Integrated assessment and management of stochastic water resources in the Murray Darling Basin

Qureshi M, E.[1] Connor, J.[2], Kirby, M.[3] and Mainuddin, M.[4]
[1,]CSIRO Land and Water, Acton ACT 2601; Email: Ejaz.Qureshi@csiro.au
[2]CSIRO Land and Water, Urrbrae, SA 5064; Email. Jeff.Connor@csiro.au
[3]CSIRO Land and Water, Acton ACT 2601; Email: Mac.Kirby@csiro.au
[4]CSIRO Land and Water, Acton ACT 2601; Email: Mohammed.Mainuddin@csiro.au

Abstract

The Murray Darling Basin is a vital region of Australian economy. However, water quantity and quality issues raise concerns about sustainable use of natural resources in the basin. In particular there are concerns about damages from increasing salinity and reduced flow in the River on built and ecological assets. There is also concern that climate change, increased water taking through farm dam development, increasing use of conjunctive groundwater will exacerbate issues related the quantity of water in the rivers and the groundwater aquifers. Policy approaches to address these issues will require addressing potentially conflicting interests of multiple effected parties in a balanced way.

This paper describes a modeling framework being developed for integrated assessment of impacts on diverse stakeholders of options to manage water supply and demand in the Murray Darling Basin. Two models building on the same hydrogeology – agronomic relationships are presented. One is an optimisation approach to modelling irrigator demand for water. The other is a simulation of irrigator and environmental manager behaviour in a stylised Murray Basin model with stochastic supply and price. We demonstrate application of both models to evaluation of environmental water acquisition strategies for the Murray Basin.

Introduction

Water resources throughout Australia are under increasing pressure to satisfy often conflicting environmental and economic objectives. In the Murray-Darling Basin (MDB), for example, changes to land use and river management have led to pressure on the Basin's resources, and concern over water quality and ecosystem health (MDBC, 2001). One indicator of changed river management is that the median annual flow to the sea is now only 27% of the natural (pre-development) flow (Kirby et al., 2004). Competition for scarce water resources is increasing between agricultural, urban and environmental uses.

In 2003, the Murray Darling Basin Ministerial Council decided to return the River Murray to the status of a healthy working river by increasing environmental flows through recovered water being built up over a period of five years to an estimated average 500 GL/year of ‘new’ water after five years (MDBMC, 2003). One of most difficult challenges will be implementing plans to increase the environmental flows to enhance river health as this could mean that some economic benefits from irrigation will be forgone.

Understanding implications of options to reallocate flow requires interrelated land-water modelling systems capable of answering the following questions: (a) What is the optimal allocation of water and land resources taking into account existing physical, technical, institutional and financial constraints? (b) What are the differences between actual and benefit-maximising allocation and where can additional benefits be achieved most efficiently? (c) Which policy options are available to address the above mentioned issues? (d) Which alternative options are technically, economically and politically most feasible when there is conflict in the objectives of stakeholders? (e) How large are trade offs that can be expected from water reallocation policy between consumptive and non-consumptive water use activities?

To produce results that are useful for policy prescription, an appropriate model will have to account for the influence of uncertain water supply. This is because water supply and, to an extent, demand vary significantly across the MDB from year to year depending on evaporation and rainfall. This in turn leads to highly variable prices of water (see, for example, Zaman et al, 2003 who presents data for the Goulburn Broken Exchange that shows a large jump in prices from 1999-2001 to the drought year of 2002-3). Despite the obvious importance to stochastic water supply and demand to understanding the economics of water reallocation, many past attempts to model water trade in the Murray (e.g. Bell and Heaney, 2000; Eigenraam, 1999) do not account for the stochasticity of water supply, demand and price.

This paper presents progress to date in building a suit of integrated biophysical-economic models for the Murray Darling Basin. One is an optimisation approach to modelling irrigator demand for water. The other is a simulation of irrigator and environmental manager behaviour in a stylised Murray Basin model with stochastic supply and price. We demonstrate application of both models to the evaluation of environmental water acquisition strategies for the Murray Basin.

The integrated River modeling framework

This paper is the result of current efforts by CSIRO to develop a model of the Murray Darling Basin for rapid assessment of the general feasibility of options and likely effectiveness of policy and decision making rules. While the model in its current state of development can only be considered a simplified representation, the goal is to incorporate increasingly detailed representation where this has important influence on outcomes of strategies to manage the River.

Thirteen catchments of the southern part of the Murray Darling Basin (which are called regions in the economic component of the modeling framework) are used to assess the impact of intraregional water trade, as shown in Figure 1. These catchments include: Upper Murray, Kiewa, Ovens, Broken, Goulburn, Campaspe, Loddon, Avoca, Murray-Riverina, Murrumbidgee, Mallee, Wimmera-Avon and Lower Murray.

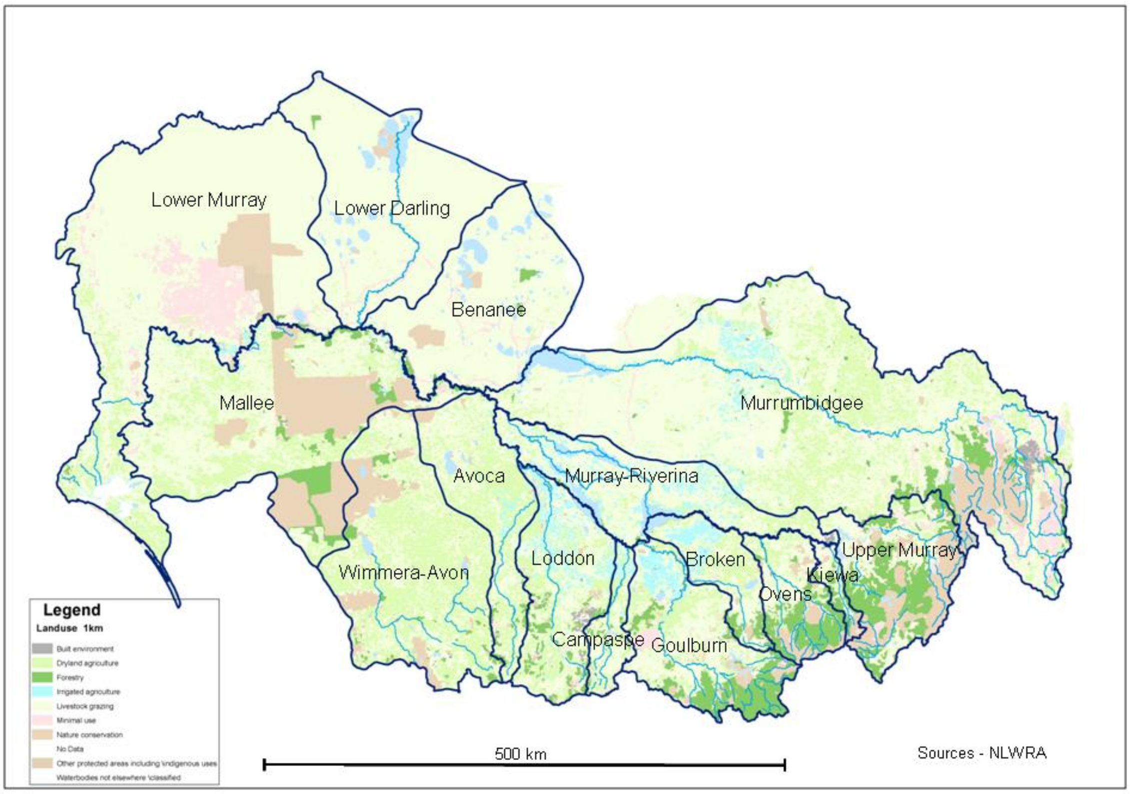

Figure 1: Catchments of the southern Murray Darling Basin

The framework consists of water supply and water demand components. The supply side is a description of the hydrology, including the stochastic nature of supply. The supply side can be integrated with either of two water demand models (both of which are demonstrated in this paper):

- an optimization specification of the management and demand of irrigation water; and,
- a simulation specification of irrigation water demand and an environmental agent interacting with the supply and demand of water for irrigation and the environment.

After describing the supply side hydrology component, the demand side models are described. In each instance an application of the model that offers insight into implications of providing additional flows for the environment is described as well.

The Supply side hydrology component

The model is based on annual rainfall and flows, and is shown schematically in Figure 2.

