The impact of climate change on the irrigated agricultural industries in the Murray-Darling Basin

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Climate change is expected to significantly reduce water availability in the Murray-Darling Basin. This paper details a bio-physical economic model of the Basin regions which has been developed to estimate the effect of reduced water availability on irrigated agriculture. In the model, regions are linked through a network of water and salt flows, while crop yields respond to irrigation and salinity. The model allows water trade to be restricted to regions or to be unrestricted across the basin. The paper also develops a hypothetical scenario to demonstrate the model.

1   Introduction

The Murray-Darling Basin (MDB) accounts for around 14 per cent of Australia's land mass and 10 per cent of its population. Agriculture tends to be a major contributor to most regional economies. Around 10 per cent of the labour force is directly employed in agriculture (compared to 3 per cent Australia wide) and a further significant proportion is employed in related manufacturing industries.

In terms of land use, agriculture dominates, accounting for nearly 90 million of the Basin's 106 million hectares, which produced around 39 per cent ($14.9 billion) of Australia's gross value of agricultural production ($38.5 billion) in 2005-06 (ABS 2008).

Of the 90 million hectares devoted to agriculture in the Basin, less than 2 million hectares are devoted to irrigated agriculture. In terms of total irrigation, the MDB accounts for 65 per cent of Australia's irrigated land and 66 per cent of Australia's agricultural water use (ABS 2008). The largest activities by irrigated land use in 2005-06 were pasture (720 000 hectares), cereals (330 000 hectares) and cotton (250 000 hectares) (ABS 2008).

In 2005-06, the gross value of irrigated agricultural production in the MDB was around $4.6 billion. This is around 44 per cent of the total value of irrigated product in Australia ($10.5 billion). The largest activities in terms of gross value of irrigated output were dairy ($938 million), fruit ($898 million), cotton ($797 million) and grapes ($722 million) (ABS 2008).

The predicted future climate for the Murray-Darling Basin is expected to be one of lower average rainfall and higher average temperatures (Alcamo et al. 2005). The recently released CSIRO assessment of water availability in the MDB confirms that view (CSIRO 2008). A reduction in rainfall will directly affect Basin agricultural production in two ways. Firstly, reduced rainfall will reduce crop yields, and secondly, the quantity of water available for irrigation will fall. Demand for water will also be affected by government policy related to increasing flows in environmentally stressed water systems.

Reduced access to irrigation water will have a direct impact on irrigators' incomes, as well as an indirect impact on regional economies. In developing the sustainable diversion limits within the MDB it will be important these impacts are well understood.

In this paper, ABARE's bio-physical economic model of the irrigated agricultural industries in the Murray-Darling Basin is documented and its use is demonstrated with a hypothetical case study.
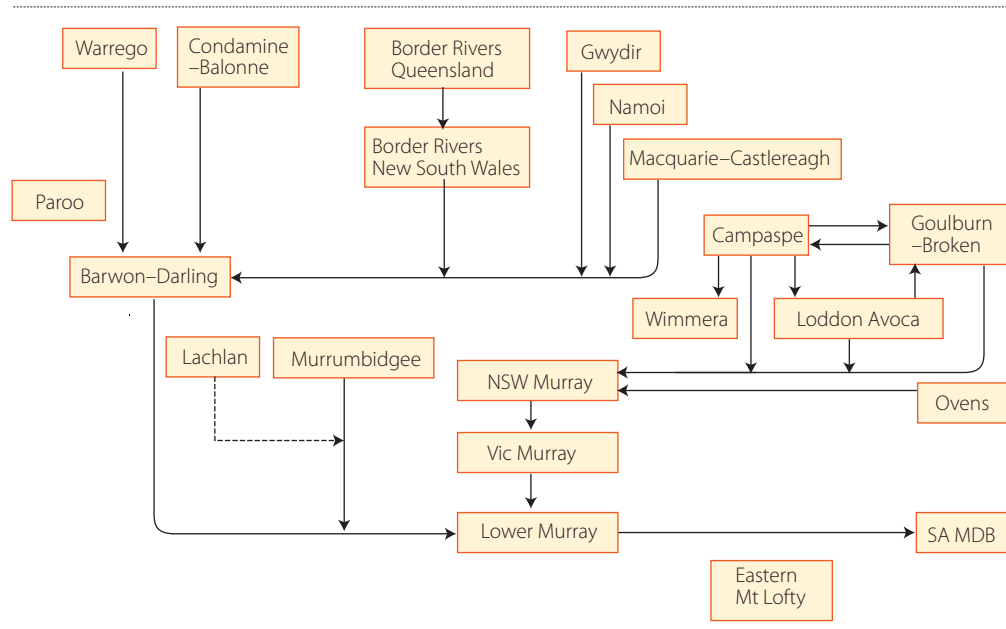
2   The model

Key features, advantages and limitations

The model is a comparative static partial equilibrium model of water markets in the MDB. It is a bio-physical economic model which uses inputs on rainfall, surface water availability and surface water diversions to estimate changes in irrigators' incomes and land use by region and activity.

