

Impacts of climate change on lower Murray irrigation*

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This article evaluates irrigated agriculture sector response and resultant economic impacts of climate change for a part of the Murray Darling Basin in Australia. A water balance model is used to predict reduced basin inflows for mild, moderate and severe climate change scenarios involving 1, 2 and 4°C warming, and predict 13, 38 and 63% reduced inflows. Impact on irrigated agricultural production and profitability are estimated with a mathematical programming model using a two-stage approach that simultaneously estimates short and long-run adjustments. The model accounts for a range of adaptive responses including: deficit irrigation, temporarily following of some areas, permanently reducing the irrigated area and changing the mix of crops. The results suggest that relatively low cost adaptation strategies are available for a moderate reduction in water availability and thus costs of such a reduction are likely to be relatively small. In more severe climate change scenarios greater costs are estimated. Adaptations predicted include a reduction in total area irrigated and investments in efficient irrigation. A shift away from perennial to annual crops is also predicted as the latter can be managed more profitably when water allocations in some years are very low.

Key words: climate change, economics, irrigation.

1. Introduction

The Murray-Darling River Basin (MDB) (Figure 1 inset) is Australia's most productive agricultural region, contributing nearly 40 per cent to the country's \$AUD 35 billion agricultural gross value product in 2003 (Bryan and Marvanek 2004; Mullen and Crean 2007). Irrigated agricultural production is responsible for over 1/3 of the agricultural gross value product nationwide and nearly 71 per cent of irrigated production occurs in the MDB generating

* This paper was produced as part of the CSIRO Water for a Healthy Country National Research Flagship and the Lower Murray Landscape Futures Program. Valuable comments were made by Ejaz Qureshi and Jim McColl, and two anonymous reviewers provided constructive feedback and suggestions.

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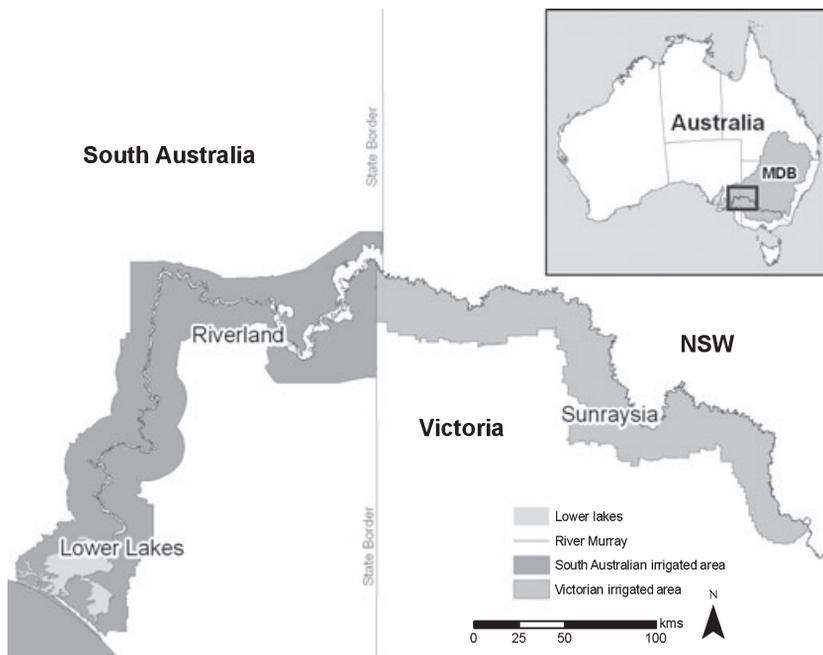


Figure 1 Study area location map with MDB in the insert. (Note that the Victorian/NSW border is the river Murray itself).

from \$3 to \$5 billion in revenues annually (Cape 1997; Bryan and Marvanek 2004; Murray-Darling Basin Commission, 2008a).

Climate change appears to be reducing flows into the Basin's rivers. For example, the 12 month period ending March 2007 is the driest such period for the River Murray over the entire 115 years of historical inflow record-keeping (Murray-Darling Basin Commission, 2007). Furthermore, the basin is over-allocated with median annual flow to the sea now only 27 per cent of the natural (pre-development) flow (Murray-Darling Basin Ministerial Council, 2002).

This article is an evaluation of the economic impacts of reduced water allocation levels on the irrigation sector in a part of the MDB. A basin-wide water balance model is used to estimate changes in inflows to major dams in the MDB system under different climate change scenarios. The climate change scenarios we assess include a mild (1°), moderate (2°), and severe (4°) increase in temperature (Celsius) that result in 13, 38, and 63 per cent reductions in Basin water inflows, and 4, 8 and 15 per cent increases in crop evapotranspiration respectively. The rainfall and runoff projections for the mild and moderate climate change scenarios in this study are similar to the CSIRO Murray Darling Basin Sustainable Yields (MDBSY) project mild and dry scenarios (which are based on IPCC 2030 projections for Southern Australia). The severe climate scenario considered is similar in terms of temperature, rainfall and inflow estimates to the higher end of the IPCC 2070 predictions

for Southern Australia (CSIRO and Bureau of Meteorology, 2007; CSIRO, 2008).

