System Dynamics Optimisation Approach to Irrigation Demand Management

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EXTENDED ABSTRACT

Significant problems of water shortage and deteriorating water quality are contributing to a growing water crisis in many countries. This situation requires creative solutions to achieve sustainable resource management. In the Murrumbidgee river basin, irrigation extraction and land clearing have had major impacts on the river environment (DLWC 1995). Irrigation demand has changed the natural flow regime of the river which has induced significant environmental changes. Increased demands for water have led to reduced river flows and a reversal of the seasonal flow patterns.

Finding ways to meet irrigation demands and also achieve positive environmental and economic outcomes requires the aid of modelling tools to analyse the impact of alternative policy scenarios. These scenarios seek to assess the impact of options for the allocation of limited water resources between agricultural production and the environment.

This paper presents a novel approach for optimizing these objectives by combining system dynamics and constrained linear objective optimisation approaches. The network simulation optimisation model NSOM has been coupled with a linear programming mathematical algorithm that includes the system constraints. The model uses an economic rationale (i.e. a farmer's economic decision to maximise the gross margin per Megalitre) that involves assessing alternative cropping mixes and selecting the crop mix that maximises the net return and minimises water used.

The optimisation results from this model have been compared with results from a commercial linear programming solver to verify the capabilities of VENSIM™ optimizer. The comparison shows that VENSIM™ optimizer does achieve the same results.

This paper concludes that system dynamic optimisation approach is a useful tool for irrigation companies and catchment managers to evaluate alternative river system management scenarios. In particular, NSOM has the capability to compare the simulation and optimisation dynamic results synchronized in time for each variable involved in the model. In general based on a preliminary analysis, it is shown that selecting the appropriate crop mix could have positive impacts and benefits for irrigation deliveries and environmental flow. Further research is required to test, calibrate the NSOM model with actual data and study multi-objectives optimisation.

1. INTRODUCTION

Integrated water management in irrigated agricultural areas is the best strategy to improve crop yields and optimise the use of the available water resources. The main limiting factors for increased agricultural production are the availability of suitable land and water. In addition, a reduction in water availability, conflicting water uses and other water-related environmental problems are rapidly increasing in many parts of the world including Australia. According to Grigg (1996), the real crisis in water management is a "creeping crisis"-which needs a sustainable response at present.

Increasingly, researchers and policy makers are advocating sustainable development as the best approach to today's and future water problems (Louks, 2000). Water scarcity or decreasing water allocations in developed countries could drive and encourage decision makers to look for improved management through changes in cropping pattern systems.

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. Taking into consideration this approach, 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. The overall goal of the current study is to re-allocate crops in such a manner that the optimal pattern is achieved by minimising the water deficit (difference between available water and total water requirement) in an agriculture area while maximising the economic return.

The current study is carried out on a regional scale at an irrigation area level. The model changes the cropping mix and determines the optimal crop mix that will maximise the net return and gross margin per Megalitre and minimise water use. The optimal crop mix is determined through testing one case where each crop area has been allowed to vary within the set boundary values.

The study has been performed using the system dynamics programming tool VENSIM™ with an optimiser algorithm. The network simulation optimisation model NSOM was developed to determine the amount of irrigation water demand for each case scenario. Development of mathematical models to generate optimal irrigation policies has been performed by researchers since 1970. Most of the optimisation models have adopted linear programming (LP), Quadratic programming (QP) and dynamic programming (DP) approaches.

2. SYSTEM DYNAMICS

Irrigation water demand management is a difficult variable to impact due to the pressure of uncontrolled variables such as climatic conditions. Difficulties increase further when economic and environmental perspectives are integrated with realities of biophysical processes. The dynamic character of contributing variables and how they affect water use in the future is not captured through traditional modelling approaches. Although the application of optimisation techniques has been a major field of research in water resources planning for many years, their successful adaptation to practical water allocation problems has not been validated in practice, partly due to the fact that most applications have dealt with oversimplified systems (Yeh 1985; Simonovic and Fahmy, 1999).

