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

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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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Abstract

The Murray–Darling Basin comprises over 1 million square kilometres; it lies within four states and one territory; and over 12,800 gigalitres of irrigation water is used to produce over 40 per cent of the nation's gross value of agricultural production. 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 nonlinear 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.

Key words: Irrigation, Uncertainty, Salinity

Modelling basin level allocation of water in the Murray–Darling Basin in a world of 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, stretches through four eastern Australian states and the Australian Capital Territory and covers an area the size of France and Spain. It supplies almost three-quarters of Australia's farm irrigation water and produces around 40 per cent of Australia's gross value of agricultural production, worth about $9 billion a year.

The central problems of the Basin arise from the rapid expansion of irrigation during the 20th century. By the time a Cap was imposed on diversions in 1995, 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.

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 for water for the environment; and the separation 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’[2]), and raised concerns about 'stranded assets'[3] 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 entitlement holdings, 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

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

[3] Capital assets are said to be ‘stranded’ when regulatory changes reduce demand, driving returns below the cost of capital. The issue is discussion, in the irrigation context by Freebairn and Quiggin (2006a).

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 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. Nonlinear 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). Discrete stochastic programming methods have used a state-contingent representation of uncertainty, but have not exploited the full power of the Arrow–Debreu notion of state-contingent commodities. Important applications of discrete stochastic programming to Australian agriculture include Brown and Drynan (1986), Kingwell (1992) and Kingwell et al. (1993).

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. Griffith and O'Donnell (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 nonlinear 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.

The paper is organised as follows. Section 2 gives a brief overview of relevant characteristics of the Murray–Darling Basin with a primary focus on agricultural production. Section 3 gives a formal description of the model. Section 4 describes the implementation of the model and the data used in its construction. Section 5 presents results for sequential and global solutions. Section 6 describes possible applications and future developments. Finally, some concluding comments are given.

2. Agriculture in the Murray–Darling Basin

The Murray–Darling Basin is Australia's most important agricultural region. The Basin is the largest drainage region in Australia, spreading over 14 per cent of the surface area of Australia.

FIGURE 1 NEAR HERE

Table 1 provides a summary of land and water use in the Basin.

Table 1: Irrigation in the Murray–Darling Basin 2001

Commodity	**Area#** (Ha '000)	**Water Use*** (GL)	**Gross Value*** ($ million)
Pasture	926.8	3,849.7	94.1
Cereals	452.4	3,301.1	263.4
Cotton	416.3	2,798.9	979.6
Rice	182.1	2,360.5	322.3
Grapes	121.2	651.9	2,044.0
Stone & Pome Fruit	47.1	161.7	552.6

Vegetables	43.2	256.8	105.7
Citrus	33.5	252.7	150.2
TOTAL	**2,222.6**	**13,633.2**	**4,511.8**

adapted from ABS 2004
* derived from collected gross margin budgets by Risk and Sustainable Management Group, University of Queensland.

While irrigation systems provide a means of transferring water from areas of high runoff to the drier lowland plains, quality and availability of water cannot be guaranteed during droughts. For example, in the Lower Murray–Darling, the average annual rainfall is about 300 millimetres, and the average evaporation rate is about six times higher than the average rainfall. Summers are hot, with temperatures often reaching more than 40ºC.

The geological history of the Basin, coupled with an arid climate, predisposes much of the region's irrigated land to salinity. Where rainfall is insufficient to wash natural salts below the soil profile, rising watertables induced by heavy irrigation can bring the salts back to the root zone. Clearance of deep-rooted trees and perennial plants also causes saline watertables to rise. This process is normally referred to as 'dryland salinisation' but it also takes place in irrigated areas, and amplifies the effects of irrigation in raising water tables and bringing salt to the surface.

Return flows from irrigated areas and natural runoff mobilise salts, which are carried into the river system and its reservoirs. As salt builds up in the system, and the water becomes saltier, the salt is redistributed across the landscape through irrigation, leading to a salt build-up in the most productive soils of the Basin (Cullen 2001). Therefore, the dynamics of rainfall, runoff, and salt inflows and outflows act as a dynamic constraint on the productive capacity of the Basin. These effects vary across the Basin, reflecting local conditions, farming systems, the land and water management regimes adopted, and the engineering works designed to regulate salt and water flows. Climate variability and change further complicate these dynamics.