While the hydrological impact of climate change is modelled across the entire basin, the economic impacts of reduced irrigation water are assessed only for the Lower Murray irrigation area (Figure 1). This region, located in the south west corner of the MDB, is characterised by a predominance of high value irrigated horticulture and viticulture, and is considered to be particularly sensitive to reduced irrigation water. The Victorian component includes the region commonly known as Sunraysia in the east, and extends to the South Australia/Victoria state border. The South Australian region comprises the Riverland areas starting at the South Australian border with Victoria and extending southwest; the Lower Lakes region extends from the Riverland to the Murray mouth.

The article is organised as follows. Section 2 is a literature review focusing on how this research adds to a relatively sparse literature on the economic impacts of climate change on MDB irrigated agriculture. Section 3 describes methods, beginning with a description of the basin-wide water balance model used to estimate changes in inflows to major dams in the MDB system under different climate change scenarios. A discussion of how changes in inflows within the region are linked to changes in irrigation water allocation levels is then provided. This is followed by a description of the irrigated agricultural sector model used to estimate economic impacts of reduced water. Section 4 describes the consequences of climate change induced water scarcity in the region, both with and without the ability to import water into the region through water trade. Section 5 concludes the article with a summary of its findings.

2. Literature review

There is a significant body of literature investigating the impacts of climate change on U.S. agriculture, particularly through the use of agricultural sector mathematical programming models (e.g., Adams *et al.* 1995, 1999). These models typically include carbon dioxide (CO₂) levels, temperature and water availability projections from climate models as inputs, and model the yield responses to changes in these inputs. Adams *et al.* (1999) evaluates how the costs to U.S. agriculture from climate change vary with the latitude for major US farming regions and finds that for regions with more options available for confronting climate change, costs of adapting are lower. Howden and Jones (2001) assessed climate change economic impacts on the Australian dryland grain sector. Their assessment accounts for yield and quality impacts from changes in CO₂, temperature, and water availability; they also include a wide and representative set of adaptation strategies.

Chen *et al.* (2001) assessed the economic impacts of climate change on the regional economy surrounding the Edwards Aquifer, Texas with a mathematical programming model. The authors found that the reduced

recharge of the aquifer from climate change and a consequent increase in pumping costs resulted in a 1–2 per cent reduction in regional irrigated agricultural profits. Mejías *et al.* (2004), alternatively, applied a similar model to an evaluation of reduced water availability and water pricing policies in a Spanish irrigated agriculture setting. They concluded that water availability is a key determinant of the effectiveness of price as an instrument to reduce water demand. Their results suggest an inelastic demand for water during drought years and higher prices. To our knowledge, though, there have been no studies of the economic impacts of climate change on Australian irrigated agriculture published in peer reviewed journals to date.

There also is a body of literature using econometric analysis to evaluate the potential impacts of climate change on agriculture, e.g., Mendelsohn *et al.* (1994) and Deschenes and Greenstone (2007). The ability of these papers to offer targeted policy advice, though, is somewhat limited given the level of aggregation across very disparate types of farming activities (e.g., perennial crops, annual crops, pasture, grazing) and the limited data on more recent and potentially important responses to climate change by growers (i.e. out-of-sample issues). The programming approach seems better suited to characterise climate adaptation responses and costs given issues arising from diversity in farming activities and limited historical data characterising responses to projected future climate conditions.

3. Model

The model used in this analysis follows the Danzig two-stage approach with recourse (Danzig 1955) as applied to evaluating the consequences of reduced water use in Texas (McCarl *et al.* 1999) and Spain (Mejías *et al.* 2004). The first stage models the choice of long-run capital investments that remain fixed for a number of years regardless of annual stochastic variation in water allocation and water price. The second stage models the short-run (annual) decisions regarding water application rates and acreage fallowed. These short-run decisions are conditional on the fixed capital level chosen in the first stage. This comparative static approach doesn't involve an explicit assumption regarding time until full long-run adjustment. However, given that the economic life of the relevant assets is in the order of 20–30 years, we assume that full adjustment would be within that timeframe.

3.1 Modelling water allocation impacts of climate change

The model of potential climate change impacts on MDB water allocations simulates rainfall-runoff partitioning, river flow, and water sharing rules (Kirby *et al.* 2006). Water balance at a monthly scale is maintained as rain is partitioned into run-off, evaporation, and evapo-transpiration. Runoff becomes flow and accumulates down the river system and in dams and is adjusted for losses and diversions including irrigation. The water balance is

Table 1 Climate change scenarios and consequences on rainfall and runoff*

	Temperature change (°C)	PET change (%)	Rainfall change (%)	Runoff change (%)†
Mild	+1	+4	-5	-13
Moderate	+2	+8	-15	-38
Severe	+4	+15	-25	-63

*Estimates based on results from Pittock (2003) unless otherwise noted.

†Estimates based on Kirby *et al.* (2006).

modelled for the mild, moderate, and severe climate change scenarios as explained in the introduction and shown in Table 1.

The modelled changes in inflows influence water availability in the two states in our analysis (Victoria and South Australia) differently as a result of dam water storage sharing rules which we assume are similar to the sharing rules in the current Murray-Darling Basin Agreement. To predict allocations, we use the Murray-Darling Basin Commission's river operations model, BIGMOD_MSM that was developed for this purpose. BIGMOD_MSM is run under baseline conditions assuming rainfall and runoff consistent with the 25 year (1975–2000) reference climate sequence and re-run with reductions in in-flows consistent with the climate change scenarios identified in Table 1. Changes in the level of runoff are shown in the last column of Table 1. Notably, predicted runoff reductions are greater than assumed rainfall reductions due to the fact that rainfall-runoff partitioning is a non-linear relationship with runoff being more responsive than rainfall to climate change events. The estimated impacts of these climate change scenarios on irrigation water allocation levels (and reliability) are presented in Table 2.