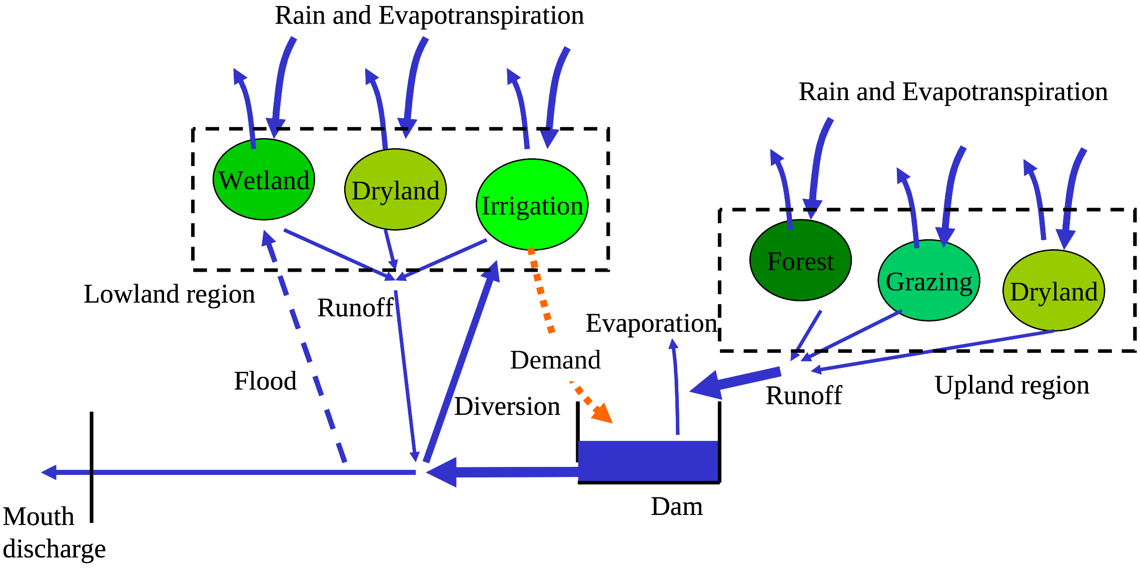

Figure 2: Schematic representation of prototype spatial model, land use and hydrology components. Two regions are shown, with three land uses each, whereas the model has 39 regions with several land uses each. The blue arrows depict physical flows of water, whereas the orange arrow depicts the control of demand over the operation of the dam. The dotted arrow indicates that floods are only occasional.

Land use, rainfall, evapotranspiration and run-off

Each of the sub catchments of the Murray Basin is divided into several land uses including forests, grazing, dryland cropping, irrigated pasture (dairy), irrigated rice, irrigated grapes, urban, and open water. Land use, distributed spatially, is the first set of input data.

Rainfall, distributed spatially, is the second set of input data. Rainfall is partitioned into evapotranspiration and run-off using the relationships developed by Raupach et al. (2001), using a method similar to that of Zhang et al. (1999).

$$ET \quad = \quad ET_{Pot}\left(\frac{\left(P/ET_{Pot}\right)^{a}}{\left(1+\left(P/ET_{Pot}\right)^{a}\right)}\right)^{1/a} \qquad (1)$$

Where ET is the actual evapotranspiration, ET_{Pot} is the potential evapotranspiration, P is precipitation in each state of nature (i.e. low, medium or high rainfall), and a represents an adjustable parameter which takes values from 1.5 for grass catchments to 2.48 for forested catchments. Equation 1 requires the spatial potential evapotranspiration, which is the third set of input data. Run-off, RO, is calculated from:

$$RO \quad = \quad P - ET \qquad (2)$$

Evaporation from open water, E, is calculated from a simple proportionality with potential evapotranspiration:

$$E \quad = \quad C_1 ET_{Pot} \qquad (3)$$

C_1 is the proportion of actual evapotranspiration to potential evapotranspiration of each crop in each region. The evapotranspiration demand of irrigation is based on spatial water use data, taken from Bryan and Marvanek (2004).

Floods and discharge from the mouth

The run-off is partitioned into diversions (*D*), floods (*F*), discharge from the mouth (*M*), and losses (*L*):

$$RO \quad = \quad D + F + M + L \tag{4}$$

Floods partly spill onto floodplain / wetland areas, and partly result in greater discharge at the mouth. Floodplain wetting becomes ET of wetland or other river corridor vegetation. The link between diversions and irrigation supply and demand is given below.

The mouth discharge is water remaining after other uses are satisfied, though we assume that in drought years irrigation use is moderated so that some water still discharges from the mouth. The losses include seepage from the river channel (perhaps to groundwater) and pumping not accounted for in the diversions.

Irrigation requirements

The irrigation requirement models described in the next sections depend fundamentally on diversion requirement, $D_{require}$ necessary to realise full potential crop yields, $I_{require}$:

$$D_{require} \quad = \quad \left(I_{require} - P\right) / IR_{Eff} \tag{5}$$

where $D_{require}$ is the diversion requirement to realise full potential yield, and the irrigation efficiency ($0 < IR_{eff} < 1$) accounts for losses between the diversion point and the crop use of the water. $I_{require}$ is the evapotranspiration for an irrigation area to realise full potential crop yield, P is the amount of the irrigation requirement provided by rainfall. The diversion requirement varies from year to year because both the evapotranspiration requirement and the rain dairy.

Management of dam storage

The dam storages operate according to a simple set of rules.

1. If the runoff in any year is less than diversion demand, water in the dams is released for irrigation diversions. The stored water might or might not be sufficient to satisfy the remaining demand.
2. On the other hand, if runoff is more than diversion demand, the excess is stored in the dams.
3. If the runoff is greater than the diversion demand plus unfilled capacity in the dams, a flood results.
4. The maximum storage capacity is 15000 Gl (approximately the combined capacity of lakes and water storages in the Murray basin, excluding the lower lakes near to the Murray mouth since water from these cannot influence the river flow).

Dam storage is carried over from one year to the next, and moderates the influence of rainfall variation on diversion supply.

Crop water production function - agronomic component

We used a quadratic yield - ET crop response function to reproduce the non-linear form observed in studies such as those on wheat and sorghum by Keating et al. (2002), and on wheat, barley, and sugarcane by Gulati and Murty (1979) who reported that yield -ET relations for these crops are best described by quadratic functions of the form:

$$ylda_{(srj)} \quad = \quad a_{(s,r,j)} + b_{(s,r,j)}\left(ETa_{(s,r,j)}\right) + c_{(s,r,j)}\left(ETa_{(s,r,j)}\right)^2 \qquad (6)$$

where

r =	Irrigation demand sites (regions)
j=	Cropping activities
s =	States of nature – low, medium or high rainfall
$ylda$	Actual yield (t/ha)
ETa	Actual evapotranspiration (mm)
a, b, c	Crop yield response coefficients, which vary from crop to crop and from region to region.

The coefficients in equation (5) were derived by combining field data on yield and water requirements from Bryan and Marvanek (2004) and the slope of the FAO crop yield response function (Doorenbos and Kassam, 1979), and fitting the quadratic.

B. Modeling irrigation water demand with optimisation

This section describes one of two separate models of water demand reported on in this paper, using an optimization based approach. The overall objective of this irrigation water demand model is to characterise the pattern of response and cost to irrigation that would be expected under alternative water demand and supply scenarios (including scenarios where demand for environmental flow were significant).

The Objective Function

At the heart of the irrigation demand optimization model is an objective function to maximise the aggregate net profit from water use for irrigation modeled in aggregate for regions. Each region is treated as though it were a decision maker attempting to maximize economic returns from producing irrigated crops and participating in temporary water markets. Stochastic water availability and irrigation requirements are treated as states of nature. These states are included in the model to understand how irrigators will respond when there is low, medium or high water availability for irrigation.

For each state of nature (s), the net profits ($\prod_s$) from regions are equal to the aggregate revenue minus variable cost, water supply cost and water charges:

$$\max \prod_s = \sum_r \sum_j P_{rj}\, ylda_{rj} A_{srj} - \sum_r \sum_j OC_{rj} A_{srj} - $$
$$- \sum_r \sum_j WCh_{rj} A_{srj} w_{srj} \qquad \forall s \qquad (7)$$

where

P	Crop price ($/ha)
$ylda$	Actual yield (t/ha)
A	Harvested area (ha) – the decision variables
OC	Other cost ($/ha)
WCh	Water charge ($/ml)
w	Water delivered (ml/ha)

Water charges, charging strategies, and rules for security of supply all differ from region to region, and are under review in response to water reform (COAG, 2004; Heaney et al., 2004). For convenience, we assume that a single charging regime operates: this will show the main principles without the complication of regional differences.