The 22 regions used in the model are based on the boundaries used by CSIRO in their sustainable yields assessment. The 18 regions analysed by CSIRO were constructed around river valleys, utilising existing hydrological models where possible. ABARE has modified two regional boundaries to facilitate analyses by relevant state jurisdictions (the Border Rivers and Murray sub-catchments crossed state boundaries). This involved splitting the Border Rivers sub-catchment into Border Rivers Queensland and Border Rivers NSW and the Murray sub-catchment into Murray NSW, Lower Murray-Darling (NSW), Murray Victoria, and Murray South Australia. There are 14 land use activities specified in the model including citrus, grapes, stone fruits, pome fruits, almonds, olives, vegetables, cotton, rice, grains, oil seeds and dairy.

The model uses a nodal framework which tracks water flows from upstream to downstream regions (figure a). The model solves for the socially optimal level of water use among competing activities along a simple river network where upstream users impose salinity damages on downstream users. This unrestricted trade version of the model assumes the institutional changes necessary to adapt to reduced water availability for irrigation at regional and Basin levels would be implemented. These changes include removing limits on trade from certain regions and implementing appropriate regional water sharing plans at a reduced level of water availability.

a Linking of regions

A restricted trade version of the model solves for the optimal level of water use among competing activities in any region, but the effects of those decisions on downstream irrigators are ignored. In the restricted trade version of the model, there is essentially trade within regions, but not between regions.

The model has been designed to estimate the economic impacts of reduced water availability and to evaluate alternative institutional arrangements to share the limited water. A particular feature of this annual model is that concave yield response functions are used to model intra-seasonal optimal water allocation decisions to meet seasonal excess evaporative demand over rainfall. Estimating concave yield response functions enables the specification of flexible production functions and accounts for the effect of reduced rainfall on net irrigation requirements.

The model has some advantages over most programming models developed for the Basin which specify Leontieff production technology, such as the model of Adamson, Mallawaarachchi and Quiggin (2007). These advantages are mainly because of the incorporation of flexible production functions and include:

- the ability to calibrate exactly to observed input use levels for each activity in each region as the base case model solution preserves the observed diverse land use pattern.
- both land and water use by all activities respond at the margin to increased water scarcity rather than just the least profitable activity responding, as found in most models with Leontieff production technology. This allows for 'smooth' responses to shocks compared to sharp responses in models with Leontieff production technology.

However, the model has a number of limitations:

- The model is capable of measuring the impact of irrigation water salinity on crop yield. However, the irrigation water salinity—crop yield link in the model is currently turned off because there is little information available on the effect of reduced surface run-off on salt loads exported to the river. The model also assumes groundwater availability remains constant despite assumed reductions in rainfall and run-off because little information is available on the effect of climate change on groundwater recharge.

- The model assumes the reliability of water supply remains unchanged as water availability falls. However, climate change will have long-term effects on the frequency of different climatic events. The overall profitability of agricultural activities, particularly in investments in permanent horticulture is reliant on specific climatic events. This should ideally be explicitly incorporated in the model. The state-contingent approach used by Adamson et al. (2007) is one way of addressing this issue.

- The effect of a potential rise in temperature on crop evapotranspiration is not incorporated because relevant data is not available. When data on the impact of CO_2 fertilisation on potential crop yields and the evapotranspiration becomes available and can be incorporated into the model, the effects of climate change can be estimated with and without CO_2 fertilisation.

- The characteristics of demand for water by environmental, industrial and urban sectors are not incorporated in the model so the issue of sharing the reduced supply of water amongst all Basin water users cannot yet be examined. Incorporating these characteristics and expanding the model to allow for endogenous investment in irrigation infrastructure and water savings would improve the utility of the model.

Model formulation

The model is formulated as a mixed complementarity problem (MCP) and is run using the Path solver in GAMS. The MCP form comprises price and quantity equations and additional complementary slackness conditions. An additional complementary slackness condition is required if the price or quantity equation is expressed as an inequality.

In the most general form of the mixed complementarity formulation, a price (quantity) equation expressed as an inequality is paired with the quantity (price) level in a complementary slackness (CS) condition that is inferred by the Path solver in GAMS. In general, for activity x measured in quantity units, the price equation becomes the zero profit condition and can be expressed as inequality *g(x)>= 0*. The zero profit or price condition (marginal benefits less marginal cost) states that the marginal benefit cannot exceed marginal cost and if marginal benefit is less than marginal cost the activity x will not be undertaken *(x=0)*.

