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ABSTRACT

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 1^0, 2^0, 4^0 Celcius *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 fallowing some areas, and permanently reducing irrigated area and changing the mix of crops.*

The results suggest that relatively low cost adaptation strategies are available for moderate reduction in water availability and thus costs of such 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, investments in efficient irrigation, and a shift away from perennial to annual crops as the latter can be managed more profitably when water allocations in some years are very low.

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INTRODUCTION

The Murray-Darling River Basin (MDB) accounts for 41% of Australia's gross value of agricultural production with over $3 billion in revenues generated from irrigated agricultural production (Bryan & Marvanek, 2004). From a municipal and/or industrial perspective, water diversions from the MDB are important, even if the amount diverted is much smaller than for irrigation. The MDB supplies drinking water to numerous cities as well as major urban centres such as Canberra, Adelaide, and around three million people in rural Australia who are directly dependent on these supplies (Dept. of the Environment and Water Resources, 2007). Finally, the region is home to approximately 30,000 wetlands that support native wildlife; furthermore, a number of these wetlands have garnered special status under the Ramsar Convention, an intergovernmental treaty for the conservation of wetlands (Dept. of the Environment and Water Resources, 2007).

The confluence of two trends, unfortunately, threatens to create a level of water scarcity in the region that will prohibit the MDB in its ability to provide sufficient water for these three sectors. While some may question whether, and to what extent, the current level of water scarcity confronting the region is due to climate change, there is clear evidence that inflows into the region have reached record minimum levels, even when compared to the previous worst drought on record—the drought of 1895 to 1902 (Bureau of Meteorology, 2007). Also unquestionable is the fact that 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). The second trend relates to the continued over-allocation of water rights to use MDB water. Water in the MDB is highly-allocated, with median annual flow to the sea now only 27 per cent of the natural (predevelopment) flow (Murray-Darling Basin Ministerial Council, 2002). This over-allocation reduces the river's ability to weather drought which, subsequently, places pressure on ecologically valuable MDB floodplains and estuaries (Overton, 2004; Jones et al., 2002).

The objective of this article is to evaluate the economic impacts of reduced water allocation levels on the irrigation sector in the MDB. A better understanding of the potential impacts of climate change on one of the three main water demanding sectors in the MDB will give policy makers better information on the trade-offs of different water allocation policies. To accomplish our analysis, 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. Changes in inflows within the region are then linked to changes in both the average level and variability of irrigation water allocation levels using a systems operation model developed and used by the MDB River Management Authority. These stochastic irrigation water allocation levels for two states within Australia—Victoria and South Australia—then serve as inputs into a regional agricultural production model.

The impacts of three different climate change scenarios on irrigated agricultural production and profitability are estimated using a two-stage approach developed by Danzig (1955), and more recently used in water resource economics applications by McCarl et al. (1999), Mejías et al. (2004) and Zhu et al. (2005). As noted in McCarl et al. (1999), the two-stage approach consists of long-run decisions (eg. capital investment in irrigation and land, land allocated to a particular mix of crops) that are fixed regardless of the state of nature in any particular year, and short-run decisions (eg. applied water rates and acreage of land fallowed) that are made once the state of nature is revealed. In our application, the state of nature is represented by a probability distribution associated with different water allocation levels in any particular year. As the climate change scenario becomes more severe, the mean and variability of the water allocation decreases and increases, respectively. The two-stages, which are estimated simultaneously, allow us to evaluate short-run and long-run adaptive responses by growers to increased water scarcity and increased variance in allocation levels brought about by climate change.

This article contributes to the literature in several ways. First, it adds to a relatively sparse literature on assessment of the economic impacts on Australian irrigated agriculture from reduced water allocation reliability as result of climate change in Australia. Second, it provides a preliminary assessment of climate change in irrigated agriculture in a manner that maintains water balance and allows for both long-run and short-run adaptation by growers. Finally, it represents a new application of the Danzig model in a manner that allows the model to represent reasonable responses by growers to changes in both the mean and variability of water availability.

LITERATIVE REVIEW

There is extensive literature on the potential biophysical and economic impacts of climate change on agricultural production. The impacts of climate change on U.S agriculture have been examined primarily through the use of agricultural sector mathematical programming models (eg. Adams et al., 1999; Adams et al., 1995; Reilly et al., 2003). These models typically include carbon dioxide levels, temperature, and water availability projections from climate models as inputs and then 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 in which agriculture is allowed to adapt. Adaptation opportunities include:

shift to warmer season crops, plant and harvest earlier, or other on-farm management responses. As expected, the more options available to growers for confronting climate change, the lower are the costs of adapting. Adams et al. (2003) find that scale is important in assessing economics impacts of climate change on agriculture. Coarser resolution national agricultural economy models are found to mask regional limiting factors and thus often underestimate the costs of climate change. In the Australian context, Howden and Jones (2001) provide a detailed assessment of climate change impacts on the Australian dryland grain farmer sector. Their assessment accounts for yield and quality impacts from changes in carbon dioxide levels, temperature, and water availability; they also include a wide and representative set of adaptation strategies.

