The Australian Journal of Agricultural and Resource Economics, 51, pp. 263–281

Water use and salinity in the Murray–Darling Basin: A state-contingent model*

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The supply of water for irrigation is subject to climatic and policy uncertainty. The object of the present paper is to show how the linear and non-linear programming models commonly used in modelling problems such as those arising in the Murray–Darling Basin may be adapted to incorporate a state-contingent representation of uncertainty. Estimates showing the potential value of improved water use are also derived.

Key words: irrigation, salinity, uncertainty.

1. Introduction

With the exception of global climate change, the sustainable management of the Murray–Darling Basin is the biggest single environmental and resource policy issue facing Australia at present. The Basin covers over one million square kilometres in four eastern Australian states and the Australian Capital Territory. It consumes almost three-quarters of all irrigation water used in Australian agriculture and, in 2001, produced over 50 per cent of Australia's gross value of agricultural production, worth about $17.7 billion a year (ABS 2004).

The central problem of the Basin arises from the rapid expansion of irrigation during the 20th century. By the time a limit, know as the Cap, was imposed on diversions in 1995, prohibiting further growth in average annual allocations, nearly 100 per cent of normally available flows had been allocated, and many catchments had been overallocated. The resulting problems included increasing irrigation-related salinity, rising water tables and inadequate flows of water to sensitive ecosystems. In addition, the Basin is affected by a range of problems common to agricultural systems throughout Australia, including dryland salinity, acid soils and a number of invasive weeds and pests. Managing this complex land use system amidst a continuing downward trend in farmers' terms of trade and increasing competition for water is a major policy challenge.

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* The views expressed here do not represent those of the Australian Government Department of Agriculture Fisheries and Forestry, where Thilak Mallawaarachchi is also affiliated.

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doi: 10.1111/j.1467-8489.2007.00380.x

Water policy reform has been a key priority for the Australian Government for more than a decade, since the Council of Australian Governments agreed to a water reform framework in 1994. This framework explicitly linked economic and environmental issues within a coherent and integrated package of reform measures, with objectives including: pricing water for cost recovery; allocation of water for the environment; and the decoupling of land and water titles to create effective 'water property rights' that allowed for trading in water entitlements. While progress in implementing the reforms at the institutional level has varied amongst the jurisdictions, trade in water entitlements has expanded. Prices have moved towards cost recovery.

The water reform process has also shown that measures aimed at improving the management of the system can have unintended effects, which could undermine the intended outcomes. As with other irrigation schemes around the world, the construction of irrigation systems designed to 'droughtproof' agriculture have led to the expansion of industries that depend on reliable water supplies. Engineering schemes to mitigate salinity have encouraged expanded water use, which has partially offset the mitigation benefits. Incentives to reduce water use have encouraged farmers to minimise return flows of water from irrigated land back to the river system, thereby reducing available supplies for others. The introduction of trade in water rights has led to the activation of previously dormant water licenses ('sleepers' and 'dozers'[1]), and raised concerns about 'stranded assets'[2] and about implications for future funding of regional irrigation infrastructure.

Changing community values, incorporating a greater appreciation of the natural environment, the rising value of water entitlements, and possible reductions in inflows of water to the Basin because of climate change, have highlighted the need to continue to pursue water sector reform. In particular, the Council of Australian Governments noted the need to clarify water property rights, especially to deal with the tension between establishing certainty for water users and the need for adaptive management to address environmental needs.

The policy response to these concerns is embodied in the *National Water Initiative*, signed in June 2004 following the commitments from state and federal governments, made in August 2003, for a funding allocation of $500 million over five years. The *National Water Commission Act 2004* (Cwlth) created the National Water Commission as an independent statutory body.

In directing these reforms, the policymakers have relied upon information available to them on the basis of implicit or explicit models of the behaviour of water users. As the scarcity of water increases and the tension between the consumptive and environmental uses of water becomes more widespread, the

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[1] 'Sleepers' are water licenses that have been allocated but never used. 'Dozers' are licenses with a history of use but no current use.

[2] Capital assets are said to be 'stranded' when regulatory changes reduce demand, driving returns below the cost of capital. The issue is discussed, in the irrigation context, by Goesch (2001).

role of uncertainty about the availability of water in its alternative uses and the implications of different use patterns for the total value of the resource to the Basin community needs to be better understood. Improved modelling of the decisions of water users, including the consideration of uncertainty is therefore a crucial requirement for improvements in public policy.

One of the first models of water use in the Murray–Darling Basin was that of Quiggin (1988, 1991). This model illustrated the extent to which the benefits of engineering solutions to salinity mitigation might be offset by unconstrained behavioural responses. In particular, the model illustrated how the profit maximising behaviour of land users in one reach of the catchment could affect the choice of land use and productivity in other locations. Management of these transboundary externalities resulting from spatially distributed activities such as farming is made particularly difficult because of uncertainty about the behaviour of land users. On the other hand, in the absence of binding constraints that modify behaviour, externalities in irrigation will rise, with resultant high economic costs.

An acknowledged limitation of the Quiggin (1988, 1991) model was the inadequate treatment of uncertainty and variability. The model was purely deterministic in form. Non-linear effects of variability were taken into account by using flow and salinity values corresponding to a worse-than-median year. This approach may be interpreted as using a certainty equivalent to model irrigator responses to uncertainty.

