Modelling basin level allocation of water in the Murray Darling Basin in a world of Uncertainty

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Abstract

The Murray-Darling Basin comprises over 1 million km^2; it lies within four states and one territory; and over 12, 800 GL of irrigation water is used to produce over 40% of the nation's gross value of agricultural production. This production is used by a diverse collection of some-times mutually exclusive commodities (e.g. pasture; stone fruit; grapes; cotton and field crops). The supply of water for irrigation is subject to climatic and policy uncertainty. Variable inflows mean that water property rights do not provide a guaranteed supply. With increasing public scrutiny and environmental issues facing irrigators, greater pressure is being placed on this finite resource. The uncertainty of the water supply, water quality (salinity), combined with where water is utilised, while attempting to maximising return for investment makes for an interesting research field. The utilisation and comparison of a GAMS and Excel based modelling approach has been used to ask: where should we allocate water?; amongst what commodities?; and how does this affect both the quantity of water and the quality of water along the Murray-Darling river system?

Key words: Water, Uncertainty, Salinity, GAMS v EXCEL & Optimisation

Introduction

With the arguable 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 area involved, over one million square kilometres, encompasses much of Eastern Australia and covers an area the size of France and Spain, stretching through four states in eastern Australia and the Australian Capital Territory. It consumes almost three-quarters of Australia's farm irrigation water and produces around 40% of Australia's gross value of agricultural production worth about $9 billion per annum.

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.

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[*] Views expressed here do not represent that of the Australian Government Department of Agriculture Fisheries and Forestry, where Thilak Mallawaarachchi is also affiliated.

The resulting problems included increasing 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 (COAG) agreeing 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, significant progress has been made to date in all areas of water reform. In particular, the policy and institutional settings are now significantly different from those in 1994, where trading of water entitlements have improved and water allocation decisions at all levels now include consideration of implications on the environment. Moreover, changes such as cost recovery in irrigation supplies and the opportunities for trading water entitlements have led to improvements in water use efficiency.

The 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. Similar to other irrigation schemes across the world, the Basin’s 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, thus sustaining the problem that it was meant to solve. Incentives to reduce water use have encouraged farmers to minimise return flows, thereby reducing available supplies for others. The introduction of trade in water rights has led to the activation of previously dormant ‘sleepers’ and ‘dozers’, and raising concerns about 'stranded assets' and implications for future funding of regional irrigation infrastructure.

Changing community values, incorporating a greater appreciation of the natural environment, rising value of water entitlement holdings, and possible reduction in inflows because of climate change, etc have highlighted the need to continue to pursue water sector reform. In particular, COAG 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 are embodied in the *National Water Initiative (NWI)*, signed in June 2004 following the commitments from state and federal governments, made in August 2003, for a substantial funding allocation of $500 million over 5 years. During the 2004 election period, State and Territory governments withdrew from discussions on implementation of the NWI, expressing concerns with funding issues relating to the Australian Water Fund and the future of National Competition Policy (NCP) payments after the current NCP arrangement ends in 2006. However, it seems likely that these disputes will be resolved by negotiation, and that the reform initiatives will proceed with the support of all Australian governments.

The *National Water Commission Act 2004* (Cth) became effective on 17 December 2004, paving way for the establishment of the National Water Commission (NWC) as an independent statutory body for driving the national water policy reform agenda. A key function of the NWC is to implement the NWI and to advise the Commonwealth and the COAG on national water policy reform.

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 increasing and the tension between the consumptive and environmental uses of water more widespread, uncertainties attached to the availability of water in its alternative uses and implications on different use patterns on 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 impact on 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 the uncertainties attached to the behavioural patterns of variables. 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.

Despite its theoretical advantages, empirical applications of the state-contingent approach have been slow to arrive. Griffith and O’Donnell (2004) show how a state-contingent approach may be applied to the estimation of production frontiers, and Chambers and Quiggin (2005) examine asset pricing. Rasmussen (2003) examines input demand.

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, rather than a detailed scale-model of the system to be used as a basis for forecasting. In this case, the main concern is with policies to allocate and manage risk.

