Development of an Integrated Modelling Framework for the Assessment of River Management Policies

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EXTENDED ABSTRACT

Many rivers in developed countries are entering a state where demands on the system are met with diminishing reliability and there are significant negative external effects related to the use of the resource. Careful management is required to ensure that irreversible damage to the economic, environmental and social systems reliant upon these resources are minimised. In an effort to better manage these rivers, water resource managers are no longer turning only to 'hard' infrastructure or technology based approaches in isolation. Other, 'softer' approaches focusing on changing attitudes, behaviours and the perception of the value of water are being considered by managers in conjunction with traditional policies of using infrastructure to alter natural processes.

In order to determine which combination of policies is most likely to meet management objectives, river managers require a model capable of representing the relevant system dynamics. Hard management policies have traditionally been modelled using simulation models, whereas policies aimed at altering the decision processes of the actors within the system have commonly been comparatively static in nature, and often use a whole-of-system optimisation approach. These two approaches to assessing different types of management policies do not integrate particularly well.

This paper outlines a proposed conceptual model for an exploited river system and a framework with which to implement the proposed model that will allow for analysis of a combination of both hard and soft management policies.

The proposed conceptual model represents an exploited river system at three levels, those of the regulator, the water user, and the environment.

A river manager represents the regulator level of the system. The river manager has both environmental and economic objectives. The set of management policies available to the manager to try and meet these objectives is set by the modeller. Sharing information between the river manager and irrigator allows management policies aimed at altering water use behaviour to be tested along with more traditional infrastructure-based policies implemented directly by the river manager.

By representing irrigators at an individual level, the proposed conceptual model allows for overarching assumptions of water user behaviour used in the past to be replaced with more realistic behavioural models. Using multiple instances of the irrigator agent, and an explicit spatial representation of environmental processes, facilitates heterogeneity of water user behaviours within the system.

In order to implement the proposed conceptual model, a model framework has been developed using an agent based architecture. The framework is developed using Cormas, an agent based modelling platform using the SmallTalk object oriented programming language. The basic Cormas classes have been further developed to represent the agents in the conceptual model and their behavioural processes. The framework allows the modeller to specify the manner in which the agents interact so that the proposed conceptual model can be customised. This allows the modeller to identify scenarios where certain river management policies are likely to be more or less effective.

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; Rosegrant et al., 2000).

As rivers and other exploited water resource systems enter this mature phase, careful management is required to ensure that irreversible damage to the economic, environmental and social systems reliant upon them are minimised. Water resource managers now realise that in isolation, 'hard' infrastructure or technology based approaches are not the most 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 (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. The challenge for the water resource modeller is to develop a model framework that will allow for these new management techniques to fit in with already developed physical process models that describe system dynamics.

Models used for water resources policy analysis can be broadly categorised into two groups: optimisation or simulation based (Maidment et al., 1983). Whilst historically popular hard management policies are well suited to being modelled using simulation models, policies aimed at altering the decision processes of the agents have commonly been comparatively static in nature. As softer policies, such as water trading, have been developed, models have tended to use a whole-of-system optimisation approach (Connor, 2003; Hall et al., 1994; Peterson et al., 2004). These two approaches to assessing different types of management policies do not integrate particularly well.

In reality, actors within water resource systems do not behave in a way that can be easily represented as a whole-of-system optimisation problem, as they are far more likely to make individual decisions based on their own experiences and attitudes, rather than in accordance with the greater good (Bossel, 2000). For policy makers to gain an understanding of the dynamics of the system they are aiming to manage, it is essential they have access to models that truly represent the integration of economic, environmental and social systems. The key to this integration is the explicit modelling of human behaviour. By including this behaviour, some of the complex links between water managers, users and the environment can be considered.

The key objective of the work outlined in this paper is to describe an integrated model framework that can be used to assess different combinations of hard and soft river management policies and identify areas in which these policy combinations are most effective. It is important that the framework is capable of considering different external influences on the system, such as climatic and economic perturbations.

2. CONCEPTUAL MODEL

The proposed conceptual model represents a river system in a mature setting, such as that described earlier, at three distinct levels, to which all primary agents within the system can be attributed. They are:

- **Regulator**
  All agents at this level have the ability to impose constraints on the dynamics of the system by bounding available behaviours of agents at the consumer level, or modifying the relationship between components at the environmental level.
- **Water User**
  Water user agents exploit the river to meet some self imposed goal whilst behaving within the constraints imposed by regulator and environmental agents.
- **Environment**
  There are several different types of environmental agent, some reactive (such as crops and surface/groundwater interaction) and some not so (climatic models), however, all are non-cognitive in their dynamic.

