Complex Adaptive System Modelling of River Murray Salinity Policy Options

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The River Murray Basin as a complex adaptive system

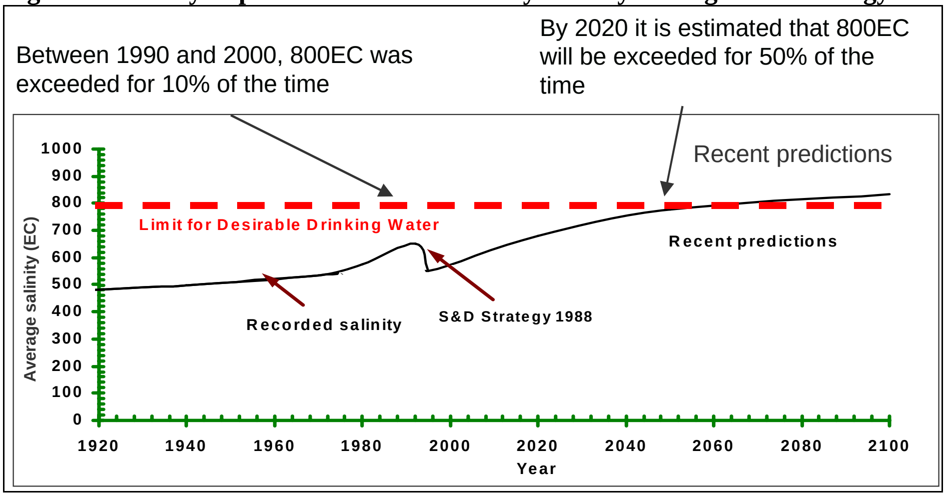
The River Murray Basin (RMB), exhibits key characteristics of a complex adaptive systems (CAS) (Folke et.al., 2002; Holling and Gunderson, 2002). Before European settlement the system exhibited constant changes such as large annual and seasonal variability of flow but within a domain that allowed a relative stable ecological equilibrium for ecosystem components such as late succession floodplain Redgum and Blackbox communities survived over centuries. It is becoming increasingly evident is that change processes set in motion through introduction of human interventions to develop dryland and irrigated farming in the basin over a century ago are now increasingly resulting in 'flips' to new ecological regimes. These shifts, some of which may be impossible to reverse, are already resulting in costly damages to human built infrastructure and system ecological health (SA Government, 2001; Connor 2003).

A key CAS characteristic of RMB is ecosystems and institutional variables changing on different time scales – fast variables (varying within a year) include water diversion within constraints of institutional allocation and temporary water trade rules, annual irrigation drainage, commodity prices, random seasonal evapotranspiration and rainfall and flow variation. Intermediate variables (include irrigation land, capital equipment and permanent water allocations, and slower variables include water table rise, floodplain vegetation dying, and public infrastructure deterioration and replacement.

Like other CAS, the RMB switch in states is an adaptive change in response to interactions between natural system and human institutional system elements. In many ecosystems, some important natural processes leading to periods of rapid reorganisation are the result of cumulative effects of slow variable (Holling and Gunderson, 2002). This is certainly the case with hydrologic processes leading to salinity. System state changes which are beginning to be observable today include elevated water tables, and elevated river salt loading. with consequent ecosystems and economic impacts are substantially the result of water and land allocation decisions that were made many decades ago (Government of South Australia, 2003).

While the human interventions leading to river system state changes have been proceeding for more than a century, it was only in the 1970's and 1980's that their potentially costly impacts began to be recognised. The period of institutional re-organisation that this recognition gave rise to resulted in development of policy that is often sited as one of the worlds most progressive institutional arrangements to deal with a cross jurisdictional water quality issue in a large river catchment, the Salinity and Drainage Strategy (SDS) (Murray Darling Basin Ministerial Council, 1988). The SDS primarily involved investments in engineering infrastructure to divert saline water resulting from land clearing and irrigation away from the river to evaporation basins. An ensuing period of relatively stable institutional arrangements to deal with salinity followed where it appeared that the strategy was successfully addressing the manifestation of the problem, elevated salinity concentrations in the River.