As shown in Table 2 the probability distributions associated with different water allocation levels are represented with four water allocation states of nature – low, moderately low, moderately high, and high. The level of allocation associated with each state of nature changes depending on the climate change scenario. For example, low availability years become more the norm as the climate moves from no change to severe change.

3.2 Estimating irrigation sector impacts of climate change

The objective function for each region is:

Maximise

$$\left[- \sum_j \text{crop_establishment_cost}_j - \sum_j \sum_h \text{irrigation_establishment_cost}_{j,h} \right] * A_{j,h} \quad (1a)$$

$$+ \sum_s \text{prob}_s * \sum_j \sum_h \text{crop_price}_j * \text{YIELD}_{s,j,h} * \text{AI}_{s,j,h} \quad (1b)$$

$$- \sum_s \text{prob}_s * \text{water_variable_cost}_s * \left[\sum_j \sum_h \text{WATER}_{s,j,h} * \text{AI}_{s,j,h} - \text{allocation}_s \right] \quad (1c)$$

$$- \sum_s \text{prob}_s * \sum_j \sum_h \text{other_variable_cost}_j * \text{AI}_{s,j,h} \quad (1d)$$

The choice variables are presented in capital letters. $A_{j,h}$ is area (hectares) available for crop j using irrigation system h ; $\text{AI}_{s,j,h}$ is area (hectares) available for crop j using irrigation system h that is irrigated in state of nature s (as opposed to being fallowed); $\text{YIELD}_{s,j,h}$ is yield level (tonnes) for crop j , irrigation system h , and state of nature s ; and $\text{WATER}_{s,j,h}$ is water (ML) applied to crop j using irrigation system h in state of nature s .

Similarly, the parameters are represented in lower case letters in the objective function. The parameter $\text{crop_establishment_cost}_j$ is the fixed non-irrigation cost associated with crop j ; $\text{irrigation_establishment_cost}_{j,h}$ is the fixed cost of irrigation system type h for crop j ; crop_price_j is the price per unit yield for crop j ; $\text{water_variable_cost}_s$ is the sum of the cost per ML of water delivery (which is constant across states of nature) and the cost per ML of water allocation that captures the scarcity value of water (and varies across states of nature). The parameter allocation_s is the level of water (ML) allocated to each region in state of nature s ; and $\text{other_variable_cost}_j$ is the variable cost of production for crop j not related to irrigation.

Table 2 Predicted water allocation levels to SA and Victorian irrigators for alternative climate change assumptions

Climate scenario	Water availability	<i>P</i> -value (%)	SA water allocation (%)	Victorian mallee water allocation (%)
No change	Low	12	100	100
	Moderately low	38	100	100
	Moderately high	38	100	100
	High	12	100	100
Mild	Low	12	40	50
	Moderately low	38	82.5	90
	Moderately high	38	82.5	100
	High	12	100	100
Moderate	Low	12	0	50
	Moderately low	38	65	65
	Moderately high	38	65	100
	High	12	100	100
Severe	Low	12	0	0
	Moderately low	38	0	65
	Moderately high	38	65	65
	High	12	100	100

Equation (1a) characterises the long run (first-stage) irrigation and cropping infrastructure capital investment choices made prior to knowledge of the annual stochastic outcomes. Equation (1b–d) characterise the short-run (second-stage) decisions that can be varied after stochastically determined factors affecting production are revealed. This includes decisions to irrigate or fallow land with irrigation capital and choice of applied water rates.

3.3 Modelling water trade and water price

Equation (1c) allows for decisions to buy and sell annual water allocations. The expression, $\sum_j \sum_h \text{WATER}_{s,j,h} * \text{AI}_{s,j,h}$ -allocations, represents the net level of water allocations transferred into or out of the region. When this term is positive, water is brought into the region through water purchases; when negative, water is transferred out of the region through water sales. The model is run with and without the option of water trade so as to evaluate the value of this policy option, especially as water availability changes. In developing the relationship between water allocation and water prices, we follow Brennan (2006) who uses regression analysis to estimate such a relationship. The resulting equation ($R^2 = 0.89$), which uses annual temporary water price and water allocation data from 1998 to 2004, is as follows:

$$\ln(P) = 7.0333 - 0.48466A - 0.0086R \quad (2)$$

where P is the price of water (\$/ML). Each irrigator in the region has an entitlement to be delivered an amount of water denominated in ML. Depending on dam storage levels the water authority chooses a percentage of entitlement (A) up to 100 per cent to distribute to irrigators. This fraction of entitlement A is known as an irrigator's annual allocation. Finally, R in Equation (2) represents the cumulative season rainfall (mm). We estimate water prices that each region confronts with this equation and the water allocations and rainfall levels assumed for each climate change scenario. The results are presented in Table 3.