Figure 1 shows the main components of the system as represented by the proposed conceptual model. Information flow is shown as dashed arrows, with resource flows (eg. water, capital etc.) denoted using solid arrows.

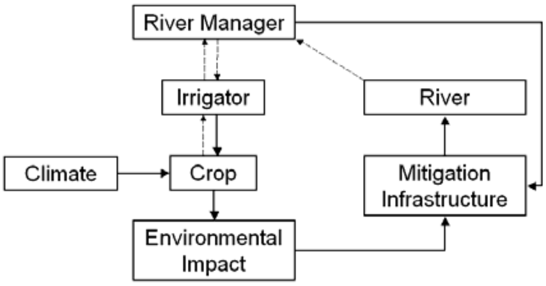

Figure 1 Conceptual model overview

The two cognitive agents within the system are the river manager (the only agent in the regulator category) and the irrigators (the only water users represented). The remaining agents within the system belong to the environmental stratum. Further description of these aspects of the system follows.

Regulator – River Manager

The river manager agent is responsible for formulating a set of operating protocols in order to meet multiple management objectives. The two key objectives of the management regime are to ensure near optimal social benefits are obtained through utilising the river as an exploitable resource (typically measured as an aggregate economic indicator for the whole system) and that the system environmental state is such that indicators are limited to lie within an acceptable range. The primary interactions are with water users (by defining acceptable behaviours) and also the environment (through interaction with and potentially modifying existing environmental processes). Figure 2 shows a schematic of processes at the river manager level.

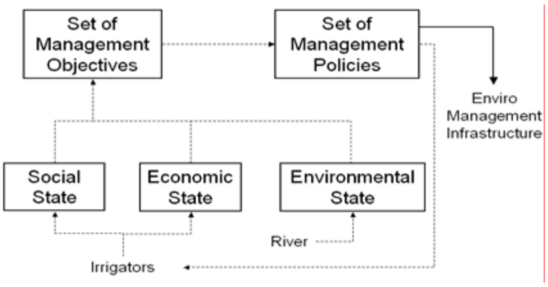

Figure 2 Schematic of system processes attributable to the river manager

The timing of any change that the river manager may instigate is dependent on the feedback of information about the system state to the manager. The primary options available to the river manager for altering system state are:

- Altering environmental processes by intervening in natural process cycles
- Interacting with water users to influence water use behaviours

The framework allows for various combinations of these two approaches by representing the river manager as a separate entity, enabling detailed specification of management approaches and objectives.

Water User – Irrigators

Representation of the irrigator agents is crucial to the validity of the conceptual model. The irrigators are the central actors in the system because agents at both the regulator and environment level shape the set of behavioural options available to the irrigator. One of the necessary interactions within the system if 'soft' policy options are to be modelled realistically is that between the river manager and the irrigator. Figure 3 outlines the structure of the irrigator agent.

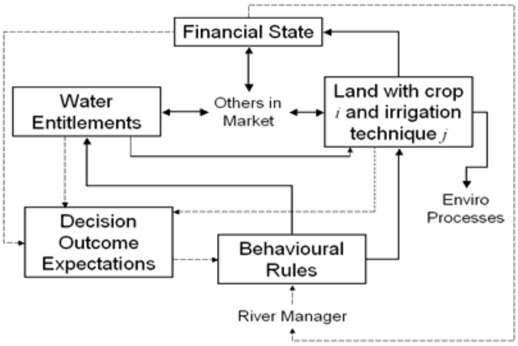

Figure 3 Schematic of system processes at the irrigator level

A defining feature of the irrigator specification is that there are numerous instances of the irrigator within the system. By representing the irrigators at an individual level, it enables the conceptual model to include diversity in water user motivations and situations. This ability to represent heterogeneity in the system is one of the primary advantages of a simulation model framework such as this. In reality, individuals make decisions relating to the way they use resources based on information available to them and a set of decision criteria. Both the decision criteria and information available to the individual are a vary with space and time and other factors.

The conceptual model enables interaction between the irrigators, shown in Figure 3 as 'others in market'. This interaction is the mechanism upon which many soft resource management policies rely to facilitate their implementation. For example, trade in water realistically happens when there is a gradient in both the demand for a resource, and the perceived value of that resource. The magnitude and direction of the differences in demand and individual valuation is dependent on time and location specific conditions that each individual irrigator is faced with.