The model described in the next section captures the key attributes of this complexity at a scale relevant for Basinwide exploration of policy options to enhance net social benefits from the use of water in the Murray–Darling system.

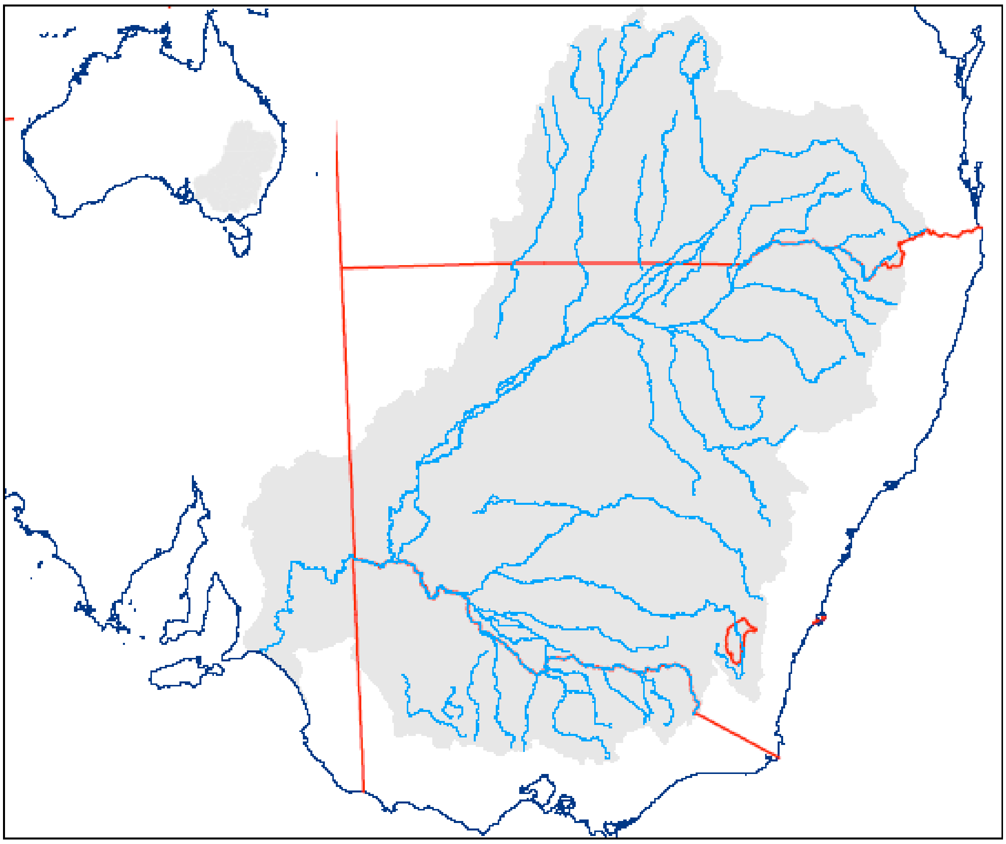

Figure 1: The Murray–Darling Basin

Source: The Murray–Darling Basin Commission (www.mdbc.gov.au)

3. Formal model description

A range of models 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 land returns, and dryland and instream salinity under various water use scenarios. All these models however were restricted to the southern Murray Darling Basin. Of these models, that of Hall et al is closest to the approach taken in Quiggin (1988, 1990) and extended here.

The basic model

The river system is divided into regions $m = 1...K$. 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 and state of nature is measured by a flow variable 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.

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.

Activities

In each region, land is allocated across A_k different activities. For one hectare of land an activity is represented by:

(i) outputs of each state-contingent commodity (dimension M×S);

(ii) water use in each state of nature (dimension S); and

(iii) other inputs (dimension *N*).

In general, then, an activity is represented by (N+S) + (M×S) coefficients. However, we will simplify by assuming that each activity produces only one commodity output, differentiated by the state of nature, so that the number of coefficients is N+2S. Hence, for each region k, the matrix of activity coefficients has dimensions Ak × (N+2S).

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 practices, such as drip irrigation and high density plantings, that reduce return flows and affect farm output and profitability.

