A System Dynamic Approach and Irrigation Demand Management Modelling

Amgad Elmahdi[1], **Hector Malano**[2] **and Shahbaz Khan**[3]

[1]Phd Candidate, Civil & Environmental Engineering Department The university of Melbourne Uni-3010 Victoria-Australia.

Tel: +61-3-8344 7237; Fax: +61-3-8344 6868; A.Elmahdi@civenv.unimelb.edu.au

[2] CRC Irrigation Future, Dept Civil & Env Engineering, The University of Melbourne, Vic 3010- Australia

Tel: +61-3-8344 6645; Fax: +61-3-8344 6868; h.malano@devtech.unimelb.edu.au

[3] CRC for Irrigation Futures, CSIRO Land and Water, Griffith, 2680 NSW.

Tel: +61-2 6960 1500; Fax: +61-2 6960 1600; shahbaz.Khan@csiro.au

Abstract

Irrigation, over extraction and land clearing has had major impacts on river environment particularly in the Murrumbidgee river catchment. Increased water demands for agriculture and other uses have led to low flows and changes in the seasonal flow patterns. However, as further growth in water diversions is not possible due to the imposition of the Murray Darling Basin Cap, the need to achieve improved environmental and economic outcomes in allocation policies requires greater efficiency in the use the limited water resources.

This paper presents a system dynamics approach to modelling aimed at assisting stakeholders in understanding, predicting and resolving potential water sharing conflicts which have becomes more acute after the imposition of Cap on diversions and new environmental flow rules. A dynamic agricultural network simulation model based on an economic concept was developed to analyse the historical water allocation in the Coleambally irrigation area within the constraints of existing environmental flow rules. This is the first attempt to apply a system dynamics approach for irrigation demand management at the irrigation area level. This network model uses a node-link approach to represent the Coleambally irrigation system. The model is tested using various hypothetical scenarios, such as change the crop areas, environmental flow targets, and water pumping. Furthermore, the model is shown to be a useful policy and planning tool for water supply authorities, policy and decisions makers and irrigators.

Keywords: System Dynamic, Irrigation management, Environmental flows, planning

Preferred presentation Format: platform

1. Introduction

Over the last 100 years the natural state of Murrumbidgee River has been changed significantly by using water for agriculture, recreation, industry and domestic needs. These diversions have created significant economic benefits with clear evidence of increasing environmental stress within the river [3]. The three main limitations of increasing water supply are hydrological, environmental and financial. As a result, increasing emphasis is being placed on demand management in managing water resources in the Murrumbidgee. According to Winpenny [8] in short, there are four major demand management options: reduce waste and physical losses in distribution systems, increase recycling of water in all industries, reallocate existing water supply more evenly and equitably, and treat water as an economic good and increase water prices. Only in the last decade, as the scarcity of water, degraded water environment and over extraction has become apparent, sufficient attention has been placed to managing water based on sustainable water management using environmental and economic sustainability principles. In water resource management, sustainability implies a notion of balance or equilibrium between water demands and the preservation of the water ecosystem.

The Murrumbidgee catchment is facing severe and growing challenges in maintaining and meeting the irrigation demand for water. In addition, water used for irrigation will likely have to be diverted increasingly to meet the needs of other users. At the same time, environmental and other in-stream water demands become more important as economies develop. A large share of water to meet new demands could come from water saved from existing uses through a comprehensive reform of water policy. To address the need for a better balance between river health and use, the New South Wales Government introduced a major package under the umbrella of the COAG reforms and the CAP including water-sharing plans and environmental target flow rules. The major goals of the policy were the achievement of more explicit and careful sharing of water between the environment and water users to mitigate the impacts of high summer flows for irrigation by release of environmental flows.

Not surprisingly, since the introduction of CAP, Water Sharing Plans and Environmental flow rules, the allocations announced at the start of the season have usually been reduced and never reached 100 % of the entitlements. There is a major drive to study and understand the water sharing conflict within the context of farmer's economic needs in the Coleambally irrigation area. Thus, the main objectives of this research are to describe a system dynamics approach to modelling a complex irrigation system and to analyse the historical water allocation for the Coleambally irrigation area within the constraints of environmental flow rules based on an economic rationale.

2. The Study Area

The Murrumbidgee catchment is located in NSW, Australia and has an area of about 84,000 km2. The Coleambally sub-catchment is located on the southern side of the Murrumbidgee River (Figure 1). Irrigation also occurs along the length of Murrumbidgee River through private diverters. The Coleambally irrigation area, CIA is the second largest area of irrigation production, accounting for 75,000 hectares of irrigated area. The major irrigated agricultural enterprises include rice, wheat, oilseeds, citrus, wine grapes, stone fruit, vegetables, and annual and perennial pastures supporting livestock enterprises including prime lamb, wool and beef production. Gogeldrie Weir, some 50 km downstream of Berembed, was completed in 1959 to enable the diversion of extra water to the Murrumbidgee Irrigation area MIA and associated Districts and later to the CIA.

2.1 Allocation for Coleambally irrigation area

It has been reported [2] that under normal conditions, irrigators could expect to receive their full allocations in all years except in the driest of years (see Table 1). An initial allocation made at the commencement of the season is updated continuously during the season due to increases in rainfall in the area. Historical allocation announcements show that initial allocations were either set at their maximum level (100% or higher) at the start of the irrigation season or set at a lower level and then considerably increased as the season progressed.

