System Dynamics Approach for Modelling Seasonality of River Flows

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Keywords: *System dynamics, seasonality of river flows, irrigation demand management, environmental flows, demand optimization.*

EXTENDED ABSTRACT

Large storages and regulation of river flows for the purposes of irrigation, flood mitigation or power generation adversely affect the natural seasonal patterns of the river flows. There is a trade-off between level of human interventions in the river system for human benefits and the degree of maintaining the natural seasonality of rivers flows in irrigated catchments. In the absence of utilising other supplementary options, withdrawals from reservoirs constructed on the Australian rivers, mainly for irrigation purpose during dry season, are very high as compared to wet season.

Murrumbidgee River Catchment covers 8% of the MDB with average annual rainfall of 594 mm and average annual flow of 4300 GL. About 65% of the average annual flow volumes are allocated to water users in the valley. The role of the river has been effectively changed into an irrigation conveyance channel. Irrigation in the Murrumbidgee Irrigation Area (MIA) and the Coleambally Irrigation Area (CIA) is the major user of surface water in the Murrumbidgee River catchment. Increased summer irrigation demand and flow regulation by two major storages has changed the natural flow regime of the river. This has resulted into reduced environmental flows and flow conveyance problems (during high demand season) in some parts of the catchment.

A system level holistic approach is required to understand the complex interactions among river inflows, climate variability, storage, water demand patterns, environmental impacts of consumptive uses of water, and the minimum environmental flow obligations. The dynamic nature of abovementioned variables and the system response can not be captured by the traditional modelling approaches. System dynamics (SD) therefore, is an appropriate approach to conceptualise and simulate complex and dynamic water system processes deterministically which are otherwise partly simulated by conventional hydrologic and stochastic modelling approaches.

The objective of the study was to investigate alternative options to minimize or shift gap between the average natural/unregulated flows and the average current/regulated flows at the most downstream station called Balranald on the Murrumbidgee River. Different irrigation demand management options in terms of off-stream water savings and economic returns were simulated in a system dynamics environment using the Vensim software tool.

The results from the SD modelling shown in Figure A present the simulated effects of different demand management interventions on the current flow regime of the Murrumbidgee River at the Balranald station. Of which, optimum summer-winter crop mix seems to be the most effective option however, it major structural adjustments to farmers before implementation.

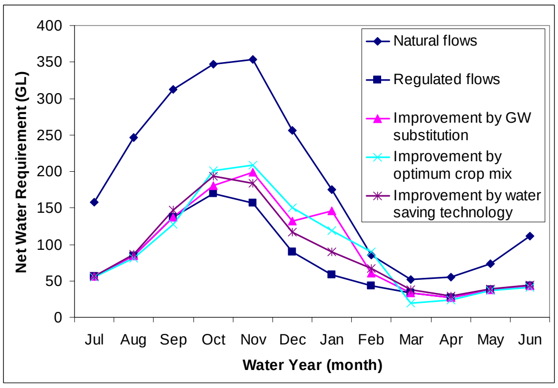

Figure An Effect of the three irrigation demand management options on the river flows at Balranald station

1. INTRODUCTION

The complex climatic variability and human-induced interventions control the dynamic response of the river flow systems. Storage and regulation of river flows for the purposes of irrigation or power generation adversely affect the natural seasonal variations in the river flows. There is a trade-off between level of human interventions in the river system and the degree of maintaining the natural seasonality of rivers flows in irrigated catchments. In the absence of utilising other supplementary options, withdrawals from reservoirs constructed on the Australian rivers mainly for irrigation purpose during dry season are very high as compared to wet season. The summer dominated diversions enhance change in the natural seasonality of the river flows, which poses adverse effects on the river environment. Thinking in a catchment context, there can be several alternative options to manage the irrigation water demand and investigate positive or negative impacts of each alternative solution on the seasonality of river flows.

