Development of an Integrated Modelling Framework to Investigate Environmental and Economic Management Objectives in an Irrigated Landscape

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EXTENDED ABSTRACT

Water resources can be considered as either developmental or mature when referring to their level of exploitation. A mature management setting is characterised by high levels of competition between conflicting demands and increasing negative externalities of use. Careful management is required to try and maintain the ongoing economic, environmental and social viability of the system reliant upon the resource.

In recent times, policies for managing rivers in this mature state have shifted from those focussing on traditional ‘hard’ infrastructure-based approaches to considering ‘soft’ policies aiming to change the behavioural practices of water users. Various economic instruments can be used as this mechanism for behavioural change.

In Australia, many rivers are now at a point where the impact of externalities generated by irrigation appear to threaten the viability of social, environmental and economic systems reliant on the water resource. One impact that is had an increasingly large effect on other users of the system is higher river salinity levels due to increased infiltration in the catchment as a result of wide-spread irrigation activity.

Several ‘soft’ management policies have been debated in managing salinity in Australia’s Murray-Darling Basin (MDB) including widespread water trading on both a permanent and temporary basis and financial incentives for increasing on-farm water use efficiency.

This paper describes the development of a model that aims to provide policy makers with a tool to investigate the sensitivity of the modelled system to different parameters describing management policy options. The aim of the model described in this paper is not to provide a highly calibrated predictive output, but a virtual laboratory to investigate which areas may require further detailed data collection to better understand the impacts of proposed policies.

The integrated modelling framework represents the exploited river system with three interacting subsystems: the environment, the actor, and the regulator. Each of these subsystems is broken down further into components describing a particular part of the system; for example climatic processes, groundwater processes and the decision processes of the farmer.

The model describing the decision processes of the farmer is based upon the long-run resource allocation decision relying on the outcome of short-term resource use decisions. The long-run decision is described as a series of processes including self-assessment, identification of potential investment options, analysis of these potential options, selection of the most appealing option and implementation of this option.

To simulate the potential impact of different levels of irrigation water delivery pricing on several indicators of economic and social system state, the integrated modelling framework was implemented using Cormas. Preliminary results suggest that moderate levels of water delivery pricing are likely to maintain the economic efficiency of water use while limiting the number of farmers who are forced to leave the industry due to limited economic viability.

The integrated modelling framework will be used to further investigate the sensitivity of the river system to alternative policy options for managing salinity resulting from irrigation. A key part of this work will look at the effect different representations of farmer decision-making processes on model output.

1. INTRODUCTION

Water resources, such as exploited river systems, can be categorised as being in either a developmental or mature management setting (Randall, 1981). Typical characteristics of river systems in a mature management setting are the escalating competition between demands for an increasingly scarce resource and generation of significant externalities resulting from use of the water. It is becoming increasingly obvious in countries such as Australia, Chile and the United States that many of the river systems relied upon to support economic, environmental and social systems are entering this mature phase (Bjornlund et al., 2002; Quiggin, 2001).

As rivers enter this mature phase, careful management is required to ensure that irreversible damage to associated economic, environmental and social systems are minimised. Water resource managers now realise that in isolation, 'hard' infrastructure or technology based approaches are not always an effective way to manage highly exploited water resources and that one of the most fundamental necessary changes in management involves policies aimed at changing attitudes, behaviours and the perception of the value of water, often through the implementation of economic instruments designed to influence water users (Crase et al., 2000). One of the difficulties in defining these so-called 'soft' management policies is the uncertainty involved with predicting the actual impact these policies will have on system state. Unlike infrastructure designed to interact with a relatively well understood environmental system, soft policies rely on the interaction of human agents to be effective.

As an example, many of Australia's river systems currently support both urban and rural economies through industry and agriculture. To most Australians, the Murray-Darling Basin (MDB) has become the best-known example of water resource degradation that threatens the viability of these systems. The MDB is a prime example of high levels of competition for water and some of the more severe environmental externalities associated with irrigation, including salinisation.

River salinisation in the Murray-Darling system is a naturally occurring phenomenon. Replacement of native deep-rooted vegetation with shallow-rooted crops has lead to an increase in recharge to the naturally saline aquifer. This recharge has changed most dramatically in areas near the river that have been subjected to further increases in infiltration due to the application of irrigation water sourced from the river. The increased recharge has lead to widespread aquifer mounding, resulting in increased discharge of the naturally saline groundwater to the river.