Sets, variable names and exogenous parameters are noted in box 1 along with quantity and price equations. A description of the model is presented in the following sections.

box 1   **Notation**

i	inputs to production, i = water (w) and land (l)
k	source of water, k = surface water (s) and groundwater (g)
j	agricultural production activities j = citrus, stone fruit, grapes, almond, pome fruits, dairy, rice, cotton, lucerne, grains, dryland agriculture.
u	index number of the discrete quantity of budgeted water u=1,2,…..,n
m	month m= Aug, Sep,………..,Jul

Parameters

POP_{rj}	price of output j in region r ($/tonne)
$QSLND_{r}$	supply of land in region r ('000 ha)
$QSLW_{r}$	local supply of surface water in region r (GL/y)
$QGWT_{r}$	total allocation of groundwater in region r (GL/y)
h_{r}	water application efficiency in region r (proportion)
$closs_{r}$	transmission losses of water in region r (proportion)
$LSLT_{r}$	salt content of local surface water in region r (mg/litre)
$XDMTH_{0}$	minimum required water flow at river mouth (GL/y)
$\delta_{j\,rj}$	proportional reduction in output from a unit increase in salinity when over threshold
$c1_{rj}$	parameter on quadratic operating cost function ($/tonne)
$c2_{rj}$	parameter on quadratic operating cost function ($/tonne squared)
$d1_{rj}$	parameter on quadratic groundwater extraction cost function ($/ML)
$d2_{rj}$	parameter on quadratic groundwater extraction cost function ($/ML squared)
x_{ju}	u^{th} discrete quantity of water budgeted for crop j (ML/ha)
$ET_{jm}^{\ max}$	potential evapotranspiration of crop j in month m (ML/ha)
Ky_{jm}	Yield penalty factor for crop j in month m
ER_{jm}	Effective rainfall for crop j in month m
SM_{jm}	Soil moisture available for crop j in month m
$SLTRW_{rj}$	salt content of rain water used by crop j in region r (mg/litre)
LF	salinity leaching factor
K	Coefficient used in Rhoades equation
$SLTTHRESH_{rj}$	salinity threshold for crop j in region r (mg/litre)
$UQRWU_{rj}$	effective rainfall on unit land area of crop j in region r (ML/ha)

Variables

WXP_{r}	surface water flow downstream from region r (GL/y)
SLT_{r}	salt content of river water flowing downstream from region r (mg/litre)
AP_{rj}	area of crop j planted in region r (ha)
Y_{rj}	yield of crop j in region r (tonne/ha)
QWU_{rk}	volume of water from source k used in region r (GL/y)
PDL_{r}	user price of land in region r ($/ha)
PDW_{r}	user price of water in region r ($/ML)

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box 1   **Notation**   *continued*

$PDGW_r$	groundwater restricted trade price in region r ($/ML)
PWX_r	surface water flow price ex region r $(/ML)
$PSLTR_r$	user charge for causing salinity in region r ($/tonne of salt)
$SLTOVrj$	salinity over base year zero damage threshold (mg/litre)
$UQWU_{rj}$	volume of irrigation water applied for unit land area of crop j in region r (ML/ha)
MPW_{rj}	marginal product on an annual unit of water for crop j in region r (t/ML/ha)
Y^a_{ju}	actual yield of crop j obtained from quantity u of budgeted water (t/ha)
$ET_{jum}{}^a$	actual evapotranspiration of crop j with quantity u of water applied in month m (ML/ha)
q_{jum}	volume of irrigation water applied in month m for crop j with annual water budget of u (ML/ha)
$SLTAW_{rj}$	average salt content of all water applied to crop j in region r (mg/litre)
$SLTRZ_{rj}$	average salinity of the moisture in the root zone at field capacity for crop j in region r (mg/litre)
RY_{rj}	Relative yield with salinity over threshold for crop j in region r (mg/litre)

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The model

Land allocation

$$1 \qquad \left(c1_{rj} + c2_{rj}\, AP_{rj} Y_{rj}\right) Y_{rj} + PDL_r + PDW_{rs} UQWU_{rj} \geq POP_{rjs} Y_{rjs} (1 - \delta_{rj} SLTOV_{rs})$$

All agricultural activities are modelled as a single product. The representative producer of crop j in region r decides what inputs to use to maximize profit, taking intermediate input and output prices as given in competitive markets. Equation 1 matches, for each region and activity, the cost of production per hectare (unit cost) given in the LHS with the gross revenue per hectare adjusted for salt impacts on the RHS.

On a per hectare basis, the total unit cost consists of the marginal cost of intermediate inputs plus the land rent and user cost of water. The gross revenue is given by the product of the price of output, yield per hectare and the penalty on yield (which depends on the sensitivity of the crop to salinity in soil moisture).

For each region and activity, if the unit cost of production always exceeds the gross revenue received after adjusting it for salt damage, $POP_{rjs} Y_{rjs} (1 - \delta_{rj} SLTOV_r)$, then the activity is not profitable and production and input use will be nil. If production occurs it must be profitable. For this to be so, assuming zero pure profit (following the general form of the CS condition specified above), price adjusted for salt impact must equal unit cost at the optimal output level. The precise level of output is determined by input prices that are endogenous to the model. Endogenous land and water prices are determined on markets where producers compete for the limited resources available.

