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USING A SYSTEM DYNAMICS APPROACH TO MODEL SUSTAINABILITY INDICATORS FOR IRRIGATION SYSTEMS IN AUSTRALIA

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ABSTRACT. An indicator defined as a function of the total water diversion through the Coleambally canal and the potential irrigation demand is selected to represent the sustainability of the irrigation water system in the Coleambally irrigation area, Australia. A simulation procedure using a system dynamics approach was developed to evaluate the indicator. The procedure includes water diversion assessment, potential crop water demand and total gross margin.

Three cases of water supply options (surface water, ground water pumping and water trading), two cases of changes in the total agricultural area and three cropping pattern scenarios were simulated to better understand their impact on sustainability. The simulated results indicate that increasing the agricultural area reduces the sustainability of the irrigation system because the demand of water increased despite increase in the gross margin. The scenarios show that imposed water trading and ground water pumping would considerably increase the supply system having a positive impact on the sustainability. The paper concludes that a multi-objective sustainability indicator taking account of economic and environmental issues could be more useful.

KEY WORDS: Economic, environment, system dynamics, sustainability indicator, water management.

1. Introduction.

Good water management means to make decisions and implement them in such a way to move toward a goal without reducing the future options. Reducing future options may make effective water management impossible, or at least more difficult. Therefore, introduced or merged new technologies such as system dynamics to study and evaluate the irrigation system to introduce a sustainability indicator is needed for better understanding of the irrigation system. Moreover, achieving sustainability is possible with some cost while management actions would reduce sustainability wherever they constricted future options.

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. Sustainable development and sustainability are contested terms, with a range of approaches and definitions (Beder [1996], Johanston [1997]). Increasingly, researchers and policy makers are advocating sustainable development as the best approach to today's and future water problems (Louks [2000]).

Many researchers have pointed out that the fundamental factors of the water crisis (Baumann and Boland [1998], Grigg [1996], Loucks [2000]) are: population growth, economic growth and urbanization; rise in per capita water use; a finite supply of fresh water; pollution and contamination; and increase in the frequency and severity of drought. Moreover, water scarcity could push and encourage people to emigrate to look for water sources which might lead to water wars. People who experience this problem can be called "water refugees."

According to the Department of Land and Water Resources (DLWC [1998]) water is a finite resource, and the signs are that it has reached the limit of reasonable use. In addition, in irrigation demand management, sustainability implies a notion of balance or equilibrium between crops water demands and the in-stream demand. The traditional approach to managing water has been to build dams to provide a secure water supply for water users. This approach has been wasteful and has had some devastating impacts on the environment. Consequently, there has been emphasis on demand management in water resources management (Winpenny [1994]). Furthermore, only in the last decade, as the scarcity of water and degraded water environment have become apparent, has it been proposed that water management in the future should be based on sustainable water management using sustainability principles that take into account environmental and economic aspects.

Water is required for different purposes and users, and these compete for quantity, quality and timing. It becomes a matter for competition in terms of quantity, quality and timing. Moreover, uncertainty in water allocations, environmental flow requirements and intensive cropping systems require a better understanding of the irrigation system by applying different sustainability criteria. In this context, three cases of water supply options (surface water, ground water pumping and water trading), plus two cases of changes in the total agricultural area and three cropping pattern scenarios were simulated to better understand their impact on the projected sustainability indicator.

2. The study area. The current study is carried out on a regional scale, i.e., Coleambally irrigation area in the Murrumbidgee catchment. The Murrumbidgee catchment is located in New South Wales (NSW), Australia and has an area of about 84,000 km^2. The Coleambally sub-catchment is located on the southern side of the Murrumbidgee River, see Figure 1. The Coleambally Irrigation Area (CIA) is the second largest area of irrigation production in NSW, 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 such as prime lamb, wool and beef production. Irrigation also occurs along the Murrumbidgee River through private diverters.