Therefore, there is a need to explore new tools to represent the complex relationships found in irrigation systems. One promising option is system dynamics (SD), a feedback-based, object-oriented approach. Although not a novel approach, system dynamics offers a new way of modelling the future dynamics of complex systems. 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.

The most important feature of system dynamics is that it helps to elucidate the endogenous structure of the system under consideration, and demonstrate how different elements of the system actually relate to one another. This then facilitates experimentation as relations within the system are changed to reflect different decisions.

What makes using system dynamics different from other approaches used for studying complex systems (such as optimisation) is the use of feedback loops. The SD tool used in this study to model irrigation demand has four basic building blocks; stock, flow, connector and converter. Stocks (levels) are used to represent anything that accumulates; an example would be water stored in storage or dams. Flows (rates) represent activities that fill and drain stocks; an example includes releases or inflows. Connectors (arrows) are used to establish the relationship among variables in the model, the direction of the arrow indicates the dependency relationships. They carry information from one element to another element in the model. Converters transform input into output.

Stocks and flows help describe how a system is connected by feedback loops which create the nonlinearity found so frequently in modern day problems. Figure 1 describes the causal loop diagram with some positive (+) feedback and negative (-) relationships. Computer software is used to simulate a system dynamics model of the problem being studied. Running "what if" simulations to test certain policies on such a model can greatly aid understanding of how the system changes over time.

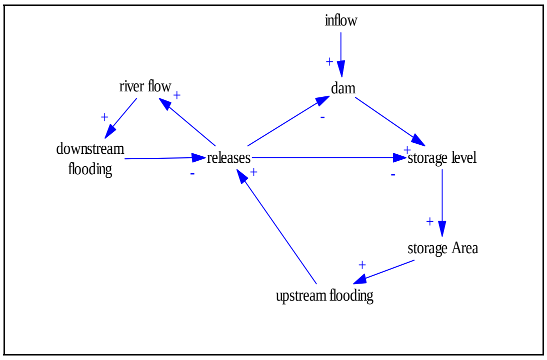


Figure 1. Causal loop diagram

Moreover, the inherent flexibility and transparency is particularly helpful for the development of simulation models for complex water systems with subjective variables and parameters (Simonovic 2000). Compared with the conventional simulation such as hydrological modelling or optimisation models, the system dynamics approach can better represent how different changes in basic elements affect the dynamics of the system in the future. It is therefore particularly useful for representing various ‘what if’ scenarios within complex systems, particularly when there are strong influences from environmental or economic elements.

Recent applications of the SD approach in the field of water resources have been few but include work on river-basin planning (Palmer et al. 1999), an assessment of water resources long-term water resource planning and policy analysis (Simonovic and Fahmy 1999), reservoir operation (Ahmed and Simonovic, 2000), and analysis of water allocation within the constraints of environmental flow rules based on economic rationale (Elmahdi et al 2004).

3. CONCEPTUAL MODEL

A Network Simulation Optimization Model (NSOM) (Elmahdi et al. 2004) has been developed to test the feasibility and issues in applying system dynamics to the problem of effectively balancing water allocation needs. The purpose of the model is to analyse the historical water allocation for an irrigation area within the constraints of environmental flow rules based on economic rationale (Figure 2 and Table 1). The model uses VENSIM$^{\text{TM}}$ as a software development tool to configure the water balance network model. The outputs of NSM model are total cost, total yields, total return, irrigation demand, gross margin, losses, surface water used, ground water pumping. Fundamentally, a water balance must be determined which can best match the demand and environmental flows within system constraints.

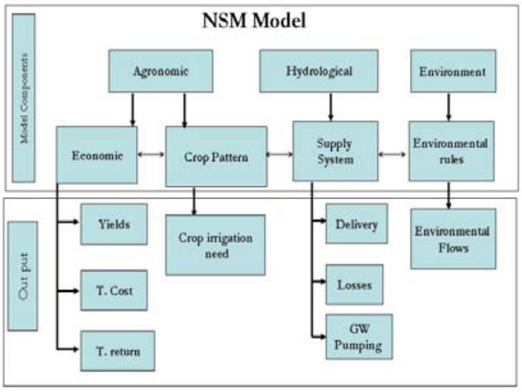
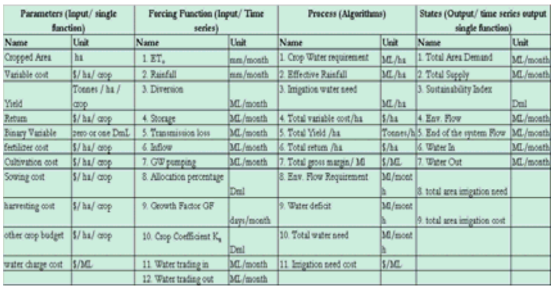