For each state of nature s, water delivered (w_{srj}) for region *r* and activity *j* (ML/ha) is calculated as:

$$w_{srj} = \frac{\left(ETa_{rj} - EffRain_{srj}\right)/100}{IrriEff_{rj}} \qquad (8)$$

where for each state of nature s, irrigation region *r* and cropping activity *j*

ETa = Actual evapotranspiration (mm)
EffRain = Effective rainfall (mm)
IrriEff = Overall irrigation efficiency

Water Constraints

Water availability constraints are of the general form:

$$\sum_r \sum_j w_{srj} A_{srj} \le TotWat_s - Env_s \quad \forall_s \qquad (9)$$

where $TotWat_s$ is the total available water (ML) for each state of nature less water for environmental flows (Env) which is assumed constant for each state (*s*). The right side of the equation is equal to D_s, the water available for diversions under any state. This water constraint ensures that for each state of nature s, the sum of the amount of water required by all crops *j* and region *r* will not exceed the total amount of water available for state s in addition to setting aside water for the environmental flows, i.e.

$$\sum_j ws_{rj} A_{srj} \le WatR_{sr} - Env_s \qquad \forall_s, r \qquad (10)$$

where $WatR_{sr}$ is the water available for each state and region (ML) and Env_s is assumed to equal D_{sr}, the water available for diversions in any region and state. The water constraints ensure that total water quantities required by all crops in any region will be limited by the total water available in that region.

Land Constraints

The equations for land availability constraints are of the form:

$$\sum_r \sum_j A_{srj} \leq TotLand \qquad \forall\ s \tag{11}$$

where *TotLand* is the total available area for irrigation (ha). This land constraint ensures that for each state s, the sum of the land areas required by all regions *r* and crops *j* will not exceed the total available area for irrigation.

$$\sum_j A_{srj} \leq LandR_r \qquad \forall\ s, r \tag{12}$$

where $LandR_r$ is total available area for irrigation for each region (ha). These land constraints ensure that for each state, the sum of the land areas of the crops under each region will not exceed the area available for irrigation in each region.

In the optimisation model, 10 agricultural activities which occupy most of the Murray Basin are considered in the analysis, including vegetables, grapes, rice, oilseeds, fruits, cereals, legumes, pasture for beef, pasture for dairy and pasture for sheep. These activities have been classified into two groups: temporary activities and permanent activities. Temporary activities include oilseeds, cereals, legumes, pasture for beef, pasture for dairy and pasture for sheep while permanent activities include vegetables, fruits, grapes and rice. Rice is included as a permanent activity because it cannot be grown other than in specific areas and on specific soil types. The temporary activities may compete for both land and water in a given catchment. However, the permanent activities can only compete for water in a catchment depending on the total volume of water and are not allowed to compete for land. This restriction (in the short run) on land is due to either major investment needed for the expansion of these activities or due to an administrative/agronomic constraint in the case of rice production. The model does not impose any marketing/demand constraint and assumes a constant price of each agricultural product given the export oriented nature of these activities. The model assumes that output is a function of water only (i.e. water yield response function) and no contribution of land and capital is considered in the analysis. A single irrigation efficiency value is used for all agricultural activities and regions in the analysis but the model can be extended to incorporate different efficiency levels in different activities. Clearly, both assumptions regarding irrigation will require elaboration in future modeling to add key elements of realism.

Stochastic water supply

We used a low rainfall scenario with a 35% reduction in total water availability in the system. Irrigation authorities generally keep some volume of water as a buffer in their stores/dams and to overcome the shortage of irrigation water allocations, the authorities are assumed to compensate up to 10% from their stored water. This means in a low rainfall season, irrigators will still face 25% reduction in their water allocations. In a high rainfall scenario, we assume the irrigators get 17% more water than a normal season.

Solution algorithm

A non linear programming (NLP) structure has been selected instead of the more common linear programming approach primarily because of the nonlinearities involved in the relationships between crop water stress and crop yields. The NLP obviously offers much greater flexibility in model structure. The model has been coded in the modelling language of the General Algebraic Modelling System (GAMS) (Brooke et al., 1988). GAMS is a high level modelling system for mathematical programming problems. A nonlinear solver MINOS5 has been used in model simulation.

Results

Applications of the water demand optimisation model

The optimization based water demand model is applied together with the hydrology based model of supply in two applications. One application is a set of simulations structured to assess the economic impact of alternative water charging regimes when irrigators face stochastic rainfall and water allocations due to uncertain weather conditions. The second application is an assessment of the farm level economic impacts of reducing irrigation water allocations to supply 500 GL of environmental flows when irrigators face low, medium or high water allocations scenarios. Two variants of the second application are assessed. One involving a proportionate reduction in allocation from all regions, the second, is a scenario involving all reductions in allocation being taken from areas where the value of water is low.

Economic impact of water charges

In the existing charging system, different water costs (charges) are payable by irrigators to the water authorities. These charges (t/ha) estimated by Bryan and Marvanek (2004) vary from less than a dollar per ha to more than $300/ha. These are the charges that irrigators pay to the irrigation authorities and/or corporations in different regions for growing different agricultural activities. In the analysis, various charging regimes ranging from $25 to $200 per Ml are imposed and their impact on irrigators's net profitability is examined along with impact on each region. Using these charges, the model determined optimal level of water and land use by each activity in each region for three states of nature. Table 1 presents all major land use activities and number of hectares occupied by each activity in the southern MDB catchments. Murrumbidgee is largest catchment with an area of about 312,000 ha while Kiewa is smallest with an area of 936 ha. Dairy is major user of land in the Basin while legumes occupy only about 8000 ha. Table 2 presents optimal areas under each crop when $25/ML (are assumed base case) are used and medium rainfall and water allocation state is considered.

Table 1: Major land use activities and their areas (ha) in the southern MDB catchments

	Rice	Grape	Beef	Dairy	Sheep	Oilseeds	Fruit	Legumes	Cereals	Vegetab
UMurray	0	140	3120	2254		0	75	102	0	0
Kiewa	0	72	434	340		0	89	0	0	0
Ovens	105	2442	2748	599	410	0	76	1513	0	0
Broken	1259	278	8593	90561	1989	194	4639	352	4036	822
Goulb	0	1512	4883	95642	6808	96	5216	411	2812	2871
Campas	0	0		27428	1220	0	101	221	1021	40
Loddon	263	537	12905	136423	29000	451	1114	1362	16565	3569
Avoca	132	2991	93	7323	5132	0	2898	385	1302	2521
MRiver	58736	761	33410	115956	4458	1070	150	521	53793	1009
Murrum	102687	13047	55051	17400	8329	4925	7383	2921	93007	7258
Mallee	0	28323	1547	2778		173	9860	59	256	4760
WimAvon	0	2492	263		833	0	1582	0	88	308
LMurray	0	14810	6236	6743	1315	0	3625	226	620	2036
Total	163182	67405	129284	503445	59494	6910	36808	8073	173500	25195

Table 2: Optimal areas under each crop when $25/ML water charges are used

	Rice	Grape	Beef	Dairy	Oilseeds	Fruit	Legumes	Cereals	Vegetab	Used area	Give area
UMurray		140	3120	235						3494	
Kiewa		72	434	197						703	
Ovens	89	2432	2335	87						4944	
Broken	1259	278	8593	57822		4639		4036	822	77449	11
Goulb		1512	4883	62167				2812	2871	74246	12
Campas				17828				1021	40	18890	3
Loddon	263	537	12905	88675	451	1114	1362	16565	3569	125441	20
Avoca	132	2991	93	4760		2898		1302	2521	14698	2
MRiver	56143	761	22461		1070	150	443	53793	1009	135831	26
Murrum	54367	13047			4925	7383		93007	7258	179987	31
Mallee		9310				9860			4760	23930	4
WimAvon		2492	92			1121		31	308	4044	
LMurray		5875				3625			2036	11535	3
Total	112254	39447	54916	231771	6447	30790	1805	172567	25195	675192	117

Table 2 results are the theoretical optimal areas for each crop, under the simplifying assumptions of the analysis that a decision-maker allocates water to most profitable uses. These results do not necessarily compare to the current actual areas (as shown in Table 1), since these are not necessarily optimal, and also have arisen under conditions different from our simplifying assumptions. Crops that demand large amounts of water and/or have lower economic values account for relatively less area in the model compared to the ones that demand small amounts of water and/or have higher economic values. The large reduction arises because some crops are no longer grown in some areas due to their poor performance. For example, the activity “pasture for sheep” is out of production due to its poor economic performance compared to other activities.