Figure 1: Salinity impacts of the River Murray Salinity Management Strategy



The focus of article is the Lower River Murray main stem as shown in Figure 2. The reason for this geographic focus as shown in Figure 3 is that a disproportionate amount of total salinity loading to the River occurs in lower reaches below Swan Hill in Victoria and relatively little salt contribution occurs in upper reaches of the River and in the Darling.

Figure 2: Lower Murray Study Area

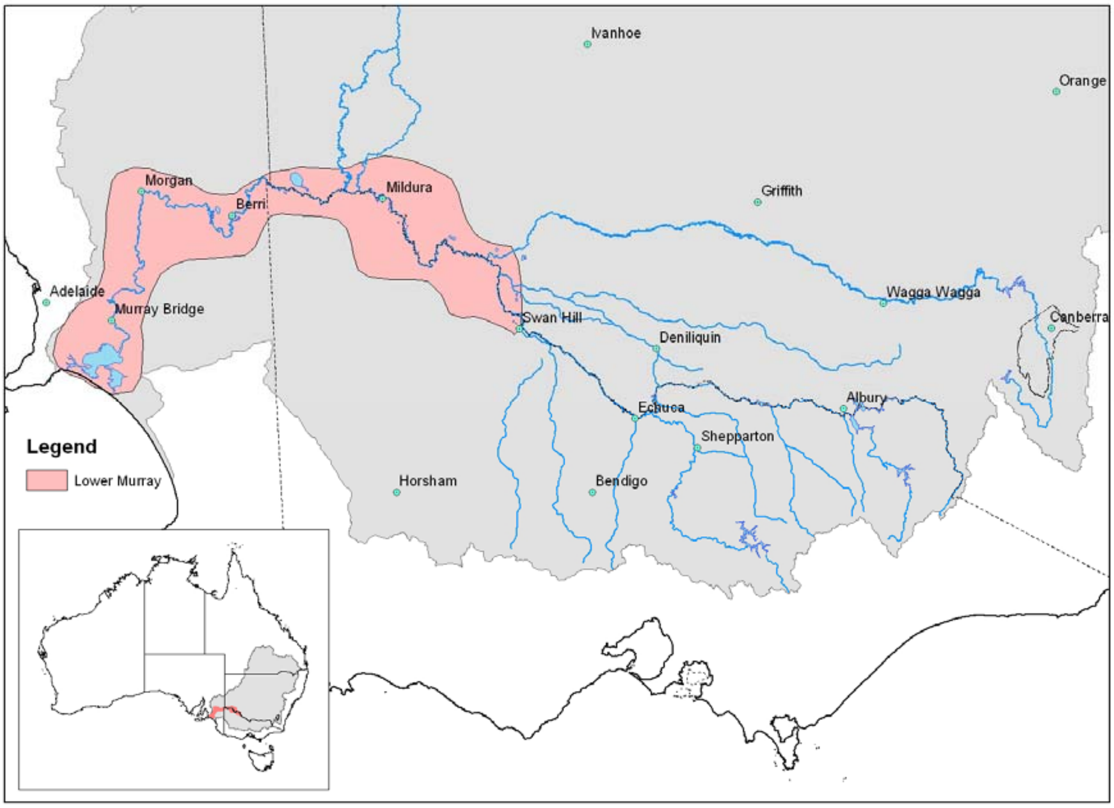
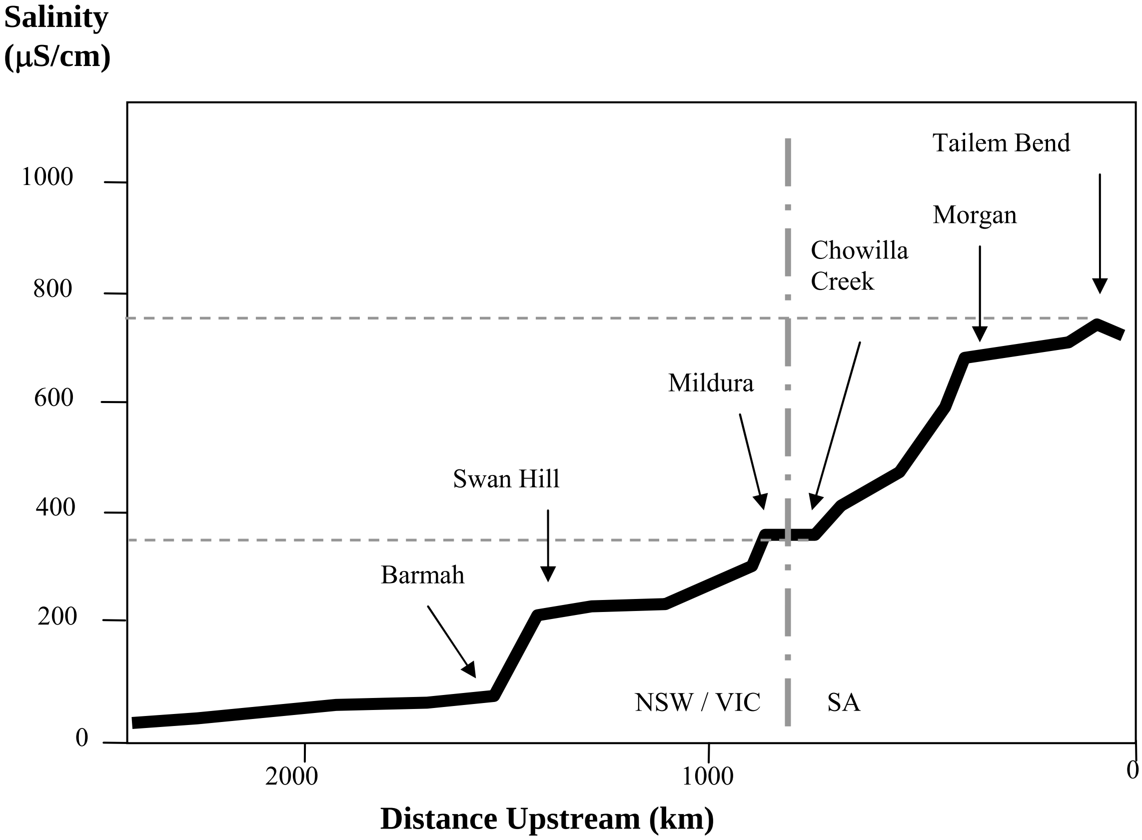