Only a limited number of studies have assessed the impacts of climate change on irrigated agriculture in a manner that explicitly recognizes the water balance between climate change, the hydrology of the system, and water allocation to irrigated agriculture. Globally, increased rainfall is predicted, but reductions in rainfall are projected for some parts of the world, eg. Pakistan and parts of Indonesia (Preston et al., 2006). Gleick and Chalecki (1999) evaluate the impact of climate change on two major U.S. rivers—the Colorado and the Sacramento-San Joaquin. They conclude that global warming will most likely cause a shift away from spring and summer run-off toward more winter run-off with likely consequences including reduced irrigation water availability.

Getting the water balance correct is particularly important for this sort of analysis given how vulnerable inflows into south eastern and Western Australia (and consequently water supplies for irrigation) are to rainfall. For example, in southwest WA, mean rainfall has declined dramatically from the late 1960s. Reduction in river flows, and hence dam inflows, is nearly threefold greater than the reduction in mean rainfall. That is, an average rainfall decline of 10-20% has resulted in an approximate 40-60% decline in dam inflow.

Drawing a link between climate and rainfall, Arnell (1999) predicted that a 1 to 2 degree Celsius increase in temperature would result in a 12 to 25% reduction in MDB water availability. Beare and Heaney (2002), alternatively, predict that there will be a 4 to 5% reduction in water availability in the MDB with mild climate change, and a 16 to 25% reduction in water availability for a moderate climate change scenario involving an average 2^{o} Celsius change.

A North American analysis of the economic impacts of climate change on irrigated agriculture by Chen et al. (2001) assessed the economic impacts of climate change on the water dependent Edwards Aquifer, Texas regional economy. Using a mathematical programming approach, they assessed the impact of climate change through its influence on regional groundwater dynamics while allowing for adaptation strategies such as changes in crop mix and irrigation technology. The authors found that the reduced recharge of the aquifer from climate change, which subsequently resulted in increased pumping costs, led to a 1 to 2% reduction in regional irrigated agricultural profits. Mejías et al. (2004), alternatively, apply a similar model to evaluate impacts of reduced water availability and water pricing policies to Spanish irrigated agriculture. They concluded that water availability is a key determinant of pricing policies effectiveness and controlling demand. They projected demand continuing to grow in the face of high water prices in drought years. To our knowledge though, there have been no studies to date of the economic impacts of climate change on Australian irrigated agriculture.

MODEL

The model used in this analysis follows the Danzig two-stage approach with recourse (Danzig, 1955). More recently, this two-stage approach was applied to evaluating the consequences of reduced water use in Texas (McCarl et al., 1999) and Spain (Mejías et al., 2004). For our purposes, we apply this two-stage approach in an effort to model irrigator decision-making under lower and less reliable water allocations to two states in Australia. 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; when a market is included, it also models water purchases and sales. These short-run decisions, which vary with stochastically determined water allocation and price level, are conditional on the fixed capital level chosen in the first stage. The model consists of seven components.

Modelling Water Allocation Impacts of Climate Change

To investigate the potential impacts of climate change on water allocations in the Murray-Darling Basin through changes in river flow, a water use account was developed which simulates rainfall-runoff partitioning, river flow, and water allocation within the Murray-Darling Basin. Specifically, flow impacts within the basin were investigated for mild, moderate, and severe climate change scenarios involving assumed increases in average temperature across the region by 1, 2, and 4 degrees Celsius. These climate scenarios were chosen based on the reported outcomes from recent published studies. For example, the Australian Greenhouse Office (AGO) predicts ranges of warming within Australia of between 0.4 to 2.0 degrees Celsius by 2030, and between 1.0 to 6.0 degrees Celsius by 2070 (Pittock, 2003).

Table 1 shows the reductions in potential evapotranspiration (PET) and rainfall predicted to result from these temperature rises.

TABLE 1 ABOUT HERE

The implications of the changes in PET on river flow and runoff in the Murray-Darling Basin were modelled using the methodology developed in Kirby et al. (2006). Specifically, beginning with PET and rainfall as inputs, rain is partitioned between runoff and evapotranspiration (ET) (Zhang et al., 2001). Water balance at a monthly scale which is maintained as runoff becomes flow and accumulates down the river system; adjustments for losses and diversions for irrigation are included. For the particular regions within the river basin we consider, the consequences of climate change on PET and rainfall were uniformly applied; every rainfall event had a uniform impact on both regions; the impact though, varied across the climate scenario. No seasonal differences were included.