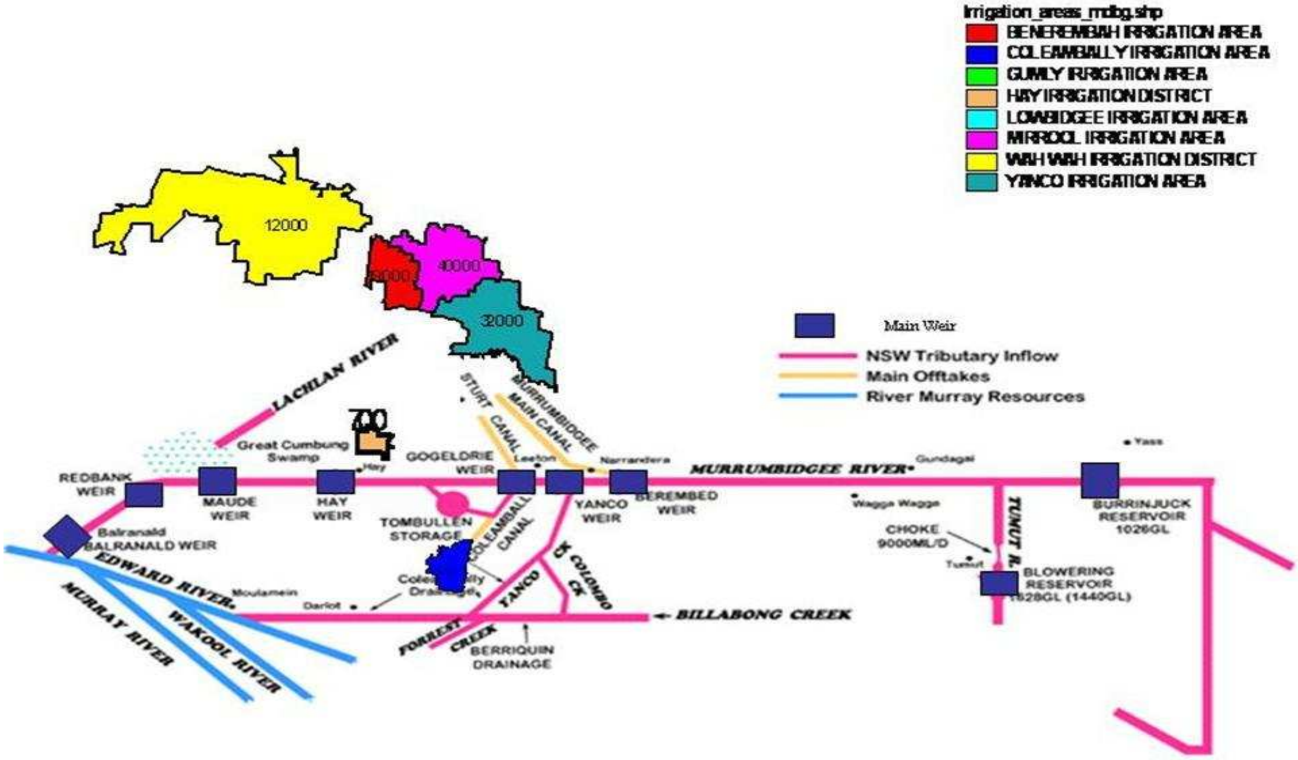

Figure 1 Main off-take canals and irrigation areas

Table1: Allocation percentage announcement comparison[1]

Water year	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	
1980/1981	67	67	85	95	100	100	100	
1981/1982	100	100	100	100	100	100	100	
1982/1983		100	100	100	100	100	100	
1983/1984	65	75	100	120	120	120	120	
1984/1985	100	140	140	140	140	140	140	
1985/1986	120	120	120	120	120	120	120	
1986/1987	100	120	120	120	120	120	120	
1987/1988	100	120	120	120	120	120	120	
1988/1989	120	120	120	120	120	120	120	
1989/1990	120	120	120	120	120	120	120	
1990/1991	120	120	120	120	120	120	120	
1991/1992	120	120	120	120	120	120	120	
1992/1993	110	120	120	120	120	120	120	
1993/1994		120	120	120	120	120	120	
1994/1995		***100***	***100***	***100***	***100***	***100***	***100***	***Cap***
1995/1996	100	105	105	105	105	105	105	
1996/1997	100	100	100	100	100	100	100	
1997/1998	***80***	***88***	***90***	***90***	***90***	***90***	***90***	***WSP***
1998/1999	60	72	79	81	81	81	85	
1999/2000	**50**	**53**	**60**	**67**	**67**	**73**	**78**	**Env.Flow**
2000/2001	59	60	80	90				
2001/2002	47	53		65			72	
2002/2003	34	38						

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[1] Data Source: Pers.Comm. S.Khan (2003)

Not surprisingly, since the introduction of Cap, Water Sharing Plans and Environmental flow rules, the allocation announced at the start of the season has usually been reduced and never reached 100 % of the entitlements (Figure 2). This is a major drive to study and understand the impact of water reforms on farmer's economic situation. Moreover, since 1994 there has been increased emphasis in water trading as a solution for solving water-sharing problems in the Murrumbidgee and across the Murray Darling basin. But this policy threatens the potential benefits of the CAP for both water users and the environment. In particular, the limitation on diversion based on the 1994 level of development has had some impacts on the water trade price and activation for dozer licenses. As the volume of water entering the area has decreased when compared to the previous years, the volume of water leaving the area has increased as shown in 2003 for CIA. This can be attributed to the low water allocation for the season and increased prices for temporary transfer causing many farmers to decide on selling their water rather than planting their farm.