Table 3 Water prices (\$/ML/year) predicted with regression for climate scenarios

Water allocation year	Climate scenario			
	Baseline	Mild climate change	Moderate climate change	Severe climate change
Very low, 6th percentile	108	313	459	556
Moderately low, 24th percentile	62	180	278	459
Moderately high, 76th percentile	38	142	217	278
very high, 94th percentile	13	35	55	55
Scenario average	53	164	249	353

As expected, the lower the water allocation, the greater the market price for water and vice versa. Notice that when there is no interstate water market, Equation (2) captures the scarcity value of water within each state that arises due to intra-state water trade. When we evaluate the potential gains to interstate trade, we use the same equation to derive the price of water that growers confront, but do not impose a constraint on the amount of water growers can buy or sell.

Technically, water price predictions with this regression relationship are only valid within the range of supply, demand and price used in the original regression. It is questionable whether this equation is accurate outside of the range of values used in the original regression. A short-coming with the use of this regression to determine water price is that for more severe climate change scenarios, water prices are predicted that lie outside of the original regression sample range. Conceptually, it would be desirable to model water price endogenously as a function of basin scale demand and supply shifts that result from climate change; such an investigation is beyond the scope of our current analysis involving one part of the basin. We are, however, heartened in the knowledge that prices predicted for very low allocation levels using the Brennan equation are not dissimilar to prices observed in the last two very low allocation years (2007 and 2008).

3.4 Modelling temporary fallowing of irrigable land

Evidence from actual water market transactions suggests that the area of lower value annual crops, particularly pasture, tends to expand in years of high allocation and low water price. Livestock farmers hold rather than sell their allocations in such years and use the allocations to produce their own fodder or pasture. In a low allocation and high water price year, farmers tend to sell their water allocation and buy feed rather than grow their own fodder or pasture.

The possibility of foregoing irrigating land equipped with the capital assets (including irrigation capital) in some years is allowed. This possibility is introduced with two area choice variables: $A_{j,h}$, the area with capital investment making irrigation possible, and $AI_{s,j,h}$, that portion of $A_{j,h}$ for which water is actually applied (dependent upon state of nature s); the remaining non-irrigated portion of $A_{j,h}$ is fallowed. This relationship is represented by the following constraint:

$$AI_{s,j,h} \leq A_{j,h} \text{ for all } s, j, h \quad (3)$$

Choosing a hectare of activity $A_{j,h}$ incurs the fixed costs associated with providing the capacity to produce an irrigated crop (such as an irrigation system, plant stock and trellising in the case of viticulture). Variable costs, alternatively, are incurred only if activity $AI_{s,j,h}$ is chosen thereby indicating that a unit of potentially irrigable land is actually irrigated. Of course, when potentially irrigable land is fallowed variable costs are not incurred; additionally, fallowing land allows one to sell the water saved from fallowing.

3.5 Modelling crop yield response to water and deficit irrigation

We model irrigated crop yield as an increasing function of applied water up to a point beyond which additional water reduces yield due to lack of aeration in the root zone. The quadratic yield-water response function used is:

$$\text{YIELD}_{s,j,h} = a_j + b_j * \text{EFFECTIVE_WATER}_{s,j,h} + c_j * \text{EFFECTIVE_WATER}_{s,j,h}^2 \quad (4)$$

The parameters a , b , and c are the intercept, linear and quadratic coefficients, respectively. The function is an adaptation of the widely used Food and Agriculture Organization (FAO) crop-water yield functions (Doorenbos and Kassam 1979), varying from the original FAO formulation with the inclusion of the quadratic term. It is calibrated based on local yield, water requirement, and water production data from Jayasuriya (2004) and Qureshi *et al.* (2007).

The variable $\text{EFFECTIVE_WATER}_{s,j,h}$ in Equation (4) is defined as the total quantity of water available (ML/ha) for the crop, including irrigation water and effective rainfall when irrigation system efficiency is taken into consideration. Equation (5) identifies this relationship:

$$\text{EFFECTIVE_WATER}_{s,j,h} = (\text{WATER}_{s,j,h} * ie_h + \text{rain}_s) \quad (5)$$

where ie_h is the irrigation efficiency and represents the fraction of applied irrigation water available to the crop as opposed to being lost to surface runoff or deep drainage.

In the case of perennial horticulture and viticulture crops in hot, semi-arid settings such as the Lower Murray, a second threshold level of water application, which we refer to as the ‘future yield impact threshold’, also requires consideration. Below this threshold, not only is there no yield in the current period but yield capacity is also reduced for several additional years.

Threshold effects are incorporated into the quadratic yield response function as shown in Equations (6) and (6a–e):

$$\begin{aligned} \text{YIELD}_{s,j,h} = & I1 * [-\text{potential_yield}_j \\ & * (1 - \text{EFFECTIVE_WATER}_{s,j,h} / \text{water_threshold}_{s,j,h})] \\ & + I2 * [a_j + b_j * \text{EFFECTIVE_WATER}_{s,j,h} \\ & + c_j * \text{EFFECTIVE_WATER}_{s,j,h}^2] \end{aligned} \quad (6)$$

