Drought states are unchanged.

In the second approach, referred to as the ‘probability change approach’, the rainfall and inflow levels associated with Wet, Normal and Drought states are left unchanged, but the probability of Drought states increases from 0.2 to 0.4, while the probability of Wet states decreases from 0.3 to 0.1. The resulting reduction in mean inflows is 15 per cent, which is similar to the reduction in average flows for the Basin as a whole in the proportional reduction simulation.

However, modelling the reduction in mean rainfall as an increase in the frequency of drought has quite different effects on the higher moments of the distribution. A proportional reduction in inflows in all states of nature produces equiproportional reductions in the mean, standard deviation and other moments of the distribution. By contrast, increasing the probability of drought increases the variance of inflows.

The main difficulty with the probability change approach is that the model is built on the assumption that the state of nature is the same for all regions. So, a change in the relative probabilities of different states of nature produces the same change in average flows in all regions. By contrast, as shown in Table 2, modelling implies that different regions will experience different changes.

This problem has been addressed by adjusting the state-contingent inflows in each region by a proportion equal to the difference between the projected

reduction in inflows for the Basin as a whole (15 per cent) and the reduction projected for the region in question, given in Table 2. When combined with the change in probabilities, this adjustment ensures that changes in average inflows match those given in Table 2.

For example, inflows in each state for the Condamine region are reduced by 12 per cent. Combined with the 15 per cent reduction in average flows arising from the change in relative probabilities, this yields a total reduction in average flows of 27 per cent. Conversely, inflows in the South Australian Murray Basin are increased by 2 per cent, which, combined with the probability change, yields a total reduction of 13 per cent, as in Table 2.

The probability change approach has important advantages. An appealing feature of the state-contingent representation is that the effects of small changes in probabilities may be estimated directly from the output of the model, without the need to solve the model a second time. Probabilities may be regarded as prices attached to the bundles of outputs produced in the associated states. Consider the case where technology and preferences are differentiable. By the envelope theorem, the equilibrium change in net returns for small price changes is approximately equal to the change in the value of output calculated at the initial equilibrium.

Exactly the same point applies to changes in probabilities in the state-contingent representation. For small changes in probabilities, the change in social value may be approximated by applying the relevant change in probabilities to the social values estimated for the initial equilibrium.

In a linear programming problem of the kind considered here, the assumption of differentiability is not satisfied exactly. However, we might reasonably expect that, in the global solution, the large number of constraints would ensure that no single constraint would produce a substantial departure from differentiability, and that the envelope theorem would give a reasonable approximation. Regardless of differentiability, the optimality of the global solution ensures that the linear approximation yields a lower bound for social value in the new equilibrium.

On the other hand, since the sequential solution is not globally optimal, and is solved stage-by-stage, these arguments do not necessarily apply. The envelope approximation need not provide a lower bound and may not be accurate even locally.

3. Results and discussion

The analysis yields six sets of results. Sequential and global solutions are derived for the baseline simulation of the current climate and for the two climate change simulations (the proportional reduction and probability change approaches). These results are presented in Tables 3–8. Table 9 is a summary table showing the expected social value in each region for all six simulations.