At present, the model is under development. The first phase of the modelling project has been completed with the extension and generalization of Quiggin (1988, 1991) to develop a basin-wide optimisation model incorporating all Catchment Management Authority (CMA) regions in the Basin. The incorporation of state-contingent uncertainty is still in its early stages. The purpose of the present paper is to describe the design of the model and to provide some preliminary results to illustrate modelling objectives.

The paper is organised as follows. Section 1 gives a brief overview of relevant characteristics of the Murray-Darling Basin with a primary focus on agricultural production. Section 2 gives a formal description of the model. Section 3 describes the implementation of the model and the data used in its construction. Section 4 presents some preliminary results. Section 5 sets out the research and development program for the project. Finally, some concluding comments are given.

1. 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% of the surface area of Australia. Much of the landscape is characterised by extensive plains intersected by rolling hills, and lies predominantly below the 200-meter isoheight. The rivers largely originate at the steep mountains of the Great Dividing Range, which also defines the southern and eastern border for the basin. Irrigated farming on the river valleys of the Murray and Darling, and its tributaries are vital for the Basin's agriculture industry because the interior of the country, west of the dividing range is largely arid (Figure 1).

The development of a public irrigation infrastructure, comprising of a series of tanks, barrages and a network of irrigation canals provided the basis for the Basin's irrigation industry since 1880. Historically, the major activities included horticulture, primarily producing citrus, grapes, stone fruits and pome fruits, and irrigated pasture for dairy, beef cattle and fat lamb production. More recently irrigated rice and cotton have emerged as significant activities on land previously used for pasture and cereal crops. Wine grapes are one of the fastest expanding irrigated crops in Australia and in the Basin, where the area of irrigated grapes has increased from around 40,000 ha in 1990 to 125,000 ha in 2000. Despite these changes to irrigated land use, a high proportion of the irrigation water in the Basin is used on crops or pastures which fail to reach their full potential for economic yield. This is particularly true for farms with a mixed range of cropping and non-dairy livestock enterprises, where return on irrigation water is often relatively low (Table 1).

While irrigation systems provide a means to transfer 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 mm, and the average evaporation rate is about six times higher than the average rainfall. Summers are hot with temperatures often reaching more than 40ºC. Moreover, the geological history of the basin, coupled with arid climate predisposes much of the region’s irrigated land to salinity. Where rainfall is insufficient to wash down natural salts beyond the soil profile, rising watertables induced by heavy irrigation can bring the salts back to the root zone. Return flows from irrigated areas and natural runoff mobilise these salts 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 with irrigation, leading to a salt build up in the most productive soils of the basin (Cullen 2001). Therefore, the dynamics of rainfall, runoff, salt inflows and outflows act as a dynamic constraint on the productive capacity of the Basin. These impacts vary across the Basin, reflecting local conditions, farming systems and land and water management regimes adopted and the engineering works designed to regulate salt and water flows. Climate variability and change imposes a further dimension to these dynamics.