Changes in salt loads

The main interaction between producers arises from the fact that changes in salinity levels, arising from the decisions of upstream water users, affect crop yields for downstream irrigators. The model therefore incorporates 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. Constraints on water availability will be determined by the interaction between upstream water use, institutional arrangements and policy variables.

The model is solved on an annual basis, taking such variables as the level and salt concentration of water tables 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.

4. Model implementation

Model Design

The illustrative model of Quiggin (1988) specified:

M = 6 (The six regions were sections of the Murray.);

Q = 1 (Salinity was the only quality variable.);

N = K = 4 (The four commodities were grapes, citrus, stone fruits and pasture.); and

S = 1 (The model was deterministic.).

Inputs were land, labour, water and other, with separate constraints on the availability of water, of operator labour and of land for horticultural and other crop activities.

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 place of the $M = 6$ regions, the extended model has $M = 19$, corresponding to catchment management regions in the Murray-Darling Basin, defined by natural resource agencies of the relevant state governments (region 19 represents urban water use in Adelaide).

In particular, the model now encompasses the entire Murray–Darling system, including the Darling and its basin as well as the Murray–Murrumbidgee system. The associated network of flows is illustrated in Figure 2.

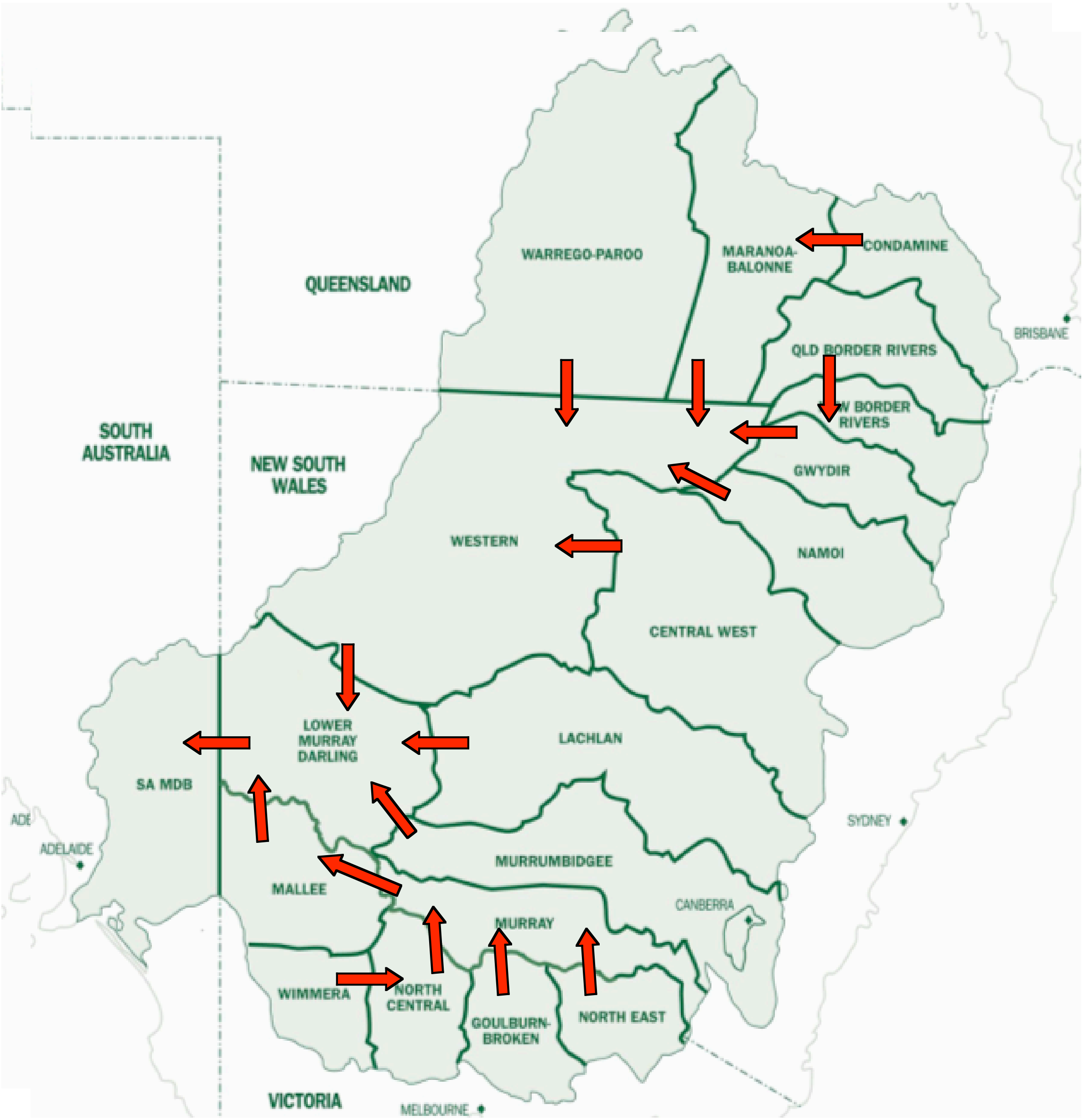

Figure 2 Modelled flow pattern for the Murray–Darling Basin

The model includes 18 representative farm blocks corresponding to Catchment Management Authority regions within the Basin.[4] The activity mix modelled by Quiggin (1998, 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.

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

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 gross margin budgets.

Incorporating variability

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 this and other respects, geographical information system (GIS) technology has proved valuable in integrating data from different sources, based on inconsistent

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[4] Although the Australian Capital Territory is a separate Catchment Management region, for the purposes of this model it has been amalgamated with the Murrumbidgee catchment. The Border Rivers and Gwydir catchments are also combined because they were, until recently, managed by a single Catchment Management Authority.

and overlapping divisions of the study area into data units.

In addition to water, the model inputs include the three classical factors of production: land, labour and capital, and a generic cash input. 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.

In general, input and output prices are assumed to be the same in all regions. However, the model allows for various different rules for setting water prices.

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.

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, as in Kingwell et al (1993).

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 by 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.

Implementation

Two closure assumptions are considered : sequential and global 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.

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 18 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.

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 Agriculture Census, 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.