Table 3 Sequential solution, current climate

Catchment	Irrigated area ('000 ha)	Water use (GL)			Salinity (EC)			Social value (\$m)		
		Normal	Drought	Wet	Average	Normal	Drought	Wet	Average	Wet
Condamine	75.4	377.2	24.0	382.0	308.0	21.3	25.0	23.0	22.5	41.4
Border Rivers, Qld	49.6	248.0	41.5	255.6	209.0	30.6	36.0	33.1	32.4	63.1
Warrego-Paroo	0.7	3.5	3.5	3.5	3.5	38.9	47.2	41.7	41.4	1.5
Namoi	81.3	567.8	3.7	568.5	455.2	141.8	166.9	153.3	150.3	-1.4
Central West	89.3	656.1	57.8	667.7	539.9	75.6	90.0	81.5	80.2	42.1
Maranoa Balonne	8.0	40.1	40.1	40.1	40.1	57.9	27.8	50.8	49.7	17.3
Border Rivers-Gwydir	145.2	1003.5	5.1	1004.5	804.1	23.4	18.1	22.7	22.1	-0.6
Western	26.2	183.7	0.0	183.7	146.9	1783.9	136.2	501.6	1069.6	31.5
Lachlan	79.3	707.9	71.8	722.3	585.0	220.6	259.5	238.5	233.8	108.5
Murrumbidgee	369.7	2551.5	1703.5	3061.8	2535.0	77.6	91.5	83.8	82.2	166.3
North East	17.9	91.8	91.8	110.2	97.3	33.5	39.6	36.2	35.5	52.0
Goulburn-Broken	341.9	1671.8	1671.8	2006.2	1772.1	35.6	37.6	40.8	37.6	51.9
Wimmera	26.1	97.2	97.2	116.6	103.0	200.8	288.7	207.7	220.5	16.9
North Central	339.2	1550.0	1550.0	1860.0	1643.0	117.1	209.3	123.2	137.3	-28.5
Murray	260.3	1754.8	1099.7	2105.6	1729.0	71.8	85.3	77.5	76.2	4.3
Mallee	36.5	200.9	200.9	241.1	213.0	220.3	1203.7	214.9	415.3	-183.8
Lower Murray Darling	17.5	104.3	104.3	125.2	110.6	441.9	209.1	321.1	359.1	129.0
SA MDB	81.5	448.1	448.1	537.7	475.0	438.1	556.5	356.7	437.4	419.7
Adelaide	0.0	206.0	206.0	206.0	206.0	453.7	626.7	365.6	461.9	309.0
Environmental flows	—	4531.3	1149.4	7451.4	4731.0	700.8	1372.6	524.8	782.3	57.5
Total	2045.7	12 464.3	7420.8	14 198.0	11 975.8	—	—	—	—	1264.8
										7087.9
										4889.4

Table 4 Global solution, current climate

Catchment	Irrigated area ('000 ha)	Water use (GL)			Salinity (EC)			Social value (\$m)		
		Normal	Drought	Wet	Average	Normal	Drought	Wet	Average	Wet
Condamine	75.4	377.2	24.0	382.0	308.0	21.3	25.0	23.0	22.5	41.4
Border Rivers, Qld	49.6	248.0	41.5	255.6	209.0	30.6	36.0	33.1	32.4	63.1
Warrego-Paroo	0.7	3.5	3.5	3.5	3.5	38.9	47.2	41.7	41.4	1.5
Namoi	81.3	567.8	3.7	568.5	455.2	141.8	166.9	153.3	150.3	-1.4
Central West	89.3	656.1	57.8	667.7	539.9	75.6	90.0	81.5	80.2	42.1
Maranoa Balonne	8.0	40.1	40.1	40.1	40.1	57.9	27.8	50.8	49.7	17.3
Border Rivers-Gwydir	133.8	930.3	13.6	932.7	747.7	23.4	18.1	22.7	22.1	3.0
Western	26.2	183.7	0.0	183.7	146.9	143.9	137.5	476.1	897.3	-1.4
Lachlan	79.3	707.9	71.8	722.3	585.0	220.6	259.5	238.5	233.8	108.5
Murrumbidgee	291.8	2023.4	1378.0	2428.1	2015.8	77.6	91.5	83.8	82.2	281.3
North East	7.7	41.8	41.8	50.2	44.3	33.5	39.6	36.2	35.5	55.4
Goulburn-Broken	217.1	1066.1	1066.1	1279.4	1130.1	35.0	36.5	40.2	36.9	93.1
Wimmera	2.1	11.3	11.3	13.6	12.0	200.8	288.7	207.7	220.5	13.1
North Central	336.1	1319.9	1319.9	1583.8	1399.0	96.9	138.5	104.6	107.5	-19.4
Murray	260.3	1754.8	1099.7	2105.6	1729.0	71.8	85.3	77.5	76.2	4.3
Mallee	36.5	200.9	200.9	241.1	213.0	161.6	384.7	164.8	207.2	247.9
Lower Murray Darling	17.5	104.3	104.3	125.2	110.6	371.1	177.9	285.8	306.9	129.0
SA MDB	81.5	448.1	448.1	537.7	475.0	335.7	305.1	291.5	316.3	679.3
Adelaide	—	206.0	206.0	206.0	206.0	346.1	330.6	298.3	328.7	309.0
Environmental flows	—	5632.4	2309.2	3574.4	5850.3	512.6	583.7	416.2	497.9	115.5
Total	1794.2	10 891.3	6132.1	12 326.0	10 370.1	—	—	—	—	2182.5
										6883.2
										5053.4