$I1$ and $I2$ are indicator variables with the following designations:

$$\text{For } 0 \leq \text{EFFECTIVE_WATER}_{s,j,h} \leq 0.25 * (\text{et}_{s,j} - \text{rain}_s) / ie_h; \quad (6a)$$

$$I1 = 1, I2 = 0;$$

$$\text{for } 0.25 * (et_{s,j} - rain_s)/ie_h < \text{EFFECTIVE_WATER}_{s,j,h} \leq 0.50 * (et_{s,j} - rain_s)/ie_h \quad (6b)$$

$$I1 = 0, I2 = 0;$$

$$\text{else } I1 = 0, I2 = 1. \quad (6c)$$

For annual crops, Equation (6) is used, but with the following conditions:

$$\text{For } 0 \leq \text{EFFECTIVE_WATER} \leq 0.5 * (et_{s,j} - rain_s)/ie_h, \quad (6d)$$

$$I1 = 0, I2 = 0;$$

$$\text{else } I1 = 0, I2 = 1. \quad (6e)$$

This is a piecewise representation of the variable `EFFECTIVE_WATER` in three parts following the general methodology described by Hillier and Lieberman (1986). For perennial crops and water applications below 25 per cent of the crop water requirement, Equation (6a) is binding and thus yield is determined by the term $\text{potential_yield}_j * (1 - \text{EFFECTIVE_WATER}_{s,j,h} / \text{water_threshold}_{s,j,h})$. This term represents the yield response to water in the application rate range below the future yield loss threshold, equal to 25 per cent of annual water requirement. This term computes future yield loss as equal to one year's worth of potential yield if zero water is applied, zero if the threshold level of effective water requirement is applied and linear interpolation between one year's potential yield loss and zero for water application rates between 0 and 25 per cent of annual crop water requirement. For water application rates between 25 per cent and 50 per cent of crop water requirement, Equation (6b) is binding for perennials and thus yield is zero (with no future yield loss). When conditions specified in Equation (6c) hold, our yield function follows the quadratic relationship as specified in Equation (4). Equation (6d,e) apply to annual crops. When Equation (6d) is met, water application rates are less than 50 per cent and hence yield is assumed to be zero. Similarly, when this condition does not hold, water application rates are above 50 per cent and the quadratic yield relationship specified in Equation (4) applies.

Whilst it would clearly be desirable to consider yield impacts of increased CO_2 concentration, limited relevant empirical information from Australian studies are presently available for the crops relevant to this study. Bloom (2009) summarises the state of the art in understanding, suggesting that while there is some evidence of a CO_2 fertilisation effect, in

most plants, there is a process called CO₂ acclimatisation which means that the enhanced yield impact of CO₂ diminishes over time. Furthermore, Bloom summarises newer research showing that as CO₂ levels increase, the ability of plants to convert nitrate is decreased as well as the amount of mineral nitrogen in the environment; both effects will serve to diminish the yield enhancing impact of CO₂ fertilisation. On this basis we omit CO₂ impacts on yield in this study. This may mean that our estimates include some error. Our most salient point of reference in inferring possible direction of bias is the existing studies of similar perennial crops, including wine grapes, oranges and almonds, in California (Rosenzweig *et al.* 1996; Lobell *et al.* 2006). These studies conclude that the negative yield impacts of increasing temperature are generally offset by the yield benefits of elevated CO₂ levels. By omitting CO₂ impacts on yield in this study, we may be slightly over estimating the total yield losses attributable to climate change. However, given that omitted CO₂ impacts are likely to be an order of magnitude or less than water supply impacts of climate change that we do include, we believe that this omission is unlikely to introduce major bias to our findings.

We also note that climate change may have an indirect effect on crop yield through changes in the salinity concentrations of applied water. Reduced water availability in the Murray is likely to have two counteracting impacts on river salinity levels and consequently crop yields. First, less available water and higher water prices are likely to drive improvements in irrigation efficiency. This will reduce drainage below the root zone and thus reduce salt loads that are carried with drainage to the river (Connor 2008). Second, lower flow levels resulting from reduced water availability will tend to decrease dilution of salt in the river and lead to elevated salinity levels (Connor 2008). Modelling the complex spatial and temporal aspects of these effects is beyond the scope of the current analysis but should be evaluated in detail in future work.

3.6 Modelling irrigation efficiency response

The range of irrigation system and management choices included in the model and the assumed irrigation efficiency of each irrigation technology is shown in Table 4. The values are based on regression analysis relating irrigation practice to efficiency as summarised in Kaczan and Connor (2007).

3.7 Crop mix constraints

A long standing challenge with mathematical programming models of profit maximisation at the regional level is to avoid solutions that identify only a single (most profitable) crop when, in fact, most agricultural regions consist of a mix of cropping activities that include some less profitable activities. Reasons for growers and regions being represented by a mix of crops include

Table 4 Irrigation efficiencies by crop type, irrigation technology, and management style

	Citrus	Wine	Apricot	Field crop	Veg	Nuts
Good management						
Drip	0.88	0.94	0.88	0.88	0.88	0.88
Pivot	NA	NA	NA	0.88	0.88	NA
Furrow	0.8	0.8	0.8	0.8	0.8	0.8
Under canopy	0.85	0.85	0.85	NA	NA	0.85
Overhead	0.85	0.85	0.85	0.85	0.85	0.85
Average management						
Drip	0.83	0.87	0.83	0.83	0.83	0.83
Pivot	NA	NA	NA	0.83	0.83	NA
Furrow	0.75	0.75	0.75	0.75	0.75	0.75
Under canopy	0.8	0.8	0.8	NA	NA	0.8
Overhead	0.8	0.8	0.8	0.8	0.8	0.8
Poor management						
Drip	0.78	0.82	0.78	0.78	0.78	0.78
Pivot	NA	NA	NA	0.78	0.78	NA
Furrow	0.68	0.68	0.68	0.68	0.68	0.68
Under canopy	0.73	0.73	0.73	NA	NA	0.73
Overhead	0.73	0.73	0.73	0.73	0.73	0.73