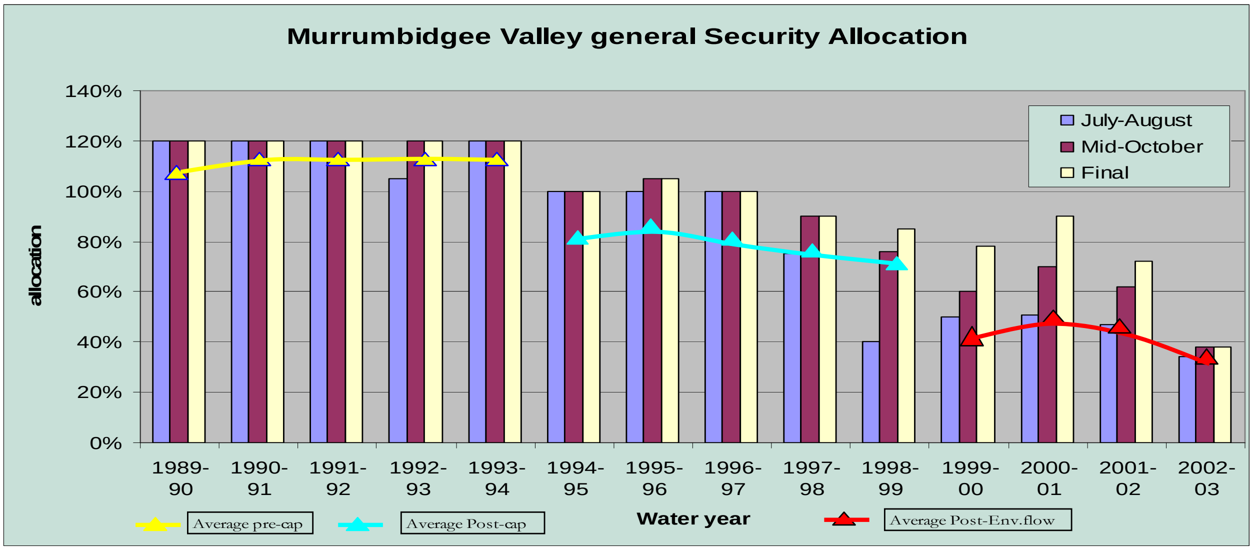

Figure 2 Murrumbidgee Valley General Security Allocations[2] 1989-90 to 2002-03

3. System Dynamic Approach

In a complex water resource system such as the one studied in this research, the problems usually include many kinds of subjective variables. Difficulties mainly arise from the integration of economic and environmental perspectives with the technical elements. The dynamic character of the main variables and how they affect water use in the future is not captured through the traditional approach such as simulation and optimization of water allocation. Although the application of optimization techniques has been a major field of research in water resources planning for many years, their stand alone adaptation to practical applications has not been satisfactory, partly due to the fact that most deal with oversimplified systems [7, 6]. Therefore, there is a need to explore new tools for representing the complex relationships found in irrigation systems. One of those promising options is the system dynamics (SD), a feedback-based, object-oriented approach. Although not a novel approach, system dynamics offer a new way of modelling the future dynamics of complex systems. System dynamics is based on [6] 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 to elucidate the endogenous structure of the system under study, to see how different elements of the system actually relate to one another and to experiment with changing relations within the system when different decisions are included. In system dynamics, the relation between structure and behaviour is based on the concept of information feedback and control. What makes using system dynamics different from other approaches such as optimization and linear

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[2] Data source: pers. comm. S.Khan (2003)

approaches to studying complex systems is the use of feedback loops. Stocks and flows help describe how a system is connected by feedback loops which create the nonlinearity found so frequently in modern day problems [i.e. in the old days, the problems are linear]. Computer software is used to simulate a system dynamics model of the situation being studied. Running "what if" simulations to test certain policies on such a model can greatly aid in understanding how the system changes over time.

Moreover, the inherent flexibility and transparency is particularly helpful for the development of simulation models for complex water systems with subjective variables and parameters. This flexibility allows the application of hierarchical decomposition in the model development and the transparency raises the possibility of practitioners' involvement in the model development, increasing their confidence in the model operation and its outputs [5]. Compared with the conventional simulation such as hydrological modelling or optimisation models, the system dynamics approach is better to represent how different changes in basic elements affect the dynamics of the system in the future. It is therefore particularly useful for representing complex systems with strong influences from environmental or economic elements. Recent applications of the SD approach in the field of water resources have been few and on a small scale. It includes river-basin planning [4], assessment of water resources long-term water resource planning and policy analysis [6] and reservoir operation [1].

Using Vensim[3] as a software development tool to configure the water balance network model, a system dynamics **N**etwork **S**imulation **M**odel (**NSM**) was developed to attempt the analysis of historical water allocation for the Coleambally irrigation area within the constraints of environmental flow rules based on economic rationale. The purpose of Vensim is to help solve problems that would be hard to address mathematically without the aid of simulation. Moreover, the Vensim environment will insulate the user from both the underlying mathematics and the details of the language specification. Moreover, the Vensim modelling language is a rich and readable way of representing dynamic systems. It has several capabilities such as the flight simulator approach, building a control room, synthesis, reality check, sensitivity testing, multivariate sensitivity simulation , subscript tools and optimization which can be used to validate and estimate parameters (calibration) or to select among alternative polices (policy optimization) to achieve the best.

4. Network Simulation Model (NSM)

The Murrumbidgee River was divided into five reaches based on the available information and data about inflow and outflow with diversion and demand as follow:

- Dams – Wagga Wagga
- Wagga Wagga – Narrandera
- Narrandera - Darlington Pt
- Darlington Pt – Hay
- Hay – Balranald

The network model will focus on the three reaches, which serve the Coleambally irrigation area starting from Wagga Wagga to Hay. Thus the network model consists of a link from a supply node (e.g. weir, ground water and water trading) as one boundary of the system, a demand node (e.g. irrigation area or district, environmental flow, water trading) as the second boundary of the system, and a distribution node or the links connecting the nodes including river reaches that may carry environmental flows as well as irrigation canals as shown in Figure 3.

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[3] Vensim is a Trade Mark of Ventana 1996