Table 5 Sequential solution, proportional reduction

Catchment	Irrigated area ('000 ha)	Water use (GL)			Salinity (EC)			Social value (\$m)		
		Normal	Drought	Wet	Average	Normal	Drought	Wet	Average	
Condamine	75.4	377.2	24.0	382.0	308.0	28.3	33.3	30.6	30.0	251.5
Border Rivers, Qld	49.6	248.0	41.5	255.6	209.0	40.3	47.5	43.5	42.7	188.0
Warrego-Paroo	0.7	3.5	3.5	3.5	3.5	50.2	61.8	53.7	53.6	1.5
Namoi	81.3	567.8	3.7	568.5	455.2	176.4	208.1	190.0	187.0	110.3
Central West	77.6	566.7	57.8	578.2	468.4	92.8	111.0	99.9	98.6	185.0
Maranoa Balonne	8.0	40.1	40.1	40.1	40.1	73.4	33.2	63.0	62.2	20.7
Border Rivers-Gwydir	145.2	1003.5	5.1	1004.5	804.1	28.0	21.4	27.0	26.4	200.3
Western	0.0	0.0	0.0	0.0	0.0	42	163.5	847.0	21	369.8
Lachlan	79.3	707.9	71.8	722.3	585.0	247.3	291.2	267.0	262.1	214.9
Murrumbidgee	369.7	2551.5	1703.5	3061.8	2535.0	84.1	99.2	90.8	89.1	768.2
North East	17.9	91.8	91.8	110.2	97.3	37.4	44.2	40.4	39.7	99.7
Goulburn-Broken	341.9	1671.8	1671.8	2006.2	1772.1	40.1	42.5	46.0	42.3	428.5
Wimmera	25.5	95.1	95.1	114.1	100.8	223.0	329.0	229.0	246.1	31.7
North Central	339.2	1550.0	1550.0	1860.0	1643.0	136.4	264.8	142.0	163.9	222.9
Murray	260.3	1754.8	1099.7	2105.6	1729.0	81.1	96.4	87.4	86.0	354.8
Mallee	24.2	132.9	132.9	159.5	140.9	269.8	4936.7	258.0	1199.6	310.3
Lower Murray Darling	17.5	104.3	104.3	125.2	110.6	601.4	282.5	399.0	477.1	69.8
SA MDB	81.5	448.1	448.1	537.7	475.0	567.1	983.5	436.0	611.3	768.6
Adelaide	0.0	206.0	206.0	206.0	206.0	593.0	1212.8	450.0	674.0	103.0
Environmental flows	—	3257.3	304.0	5848.7	3444.1	954.7	5161.2	657.0	1706.7	162.9
Total	1994.9	12 121.1	7350.7	13 841.1	11 683.0	—	—	—	—	4494.2
										392.1
										6593.7
										4303.6

Table 6 Global solution, proportional reduction

Catchment	Irrigated area ('000 ha)	Water use (GL)			Salinity (EC)			Social value (\$m)		
		Normal	Drought	Wet	Average	Normal	Drought	Wet	Average	
Condamine	75.4	377.2	24.0	382.0	308.0	28.3	33.3	30.6	30.0	251.5
Border Rivers, Qld	49.6	248.0	41.5	255.6	209.0	40.3	47.5	43.5	42.7	188.0
Warrego-Paroo	0.7	3.5	3.5	3.5	3.5	50.2	61.8	53.7	53.6	1.5
Namoi	81.3	567.8	3.7	568.5	455.2	176.4	208.1	190.6	187.0	110.3
Central West	77.6	566.7	57.8	578.2	468.3	92.8	111.0	99.9	98.6	185.0
Maranoa Balonne	4.9	21.6	21.6	22.0	21.7	73.4	33.2	63.0	62.2	16.7
Border Rivers-Gwydir	92.6	642.9	12.8	645.5	517.6	28.0	21.4	27.0	26.4	148.6
Western	26.2	183.7	0.0	183.7	146.9	2164.3	166.9	578.2	1289.0	21.3
Lachlan	79.3	707.9	71.8	722.2	585.0	247.3	291.2	267.3	262.1	214.9
Murrumbidgee	290.6	2015.1	1372.8	2418.1	2007.5	84.1	99.2	90.8	89.1	709.5
North East	17.9	74.1	74.1	88.9	78.5	37.4	44.2	40.4	39.7	97.3
Goulburn-Broken	194.4	858.0	858.0	1029.6	909.5	39.8	42.1	45.7	42.1	345.3
Wimmera	23.7	95.1	95.1	114.1	100.8	223.0	329.0	229.5	246.1	32.4
North Central	206.6	892.5	892.5	1071.0	946.1	109.0	157.1	117.5	121.2	160.8
Murray	253.1	1706.5	1070.0	2047.7	1681.6	81.1	96.4	87.4	86.0	347.8
Mallee	60.4	200.9	200.9	241.1	213.0	165.6	346.3	170.9	203.3	410.0
Lower Murray Darling	17.5	104.3	104.3	125.2	110.6	445.1	223.2	331.9	366.8	141.0
SA MDB	81.5	521.6	521.6	626.0	552.9	367.1	335.8	319.0	346.4	996.7
Adelaide	—	206.0	206.0	206.0	206.0	382.2	373.8	328.7	364.5	103.0
Environmental flows	—	4746.7	1850.7	7356.0	4950.3	571.7	687.5	459.6	561.2	237.3
Total	1633.4	9993.4	5632.1	11 328.0	9521.8	—	—	—	—	4718.9
										2157.8
										367.8
										6717.5
										4806.3