For each crop, the penalty on yield because of root zone salinity as defined by Mass and Hoffman (1977) depends on the difference between the root zone salinity and the salinity threshold of the crop ($SLTOV_r$) and the sensitivity of the crop to salinity (δ_{rj}). The process employed in estimating the root zone salinity is explained in further detail in the explanation of the agronomic module.

Water use per unit of land

$$2 \qquad \left(c1_{rj} + c2_{rj}\,AP_{rj}Y_{rj}\right)MPW_{rj} + PDW_{rs} \geq POP_{rjs}MPW_{rj}(1 - \delta_{rj}SLTOV_{rs})$$

where; $\quad MPW_{rj} = b_{rj} + 2c_{rj}UQWU_{rj}$

For each irrigation activity a decision to increase production entails additional costs, including the cost of irrigation water and other inputs needed to produce additional output. The first term in the LHS of equation 2 is the cost of other inputs used in producing the marginal product of an additional unit of water, MPW_{rj} while the second term is the user price of water. In equation 2, if the cost of increasing production by applying an extra unit of water exceeds the revenue received from producing the marginal product of an additional unit of water after adjusting it for salt damage (the term on the RHS), then applying that additional unit of water is not profitable and is not appiled. If additional irrigation water is applied then it must be profitable and the marginal cost is equal to marginal profits.

As the marginal product of water is a decreasing function of the volume of water applied per hectare, the MPW_{rj} which holds equation 2 in equality will in turn determine the optimal volume of water applied per hectare, $UQWU_{rj}$. The optimal yield at this quantity of water is obtained from a yield response function given in equation 3.

$$3 \qquad Y_{rj} = a_{rj} + b_{rj}UQWU_{rj} + c_{rj}UQWU_{rj}^2$$

Each yield response function was estimated as the relationship between the maximum yields that can be obtained with different volumes of water budgeted for the whole irrigation season. The maximum yield for a given water budget was obtained by assuming farmers would allocate limited water between months within the irrigation season to minimise the penalty on the final yield. The details of estimating yield response relationships are outlined in the explanation of the agronomic module.

Input supply and demand balance

$$4 \qquad \sum_{j} UQWU_{rj}AP_{rj} \leq \sum_{k} QWU_{rk}$$

$$5 \qquad \sum_{j} AP_{rj} \leq QSLND_r$$

For each region, the demand for water and land cannot exceed supply (equations 4 and 5 respectively). In the case of water, the regional supply (RHS of equation 4) is the total sum of all

surface water and groundwater available in the region. The land, surface water and groundwater resources available in a region are all treated as homogenous inputs into agricultural production. All potential producers in the region compete for the land and water inputs in the region and for each resource there is a common rental price in all agricultural uses. Assuming something is always produced in an agricultural region, a positive market price for land and water inputs will emerge which balances competing demands with a given supply of each input.

Surface water flow balance

$$6 \qquad QSLW_r + (1 - closs_{r-1}) \times WXP_{r-1} + (1 - h_r)\sum_k QWU_{r-1,k}$$
$$= QWU_{r,k=sw,s} + WXP_{rs}$$

The surface water flow equation balances all surface water flows along a river network. At a given node *r*, supply to the river is locally sourced and/or comes from upstream river exports (adjusted for transmission losses) and return flows from water use. Available supply is to meet local irrigation demand for surface water and river exports downstream. Actual water use in a sub-catchment includes groundwater as well as surface water and return flows from upstream sub-catchments come from both sources. Actual water use less the effective water use in an upstream sub-catchment is the maximum return flow received in the downstream sub-catchment. The effective water use in a region is the efficient rate of water application, h_r, times the actual water use. The water application efficiency depends on the on-farm water application technologies used. This is currently treated as exogenous in the model.

Salt flow balance

$$7 \qquad LSLT_r QSLW_{rs} + SLT_{r-1}(WXP_{r-1} + \sum_k QWU_{r-1,k})$$
$$= SLT_r (WXP_r + \sum_k QWU_{rk})$$

The salt flow balance equation is analogous to the surface water flow balance equation where the salt content is multiplied by the water flow quantity to give the total amount of salt in the flow. Local water is assumed to have a different salt content to salt in the river flow. The salt content of applied groundwater is assumed to be the same as that for surface water in the sub-catchment. The supply of salt from local sources, upstream flows and return flows (LHS of equation 7) is balanced with the salt load in the irrigation water used and surface water exported to downstream sub-catchments (RHS of equation 7). The salinity of applied irrigation water in a region is then this total salt supply divided by the sum of the total water use and volume of water exported (the bracketed term on the RHS of equation 7). The impact of salinity on agricultural output is imposed as a negative technical change.

River mouth minimum water flow

$$8 \qquad (1 - closs_{r=lr}) \times WXP_{r=lr} + (1 - h_r)\sum_k QWU_{r=lr,k} \ge XDMTH$$

The river mouth constraint states that total flow at the mouth must be no less than the minimum flow requirement at the river mouth. The total flow at the mouth is simply water

exports from the last demand node (representing the most downstream sub-catchment adjusted for transmission losses and return flows from that node that return to the river before the mouth). If the river mouth minimum water flow constraint is overfilled then the marginal cost of meeting the target is zero. Alternatively, if it is costly to meet the river mouth minimum water flow constraint (water has a scarcity value) then the constraint will hold with equality.