The optimal usage of water for each region and for each state is presented in Table 3. Proportions of water used compared to total water allocation in each region are presented in Table 4. The results indicate that the total usage for most of the states is slightly lower than their allocation. One important finding is that, demand varies from 91%, 89% and 54%, respectively for high, medium and low allocations of water. The usage for each region varies compared to their actual allocation and allocation state. In low and high allocation states, except Goulburn, Campaspe, Loddon and Avoca, all regions utilized their total allocations. However, in high allocation state, only Murrumbidgee, Mallee and Lower Murray utilized their full water allocations while other regions used less water than their full allocation. Campaspe’s use of its total allocation in this state is negligible. The reason for using less water is partly because the region did not need water due to high allocation and high rainfall and partly because the model does not allow using more than the existing land available so that if it is not economical they simply use less land.

Table 3: Optimal water usage selected regions when $25/ML water charges are used

	Broken	Goulb	Loddon	MRiver	Murrum	Mallee	WimAvon	LMurray	Water used	Water allocated	Prop
Low	641569	625160	970032	1352474	1543162	234002	30224	153311	5822895	6389501	0.91
Medium	855425	813697	1236135	1803299	2057550	312003	40299	204414	7570617	8519336	0.89
High	128362	46689	140167	1822952	2407333	365043	44609	239164	5349959	9967623	0.54

Table 4: Proportion of water used and total water allocations in MDB regions

	Broken	Goulb	Loddon	MRiver	Murrum	Mallee	WimAvon	LMurray	Aggprop
low	1	0.85	0.79	1	1	1	1	1	0.91
med	1	0.83	0.76	1	1	1	1	1	0.89
high	0.13	0.04	0.07	0.86	1.00	1.00	0.95	1.00	0.54

The results of the systematic increase of the water charges have also been examined. When the water charges were increased from $25/ML to $200/ML, the total area under production is estimated to decline. The reduction in areas varies among the crops and the regions. Again this is due to the amount of water required and/or the return from a crop. Increase in water charges again changes the combination of the existing crops. Further, increases in water charges have made some land less economical to carry on agricultural activities and have reduced the overall area of production.

Aggregate profits of the whole basin in low, medium and high states are estimated to be $1003, $1145 and $1241 million, respectively at a $25/ML water charge rate. Increase in water charges has resulted in a decline in water usage and profitability of the agricultural activities in the basin. Water usage and net profit for the whole basin at varying water charges are shown in Figure 3. The figure presents the aggregate demand curve of water by depicting the relationship between the water charges and total quantity of water used in the basin. At the lower range of water charges considered water demand is initially inelastic. An increase in water charges from $25/ML to $50/ML is estimated to reduce total basin net profit from $1145 million to $1016 million – a reduction of $129 million with 40% reduction in demand for water. Further increase in water charges of $25 resulted in another 31% reduction in water usage in the basin. Fast decline in water usage continues with the incremental increase in water charges until $100/ML.

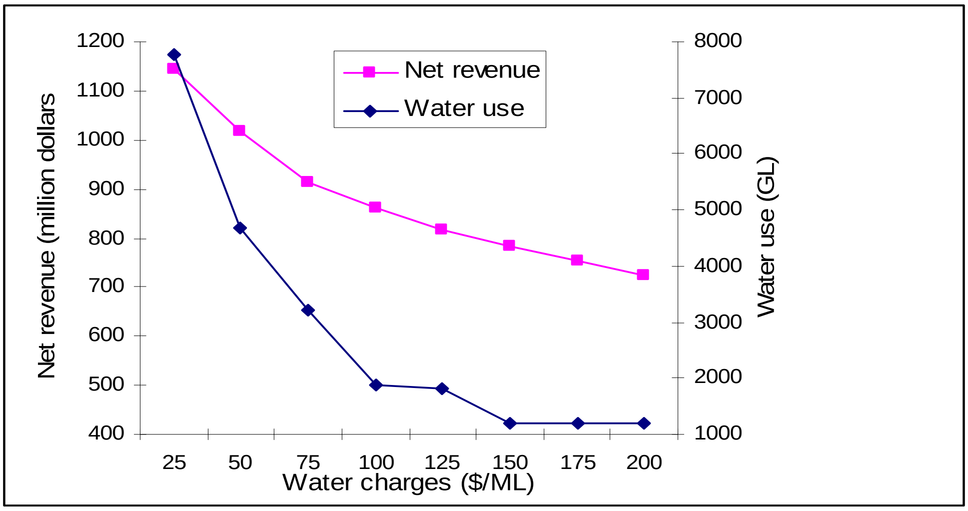

Figure 3: Aggregate water usage and net revenue at varying water charges

The reader is reminded that interregional water trading is not allowed in the model and only a limited number of temporary activities are allowed to take land from other temporary activities. The regions are forced to use only their own water allocations no matter how high the values of the commodities are that they produce. This has resulted in low and high returns per unit of water in different regions, as shown in Table 5. For example, each ML of water used in Goulburn and Loddon produced $39 and $54, respectively. These returns are much lower than each ML of water used in Mallee and Lower Murray who produced $903 and $519, respectively. The model has also been used to estimate the shadow price of water in each region. These values are also presented in Table 5. Again, the results indicate that the irrigators in Mallee and Lower Murray are willing to pay highest ($283 and $335) for each additional unit of water. The shadow prices in Murray River and Murrumbidgee are $8 and $27 per ML. The shadow price of water in all other regions is extremely low. This is because a) these regions on aggregate produce low value crops and/or b) they have more allocations and high effective rainfall which reduce demand for water.

Table 5: Net return and shadow price of water usage in different regions when $25/ML water charges are used in medium rainfall and water allocation state

	Broken	Goulb	Loddon	MRiver	Murrum	Mallee	WimAvon	LMurray

Net revenue ($)/ML	39	39	54	56	167	903	519	899
Shadow price ($)	1	0	0	8	27	283	210	335

Basin optimising solution with environmental flows

The optimization model was used to assess the cost of supplying the environment water by reducing irrigator allocations by 500 GL in two separate scenario analyses.

The first scenario involved setting aside 500 GL of irrigation water allocation for the environment assuming proportional reductions in water available in each region modeled. The model determined optimal level of water and land use by each activity in each region for three states of nature. Table 6 presents new optimal areas under each crop assuming a $25/ML water charge and a medium water allocation state. Compared to the case when there was no water for the environment, these areas are smaller as less water is available for the existing activities in the regions. Area under each activity has reduced with an overall reduction of about 2% in the basin compared to the scenario when there was no allocation for environmental flows.

Table 6: Optimal areas under each crop when $25/ML water charges are used and 500 GL is reserved for environmental flows

	Rice	Grape	Beef	Dairy	Oilseeds	Fruit	Legumes	Cereals	Vegetab	Used area	Given area	prop
UMurray		140	3120	146						3406	5690	0.60
Kiewa		72	434	174						680	936	0.73
Ovens	89	2404	2194							4687	7892	0.59
Broken	1259	278	8593	53429		4639		4036	822	73056	112723	0.65
Goulb		1512	4883	62167				2812	2871	74246	120252	0.62
Campas				17828				1021	40	18890	30031	0.63
Loddon	263	537	12905	88675	451	1114	1362	16565	3569	125441	202189	0.62
Avoca	132	2991	93	4760		2898		1302	2521	14698	22778	0.65
MRiver	55231	761	11694		1070	150	182	53793	1009	123891	269865	0.46
Murrum	49680	13047			4925	7383		93007	7258	175300	312009	0.56
Mallee		7881				9818			4760	22458	47757	0.47
WimAvon		2478	92			1018		31	308	3927	5566	0.71
LMurray		5331				3625			2036	10992	35611	0.31
Total	106655	37432	44007	227180	6447	30646	1544	172567	25195	651672	1173297	0.56

The aggregate profits of the basin in low, medium and high rainfall scenarios are $971, $1116 and $1214 million at a water charge level of $25/ML. When medium state of nature with environmental flows is compared with the scenario which had no environmental flows, there is $56 million reduction. This is the opportunity cost of environmental flows when there are medium rainfall and water allocation. However, this cost increases to $64 million when irrigators face low rainfall and low water allocations. The results indicate that there is reduction in overall water usage and regional agricultural profitability when 500 GL water is reserved for environmental flows.

