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Using system dynamics to model water-reallocation

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Abstract Improving the efficiency of water allocation has long been recognised as a key problem for the water resources management decision-makers. However, assessing the efficacy of management decision is difficult due to the complexity and interconnectivity of water resource systems. For this reason, it is vital that robust modelling approaches are employed to deal with the feedback loops inherent in the water resource systems. Whilst many studies have applied modelling to various aspects of water resource management, little attention has been given to innovations in modelling approaches to deal with the modelling challenges associated with improving decision-making.

The aim of this study is to apply a System Dynamics modelling approach to improve the efficiency of water allocation incorporating a myriad of irrigation system constraints. The system dynamic approach allows the different system components to be organised as a collection of discrete objects that incorporate data, structure and function to generate complex system behaviour. Through the application of a system dynamic approach, a robust model (named the Economical Reallocating Water Model (ERWM)) was developed which was used to examine the options of re-allocating water resources that minimize the water cost all over an irrigated agricultural area. The ERWM incorporated a wide range of complexities likely to be encountered in water resource management: surface and ground water sources, water trading between sources, system constraint such as maximum ground water pumping, rates, maximum

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possible trading volumes and differential water resource prices. Two hypothetical systems have been presented here as an example. The results show that the System Dynamics approach has a significant advantages in estimating and assessing the outcomes of alternative water management strategies through time and space.

Keywords Economic water use · Optimization · System dynamics · Water allocation · Water trading and price

1 Introduction

Significant problems of water scarcity and deteriorating water quality are contributing to a growing water crisis in many countries. In the Australian context, these issues have highlighted the importance of appropriate water allocation policy: ensuring that, as far as possible, the available water is allocated to best meet consumptive and non-consumptive uses. For example, in the Murrumbidgee River catchment, there is ongoing examination of how to improve water policy since increased demands for water have led to reduced river flows and a reversal of the seasonal flow patterns (DLWC, 1998).

According to Elmahdi et al. (2005) meeting irrigation demand and achieving positive environmental and economic outcomes requires improved modelling tools to analyse the implications of alternative policies. Therefore, there is a need to explore new modelling approaches to represent the complex relationships found in irrigation systems. One of those promising options is System Dynamics, a feedback-based, object-oriented approach (Simonovic, 2000). According to Simonovic and Fahmy (1999), System Dynamics is based on a theory of system structure and a set of tools for representing complex systems and analysing their dynamic behaviour (from the system structure, generates the system behaviour). The most important feature of System Dynamics modelling is to elucidate the endogenous structure of the system under study, to see how different elements of the system actually relate to one another in the complex system and to test changing relations within the system when different decisions are taken into consideration (Shi and Gill, 2005).

According to Elmahdi et al. (2004) modelling the irrigation system with taken account of economic and environmental aspects is a difficult modelling challenge. The model structure becomes very complex with introducing many factors and their interrelationship. Moreover, irrigation water demand management is a complex issue due to the pressure of uncontrolled variables such as climatic conditions. In addition, assessing the efficacy of management decisions is difficult due to the complexity and interconnectivity of irrigation water systems. Consequently, it is vital that applying a robust modelling approach such as System Dynamics that is able to deal with the feedback loops inherent in the irrigation water systems. Indeed, feed back loops are one of the most important features of System Dynamics.

Nowadays, decision makers are relying on models to help in assessing the impact of options for different water policies dealing with surface water, groundwater and water trading given decisions based on an economic perspective. Moreover, integrated water management in irrigated agricultural areas is the best strategy to improve crop yields and optimise the use of the available water resources (Beddek et al., 2005).

Consequently, the aim of this study is to apply a System Dynamics modelling to improve the efficiency of water allocation incorporating a myriad of irrigation system constraints. The system dynamic approach allows the different system components to be organised as a collection of discrete objects that integrate data, structure and function to generate complex system behaviour. Through the application of a system dynamic approach, a robust model (named the Economical Reallocating Water Model (ERWM)) was developed which was used to examine the options for re-allocating water resources that minimize the water cost all over an irrigated agricultural area considering maximizing the economic return.

The current study is carried out on two hypothetical irrigation areas. The study has been performed using the System Dynamics programming tool VENSIM^{TM} with an optimiser algorithm. The ERWM presented in this paper was developed to determine the amount of irrigation demand, the amount of irrigation water used to satisfy this demand from different water sources under environmental flow constraints, and the economic return.