Utilising an individual approach to modelling water user behaviour allows some of the more drastic assumptions of traditional economic agent modelling to be dropped in favour of a more realistic representation of the water user ‘landscape’ within a river system. In many traditional modelling frameworks, the behaviour of individual irrigators has been aggregated significantly and an optimisation approach at the whole-of-system level has been adopted (Bousquet and LePage, 2004).

The assumption that overarching optimisation approaches are appropriate implies that all actors within the water user sector of the system have perfect access to information and act in a highly rational manner. This leads to their decisions matching those that would provide not necessarily optimal individual outcomes, but those that are optimal at some higher aggregated level. In reality, at any given time, the system is far more likely to be in a significantly sub-optimal state resulting from the summation of decisions made at an individual level. Studies have shown that the motivation for making resource use decisions and participating in information gathering and exchange within a system can vary significantly. For example, Maybery et al. (2005) used survey techniques to illustrate that there were three distinct types of resource user in part of the River Murray catchment, Australia, with correspondingly diverse motivations shaping the way they utilised the water resources available to them.

Recent research has shown that decisions made at the individual water user level are also unlikely to be binary. Studies indicate that assumptions of uniform decision rules and thresholds across a river system are unlikely to be accurate (Tisdell et al., 2003). By including individual representations of water users, the proposed framework allows the use of probability density functions to more realistically represent decision making processes at this level. It also allows for the inclusion of basic ‘learning’ processes that utilise information feedback to individual actors. This feedback facilitates an updating of decision probabilities based on the degree to which expected outcomes of prior decisions match realised outcomes.

Environmental

The environmental processes present in a typical regulated river system are many and varied. They are characterised by their non-cognitive behaviour. Figure 4 shows the components considered in the proposed conceptual model.

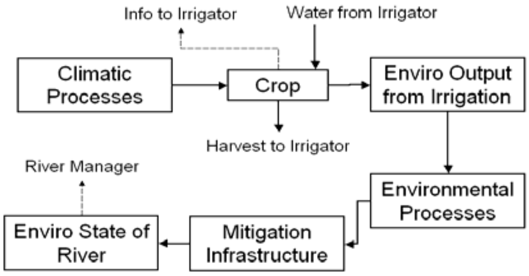

Figure 4 Schematic of environmental processes

Not all components of the environmental system belong to the natural realm. The inclusion of crops and even mitigation infrastructure as environmental agents highlights their interaction with, and influence over, natural environmental processes, even though the extent of these relationships are the result of decisions made within the regulator and water user sectors. One of the most important functions of the environmental components of the model is to provide feedback to other parts of the model on system state.

Both the temporal and spatial scales at which the environmental processes present in the system operate vary quite significantly. That is one of the strongest defining features of an exploited river system. The reason for this is because the basis on which many decisions are made, at both the regulator and irrigator level, are the result of changes in environmental state. These decisions can be made rapidly, however, the outcome of these decisions in meeting environmental objectives may not be known for some time. This is especially true in instances where surface/groundwater interaction is important, as time lags between system input and the corresponding output can be in the order of years to multiple decades. Differences in scale also have a significant influence, because the effects of past water use management policies can be evident for some time after their validity ceases.

3. PROPOSED FRAMEWORK

Model Platform

To implement the conceptual model described in the previous section, it is necessary to use a platform to construct the model framework that will allow for the integration of the components representing the different aspects of the system. Agent based modelling (ABM) platforms offer the ability to create system simulation models that integrate processes at different spatial and temporal scales by using an object oriented programming architecture. This approach allows both human and environmental processes to be represented explicitly.

There are several ABM platforms available. One such platform is Cormas, which has been developed to facilitate the creation of natural resource based dynamic systems models with the specific inclusion of cognitive human agents (Bousquet et al., 1998). Cormas uses the SmallTalk object oriented programming language and provides the modeller with a set of classes that are useful building blocks for models concerning natural resource management.

The Cormas platform allows modellers to represent their system as a set of spatial entities, passive objects and cognitive agents. As the name suggests, spatial entities represent the basic spatial setting of the system and therefore provide the matrix upon which other spatial processes can be represented. Spatial entities can be aggregated at various levels where common attributes and methods are present, allowing for simplification of the entity specification at the lowest, non-aggregated level.

Agents are designed to represent processes associated with individual actors within the system. It is possible for agents to be located either within or outside the spatial setting of the model. It is also possible for individual agents to belong to a group of similar agents that, whilst acting autonomously, are defined by some set of common attributes and methods. Cormas also provides the modeller with the option to define agents as communicating. This allows individual instances of a particular agent type to send messages to each other following a user-defined set of operation rules. These messages (themselves instances of the Cormas message class) can contain information, such as requests and replies, and enable the formation of a social network through which processes, such as trade in goods, can occur.