It has been reported by DLWC [1998] that, under normal conditions, irrigators could expect to receive their full allocations in all years except in the driest years, see Table 1. An initial allocation made at the commencement of the season is updated regularly during the season according to the amount of 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. 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 be diverted increasingly to meet the needs of other users, e.g., environmental and other in-

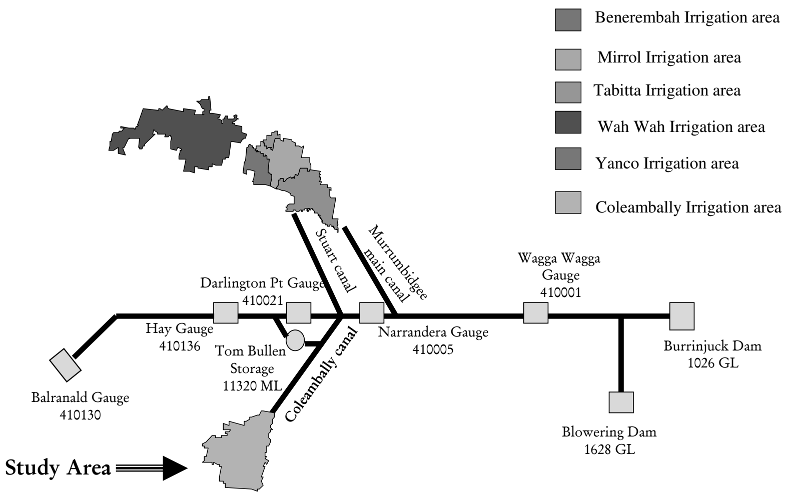

FIGURE 1. Coleambally irrigation area and main river off take canals.

stream water demands have 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, see COAG [1994, 2004].

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. Since the introduction of the Murray-Darling Basin Cap on water diversion, exchange rates for water trade between different water sources, and a variety of water sharing plans and environmental flow rules, the water allocations announced at the start of the season have been reduced, i.e., they no longer reach 100% of the entitlements. As a result, there is a major drive to study and address the impact of water reforms and reduced water availability on sustainability of the irrigation system in terms of different supply and demand options.

Moreover, since 1994 there has been an increased emphasis in water trading as a solution for water-sharing problems in the Murrumbidgee and across the Murray Darling basin. In particular, the limitation

TABLE 1. Comparison of allocation percentage announcements in the Murrumbidgee catchment, 1980–2003 (Data source: Pers. Comm. Shahbaz Khan, 2003).

Water year	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Note
1980/1981	67	67	85	95	100	100	100	
1981/1982	100	100	100	100	100	100	100	
1982/1983	na	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	na	120	120	120	120	120	120	
1994/1995	na	100	100	100	100	100	100	Cap on water diversion introduced
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	NSW Water Sharing Plan started
1998/1999	60	72	79	81	81	81	85	
1999/2000	50	53	60	67	67	73	78	Environmental flow requirement started
2000/2001	59	60	80	90	na	na	na	
2001/2002	47	53	na	65	na	na	72	
2002/2003	34	38	na	na	na	na	na	

Na means no data available.

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 through trading has increased as shown in 2003 for CIA, Figure 2. This can be attributed to the low water allocation for the season and increased

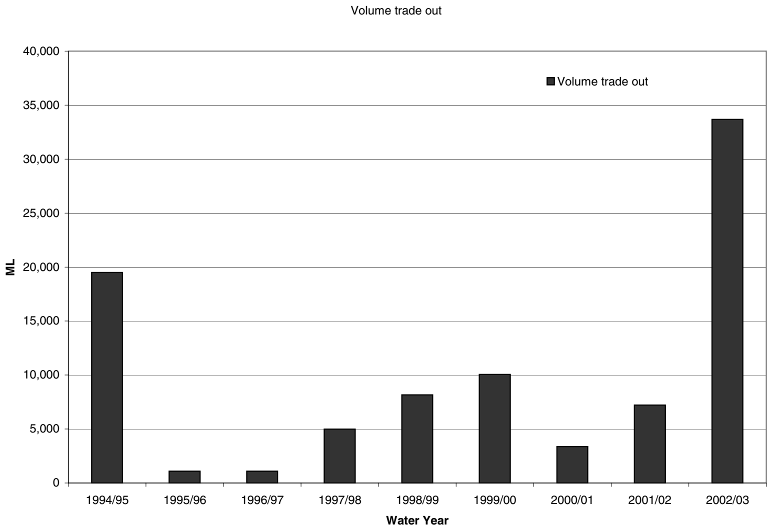

FIGURE 2. Volume transferred out of CIA.

prices for temporary transfer causing many farmers to decide to sell their water rather than plant their crops.