The dynamics of salt discharge into the river is highly complex and variable on small spatial and temporal scales, however at the macro level, trends indicate that river salinity is indeed increasing due to irrigation activity within the catchment (Knight et al., 2005). The increase in water salinity has had well-documented effects on the users of the water, from decreasing the useful life of machinery to increasing irrigation water requirements to maintain crop health and yields.

Water management policy debate in the MDB has shifted in recent years towards the widespread adoption of economic-based management tools. Policy documents such as the *National Water Initiative* and *National Plan for Water Security* (Commonwealth of Australia, 2007) place tools such as water trading and economic incentives for increased on-farm water use efficiency at the centre of the policy reform process.

Many of these policies aim to act directly on the decisions that irrigators within the system make when trying to make best use of their resources. Not only is it unclear how effective each of the possible policy options will be in managing the various environmental externalities associated with irrigation, but also how the economic and social state of the system may change in response to these changes. It is important that policy makers are aware of potential system responses to changes in the policy environment and to gain an understanding of the complex nature of the system they manage.

2. OBJECTIVES

The objective of the work described in this paper was to develop a model of a river system that is exploited for irrigation purposes that would allow for testing of assumptions made about the behavioural response to economic-based management policies. The model is based on the situation in the MDB with a focus on salinity management policy options. The purpose of this work is not to create a highly calibrated predictive model, but a virtual laboratory facilitating the exploration of system sensitivity to model assumptions and thus hopefully highlighting potential 'sweet spots' for developing effective and efficient management policy. This is particularly important when potential policies are likely to be implemented over large geographical areas with numerous actors. In these situations, there is significant difficulty obtaining rich, high resolution data that describe the human aspects of the system over a significant period of time. This is often compounded by the cross-jurisdictional nature of water resources.

3. INTEGRATED SIMULATION MODEL

3.1. Model Framework

The integrated model framework is an application and extension of the conceptual model described in Rowan et al. (2005). Figure 1 shows the representation of the modelled system within this framework.

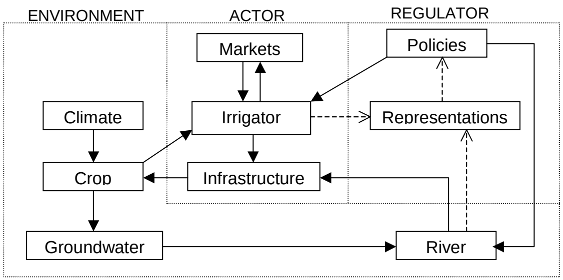

Figure 1 Integrated simulation model framework

At a high level, system components can be classified as belonging to one of three subsystems, those of the environment, actor and regulator. Components of the environmental sector of the system include not only the river but the climate, crop and groundwater processes also. The climate is considered exogenous to the system, but combined with the dynamics of the crop components, they provide the primary driver for irrigation by the human actors in the system.

The actor sector includes not only the individual irrigators, but also the infrastructure used by them to utilise environmental resources (eg water, crops), and the markets on which they rely to sell their crops and invest in resources.

The solid arrows in Figure 1 illustrate the direct flow of resources, for example the irrigator's financial investment in irrigation infrastructure which allows him to irrigate his crops with water from the river. It is the duty of the regulator to influence the interdependent actor and environmental systems by observing their condition (shown by the dashed lines) and implementing policy that meets their objectives (by adjusting the constraints upon operations, and condition of, the irrigator and river). In a situation where there are large differences in the temporal dynamics of the environmental feedback process (as is the case for groundwater – surface water interactions) then it is the link between the regulator's observation of system conditions and the implementation of management policies that provide the strongest influence on the behaviour of the actors within the system

The climate model provides the key exogenous drivers to the irrigated farming practices in the model. Annual rainfall and evaporation data are generated using a Markov time-series model as described in Grayson et al. (1996) which are then passed to the crop model.

The crop model is based on a modified version of the yield model used by Letey et al. (1986). The model takes into account both the volume of water available to the crop from irrigation and rainfall, and the level of sailinity of the water to predict crop yield and therefore water use. A simple water-balance approach is taken to determine the recharge to groundwater resulting in irrigation of the crop. Crop yield is also affected by the age of the crop. Yield reduction factors are used to incorporate losses of crop productivity based on both the immaturity of young crops and declining vigour of older crops.

The groundwater discharge model describes the relationship between groundwater recharge at a location within the system and corresponding discharge at the river. The model is based in the Unit Response Equation approach by Knight et al. (2005). Some modification of this approach was necessary to allow for non-uniform recharge conditions.

Markets for water (both permanent and temporary entitlements), land and crops are considered as exogenous to the systems model. This is based on the assumption that the portion of the overall physical system modelled using this framework is not so large to create distortion of these markets.