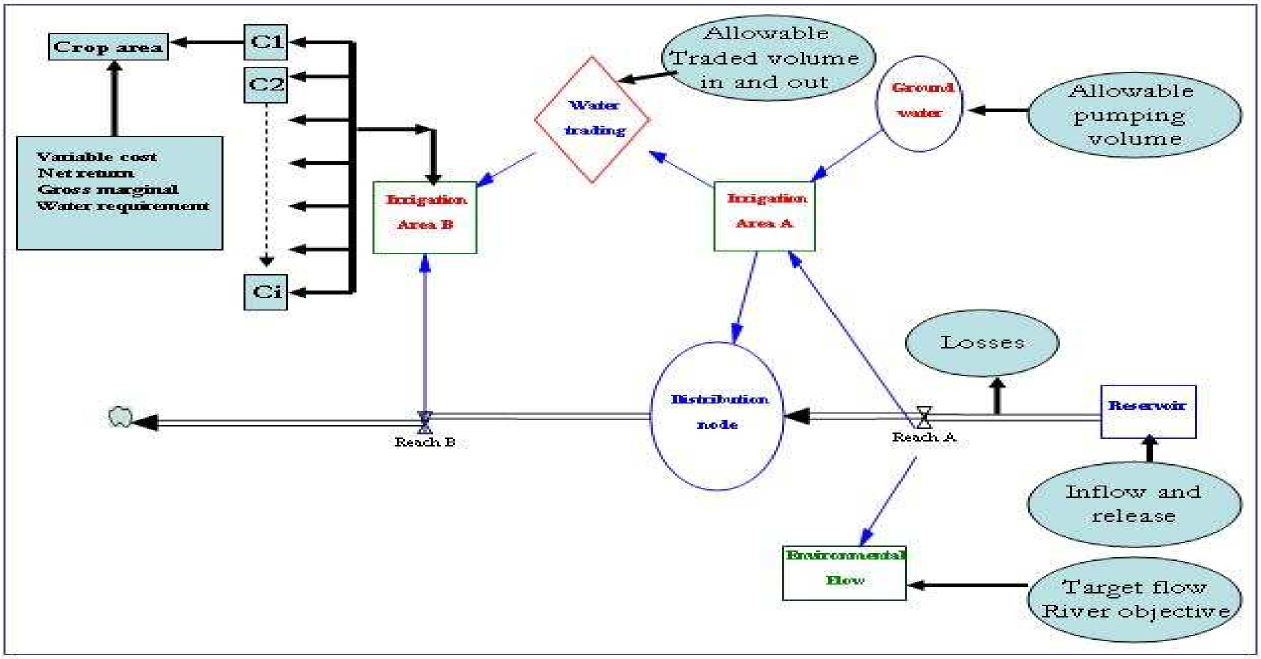

Figure 3: Network supply, demand nodes and model components

Using this concept, the model uses a hierarchical decomposition principle by modelling the irrigation water system network of the Coleambally irrigation system with all the model components at a monthly time interval. The model components could be defined as follow:

- Coleambally Irrigation Area as demand node based on the cropping pattern
- Environmental flow as demand node based on environmental target flows.
- Water trading as demand and supply node between the irrigation areas
- Coleambally main canal as supply node
- Reaches and canals as distribution node
- Ground Water pumping within the irrigation area as supply node

Consequently, each model components is modelled by integrating basic components as shown in Figure 4, which describes the internal structure of crop water requirement. The model proposed will be capable of exploring a wide variety of water supply and demand scenarios for the study area. The interactive computer based tool allows the exploration of how various water supply objectives and demand requirements can be met for future scenarios with environmental and economic constraints. Conceptually, net returns, gross margin and variable costs represent the economist principles while minimizing total pumping requirements and meet the irrigation demand represent the hydrological aspect. Furthermore, satisfying environmental rules or target flow represents the ecologists or environmentalist goals.

5. Model Application, Validation and result analysis

NSM can simulate the physical water demand from irrigation areas using a hierarchical decomposition approach to calculate water requirement based on the cropping pattern or the cropping plan and the total irrigated area. In this context, the total water requirement from the irrigation area per month is calculated (figure 4) as:

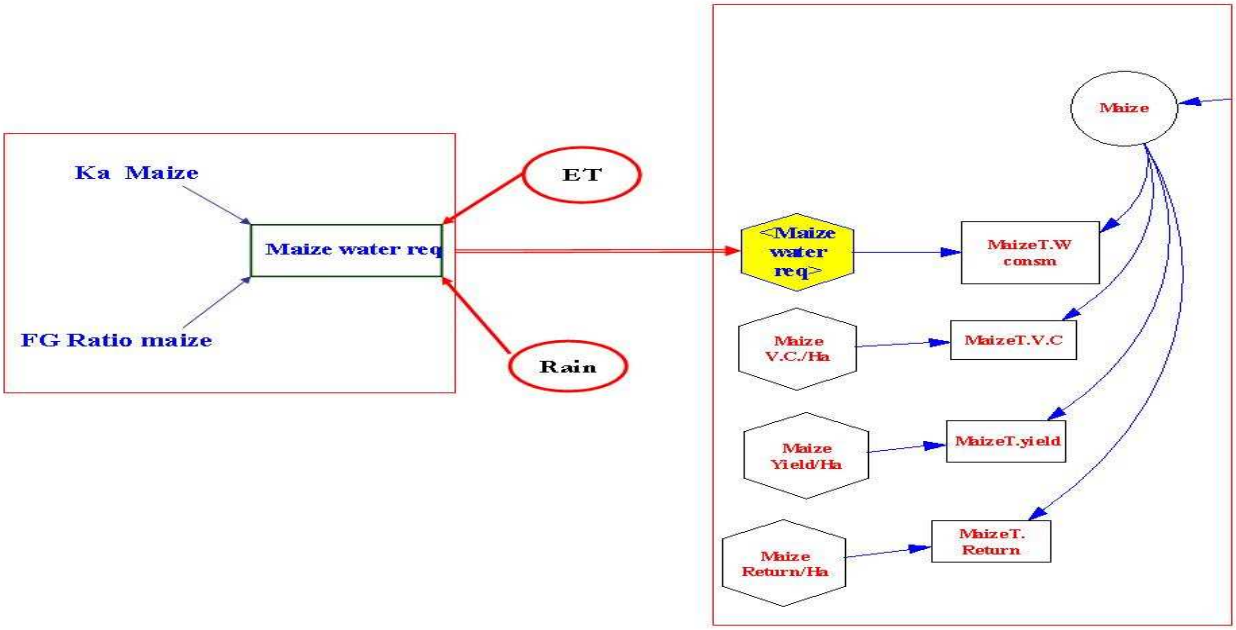

Figure 4: Calculation of crop water requirement for month

$$T.Wreq = \sum_{c} A_{(c)} xWreq_{(c,m)}$$

Where Wreq$_{(c,m)}$ is the monthly crop water requirement, and A$_{(c)}$ is the cropped area.