3. System dynamics approach. In a complex water resource system such as the irrigation system under investigation in this research, the problems usually include many kinds of stochastic variables, i.e., no trend variables. Meanwhile, difficulties often arise from the integration of economic and environmental perspectives with biophysical processes. The dynamic character of the main variables and how they affect water use in the future, however, cannot be captured through traditional modeling. Although the application of optimization techniques has been a major field of research in water resources planning for many years, their adaptation to practical applications has not been successful, partly due to the fact that most applications dealing 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 of those promising options is a feedback-based, object-oriented system dynamics approach, which offers a way of modeling the future dynamics of complex systems (Simonovic [2000], Shi

[2004]). Recent applications of the system dynamics approach in the field of water resource management have been mainly focused on issues such as river-basin planning, assessment of water resources, long-term water resource planning and policy analysis and reservoir operation (see Simonovic and Fahmy [1999], Ahmed and Simonovic [2000]), less attention has been paid to the analysis of water allocation, based on economic rationale, at the farm level within the constraints of environmental flow rules (Elmahdi et al. [2004]).

Using Vensim$^{\text{TM}}$ (Vensim is a Trade Mark of VENTANA 1996) as a software development tool to configure the water balance network model, a system dynamics Network Simulation Model (NSM) (Elmahdi et al. [2004]) was developed to analyze historical water allocation for the Coleambally irrigation area within the constraints of environmental flow rules based on economic rationale. The purpose of Vensim$^{\text{TM}}$ is to help solve problems that would be hard to address mathematically without the aid of simulation. Moreover, the Vensim$^{\text{TM}}$ environment will insulate the user from both the underlying mathematics and the details of the language specification.

4. Design of supply sustainability indicator SSI. While traditional quantities such as crop demand, water supply or diversion and irrigated area provide information about irrigation system status and act like indicators, none of them alone can indicate sustainability. Sustainability indicators cannot be selected without considering the aim of sustainable development. Sustainability of an irrigation system could be influenced by land use, different supply options and climate change. For the purpose of irrigation system management, the projected supply index could be used to indicate allowable demand.

Currently average end of system flow of Murrumbidgee River represents 5–10% of monthly dam release. This paper suggests 20% end of system flow as the minimum sustainable flow. If diversion increases above 80% of dam release, the system is considered to be unsustainable.

If the demand exceeds the supply water, river health will be affected and degraded as the demand will require and withdraw water from the environmental allocation. If the demand is less than the 80% of the supply, the system will be sustainable and river health will be improved in terms of satisfying environmental flow requirements.

An indicator defined as the ratio of the maximum possible water diversion and supply options through the Coleambally canal and the potential irrigation demand (see equation (1)) is selected to represent the sustainability of the irrigation water system in the Coleambally irrigation area, Australia.

$$SSI = \begin{cases} \dfrac{(\mathbf{S_D})_m}{\mathbf{S}_m} & \mathbf{S} > \mathbf{D} \\ 0 & \mathbf{S} \leq \mathbf{D}, \end{cases} \tag{1}$$

where **S** is the potential supply and **D** is the potential demand in month m.

The range or the value of index varies between zero and one as shown in Table 2.

A simulation model was developed to evaluate the value of the indicator using the system dynamics approach. The model procedure includes water diversion assessment, potential crop water demand and total gross margin. The Network Simulation Model (NSM) (Elmahdi et al. [2004]) which uses a system dynamics approach is an appropriate tool to analyze irrigation management strategies. This model is designed to operate on a monthly basis and can assist managers in analyzing the system's behavior under various management scenarios. It also demonstrates the effect of climate variability between cropping seasons. The conceptual and implementation details of the model are discussed in Elmahdi et al. [2004]. Briefly the model gives priority to environmental demand as the main constraint as end-of-system flow and then attempts to satisfy the biophysical crop demand.

TABLE 2. The range and status of sustainability index.

Range	Status
> 0.2	No stress of water supply system
< 0.2	Vulnerable conditions of supply system
0	Unsustainable water supply system

5. Sensitivity analysis. Three cases of supply options and two cases of total cropping area are considered as follows:

- *Case* 1. supply = Diversion
- *Case* 2. supply = Diversion + Ground water pumping
- *Case* 3. supply = Diversion + Ground water pumping + Water trading
- *Case* 4. supply = Case 3 supply with increased total area
- *Case* 5. supply = Case 3 supply with decreased total area

The five cases were tested with three hypothetical cropping scenarios (winter cropping, summer cropping and water saving). These three scenarios are compared to the status quo or current scenario in which the current cropping pattern percentage is applied. Table 3 shows the percentage of cropping area in different scenarios with ten crops. In the water saving scenario, high water requirement crops such as rice and wheat are suppressed, whereas the summer and winter scenarios propose an increase in the area planted to summer and winter crops, respectively.