Optimal surface water use price arbitrage rule

9

$$(d1_{r,k=sw,s} + d2_{r,k=sw,s}QWU_{r,k=sw,s})$$
$$+PWX_{rs} - (1-h_{r+1})PWX_{rs} - (1-h_{r=lr})PMTH_{r=lr,s}$$
$$-SLT_{rs}[(1-h_r)PSLT_{r+1,s} - PSLT_{rs}] \geq PDW_{rs}$$

The cost of an extra unit of local surface water for irrigation is the delivery charge (first term) plus the scarcity price (which is equal to the flow price) for using local water from the river (second term) less the refund on water return flows (third term and in the case of the most downstream sub-catchment, the fourth term) less the marginal benefit from an extra unit of water that avoids the downstream marginal damage cost caused by salinity (fifth term). If the total unit cost of surface water exceeds the marginal value product derived from that water use (PDW_{rs} on RHS of the equation 9) then the use of surface water is not economic. On the other hand, if the use of surface water is economic it is undertaken up to the point that the unit cost equals the marginal value product derived from that use.

In a salinity damage context, the price of salt is negative and becomes less negative moving downstream where salt concentration is greater. An extra unit of water improves the water quality to the applied crop locally by $SLT_r PSLT_r$ (which is a benefit). However, extra local water extraction (depending on the magnitude of h_r) will result in less water flow for the downstream crop. This may reduce the water quality downstream, after adjusting for return flows by $SLT_r(1-hr)PSLT_{r+1}$. Overall, in this case the net effect of having more water flow is to reduce the cost of water use.

Optimal groundwater use price arbitrage rule

10

$$(d_{1r,k=gw,s} + d2_{r,k=gw,s}QWU_{r,k=gw,s})$$
$$+PDGW_{rs} - (1-h_{r+1})PWX_{rs} - (1-h_{r=lr})PMTH_{r=lr,s}$$
$$-SLT_{rs}[(1-h_r)PSLT_{r+1,s} - PSLT_{rs}] \geq PDW_{rs}$$

The price arbitrage rule for groundwater is similar to that for surface water. In particular, the terms 3, 4 and 5 are identical to those for the surface water equation 9. The differences are in the unit cost of pumping and the pure scarcity price for using groundwater (which is the rental cost of a groundwater allowance $PDGW_r$). The unit cost of groundwater pumping is an upward sloping function of groundwater use. In empirical applications, unit cost increases with the annual groundwater extraction in a linear fashion.

11 $$PWX_r = PWX_{r+1} \times (1 - closs_r) + PMTH_{r=lr} + SLT_r(PSLT_{r+1} - PSLT_r)$$

For each region r, the price of water flow in the river, PWX_r equals the price in the downstream region adjusted for transmission losses (the first term on the RHS) plus the cost of salt damage (the last term on the RHS). If $SLT_r=0$ the price of water is constant moving downstream. If we let the salt content of water be non-zero (SLT_{r0}) the price of water flow falls moving downstream as the local price is the downstream price adjusted up for the downstream marginal damage cost caused by salinity. Salt is an economic bad so its price is negative. Salt builds up and its concentration increases moving downstream. Thus the salt price rises moving downstream (becomes less negative) so the salt term in the equation is positive.

Agronomic module

Intra-seasonal allocation of water

For simplicity, for each crop, the allocation of irrigation water between growing months is derived by assuming the state of nature in terms of the distribution of monthly rainfall and evaporative demands is known. The state of nature is assumed to be the historical climate and thus average monthly rainfall and evaporative demand are assumed. This is a reasonable assumption because what is required for each crop is the relationship between budgeted seasonal irrigation volumes and the total yield for the season and the integrated model will be run for a known state of nature.

If, for a given crop, the volume of irrigation water available for a unit of land during the season is less than the full net irrigation requirement, then the farmer is assumed to allocate this limited water optimally between different growing periods so that the penalty in the final crop yield is minimised. This is achieved by solving the following optimization problem for a $u=1, 2, ..., n$ series of discrete seasonal/annual quantities of irrigation water applied x_{ju} and measuring the resulting yield $y_{ju}{}^a$.

For each crop and discrete quantity of irrigation water(x_{ju}) the optimisation problem is to maximise the final yield, $y_{ju}{}^a$ (the objective function given in equation 12 subject to 4 constraints.