Crop water requirement Wreq$_{(c,m)}$ is calculated as a function of crop coefficient, crop growth duration, evapo-transpiration (ET mm) and rainfall (mm) in the Coleambally irrigation area.

The fraction of growth period in a given month for a given crop (FG.Ratio$_{(c,m)}$) will be calculated by:

$$\text{FG.Ratio}_{(c,m)} = \frac{\text{G.duration}_{(c,m)}}{\text{days}_{(m)}}$$

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:

$$Wreq_{(c,m)} = Ka_{(c,m)} xFG.Ratio_{(c,m)} xET_{(m)} - FG.Ratio_{(c,m)} xRain_{(m)}$$

Where Ka$_{(c,m)}$ is the crop coefficient of crop c in month m and ET$_{(m)}$ and Rain$_{(m)}$ are evapo-transpiration (modified Penman method to calculate ET)and rainfall in month *m*, *respectively*.. Figure 5 shows the rice crop water requirement calculated.

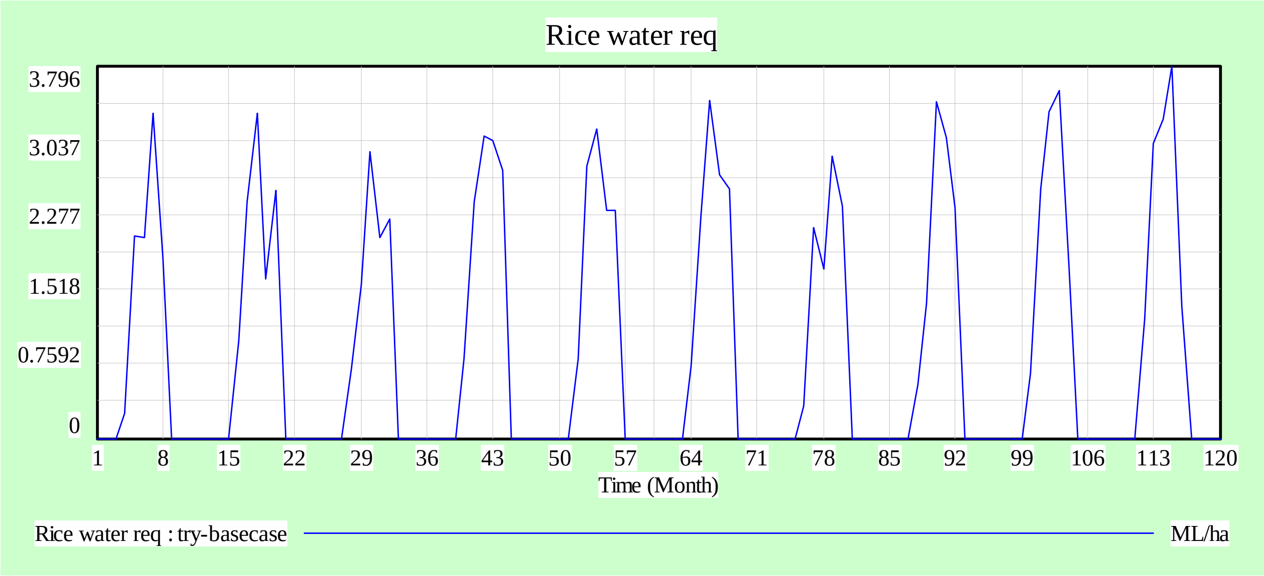

Figure 5: Rice water requirement simulated for 10 years

The simulation model allows a non-expert user to test and use the model by running the simulation for the data time series with capacity to change the cropping plan or pattern and total irrigated area to determine how the system responds to supply and demand and how much water remains at the end of the system after satisfying the irrigation supply, Tombulene storage and environmental flow target. The NSM model has been validated and tested to see if it reflects reality or mimics the real world system. Figure 6 shows the simulated flow at the end of the system compared to the observed flow at the end of the system. High correlation have been observed with R^2=0.9 which increase the confidence in the NSM with using the historical flows data. Moreover, Figure 7 shows a dramatic decrease in the flow at the end of the system during the last 3 years after applying the environmental flow rules, which reflected in average allocation less than 60 %. As recorded during the last year the allocation was 23% which it was the lowest record.