agronomic goals of disease control, economic goals of risk diversification and land quality effects. In a manner similar to previous research (e.g. McCarl 1982; McCarl *et al.* 1999; Knapp and Baerenklau 2006), we introduce a crop mix constraint that requires maintaining a constant ratio of the areas of high value perennial horticultural and viticultural crops. The constraint takes the form:

$$\alpha_j * IP_j * \sum_h A_{j,h} \geq \sum_j \sum_h IP_j * \sum_h A_{j,h} \quad (7)$$

where IP_j is a vector of binary indicator variables taking values of one for perennial crops and zero for annual crops. The constraint requires a mix of perennial crops including α_j per cent equal to the current per cent of each type. This precludes the model choosing just one perennial crop. The constraint does, however, allow substitution of annual for perennial crops if this is profitable. While in reality the mix of perennial crops changes over time depending on changing commodity price expectations, the long run changes in relative prices are difficult to foresee. This constraint limits the responses available to growers; as such, our results may overestimate the impacts of water allocation reductions although if one does consider the reasons for such a constraint outlined above, we feel that some mix will always appear, but perhaps not in the manner we have assumed. Results of sensitivity analysis provided support for the conclusion that the constraint is not significantly influencing our results. We varied the relative proportions of perennial crops assumed and found that while changing this assumption changes the absolute profit level, it has very little influence on

the percentage reduction in profits relative to the baseline as a result of greater water scarcity.

4. Results

Figure 2 presents the estimated impacts of reductions in water availability in the short-run assuming perennial planting area and crop mix are fixed. As shown, the impacts of up to a 30 per cent reduction in water allocation are minimal for both states.

The optimal short-run responses associated with these reductions seem to be *business as usual* except for some slight deficit irrigation/crop stressing. As shown, variable costs remain relatively constant. The slight profit loss arises from the revenue reductions due to lower yields as a result of the growers engaging in some deficit irrigation. As water allocations move from a 70 per cent allocation down to 30 per cent, deficit irrigation becomes more pronounced. Additional short-run responses to these lower allocations involve

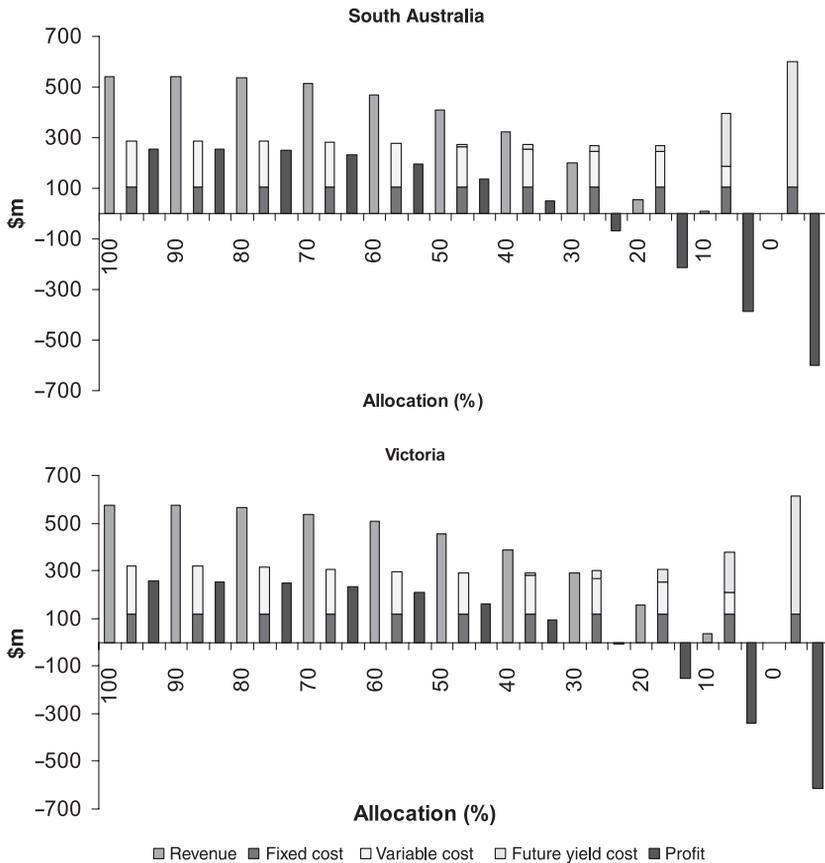


Figure 2 Estimated short-run revenue, cost and profit impacts of reduced water allocation for the South Australian and Victorian Lower Murray Irrigation Sectors.

fallowing land previously devoted to annual crops, and irrigating perennial crops with the minimum water requirement to avoid future yield loss. The reduction in variable costs from fallowing annual crop area is countered by the increase in water prices so that variable costs remain nearly constant. Revenue decreases substantially, particularly as growers fallow land and attempt to maintain a minimum level of water applications so as to forego future perennial crop damage from moisture stress. As allocations reach 20 per cent and below, though, such long term damage is unavoidable as illustrated by the large negative profits that include more than simply fixed costs—they also include the opportunity costs of foregone future production from perennial crops.

Table 5 presents the long-run adjustments to reductions in water allocation under the alternative climate change scenarios.