Representation of non-human agents within Cormas is facilitated by using passive objects. The benefit of using passive objects is that they are an almost blank canvas that inherits only the basic entity specification from the parent class. Again, passive entities can be located within or outside the spatial framework of the model.

Model Framework

It is proposed that the conceptual model outlined in Section 2 can be implemented in Cormas using a framework based on eight types of agent. Figure 5 is a schematic showing the architecture of this framework. The figure shows each agent as a single table. The uppermost division contains the agent name, with the middle division outlining the conceptual attributes of the agent, and the lower division the general methods or actions the agent is able to execute. Linkages denoted in the figure as lighter weight lines represent paths of information flow between instances of different agent types.

The framework was created by selecting the appropriate Cormas class types, and further developing their functionality to match the agents identified within the conceptual model. The type of Cormas class each agent in the framework is based upon is shown in Figure 5 using an arrow. The conceptual model is still in a developmental stage and the final architecture of the model framework will be tested during the calibration stage of application of the framework to a case study.

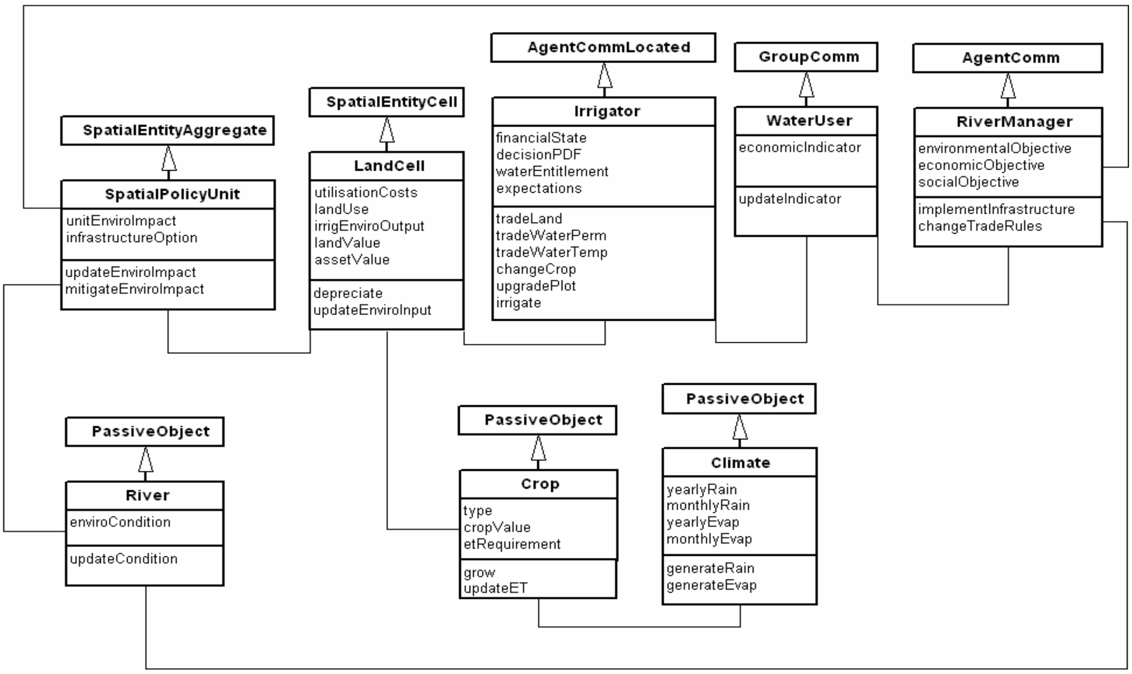

Figure 5 Schematic of model framework developed using the Corrmas platform

The spatial environment component of the proposed framework consists of two distinct spatial entities.. The basic spatial unit of the conceptual model is represented by the LandCell class of object. This object represents the interface of water use behaviour and climatic inputs with environmental outputs. The number of individual LandCell instances that are created to represent the system of interest controls the spatial resolution of environmental processes directly associated with water use.

LandCell is the unit at which the basic input to the environmental system as a result of irrigator behaviour is calculated (using the updateInput method and stored as the environmentalInput attribute). This is a function of the type of crop grown on each cell, the method of irrigation used (together represented as the landUse attribute) and irrigation practices of the irrigator. The relationship between landUse and environmentalInput is specified by the modeller to represent processes such as groundwater recharge or nutrient runoff. Depreciation of crop and irrigation infrastructure is calculated on a cell by cell basis and alters the assetValue attribute of each cell. Land values calculated by the Irrigator as part of the trading process are also stored as an attribute of each LandCell.