Table 7 Sequential solution, probability change

Catchment	Irrigated area ('000 ha)	Water use (GL)				Salinity (EC)				Social value (\$m)					
		Normal		Wet		Average		Normal		Drought		Wet		Average	
Condamine	84.8	424.2	132.5	429.0	308.0	23.9	28.1	25.9	25.8	267.6	90.1	286.8	198.5		
Border Rivers, Qld	49.6	248.0	148.5	255.6	209.0	33.6	39.6	36.3	36.3	179.3	110.3	210.6	154.9		
Warrego-Paroo	0.7	3.5	3.5	3.5	3.5	41.9	51.0	44.9	45.8	1.5	1.5	1.5	1.5		
Namoi	81.3	567.8	406.9	568.5	503.5	153.9	181.3	166.3	166.1	94.8	60.1	96.4	81.1		
Central West	89.3	656.1	392.7	667.7	551.9	78.6	93.7	84.8	85.3	186.5	83.8	243.5	151.1		
Maranoa Balonne	8.0	40.1	40.1	40.1	40.1	65.9	47.4	56.3	57.5	20.7	17.3	21.8	19.5		
Border Rivers-Gwydir	131.9	917.8	662.6	920.4	816.0	23.7	26.9	22.9	24.9	170.4	102.4	182.0	144.4		
Western	26.2	183.7	0.0	183.7	110.2	2138.3	27 423.7	533.5	12 092.0	22.2	-1.4	29.0	13.4		
Lachlan	93.0	842.3	195.4	856.7	585.0	214.8	252.6	232.3	231.7	224.6	117.7	282.2	187.6		
Murrumbidgee	290.6	2015.1	1372.8	2418.1	1798.5	73.8	86.9	79.7	79.6	709.5	283.1	961.0	564.1		
North East	17.9	78.6	78.6	94.4	80.2	32.3	38.1	34.9	34.9	97.4	57.0	140.6	85.6		
Goulburn-Broken	341.9	1270.7	1270.7	1524.9	1296.2	34.2	36.1	39.3	35.5	359.8	206.9	606.1	323.3		
Wimmera	27.1	101.0	101.0	121.2	103.0	191.3	272.1	198.3	224.3	32.1	17.1	52.8	28.1		
North Central	339.2	1232.1	1232.1	1478.5	1256.7	101.4	157.1	108.3	124.4	168.4	94.4	340.2	156.0		
Murray	294.6	1987.0	1242.7	2384.3	1729.0	70.6	83.8	76.2	76.4	388.3	-3.6	492.9	242.0		
Mallee	38.0	208.8	208.8	250.6	213.0	168.6	440.3	170.6	277.5	485.7	227.2	684.7	402.2		
Lower Murray Darling	17.5	104.3	104.3	125.2	106.4	394.2	718.2	296.0	514.0	164.1	-10.3	250.2	103.0		
SA MDB	81.5	448.1	448.1	537.7	457.1	355.4	920.7	303.4	576.3	1079.7	-8.4	1534.8	690.0		
Adelaide	0.0	206.0	206.0	206.0	206.0	366.5	1078.5	310.4	645.7	103.0	179.7	103.0	133.7		
Environmental flows	—	5519.3	608.0	3536.1	3856.4	547.2	3068.3	436.0	1544.5	276.0	30.4	426.8	192.8		
Total	2013.1	11 535.3	8247.5	13 065.0	10 373.2	—	—	—	—	5031.7	1655.3	6946.6	3872.6		