Three different climate change scenarios are evaluated—a mild and moderate scenario representing 2030 predictions and a severe, 2070 prediction. As specified in Tables 1–4, these scenarios differ in the probability distribution associated with water allocation to each region under different climate conditions.

Focusing on the biophysical indicators section of Table 5, we see that as water allocations decrease (and water prices increase) for progressively worsening climate change scenarios, growers fallow more land, apply less water, and generate less drainage. As shown, there is a greater propensity to leave some areas with irrigation capital fallow in years of low allocation, a response which occurs more frequently with more severe climate change. Indeed, nearly half of the acreage in South Australia is fallowed under the severe climate change scenario even though infrastructure to allow irrigation in years with plentiful water is maintained.

Counter to expectations, irrigation efficiencies show no definite trend. This outcome is a function of the crop-mix not being held constant. For instance, notice that from a crop-mix perspective, we see a movement out of perennial crops and into annual crops in progressively more severe climate change scenarios. This shift is driven by the larger penalty for under-watering perennial crops relative to annual crops that arises from reduced reliability of water supply, i.e., in some years there will be a lack of adequate water to avoid long-term perennial crop damage. The movement into annual crops from perennial crops also helps to explain the non-monotonic trends in irrigation efficiencies as water allocations decrease: generally, annual crops grown in the region are irrigated with less efficient irrigation technologies than the predominant perennials crops.

A similar relationship explains the changes in yield and water use from reduced water allocations. For instance, for the Victorian region, as water allocations decrease from the baseline scenario to the mild- and then to the moderate climate change scenarios, growers are estimated to engage in progressively more deficit irrigation as evidenced by the decreases in per cent Yield and per cent Water estimates. Yet, as water allocations become

Table 5 Summary of irrigation sector production responses under alternative climate change scenarios

Indicators	Scenarios														
	Baseline*			Mild climate change			Moderate climate change			Severe climate change			Moderate climate change (w/water purchase)		
	VIC	SA	VIC	SA	VIC	SA	VIC	SA	VIC	SA	VIC	SA	VIC	SA	
Biophysical indicators															
Irrigated area (ha)	51 457	40 911	51 457	38 841	49 300	32 529	41 844	16 542	51 457	40 911	0	0	0	0	0
Average area fallowed (ha)	0	0	0	-355	-2158	-4436	-5706	-16 542	0	0	0	0	0	0	0
Total water applied (GL)	481.2	373.6	429.1	294.2	385.5	216.5	291.4	130.2	452.6	353.3	69.7	48.8	41.0	22.3	59.9
Total drainage generated (GL)	69.7	48.8	57.5	34.1	48.8	26.5	41.0	22.3	59.9	40.9	85.5	86.6	87.8	85.9	86.8
Average irrigation efficiency (%)	85.5	86.9	86.6	88.4	87.3	87.8	85.9	82.9	86.8	88.4	100	92.5	91.6	0	0
Crop mix (as % of baseline)	100	100	100	92.5	91.6	0	0	0	100	100	55	50.8	50.4	0	0
Perennial	55	55	55	50.8	50.4	0	0	0	55	55	15	13.9	13.7	0	0
Nuts	15	15	15	13.9	13.7	0	0	0	15	15	0	0	0	0	0
Grapes	0	0	0	7.5	8.4	100	100	100	0	0	100	100	100	100	0
Annual crops	100	100	95	92	93	97	97	98	99	99	99	99	98	99	99
Yield	99	99	90	85	86	87	89	92	95	95	87	87	89	92	95
Water															
Economic indicators															
Private cost benefit															
Irrigation revenue as % of baseline	873.5 (\$m/year)	694.2 (\$m/year)	95%	86%	89%	56%	58%	29%	99%	99%	89%	89%	89%	99%	99%
Variable water costs as % of baseline	25.1 (\$m/year)	19.5 (\$m/year)	265%	229%	358%	240%	366%	150%	448%	450%	382.5 (\$m/year)	298.4 (\$m/year)	91%	78%	81%
Irrigation profit as % of baseline	382.5 (\$m/year)	298.4 (\$m/year)	91%	78%	81%	46%	48%	13%	95%	89%	873.5 (\$m/year)	694.2 (\$m/year)	95%	86%	89%

*The economic indicators baseline levels are in absolute terms (millions of AU\$ per year), not percentages. Yield and water rates (X) below baseline (i.e. > 100%) suggest a yield and water deficit equal to 100-X%.

increasingly low and unreliable under the severe climate change scenario, less deficit irrigation is observed—the result of a movement from perennial into annual crop production. The water allocation rules result in South Australia experiencing less reliability sooner than Victoria (e.g. see Table 3), thus we observe a movement into annual crops under the moderate climate change scenario in South Australia.

The economic indicators section of Table 5 presents estimates of agricultural revenues, water costs, and profits. Consistent with expectations, as water allocations decrease, revenues and profits decrease. Water costs, alternatively, generally increase with reductions in water allocations as irrigators are confronting proportionately higher water prices relative to reduced water applications. For South Australia, though, this occurs up to a point after which water becomes so limiting that total water expenditures decrease. The Victorian region modelled here is estimated to experience less water supply reduction than South Australia and is consequently less impacted. For instance, under the mild and moderate climate change scenarios, the Victorian region's agricultural profits decrease by 9 per cent and 19 per cent, respectively, compared to South Australia's 22 per cent and 54 per cent. While the estimated Victorian profit reduction (52 per cent) under the severe climate change scenario is considerably less relative to South Australia's (87 per cent), it is nonetheless substantial. Both yield reductions and water cost increases contribute to the precipitous decline in profits for both states.