The main constraint imposed on the system is to satisfy the environmental target flow first and then the agricultural water demand. The model was applied to a ten year time series (1993–2003) to evaluate the supply sustainability index (SSI). Figure 3 shows the sustainability index for the three supply options together with the status quo scenario. It is clear that the average SSI for 10 years shows that Case 1 and Case 2 are sustainable most of the years compared to Case 3.

As shown in Table 4, Case 3 has a 70% frequency of unsustainable years. In Case 3 the SSI falls below 0.2 reflecting vulnerable conditions imposed by historical water trading. This is a reflection of farmers with low water allocation deciding to sell their water rather than planting their crops which resulted in more water leaving the area than entering the area as reported by CICL 2003. This trend is shown in Figure 3 for the period 1995/2003.

Compared to other scenarios Figure 4 demonstrates, ground water and water trading have positive impacts on the sustainability index. Except the 2002/03 year in which the value falls to 0.1 due to unusually low allocation, all other years recorded a value greater than 23%. Case 3 has a positive impact on sustainability for all the scenarios except for

TABLE 3. Cropping pattern percentage for each hypothetical scenario.

Scenario	**Rice**	**Wheat**	**Maize**	**Barley**	**Oats**	**Canola**	**Vines**	**Win-Past**	**Soy-bean**	**Lucerne**	**Total 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%

TABLE 4. The frequency and index range for the five cases.

Case	Case 1 (Supply=Diversion)		Case 2 (Supply=Diversion+GW)		Case 3 (Supply=Diversion+GW+WT)	
Average Sust. Index	Index Range	Frequency Year unsustainable	Index Range	Frequency Year unsustainable	Index Range	Frequency Year unsustainable
Statuesque	0.10–0.26	4	0.09–0.26	4	0.12–0.24	7
Winter Scenario	0.08–0.40	1	0.09–0.40	1	0.10–0.41	1
Summer Scenario	0.14–0.27	2	0.16–0.27	2	0.17–0.28	1
Water Saving Scenario	0.11–0.39	1	0.12–0.40	1	0.13–0.41	1

TABLE 4. CONT'D.

Case	Case 4 Increased the total area with (Supply=Diversion+GW+WT)		Case 5 Decreased the total area with (Supply=Diversion+GW+WT)	
Average Sust. Index	Index Range	Frequency Year unsustainable	Index Range	Frequency Year unsustainable
Statuesque	0.07–0.24	6	0.12–0.28	2
Winter Scenario	0.05–0.36	1	0.13–0.43	1
Summer Scenario	0.19–0.24	4	0.2–0.31	0
Water Saving Scenario	0.08–0.36	1	0.17–0.44	1

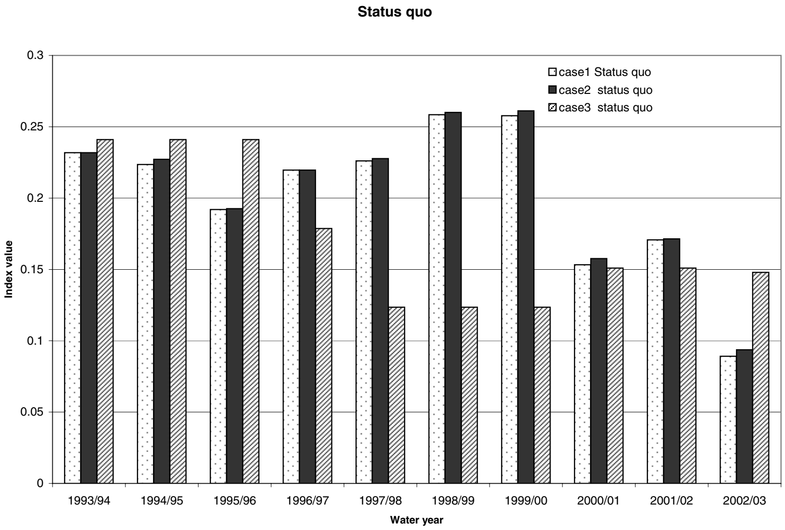

FIGURE 3. Status quo with three cases.