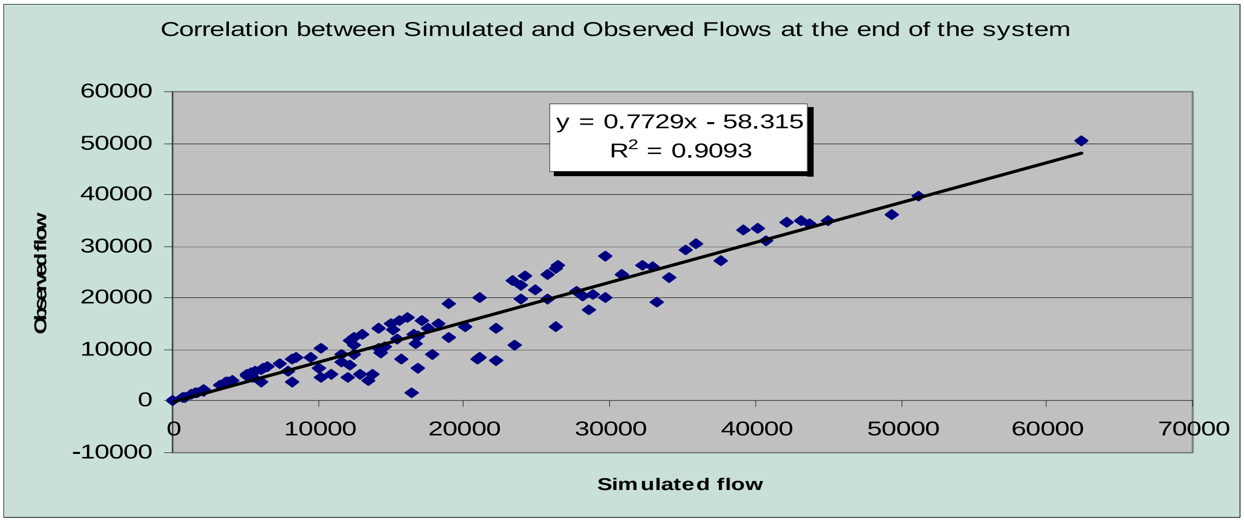

Figure 6: The flows at the end of the system

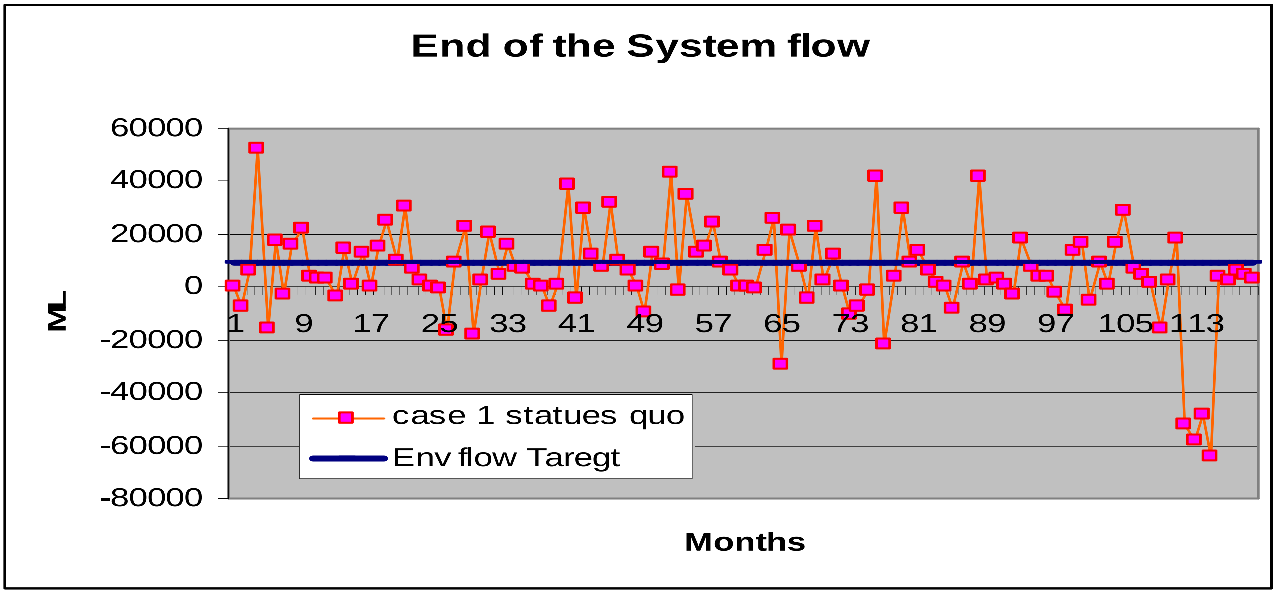

Figure 7: End of the system flow after applying Environmental flow rules

The model also calculates the total gross margin (TGM, in AU$) and variable cost can change with different demand and supply options. Figure 8 shows two cases, the status quo and an increase in the total irrigated area of 10,000 hectares last year 2002/03 under status quo scenario. It is very clear that the total gross margin has increased in case of increased total irrigated area. Moreover, it is resulted in, the demand has increased over the 10 year run (120-month water year starting from July) with 16 % during the summer season and that is reflected in a greater shortage in the supply system during the dry year, which has a negative impact on the environmental flow target.

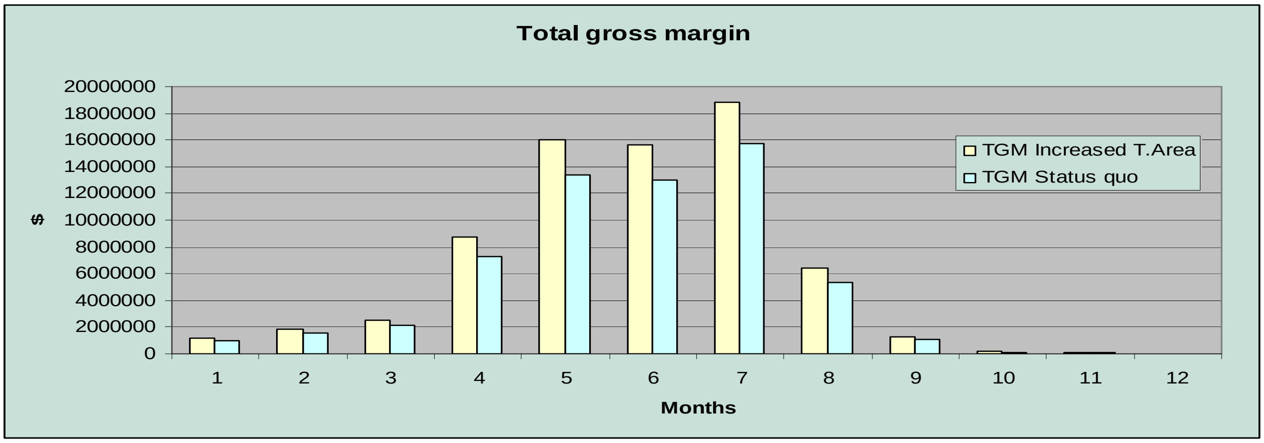

Figure 8: Total gross marginal with change the total irrigated area (2002/03)

Figure 9 shows the difference between water supply and demand at the irrigation area in the three cases:

- Case 1: the status quo,
- Case 2: an increase the total irrigated area, and;
- Case 3: a decrease the total irrigated area.

It is very clear that the difference between cases is much higher which reflects the shortage in the supply system in case of an increase the total irrigated area. Conversely, by decreasing the total irrigated area with the same cropping pattern, the demand has decreased. Thus, case 3, with a reduced total irrigated area is superior and the difference between supply and demand in most months is zero or positive value.

From the above results and discussion, it is very clear that the Network Simulation Model using system dynamics is appropriate tool to analyse irrigation management strategies by enhancing the ability of managers to analyse the system behaviour. In addition, it also proves that what is good for a season or year is not necessarily good for other seasons.