The manner in which these uniform changes in climate change within the Basin influence the two states in our analysis (Victoria and South Australia) differently is via the dam water storage sharing rules; we assume similar sharing rules consistent with the current Murray-Darling Basin Agreement. To predict how changes in river flow and runoff will be allocated between these two states under the different climate change scenarios, we use the Murray-Darling Basin Commission's river operations model—BIGMOD MSN—that was developed for this particular purpose. BIGMOD MSN is run under baseline conditions assuming rainfall and runoff consistent with the 25-year (1975 to 2000) reference climate sequence; this allows us to parameterize the model. Subsequently, we re-run BIGMOD MSN 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, a result of the fact that rainfall-runoff partitioning is a non-linear relationship with runoff being more responsive than rainfall to climate change events.

The state-level impacts of these climate changes scenarios on water allocation levels (and reliability) are presented in Table 2.

TABLE 2 ABOUT HERE

As shown, Table 2 presents the probability distributions associated with different water allocation levels to the irrigation sector under each of the climate changes scenarios considered, including a baseline case of no change. Different climate changes scenarios translate into different water availability possibilities—low, moderately low, moderately high, and high — for the South Australian and Victorian Lower Murray irrigation sectors. These estimates are based on BIGMOD outputs, information from each state regarding water allocation rules, and conversations with appropriate South Australian and Victorian water agencies.

As indicated in Table 2, the results from the “no climate change” scenario represent the fact that under the climate conditions that existed between 1975 and 2000 both regions nearly always received 100% of their water allocations. Under the mild climate change scenario Victoria is predicted to continue to receive 100% of its irrigation allocation, while South Australia receives 100% of its allocation 88% of the time (eg. in 88 years out of 100), and 80% of its allocation 12% of the time. Again, there are low, moderately low, moderately high, and high water availability years under each climate change scenario; the frequency of each though, changes depending on climate change scenario with low availability years becoming more the norm as climate moves from no change to severe. As highlighted in Table 2, quite significant reductions in water allocation reliability are predicted for the moderate climate change scenario, with greater reductions predicted for the severe climate change scenario. Also notice that there are substantial differences across the two states in terms of the mean water availability under the different climate scenarios.

Estimating Irrigation Sector Impacts of Climate Change

Following McCarl et al. (1999), the objective function for the two-stage profit maximisation problem for each region is expressed in equation (1) as follows:

Maximise

$$[-\sum_j \text{crop\_establishment\_cost}_j - \sum_j \sum_h \text{irrigation\_establishment\_cost}_{j,h}] * A_{j,h} \tag{1a}$$

$$+ \sum_s \text{prob}_s * \sum_j \sum_h \text{crop\_price}_j * \text{YIELD}_{s,j,h} * \text{AI}_{s,j,h} \tag{1b}$$

$$- \sum_s \text{prob}_s * \text{water\_variable\_cost}_s * [\sum_j \sum_h \text{WATER}_{s,j,h} * \text{AI}_{s,j,h} - \text{allocation}_s] \tag{1c}$$

$$- \sum_s \text{prob}_s * \sum_j \sum_h \text{other\_variable\_cost}_j * \text{AI}_{s,j,h} \tag{1d}$$

The choice variables include:

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

Similarly, the parameters in the objective function include:

- $\text{crop\_establishment\_cost}_j$ ~ fixed non-irrigation cost associated crop j;
- $\text{irrigation\_establishment\_cost}_{j,h}$ ~ fixed cost of irrigation system type h for crop j;
- crop_price_j ~ price per unit yield for crop j;

- $water\_variable\_cost_s$ ~ sum of the *cost per ML of water delivery*, which is constant across states of nature, and the *cost per ML of water allocation on the water market*, which varies across states of nature;
- $allocation_{s,j,h}$ ~ level of water allocation (ML) assigned in state of nature s for crop j grown with irrigation system h;
- $other\_variable\_cost_j$ ~ variable costs of production for crop j not related to irrigation.

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

Modelling Water Trade and Water Price

In equation (1) above, term (1c) characterises decisions to buy and sell annual water allocations. The expression, $\sum_j \sum_h WATER_{s,j,h}*AI_{s,j,h}$ - $allocation_s$, 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 allocation purchases; when this term is negative, water is transferred out the region through allocation sales. The model is run with and without the option of water trade so as to evaluate the value of this policy option and how that value changes with greater water scarcity.

Table 3 presents summaries from actual water market transactions over the 25-year reference period under the column titled “Baseline.” As indicated and expected, water prices are high in years of low water allocation and hot weather during the irrigation season, and low in years of high allocation and cool weather during the irrigation season (Bjornlund, 2004).

TABLE 3 ABOUT HERE

Using regression analysis, Brennan (2006) estimates the relationship between water prices and water allocation. The resulting equation (R^2=0.89), which uses annual temporary water price and water allocation data from 1998 to 2004, is as follows:

$$\ln(P) = 7.0333 - 0.48466\,A - 0.0086\,R \tag{2}$$

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% 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 use this equation to estimate water prices that each region confronts based on the water allocations and rainfall outcomes applied to each climate change scenario. The results are presented in the remaining columns of Table 3. As expected, the lower the water allocation, the greater the market price for water and vice versa.