Recent theoretical developments have shown the power of a state-contingent approach to the analysis of production under uncertainty (Chambers and Quiggin 2000). This approach, pioneered by Arrow and Debreu (1954) but little used in production economics until recently, involves the representation of uncertainty by differentiating commodities produced in different states of nature. This model has yielded useful insights into drought policy (Quiggin and Chambers 2004) and risk management in agriculture (Chambers and Quiggin 2004).

The closest approach, and one that illustrates some of the strengths of a state-contingent representation of uncertainty, is discrete stochastic programming (Cocks 1968). Important applications of discrete stochastic programming to Australian agriculture include Brown and Drynan (1986), Kingwell *et al.* (1993) and Kingwell (1994).

In the last few years, the power of the Arrow–Debreu state-contingent approach has been recognised and exploited for empirical application. Rasmussen (2003) examines input demand. Chambers and Quiggin (2005) examine asset pricing. O'Donnell and Griffiths (2006) show how a state-contingent approach may be applied to the estimation of production frontiers. O'Donnell *et al.* (2006) use a Monte Carlo approach to derive implications for efficiency analysis.

The object of the present paper is to show how the linear and non-linear programming models commonly used in modelling problems such as those arising in the Murray–Darling Basin may be adapted to incorporate a state-contingent representation of uncertainty.

The model described here is an extension and generalisation of that presented by Quiggin (1988, 1991) with a more detailed representation of the river system, including the Darling and its tributaries and a larger set of commodities. Nevertheless, as with Quiggin (1988, 1991), the main aim of the model is illustrative: to provide insights into behavioural responses to changes in policy or climate. In this case, the main concern is with policies to allocate and manage risk in the supply of water for irrigation and the environment.

The paper is organised as follows. Section 2 is a formal description of the model. Section 3 describes the implementation of the model in its sequential and global representation, and the data used in its construction. Section 4 presents results for sequential and global solutions. Section 5 outlines possible applications and future developments. Finally, some concluding comments are given.

2. Model

Various approaches have been used to model land and water allocation in the Murray–Darling Basin. The primary focus of much of the effort to model water use in the Basin has been on water trading. These include Hall *et al.* (1991, 1994) and Peterson *et al.* (2004). ABARE's SALSA model, on the other hand, focused on land use and salinity processes in the Murray–Darling Basin (Bell and Heaney 2001). SALSA has been used to generate baseline projections for dryland and instream salinity under various water use scenarios, and to assess private and social benefits and costs of improved irrigation efficiency. All these models, however, were restricted to the southern Murray–Darling Basin. Of these models, Hall *et al.* (1991, 1994) is closest to the approach taken in Quiggin (1988, 1991) and extended here.

2.1 The basic model

The river system is divided into regions $k = 1 \dots K$. The system is modelled as a directed network, as in Hall *et al.* (1994). Agricultural land and water use in each region is modelled by a representative farmer with agricultural land area L_k. There are S possible states of nature corresponding to different levels of rainfall/snowmelt and other climatic conditions. The status of the river in each region k and state of nature s is measured by a flow variable f_{ks} and Q water quality variables. The $(Q + 1) \times K \times S$ vector of status variables is determined endogenously by water use decisions.

There are M distinct agricultural commodities, and therefore $M \times S$ different state-contingent commodities. There are N inputs, committed before the state of nature is known.

In the most general case, the state-contingent output price vector will also have dimension $M \times S \times K$. However, if products are sold on competitive world markets, the price can be assumed to be the same in all regions and to be independent of the state of nature in the river system. Thus we assume that the price vector **p** has dimension M. Probabilities are specified by an S-dimensional vector π such that $\mathcal{R}\pi_s = 1$. Input prices are denoted by **q** and state-contingent water prices are by $\mathbf{p}^w$.

Chambers and Quiggin (2000) describe general technologies for state-contingent production, which may be represented by input and output sets. Chambers and Quiggin also show how a general state-contingent technology may be built up as the limit of combinations of linear activities. In the programming model described here, production is represented in these terms, with producers allocating resources between a set of linear activities. State-contingent constraints on the availability of water, along with constraints on aggregate availability of other inputs mean that the optimal solution is not, in general, to specialise in a single activity.

2.2 Activities

In each region, land is allocated across R different activities. (Some activities may be excluded from the model in some regions, reflecting the fact that soils and climate in the region concerned are not consistent with the production activity in question.)

For one hectare of land an activity is represented by: (i) outputs of each state-contingent commodity (dimension $M \times S$); (ii) water use in each state of nature (dimension S); and (iii) other inputs (dimension N).

The area of land allocated to activity r in region k is denoted l_r^k and the vector of land allocations in region k is denoted l^k.

In general, an activity may be represented by $(M \times S)$ output coefficients, N factor input requirements and S state-contingent water requirements. Hence, for each region k, the matrix $\mathbf{A}^k$ of activity coefficients has dimension $R \times (M \times S)$, the matrix $\mathbf{B}^k$ of input requirements has dimension $R \times N$, and the matrix $\mathbf{W}^k$ of input requirements has dimension $R \times S$.