Table 7 is a comparison of the opportunity cost in terms of forgone irrigation profit opportunity of providing 500 GL for environmental flow across weather states at a $25/ML water charge rate. The opportunity cost of setting aside 500 GL water for environmental flows reduced from $32 million when there were low rainfall and low water allocation state to $28 million and $26 million when there were medium and high states of rainfall and water allocations, respectively. The cost of setting aside one unit (ML) of water varies from $64 to $56 and $52, respectively under low, medium and high states.

Table 7: Estimated opportunity cost of providing 500 GL for environmental flow

	Net revenue without environmental flows (million $)	Net revenue with environmental flows (million $)	Opportunity cost (million $)	Opportunity cost ($/ML)
Low	1003	971	32	64
Medium	1145	1116	28	56
High	1241	1214	26	52

It is clearly evident from the results summarized in the table that acquiring relatively large volumes of water (500 GL) will impose large costs on irrigators. Furthermore, opportunity costs of forgone profit are inversely related to water availability state. Given that irrigators set levels of fixed assets such as land and irrigation equipment based on average or lower water availability, profitable opportunities to use additional water in years of high availability are limited. Optimisation modelling results presented here suggest that cost in terms of potential irrigation profit forgone in such years is slightly less ($4 million for making 500 GL of water available for the environment) than the medium state.

Given the least cost principle of obtaining water for environmental flows, it is reasonable to take water for the environment only from those regions where it is cheaper and relatively economical. This means no water should be taken from those regions which produce high value crops and other agricultural activities. The first part of our analysis indicates that in the basin, three regions, namely Mallee, Wimmera Avon and Lower Murray are highly productive and no water for the environment should be taken from these regions following the ‘least cost principle’ of obtaining water for environmental flows.

To model taking environmental water from regions where it is less valuable, a slight modification is made in the original model and the 13 regions have been divided into two groups – one with high returns called ‘high value regions’, including these three regions and a second with a low return called ‘low value regions’ in the modified model of the basin. New net revenue values have been obtained and the opportunity cost of environmental flows for three states has been estimated, as presented in Table 8.

Table 8: Estimated opportunity cost of providing 500 GL for environmental flow when regions are grouped in two classes

	Net revenue without environmental flows (million $)	Net revenue with environmental flows (million $)	Opportunity cost (million $)	Opportunity cost ($/ML)
Low	1003	990	13	26
Medium	1145	1135	9	19
High	1241	1233	7	14

The new opportunity costs in Table 8 indicates that grouping the thirteen regions into two classes has significantly reduced the opportunity cost of obtaining environmental flows by $19 million. The opportunity cost of obtaining one ML of water for environmental flows has also reduced from $56 to $19 in the medium state.

C. Modeling supply and demand of irrigation and environmental water with simulation

The optimisation models (such as discussed above) are useful in determining optimal usage of water subject to several constraints by optimising water benefits across different water using sectors and regions. However, there is growing critique of certain behavioural assumptions implicit in such modelling. Individuals (irrigators in this case) are assumed to act as perfect rationalists to maximise profit as if they understood with certainty the payoffs to all decisions that they could consider making. Work by social psychologists (e.g. Todd and Gigerenzer, 2003) suggest that actual decision making does not typically involve optimisation in the full economic rationalist sense. Rather, agents such as irrigators tend to make decisions based on relatively simple heuristics which involve more limited sets of choices and more limited search than would result from optimisation (Gigerenzer, 2001).

An additional limitation with the optimisation methodology is that it offers limited possibility to examine opportunities for an environmental steward to act strategically in acquiring water. Cost of acquiring environmental flow is simply estimated by restricting water available to irrigators at a constant level across weather states. However, in actuality a steward may be able to improve both environmental and irrigator outcomes by buying water for the environment in periods of high water availability when it is needed environmentally to augment floods, and selling water to irrigators in years of low availability when it is especially valuable in irrigation (Young and McColl, 2004).

To address these issues, in addition to the optimisation model of irrigation water demand described above, we have also developed a prototype simulation model that characterises water market interactions between irrigators and an agent (environmental steward) acting in the market to provide water for the environment. Simulation models are conceptually suited to realistically incorporating modelling bounded rationality water allocation decision making by irrigator and strategic behaviour of environmental steward. Simulation models have the added benefit of demonstrating the change in state of system components with time and possibly in space also.

In the analysis, two sets of players compete for water in response to the variable water supply. The first set comprises dairy, rice and grape irrigators, whereas the second set comprises a single "Environmental Steward". The objectives and treatment of the two sets are different. The simulation is driven by rules determining behaviour of irrigators and the environmental steward rather than an overall social planning objective. The individuals in the model adapt but do not learn, thus distinguishing them from agents in agent based models. Agent based models have been used in land use, water management and irrigation studies (eg Becu et al., 2003) including in the Murray (Bell, 2002). This model currently is rather more stylised than the optimisation model. For example, it involves trading of water allocations between three irrigation sectors (grapes, rice and pasture/dairy).

A general schematic of the model is presented in Figure 4. As can be seen it consists of:

- the hydrology model already described above;
- a model of irrigator behaviour in water markets depicted by irrigation; and
- a model of environmental steward behaviour in water markets depicted by trade.

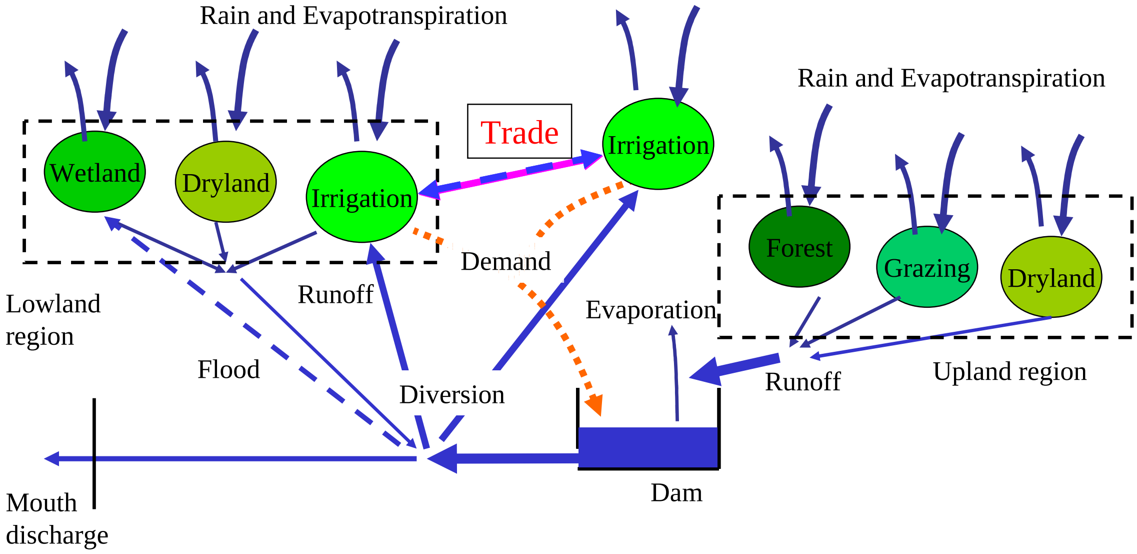

Figure 4. Schematic representation of prototype spatial model, including trading components. Two regions are shown, with three land uses each, whereas the model has 39 regions with several land uses each. The blue arrows depict physical flows of water, whereas the orange arrows depicts the control of demand over the operation of the dam. The dotted blue arrow indicates that floods are only occasional. The dotted blue and red arrow indicates that the physical transfer of water between irrigation regions depends on trade and might not always occur.