2 System dynamics modelling approach

Modelling of water resources systems can be undertaken using a variety of different approaches. It is important that an appropriate approach is selected based on the model requirements (in terms of parameters, spatial and temporal resolution), data available, expertise of users and the degree to which processes are understood (series on model choice, 2005).

According to Elshorbagy and Ormsbee (2005); models can be classified according to the processes that they describe as either lumped or distributed; they can be also deterministic, stochastic or mixed; they can be classified into event based, continuos time, and large time scale models; and, models may use analytical or numerical solution techniques. Additionally, models can be broadly classified into data-driven models and mechanistic models. Data driven models, which sometimes called black-box model or empirical models, are usually based on relationships derived from raw data and the formulation. Alternatively, Elshorbagy and Ormsbee (2005) are claimed mechanistic models, occasionally called process-based models, can be highly data-intensive and are frequently over-parameterized. However, they have been found to be useful in a wide variety of applications related to surface water management. A number of physical and process-based parameter values are often required for such modelling and the reliability of the results is questionable in the absence of large data sets.

Elshorbagy and Ormsbee (2005), identified seven specific characteristics for the best modelling approach needed. These characteristics are: (i) any hydrologic system, should be described in a simple fashion; (ii) the model should start simple, relying on the available data and could be extend with more data became available; (iii) the model should be dynamic to handle the dynamic in the system; (iv) the model should be able to represent both linear and nonlinear functions; (v) ability to represent the feedback mechanism between different variables; (vi) ability to measure and simulate human interference and any shocks in the system; and (vii) ability to examine the alternative policy or scenarios. Although it might be impracticable or hard to represent all these characteristics in one modelling approach; the emergence of System

Dynamics modeling within an object-oriented simulation approaches make it feasible (Elshorbagy and Ormsbee, 2005; Simonovic and Fahmy, 1999).

In this study, System Dynamics modeling approach is utilized. A case study is provided to explore some of the capabilities of the technique in irrigation system management, particularly water reallocation policies. Rumbaugh et al. (1991) stated out, object-oriented modeling is a way of thinking about problems using models organized around real world concepts. It is a way to organize software as a collection of discrete objects that incorporate both data structure and system behavior (Simonovic et al., 1997). Data are organized into discrete objects. These objects could be concrete (such as a river gauge or river reach) or conceptual (such as a management or policy decision). The issue of data limitations is significant in modelling irrigation water systems. Frequently, the modelling requirements of decision-makers are difficult or impossible to meet given the data available. However, System Dynamics offers an efficient approach to most effectively utilize available data and understanding of processes.

Elshorbagy and Ormsbee (2005) claimed that, the System Dynamics simulation approach relies on understanding complex interrelationships existing between different objects within a system. This is attained by structuring a model that can be able to capture the behavior of the system. The dynamics of the system could be understood through simulation of the system over time. Describing of the system and its boundaries, by using the main variables and its mathematical functions, which represent the physical processes, to generate the model behavior, is one of the main steps of a System Dynamics model.

3 A typical conceptual model for modelling water allocation

The agriculture sector in Australia consumes about 75% of total available water resources. Crop water requirements depend on many factors such as temperature, humidity, rainfall and evaporation. Typically, cropping patterns and cropping decisions are affected by several factors such as climatic forecasted growing condition and water allocation. Therefore, the cropping pattern of the different cultivated crops under a given allocation is a variable that can be used to improve the productivity of consumed water.

A System Dynamics Economical Reallocating Water Model (ERWM) was developed, based on an economic rationale, to analyse and determine the most economic water use under different water prices in the two hypothetical irrigation areas, which were constrained by environmental flow rules and pumping of ground water (see Fig. 1). Each irrigation areas represented by four crops which the user can change the crop mix between them.