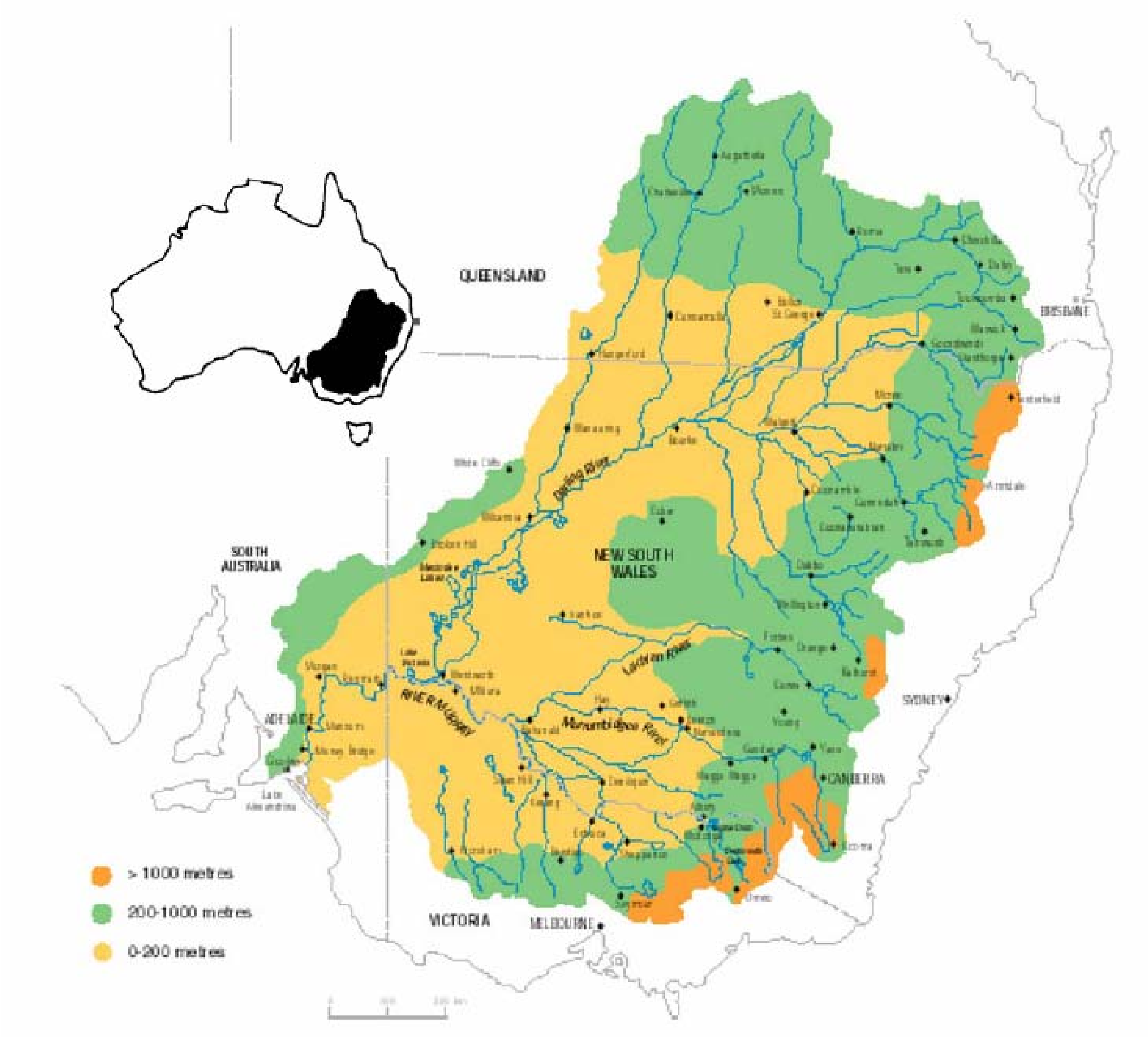

Figure 1: The Murray-Darling Basin

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

While the primary focus of the Basin's initial development was to support a viable economy based on agriculture, the Basin also supports a complex riverine ecosystem and a rich biodiversity on land under both public and private ownership. As identified in the NWI, the challenge for policymakers is to identify and assign various risks attached to management options for the Basin and to manage those risks between governments and water users at present and in the future.

Table 1: Irrigation in the Murray Darling Basin 2001

	Area ha	Water Use Ml	Gross Value $m	Gross margin $ per Ml water
Pasture	926,804	2,757,756	114	26
Cereals	452,446	3,301,061	1,935	120
Cotton	416,282	2,798,902	1,010	379
Rice	182,138	2,360,505	201	138
Grapes	121,202	651,864	1,217	4,198
Stone fruit	47,053	161,728	606	4,966
Vegetables	43,222	256,783	17	373
Citrus	33,505	285,448	103	530

Source: Australian Bureau of Statistics

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.

2. Formal model description

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. 1993.

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.

In each region land is allocated across A_k different activities.

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)

(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).

In the model, the level of water use in a given catchment is the primary decision variable. 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, which reduce return flows and impacts on 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, impact on 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. Similarly, constraints on water availability will also be determined by upstream water use (institutional arrangements and policy variables).