Each LandCell belongs to a SpatialPolicyUnit which describes environmental impacts of water use at the same resolution that decisions at the river manager level are made. The individual contributions each LandCell makes to environmental outputs from irrigation are combined for each SpatialPolicyUnit. The relationship between environmental inputs from irrigation at the LandCell level and impacts at the SpatialPolicyUnit scale is defined at this level of the model and calculated using the UpdateEnviroImpact method. Each SpatialPolicyUnit may or may not have some sort of environmental management infrastructure option associated with it. If an option does exist, it may be activated according to management policies defined at the RiverManager level. The operation of the infrastructure must be described by the modeller within the mitigation method of the SpatialPolicyUnit entity.

The SpatialPolicyUnits also supply information to the River object. The river is not represented explicitly as a spatial entity in this model framework based on the assumption that an existing model is available to describe the relationship between the spatially heterogeneous irrigation practices and the river as a whole. This relationship must be specified within the River entity (shown as the enviroCondition attribute and updateCondition method in Figure 5).

Rainfall and evaporation inputs to the system are represented as the Climate passive object. Information is generated using appropriate models specified by the modeller. It is possible to represent the climatic processes as a passive object using the assumption that variation in climatic processes is negligible across the system. Integration of climatic processes occurs through the Crop passive entity. This entity holds the data required to calculate cumulative growth over the cropping season (represented as cropValue and updated using the grow method) on a monthly basis for each of the LandCells. This, along with crop water requirement information, is available to the individual water user (Irrigator) agents responsible for each LandCell, thereby creating one of the vital links in integrating water user decision processes and environmental processes. An appropriate evapotranspiration model must be identified by the modeller and specified in the updateET method of the Crop object.

The water user is modelled using the Irrigator object. Instances of this object are located on the spatial system and are associated with a set of LandCells representing a ‘farm’. The main processes represented within the Irrigator are decisions relating to irrigation practices, and economic decisions, such as trading in land and water entitlements. The dynamics of these decisions are described by a set of decision probability density functions for options available to the Irrigator. The specification of these functions is one of the key inputs on behalf of the modeller. Data describing the decision processes must be extracted from actor behaviours within the system being modelled. The Irrigators are represented by Cormas agents with the ability to communicate by sending messages to a subset of the other Irrigators in order to facilitate trade relationships. The exact specification of the manner in which trade is allowed is a function of the trading rules set by the RiverManager.

Each Irrigator also belongs to a group of agents consisting of all other instances of the Irrigator class. This group (shown as WaterUser in Figure 5) forms the basis of communications with the RiverManager agent, based on the assumption that any policies developed by the RiverManager apply equally to all Irrigators within the system.

Common traits of the WaterUser and RiverManager agents are that both have only one instance, and therefore have no need to be located spatially within the system. The RiverManager entity contains the set of management policies and their methods of implementation as set by the modeller for testing.

4. SUMMARY

In an effort to address environmental and social issues relating to highly exploited river systems, river managers have started to look beyond traditional management approaches to include ‘soft’ economic instruments that are more flexible and have a greater chance to meet sustainability criteria.

In order to assess the effectiveness of these new approaches, a conceptual model has been developed that is able to consider both hard and soft management policies. The conceptual model can be used to give river managers a better understanding of the response of their system to different policy combinations.

The key benefit of using this approach is that it improves on some of the implicit assumptions associated with other non-individual based models. By using an explicit representation of the primary actors within the system, reactions to different environmental and anthropological constraints can be explored. This will allow river managers to gain a clearer understanding of the dynamics of the system they are managing.

Representing decision making at this level in the model framework allows for the introduction of cognitive processes, such as learning and adaptation, which heavily influence the effectiveness of any new policy environment, shaping the way in which the water is used.

The proposed model can be implemented using the agent based modelling software Cormas. Cormas provides the modeller with a set of generic agent types that have been further developed and customised to represent the components of an exploited river system, as shown in the proposed model framework. This framework allows resource managers to investigate the effectiveness of different management policy options, once the specific process relationships within their system have been specified.

The proposed model will be applied to a case study of the River Murray system in southeast Australia. The objective of this study will be to compare scenarios consisting of different ‘hard’ and ‘soft’ management policies on the basis of economic and social costs associated with meeting existing and proposed salinity targets within the system.

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