Irrigator behaviour model

We assume that there are 1000 individuals (irrigators) trading water for grape (vineyard) irrigation, 1000 trading for rice irrigation and 1000 trading for pasture (dairy) irrigation. The three industries make different profits per unit of water, and we use the values given by Eamus (2003), with grapes requiring 0.2 ML to make $100 net profit, rice requiring 1.8 ML and pasture requiring 2.7 ML. We next assume that the individuals face different circumstances (possibly many factors including soils, location, management ability). For simplicity, we characterise those different circumstances with a number drawn randomly from a normal distribution with a mean of 1 and a standard deviation of 0.27. Each individual has an expectation of profit which is the product of the circumstances and the net profit.

For simplicity, we assume that grapes are the only irrigation crop grown in the two western subcatchments, rice is the only crop grown in the northern sub-catchment, and pasture is grown elsewhere. This is a rough approximation to the distribution of irrigation industries in the Murray basin as shown by Kirby (2004). Each individual is given an allocation of 1/1000 of the average irrigation water use in each of those industries in a 20 year "historical" model run.

In any year, an individual is entitled water up to their historical allocation, but the actual amount received depends on the circumstances of the year. In a drought year, they may receive less. In a wet year, they do not receive more, and the extra water results in recharge of dams, floods and discharge from the mouth. The amount actually received may be traded. Every individual is willing to sell all of their water allocation at a price greater than their profit expectation. Every individual is willing to buy more water, up to an amount 10% greater than their historical allocation (since we assume that any individual has only so much capacity to use extra water) if this is profitable. Thus, in a dry year, each individual is allocated less water than their full allocation, and they are willing to buy enough water to return to their full allocation, plus 10% more. The scheme appears to be similar in effect though simpler in implementation to the atomistic competition example of Bell (2002).

This market choice behaviour of the agents leads to willing-to-sell and willing-to-buy (supply and demand) curves of price versus cumulative volume, from which the price and volume of water traded are determined. The supply and demand curves, and the price and volume of water traded are emergent behaviour in ARISCtrade.

The curves vary from year to year, according to the rainfall and runoff. For example, in a drought year, the irrigators wish to buy more water, and a greater volume of water is traded at a higher price. Trading of environmental water allocations further modifies the impact of these rules, as described below.

D. Environmental flows - purchasing through countercyclical trading

We assume that an "Environmental Steward" has an allocation of 500 GL per year of water, to be used to increase environmental benefits. We assume that these environmental benefits result from increasing floods (thereby promoting growth of flood plain or wetland vegetation, with consequent benefits for their dependent ecosystems), and/or increasing discharge from the mouth of the Murray. The Environmental Steward can, in any one year, choose to send the allocation down the river, bank the allocation (ie store it in a dam) for use in a later year, or send the allocation plus some or all of the banked water down the river. It is also assumed that the Environmental Steward may also buy or sell water.

In the current implementation of the model, the rules governing how the Environmental Steward uses the annual allocation are as follows:

1. in a dry year, the allocation is banked, since the river is low and no environmental advantage is gained from sending the allocation down the river;
2. in a wet year (when there is a flood), the allocation plus any banked water is sent down the river to increase the level of flood and discharge from the mouth;
3. in a year that is neither wet nor dry, the allocation is sent down the river to increase discharge from the mouth; and,
4. there is a limit (specified in the data, and 2000 Gl has been used in many simulations) to how much water the Environmental Steward can bank.

The Environmental Steward's objective is to increase the amount of water that may be used for environmental flows, and thus will attempt to purchase water with all the money raised by selling, and to purchase more than is sold. However, the Environmental Steward is required, within a small error, to finish the 20 year period with neither a financial gain nor a loss. The small error arises because the final purchase or sale is based on an estimated price, whereas the actual price deviates from this because of the entry of the Environmental Steward into the market.

The Environmental Steward trades according to a set of decision rules, linked to the rules under which environmental flow water is banked or used for flow (see Hydrology Component section above). The rules enable the Environmental Stewart to adapt buying or selling decisions to three factors: the current price in the market (P) (which varies stochastically from year to year) ; the cumulative profit or loss banked from previous buying and selling (B); and, the probability that future buying and selling will yield sufficient funds to extinguish the cumulative profit or loss. The funds likely to saved from or borrowed for future buying and selling is based on the probability of encountering a high market price ($p(H)$) or a low market price ($p(L)$), and the high and low prices (P_h and P_l). As will be shown in the results section below, the simulated prices fluctuated from year to year, with low prices in wet years and high prices in dry years. Few years show intermediate behaviour. The probabilities $p(H)$ and $p(L)$ were estimated from the number of years in 20 that had high or low prices for the simulation with environmental water allocation but no trading by an Environment Steward.

We assume that the Environmental Steward will not be the sole buyer or seller in a market. This is partly because offers to sell or buy massive quantities of water (such that the Environmental Steward is the sole buyer or seller) would raise or suppress prices to the disadvantage of the Environmental Steward and partly because we expect that such behaviour would be prevented by regulation. We arbitrarily limit the buying (V_{Bmax}) and selling (V_{Smax}) by the Environmental Steward to 300 GL and 1000 GL respectively in any year, these being approximately half the simulated total activity in wet years and dry years respectively.

The rules used by the Environmental Steward were:
1. the market price, P, which would obtain in the absence of trading by the Environmental Steward is disclosed, but no trading actually takes place.
2. The Environmental Steward determines the expected payoff from buying water.
The previously determined probability of encountering high market prices ($p(H)$)

multiplied by the number of years remaining (n_y) to the end of the simulation determine the likely money that could be raised by selling, S_l:

$$S_l \quad = \quad p(H) n_y P_h \tag{6}$$

and the total money likely to be available for purchasing water would then be $B + S_l$. The actual volume of water that could be bought is the minimum of V_{Bmax} and $(B + S_l) / P_l$. This ensures that the Environmental Steward does not buy more water than the mandated maximum volume nor accrue a debt larger than that which can be extinguished.

3. The Environmental Steward then determines the expected payoff from selling water. The previously determined probability of encountering low market prices ($p(L)$) multiplied by the number of years remaining (n_y) determine the likely money that could be raised by buying, B_l:

$$B_l \quad = \quad p(L) n_y P_l \tag{7}$$

and the total money likely to be available from selling water would then be $B + B_l$. The actual volume of water sold is the minimum of V_{Smax} and $(B + B_l) / P_h$. As with buying, this ensures that the Environmental Steward does not sell more water than the mandated maximum volume nor accrue a profit larger than that which can be extinguished. The volume sold is further limited if the amount of water banked plus the environmental allocation in the year is smaller than that determined above.

4. The decision to sell or buy is determined by the larger of the two expected payoffs, with the volume to be bought or sold indicated above.
5. Water bought is transferred into the water bank or, if the volume of water banked is the maximum permitted, is used for environmental flow in that year. The supply to irrigation use is diminished by the amount bought.
6. Water sold is transferred from the water bank or environmental water allocation, and the supply to irrigation correspondingly increased.

Assessing countercyclical trading with the simulation model

Scenarios

Kirby et al. (2004) applied ARISCtrade to several scenarios including a base case, increased irrigation efficiency, increased afforestation in upland areas of the Murray Basin, and climate change. They investigated the hydrological and trading behaviour both with and without the Environmental Steward. Here we concentrate on the decisions of the Environmental Steward.

Basic hydrological and trading behaviour

The behaviour of ARISCtrade is shown for the base case in Figure 5. The figure shows the stochastic nature of both the supply and prices and volumes traded. Water reservoirs remained full in most years except very dry years (Figure 5a). Irrigation supply was greater, due to greater demand, in dry years, except for the exceptionally dry year 3 in which there was insufficient stored water to make up for the low rainfall (Figure 5b). Whereas irrigation supply fluctuated from year to year, the overall water use (supply plus rainfall) in irrigation districts was nearly the same from year to year, except for the very dry year 3 (Figure 5c).

The market water price and volume of water traded increased in dry years, particularly in the very dry years 3 and 15 (Figure 5d and 5e). Zaman et al (2003) showed that the average pool price in temporary water trading in the Goulburn-Broken catchment averaged from 0.032 to 0.096 $m/GL in the four years from 1998/9 to 2001/2, and then jumped to 0.305 $m / GL in the dry 2002/3 season. In the first four years, the price remained low throughout most of the season, whereas in 2002/3 the price remained high throughout most of the season. While not confirming the behaviour simulated by ARISCtrade, this does suggest that our results are plausible.

