System Dynamics Analysis of a Land Based Stream Salinity Management Approach

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EXTENDED ABSTRACT

In river plains, tributary streams generally carry rainfall runoff from catchments, escape water from irrigation areas and groundwater inflows. Rainfall runoff from inland catchments and escape water from irrigated land areas are normally of low salinity as compared to that of groundwater inflows, for example in the Murray River catchment the groundwater salinity can be as high as 50,000 µS/cm. High salinity levels in the rivers are responsible for increasingly serious environmental, economic and social consequences in the downstream irrigated regions.

Preventive and remedial strategies are adopted to manage salt load in stream flows at the catchment and farm scales, particularly in dryland areas of Australia. The aim of preventive strategies is to prevent further increase in salt load by decreasing discharges of salt from catchments and from rising watertables. The aim of remedial strategies is to decrease or at least stabilize salt load in flows and to manage agricultural saline wastewater discharges. Catchment scale studies suggest that management of stream salinity require greater land use change than is economically viable. However, there has not been significant breakthrough in suggesting cost-effective farm scale stream salinity management alternatives, especially for irrigated areas.

Removal of saline water from the Box Creek Stormwater Escape Channel (SEC) in the Murray Irrigation Area by pumping into off-stream storage can improve the stream water quality. This paper presents an application of the system dynamics (SD) analysis of composite salinity of the storage water which is subjected to land based salinity management approach for contaminated waters. Contaminated surface waters are now frequently treated using a series of vegetated wetlands where intense biological processing occurs. One option for managing inevitable drainage water is to sequentially use and re-use it to grow salt-tolerant crops while concentrating the drainage to a manageable level. This treatment system is known as the "Sequential Biological Concentration (SBC)".

The results of SD iterative simulations of feedback mechanisms (Figure 1A) involved in controlling the dynamics of storage and its salinity levels show that 330 ML storage will be sufficient to extract significant amount of salt loads from the creek and supply to the SBC system of 30 ha plot in the first stage of treatment. Also it was found that the proposed SBC system is more efficient in terms of salts removed per unit volume of water extracted from the creek during the dry periods (2002-03). This paper presents a scoping study for salinity management of the Box Creek SEC receiving saline agricultural drainage through SBC setup simulated by system dynamics modelling.

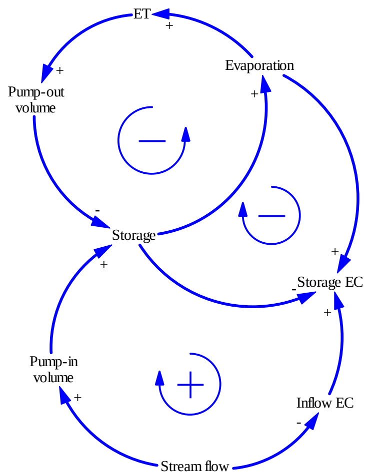

Figure 1A. Causal loop diagram of the feedback mechanism.

1. INTRODUCTION

Several factors increase salt loads in streams including; clearing of deep rooted natural vegetation from catchments and replacing them with shallow rooted crops, increasing diversions from streams for irrigation, receiving of saline agricultural return flows (drainage), and/or rising saline watertables in the adjacent areas. Increased salt load during periods of low flows in arid and semi-arid regions (mean annual rainfall 25-500 mm) are the prime contributor to environmental degradation of rivers, creeks, streams and other water bodies. These regions cover about one-third of the total globe land mass, and spread across in parts of Central America, South America, North America, the Middle East, South Asia, Central Asia and Australia. In these regions, there is considerable environmental and social pressure to reduce salt load in rivers (Blackmore et al., 1999).

In river plains, tributary streams generally carry rainfall runoff from catchments, escape water from irrigation areas and groundwater inflows. Rainfall runoff from inland catchments and escape water from irrigated land areas are normally of low salinity as compared to that of groundwater inflows, for example in the Murray River catchment the groundwater salinity can be as high as 50,000 µS/cm. Salt contribution from groundwater can predominantly be significant in reaches where groundwater gradient is towards the streams. High salinity levels in the rivers are responsible for increasingly serious environmental, economic and social consequences in the irrigated regions.