1 the actual yield cannot exceed the maximum yield adjusted for the yield penalty determined by the moisture stress in each of the growing months $(1\text{-}ET_{jum}{}^a / ET_{jm}{}^{max})$ and its significance in reducing the final yield measured by the K_{yjm} factor (equation 13).
2 for each month, the actual evapotranspiration, $ET_{jum}{}^a$ cannot exceed the volume of irrigation water applied plus the effective rainfall, ER_{jm} and amount of soil moisture that becomes available as the roots extend deeper, SM_{jm} (equation 14).
3 for each month, the quantity of irrigation water applied cannot exceed the net irrigation requirement or the difference between potential evaporative demand and the sum of effective rainfall and the additional soil moisture that becomes available to the crop (equation 15).
4 the sum of monthly irrigation water applications cannot exceed the budgeted seasonal volume of irrigation water (equation 16).

Maximize

12   Y_{ik}^a

Subject to

13     $Y_{jk}^a \le Y_{jk}^{\max}\left[1 - \sum_m Ky_{jm}\left(1 - \dfrac{ET_{jum}^a}{ET_{jm}^{\max}}\right)\right]$

14     $ET_{jum}^a \le q_{jum} + \min\left(ER_{jm} + SM_{jm}, ET_{jm}^{\max}\right)$

15     $q_{jum} \le ET_{jm}^{\max} - \min\left(ER_{jm} + SM_{jm}, ET_{jm}^{\max}\right)$

16     $\sum_m q_{jum} \le x_{ju}$

For each crop, the $u=1,2,...,n$ series of discrete quantities of water x_{ju} and resulting $y_{ju}{}^a$ are used as inputs in estimating the yield function of the form given in equation 17.

17     $Y_j^a = a_j + b_j x_j + c_j x_j^2$

The yield response functions in equation 17 represent the relationship between the maximum yields that can be obtained with different volumes of water budgeted for the whole season/year after allowing for the optimal intra seasonal/year allocation of water. Thus instead of embedding the above optimising model contained in equations 12—16, the irrigator behaviour in intra seasonal/year allocation of water is incorporated in the annual model by replacing equation 3 with equation 17.

Estimating the impact of salinity on crop yield

For each crop, the average salt content of total applied water, $SLTAW_{rj}$ is calculated as a weighted average of the salt contents of irrigation water applied, SLT_r and rainwater used, $SLTRW_r$ by the crop (equation 18). This implies that the average salt content of the total applied water depends on the share of the total water requirement met by rainfall, and assuming the salt content of rain water is negligible, the greater this share the greater the dilution effect of rainfall.

18     $SLTAW_{rj} = \left(SLT_r.UQWU_{rj}/h_r + SLTRW_r.UQRWU_{rj}\right)\Big/\left(UQWU_{rj}/h_r + UQRWU_{rj}\right)$

Crop yield is influenced by the average salinity of the root zone, $SLTRZ_{rj}$ which is different from the salinity of the applied water as it can be influenced by the leaching fraction, LF and some soil properties. For simplicity, the Rhoades (1974) equation is used to convert the applied water salinity to root zone salinity (equation 19).

19     $SLTRZ_{rj} = 0.5K.SLTAW_{rj}\left(1 + 1/LF\right)$

Where *LF* defines the leaching fraction and *K* is an empirically estimated coefficient. The leaching fraction can be defined as follows.

$$20 \quad LF = 1 - ET_{rj}^{a} / \left(UQWU_{rj} / h_r + UQRWU_{rj} \right)$$

The water applied to the crop, both in the form of rainfall and irrigation water in excess of its evaporation requirement, has a dilution or leaching effect on the root zone salinity. Rhoades (1974) has suggested a value of 0.80 for *K* for low levels of *LF* while Prendergast (1993) empirically estimated a value of 1.03 for the Shepparton area of Victoria. If *K* is to be given a value of 1.0 and 25 per cent more water is applied for leaching salt, it can be shown from equation 19 that assuming steady state conditions that $SLTRZ_{rj}$ would be 2.5 times $SLTAW_{rj}$. By taking into account these assumptions, a simplified form of the Mass Hoffman (1977) relationship can be derived as given in equation 21.

$$21 \quad RY_{rj} = 1 - \delta_j \left(SLTAW_r - SLTTHRESH_{rj} \right) = 1 - \delta_j \left(SLTOV_{rj} \right), \quad \text{for } SLTAW_{rj} \geq SLTTHRESH_{rj}$$

The actual crop yield can be less than the potential yield if the average salt content of total applied water *(SLTAW)* exceeds the salinity threshold *(SLTTHRESH$_{rj}$)*. The yield loss depends on the difference between these two salinity measures and the yield penalty rate of the crop, δ_j to salinity over the threshold.

The salt penalty function used in the model takes this simple form. Note that the term measuring the yield penalty because of salinity over the threshold *[1-δ_j (SLTOV$_{rj}$)]* is employed in equations 1 and 2 which govern the zero profit conditions determining land allocation and irrigation decisions. The use of this relationship means the salinity threshold values chosen must be those that reflect the application of 25 per cent more water for leaching on top of the amount required to meet crop evapotranspiration demand. This is because of the leaching effect, whereby the greater the *LF*, the greater the salinity threshold. This upward adjustment to crop water use to satisfy leaching requirements is also reflected in crop and regional water balance calculations in the model.