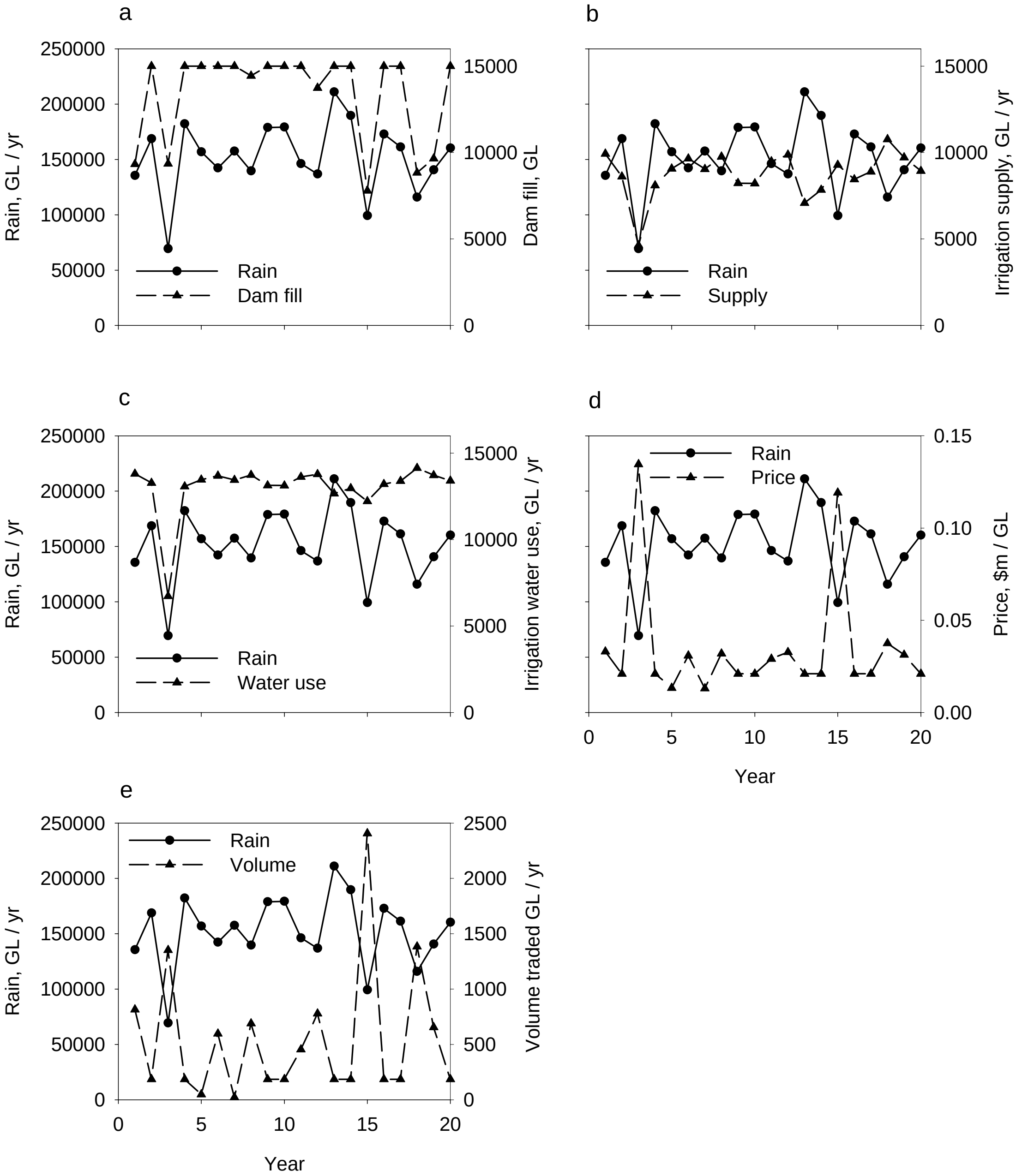

Figure 5. Behaviour of ARISCtrade: a. dam fill; b. irrigation supply (ie diversions); c. total irrigation water use including rainfall (ie, supply plus rainfall); d. price traded; e. volume traded. All plots show the rainfall for comparison.

The annual average discharge from the mouth and irrigation water supply simulated by ARISCtrade for the base case are similar to those for the Murray, as shown in Table 9.

Table 9. The discharge and irrigation supply, 1992-2000.

Annual volumes, GL / yr	Murray[1]	ARISCtrade
Mouth discharge	2970	3397
Irrigation supply	8970	8776

[1] figures taken from Water Audit Monitoring Reports, MDBC (2004).

The two main indicators of environmental water in ARISCtrade are water supply to wetlands and discharge from the mouth. These are shown for the four scenarios in Table 10. For comparison, we show the results both with and without trading by the Environmental Steward. The price and volume of trade are also shown.

Table 10. Comparison of scenarios. Wetland water use, mouth discharge, volume traded and environmental water allocation are annual averages in GL / yr. Price is annual average in $m / GL.

	Environmental water not traded	Trading by Environmental Steward
1. Base case		
Wetland	4945	5041
Mouth	5399	5418
Price	.0694	.0732
Volume traded	683	890
Environmental allocation	500	582
2. Increased irrigation efficiency		
Wetland	5499	5586
Mouth	5956	5977
Price	.0753	.0808
Volume traded	617	798
Environmental allocation	500	557
3. Increased upland forestry		
Wetland	3774	3851
Mouth	4237	4251
Price	.0733	.0762
Volume traded	677	882
Environmental allocation	500	590
4. Climate change		
Wetland	2395	2487
Mouth	2754	2793
Price	.0856	.0909
Volume traded	654	899
Environmental allocation	500	612

The table shows an increase in market activity and an increase of environmental water, in the sequence of increased irrigation efficiency, base case, increased upland forestry and climate change. This is due to the decreased supply going from one case to the next.

Conclusions

The preliminary results of integrated modeling indicate that the framework can provide robust information to help policy makers in dealing with water resource management issues. The optimization model estimates possible economic gains to water trade and agricultural water demand response to changes in water prices. The water trade model results show the benefit of moving water from low value crops to high value crops when water trading rights exist. Net profits in irrigated agriculture increase substantially compared to the case of rights for each agricultural activity. The model also estimates opportunity costs to irrigators of providing environmental flows when there is low or high rainfall and water allocation scenarios. Actual responses to water markets and withholding of water for environmental flow are likely to vary from estimated level as the results of several constraints not accounted for in modeling to date. These include information constraints, market failure, government failure and lack of property rights along with risk averse behaviour of individual growers/irrigators will also impact on adoption. Nevertheless, the scenarios do indicate the direction of adjustments in irrigation patterns that might be expected and order of magnitude estimates of costs of environmental flows under each state of nature. In reality, not all farmers have identical cost and capital structures, nor do they have equal management ability and hence revenue structures, so actual response to water price changes will likely be smooth not in abrupt steps as predicted here.

To examine unique attributes of individual irrigators, agent based simulation modelling has been used as a complement to the optimisation modelling. The agent based explicit trading model is suited to the study of individual decision response to policy changes in a system characterised by stochastic supply and market prices. In this paper the use of the method to evaluate the extent to which an environmental steward can enhance the level of water to the environment by acting strategically in the water market. The simulated steward begins with a set water allocation, buys water in years of high availability to augment environmental flows, and sells in years when water supply is low and thus demand by irrigators is high. The steward is found to be able to enhance the level of flow available for the environment without net expenditure above what might be required to acquire the assume initial 500 GL environmental allocation. The amount by which flow can be increased is estimated to vary between approximately 10% and 20% of initial environmental flow allocation across a range of scenarios considered including a baseline with repeat of historical flows and altered flow through climate change, and increase upland forestation.

The analysis demonstrates that including stochasticity of water supply in analysis as well treating a range of scenarios is suited to exploring general bounds and most likely outcomes of decision making under a wide range of conditions and is thus well suited to policy development. The intent in the future is to further develop and use this modelling capacity to, amongst other things, test the efficacy of alternative decision making strategies and rules by individuals and agents in market behaviour and water management. Several important and relevant aspects planned for consideration in future analysis, include external impacts of irrigation (such as impact on water quality and other externalities). Once information about external impacts of irrigation caused by each crop at each site is available both private and social costs and benefits will be incorporated in the analysis. Also the model does not consider impact of reduction in allocation of water for irrigation on other sectors and/or regions which are not directly involved in irrigation. Computable General Equilibrium modelling is planned to examine these impacts on several sectors, regions and national economy.