This paper addresses the similar conditions that prevail in the Murrumbidgee River Catchment. Irrigation water demand of the Murrumbidgee River Catchment is mainly concentrated in the dry period (summer) due to dominant summer cropping while the wet period occurs in the winter season in this region. To fulfil the high irrigation demand during summer flows as high as 6 to 9 gigalitre (GL) per day are released from the upstream reservoirs. In certain reaches of the river, the conveyance capacity is limited e.g. the Tumut River (9 GL per day) and the Gundagai Choke (32 GL per day) (Khan et al., 2004). During high irrigation demand period flows in these reaches find their way from the main channel into the effluent streams or creeks thus causing flooding of the adjacent areas. Since irrigation is the main user of water in the catchment, the aim of this paper is to simulate a range of engineering and management solutions that can ultimately improve or augment the improvement process of the seasonality of flows in the Murrumbidgee River. A combination of hydrological and economic approaches was used to simulate and evaluate different irrigation demand management options in terms of off-stream water savings and economic returns in a system dynamics environment using the Vensim (Ventana Systems, 2004) software tool. The results of the economic analysis are not presented in this paper. The objective of the study is to minimize or shift gap between the average natural flows and the average regulated/flows at the most downstream station called Balranald on the Murrumbidgee River as shown in Figure 1 through irrigation demand management interventions.

A system level holistic approach is required to understand the complex interactions among river inflows, storage, water demand patterns, climate variability, environmental impacts of consumptive uses of water, and the environmental flow obligations. The dynamic nature of abovementioned variables and their effect on overall system can not be captured by the traditional modelling approaches. System dynamics (SD) therefore, is an appropriate approach to conceptualise and simulate complex and dynamic water system processes deterministically which are otherwise partly simulated by conventional hydrologic and stochastic modelling approaches (Khan et al., 2007). SD is the theory of system structures and an approach for representing complex systems and analysing their dynamic behaviour (Forrester, 1961). System dynamics deals with study of how the behaviour of complex system changes through time. The field of SD was pioneered during 1950s when the principles of feedback and control were introduced to the study of economic and business management problems by J. W. Forrester and his colleagues at the Massachusetts Institute of Technology, USA (Forrester, 1995).

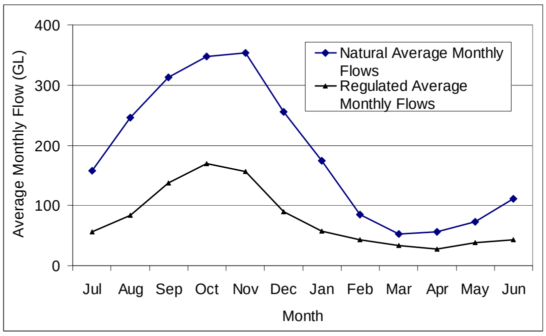

Figure 1 Natural and regulated average monthly flows in Murrumbidgee River recorded at Balranald station before it joins the Murray River

2. STUDY AREA

Murrumbidgee River is the major river in the state of New South Wales and the Australian Capital Territory originating from the Snowy Mountains near Mount Kosciusko. The mainstream of the river is 1690 km long and the major tributary of the Murray River in Murray Darling Basin (MDB). The geographic boundaries of the Murrumbidgee catchment include the Great Dividing Range in the east, the Lachlan River Valley to the north and the Murray River Valley to the south. The Murrumbidgee Valley is highly productive with average total annual turnover of economic activity of $8 billion, contributing $3.8 billion to the Gross Domestic Product (Pratt Water, 2004).

The Murrumbidgee River is highly regulated with 26 dams or weirs, over 10,000 km of irrigation canals (DLWC 1995, Kingsford 2003) and draining a catchment area of 84,000 km^2 from its source to its confluence with the Murray River downstream of Balranald (Figure 2). The weirs were constructed for domestic water supply, stock water supply, irrigation, diversion to irrigation areas and diversion to effluent streams. Two large storages, Burrinjuck (1026 GL) on the Murrumbidgee and Blowering (1632 GL) on the Tumut tributary, are located in the high altitude mountainous and high precipitation part of the catchment upstream of Gundagai (Figure 2) to capture high wet season (winter-spring) flows. Water is released from these dams to meet the irrigation demand of downstream areas during summer mostly between September and March. The main flow constraints in the Murrumbidgee system include the limited conveyance capacity of the Tumut River (<9 GL/day) and the Gundagai Choke (<32 GL/day).

The catchment is divided into three climatological zones - upper, middle and lower Murrumbidgee. Average annual rainfall (1950 – 2000) in the upper part of the Tumut catchment is 768 mm. In the middle reach at Gundagai it is around 584 mm and in the lower reach between Darlington Point and Balranald the average annual rainfall is 428 mm. Rainfall in the Murrumbidgee catchment decreases from east to west. The potential evapotranspiration varies from 1,000 mm in the east to over 1,600 mm per annum in the west.