The regions are linked by endogenously determined flows of salt and water. Water flows out of a given region are modelled as being equal to inflows, net of evaporation and seepage, less extractions, net of return flows. Extractions are determined endogenously by land use decisions as described above, subject to limits imposed by the availability of both surface and ground water.

The relationship between irrigation water use and return flows thus depends, in part, on the hydrology of the catchment. However, endogenous responses to incentives such as changes in water prices and investment in technology may also affect return flows. For example, high water prices may encourage farmers to adopt water-efficient practices, such as drip irrigation and high density plantings that reduce return flows, and affect farm output and profitability. In the present paper, the possibility of water-saving innovation is modelled by allowing producers to use alternative technologies that produce the same commodity, but differ in the relative intensity with which water and other inputs are used.

2.3 Changes in salt loads

The main interaction between producers arises from the fact that changes in salinity levels, resulting from the decisions of upstream water users, affect crop yields for downstream irrigators. The model therefore incorporates the adverse effects of salinity on yields, derived from agronomic data.

Productivity in a given state of nature will depend on salinity, which in turn will be determined by upstream water use. State-contingent salt loads s_s^k are determined by natural accessions of salt and by return flows from irrigation. The salinity level is given by the ratio:

$$\sigma_s^k = s_s^k / f_s^k. \tag{1}$$

Constraints on water availability will be determined by the interaction between upstream water use, institutional arrangements and policy variables. Given a salinity level σ_s^k each activity r incurs a yield penalty $\theta_r(\sigma_s^k)$ given by

$$\theta_r(\sigma_s^k) = 0, \sigma_s^k \le t_r \tag{2}$$

$$\theta_r(\sigma_s^k) = \lambda_r(\sigma_s^k - t_r), \sigma_s^k > t_r, \lambda_r(\sigma_s^k - t_r) \le 1 \tag{3}$$

$$\theta_r(\sigma_s^k) = 1, \lambda_r(\sigma_s^k - t_r) > 1 \tag{4}$$

where t_r is a threshold level for salinity damage in activity r, and λ_r is a yield-loss parameter. The yield loss function is therefore piecewise linear.

The model is solved on an annual basis, taking such variables as the level and salt concentration of ground water as given. Thus, dry years are associated with high salinity levels, other things being equal, because the volume of water in the system decreases more than the inflow of salt. In the medium term, however, a sequence of dry years will tend to lower water tables and reduce accessions of salt to the system.

3. Model implementation

3.1 Model design

As a starting point, we compare the model developed here with that of Quiggin (1988), which specified:

M = 6 (The six regions were sections of the Murray River. In the present paper, more regions are added.);
Q = 1 (Salinity was the only quality variable. This is unchanged.);
N = K = 4 (The four commodities were grapes, citrus, stone fruits and pasture. More commodities and activities are added in the present paper.); and
S = 1. (The model was deterministic. The incorporation of state-contingent technology, with $S > 1$, is the main concern of the present paper.)

Inputs were land, labour and 'other', in addition to water.

Quiggin (1991) extended the model by allowing for a low water use technology for producing each of the four commodities, as well as the standard high water use technology, so that $N = 8$. In addition, impacts on downstream users in Adelaide were considered. However, since no behavioural responses were modelled, the model still contained $M = 6$ regions.

The first stage of the current project was to update and extend the Quiggin (1988, 1991) model in a deterministic setting. In particular, the model now encompasses the entire Murray–Darling system, including the Darling River and its basin as well as the Murray–Murrumbidgee system. In place of the $M = 6$ regions, the extended model has $M = 18$, spatially defined regions corresponding to Catchment Management Authority regions within the Murray–Darling Basin, as defined by the natural resource agencies of the relevant state governments. Region 19 represents urban water use in Adelaide.

The activity mix modelled by Quiggin (1988, 1991) has been extended by the inclusion of four additional commodities that may be produced under irrigation (cotton, rice, grains and vegetables) and the explicit modelling of the dryland production option. As in Quiggin (1991), some commodities have alternative technologies available for production. In the case of citrus, grapes, pasture and stone fruit there are two water application technologies available, corresponding to high water use and low water use. Each has been identified by alternative regional gross margin budgets.

Productivity on each successive downstream block is determined by salinity, which in turn is determined by upstream water usage and natural inflows and outflows.

Quiggin (1988) used a single gross margin budget for each commodity. The extended model uses region-specific gross margin budgets, reflecting differences in production conditions between regions. In addition, information on soil type is used to constrain production areas for specific commodities within regions.

In addition to water, the model inputs include the three classical factors of production: land, labour and capital, and generic cash input, encompassing fuel, fertiliser and so on. A variety of input constraints are considered. Land is constrained by total area, and by soil type for particular commodities. In addition, constraints may be imposed on changes in the total area under irrigation and on the total volume of irrigation consistent with the Cap on extractions imposed in 1995. The supply of operator and household labour is assumed to be constrained in short run versions of the model, but contract labour is incorporated in the generic cash input.

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

3.2 Incorporating uncertainty

The crucial problem in incorporating uncertainty is the specification of state-contingent production activities. For each commodity, we require one or more activities. As noted above, a typical activity will be specified by a choice of *N* inputs, and, for each of the *S* states of nature, a water input and an output for the commodity. If the activity is normalised to require one unit of land, say a hectare, the output is yield per hectare.