To simplify the model further, an application efficiency *(h$_r$)* of 80 per cent (implying 25 per cent (=20/80*100) more water is applied) is also assumed which means the water lost in application deep percolates past the root zone, taking salt in excess of $SLTAW_r$ with it and crop yield is affected by changes in the salinity of applied water which include both rainfall and irrigation water.

The data used

A data set on land use by irrigated agricultural activities in a normal year is constructed from data reported in agricultural censuses conducted for 2000-01 and 2005-06 by the Australian Bureau of Statistics. Seasonal conditions in 2000-01 were relatively 'normal' while 2005-06 was a drought year. As a result, data from the 2000-01 census was used for annual crops. However, data on land use by permanent crops in 2005-06 are preferred to that in 2000-01 as it incorporates recent expansions in horticultural and grape industries. The data on historical mean surface water and groundwater availabilities in different sub-catchments are obtained from various CSIRO sustainable yield reports.

For each region, daily rainfall and pan evaporation data as measured at the most representative weather station for the past 118 years are extracted from the SILOS database. Daily rainfall and pan evaporation data were aggregated to obtain monthly time series. A historical mean monthly rainfall and evaporation data series was then obtained by averaging across all 118 years.

The monthly rainfall amounts need to be adjusted downward as the amount of monthly rainfall effective for the crop increases at a decreasing rate with the increase in actual rainfall. This is done by using a relationship developed by the United States Bureau of Reclamation.

It is assumed that when crops are planted, soils hold water up to their field capacity. However, the amount of this carryover soil moisture which the plant can access depends on the depth its roots grow to over the season. Moreover, as the roots grow deeper, the cross sectional area covered by the root zone decreases and progressively less soil moisture is found.

About 70 per cent of plant roots are found in the top half of the soil profile penetrated by the roots and, when the soil moisture is at field capacity, the uptake of soil moisture is proportional to that of root distribution (Evens, Cassel and Sneed 1996). It is the soil moisture in the top half of the root zone which is useful for crop growth. The soil moisture found in the bottom half of the root zone helps the plant survive in extreme water stress. Therefore, half of the maximum root depth is defined to be the effective root depth. For simplicity, the effective root depth is used in approximating the amount of soil moisture available. The amount of soil moisture available was estimated by simply multiplying the effective root depth by the amount of soil moisture available per unit of effective root depth. Assuming clay loam soils, soil moisture availability is assumed to be 165 millimetres per metre of effective root depth. In the case of tree crops, full depth of the root zone is assumed and the available soil moisture is assumed to be used up over the season in proportion to monthly total potential evaporation.

For each crop and month the potential evapotranspiration, ET_{jm}^{max}, is estimated by multiplying pan evaporation depth by the pan coefficient of 0.80, the crop factor for that month and the fraction of the month the crop existed. The data used for crop factors and the fraction of each month the crop existed are the same as that used in earlier ABARE research on the Murrumbidgee Valley conducted for the Pratt water initiative (Beare, Heaney and Hafi 1994). In the case of rice, the potential monthly evapotranspiration from October—January was adjusted upward to account for additional water required for ponding. Following, NSW agriculture (1996) and McClintock et al. (1998), the ponding requirement is assumed as 40 millimetres in October during establishment, 50 millimetres in November during mid tillering, 100 millimetres for December during late tillering and 250 millimetres for January from penicle initiation to the onset of flowering. The data on Ky_{um} factors was obtained from Doorenbos and Kassem (1979).

The data on the parameters of salinity threshold and yield penalty are obtained from New South Wales Department of Primary Industries and Gratton (1999). The National Salinity Audit of 1999 (Murray-Darling Basin Ministerial Council 1999) reports data on the tonnage of salt mobilised on land surface and river salinity in different river valleys in the MDB for 1998 with projections made for 2020, 2050 and 2100. According to the National Salinity Audit, on average 50 per cent of the salt mobilised is exported to the river. This percentage can vary between regions. In the Mallee zones in Victoria and South Australia where salt flows to the river through direct seepage, all the salt mobilized is exported to the river. Of the salt exported to rivers, about 40 per cent ends up in the ocean while the remainder goes with either diverted water and subsequently stays in irrigated land or with flood water and subsequently stays in low lying flood plains/wetlands.

The future river salinity predictions made in the National Salinity Audit were made assuming no salt mitigation activities. However, the subsequent MDB salinity management strategy for 2001—2015 set specific end of valley salinity targets for 2015 which resulted in investments in salt interception schemes and the introduction of tradeable salinity credits. In this model, it was assumed current and future salt mitigation activities would limit the rise in river salinity levels to 2015 target levels and as such, the base case river salinity levels used in the model are calibrated to these levels.

Illustrative application

The restricted trade version of the model with the irrigation water salinity – crop yield link turned off is run to simulate two scenarios: (1) historical climate; and (2) a hypothetical climate in which a 5 per cent reduction in rainfall results in a 10 per cent reduction in water availability across the basin. In the second scenario irrigation diversion is assumed to be reduced by the same percentage as the reduction in water availability while groundwater availability is assumed to remain unchanged.