The ERWM has three main components (i.e., agro-climatic, hydrological and economic) that are interconnected. Each component has been modelled and represented by hierarchical decomposition from the subcomponents. The hydrological component represents the hydrological system in terms of surface water, ground water and hydrological constraints of pumping target and channel capacity. The agro-climatic component represents the cropping mix, crop area, evapo-transpiration and rainfall. These two components are linked by the economic component, which controls the

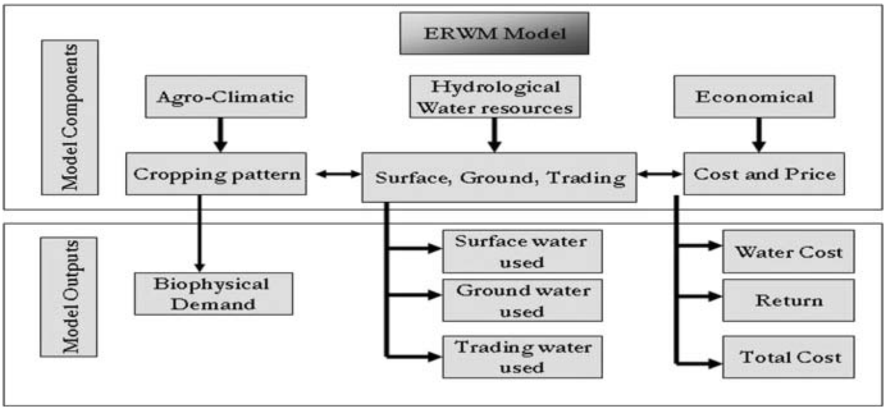

Fig. 1 ERWM model components

water price for each water source (i.e., surface water, groundwater and water from trading). Moreover, calculating the variable cost associated with each water volume from each source has been requested to satisfy the crop water demand and crop return, gross marginal and overall economic revenue.

This model assumes that there are three water sources in each irrigation area (i.e., surface water, groundwater and water from trading market). The model deals with these sources as three water banks with different prices. The model seeks to satisfy the biophysical crop demand by looking for the best economic returns based on the water sources or bank prices of each month. In addition, the model is capable to run what-if scenarios by testing different water prices, different decision rules reflecting how farmers decide on which water source to use to satisfy their demand from an economic perspective, and irrigators can change the crop mix with fixed water price to investigate which mix is the best to achieve high economic return. The outputs of the ERWM include irrigation demand, water cost for volume used from each source, total water cost, total yields, total return, gross margin, surface water used, ground water pumped to match the demand and water purchased from trading.

In this study, the software development tool VENSIM$^{\text{TM}}$ was used to configure the water and economic interrelationships. The Vensim modelling language is a rich and readable way of representing dynamic systems. One feature of the Vensim environment is that it insulates the user from both the underlying mathematics and the details of the language specification. The purposes of using Vensim is to provide a programming environment for model development and help solve problems that would be hard to address mathematically (of complex system relationships) without the aid of simulation.

4 ERWM formulation and application

The ERWM presented in this paper was developed to determine the amount of irrigation water used from different water sources, the irrigation demand and return from each scenario. Physical water demand in irrigation areas can be simulated through the

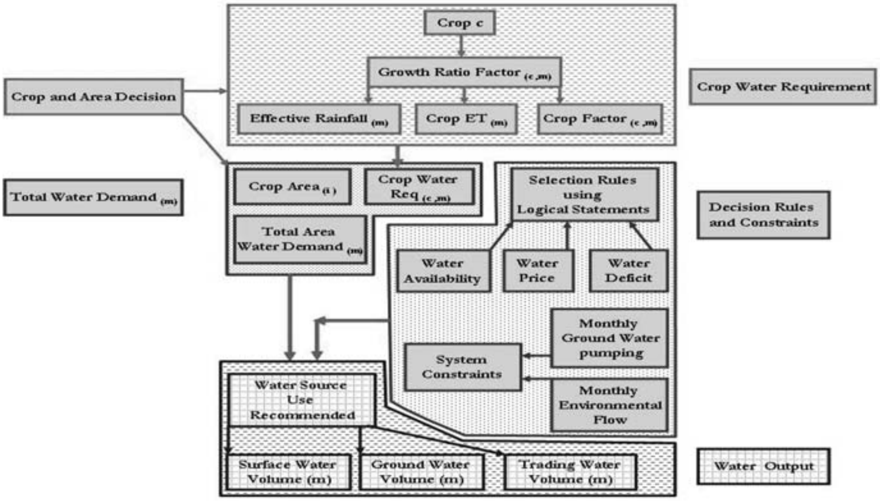

Fig. 2 The ERWM model framework and formulation

model by using a hierarchical decomposition approach to calculate crop water use requirement (based on the cropping pattern or the cropping plan and the total irrigated area) (see Fig. 2).