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 allocations and thus low water price. This is because 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 thus high water price) year, on the other hand, livestock farmers tend to sell their water allocation and buy feed rather than grow their own fodder or pasture.

Alternatively, irrigators with permanent viticulture and horticulture plantings tend to buy water to make-up deficits in low allocation years, and are willing to pay high prices for additional water given the high value of forgone production as a result of reduced irrigation on such crops. When water allocation levels are very low and water prices high, however, the profit maximising response can be to forgo yields on some perennial crops by withholding irrigation. Such an outcome occurs when profits from fully irrigating the crops (including the costs associated with purchasing additional water) are less than benefits of selling the water.

The possibility of foregoing irrigating some land equipped with the capital assets (including irrigation capital) in some years is included in the model. This possibility is introduced via the inclusion of two acreage choice variables: $A_{j,h}$, which is the acreage set aside with irrigated and non-irrigated capital investment, and $AI_{s,j,h}$, which is 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 considered fallow. This relationship is represented by the following constraint that is imposed on the model:

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

Hence, choosing a hectare of activity $A_{j,h}$ incurs the fixed costs associated with providing the capacity to produce an irrigated crop (such as land farm machinery, an irrigation system, and plant stock and trellising in the case of horticultural and viticultural crop). 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 excess allocation of water saved from fallowing.

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 root zone (de Fraiture and Perry, 2002). The specific functional form consists of a quadratic yield-water response function that is calibrated based on local yield, water requirement, and water production data from Jayasuriya (2004) and Jayasuriya and Crean (2000). This function takes the form:

$$\mathrm{YIELD}_{s,j,h} = a_j + b_j{*}\mathrm{EFFECTIVE\_WATER}_{s,j,h} + c_j{*}\mathrm{EFFECTIVE\_WATER}_{s,j,h}^{2} \qquad (4)$$

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 (FAO 53), varying from the original FAO formulation with the inclusion of the quadratic term.

The variable 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:

$$\mathrm{EFFECTIVE\_WATER}_{s,j,h} = (\mathrm{WATER}_{s,j,h}\ {*}\mathrm{irrigation\_efficiency}_{,j,h} - \mathrm{rain}_{s,j}) \qquad (5)$$

where irrigation_efficiency$_{j,h}$ represents the fraction of applied irrigation water available to the crop as opposed to being lost to surface runoff or deep drainage.

An advantage of incorporating a yield-response function into the model is that it allows for the possibility of deficit irrigation, or applying less than the full crop-water requirements and, consequently, accepting a some yield deficit. Deficit irrigation is generally viable to some threshold level, beyond which yield is zero. The threshold level assumed in this research is 50% of the applied water rate which achieves maximum yield. In the case of perennial horticultural and viticultural crops, though, too much crop stressing can have deleterious effects on future yield potential. To account for this effect, for water application below 25% of that which achieves maximum yield, a yield penalty will ensue. The yield penalty will result in a revenue loss assumed to equal between 75% and 100% of the present value of a year's revenue from the crop at maximum potential yield.

The manner in which the threshold effects are incorporated into the quadratic yield response function is via constraints on the variable EFFECTIVE_WATER. This formulation, which follows Hillier and Lieberman (1986), results in a piecewise representation of yield. For perennial crops this involves three variables to represent effective water as shown in equation (6):

$$\begin{aligned}\text{YIELD}_{s,j,h} = \; & -\text{potential\_yield}_j*(1-\text{EFFECTIVE\_WATER\_1}_{s,j,h}/\text{et}_{s,j}) \qquad (6)\\ & + 0*\text{EFFECTIVE\_WATER\_2}_{s,j,h}\\ & + (\text{EFFECTIVE\_WATER\_3}_{s,j,h}\ a_j + b_j*\text{EFFECTIVE\_WATER\_3}_{s,j,h}\\ & + c_j*\text{EFFECTIVE\_WATER\_3}_{s,j,h}{}^2);\end{aligned}$$

with constraints (6a) to (6c):

$$0 \le \text{EFFECTIVE\_WATER\_1}_{s,j,h} \le 0.25*(\text{et}_{s,j} - \text{rain}_{s,j})/\text{ie}_{j,h} \qquad \text{(6a)}$$

$$0.25*(\text{et}_{s,j} - \text{rain}_{s,j})/\text{ie}_{j,h} < \text{EFFECTIVE\_WATER\_2}_{s,j,h} \le 0.50*(\text{et}_{s,j} - \text{rain}_{s,j})/\text{ie}_{j,h} \qquad \text{(6b)}$$

$$0.50*(\text{et}_{s,j} - \text{rain}_{s,j})/\text{ie}_{j,h} < \text{EFFECTIVE\_WATER\_3}_{s,j,h} \qquad \text{(6c)}$$