3. 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 land for horticultural and other crop activities and 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 place of the $M = 6$ regions, the extended model has $M = 18$, corresponding to the catchment management regions defined by the State Government natural resource agencies.

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

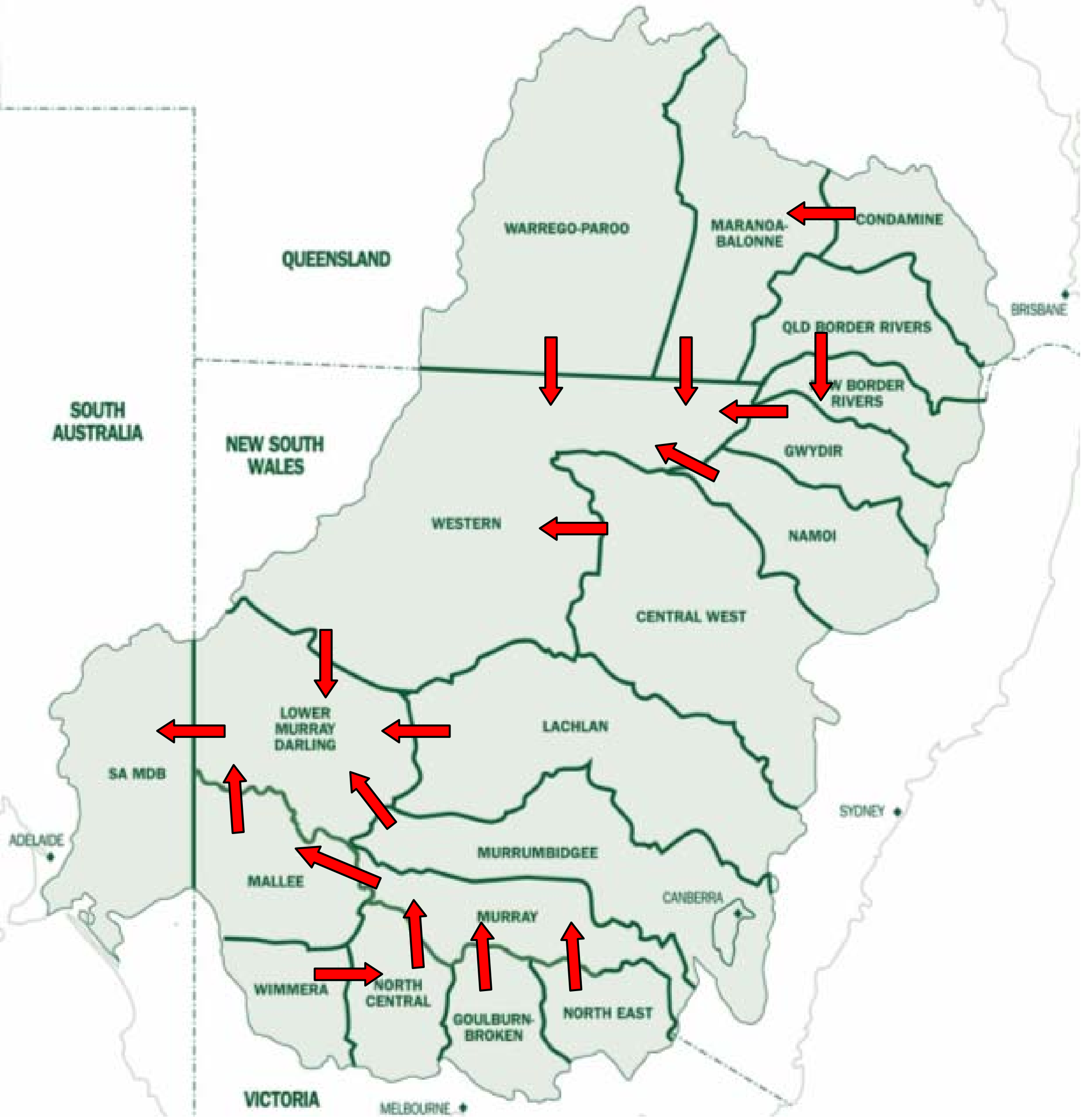

Figure 2 The Murray-Darling Basin Modelled flow pattern

Although ACT is a separate Catchment Management region, for the purposes of this model ACT has been amalgamated with the Murrumbidgee catchment. NSW Catchments Border Rivers and Gwydir are treated as one as the two catchments are managed by a single

Catchment Management Authority since recently.