A crucial feature of the model is that more than one state-contingent production pattern may be considered for a given commodity. This point is illustrated by the treatment of cotton production. To assist pest management, and sustain soil fertility, cotton is produced on a rotation system, represented here as allowing for two years of irrigated cotton production and one year of dryland agriculture over a three-year cycle. The simplest way of managing such a system is a three-field rotation, in which one-third of the land area is rotated out of irrigation each year. This activity is referred to as Cotton (Fixed Rotation).

We also model an alternative rotation system in which the entire land area is allocated to dryland agriculture in dry years, and to cotton production in wet years. Since this activity requires more active management it incurs a cost penalty relative to the Fixed Rotation activity which has the same average yield. However, if producers face variable state-contingent prices for water (or variable shadow prices associated with constraints), they may choose to adopt this activity. This activity is referred to as Cotton (Flexible Rotation).

The idea that multiple state-contingent activities may be available for the production of a single commodity is what distinguishes the approach put forward here from most previous simulation models that incorporate uncertainty. The standard approach has been to introduce stochastic variation into the outputs of each commodity. This approach allows producers to manage risk by varying their allocation of land between commodities, in the same way as investors can diversify portfolios. Dichotomous choices can also be modelled using the tools of discrete stochastic programming.

The approach adopted here, using the notion of state-contingent commodities, does not require the introduction of explicit stochastic elements, and permits the derivation of standard outputs of programming models such as shadow prices, which have a direct economic interpretation. More generally, as discussed in Chambers and Quiggin (2000), the tools of duality theory are fully applicable in a state-contingent setting. The modelling approach used here allows use of the standard duality concepts associated with linear and non-linear programming.

The modelling approach adopted here begins with published data on gross margins incorporating a recommended water allocation, on the assumption of average rainfall, which defines a non-stochastic activity as described above. Next, using data on the relationship between water availability and yield, a single state-contingent activity can be generated. By considering alternative water use strategies and modelling yield responses, multiple state-contingent technologies can be generated for the production of any given commodity.

An important issue is whether to define states of nature in terms of climatic conditions for the Basin as a whole or in terms of the availability of water to producers. Farm-level modelling is simplest if the state variable is available water and experimental shocks consist of changes in water prices and in the probability of different states. But the availability of water to any one producer is determined endogenously by the decisions of others (as well as the exogenous state variables and the policy decisions used to generate alternative simulations). Hence, it seems preferable to focus on climatic states.

3.3 Solution procedures

In view of the network structure described above, any solution procedure for the model may be derived in two parts, referred to as the single-stage constrained-optimal solution and the network solution.

In the single-stage optimisation problem, conditional on a specification of flows of water and salt into and out of a given region, the optimal allocation of land and water within the region may be determined. Since water usage, salt loads and yields are all exogenous in the single-stage problem; this may be solved using standard linear programming methods.

The network solution for the model as a whole depends on the choice of solution concepts and closure assumptions. These choices determine the flows of water and salt between regions that will be selected from the feasible set. Since the relationships between water, salt and salinity, and between salinity and yield are non-linear, the model as a whole is non-linear.

3.4 The single-stage optimisation problem

In the single stage problem for region k, salt load s_s^k is exogenously given for each state of nature, as is the maximum availability of water in each state of nature, denoted by ϕ_s^k. Hence the salinity level σ_s^k and yield loss vector θ_{rs}^k are also exogenous. In addition, availability of inputs x_n^k is held fixed.

The problem (with superscript k omitted to avoid notational clutter) is to choose the land allocation vector l to maximise

$$E[Y] = \Sigma_r\ \Sigma_s\ \pi_s[((1 - \theta_r(\sigma_s))\ (\Sigma_m\ p_m\mathbf{A}_{rms}\mathbf{l}_r)) - \Sigma_r\ \Sigma_s\ p_s^w\mathbf{W}_{rs}l_r)] - \Sigma_n\ q_n\mathbf{B}_{rn}l_r \quad (5)$$

subject to the constraints

$$\Sigma_r\ \mathbf{B}_{rn}l_r \leq x_n,\ n = 1 \ldots N \quad \text{and}$$

$$\Sigma_r\ \mathbf{W}_{rs}l_r \leq f_s,\ s = 1 \ldots S.$$

That is, the representative farmer seeks to maximise expected profit $E[Y]$ subject to the N constraints on resource inputs and the S state-contingent constraints on water use.

The use of expected profit as the objective implies risk neutrality. However, the state-contingent model can be modified to incorporate risk aversion. Given a von Neumann–Morgenstern utility function u, the objective probability vector π may be replaced by endogenously determined state-claim prices, normalised to add to 1:

$$\rho_s = \pi_s u'(y_s) / \Sigma_t \, \pi_t u'(y_t). \tag{6}$$

In finance theory, these normalised state-claim prices are referred to as 'risk-neutral probabilities'. The risk-neutral probabilities required to solve problems with an expected-utility objective function may be derived iteratively, beginning with the objective probabilities π, then deriving the implied risk-neutral probabilities ρ, and using these in the next iteration. The proposed approach, incorporating the methods of duality theory, is an alternative to the direct approach used by Kingwell (1994) and Pannell and Nordblom (1998), based on Patten *et al.* (1988), in which a non-linear objective function is employed.