The purpose of the simulations is to demonstrate that model results are consistent with economic theory and observed responses to changes in water availability. The impacts of the hypothetical scenario are measured by comparing the results from the two model runs and are discussed below. It should also be noted that the impact measured is without inter regional trade and does not include the potential negative effect of an increase in salinity of irrigation water.

1 Regional impact of a 10 per cent reduction in water availability

Region	GVP %	Farm income %	Water use %
Northern MDB			
Condamine	−1	−1	−4
Border (Qld)	−4	−1	−9
Border (NSW)	−3	−1	−9
Warrego	−5	−2	−9
Namoi	−1	0	−3
Macquarie	−2	−1	−5
Moonie	−3	−1	−10
Gwydir	−4	−1	−9
Barwon Darling	−5	−3	−10
Lachlan	−2	−1	−6
Southern MDB			
Murrumbidgee	−4	−2	−9
Goulburn Broken	−6	−3	−9
Campaspe	−6	−3	−9
Wimmera	−6	−3	−10
Loddon	−6	−3	−10
Murray (NSW)	−5	−4	−9
Murray (Vic)	−6	−3	−10
Lower Murray–Darling	−3	−2	−8
SA Murray	−4	−2	−8
Eastern Mt Lofty ranges	−3	−1	−7
MDB	−4	−2	−9

Results

Under the scenario of a 10 per cent reduction in water availability, aggregate land and water use in irrigated agriculture in the basin is estimated to decrease by 4 and 9 per cent respectively, resulting in a 4 per cent decrease in the GVP of irrigated agriculture and 2 per cent decrease in aggregate farm income (table 1). Some previously irrigated land is expected to be converted to dryland agricultural activities under this scenario. Water use is reduced across all activities. Total water use includes both surface water diverted and groundwater pumped and as such decreases less than the cut in surface water diversion (especially in the Condamine, Namoi, Lachlan and Eastern Mt Lofty Ranges regions).

Among irrigated cropping activities land moves from the lower value dairy, grains, fodder and rice to higher value permanent horticulture, grapes and vegetable activities. Under the hypothetical

scenario, the high value horticultural, grape and vegetable activities are projected to expand in area while reducing aggregate water use with the use of deficit irrigation. Deficit irrigation is one of the adaptation options available to mitigate the negative impact of reduced water availability. In most cropping activities, deficit irrigation is projected to result in reductions in per hectare water use at the cost of smaller reductions in yields (table 2). This is consistent with results obtained by Kirda et al. (1999) on the benefits of deficit irrigation.

2 Impact of a 10 per cent reduction in water availability on irrigated agricultural industries in the MDB

industry	land use	water use	GVP	farm income	yield/ha	water use/ha
	%	%	%	%	%	%
Almond	1	−2	−1	−1	−2	−3
Canola	−1	−7	−3	−1	−2	−6
Citrus	1	−4	−2	−2	−3	−4
Cotton	0	−7	−3	−1	−3	−7
Dairy	−4	−8	−7	−3	−3	−5
Grains	−7	−13	−8	−2	−1	−7
Grapes	3	−4	−2	−1	−5	−6
Lucerne	−9	−12	−11	−4	−3	−4
Olives	6	−4	−2	−1	−7	−9
Pome fruits	4	−2	−1	−1	−5	−6
Rice	−10	−11	−11	−4	−1	−1
Stone fruits	0	−3	−2	−2	−3	−3
Vegetables	3	−2	−1	−1	−3	−5
All industries	−4	−9	−4	−2	–	–

Conclusions

To estimate the effect of reduced water availability because of climate change on the irrigated agriculture sector requires a modelling framework incorporating the relevant bio-physical, economic and institutional factors. This paper outlines a model which has been developed to incorporate many of these factors and demonstrates its usefulness in providing information on the effects of reduced water availability.

The results obtained from a scenario involving a hypothetical reduction in water availability in MDB are consistent with economic theory and observed responses to changes in water availability. The results also demonstrate the benefits of incorporating flexible production technology based on concave crop yield response functions. All industries responded to a hypothetical reduction in water availability, a desirable feature that would have been absent if the model was specified using Leontieff production technology.

It is likely that the crop yield response to irrigation water salinity will be as important to understand as the crop yield response to irrigation water in assessing the effects of reduced water availability. However, the irrigation water salinity–crop yield link in the mode is currently turned off as little information is available on the impact of surface run-off on salt loads

exported to river and on the yield penalty associated with varying levels of salinity. Also, little information is available on the effect of climate change on groundwater recharge. As a result, groundwater availability is assumed to remain constant despite lower rainfall and run-off because of climate change. Once reliable information is available on these relationships, the full impact of reduced water availability can be estimated and the potential benefits of institutional adaptation measures such as removing inter-regional barriers to trade can be more fully explored.

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