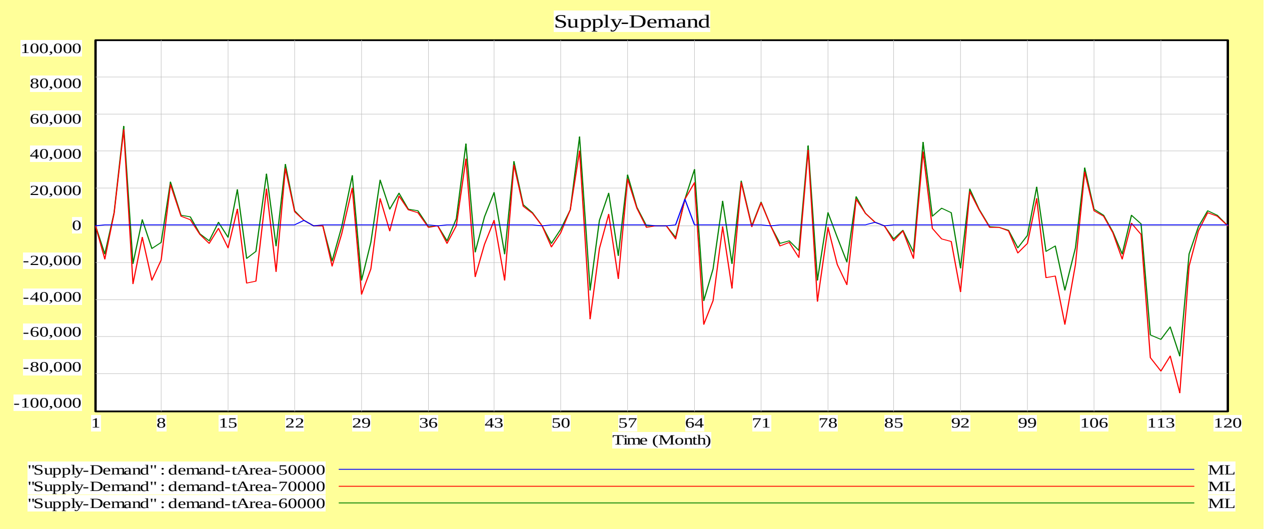

Figure 9: the difference between supply and demand with decreased total irrigated area

6. Sensitivity Analysis

Three cases of irrigated area development (present irrigated area, decreased total irrigated area and increased total irrigated area) were tested with three hypothetical scenarios (winter cropping, summer cropping and water saving). These three scenarios are compared to the status quo scenario in which current cropping pattern percentage is applied. Table 2 shows the percentage of cropped area in different scenarios with 10 crops.

Table 2: Cropping pattern percentage for each hypothetical scenarios

Scenario	Rice	Wheat	Maize	Barley	Oats	Canola	Vines	Win-Past	Soybean	Lucerne	T.Area
Status quo	42%	20%	5%	5%	2%	1%	1%	16%	7%	1%	100%
Winter	10%	23.6%	4%	8%	8%	11%	3%	24%	8%	0.4%	100%
Summer	43%	8%	16%	4%	1.6%	1.6%	3.2%	4.8%	16%	0.8%	100%
Water saving	0%	0%	4.8%	24%	24%	24%	4.8%	8%	4.8%	4.8%	100%

In the water saving scenario, the high water requirements crops are forgone. While, the summer and winter scenarios propose increased the cropped area of summer and winter crops respectively. The main constraint imposed on the system was to satisfy the environmental target flow first and then the agricultural water demand. Table 3 shows gross margin, total income and variable cost which resulted from the different scenarios. From an economic point of view (maximising the total income) the summer scenario provides a positive result in all three cases. Another economic perspective could be looking to minimising the cost and in that case the water saving scenarios provides a positive result for all three cases and at the same time minimising the use of the resource.

Because the water saving scenario has avoided high water requirements crops for rice and wheat, which are mainly responsible for high water demand and high cost during summer and winter season respectively.

Table 3: Total gross marginal, total income and total variable cost in the three cases with hypothetical scenarios

	Case 1 status quo			Case 2 increased T. Area			Case 3 Decreased T. Area		
Scenarios	TGM $Au	T. Income $Au	V. Cost $Au	TGM $Au	T. Income $Au	V. Cost $Au	TGM $ Au	T. Income $Au	V. Cost $Au
Statues quo	56.01	105.17	49.16	66.93	125.67	58.74	49.08	92.16	43.07
Winter scenario	23.57	57.7	34.12	28.82	69.6	40.77	21.14	51.04	29.9
Summer scenario	64.42	120.4	55.98	77.04	144.05	67.01	56.4	105.63	49.14
Water scenario	10.7	42.4	31.7	12.8	50.9	38.05	9.43	37.3	27.9

Conversely, the environmental goals or perspective is looking at satisfying the environmental flow target. Figure 10 shows the flow for the three cases at the end of the system with the summer scenario compared to the environmental flow target. It is very clear that the average flow for 10 years shows that during the summer months the target flow was not satisfied. Despite this, Case 3 with a decreased total irrigated area is superior to Case 1 and Case 2. On the other hand, the winter and water saving scenarios have shown good results in satisfying the environmental flows target over the 10-year period when compared to the summer scenario. Overall, Case 3 (decrease in total irrigated area) has shown a greater positive impact on environmental flow than Case 1 (status quo).