The fact that risk aversion may be modelled using standard concepts of economic theory within a linear programming framework illustrates the strength of the state-contingent representation of production under uncertainty. Since standard economic analysis is applicable to state-contingent commodities, the standard interpretations of linear programming solution values and shadow prices are directly applicable, as is the associated duality theory. As argued by Quiggin and Chambers (2006), there is no need to develop a separate theory of production or preference to deal with problems involving uncertainty; the standard logic of choice is fully applicable.

3.5 The second-stage solution

The second stage of the problem involves the determination of water flows and salinity for all regions. A variety of second-stage solutions may be used to close the model described above. For example, water use may be constrained by the Cap, with salinity levels determined as water flows through the network. Alternatively, end-point constraints may be imposed requiring a minimum flow to the sea or a maximum salinity level for water supplied to Adelaide.

Broadly speaking, closure assumptions for a model of this kind may be divided into two classes. Solutions in the first class involve sequential optimisation at each stage of the system. Solutions in the second class consist of global optimisation for the system as a whole.

Under sequential closure assumptions, optimisation is undertaken at each stage, subject to exogenous constraints that are not varied in the optimisation. The specification of the sequential optimisation is similar to that of Hall *et al.* (1991), where the scope of the model has been expanded as stated earlier. In this version of the model, for each catchment, the incoming water and salt levels are determined exogenously by upstream use and natural flows. At each stage, the optimisation yields the allocation of land and water that maximises profit for the catchment within the constraints of available land, technology options and the price settings for inputs and outputs. The objective function evaluates the regional value added for the chosen activities.

The catchments are linked sequentially, on the basis of existing flow patterns. The network captures the cumulative water volume and salt loads from the sources of the system in the Great Dividing Range to the Lower Murray–Darling Catchment that encompasses the South Australian portion of the Basin where the river system joins the sea. Thus, the solution is obtained as the outcome of a sequence of linear programming problems.

In the globally optimal solution, the problem is formulated as a dynamic programming problem, where the catchment areas along the river system take the place of successive time periods in a typical dynamic program. Unlike the sequential optimisation, in this version of the model, the optimal allocations for each of the 19 catchments modelled are determined concurrently. The incoming water and salt levels are treated as endogenous except for the initial conditions. By comparing the results in the two models, the total damage associated with salinity and the losses in asset value due to open access can be estimated.

Whichever closure assumption is used, the model as a whole is non-linear, since it incorporates non-linear relationships between water flow, salt loads, salinity and yields. However, the fact that the allocation of land within each catchment is solved as a linear program, conditional on the water flow and salt load determined upstream, renders the model computationally tractable.

3.6 Data

Data limitations are one of the main constraints in model development. Data on flows of water and salt are derived from the Murray–Darling Basin Commission, supplemented where relevant from various published sources, including the Catchment Management Authority publications. The observed flows arise from existing patterns of land use, and will be changed by alternative patterns of land and water use. The approach used in modelling is to posit ‘natural’ flows in the absence of agricultural production, then to calibrate assumptions about return flows and associated salt loads so that, given existing patterns of land and water use, model flows are broadly consistent with observed flows.

Flow modelling is a complex task, in the light of the complex hydrological issues discussed previously and in the context of the multijurisdictional management of the river system across the Basin. GIS technology has proved valuable in integrating data from different sources, based on inconsistent and non-overlapping divisions of the study area into Catchment Management Areas. For example, the production statistics are based on the 2001 Agriculture

Census (ABS 2004), where data is organised on a Statistical Local Area basis, whereas the water flow data is collected for drainage areas, which have recently been amalgamated to form a series of Catchment Management Authority regions.

4. Solutions

As in Quiggin (1988), two closure assumptions were used, one sequential and one global. In the sequential solution, no restrictions on water use were imposed, except the requirement that extractions should not exceed inflows. This solution represents the outcome in the absence of policy controls (but assuming sufficient irrigation capital to allow extraction of flows in each region). The global solution, also unconstrained, involves maximising the expected surplus generated by the Basin as a whole.

The two cases considered here are not intended to simulate actual outcomes of existing policies. Actual policy involves a range of constraints on water use, the most important of which is the Cap. In simulations not reported in this paper, sequential solutions with constraints defined by the Cap match existing land allocation and water use fairly closely.

The simulations reported in this paper are designed to estimate the scope for welfare improvement relative to a baseline of non-intervention and to indicate how the allocation of water and land in the non-intervention baseline differs from the socially optimal outcome. The modelling analysis suggests that lower levels of water use would produce welfare improvements because of the salinity impacts that accompany higher levels of water use.

State-contingent water use, salinity and revenue in the sequential solution are reported in Table 1a, for each of the regions in the model. The solution is characterised by high levels of use in upstream catchments, particularly in the main segments of the Murray and Murrumbidgee. High upstream use implies low flows and high salinity levels in the Lower Murray–Darling and South Australian sections of the Basin with the result that no irrigated agriculture takes place.