Representation of the irrigators as human decision makers requires the abstraction of information from varied data sources ranging from narrow-scope attitudinal surveys to broad-scale spatial data sets. In many cases (such as in the MDB), comprehensive data specifically describing irrigator decision making processes are not readily available. In such cases it is necessary to make assumptions on the behaviour of the actors within the system. In this instance, the description of the irrigator decision making model is described in more detail in the following section.

This system lends itself well to the use of an agent-based modelling architecture. Where many past modelling efforts investigating integrated water resources management have used highly aggregated spatial scales and relied on assumptions of rational economic behaviour and perfect knowledge on the part of the irrigator, the ABM approach allows for consideration of spatial and temporal heterogeneity both in the specification of actor decision rules and actor state.

3.2. Irrigator Decision Model

All farmers face decisions on how to best invest in infrastructure in an effort to optimise farm outcomes with reference to their own management objectives. This process is constrained by the availability of resources, particularly capital and knowledge. The availability of these resources to each individual farmer will change over time depending on the ongoing performance of his farm operation and his awareness of the state of the system his farm is part of.

Considered in isolation, the farmer's long-term decision process is based on the performance of his own short-term management decisions and his perception of the system around him as shown in Figure 2. The circular arrow on the short-run resource use decision indicates that several of these decisions may be made in series in between long-run resource allocation decisions.

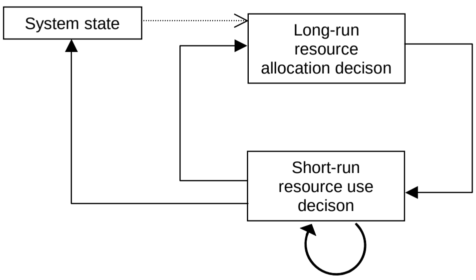

Figure 2 Irrigator decision process

For the purpose of this paper, it is assumed that a farmer's short-run resource use decision is based on the decision of how much irrigation water to apply to his crop. It is assumed throughout this paper that a farmer will apply the lowest level of irrigation water that will allow the seasonal evapotranspiration needs of his crop to be fully met. The long-run resource allocation decision can be further broken down into five constituent processes, as shown in Figure 3. These processes are further described below.

Self Assessment

The self assessment stage enables the temporal aspects of system dynamics to be incorporated into the farmer decision making model by providing an up-to-date basis upon which he can compare the expected performance of any alternative resource allocation decision with his existing farming strategy. This is achieved by periodically updating the attributes that describe the condition of each farmer. There are two components to the updating process. Firstly, the financial state of the farmer is considered, followed by the farmer's perception of the state of the system.

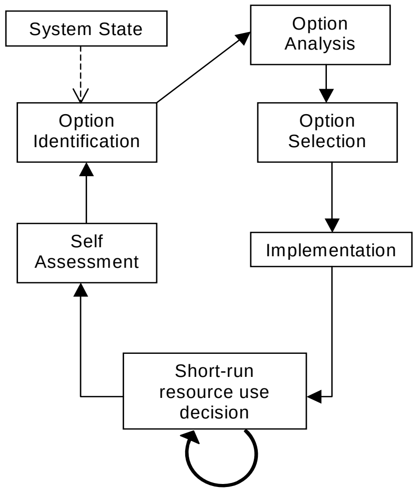

Figure 3 Long-run resource allocation decision of the irrigator

The financial state of the farmer is based on the net value of assets owned by the farmer, and his cash bank balance. In this model it is assumed that a farmer owns his own land and water entitlement separately, both of which can either appreciate or depreciate in value over time. The other asset belonging to a farmer with salvageable value is the irrigation infrastructure on his farm. It is assumed this infrastructure depreciates exponentially with time over the maximum possible life of the initial investment.

The cash bank balance of each farmer is updated after each annual time step based on the profit (or loss) made in the previous farming season. Farmer revenue is assumed to be only from income derived from the sale of crops resulting from the farm operation. Annual costs of operation are split into fixed and variable components.

Fixed costs are those relating to the initial investment in the current farm operation including land, irrigation infrastructure, crop plantings and ownership of an appropriate level of water entitlement. The fixed costs are amortised over the maximum life of an investment by the allocation of a bank loan covering these costs, which must be serviced by the farmer on an annual basis. The fixed cost component also includes a fixed labour cost which is assumed to be the minimum annual income requirement for the farmer.