5. Sequential and globally optimal solutions

Following Quiggin (1988), two closure assumptions were used. The first, referred to by Quiggin (1988) as the open access solution involved sequential optimisation at each stage of the system, with upstream catchments being solved first. No restrictions on water use were imposed. This solution, which will be referred to as the sequential solution, represents the outcome in the absence of policy controls (but assuming sufficient irrigation capital to allow extraction of flows in each region).

The second solution concept referred to by Quiggin (1988) as the global optimum or common property solution involves maximising the expected surplus generated by the Basin as a whole. This solution will be referred to as the global solution.

The two cases considered here are not intended to simulate actual outcomes of existing policies. Rather they 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. Actual policy involves a range of constraints on water use, the most important of which is the CAP. However, the modelling analysis suggests that lower levels of water use would produce welfare improvements.

State-contingent water use, salinity and revenue in the sequential solution is reported in Table 2a, 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 river with the result that no irrigated agriculture takes place.

TABLE 2A NEAR HERE

Water use for the global solution is given in Table 2b. The most notable result is that an increased social return could be achieved with a substantial reduction in total water use. 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.

The state-contingent allocation of water use is also important. The sequential solution involves large, and relatively inflexible extractions of water from the river system and therefore exacerbates the relative 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 relate to salinity levels in downstream regions. Whereas salinity levels in the unconstrained sequential solution reach levels that are too high to permit agricultural or urban use (particularly in low-flow years), salinity levels in the global solution are below 800mg/L, generally considered the limit for potable water, in all states of nature.

TABLE 2B NEAR HERE

Table 3 summarises the differences in objective functions. The global solution involves relatively modest losses in average returns for upstream regions, but yields substantial increases in returns for downstream regions. This is exactly what would be expected when an externality is internalised.

Another significant feature of the solution, also observed by Quiggin (1988) is that the social loss associated with the open access 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.

TABLE 3 NEAR HERE

Land allocations for the two solutions are given in Tables 4a and 4b. The sequential solution is fairly similar to the existing allocation of land. In the absence of a Cap on extractions, water-intensive land uses 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 flood irrigation technology. 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. 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.

TABLES 4A and 4B NEAR HERE

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 water-saving irrigation 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 Bell and Heaney (2001), Hall et al (1991, 1994), Peterson et al (2004) and Quiggin (1988).

6. Applications

The first applications 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 (2006b) 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 (2006b) 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, Mallawaarachchi and Quiggin (2006) present simulation results consistent with the conclusions of Freebairn and Quiggin (2006b).