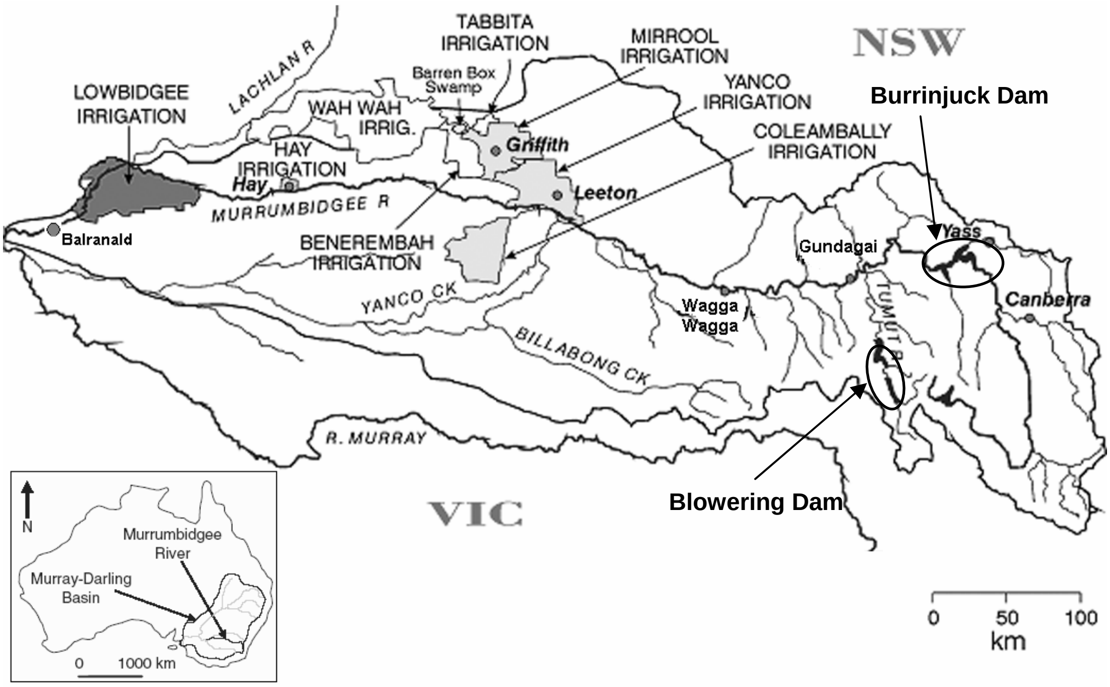

Figure 2 Murrumbidgee River catchment

This paper focuses on two main irrigation areas (Figure 2) which are major users of water in the Murrumbidgee catchment: the Murrumbidgee Irrigation Area (MIA) and the Coleambally Irrigation Area (CIA). A small change in demand pattern of these two irrigation areas can bring about significant change in the overall system. Water-year in this area starts from 1st of July and ends on 30th of June next year. The key characteristics of these areas are given below:

2.1. Murrumbidgee Irrigation Area (MIA)

The MIA is located in the middle to lower part of the middle climatological zone of the Murrumbidgee catchment (Figure 2) covering approximately an area of 3,624 km^2. It is composed of the Yanco, Mirrool, Benerembah, Wah Wah and Tabbita irrigation districts with bulk water license of 1200 GL. The topography is a relatively flat open plain at an elevation of 100-135 m above mean sea level. Metered water is delivered onto farms and farmers pay for the volume of water supplied which is used for growing crops such as grapes, citrus, rice, wheat, barley, oats, canola, soybeans, maize, sunflowers, lucernes and pastures for sheep and cattle. Drainage water from irrigation farms in Yanco, Benerembah and Mirrool flows through the Mirrool Creek to the Barren Box Swamp and then into the irrigation districts of Benerembah, Tabbita and Wah Wah.

2.2. Coleambally Irrigation Area (CIA)

The CIA is located to the south of the Murrumbidgee River (Figure 2). The irrigation area was developed during the 1960's to make use of water diverted westward as a result of the Snowy Mountains Hydro-Electric Scheme. Water is diverted to the area from the Murrumbidgee River at the Gogeldrie Weir. CIA covers an area of 79,000 ha held in 452 farms and has a bulk license of 629 GL of water which is used for irrigation. Drainage water flows via Yanco and Billabong Creeks before entering the Murray River. Irrigation water is used for growing crops such as rice, wheat, barley, oats, canola, soybeans, maize, sunflowers, lucernes, grapes, prunes and pastures for sheep and cattle. Irrigation has turned what used to be less productive land into highly productive land. Export of produce from CIA is very important for the regional economy as over 80% of rice produce of the area is destined for overseas markets.