Preventive and remedial strategies are adopted to manage salt load in stream flows at the catchment and farm scales, particularly in dryland areas of Australia (Herron et al., 2002; Beverly et al., 2003; Cresswell et al., 2003; van Bueren and Price, 2004). The aim of preventive strategies is to prevent further increase in salt load by decreasing discharges of salt from catchments and from rising watertables. The aim of remedial strategies is to decrease or at least stabilize salt load in flows and to manage agricultural saline wastewater discharges. Catchment scale studies suggest that management of stream salinity require greater land use change than is economically viable (Herron et al., 2003; Tuteja et al., 2003). Therefore, instead of focusing on the opportunity cost of catchment scale interventions; exploring interventions that are potentially viable at farm scale could be an appropriate strategy for stream salinity management as mentioned by Nordblom et al., (2004), and Lefroy et al., (2005). Duncan, et al. (2005) reviewed pervious studies of salt mobilisation processes and management strategies in irrigation areas of Australia. However, there has not been significant breakthrough in suggesting farm scale cost-effective stream salinity management alternatives, especially for irrigated areas.

System Dynamics (SD) is an approach to simulate the behaviour of the complex systems which are composed of processes driven by feedback mechanisms and where the causes and effects can change based on the time dependent boundaries of the systems. The SD approach is an appropriate deterministic technique for simulating complex problems in integrated water resources management and seeking best management solutions while keeping track of the whole system response (Khan et al., 2007a).

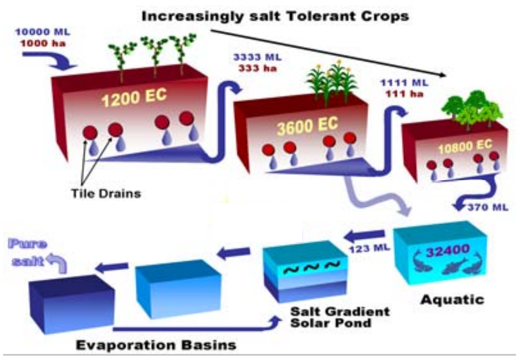

Figure 1. Schematic of possible layout, flows and concentrations of the SBC system (adapted from Khan et al., 2007b)

Removal of saline water from the Box Creek Stormwater Escape Channel (SEC) by pumping into off-stream storage can improve the stream water quality. This paper presents an application of the system dynamics analysis of composite salinity of the storage water which is subjected to a land based water salinity management approach for contaminated waters. Contaminated surface waters are now frequently treated using a series of vegetated wetlands where intense biological processing occurs. One option for managing inevitable drainage water is to sequentially use and re-use it to grow salt-tolerant crops while concentrating the drainage to a manageable level. This treatment system is known as the "Sequential Biological Concentration (SBC)". A schematic diagram of the SBC system layout is shown in Figure 1 with example values of flow volumes and salinity of each SBC stage (plot). The SBC idea emerged out as a viable option (Khan et al, 2007b) for enhancing use of saline waters for irrigated cropping and solving associated risks of saline water irrigation that is not environmentally sustainable. Specifically, the concept of SBC of salts aims to reduce drainage effluent volumes from irrigated lands (Mann et al., 2003). This paper deals with diversion and storage of saline water volumes from the Box Creek SEC and their provision for treatment by an SBC system.

2. STUDY AREA

The Murray-Darling Basin (MDB) covers about one-seventh the total area of Australia. It has a catchment of around 110 megahectares (Mha), which covers 75% of New South Wales (NSW), 56% of Victoria, 15% of Queensland and 7% of South Australia. To combat the environmental problems Land and Water Management Plans (LWMPs) were designed using both the preventive and remedial strategies for managing salt load from the irrigated areas and are widely being implemented in the MDB. For the implementation of these LWMPs, each state will receive salinity credits of 15 electrical conductivity (EC) units. One EC unit is equivalent to microSiemens per centimetre (μS/cm). Thus, by dividing the EC unit by 1000, water salinity can be referred to as deciSiemens per metre (dS/m).

In the NSW Murray Irrigation Area (MIA), Murray Irrigation Limited (MIL) is the implementation authority for the Murray LWMPs. MIA covers an area of nearly 0.95 Mha spread over 3090 landholdings (primarily irrigation farms) spread in four irrigation districts namely Berriquin, Denimein, Wakool and Deniboota (Figure 2).