For annual crops, equation (6) is used, but with the following constraints:

$$\text{EFFECTIVE\_WATER\_1}_{s,j,h} = 0 \qquad \text{(6d)}$$

$$0 < \text{EFFECTIVE\_WATER\_2}_{s,j,h} \le 0.5*(\text{et}_{s,j} - \text{rain}_{s,j})/\text{ie}_{j,h} \qquad \text{(6e)}$$

$$0.5*(\text{et}_{s,j} - \text{rain}_{s,j})/\text{ie}_{j,h} < \text{EFFECTIVE\_WATER\_3}_{s,j,h} \qquad \text{(6f)}$$

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 are shown in Table 4. The values are based on regression analysis and literature review. Specifically, data for regression analysis was sourced from a local irrigation performance benchmarking study (Skewes and Meissner, 1997) which provided details of irrigation management and outcomes for 36 wine/grape irrigators and 39 citrus irrigators.

TABLE 4 ABOUT HERE

The term *management* refers to an amalgamation of scheduling and maintenance levels which growers have control over and which influence the performance of the irrigation technology. These characteristics were used to classify irrigators as 'average,' 'above average' or 'below average' as shown in Table 5. Scheduling techniques deemed advanced were those that incorporated an objective means of feedback from the field conditions. Thus, a capacitance probe is considered 'advanced,' while a calendar or personal assessment is not.

TABLE 5 ABOUT HERE

One component of cost influenced by choice among irrigation management is the fixed cost of capital associated with an irrigation system. This is represented in the model objective function as "$\text{irrigation\_establishment\_cost}_{j,h}$". The specific costs associated with this item include the costs of irrigation systems and capital required for irrigation monitoring (capacitance probes, telemetry stations). In much of the study area water is delivered to farms in pipes at pressure sufficient to run sprinkler systems without supplementary pumping. This is not the case in a limited number of districts where water is delivered at low pressure; these districts are the only part of the study area where a significant amount of furrow irrigation still exists. In these areas supplementary booster pumps are required to convert from furrow irrigation to sprinkler systems. This additional cost is accounted for by adding the capital cost of booster pumps to the cost of all sprinkler irrigation systems in these districts.

Crop Mix Constraints

A long standing challenge with mathematical programming models of profit maximisation where multiple crops are grown arises because such models tend to identify solutions involving production of a single, most profitable crop. 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 agronomic goals of disease control, economic goals of risk diversification, and land quality effects. In this modelling effort, the issue is dealt with through introduction of a crop mix constraint that requires maintaining a constant ratio of the areas of high value perennial horticultural, viticultural, and vegetable crops. The constraint takes the form:

$$0.15^* \, IP_j{}^*A_{j,h} \geq \textstyle\sum_h IP_j{}^*A_{j,h} \qquad (6)$$

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 at least 15% of each type rather than one perennial crop but allows 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. Assuming constraints to the level of change in the mix of these commodities at current prices gives a reasonable approximation to the expected aggregate returns and water demands for these crops.

RESULTS

The impacts of alternative climate change scenarios are evaluated using the above model. Both short-run and long-run adjustments are analysed in terms of the responses by the irrigated agricultural sector to reduced water allocations that are predicted to occur under the climate change scenarios we consider. Irrigation sector responses and impacts are evaluated based on changes in irrigation sector revenues, costs, and profits. Sectoral adjustments in terms of changes in irrigation efficiencies, crop mix, and cultivated and irrigated acreage also are presented. Under the short-run analysis, water allocation reductions ranging from 10% to 90% are evaluated. Capital assets such as perennial planting acreage and crop mix are assumed fixed. Irrigators face the choice of reducing applied water rates and/or temporarily leaving some crops unirrigated. Under the long-run analysis, the irrigation sector can adjust by changing crop mix, irrigation technology, irrigated land with irrigation infrastructure, and by engaging in the same short-run strategies.

Figure 1 presents the short-run agricultural impacts from a reduction in water availability to each state. Given that this is a short-run evaluation, the opportunities for growers to respond are limited and thus we would expect the short run impacts to be large relative to the longer term impacts. As shown, the impacts of up to a 30% reduction in water allocation are minimal; a 40% reduction suggests slightly more, albeit certainly not substantial, impacts on profits.

FIGURE 1 ABOUT HERE

Optimal responses for these levels of reduction, given irrigation systems are fixed, seem to be *business as usual* except for some slight crop stressing. As shown, variable costs stay somewhat constant; the slight impact on profit is being driven by revenue reductions from lower yields as a result of the growers engaging deficit irrigation as water allocations move from a 60% allocation down to 30%,. Part of the short-run response in this allocation range involves temporary fallowing of annual crops by totally withholding irrigation and providing perennial crops with only the minimum required to avoid future yield loss. The reduction in variable costs from fallowing annual crop acreage is balanced by the increase in water prices such that variable costs stay somewhat constant. Revenue decreases substantially, particularly as growers fallow land and try to maintain a minimum level of water applications so as to forego future perennial crop damage from moisture stress. As allocations reach 20% and below, though, such long term damage is unavoidable as illustrated by the large negative profits that include more than simply fixed costs — they include the opportunity costs of foregone future production from perennial production.