Table 9 Expected social value (\$m): summary for all six simulations

Catchment	Current climate		Proportional reduction		Probability change	
	Sequential	Global	Sequential	Global	Sequential	Global
Condamine	214.9	214.9	214.9	214.9	198.5	194.1
Border Rivers, Qld	171.8	171.8	171.8	171.8	154.9	150.4
Warrego-Paroo	1.5	1.5	1.5	1.5	1.5	1.5
Namoi	86.7	86.7	86.7	86.7	81.1	65.2
Central West	182.6	182.6	172.7	172.7	151.1	140.9
Maranoa Balonne	20.4	20.4	20.4	18.2	19.5	17.3
Border Rivers-Gwydir	162.2	158.4	162.2	123.2	144.4	128.3
Western	24.1	24.1	1.6	19.0	13.4	18.1
Lachlan	211.0	211.0	211.0	211.0	187.6	185.7
Murrumbidgee	734.8	700.2	734.8	699.7	564.1	564.1
North East	103.4	98.8	103.4	101.7	85.6	83.0
Goulburn-Broken	436.1	380.5	436.1	362.4	323.3	311.4
Wimmera	34.9	26.8	34.7	34.6	28.1	22.0
North Central	231.3	206.8	231.3	171.1	156.0	146.1
Murray	313.9	313.9	313.9	308.2	242.0	232.9
Mallee	394.7	481.0	221.0	492.2	402.2	425.1
Lower Murray-Darling	172.1	186.6	132.0	171.3	103.0	162.3
SA MDB	1012.3	1150.6	774.7	1054.1	690.0	978.8
Adelaide	144.2	144.2	106.7	144.2	133.7	185.4
Total	4889.4	5053.4	4303.6	4806.3	3872.6	4251.1

3.1 Baseline simulations of current climate

The results of the baseline simulations of the current climate, presented in Tables 3 and 4 show, for the sequential and global solutions respectively, water use, salinity and social value for each of the regions in each state of nature (Normal, Drought and Wet). As in Adamson *et al.* (2007), the sequential solution involves higher extractive water use, higher salinity levels and lower environmental flows than does the global solution.

However, the two simulations reported here differ less than do the unconstrained global and sequential solutions considered by Adamson *et al.* (2007), mainly because both solutions are constrained by the Cap requirement that average extractions of water should not exceed the level reached in 1994. The imposition of the Cap brings the sequential solution closer to the global optimum, restricting low-value water use in upstream catchments. On the other hand, the fact that the global solution is also constrained by the Cap necessarily reduces the value of the target variable relative to the unconstrained optimum. Moreover, the imposition of the Cap constraints produces an allocation of land and water that is closer to the observed pattern of use, at least prior to the current severe drought. Since the Cap was based on prevailing patterns of land and water use, this is unsurprising.

3.2 Climate change: proportional reductions in inflows

Tables 5 and 6 present simulation results, for sequential and global solutions respectively, for the effects of climate change modelled using the proportional reduction approach.

The simulations indicate that reduced inflows arising from climate change would impose significant social costs. As shown in Table 9, total social value, relative to the current climate, declines by about \$500 million in the sequential solution and \$200 million in the global solution.

Comparison of Table 3 (sequential solution, current climate) and Table 5 (sequential solution, proportional reduction in inflows) shows that, for sequential solutions the reduction in social value due to climate change occurs mainly in the downstream regions, such as the South Australian section of the Murray–Darling Basin, in Adelaide and through reduced environmental flows. This outcome reflects the model assumption that the Cap on extractions remains unchanged, so that only modest adjustment is required in upstream regions. The reduction in social value due to climate change is reflected in reduced flows and lower water quality in downstream regions.

Similarly, comparison of Tables 3 and 5 shows that, in the sequential solution, the area allocated to irrigation declines only modestly as a result of a proportional reduction in inflows. The allocation of land between activities, reported in an appendix available from the authors, is broadly similar before and after climate change.