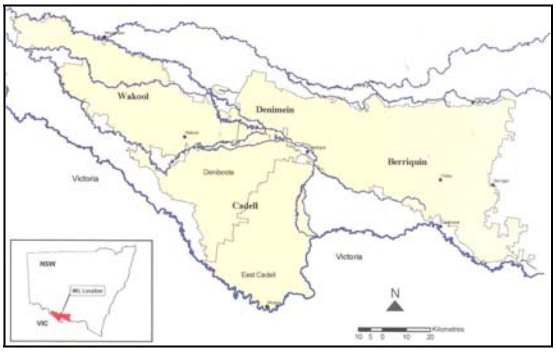

Figure 2. Map of the Murray Irrigation Limited irrigation districts (area of operation) Source: Murray Irrigation Limited

In the early 1950's, the Box Creek SEC was constructed to provide an outlet for stormwater and agricultural drainage from the Berriquin and Denimein irrigation districts. The Box Creek SEC, which is 133 km long with a catchment area in of 0.05 Mha, is an integral component of the MIA supply and stormwater escape system. The water quality of Box Creek SEC with respect to salinity and nitrogen has deteriorated over time. However, turbidity and phosphorous are found to be within acceptable ranges.

Generally, salinity levels of flows in the Box Creek SEC during irrigation and rainfall seasons were observed around 1.30 dS/m, however during low flow season, salinity levels were observed higher than 5.20 dS/m. The MIL is responsible to improve the environmental management of the Box Creek SEC for the last 38.95 kilometre long section of the creek starting from downstream of the Riverina Highway to Barratta Weir. After this weir, the Box Creek SEC flows enter the Edward River. Water that flows from the Box Creek SEC into the Edward River must not increase more than 0.80 dS/m the salinity of water in the Edward River. Although the contribution of flows from Box Creek SEC is fairly low (approximately 7%) relative to the total flows volume leaving the MIA yet it contributes significantly (approximately 45%) to the total salt load that leaves the MIA. Therefore, salinity management of the Box Creek SEC flows have potentially significant impact on achieving salinity benefits for the Murray River.

3. METHODOLOGY

3.1. Data Analysis

Climate and Hydrology

Figure 3 presents average daily rainfall and potential evaporation observed at Finley Meteorological Station (latitude 35.57S and longitude 145.53E) from 1986 to 2005. A water deficit exists from August to May which necessitates irrigation for growing crops. For the months of June and July, rainfall equals potential evaporation; which imply very little irrigation requirement of the crops.

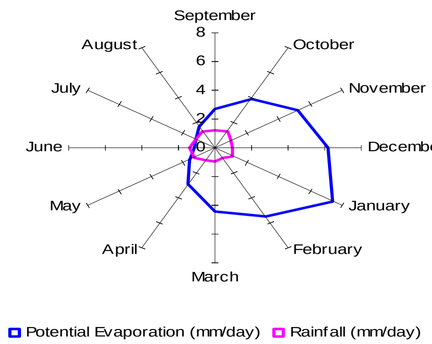

Figure 3. Comparison of rainfall and potential evaporation observed at Finley from 1986 to 2005.

The analysis was restricted to the period of July 1997 to June 2005 due to availability of flow and salinity data during this period. During this period, the lowest rainfall was observed during July 2002 to June 2003 (dry year), and the highest rainfall was observed during July 1999 to June 2000 (average year). Thus the selected data period represents climatic conditions when rainfall was around average and below average. Figure 4 presents the observed salinity and flows in the upper catchment section of the Box Creek SEC from June 1997 to June 2005. There is contrary trend between the flows and the salinity. With high flows, the salinity is low; which may indicate dilution. When flows are low, the salinity becomes high.