Table 6 presents the long-run adjustments to reductions in water allocation under different climate change scenarios.

TABLE 6 ABOUT HERE

As mentioned earlier, growers have more flexibility to adjust to changes in water allocation in the long term relative to the short term. Three different climate change scenarios are evaluated — mild climate change, moderate climate change, and severe climate change. As specified in Tables 1 to 4, these scenarios differ in the probability distribution associated with water allocation to each region under different climate conditions. As a point of reference, the first column presents the

"Baseline" scenario, in which the programming model maximizes profits subject to the constraints (1) through (6). Under the Baseline scenario, long run water allocation expectations are assumed to be 100%.

Focusing on the Biophysical Indicators section of Table 6, we see that as water allocations decrease (and subsequently water prices increase) from progressively worsening climate change scenarios, growers fallow more land, apply less water, and generate less drainage. As shown, there is a great propensity to leave some areas with irrigation capital fallow in years of low allocation which occur more frequently with more severe climate change (notice that nearly half of the acreage in South Australia under the Severe Climate Change Scenario has irrigation infrastructure on it yet is being fallowed).

Contrary to initial expectations, irrigation efficiencies show no definite trend. This outcome is a function of 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. The reason for this shift is that there is a larger penalty associated with reduced reliability of water applications with perennial crops than with annual crops since there will be some years in which there would not be adequate water available to avoid long term 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. Annual crops grown in the region are generally less water-use efficient than the predominant perennials.

A similar relationship explains the changes in yield deficits and water deficits with reduced water allocation. For instance, consider the state of Victoria. As water allocations decrease from the Baseline Scenario to the Mild - and then to the Moderate Climate Change Scenarios, growers are engaging in progressively more deficit irrigation as evidenced by the decreases in % Yield Deficits and % Water Deficits. Yet, when the water allocations get very unreliable and low under the Severe Climate Change Scenario, we see less deficit irrigation on average - a result of a movement into annual from perennial crops. Since the water allocation rules result in South Australia experiencing less reliability sooner than Victoria (eg. see Table 3), we observe a movement into annual crops under the Moderate Climate Change Scenario.

Under the Economic Indicators section of Table 6, the impacts of the lower water allocations on state agricultural revenues, water costs, and profits are presented. Consistent with expectations, as water allocations decrease, revenues and profits decrease. Water costs, alternatively, generally increase with decreases in water allocations and states are confronting proportionately higher prices relative to their reduced usage. Yet for South Australia, the results suggest that this can occur up to some point, after which water becomes so limiting that total water expenditures decrease. Obviously, the state of Victoria is more capable of dealing with the lower water allocations than South Australia. For instance, under the Mild and Moderate Climate Change Scenarios, Victoria's regional agricultural profits decrease by 9% and 19%, respectively, compared to South Australia's 22% and 54%, respectively. Of course, while Victoria's profit reduction (52%) under the Severe Climate Change Scenario is considerably less than the impact in South Australia (87%), it is nonetheless substantial. We see that both yield reductions and water costs contribute to the precipitous decline in profits for both states.

A policy option that might help growers respond to these lower water allocations is to open up the permanent water market thereby giving growers the opportunity to purchase water, even at higher prices, from elsewhere in the river basin. The last column in Table 6 evaluates the impact of such an option under which the price is reflective of the reduced allocation consistent with the Moderate Climate Change Scenario, but there is no constraint on how much water growers can purchase (or sell).[2] As shown, allowing growers in these two states to participate in a water market reduces the impact of the individual state-level allocations quite substantially. Profits decrease by only 5% and 11% in Victoria and South Australia, respectively, compared to 19% and 54% under the same climate change scenario 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, as slightly less water is applied yet only a 1% yield deficit difference relative to the baseline scenario is observed.

SUMMARY AND CONCLUSIONS

This study provides one of the first comprehensive assessments of the economic impacts of potential climate change on the irrigation sector for an important part of the Australian Murray Darling Basin. One component of this analysis includes an identification of the response to a single year reduction in water available assuming no capital adjustments are possible. Given the significant opportunities to deficit irrigate with relatively little yield loss, a 30% reduction in water allocations result in a relatively limited economic impact on agriculture, i.e., a 3% reduction in revenues and a 9% reduction in profits. In contrast, the limited short-run responses to a 70% or greater reduction in water allocation results in substantial profit loss. The water

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[2] Of course it is assumed that there is a well-functioning market and the equilibrium market price from that market is estimated using equation (2) above and based on Brennan (2006). In this particular set up, the water would most likely come from another region in Victoria and a region in New South Wales where there is an abundance of low-valued crop production.

allocations associated with such severe climate change are below the minimal levels that would avoid long-term damages to perennial crops; the result is future yield and revenue losses.