The model includes 18 representative farm blocks corresponding to Catchment Management Authority regions within the Basin. The commodities investigated include four irrigation crops each at two levels of water use (Table 2). The model of Quiggin (1998, 1991) has been further 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 block downstream is modelled by salinity at each stage determined by upstream water usage and natural inflows and outflows.

Table 2 Commodities Investigated

	Technology & Water Use	
Commodity	Standard	High & Low
Citrus		Yes
Cotton	Yes	
Grains	Yes	
Grapes		Yes
Pasture		Yes
Rice	Yes	
Stone Fruit		Yes
Vegetables	Yes	
Dryland Option		

As in Quiggin (1991), some commodities have alternative technologies available for production. Thus we differentiate between standard technology and a high and low technology option for the commodities. In the case of citrus, grapes, pasture and stone fruit there are 2 major groups of water application technology available in production systems. Each has been identified by alternative gross margin budgets.

Incorporating variability

Whereas 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 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 constraints are considered on inputs.

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 MDBC Cap. 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 flexibility to adopt a range of pricing rules for capital from short run marginal cost (operating cost only) to long run average cost, and imposing appropriate constraints on adjustment, to derive both short-run and long-run solutions.

Implementation

There are two sets of models— open access and common property (Quigin 1998). Under open access, in a sequential linear program that correspond to each stage of the river system, farmers maximise their profits without regard for downstream effects, within the constraints imposed by quality and quantity of incoming water, available technology and other resources. The specification of the sequential optimisation is similar to Hall. Mallawaarachchi and Batterham (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 known *apriori* and the optimisation yields the solution for the level of water use 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 sequentially linked on the basis of existing flow patterns and the network captures the cumulative water volume and salt loads from Condamine-Balonne catchment of southern Queensland to the Lower Murray Darling Catchment that encompasses the South Australian portion of the Basin where the river system joins the sea.

Under the common property approach, the resource use pattern that maximises the value of the asset is sought. The problem is formulated as a dynamic programming (DP) problem, where the catchment areas along the river system take the place of successive time periods in a typical DP. Unlike the sequential optimisation, in this version of the model, the optimal allocation for each of the 18 catchments modelled are determined concurrently where the incoming water and salt levels are treated as endogenous except for the initial conditions. The optimisation yields the global solution for the Basin, with the decision variable being the level of water use 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.

By comparing the results in the two models, the total damage associated with salinity related externalities, or the losses in asset value due to open access can be estimated.

Modelling platform - GAMS Vs. Excel

The modelling system is implemented in both GAMS and Excel for reasons of portability and verification purposes. Excel provides an all-inclusive platform, where the optimisation is linked directly to a database containing gross margin data and resource data sets. Outputs can be visually interpreted using built-in graphic functions. The process is automated using Visual Basic scripts providing a simple to use modelling apparatus.

The GAMS platform allows database functionality including direct access to Excel spreadsheets. The model is formulated as a set of abstract equations using indexed sets, leading to a problem formulation that is very close to the formulation using algebraic notations. The algebraic model can be scaled up by changing the dimension of sets that links the equation's parameters and variables.

In this modelling project the combination of GAMS and Excel offer additional advantages. Excel takes in data entry, manipulation and the aggregation of various data sets to the Catchment Management Authority region level. Optimisations are developed in both systems allowing greater opportunities to iron out bugs. Because data appears to be more volatile than the problem structure, this system allows us to separate data and model structure (Huerlimann 1999), where data management benefits from advanced Excel tools. Whereas, it makes sense to keep the difficult equations making up the optimisation model as a GAMS file, but use a spreadsheet to do initial data entry and to present the final results. GAMS will also offer an effective experimental tool in extending the model to capture stage-contingent uncertainty, as propagating activities is easier in the GAMS format. Nordhaus and Boyer (1999) describe the application of a similar system using GAMS and Excel, in the United Kingdom in global climate change modelling.