Comparison of Table 4 (global solution, current climate) and Table 6 (global solution, proportional reduction in inflows) shows a different pattern. In the global solution the reduction in social value due to global warming, is distributed more evenly across regions. There is more adjustment in upstream regions, including the Central West, and Goulburn–Broken regions. The increase in costs borne by downstream regions is correspondingly smaller.

The aggregate social loss associated with the global solution is significantly lower than that associated with the sequential solution. This suggests that improvements in the function of water markets could support adaptation to climate change, at least if change takes the form of a proportional reduction in state-contingent inflows.

3.3 Climate change: probability change approach

In the probability change approach, climate change with higher temperatures and lower rainfall may be represented by reducing the probability of the Wet state from 0.3 to 0.1 and increasing the probability of the Drought state from 0.2 to 0.4. Tables 7 and 8 present simulation results for increased probability of drought for the sequential and global solutions respectively.

The results show a substantially larger loss of social value than was found using the proportional reduction approach. As shown in Table 7, social value in the sequential solution declines by around \$1 billion, from \$4889 million to

\$3873 million. The global solution, presented in Table 8, shows a slightly smaller decline from \$5053 million to \$4251 million.

Before considering these results further, it is useful to examine estimates derived from approximations based on the envelope theorem. As an example, consider the global solution with current climate, presented in Table 4. The social values for the three states Normal, Drought and Wet are \$5103 million, \$2182 million and \$6883 million respectively. With probabilities of 0.5, 0.2 and 0.3, the expected social value is \$5053 million. Changing the probabilities to 0.5, 0.4 and 0.1, with no change in activities, yields an expected social value of \$4113 million, a reduction of \$1040 million relative to the initial solution.

This approximation may be tested directly. As shown in Table 8, the global solution with increased probability of drought yields state-contingent social values of \$5096 million, \$2534 million and \$6894 million for an expected social value of \$4251 million. As would be expected from the logic of optimisation, the global solution has an expected social value higher by \$139 million than that obtained using the approximation derived from the envelope theorem. This difference is the estimated net benefit of adjustment. Also as expected, the increase in probability of drought state leads to adjustments that increase social value in the Drought state and reduce social value in the Wet state.

The finding that an increase in the probability of droughts is likely to produce a greater reduction in social value than a proportional reduction in inflows yielding the same change in average inflows is a robust feature of the model presented here. This can be demonstrated by considering upper bounds derived from the model solution.

An upper bound for the loss of social damage in the proportional reduction scenario may be obtained by reducing all activities, and therefore all revenues, in proportion to the reduction in inflows. By contrast, for the probability change scenario, an estimate, exact for small changes, can be derived from the envelope theorem. As long as state-contingent returns are more variable than state-contingent inflows, this estimate will exceed the upper bound for the proportional reduction scenario. In our model, farmers commonly incur losses in the Drought state. Since inflows cannot be negative, the required condition is trivially satisfied.

4. Future research

The research presented here remains preliminary. A number of extensions to the analysis could usefully be considered.

First, the implications of higher temperatures for yields and for the water requirements of crops should be taken into account. Some analysis taking these variables into account has been undertaken by Trang (2006), but only for a limited range of crops and regions.

Second, the current model is based on a distribution of annual flows, implicitly taking the impact of storage policies as given. It would be useful to

model storage policies explicitly and to simulate long runs of data based on historical or projected rainfall distributions. It seems likely that the impact of more frequent droughts could be offset, in part, by maintaining higher levels of storage, an outcome that might be promoted by the creation of intertemporal markets (Alaouze 1991; Brennan 2007).

Finally, it would be useful to consider whether increasing the number of states of nature would improve the usefulness of the model. Such an increase would require more information about crop yields and input requirements in different states of nature.

5. Concluding comments

The effects of climate change on the Murray–Darling Basin remain uncertain. The most notable feature of the results derived here is that an assessment of the effects of climate change is sensitive to the state-contingent specification of changes in inflows, and is significantly larger if climate change takes the form of an increase in the frequency of droughts than if inflows decline proportionally in all states of nature. The management of climate change will require careful attention to the state-contingent analysis of drought policy (Quiggin and Chambers 2004) and to the structure of property rights (Freebairn and Quiggin 2006).

The adverse effects of climate change may be partially, but not entirely, offset by adjustment. Public policy should be designed to facilitate such adjustment.

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