Long-run adjustments are also estimated for mild, moderate and severe climate change scenarios involving one, two, and four degree Celsius increase in temperature. For the more severe climate change scenarios, the average level of water supply is expected to decline and its variability from year to year increase. The model presented here estimates adjustments in capital stocks of irrigation systems and other fixed assets required in irrigated crop production to changes in the level and variability of long run water supply from climate change. Short-run adjustments to stochastic water supply including water applications, temporary fallowing in low water allocation years given capital are modelled simultaneously.

Under the mild climate change scenario, the primary responses are increased deficit irrigation and greater investments in more efficient irrigation technology. As shown in Table 6, for the mild climate change scenario an 11% and 21% reduction in average water supply in Victoria and South Australia is experienced, respectively, resulting in a 5% and 14% estimated reduction in sector income, respectively. The moderate and severe climate change scenarios for South Australia and the moderate climate change scenario in Victoria are characterised by low reliability of water supply including years of very limited or zero supply. An interesting and important response to severe changes in water allocation is shown to be the switching from perennial crops to predominantly or exclusively annual crops. The reason for this switch is that horticultural and viticultural crops suffer reduced future yield potential when minimal water can not be applied, whereas annual cropping fields can be fallowed in years of zero water supply and returned to full productivity in the first year water supply moves above the critical threshold. The costs of such a significant shift in the structure of the irrigation sector are estimated to be more than proportional to the reduction in average water allocation; yet less than proportional to the short-run cost of very low allocations.

Finally, we found 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 change scenario with water markets, the net impact is minor in that revenues and profits from irrigated agriculture decrease only by 1% and 7%, respectively.

This analysis is based on climate change scenarios that use some simplifying assumptions. The expected climate changes in the Murray-Darling Basin are not uniform across the basin, nor uniform throughout the year. The runoff, storage and flow in the river system may therefore differ from those shown here. Nevertheless, we believe that our scenarios cover a wide range of possible impacts and hence a wide range of economic outcomes.

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Figure 1. Estimated short-run revenue, cost and profit impacts of reduced water allocation for the South Australian and Victorian Lower Murray Irrigation sectors