Variable costs are based on typical operating values of a farm operation growing a particular type of crop and using a particular type of irrigation infrastructure, along with costs that are directly attributable to the application of irrigation water. These variable irrigation water costs are dependent on the volume of irrigation water applied by the farmer over a growing season and include the cost (revenue) associated with buying (selling) access to irrigation water on a temporary basis, cost from delivery charges demanded by the resource manager, and energy requirements for running irrigation the system depends on the physical location of the farm operation.

The perception of system state each farmer has is dependent on which parts of the system are known to the farmer. In this application of the model, as the system size is small (20 farmers), it is assumed all farmers are known to each other.

Option Identification

The purpose of the option identification process is to generate a set of possible alternative investment options for each farmer. The set of possible investment options is a function of the knowledge a farmer has (ie which options are known to him) and his ability to finance investment in any of them.

The construction of a set of known alternative options for each farmer is achieved using a process based on that described by Berger (2001) where the level of implementation of a technology across the system defines whether or not a farmer of particular receptiveness to innovation is aware of it. In this case, the farmer has sets of known crop types and irrigation application technologies to select from.

From within the set of known investment options, there exists a subset of potential investment options available to the farmer to select from at any time. In this model, the set of potential options takes one of two forms. In situations where a farmer's access to cash is below the expected costs of operation for upcoming season, the farmer can only consider selling some of his existing assets to raise cash. Otherwise, a farmer is able to potentially invest in any option he knows about.

No matter what the current financial standing of the farmer, the subset of potential investment options includes quitting farming and investing the proceeds off-farm.

Option Analysis

Using the set of potential options identified in the previous step, the farmer must determine what level of investment best meets his objectives for each investment option. In this model, it is assumed that farmers' overriding motivation is to improve their financial standing by maximising profits. The level to which a farmer can invest in each potential alternative option is constrained by rules defining his access to capital to invest and the availability of suitable land adjacent to his current farm operation.

Option Selection

The options (including continuing with the current farm operation) are compared on the basis of their expected equivalent annual worth over the maximum life of the investment.

This individual decision-making process occurs on an annual basis.

4. IMPLEMENTATION AND EXECUTION

The model was implemented using Cormas (Bousquet et al., 1998). Cormas provides a development and execution environment for agent based models of renewable resource systems.

The simulation model was initialised using a hypothetical landscape with conditions typical of those in a general irrigation area in the lower Murray system. Although the parameters describing the spatial landscape of the model were constant between all runs, the initial crop and irrigation type used by each farmer, and their initial endowment of cash, was set using a randomised selection procedure. The model provides three types of crop (citrus, nuts and wine grapes) and three types of irrigation technology (flood, sprinkler or drip) for farmers to select. Each scenario was simulated 100 times with randomised initial conditions.

The simulation model was executed over 100 annual time steps. Although it is unlikely that system conditions would persist for this period of time without changes due to innovation etc., a time series of outputs of this length allow for the comparison of system dynamics under the various scenario conditions.

The scenarios considered in this paper constitute an investigation of the impact that the level of water delivery charges has on several aspects of the social and economic state of the system. The level of water delivery charges considered varied between \$10 and \$100 per megalitre of irrigation water used. Twelve scenarios with varying levels of water delivery charges were executed, however in the interest of clarity, only five runs are presented in this paper.

5. RESULTS AND DISCUSSION

The preliminary results described in this paper give an indication of the impact that water delivery pricing has on several aspects of the economic and social condition of the modelled system, given the assumptions of decision-making processes described earlier.

The results presented in the following figures and used as a basis for discussion in this paper are the twenty-year moving average of model output averaged over 100 simulation runs with randomised initial conditions. This approach was considered appropriate to remove system fluctuation associated with specific annual events and processes whilst providing a reasonable indication of system change over a period that could be reasonably expected as the lifetime of farm infrastructure investments.

As Figure 4 shows, water delivery pricing causes some difference in the system-wide economic benefits derived from the use of irrigation water. It is interesting to note that higher water delivery charges do not necessarily promote higher economic efficiency in the use of water, with only small difference in the per-megalitre value of system output for high and low water delivery charges. Although the simulation appears to show that this indicator is maximised with moderate water delivery charges (near $50/ML), there is no definitive case for selecting this level of delivery charge based solely on this result. What can be taken from these data is that a moderate level of water charge does not appear to have a detrimental effect on the economic value of irrigation water.