Data

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 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. This 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 at a Statistical Local Area (SLA) basis, whereas the water flow data are based on a drainage area basis, which has recently being amalgamated to form a series of Catchment Management Authority (CMA) regions. CMAs are to be used as the unit of management across Australia for all natural resource management planning.

Data represents one of the limiting factors in the model development and the results presented below are based on data constructs for the purpose of illustration only.

4. Preliminary results

We used the non-stochastic version of the basin-wide sequential optimisation model to derive some preliminary results to illustrate functionality and modelling objectives.

Base simulation

In the base simulation, a ceiling is imposed at 2001 levels on the area of irrigated production and the results of the optimal allocation is examined under estimates of farm input requirements and input and output prices for 2001. Inflows of water and salt levels were calibrated to reflect the current conditions.

Within the limitations of the current data sets used, the model reasonably reflects the situation of irrigation agriculture in the Basin at present.

Both water use and gross value of production are largely in the same order of magnitude as those reported by ABS. However, the area under agriculture in the solution is about 1/3 less l than the current estimate based on ABS data (Table 3). This difference is partly because the gross margin data reflects recommended management practices, whereas the management practices vary widely within an area represented by a Catchment Management Authority region. It should be noted that the solution reflects an optimal allocation that maximises regional net returns, within the information set used. As discussed earlier, there is considerable variability in farm performance across the regions and some land uses currently in place in the catchment are not economically optimal.

A notable feature is that the area of cotton, grapes and vegetables in the optimal solution is considerably closer to the current level. This indicates that the management practices and performance levels are less variable within these industries compared to highly variable pasture and cereal cropping activities. Notably the area under rice was also lower than the current level, which can also be explained by the relatively low gross margins associated with rice farming (Table 1). Lower citrus area in the model solution is a reflection of both the relative profitability of grapes, due to its low water use and the fact that as salinity levels build up as water moves down the Basin, citrus yields are affected by salinity making it less attractive in the southern catchments.

Simulated reduction in inflows

Drought conditions as experienced recently across the Basin can impact on inflows to the river system. Although such changes are not usually uniform across the Basin and flows can be regulated using storages and barrages, simulation results of a uniform reduction in inflows are of interest.

As reported in Table 4, a uniform 20 per cent reduction in inflows to the system across all CMA regions resulted in a 15 per cent reduction in total water use and a 7 per cent fall in regional value added. This was due to land use switching over to more water efficient and high value activities with the reduced availability of water.

The impact on salinity levels of a 20% reduction in flow was negligible, although at a higher level of reduction in availability, the salinity levels fall slightly, in particular in some southern regions. This is due to lower return flows, which reduce the rate of salt enrichment in the system. This result is consistent with the observations during the 2003-04 drought (MDBC 2004). In simulations that included a dryland activity, a striking feature is that for some regions, reduced water supplies could increase the gross value of production, as production under low water use technologies become feasible and optimal as water is becoming a limiting factor and losses in irrigation are partly offset by increasing areas under dryland activities.

Table 3: Illustrative Land Allocation Under the Base Solution (ha)

Catchment Management Authority Region	**Cereals**	**Vegetables**	**Grapes**	**Cotton**	**Rice**	**Pastures**	**Stone fruit**	**Citrus**	**Total Used**
Condamine	18489	2017	199	40017	0	873	0	0	61595
Border Rivers Qld	2298	0	659	31241	0	1542	0	2530	38270
Warrego Paroo	0	0	0	541	0	0	0	3	544
Maranoa Balonne	0	0	337	34418	0	0	0	0	34755
Border_Rivers_Gwydir	0	0	103	91745	0	0	0	0	91848
Namoi	0	630	210	101938	0	0	0	0	102778
Central West	4098	1482	4157	58952	56	10794	0	1796	81335
Western	102	0	189	14780	0	93	0	125	0
Lachlan	0	3988	2965	0	0	42379	0	0	49332
Murrumbidgee	125831	6669	13749	66	79125	52093	2692	8075	288300
Murray	0	2494	1654	6	0	123433	0	0	127587
North East	0	0	3452	0	0	9572	335	542	13901
Goulburn-Broken	0	4298	2269	0	0	123382	2760	0	132709
Wimmera	353	32	959	0	0	4090	0	0	5434
North Central	0	2419	900	0	0	12358	222	0	15899
Mallee	0	0	19630	0	0	0	0	0	4815
Lower Murray Darling	4115	518	8278	7935	0	4719	0	1992	27557
SA MDB	0	16619	67187	0	0	40307	0	0	124113
Total Basin	**155286**	**41166**	**126897**	**381639**	**79181**	**425635**	**6009**	**15063**	**1230876**
Total Basin - ABS	**441044**	**41369**	**114897**	**405489**	**178151**	**806219**		**64438***	**1924984**