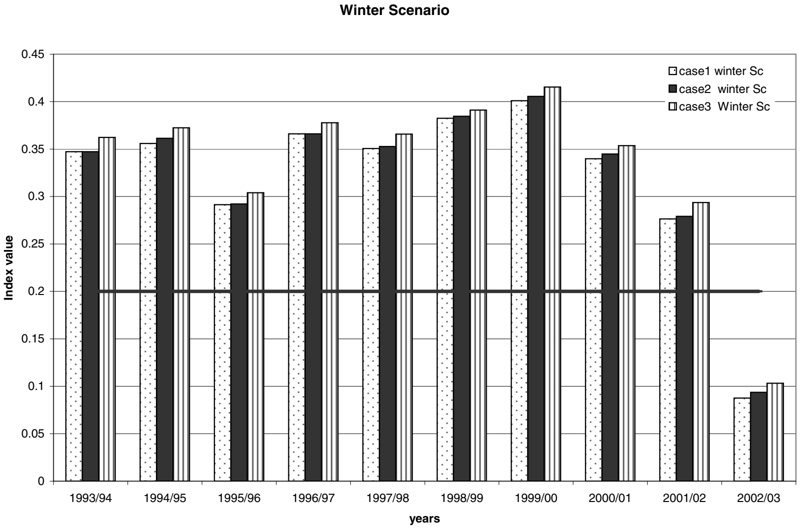

FIGURE 4. Winter scenario with three cases of supply options.

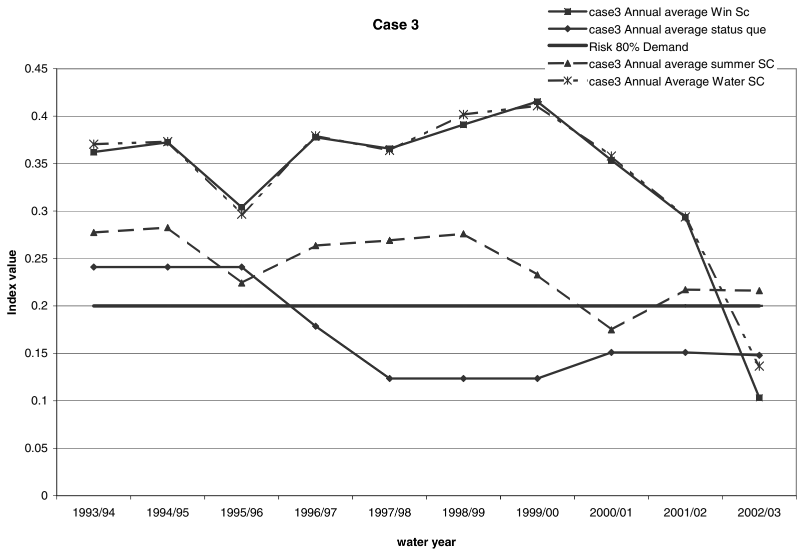

FIGURE 5. Case three with all scenarios.

the status quo scenario. In Case 2 of the status quo scenario, ground water pumping is shown to have a more positive impact than Case 3 water trading.

In broad spectrum, Figure 5 shows within the same case that both the winter and water saving scenarios have positive impacts on sustainability as demand is less than 80% of the available water. The values of SSI in winter and water scenarios are much higher than summer and status quo scenarios.

Moreover, Figures 6 and 7 show the different scenarios with the last two cases changed by the total irrigated area. The overall best scenario is the water saving scenario as the high water requirement crops are avoided. Although the winter scenario is sustainable most of the years, still the water saving scenario is the best as it has achieved high range values during the last ten years and through all five cases.

It is clear that there is a trade off between sustainability as shown by the water saving scenario and total gross margin. Table 5 shows the total gross margin, total income and total variable cost resulting from the different scenarios under Case 3. From an economic point of view

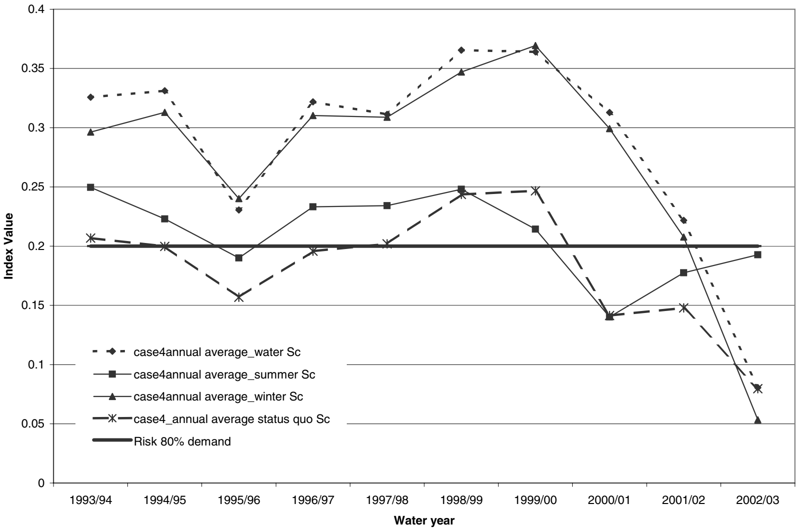

FIGURE 6. Case 4 increased total irrigated area with all scenarios.