Figure 2. NSM model components

The purpose of VENSIM$^{\text{TM}}$ is to provide a programming environment for model development and help solve problems that would be hard to address mathematically without the aid of simulation. Moreover, the VENSIM$^{\text{TM}}$ environment effectively insulates the user from both the underlying mathematics and the details of the language specification. Furthermore, the VENSIM$^{\text{TM}}$ modelling language is a rich and readable way of representing dynamic systems.

In the Murrumbidgee irrigation districts, the last decade has brought major water policy initiatives. Furthermore, the combination of significant dry periods along with the introduction of CAP, Water Sharing Plans and resulting environmental flow rules, has led to the allocations announced at the start of the season being reduced and never reaching 100% of entitlement. This situation has driven a significant effort to study and overcome the consequences of reduced water availability within the context of farmer’s economic needs. Thus, the main objective of this research is to garner insights about how best to optimize the irrigation system within the constraints of the system (both physical and institutional) based on an economic rationale by developing and applying NSOM.

Table 1. NSOM model parameters, forcing function, process and states.



Parameters (Input/ single function)		Forcing Function (Input/ Time series)		Process (Algorithms)		States (Output/ time series output single function)	
Name	Unit	Name	Unit	Name	Unit	Name	Unit
Cropped Area	ha	1. ET_o	mm/month	1. Crop Water requirement	ML/ha	1. Total Area Demand	ML/month
Variable cost	$/ ha/ crop	2. Rainfall	mm/month	2. Effective Rainfall	ML/ha	2. Total Supply	ML/month
Yield	Tonnes / ha / crop	3. Diversion	ML/month	3. Irrigation water need	ML/ha	3. Sustainability Index	Dml
Return	$/ ha/ crop	4. Storage	ML/month	4. Total variable cost/ha	$/ha	4. Env. Flow	ML/month
Binary Variable	zero or one DmL	5. Transmission loss	ML/month	5. Total Yield /ha	Tonnes/h	5. End of the system Flow	ML/month
fertilizer cost	$/ ha/ crop	6. Inflow	ML/month	6. Total return /ha	$/ha	6. Water In	ML/month
Cultivation cost	$/ ha/ crop	7. GW pumping	ML/month	7. Total gross margin/ Ml	$/ML	7. Water Out	ML/month
Sowing cost	$/ ha/ crop	8. Allocation percentage	Dml	8. Env. Flow Requirement	Ml/month	8. total area irrigation need	
harvesting cost	$/ ha/ crop	9. Growth Factor GF	days/month	9. Water deficit	Ml/month	9. total area irrigation cost	
other crop budget	$/ ha/ crop	10. Crop Coefficient K_c	Dml	10. Total water need	Ml/month		
water charge cost	$/ML	11. Water trading in	ML/month	11. Irrigation need cost	$/ML		
		12. Water trading out	ML/month				

4. NSOM MODEL FORMULATION AND APPLICATION

The objective function of the NSOM model is formulated to maximise the net return and minimise the amount of irrigation water used. This is achieved by maximising one function formulated as a ratio of net return (Equation 1) over water use (Equation 2).

As the objective function and the constraints are of the linear form, a linear programming function can be used. The linear programming technique is utilized to determine the optimal allocation of the cropping area taking into consideration the specified constraints. The NSOM has been applied to the Coleambally irrigation area (CIA) in NSW. CIA region is characterised with its climate and consequently its crop consumptive use.