* All fruits excluding grapes

Table 4: Impacts of a Change in Water Availability on Water Use and Salinity Status and the Value of Production

	Water Use GL		Salinity mgL^{-1}		Gross Value $m	
Catchment Management Authority Region	Base	-20%	Base	-20%	Base	-20%
Condamine	278.0	222.4	29	29	151	139
Border Rivers Qld	199.6	199.58	73	73	133	133
Warrego Paroo	2.7	2.72	89	89	2	2
Maranoa Balonne	173.0	138.4	39	38	121	99
Border_Rivers_Gwydir	642.5	611.2	98	98	213	203
Namoi	718.0	574.4	154	154	241	194
Central West	639.8	605.6	122	122	280	276
Western	106.3	106.31	158	154	40	40
Lachlan	541.0	432.8	352	352	180	160
Murrumbidgee	2865.3	2531.2	24	24	791	767
Murray	1501.0	1200.8	273	267	331	275
North East	129.6	129.61	50	50	71	71
Goulburn-Broken	1531.0	1224.8	121	121	332	274
Wimmera	54.1	54.09	391	391	19	19
North Central	167.0	133.6	247	247	46	39
Mallee	53.0	42.4	416	408	178	145
Lower Murray Darling	208.9	168.8	262	258	269	268
SA MDB	767.0	613.6	297	297	917	889
Total Basin	**10577.9**	**8992.3**			**4315**	**3994**

5. 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).

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. However, in these models, there is no possibility of managing the risk associated with the production of any particular commodities.

The approach planned here will begin 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. Some preliminary results of this approach is presented in this paper. Next, using data on the relationship between water availability and yield – a water production function, for a particular irrigation activity, a single state-contingent activity can be generated.

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.

Thus, on full development, the model will provide a basis to evaluate likely irrigator behaviour under different states of nature for climate (rainfall distributions) and technology options for using available land and water in irrigation enterprises. Because of the linked water quantity and quality flows through the water distribution network, the model can explore implications for downstream water users of decisions made upstream.

Proposed applications

Initially, the main area of application will be the analysis of alternative policies regarding water rights and water prices and the implications of those policies for the sharing and management of risk. As an example, consider the issue of designing water rights to respond to variations in aggregate supply. Freebairn and Quiggin (2004) 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 the system of priority rights is unequivocally superior, in a model with two states of the world. 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 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 will be more appropriate.

A second 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.

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 regime. 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 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 development and application view points.

The results presented, though only preliminary, imply that the worst case scenarios predicted under climate change will have differing implications on different parts of the Basin, with those catchments with higher salt loads are likely to face reduced options to manage, unless opportunities become available to reduce salt loads significantly. Those industries already adopting near-precision agriculture enjoy the first mover advantage in securing water rights and allocating water to its best use. However, sustaining returns on their investment may rest on decisions by their upstream counterparts who can influence the salinity levels of the water they use.

At the present time there is significant uncertainty around the quality and consistency of information on the availability of water across the Basin. This uncertainty is particularly acute for the relationship between different components of the water cycle, mainly the water balance influenced by rainfall, evaporation, transpiration, surface runoff and groundwater.

While current research is attempting to address these uncertainties (John Sims, Bureau of Rural Sciences, personal communication, February 2005[1]), 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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