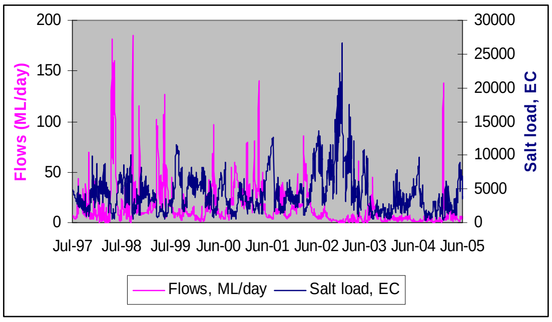

Figure 4. Observed flows and salinity levels in Box Creek SEC from July 1997 to June 2005

Probability of Flows and Salinity

As evident from Figure 4, the historical flows in the Box Creek SEC vary over a vast range (0 to 45 ML/day) during a year. Low flows are more important from the view point of treatment for salinity as they carry more salts. Therefore it is imperative to determine the minimum extractable flows from the creek and their probability of occurrence for pumping into an off-stream storage and subsequent treatment of SBC system. A percentile analysis for both the daily flows and salinity for the period from July 1997 to June 2005 was carried out to describe probability of flows and their respective salinity (Table 1).

There was 90% probability that flows would exceed from 1.77 ML/day, and 10% probability of exceeding flows from 30.58 ML/day. Similarly, there was 90% probability that salinity would not exceed above 8.3 dS/m, and there was 10% probability of receding salinity below 1.4 dS/m. Further analysis also showed that even for the driest year of 2002/03, the minimum flow of 1.77 ML/day was available for 250 days. Even during this period, 336 ML/year pumping potential was observed by pumping 25% of stream flows when actual daily flows are greater than 1.77 ML/day. Therefore 1.77 ML/day was taken as a benchmark value (minimum probable flow) of stream discharge to trigger pumping from the creek into off-stream storage.

Table 1. Probability analysis of flows and their respective salinity in the Box Creek SEC.

Percentile	Stream flows (ML/day)	Salinity (dS/m)
0%	0.004	26.7
10%	1.77	8.3
20%	2.96	6.3
30%	4.34	5.1
40%	5.70	4.2
50%	7.68	3.6
60%	9.88	3.1
70%	13.77	2.4
80%	18.92	1.9
90%	30.58	1.4
100%	184.60	0.3

3.2. The System Dynamics Approach

Since highly saline flows in the Box Creek SEC occur at different times with different flow rates, it is required to pump and store this water whenever available into off-stream storage for subsequent application to the SBC system. The objective of the SD analysis presented in this paper is to find out suitable capacity of the off-stream storage and the effect of different sizes of the first irrigation plot (with Lucerne crop) of the SBC system and other climatic processes (rainfall and evaporation) on the dynamics of salinity and volume of the storage to find out optimum size of the storage and the SBC system. A flowchart of approach adopted in this study is shown in Figure 5.

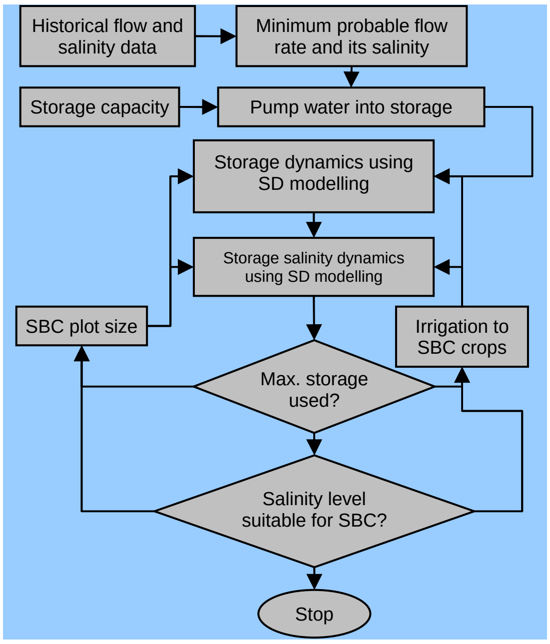

Figure 5. Flowchart of methodology for SD analysis of storage and SBC system.

Exploring the Causal Loops

The causal loop diagrams (also called influence diagrams or feedback loops) are called that because each link has a causal elucidation, i.e. an arrow heading from A to B indicates that A causes B. Causal loop diagrams are helpful in conceptualizing the system structures. The causal loop diagram for the system under consideration is shown in Figure 6. It consists of three feedback loops. The first negative feedback loop represents interaction between evaporation and storage volume: the higher the evaporation, the higher the evapotranspiration (ET), then higher the irrigation (volume extracted from the storage) and the lesser the storage, which in tern decreases evaporation, completing the negative loop. The second feedback loop represents interaction between storage EC and evaporation: high storage EC indicates low storage which indicates low evaporation, which intern decrease storage EC thus completing the negative loop. The third causal loop represents interaction between pump-in volume and storage EC: the higher the pump-in volume, higher the storage, then lesser the storage EC, which implies less inflow EC and high stream flow (dilution effect), which in tern increase increases pump-in volume, completing the positive feedback loop.