4.1 Objective Function

$$
\begin{aligned}
&\mathrm{MNB} = \sum_{c} \mathrm{Y}_c * \mathrm{P}_c * \mathrm{A}_c - \\
&(\sum_{c}\sum_{m}\{\mathrm{IN}_{(c,m)} * \mathrm{A}_c * \mathrm{IC}\} \qquad (1)\\
&+ \sum_{c}\sum_{m}\mathrm{GWP}_{(c,m)} * \mathrm{PC} + \sum_{c}\mathrm{A}_c * \mathrm{VC}_c)
\end{aligned}
$$

$$MWN = \sum_{(c,m)} IN_{(c,m)} \times A_{(c)} + \sum_{c}\sum_{m} GWP \quad (2)$$

where **MNB** is maximum net benefit, $\mathbf{Y}_c$ is yield for crop c (tonnes/ha), $\mathbf{P}_c$ is crop price ($/tonnes), $\mathbf{A}_c$ is the crop area for crop c (ha), $\mathbf{IN}_{(c,m)}$ is the irrigation water need for crop c in month m (Ml/ha), **IC** is irrigation or water cost ($/ML), $\mathbf{GWP}_{(c,m)}$ is supplementary ground water pumping for crop c in month m (ML/ha), **PC** is ground water pumping cost ($/ML), $\mathbf{VC}_c$ is variable cost per ha for crop c (fertilizers, herbicides, sowing, etc) ($/ha) and **MWN** minimises water need.

The first item of the first objective function gives the total income, the second item gives the irrigation cost from surface water, the third item gives the ground water pumping cost to match the demand and the fourth item gives the total variable cost such as fertilizers and pesticides cost. The first item in the second objective function gives the total irrigation needed and the second item gives the total ground pumping.

The final ratio objective function **MR** maximises the ratio of maximum net return over minimum water needed (Equation 3):

$$MR = MNB / MWN \qquad (3)$$

The objective function is subject to the following physical and environmental constraints (Equations 4-8):

4.2 Area Availability to Total Area

$$\sum_{(c)} \mathrm{A}_{(c)} \le \sum \ \mathrm{TA} \qquad (4)$$

The sum of all crop area is equal or less the total farm area, where **TA** is the total area.

4.3 Water Demand to Water Availability

$$\sum_{(c,m)} \mathrm{IN}_{(c,m)} * \mathrm{A}_{(c)} \le \sum \mathrm{WA} \qquad (5)$$

Total irrigation water needed in the irrigation area should not exceed total water available for the irrigation area.

4.4 Pumping Target for Each Month

$$\sum_{(c,m)} \mathrm{GWP}_{(c,m)} \le \mathrm{Pump}_{(m)} \qquad (7)$$

Total pumping from irrigation area in any month should not exceed the allowable pumping, used to meet water requirement (to avoid GW mining and pollution of aquifers).

4.5 Environmental Flow Target

$$\mathrm{EF}_m \ge \mathrm{TEF}_m \qquad (8)$$

The environmental flow in each month should equal or exceed the target flow is where **EF** is environmental flow in month m at the end of the system. In practice, this is equal to 300 ML/ day when the allocation exceeds 80% and 200 ML/day when the allocation less than 80% and **TEF** is target environmental flow in month m. Of course, to meet the end of system target, it is important to account for all abstractions which is outside the scope of this study.

Decision variables are the amount of land at irrigation area for growing crop c (ha), denoted as A_{c}. The assumption is same irrigation efficiency and soil type. It is important to adjust crop patterns on an economic basis and optimum uses of resources.

To demonstrate the potential of this approach, the NSOM model has been applied to CIA for one year with a low allocation and for 10 selected crops. It is important to note that this example has not yet been calibrated for the CIA irrigation area. Further research is needed to validate the model and test the sensitivity parameters, in particular, losses.

5. PRELIMINARY MODEL RESULTS

The purpose of NSOM is to demonstrate the capability of system dynamics to simulate and optimize a complex system such as irrigation system. It is the first attempt to build a linear constraint optimisation case through system dynamics.