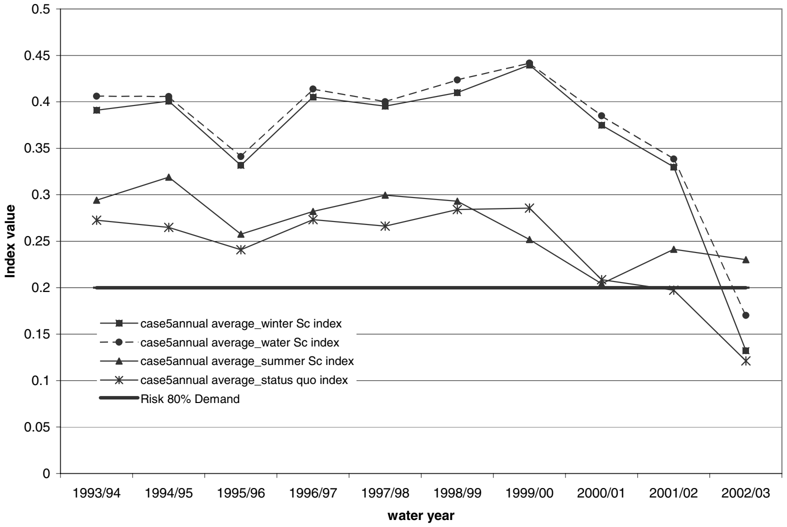

FIGURE 7. Case 5 decreased total irrigated area with all the scenarios.

TABLE 5. The total gross marginal with the three cases and scenarios.

Case 3	Status quo scenario	Summer scenario	Winter scenario	Water saving scenario
TGM $Au	56.01	64.40	23.57	10.70
Tot. Income $Au	105.17	120.40	57.70	42.40
V. Cost $Au	49.16	55.98	34.12	31.70

(maximizing gross income) the summer scenario of the Case 3 provides a positive result.

Another economic perspective especially for farmers of the developing countries could be obtained by looking at minimizing the cost, and in that case the water saving scenarios provide a positive result for all three cases and at the same time minimize the use of the resource. Because the water saving scenario has avoided high water requirement crops such as rice, which are mainly responsible for high water demand and high cost during the summer and winter seasons, respectively.

6. Conclusion. Water sustainability over the long term management includes land use and conservation aspects which can promote the efficient use of water under normal and extreme conditions. This paper reports a system dynamics approach to irrigation demand management and design water supply sustainability index SSI, by linking the hydrological constraint with environmental and economic issues. Using historical allocation, pumping and trading data to study and understand the water conflict between irrigation and environmental users combined with the economic issue. Moreover, several scenarios and cases could be drawn through changing the cropping pattern and total cropped area through using NSM model. Thus, SSI presented herein has shown the capability to evaluate and determine the supply system performance with introduced different supply options and development of the irrigated area based on projected 80% demand.

Furthermore, several scenarios have been tested and evaluated using SSI index. This index helped in the periodic evaluation of the system. Moreover, this research has demonstrated the potential of a system dynamics approach to be used by stakeholders and decision makers to improve the quality of policy making in terms of sustainable irrigation water management. Finally, this index could be a useful tool for better a understanding of the supply system with demand constraint.

The SSI indicator presented in this research has potential to apply to different sectors of water users in order to achieve the best values of environmental, social and economic outcomes. Further investigation is needed to develop much more realistic indicators to compare water system based on triple bottom line outcomes.

The uncertainty conditions have an effect on water supply systems which need cooperation among water users and local, regional and national planners. Variability in water flow is a natural phenomenon and should be preserved if such systems are to sustain their natural ecosystems. However, very extreme events such as drought typically bring substantial economic damage. Furthermore, the control and management of the extreme events have a high priority in achieving sustainability. Thus sustainability criteria recommended should include risk measures and management as part of the overall assessment of possible system failures and their possible consequences.

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