The major hydro-ecological issues in this catchment include altered flow regimes and their impacts on river and wetland ecosystems, water quality, dryland and irrigation salinity. Many irrigators are fearful of losing valuable entitlement and access to water supplies. There are concerns about groundwater depletion and the risk of groundwater contamination (Khan, 2004). Moreover, the impacts of these altered flow regimes on wetlands along the watercourses are significant, and vary markedly depending on the nature and extent of the alteration to the flow regime (Ritchie and James, 2000). Since irrigation in MIA and CIA uses major share of water in the catchment, the aim of this paper is to simulate using SD approach a range of hydrologic and management options for irrigation demand at irrigation area level that can ultimately improve or augment the restoration process of the seasonality of natural flows in the Murrumbidgee River.

3. METHODOLOGY

Since MIA and CIA are the major users of water in the valley, their small adjustment in irrigation demand can bring about significant change in the gap between the natural and regulated flows. The selected alternative demand management options investigated in this article are listed below:

- Groundwater substitution
- Summer-winter crop mix
- Improved irrigation efficiency

Irrigation demand is computed for the three alternative options based on the assumed spatial and temporal distribution of crops, better use of groundwater and adoption of water saving technologies. For each management option overall impact on irrigation demand, reduction of peak water demand and or shift of demand from summer to winter is assessed. The main steps of the adopted methodology are shown in Figure 3.

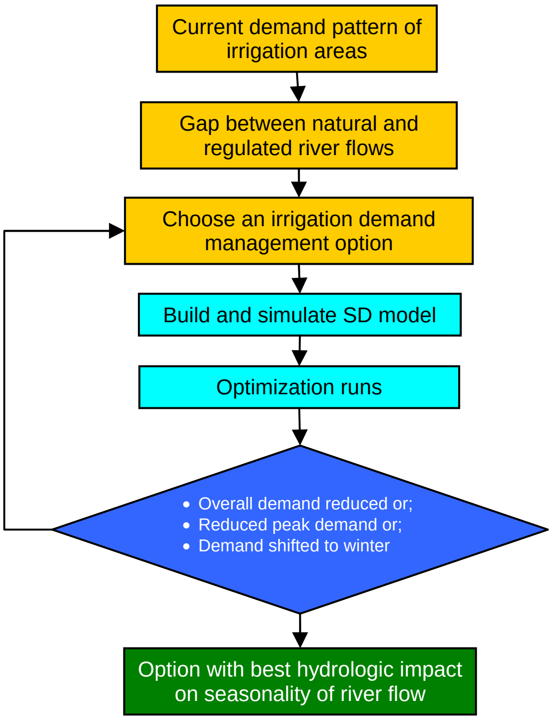

Figure 3 Flowchart of adopted methodology

Vensim software tool was used to develop a SD model of the irrigation system by incorporating variables like individual crop areas, monthly crop water requirement per ha and the total monthly available water. Crop water requirement was calculated using FAO Penman-Monteith model (Allen et al., 1998).

3.1. Exploring the Causal Loop Diagrams

Causal loop diagrams (also called influence diagrams) represent major feedback mechanisms, which reinforce (positive feedback loop) or counteract (negative feedback loop) a given change in a system variable (Sterman, 2000). The causal loop diagrams are helpful in conceptualizing the system structures and understanding how different variables are inter-dependent. Two causal loop diagrams/mechanisms were professed in the system under consideration. The first causal loop diagram (Figure 4) represents the interaction among different variables at the river system level. For example, higher the inflows, higher the dam storage level and higher the dam releases, which inturn increase environmental flows through the river system, which implies higher inflows, thus completing a positive feedback loop. Similarly, higher the dam storage level, higher the releases, then higher the diversions and the irrigation supply, which in turn reduce dam storage levels thus completing a negative feed back loop.