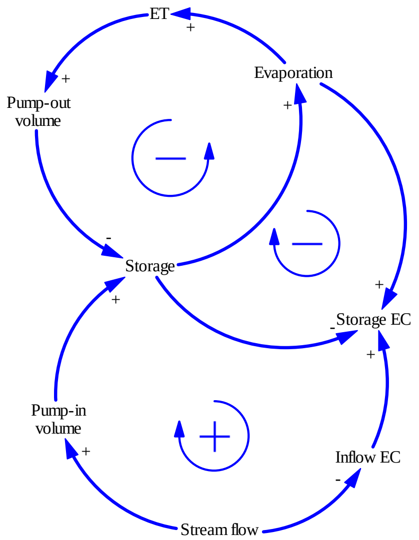

Figure 6. Causal loop diagram of the feedback mechanism.

System Dynamics Simulation Model

In SD model building process, the stock and flow (or Level and Rate) diagrams are the most common first step and are ways of representing the structure of a system with more detailed information than is shown in a causal loop diagram. They help define types of variables that are important in causing behaviour and show accumulations in a system. The next step in SD simulation process is to attach algebraic relationships to all the variables appearing in a stock and flow diagram. The SD simulation model of the system under consideration was implemented using Vensim software tool (Ventana Systems, 2004) as shown in Figure 7. It consists of stock and flow diagrams describing dynamic relationship among storage volume, storage EC, inflows (pumping from the creek) and irrigation (pumping out of storage) and its salinity level for application to SBC system. Some of the algebraic relationships governing the simulation model are given in the next subsections.

Net Storage Volume Computation

The model computes net storage volume present in the reservoir with given capacity for each time step (daily) using Equation 1.

Net Storage Volume = *INTEG* [*IF THEN ELSE* (*Storage* <= *Storage Capacity*, *Inflow x Time Step*, *0*) - *Irrigation* + *Rainfall* - *Evaporation*, *Initial Storage*] **(1)**

Where, 'INTEG' is the built-in function in Vensim to integrate daily storage over the simulation period and the 'IF THEN ELSE' condition makes sure that water is pumped into the reservoir only if it has not reached its full capacity.

Storage Composite Salinity Computation

The daily storage salinity is the composition of inflow EC and the current storage EC. The model computes daily storage composite EC using the formula given by Equation 2.

Storage Composite Salinity = *DELAY FIXED* [(*Storage x Storage EC* + *Inflow x Time Step x Inflow EC*) / (*Storage* + *Inflow x Time Step*), *Time-1*, *Initial Storage EC*] (2**)**

Where, all parameters are expressed in dS/m; and net daily storage water quality is computed at each time step using DELAY FIXED function with 'Time – 1' parameter, which allows use of value of the Storage EC computed at the previous time step; and hence avoids simultaneous equations problem. The SD model was simulated with a daily time step for the period from July 1997 to June 2005.

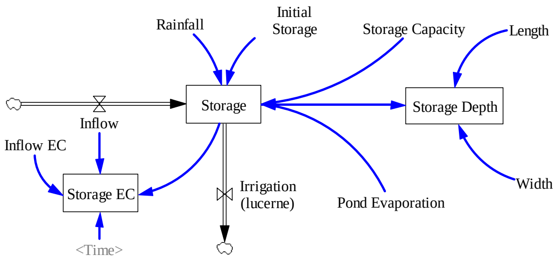

Figure 7. Layout of the system dynamics model in Vensim environment.