In this context, the total water requirement from the irrigation area per month is calculated as:

$$T.W_{\text{req}} = \sum_{i} A_c W_{\text{req}(c,m)} \tag{1}$$

where $T.W_{\text{req}(c,m)}$ is the monthly crop water requirement, and $A_{(c)}$ is the cropped area for Irrigation region i. Crop water requirement $W_{\text{req}(c,m)}$ is calculated as a function of crop coefficient, crop growth duration, evapo-transpiration *(ET mm)* and rainfall (mm). The fraction of growth period in a given month for a given crop ($FG.Ratio_{(c,m)}$) will be calculated by:

$$FG.Ratio_{(c,m)} = \frac{G.duration_{(c,m)}}{days_{(m)}} \tag{2}$$

Where $G.duration_{(c,m)}$ is the growth duration of a crop C in month m and Days is the total days of month m. The crop water requirement per mega litre is calculated as follows:

$$W_{\text{req}(c,m)} = Ka_{(c,m)} \times FG.Ratio_{(c,m)} \times ET_{(m)} - FG.Ratio_{(c,m)} \times Rain_{(m)} \tag{3}$$

where $Ka_{(c,m)}$ is the crop coefficient of crop C in month m and $ET_{(m)}$ and $Rain_{(m)}$ are evapotranspiration (using a modified Penman method to calculate ET) and rainfall in month *m,* respectively. After defining the connections between model components, selection rules were incorporated in the model using logical statements of IF-THEN-

ELSE structure. For example, these statements explain that if there is water deficit after using the surface water available in this month and assuming the ground water price is less than the surface water trading price, then any deficit will be satisfied from ground water. If there is still a water shortage the model will look for other water trading options.

The model calculate the water used from each resource, final shortage, water cost and economic return to the region. The variables which are defined by the irrigators to plan his farm are the resource prices and the amount of land in the irrigation area for growing crop c (ha), denoted as A_c.

5 Model results

The model is used to determine the most economical water use with different water prices in two hypothetical irrigation regions that are constrained by supply capacity of the system. Moreover, efficient water use is achieved by changing the crop patterns, while the total irrigation area is unchanged. Four scenarios have been simulated and compared with the base case scenario. Table 1 describes all of the scenarios; the bold line indicates the changes in different scenarios. The base case scenario gives how the system work and what is the profit and economic productivity. According to Beder (1996) economic productivity is one of the measure indicators of the irrigation system. Economic productivity calculates by dividing the profit over total water used.

Figure 3 shows the comparison of total return in scenarios 2–4. It is very clear that the high return ($/ha) comes in scenario 2, which also gives low economic water productivity ($/Ml water used). This is demonstrating high return does not necessarily lead to high economic productivity because of total water use as shown in Fig. 4. Moreover, decreasing the cultivated area of Maize and increasing the area of barley as scenario 2, could achieve high economic return but not high economic productivity even with the same water price and spreading the water peak demand. In addition, the highest net return comes in scenario 1, because ground water price became cheaper than water market trading price.

In addition by changing the price, it is clear the farmer decision on which water source could be used to irrigate his or her farm is changing over time to achieve high economic productivity. Ground water used has increased during the shortage months and water trading use has declined because of ground water bank price is much cheaper than water trading bank price.

Table 1 Base case and scenarios

Scenario	Water market price ($/ML)	Surface water price ($/ML)	Ground water price ($/ML)	Rice area (ha)	Wheat area (ha)	Barley area (ha)	Maize area (ha)	Total area (ha)
Base case	200	20	260	32 000	20 000	18 000	27 000	97 000
SC1	200	20	**150**	32 000	20 000	18 000	27 000	97 000
SC2	200	20	260	32 000	20 000	**27 000**	**18 000**	97 000
SC3	200	20	260	**20 000**	**32 000**	18 000	27 000	97 000
SC4	200	20	260	**18 000**	20 000	**32 000**	27 000	97 000