A second potential area of application concerns climate change. Climate change not only leads to changes in the probability distribution of aggregate rainfall, most probably in the direction of greater variability through high intensity events, but also to increased subjective uncertainty. This raises complex policy issues regarding the allocation of risk as foreshadowed in the National Water Initiative. Modelling will assist our understanding of these issues and provide useful insights into policy development.

7. 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. The approach used to develop the model in two software systems, GAMS and Excel, has been advantageous both in development and in application.

The results presented, though only preliminary, imply that the worst case scenarios predicted under climate change will have differing implications for different parts of the Basin. The distribution of costs and benefits will depend on the way in which the principles set out in the National Water Initiative are implemented.

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, mainly the water balance influenced by rainfall, evaporation, transpiration, surface runoff and groundwater, and on the way in which dryland salinity and rising water tables interact with irrigation-related salinity.

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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Table 2a: Values of state-contingent solution variables: Sequential solution

Catchment	Water Use (GL)				Salinity (mg/L)				Return ($/m)			
	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**	1,569.5	4,037.7	**852.7**	**1,848.1**	$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	1,878.9	1,878.9	**2,262.5**	**1,994.0**	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	1,671.8	1,687.9	**1,999.8**	**1,773.4**	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	2,707.1	2,712.9	**3,252.6**	**2,871.9**	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	1,442.1	**441.9**	**682.2**	$210.8	-	$531.2	**$57.0**
Lower Murray Darling	0.0	0.0	**0.0**	**0.0**	630.0	1,786.6	**516.0**	**827.1**	$0.0	$0.0	$0.0	**$0.0**
SA MDB	0.0	0.0	**0.0**	**0.0**	914.9	2,832.3	**749.2**	**1,248.6**	$0.0	$0.0	$0.0	**$0.0**
Adelaide	0.0	0.0	**0.0**	**0.0**	1,065.4	3,536.5	**876.0**	**1,502.8**	$0.0	$0.0	$0.0	**$0.0**
TOTAL	**10,317.0**	**9,080.9**	**11,832.3**	**10,524.4**					**$2,514.9**	**-$322.1**	**$3,817.5**	**$2,338.3**
FLOWS to SEA	**6,608.8**	**1,801.8**	**8,384.2**	**6,180.0**	**1,212.4**	**4,283.7**	**1,000.4**	**1,763.1**				

Table 2b: Values of state-contingent solution variables: Global solution

Catchment	Water Use (GL)				Salinity (mg/L)				Return ($/m)			
	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**	1,160.1	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	**4,113.3**	**1,571.3**	**4,386.3**	**3,686.8**					**$2,897.0**	**$384.6**	**$4,344.6**	**$2,828.8**
FLOWS to SEA	**10,951.4**	**7,058.6**	**13,596.4**	**10,966.3**	**581.1**	**810.5**	**472.1**	**594.3**				

Table 3: Comparative values of objective function values

Catchment	**Sequential**	**Global**
Condamine	**$242.7**	**$234.9**
Border Rivers, Qld	**$172.6**	**$167.1**
Warrego–Paroo	**$1.5**	**$1.4**
Namoi	**$88.0**	**$85.2**
Central West	**$168.2**	**$161.2**
Maranoa Balonne	**$10.4**	**$9.8**
Border Rivers–Gwydir	**$98.4**	**$89.9**
Western	**$0.0**	**$14.0**
Lachlan	**$118.6**	**$103.5**
Murrumbidgee	**$506.3**	**$448.6**
North East	**$103.4**	**$98.2**
Goulburn–Broken	**$435.1**	**$278.1**
Wimmera	**$10.6**	**$7.8**
North Central	**$93.8**	**$65.3**
Murray	**$231.7**	**$82.2**
Mallee	**$57.0**	**$521.2**
Lower Murray Darling	**$0.0**	**$76.8**
SA MDB	**$0.0**	**$303.0**
Adelaide	**$0.0**	**$80.5**
TOTAL	**$2,338.3**	**$2,828.8**

Table 4a: 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									
TOTAL	**9.6**	**160.6**	**7.0**	**162.7**	**245.1**	**185.7**	**889.4**	**420.6**	

Table 4b: 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									206.0
TOTAL	**42.6**	**208.0**		**380.1**					**206.0**