A key assumption within the current version of NSOM is that the irrigation area has the same efficiency across the spatial dimension. Additionally, the model doesn't account for soil suitability or switching costs to move between different crops (in practice the infrastructure costs of shifting could be high and this will need to be considered as part of future research).

The model has been used to determine the optimal water use and the crop pattern of the different crops. The base case crop pattern of one year has been compared with the optimal crop pattern. The total cultivated area is kept without change. The areas of the different crops have been allowed to change so that the optimal crop area of these crops is determined. One case has been studied where the area of each crop was allowed to change within a certain limit where both the minimum and maximum allowed total crop area is changed from the base case crop area cultivated in that year. This limit is 50% - 150%.

The optimal cropping mix of the crop areas and amount of irrigation water is determined. Table 2 shows the base case crop pattern in year 2003 while Figure 3 shows the base case crop consumptive use in CIA.

Assuming the water efficiency is the same in the CIA area. The NSOM model is solved to determine the optimal allocation of the 10 crops (Figures 4-8).

Table 2. The actual crop pattern

Crops	Base case Area ha
Rice	26363
Wheat	12533
Oats	1255
Barley	3138
Maize	3138
Canola	627.69
Soybean	4393
Win pasture	10043
Lucerne	627.69
Vines	679.69
Total	62798.07

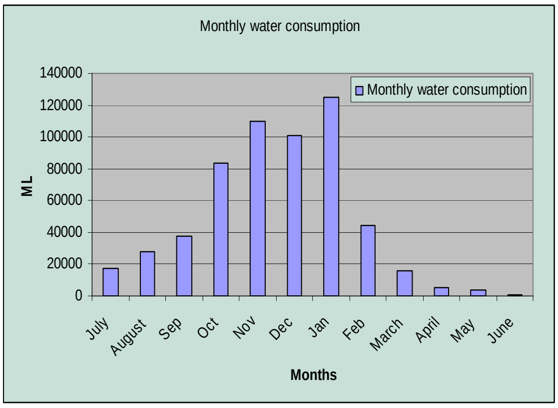


Figure 3. Monthly crop water consumption

It is clear from Figures 4 and 5 that the total water use and the distribution of all the crops have been changed from the actual case. The cultivated area of these crops with high consumptive use has been decreased while those with low consumptive use have been increased.

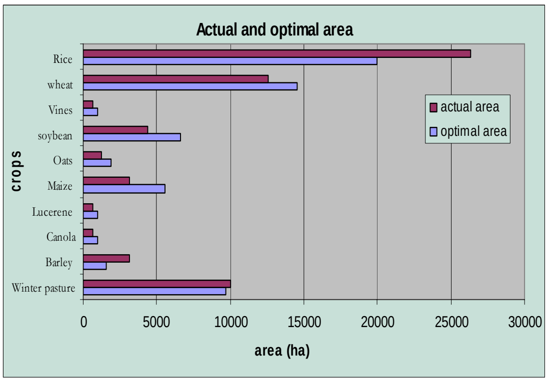


Figure 4. Actual (base case) and optimum cropping area

Figure 6 shows the monthly variation in irrigation water need, it is very clear the demand curve has been changed from the actual case particularly during the summer season.