Acknowledgements

This paper was produced as part of the CSIRO Flagship Program Water for a Healthy Country. Mike Young made some valuable comments about policy and regulation of water in the Murray Basin. Comments and suggestions by Wendy Proctor on an earlier draft of this paper are also acknowledged.

References

Becu, N., Perez, P., Walker, A., Barreteau, O. and Le Page, C., (2003). Agent base simulation of a small catchment water management in northern Thailand: Description of the CATCHSCAPE model. Ecological Modelling, 170, 319-331.

Bell, R. and Heaney, A., (2000). A Basin Scale model for assessing salinity management options: model documentation, ABARE Technical working paper 2000.1, Canberra.

Bell, R., (2002). Capturing benefits from water entitlement trade in salinity affected areas: A role for trading houses? Australian Journal of Agricultural and Resource Economics, 46, 347–366.

Bjornlund, H., (2004). What impedes water markets? Water (Journal of the Australian Water Association), 31 (7), 61-65.

Bradford, A., Zhang, L., and Hairsine, P., (2001). Implementation of a mean annual water balance model within a GIS framework and application to the Murray Darling Basin. CRC for Catchment Hydrology, Technical Report 01/8.

Bryan, B.A. and Marvanek, S., (2004). Quantifying and valuing land-use change for ICM evaluation in the Murray-Darling Basin 1996/97 – 2000/01. CSIRO Land and Water Stage 2 Report for the Murray-Darling Basin Commission.

Chiew, F., Harle, K., Howden, M., Kirby, M., Peel, M., Siriwardena, L. and Viney, N. R., (2003). Catchment water yield and water demand projections under climate change scenarios for the Australian Capital Territory. Report to ACTEW, CSIRO Land and Water.

COAG (Council of Australian Governments), (2004a). Intergovernmental Agreement on Addressing Water over-allocation and achieving Environmental Objectives in the Murray-Darling Basin between the Commonwealth of Australia and the Governments of New South Wales, Victoria, South Australia, and the Australian Capital Territory.

COAG (Council of Australian Governments), (2004b). Intergovernmental Agreement on a National Water Initiative between the Commonwealth of Australia and the Governments of New South Wales, Victoria, Queensland, South Australia, the Australian Capital Territory and the Northern Territory.

Doorenbos, J. and Kassam, A. H., (1979). Yield Response to Water: FAO Irrigation and Drainage Paper 33, FAO, Rome.

Eamus, D., (2003). The real cost of agriculture. Australian Science, August 2003, 35-37.

Eigenraam, M., (1999). Economic assessment of water market reform using the water policy model, Working paper, Economics Branch, Department of Natural Resources and Environment, Victoria.

English, B., Bearley, T. and Coggan, A., (2004). Environmental flow allocations and counter-cyclical trading in the river Murray System, Paper presented at the Australian Agricultural and Economics Society Annual Conference, 11-13 February 2004, Melbourne.

Etchells, T., Malano, H.M., and McMahon, T.A., (2003). Developing a methodology to calculate water trading exchange rates. Australian Journal of Water Resources, 7 (1), 41-47.

Gigerenzer, G., (2001). The adaptive toolbox, in Gigerenzer G and Selten R. Bounded rationality edn, The Adaptive toolbox. Cambridge, Massachusetts: MIT Press.

Goesch, T. and Heaney, A., (2003). Government purchase of water for environmental outcomes, ABARE ereport 03.22, prepared for the Natural resource management Business Unit of the Australian Government department of Agriculture, Fisheries and forestry, Canberra.

Gulati, H. S. and Murty, V. V. N., (1979). A Model for Optimal Allocations of Canal Water based on Crop Production Functions: Agricultural Water Management, 2(1), 79-91.

Heaney, A., and Beare, S., (2001). Water trade and irrigation: defining property rights to return flows. Australian Commodities, 8 (2), 339-348.

Jones, R., Whetton, P., Walsh, K., and Page, C., (2001). Future impact of climate variability, climate change and land use change on water resources in the Murray Darling Basin. Overview and draft program of research. CSIRO Atmospheric Research, September 2001.

Keating, B. A., Gaydon, D., Huth, N. I., Probert, M. E., Verburg, K., Smith, C. J. and Bond, W., (2002). Use of Modelling to Explore the Water Balance of Dryland farming Systems in the Murray-Darling Basin, Australia: Europ. J. Agronomy, 18, 159-169.

MDBC, (2001). Integrated Catchment Management in the Murray Darling Basin 2001-2010: Delivering a Sustainable Future. Murray Darling Basin Commission, Canberra.

MDBC, (2002). The Living Murray: a discussion paper on restoring the health of the River Murray. Murray Darling Basin Commission, Canberra.

MDBC, (2004). Water Audit Monitoring Reports. Murray Darling Basin Commission, Canberra, available at http://www.mdbc.gov.au/naturalresources/the_cap/the_WAM_report.htm

MDBMC, (2003). Murray Darling Basin Ministerial Council Communique, 14 November, Canberra.

Morris, Joe, (2004). Economics of the Water Framework Directive: Purpose, Principles and Practices. Applied Environmental Economics Conference, 26 March 2004, The Royal Society.

National Land and Water Resources Audit, 2001. Australian Agriculture Assessment, Volume 1. Appendix 1, Tables on p. A16-A18, River basin budgets.

National Land and Water Resources Audit, 2002. Australian Catchment, River and Estuary Assessment, Volume 2. Appendix 3, Tables on p. 340-343, Summary assessment findings for each river basin.

Nias, Deborah J., Patricia Alexander and Mathew Herring, (2003). *Watering private property wetlands in the Murray Valley, New South Wales*. Ecological Management and Restoration, Vol. 4 No. 1, April 2003.

Quiggin, J., (2001). Environmental economics and the Murray-Darling river system. The Australian Journal of Agricultural and Resource Economics, 45 (1), 67-94.

Raupach, M.R, Kirby, J.M., Barrett D.J. and Briggs, P.R., (2001b). Balances of Water, Carbon, Nitrogen and Phosphorus in Australian Landscapes: (1) Project Description and Results. CSIRO Land and Water. Technical Report 40/01.

Raupach, M.R, Kirby, J.M., Barrett D.J. and Briggs, P.R., Lu, H. and Zhang, L., (2001a). Balances of Water, Carbon, Nitrogen and Phosphorus in Australian Landscapes: (2) Model Formulation and Testing. CSIRO Land and Water. Technical Report 40/01.

Ribaudo, M.O., Horan, R.D. and Smith, M.K., (1999) Economics of Water Quality Protection from NonPoint Sources: theory and Practice, United States Department of Agriculture, Economic Research Service, Agricultural Economic Report Number 782.

Todd, P.M. and Gigerenzer, G., (2003). Bounding Rationality to the World, Journal of Economic Psychology, vol. 24, 143-65.

Turner, R.K., Pearce, D. and Bateman, I., (1994). Environmental Economics: An Elementary Introduction, Harvester Wheatsheaf, Sydney.

Young, M.D and McColl, J.C., (2004). Parting the Waters: Frontiers in Water Management. Dialogue 23(3), 4-18.

Young, M.D. and McColl, J.C., (2003a). Robust Reform: Implementing robust institutional arrangements to achieve efficient water use in Australia. CSIRO Land and Water.

Young, M.D., and McColl, J.C., (2003b). Robust separation: implementing robust institutional arrangements to achieve efficient water use in Australia. CSIRO Land and Water.

Zaman, A.M, Davidson, B, and Malano, H.M., (2004). What is driving temporary water trading in the Goulburn-Broken Catchment? Paper presented at the Australian Agricultural and Economics Society Annual Conference, 11-13 February 2004, Melbourne.

Zhang, L., Dawes, W.R. and Walker, G.R., (1999). Predicting the effect of vegetation changes on the catchment average water balance. CRC for Catchment Hydrology Report 99/12. Balances of Water, Carbon, Nitrogen and Phosphorus in Australian Landscapes: (2) Model Formulation and Testing. CSIRO Land and Water. Technical Report 40/01.