Water use for the global solution is given in Table 1b. The most notable result is that an increased social return could be achieved with a substantial reduction in total water use relative to the sequential solution. This result reflects the fact that, under the sequential solution, large volumes of water are used in activities where the average and marginal product of water is quite low. In the global solution, water is reallocated to high-value uses.

The state-contingent allocation of water is also important. The sequential solution involves large and relatively inflexible extractions of water from the river system and therefore exacerbates the natural variability of flows. The globally optimal solution involves greater flexibility in the use of water in irrigation, and therefore tends to offset natural variability to some extent.

The most important differences between the two solutions relate to salinity levels in downstream regions. Whereas salinity levels in the unconstrained sequential solution (Table 1a) reach levels that are too high to permit agricultural

Table 1a Values of state-contingent solution variables: sequential solution

	Water use (GL)				Salinity (mg/L)				Return ($m)			
Catchment	Normal	Dry	Wet	Average	Normal	Dry	Wet	Average	Normal	Dry	Wet	Average
Condamine	424.2	308.2	429.0	402.4	29.1	48.9	24.2	31.6	253.2	166.3	276.1	242.7
Border Rivers, Qld	248.0	237.6	255.6	248.2	74.0	124.4	61.6	80.4	169.6	127.7	207.6	172.6
Warrego–Paroo	3.5	3.5	3.5	3.5	94.3	163.7	77.8	103.2	1.5	1.5	1.5	1.5
Namoi	567.8	441.9	568.5	542.8	154.1	259.2	128.1	167.3	93.4	63.2	95.6	88.0
Central West	642.7	44.6	651.8	525.8	124.3	211.5	103.1	135.4	177.9	30.9	243.6	168.2
Maranoa Balonne	24.1	24.1	24.1	24.1	85.2	141.3	67.1	91.0	10.4	10.3	10.3	10.4
Border Rivers–Gwydir	566.3	566.4	567.4	566.6	124.8	221.4	102.7	137.5	93.4	88.5	113.1	98.4
Western	0.0	0.0	0.0	0.0	1569.5	4037.7	852.7	1848.1	0.0	0.0	0.0	0.0
Lachlan	820.2	411.7	904.6	763.8	353.6	594.1	294.0	383.8	132.4	–45.4	204.9	118.6
Murrumbidgee	1878.9	1878.9	2262.5	1994.0	24.0	40.4	19.9	26.0	494.7	172.4	748.3	506.3
North East	91.8	92.3	110.0	97.4	38.9	65.7	32.4	42.3	99.7	52.0	143.8	103.4
Goulburn–Broken	1671.8	1687.9	1999.8	1773.4	134.1	225.5	111.5	145.6	428.5	46.8	704.9	435.1
Wimmera	51.0	51.4	61.0	54.1	477.1	980.1	379.7	548.5	13.7	–26.9	30.5	10.6
North Central	336.5	336.5	402.1	356.1	278.9	533.3	227.9	314.5	87.1	9.8	161.0	93.8
Murray	2707.1	2712.9	3252.6	2871.9	243.0	472.8	203.6	277.1	248.6	19.4	345.1	231.7
Mallee	283.2	283.2	339.8	300.2	522.5	1442.1	441.9	682.2	210.8	–1038.6	531.2	57.0
Lower Murray Darling	0.0	0.0	0.0	0.0	630.0	1786.6	516.0	827.1	0.0	0.0	0.0	0.0
SA MDB	0.0	0.0	0.0	0.0	914.9	2832.3	749.2	1248.6	0.0	0.0	0.0	0.0
Adelaide	0.0	0.0	0.0	0.0	1065.4	3536.5	876.0	1502.8	0.0	0.0	0.0	0.0
TOTAL	10 317.0	9080.9	11 832.3	10 524.4					2514.9	–322.1	3817.5	2338.3
FLOWS to SEA	6608.8	1801.8	8384.2	6180.0	1212.4	4283.7	1000.4	1763.1	—	—	—	—