A policy option that might help growers respond to lower water allocation is to open up the permanent water market thereby giving growers the opportunity to purchase water, even at higher prices, from elsewhere in the MDB. The last column in Table 5 presents the estimated impact of such an option. Water price is reflective of the reduced allocation consistent with the moderate climate change scenario, yet there is no constraint on how much water growers can purchase (or sell). As shown, allowing growers to participate in a water market reduces the impact quite substantially. Under the same climate scenario, profits decrease by 5 per cent and 11 per cent in Victoria and South Australia, respectively, compared to 19 per cent and 54 per cent without water markets. While water expenditures increase quite substantially under this scenario, revenue levels are maintained. In effect, growers have purchased that amount of water so as to mimic the solution to the baseline scenario, albeit with much higher expenditures on water. There is a slight increase in irrigation efficiency under the market scenario such that reductions in applied water use and reductions in yield are both less than in the absence of water trade.

5. Summary and conclusions

This study provides one of the first integrated assessments of the economic impacts of potential climate change on irrigated agricultural production in an important part of Australia's food basket, the Lower Murray region of the

Murray-Darling River Basin. One component of our analysis evaluates the response to a single year's reduction in water availability assuming no capital adjustments are possible. Given significant opportunities to deficit irrigate with relatively little yield loss, a 30 per cent reduction in water allocation results in a relatively minor economic impact on agriculture, i.e., a 3 per cent reduction in revenues and a 9 per cent reduction in profits. In contrast, the limited short-run responses to a 70 per cent or greater reduction in water allocation results in substantial profit loss. The water allocations associated with such severe climate change are below the minimal levels required to avoid long-term damages to perennial crops that are an important part of agriculture in the Lower Murray; consequently, future yield and revenue losses are unavoidable.

Long-run adjustments are also estimated for mild, moderate 2030 and severe 2070 climate change scenarios. For the more severe climate change scenario, the average level of water supply is expected to decline and its year to year variability increase. The model presented here evaluates how the capital stocks associated with irrigation systems and other fixed assets adjust to changes in the level and variability of long run water supply. Short-run adjustments, including deficit irrigation and temporary land fallowing, also are included and modelled simultaneously with the long-run adjustments. The short-run adjustments are modelled in a probabilistic framework involving a stochastic water supply.

Under the mild climate change scenario, the primary responses consist of increased deficit irrigation and greater investments in more efficient irrigation technology. An 11 per cent and 21 per cent reduction in average water supply in the Victorian and South Australian regions considered are estimated to result in 5 per cent and 14 per cent reductions in sector income, respectively. The moderate and severe climate change scenarios for South Australia and the severe climate change scenario for Victoria are characterised by low reliability of water supply including years of very limited or zero supply. An interesting and important response is increasing annual crop production and decreasing perennial crop production. The explanation for this outcome is that horticultural and viticultural crops suffer reduced future yield potential when minimal water requirements are not met; annuals, alternatively, can be fallowed in years of zero water supply and returned to full productivity in the first year of adequate water supplies.

A final important finding is that, to the extent that water is available for purchase from the upstream low-valued irrigated cropping sector, agricultural productivity could be expected to be maintained at near baseline levels, albeit with expenditures on water purchases rising to nearly five times their baseline levels. Yet even with the increase in water expenditures under the moderate climate change scenario with water markets, the net impact is minor in that revenues and profits from irrigated agriculture decrease by 1 per cent and 7 per cent, respectively.

As one of the first empirical analyses of the economic impact of climate on Murray Darling Basin irrigated agriculture, there are limitations to this study that should be addressed in future research. One desirable extension would be an entire basin evaluation; another would be a regional analysis that would better characterise yield response to CO₂ concentration and incorporation of this information in economic modelling. Further study would also be useful to better understand how lower flows as a result of climate change are likely to impact salinity in the Murray, how the irrigation sector is likely to respond, and how this would influence irrigated agricultural profits, revenues, output and costs. We also note that all scenarios considered here involve drier and hotter climate with less available water. At least one of the IPCC ensemble climate runs predicts hotter but wetter conditions for Southern Australia under climate change. While this study has evaluate impacts of the most likely climate scenarios for the region, further work would be desirable that evaluates optimal economic response given fundamental uncertainty regarding the nature of the future climate conditions likely to arise.

Finally, the analysis does not assess impacts of afforestation projects, water buybacks, farm dam development expansions, nor farm or conveyance system efficiency upgrades which reduce return flows. While all of these activities may reduce future flows in the MDB (Murray-Darling Basin Commission, 2008b), this article focuses solely on climate change as it was surmised to be the single largest threat to water availability by an order of magnitude or more in the recent Murray Darling Basin Sustainable Yield project (CSIRO, 2008). While other sources (e.g. Murray-Darling Basin Commission, 2008b) estimate that these additional threats to water availability may be more significant than suggested by CSIRO (2008), the magnitude of these future impacts depends critically on assumptions regarding future development trends and policies to control these threats to water availability. Consequently, a meaningful treatment of the issue around threats to water availability in addition to climate change is beyond the scope of this article and deserves its own separate and detailed evaluation.

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