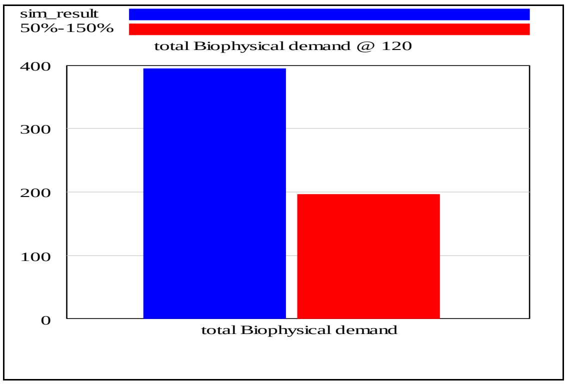


Figure 5. Actual (base case) and optimum total water use

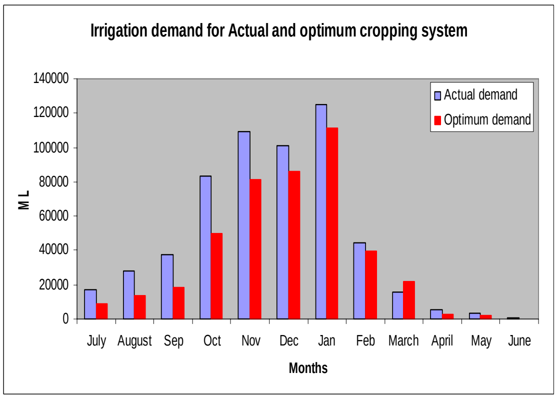


Figure 6. Actual and optimum monthly crop consumption in ML

The main objective of this study is to maximize the net profit and minimize the irrigation water used through the optimal crop mix area. Figure 7 shows the net profit increased from the base case.

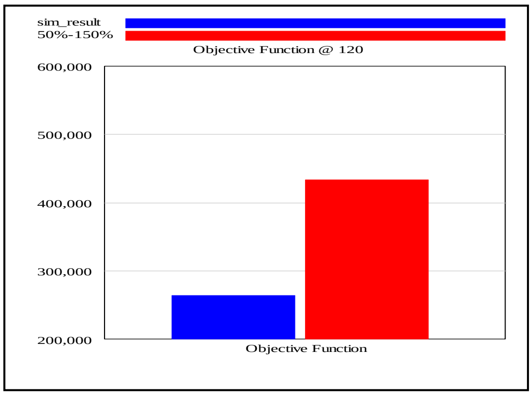


Figure 7. Actual (base case) and optimum net profit

The total irrigation water used has been decreased by 23%, which could be used to help improve the seasonality of flows and the river health in terms of environmental flows.

This paper represents the first attempt to build the optimization case approach using system dynamics. Therefore, the same case has been built in other linear programming commercial software, to test the sensitivity and capability of system dynamic.

Figure 8 shows the optimum crop area estimated by system dynamic compared with other LP programming. The advantage of system dynamic is dealing with complex system and this tool has the capability to compare the simulation and optimisation dynamic results synchronized in time for each variable involved in the model.

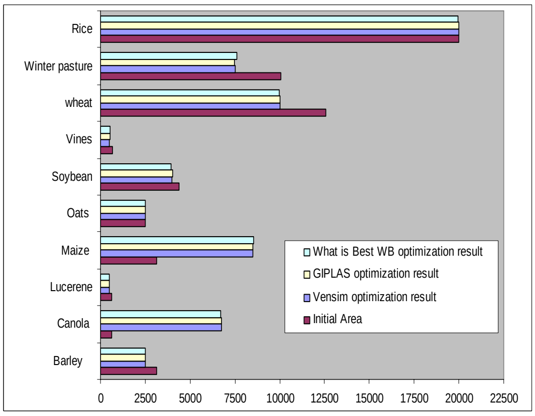


Figure 8. Actual and optimum area with different LP programming

6. CONCLUSIONS AND RECOMMENDATIONS

A system dynamic optimisation (linear) programming model has been developed to determine the optimal water use and crop pattern of an agricultural area against two objectives: to maximize the net profit and minimize the amount of the irrigation water used. To demonstrate proof of concept, a preliminary NSOM model has been applied to the Coleambally Irrigation Area considering that the same efficiency without calibration. The optimal crop area has been determined for one year. One case has been studied where the crop area has been allowed to change within a certain limit.

The preliminary analysis results show that a considerable amount of water volume can be saved and reused. The volume savings could be used to improve the seasonality of flows (by changing the demand curve as shown in figure 6) and in consequence improve the river health. The water volume saved is estimated to be about 23% when the crop areas are allowed to change between 0.5 and 1.5 times the actual cultivated crop area. This study provides insight as to how best to manage the agricultural area in CIA when there is a shortage of the irrigation water. Moreover, this paper concludes that a system dynamic approach has the potential to help stakeholders optimize the system, by evaluating and analysing key decision variables. It is recommended that further research be conducted to validate the model and investigate the economic and environmental implication of applying this model.

7. ACKNOWLEDGMENTS

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