4. RESULTS AND DISCUSSION

As mentioned in section 3.2, at least of 336 ML/year was found as potentially available storage from the creek each year. Therefore a reservoir with storage capacity of 350 ML (including 20 ML freeboard) was considered in the analysis of storage EC and the SBC system. For SD model, two simulation scenarios were considered for simulation period from July 1997 to June 2005. Scenario 1 represents the situation when the initial storage was zero. In case of Scenario 2, initial storage of 330 ML with EC level of 1.35 dS/m was considered. In both of these scenarios, irrigation water requirements for different sizes of the first SBC plot under perennial pasture (lucerne) were met by pumping water from the storage, and pumping from the creek into the storage was only permitted when storage was less than or equal to 330 ML. The model was simulated iteratively to find the maximum possible irrigated area under SBC system without running the 330 ML storage dry. For Scenario 1, changes in the daily storage and the salinity level corresponding to SBC plot areas of 30 ha, 35 ha and 40 ha, are presented in Figure 8 and Figure 9, respectively. The storage remained sufficient for the irrigation area less than or equal to 30 ha; however storage salinity was highest during July 2002-June 2003 as expected due to low storage volume. Similar findings were obtained for the Scenario 2 (results not shown). This implies that initial storage and its salinity plays a limited role in maintaining quantity and quality during dry climatic conditions; but flow volumes and their respective salinity levels are the main factors controlling the quantity and quality of storage.

There is also no significant difference between the both scenarios, when annual salt removal per unit of water pumped was compared for the SBC plot size of 30 ha. Maximum salts per unit of water pumped from the creek were removed during the year 2002/03, which is the driest year during the study period.

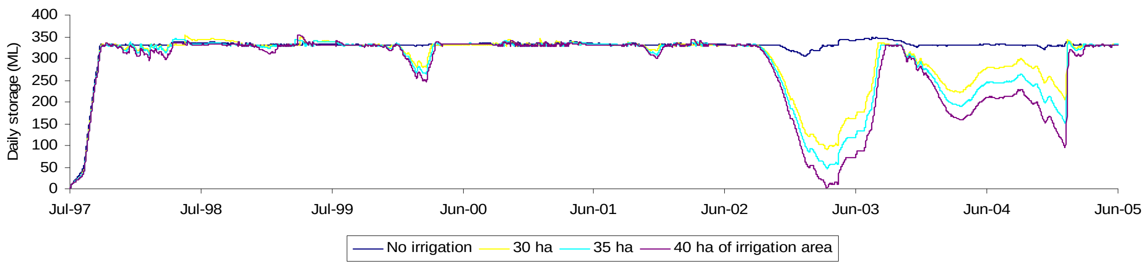

Figure 8. Simulated daily storage (ML) for three SBC irrigation plot sizes for Scenario 1.

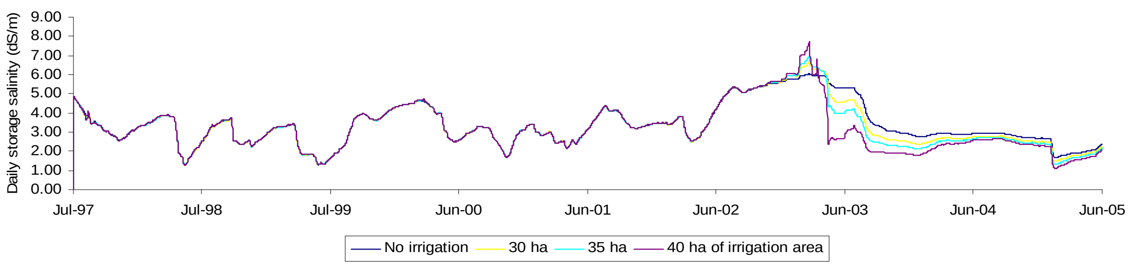

Figure 9. Simulated daily storage salinity (dS/m) for three SBC irrigation plot sizes for Scenario 1.

5. CONCLUSIONS

The following conclusions can be drawn from the work presented in this article.

1. Given the dynamic nature of storage salinity for different irrigation plot sizes of SBC system, the SD is the appropriate approach to simulate such dynamic behaviours.
2. As the SD model was simulated for a relatively dry period, the 30 ha area for the first stage of SBC system seems to be a conservative estimate.
3. The proposed storage and the SBC system remains at the peak of performance in terms of salts removed per unit volume of water extracted from the creek during dry seasons.
4. The whole system is recommended as an effective solution for the management of stream salinity of BOX Creek SEC.

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