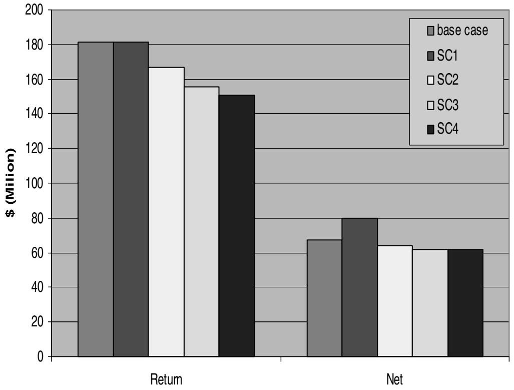

Fig. 3 Total return and net return

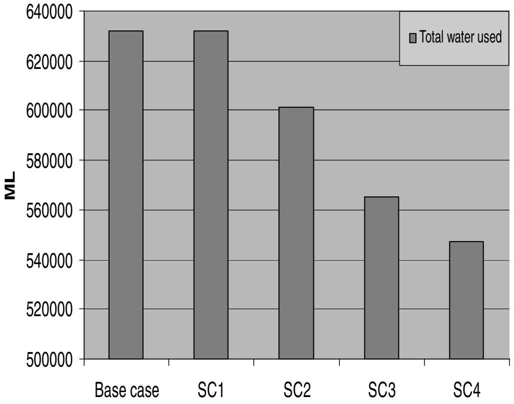

Fig. 4 Total water use

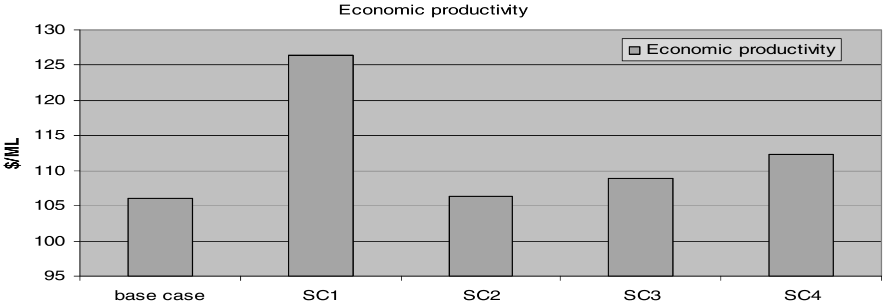

Fig. 5 Economic productivity for all the scenarios

Figure 5 illustrates that in the case of changing water costs, scenario 1 is the best compared with other scenarios. But if farmers (as well as policy makers) are interested in high return per mega liter of water used, then the case of scenario 4 achieved high economic water productivity.

These results highlight the conflict and the main issue of water policy, that is, farmers are interested in high return ($/ha) because all their capital cost are linked to their farm area but water policy makers are interested in economic water productivity

($/ML). This issue is still under examination. The total irrigation water used has declined in scenarios 2–4 (see Fig. 4). The saved water from irrigation could be used to help in improving the seasonality of flows and the river health in terms of environmental flows with achieves high economic productivity.

6 Conclusions and recommendation

System Dynamics modelling is presented in this paper as a viable alternative tool in data sparse conditions, and as a possible modelling approach when participatory approach applied to encourage decision-makers to be involved in model structure. There has been limited water resource management literature available on the use of System Dynamics and its full capabilities have not yet been fully explored for irrigation system modeling. One of these activities is tested in this paper, by using and applying System Dynamics for water reallocation model within system constraints and where a lack of data has precluded traditional hydrologic modelling approaches. While the proposed modeling approach can be successful in covering most of the features needed for hydrologic modeling, there are shortcomings, such as representing spatial variability. This shortcoming may be overcome using System Dynamics linked with geographical information system to capture the spatial distribution (i.e. each pixel could have its own module).

The System dynamics approach allows evaluation of different decisions and policies, and can provide answers to many questions about the water use, environmental flow targets, cropping policies or plans and water allocation. This case study demonstrates the potential of a System Dynamics approach as an extension tool for improving stakeholder involvement and decision making. The ERWM model presented herein has shown the capability to estimate and water assessment with changes in the cropping pattern under development three cases and change of water price. Furthermore, it helps to examine 'what if' scenarios and prove the fact that what is good for one year or season such as cropping pattern or demand management may not necessarily be good for the another season or water year. Indeed, this model can be extended and applied to simulate various policy scenarios. Overall, this model could be a useful policy and planning tool for irrigators, water policy decision makers and water supply authorities.

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