Table 1b Values of state-contingent solution variables: global solution

	Water use (GL)				Salinity (mg/L)				Return ($m)			
Catchment	Normal	Dry	Wet	Average	Normal	Dry	Wet	Average	Normal	Dry	Wet	Average
Condamine	424.2	24.0	429.0	345.6	29.1	48.9	24.2	31.6	276.3	40.1	295.7	234.9
Border Rivers, Qld	248.0	37.9	255.6	208.3	74.0	124.4	61.6	80.4	185.8	39.1	221.4	167.1
Warrego–Paroo	3.5	0.0	3.5	2.8	94.3	163.7	77.8	103.2	1.8	0.0	1.8	1.4
Namoi	567.8	3.7	568.5	455.2	154.1	259.2	128.1	167.3	110.3	–8.9	106.2	85.2
Central West	475.1	57.8	486.7	395.1	124.3	211.5	103.1	135.4	170.5	39.2	227.1	161.2
Maranoa Balonne	24.1	0.0	24.1	19.3	85.2	72.2	67.1	77.2	12.3	0.3	12.0	9.8
Border Rivers–Gwydir	480.6	12.8	483.2	387.8	124.8	184.3	102.7	130.1	109.6	1.1	116.4	89.9
Western	110.2	0.0	110.2	88.2	1160.1	556.8	713.4	905.4	18.6	–2.1	17.0	14.0
Lachlan	416.5	71.8	430.9	351.9	353.6	594.1	294.0	383.8	113.3	–69.7	202.6	103.5
Murrumbidgee	250.7	250.7	300.8	265.7	24.0	40.4	19.9	26.0	414.5	284.6	614.9	448.6
North East	40.7	40.7	48.8	43.1	38.9	65.7	32.4	42.3	94.4	55.4	133.1	98.2
Goulburn–Broken	115.6	115.6	138.7	122.5	134.1	225.5	111.5	145.6	268.3	152.5	378.2	278.1
Wimmera	9.7	9.7	11.6	10.2	477.1	980.1	379.7	548.5	9.4	–17.2	21.8	7.8
North Central	31.6	31.6	37.9	33.5	263.8	485.0	215.3	293.5	65.4	8.1	103.3	65.3
Murray	49.8	49.8	59.7	52.8	198.1	339.1	164.6	216.3	81.0	32.5	117.5	82.2
Mallee	283.2	283.2	339.8	300.2	308.4	529.2	256.3	336.9	521.4	20.9	854.2	521.2
Lower Murray Darling	73.9	73.9	88.7	78.3	354.4	517.3	288.5	367.2	71.3	–49.3	169.9	76.8
SA MDB	302.2	302.2	362.7	320.4	483.7	695.3	393.4	498.9	285.1	–183.4	657.0	303.0
Adelaide	206.0	206.0	206.0	206.0	534.4	756.8	434.8	549.0	87.6	41.2	94.8	80.5
TOTAL	4113.3	1571.3	4386.3	3686.8					2897.0	384.6	4344.6	2828.8
FLOWS to SEA	10 951.4	7058.6	13 596.4	10 966.3	581.1	810.5	472.1	594.3	—	—	—	—

Table 2 Comparison of expected social returns

Catchment	Sequential ($m)	Global ($m)	Change (%)
Condamine	242.7	234.9	−3.2
Border Rivers, Qld	172.6	167.1	−3.2
Warrego–Paroo	1.5	1.4	−6.7
Namoi	88.0	85.2	−3.2
Central West	168.2	161.2	−4.2
Maranoa Balonne	10.4	9.8	−5.8
Border Rivers–Gwydir	98.4	89.9	−8.6
Western	0.0	14.0	NA
Lachlan	118.6	103.5	−12.7
Murrumbidgee	506.3	448.6	−11.4
North East	103.4	98.2	−5.0
Goulburn–Broken	435.1	278.1	−36.1
Wimmera	10.6	7.8	−26.4
North Central	93.8	65.3	−30.4
Murray	231.7	82.2	−64.5
Mallee	57.0	521.2	814.4
Lower Murray Darling	0.0	76.8	NA
SA MDB	0.0	303.0	NA
Adelaide	0.0	80.5	NA
TOTAL	2338.3	2828.8	21.0

Note: NA, not applicable.

use in the South Australian region of the Basin or urban use in Adelaide (particularly in low-flow states of nature), salinity levels in the global solution (Table 1b) are low enough to permit such uses in all states of nature, though with adverse salinity effects in dry states.

Table 2 summarises the differences in the expected value of social returns between the global and sequential solution. Relative to the sequential solution, the global solution involves relatively modest losses in average returns for upstream regions, but yields substantial increases in returns for downstream regions. This demonstrates the upstream–downstream trade-offs in the process of internalising the externalities associated with water use. In this case, the result is exactly what would be expected when an externality is internalised.[3]

Another significant feature of the solution, also observed by Quiggin (1988), is that the social loss associated with the sequential solution, relative to the global optimum, is significantly greater than the value of the direct loss in yield due to salinity. (This loss is not reported in the tables, but can be inferred, for each commodity, from the salinity level.) In the sequential solution, the value of the loss in yield due to salinity is approximately $100 million, but the social loss in the sequential solution, relative to the global optimum, is more than $400 million. The bulk of this loss arises because activities in downstream catchments are not feasible due to high levels of salinity.

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[3] An exception would arise in the case of an inframarginal externality, but this is not relevant here.

Land allocations for the two solutions are given in Table 3a,b. The sequential solution is fairly similar to the existing allocation of land. In the absence of a Cap on extractions, water-intensive land uses, including cotton, rice, irrigated wheat and irrigated pasture for dairy production, dominate the solution.

The global solution differs from the sequential solution in several respects. The area irrigated declines, with land being returned to dryland production. Rice production disappears altogether. This reflects the fact that rice production is modelled using a relatively water-inefficient technology, which becomes unprofitable as the shadow price of water increases. Endogenous adoption of more water-efficient technology might lead to an outcome in which rice production is maintained. Similarly, activities like irrigated wheat production and irrigation of dairy pasture, where the average and marginal product of water are low, drop out of the optimal allocation. However, land withdrawn from irrigation may be used to produce the same commodities without irrigation.

In the sequential solution, water is too saline for urban use by the time it reaches South Australia. By contrast, the global solution allows urban use in Adelaide.

High-value uses such as grapes expand, as would be expected with an increase in the availability of irrigable land as other activities decline. Finally, and most significantly in terms of the state-contingent representation, whereas the fixed rotation technology for cotton production is dominant in the sequential solution, only the flexible rotation technology is used in the global solution.