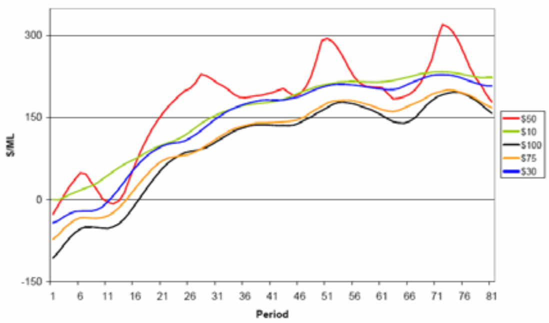

Figure 4 Economic efficiency of irrigation use under various water delivery pricing conditions

Figure 5 shows the number of farms remaining in the modelled system and is an indicator of the rate of farmer exit from the system due to the non-viability of farming options available to the farmer when compared with alternative off-farm investment opportunities. Steeper initial decreases in the number of farms show that the system undergoes a period of more rapid change to adjust to the new conditions described by the model input parameters.

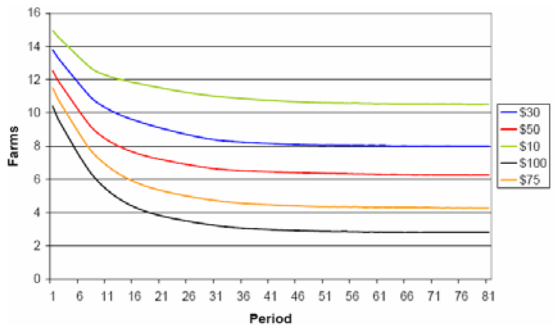

Figure 5 Number of active farms under various water delivery pricing conditions

The number of farms remaining in the system at any point in time is an indicator of the magnitude of forced exits from farming due to economic non-viability of farm operations, or attractiveness of off-farm investment alternatives. The large initial rate of decrease in the number of farms in the system that is evident for each scenario (Figure 5) is a result of the presence of a number of non-viable farms in the initial state of the model. As the initial conditions are similar for each scenario, and the results are aggregated from numerous individual simulations, it can be assumed that the rate of this initial decrease in the number of farms, and the final number of remaining farms, is predominantly dependent on the cost of water delivery.

The output describing the change in the number of farms indicates that higher costs of water delivery can affect the ability of farmers to adjust their farm operations to ensure the ongoing economic viability of their farm.

Figure 6 shows the overall area of land farmed at a point in time in the model system. The graph indicates that a moderate cost of delivery has the least effect on the overall proportion of the model system devoted to farming of crops.

When the modelled area of land under farming is considered alongside the number of farms in the system, the initial decrease in farmed area followed by an increase to levels similar to initial conditions under moderate water delivery pricing, indicates that farm sizes will tend to increase under moderate water delivery pricing. It appears that farm sizes are likely to increase for all scenarios but those with high water delivery prices. This is attributable to the higher capital costs associated with irrigating under these conditions, reducing the rate of accrual of capital available to the farmer for expansion.

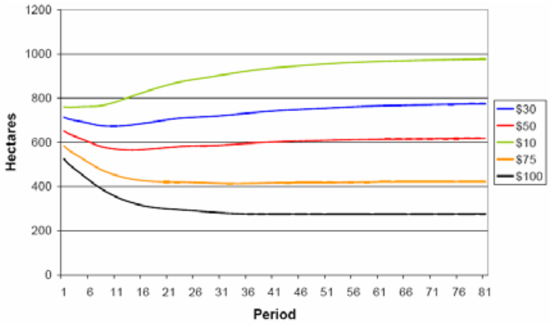

Figure 6 Total area farmed within the system under various water deliver pricing conditions

The overall reduction in farmed area with increased water delivery prices, along with the lack of an obvious relationship between delivery prices and economic efficiency of water use, appear to indicate that the decreased profitability of any alternative farming operation as a result of higher water delivery prices might outweigh the efficiency gains achieved by updating infrastructure. This, when coupled with the continuing economic burden of sunk costs resulting from past long-term decisions, can have a visible effect on the viability of changing to less water-intensive farm operations.

6. CONCLUSIONS

These preliminary results indicate that moderate water delivery pricing is likely to maintain the value of irrigation water use without causing widespread change in other system parameters, such as the area of land devoted to farming and limiting the number of irrigators forced to exit the system.

The results given in this paper are heavily dependent on the assumptions of irrigator decision making methods made in the construction of the model. Further development of this integrated modelling framework will look more closely at how different representations of this part of the system affect the model output.

It is the intention that this model will be further used to identify the sensitivity of system parameters related to the management of salinity from irrigation to those potentially controlled by management policies. It is hoped that this approach will allow for a better understanding of system characteristics and help facilitate the development of effective and efficient salinity management policy.

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