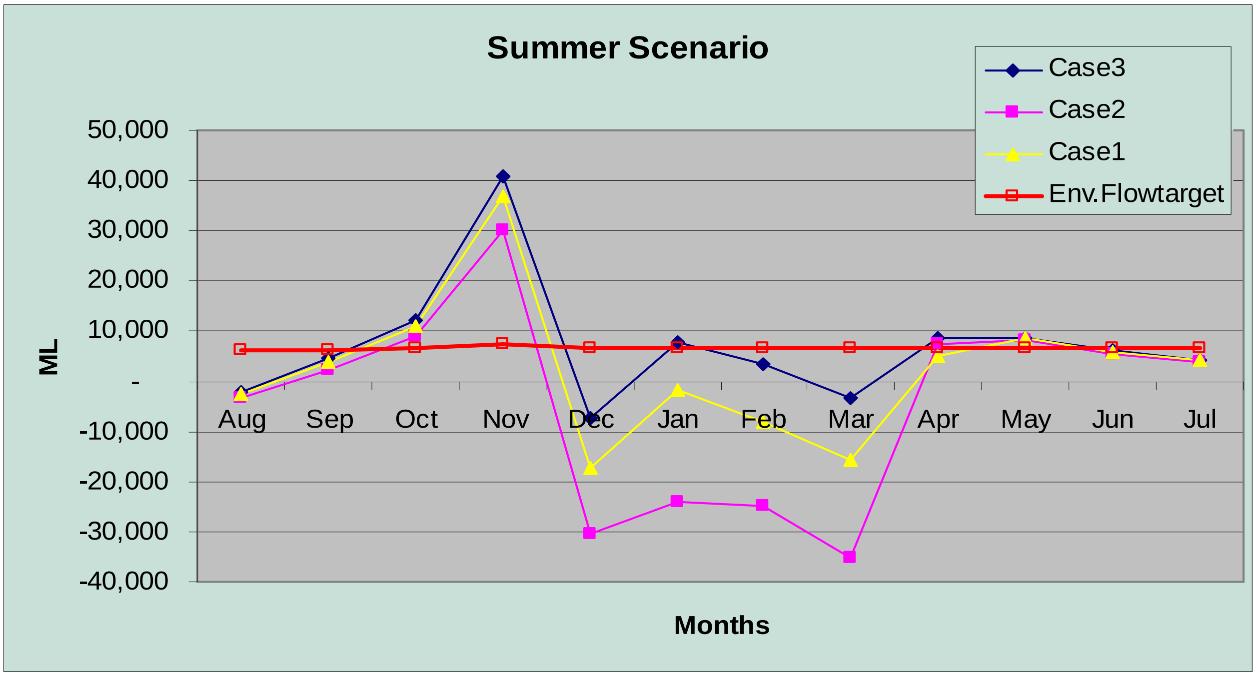

Figure 10: Summer scenario with environmental flow

Figure 10 shows the flow for Case 3 at the end of the system with summer and water saving scenarios compared with the environmental flow target. Moreover, the water saving scenario has shown improvement in the end-of-system flows during the summer months. In general, Case 3 shows better performance than the other two cases throughout the 10 years of simulation.

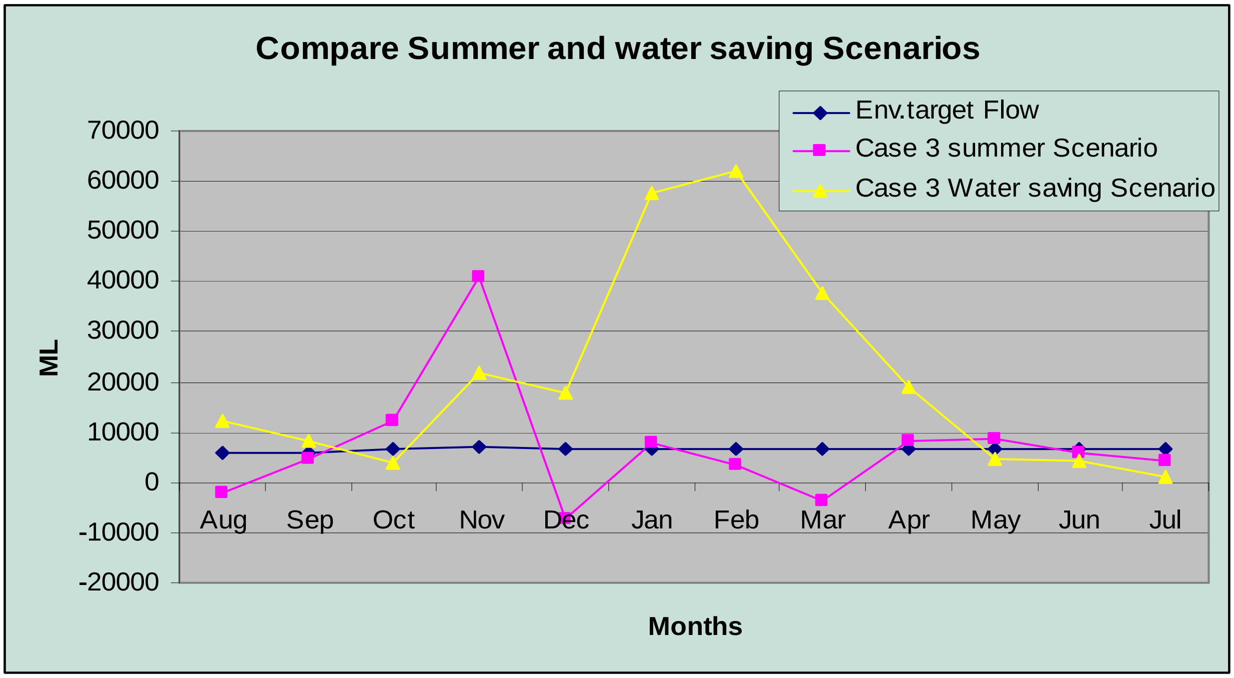

Figure 11: Case 3 (decreased the total irrigated area) summer and water saving scenarios with environmental flow

7. Conclusions Remarks and future directions

This paper reports the first attempt to apply a system dynamics approach to irrigation demand management, by linking the hydrological aspects with environmental and economic considerations. Several scenarios and cases were designed by changing the cropping pattern and total cropped area. The NSM model helped to prove the fact that what is good for one year or season such as cropping pattern or demand management it is not necessarily good for the second season or water year according to changes in water allocations and diversions resulting from climatic change. Indeed, this model can be extended and applied to simulate various policy scenarios. The system dynamics simulation approach allows evaluation of alternative strategies and can provide answers to many questions about the environmental flow targets, cropping policy or plan and water allocation. This case study demonstrates the potential of the system dynamics approach as a decision support tool for improving stakeholder and decision maker involvement and confidence in modelling.

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