These results represent long-term solutions for an aggregate model, in which a range of simplifying assumptions have been made. Capital is assumed completely flexible in the long run. Only limited account has been taken of heterogeneity in land, climate, operator skills and other variables that may affect land allocation within a region. Similarly, there is only limited modelling of the possibility of endogenous adoption of water-saving irrigation technology in activities such as rice production, though there is no difficulty, in principle, in taking this possibility into account. Furthermore, the global solution is based on the assumption of socially optimal systems of state-contingent water rights and smoothly functioning markets without transactions costs. Although rights are more clearly specified than in the past, and transactions costs are declining, these conditions are not fully realised.

Thus, the global solution derived here implies more radical adjustments in land and water use than would be observed under feasible improvements in policy. In particular, the total area irrigated declines substantially, and irrigation is focused on high-value activities. Nevertheless, the direction of adjustment is consistent with the results of microeconomic analysis, and broadly similar to that derived from previous modelling exercises such as Quiggin (1988), Hall *et al.* (1991, 1994), Bell and Heaney (2001) and Peterson *et al.* (2004).

Table 3a Land allocations ('000 ha): sequential solution

Catchment	Citrus	Grapes	Stone fruit	Cotton flexible	Cotton fixed	Rice	Wheat	Dairy	Adelaide water
Condamine		4.8		23.2	56.8				
Border Rivers, Qld	1.3	6.3		2.1	39.9				
Warrego–Paroo					0.7				
Namoi		0.7		18.0	62.6				
Central West		7.2	4.4	77.7					
Maranoa Balonne					4.8				
Border Rivers–Gwydir			2.6		80.2				
Western									
Lachlan		10.7		41.7			105.4		
Murrumbidgee		43.5				11.5	405.1		
North East		7.4						10.5	
Goulburn–Broken		21.0						320.9	
Wimmera		1.8						8.5	
North Central		5.7						84.7	
Murray	8.3					174.3	379.0		
Mallee		51.5							
Lower Murray Darling									
SA MDB									
Adelaide (GL water)									
TOTAL	9.6	160.6	7.0	162.7	245.1	185.7	889.4	420.6	

Table 3b Land allocations ('000 ha): global solution

Catchment	Citrus	Grapes	Stone fruit	Cotton flexible	Cotton fixed	Rice	Wheat	Dairy	Adelaide water
Condamine		4.8		80.0					
Border Rivers, Qld	1.3	6.3		42.0					
Warrego–Paroo				0.7					
Namoi		0.7		80.6					
Central West		11.6		54.2					
Maranoa Balonne				4.8					
Border Rivers–Gwydir		2.6		66.8					
Western				15.7					
Lachlan		14.4		35.2					
Murrumbidgee	33.0	10.6							
North East		7.4							
Goulburn–Broken		21.0							
Wimmera		1.8							
North Central		5.7							
Murray	8.3								
Mallee		51.5							
Lower Murray Darling		14.8							
SA MDB		55.0							
Adelaide (GL water)									206.0
TOTAL	42.6	208.0		380.1					206.0

5. Applications

The first applications of the model described here have been to the analysis of alternative policies regarding water rights and water prices, and the implications of those policies for the sharing and management of risk, in particular the issue of designing water rights to respond to variations in aggregate supply. Freebairn and Quiggin (2006) consider two options: a single category of water right with proportional adjustments of all allocations, and a system of high-priority and low-priority rights. Freebairn and Quiggin conclude that, in a model with two states of the world, the system of priority rights is unequivocally superior. In an agricultural system with a higher proportion of production derived from long-lived perennial assets with high initial investment costs, such as horticulture, the potential benefits of such a system cannot be over-emphasised.

The analytical approach used by Freebairn and Quiggin (2006) does not extend easily to a framework with more than two states of the world and multiple classes of property rights. For these purposes, a simulation model like that described in this paper is more appropriate. Adamson *et al.* (2006) present simulation results consistent with the conclusions of Freebairn and Quiggin (2006).

6. Concluding comments

The problem of uncertainty is a central issue in the sustainable management of the Murray–Darling Basin. Farmers and other water users adopt a range of strategies to manage and mitigate uncertainty. The state-contingent approach provides the best way to model flexible responses to uncertainty and the effects of alternative property rights regimes. The aim of this paper is to show how the state-contingent approach can be used as a basis for simulation modelling. The model extends the previous work, such as that of Quiggin (1988, 1991) and Hall *et al.* (1994) by incorporating all catchments of the Basin within a single modelling structure and by providing an alternative conceptual basis to incorporate risk and uncertainty in linear programming models for policy analysis.

There is significant uncertainty regarding the quality and consistency of information on the availability of water across the Basin. In particular there is inadequate information on the relationship between different components of the water cycle, including rainfall, evaporation, transpiration, surface runoff and groundwater, and the associated changes in salt loads. While current research is attempting to address these uncertainties, farmers and other resource managers need to take decisions on enterprise choice involving longer term investments within an uncertain set of state variables. The state-contingent approach to modelling decision making under uncertainty being developed in this project aims to provide a decision framework suitable for policy analysis to address these strategic issues.

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