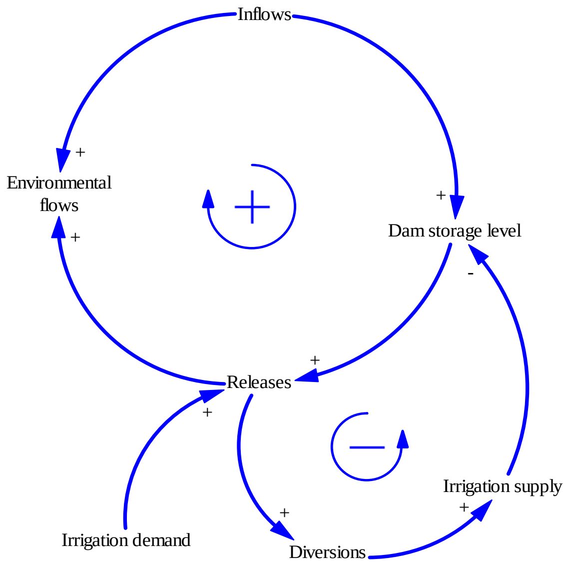

Figure 4 Causal loop diagram of releases and diversions in a river system

Figure 5 presents the causal loops diagram of the variables involved at the irrigation system level effectively presenting feedback loops involved in two irrigation management strategies namely (i) changing crop mix and (ii) the augmentation of surface irrigation demand with groundwater pumping.

The interpretation of above mentioned causal loop diagrams advocates that it is not possible to simulate such complex and dynamic interactions using simple hydrologic models. Therefore the use of SD approach is justifiable for such problems.

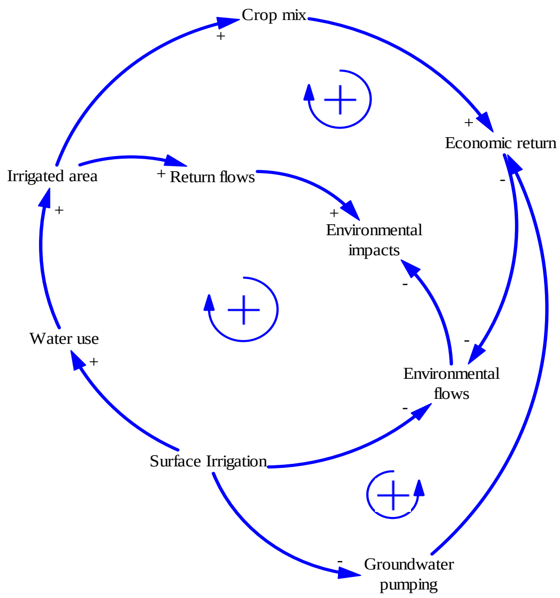

Figure 5 Causal loop diagram of input output variables of an irrigation system

3.2. The System Dynamics Model

The SD approach used in this study to simulate irrigation demand has four basic building blocks; stock, flow, connector and converter. Stocks (also called levels) represent anything that accumulates; an example would be water stored in reservoirs. Flows (also called rates) represent activities that fill and drain stocks as the simulation proceeds; for example releases or inflows. Connectors (arrows) are used to establish the relationship among variables in the model; an arrow from A to B indicates that A causes B i.e. B depends on A. They carry information from one element to another element in the model. Converters are mathematical functions that transform input into output. The causal loop diagrams depict the static picture of interactions among the model variables while a SD model can be developed to simulate the entire life cycle of the system under consideration.

4. RESULTS AND DISCUSSION

Figure 6 shows the typical net crop water requirement pattern of the two major irrigation areas (MIA and CIA) for dry (1994), wet (1991) and average (1995) climatic conditions based on analysis of climatic data from 1991 to 1999. Figure 6 signifies that irrigation water demand of the area is mainly concentrated in dry season (November – February) due to dominant summer cropping peaking up to 310 GL while the wet period occurs in the winter season (May – August) when the irrigation demand is almost zero in this region.

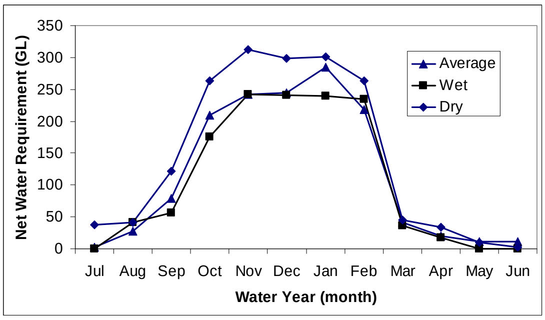

Figure 6 Combined net crop water requirement pattern of MIA and CIA for wet, dry and average climatic conditions

The SD model simulation was run over the whole water year (July to June) for 2000/01 where average climatic conditions prevailed. Simulation results of the modelled three demand management options are discussed in the following sections.