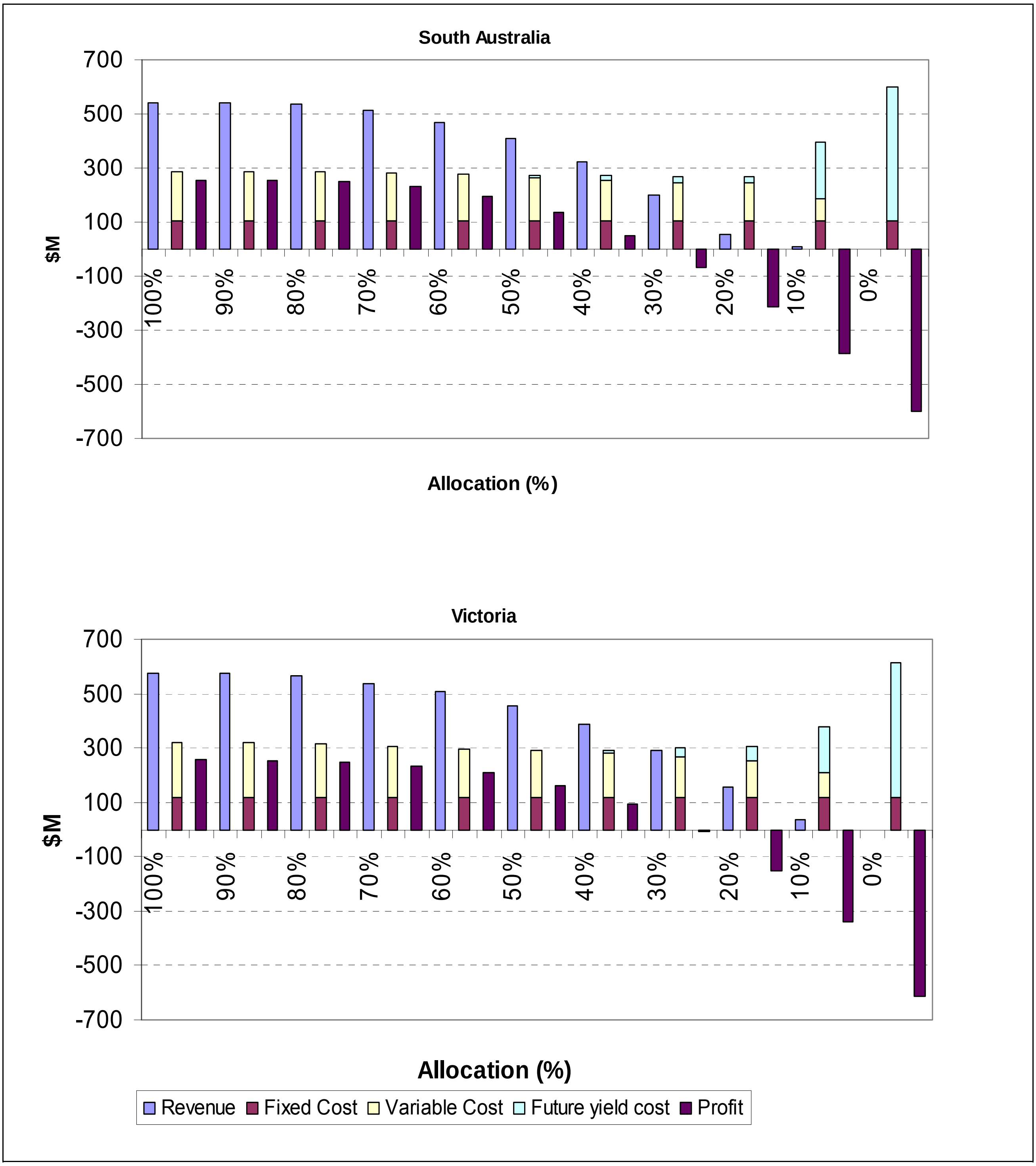

Table 1. Climate change scenarios and consequences on rainfall and runoff[*]

	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).

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

Climate Scenario	Water Availability	Probability	SA Water Allocation %	Victorian Mallee Water Allocation %
No change	Low	12%	100%	100%
	Moderately Low	30%	100%	100%
	Moderately High	24%	100%	100%
	High	34%	100%	100%
Mild	Low	12%	80%	100%
	Moderately Low	30%	100%	100%
	Moderately High	24%	100%	100%
	High	34%	100%	100%
Moderate	Low	12%	17%	39%
	Moderately Low	30%	54%	73%
	Moderately High	24%	67%	90%
	High	34%	100%	100%
Severe	Low	12%	0%	2%
	Moderately Low	30%	0%	16%
	Moderately High	24%	6%	43%
	High	34%	24%	84%

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

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

Good Management

	Citrus	Wine	Apricot	Field Crop	Veg	Nuts
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

	Citrus	Wine	Apricot	Field Crop	Veg	Nuts
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

	Citrus	Wine	Apricot	Field Crop	Veg	Nuts
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

Table 5. Irrigation management practices

Average	Irrigator does not use advanced scheduling techniques and exhibits maintenance levels within one standard deviation of the mean
Above average	Irrigator uses advanced scheduling techniques and exhibits maintenance levels greater than one standard deviation of the mean
Below average	Irrigator does not use advanced scheduling techniques and exhibits maintenance levels less than one standard deviation of the mean

Table 6. Summary of irrigation sector production responses under alternative climate change scenarios

Scenarios / Indicators	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
BIOPHYSICAL INDICATORS										
Irrigated Area (ha)	51457	40911	51457	38841	49300	32529	41844	16542	51457	40911
Average Area Fallowed (ha)	0	0	0	-355	-2158	-4436	-5706	-16542	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
Total Drainage Generated (GL)	69.7	48.8	57.5	34.1	48.8	26.5	41.0	22.3	59.9	40.9
Average Irrigation Efficiency (%)	85.5%	86.9%	86.6%	88.4%	87.3%	87.8%	85.9%	82.9%	86.8%	88.4%
Crop mix										
% Perennial	100%	100%	100%	92.5%	91.6%	0%	0%	0%	100%	100%
- % Nuts	55%	55%	55%	50.8%	50.4%	0%	0%	0%	55%	55%
- % Grapes	15%	15%	15%	13.9%	13.7%	0%	0%	0%	15%	15%
% Annual Crops	0%	0%	0%	7.5%	8.4%	100%	100%	100%	0%	0%
% Yield Deficit	100%	100%	95%	92%	93%	97%	97%	98%	99%	99%
% Water Deficit	99%	99%	90%	85%	86%	87%	89%	92%	95%	95%
ECONOMIC INDICATORS										
Private cost benefit										
Irrigation Revenue as % of Baseline	873.5 ($m/yr)	694.2 ($m/yr)	95%	86%	89%	56%	58%	29%	99%	99%
Variable Water Costs as % of Baseline	25.1 ($m/yr)	19.5 ($m/yr)	265%	229%	358%	240%	366%	150%	448%	450%
Irrigation Profit as % of Baseline	382.5 ($m/yr)	298.4 ($m/yr)	91%	78%	81%	46%	48%	13%	95%	89%

* The economic indicators baseline levels are in absolute terms (millions of AUS$ per year), not percentages.