4.1. Groundwater Substitution

To reduce pressure on surface water supply and avoid flooding in upper reaches of the river, a fraction of the surface water use was substituted by the groundwater during the peak period of daily irrigation demand. The SD model was set up to substitute additional irrigation water requirement with groundwater to keep the surface water demand not to exceed 200 GL/month. In this case, the total amount of groundwater pumped is 200 GL over a period of four months, resulting into saving of same amount of surface water that can be contributed to improve the seasonality of the river flow as shown in Figure 7. A possible management intervention may be to promote groundwater use during the summer months especially during November to February while the surface water is made available during the winter months.

4.2. Summer-winter crop mix

As the cropping patterns of MIA and CIA are dominated by the summer crops which require more irrigation water, an appropriate mix of crops grown in summer and winter can effectively reduce the high water demand during hot months. The SD optimization model was set up with the objective of optimization to reduce total water requirement while change in any summer crop-area must not exceed 15% while maintaining same economic returns for the year 2000/01. An optimum mix of summer and winter crops obtained is given in Table 1. It reduces the total water demand from 1394 GL to 1176 GL. The effect of the alternative crop mix on downstream river flows is shown in Figure 7.

Table 1 Current and optimum mix of summer and winter crops in MIA and CIA for the year 2000/01 (Percent of the total irrigated area in MIA & CIA)

Crop	Current crop area (%)	Optimized crop area (%)
Maize	2.65	6.00
Wheat	23.52	25.00
Barely	2.61	2.61
Canola	2.11	2.00
Oat	1.91	4.00
Soybean	3.39	3.39
Sum. vegetables	0.68	0.68
Win. vegetables	0.68	2.00
Rice	33.25	18.25
Sum. pasture	1.79	1.79
Win. pasture	15.53	15.53
Citrus	3.97	8.00
Lucerne (cut)	0.09	0.09
Lucerne (uncut)	1.13	0.00
Stone fruit	0.48	0.48
Vines	6.22	10.00

4.3. Improved irrigation efficiency

By improving the on-farm water use efficiency, less water will be required to maintain the same level of production. Use of two pressurised irrigation technologies; drip irrigation system (DIS) and sprinkle irrigation system (SIS), was investigated. DIS was selected for horticultural crops, vines and citrus, while SIS for the other crops. Adoption of such technology would reduce the total irrigation demand by 11%. The river flow augmented by water saved from improved irrigation efficiency is shown in Figure 7.

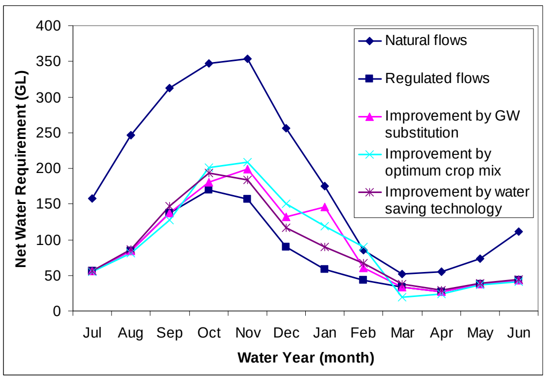

Figure 7 Comparison of effect of the three irrigation demand management options on the river flows at Balranald

5. CONCLUSIONS

Irrigation is the major user of water in the Murrumbidgee River catchment. Increased summer irrigation demand and flow regulation by two major storages has changed the natural flow regime of the river flows. This has resulted into environmental degradation and flow conveyance problems in some parts of the catchment.

The SD simulation of various demand management options conclude that substitution of surface water with groundwater reduce surface water demand by 200 GL, the alternative crop mix can save 218 GL and adoption of pressurized irrigation technologies can save up to 153 GL of irrigation demand. The saved water can augment the improvement process of the river health by reducing gap between natural flows and the current flows. For example summer-winter crop mix option increased maximum river flow at Balranald from 170 GL/month to 209 GL/month.

It is however, not possible to completely restore the seasonality of the river flows to the natural condition due to the large volume of diversions from the river for consumptive use.

6. ACKNOWLEDGEMENT

Authors wish to acknowledge funding support from the Cooperative Research Centre for Irrigation Futures.

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