Figure 3: Contributions to salinity concentration at Morgan from upper and lower Murray



As is often the case in CAS, initial institutional response appeared to be capable of producing stable and predictable outputs for a considerable period of time. It is increasingly evident that the SDS has not addressed the fundamental variables that are influencing system state changes. River salt concentrations have continued to rise as shown in Figure 1, mounds of elevated saline groundwater have continued to build and are resulting in accelerated system state changes such as ecologically significant floodplain tree community dying (Overton et al, 2003).

There is an increasing recognition in the biophysical and social science community of the CAS nature of water resource systems like the RMB (Pahl Wostle, 2003; Gunderson, 1999). This paper reports on CAS simulation of the RMB to compare capacity of institutional options to maintain functioning of key river system within a "bandwidth" that limits irreversible system state changes and highly adverse consequences. The modelling emphasises the CAS nature of the system and on institutional rules to accommodate choosing actions differently based on condition of the system has been referred to as state contingent management (Wills, 2003) or threshold based management (Roe and Van Eeten, 2001).

Modelling salinity management options in a complex river basin

In recognition that the RMB represents CAS coupled system of people (i.e. irrigators, urban water users, those who enjoy recreation) a model for evaluating institutional options is being developed by the authors including:

1. A variety of distinct individual human and non-human agents following behavioural rules aimed at replication or enhancement: irrigated farming crops and floodplain vegetation communities, different types of land and water managers (e.g. irrigators with a variety of behaviours, and a river management agency).

2. Interactions between agents influenced by site specific temporally varying conditions such as irrigated crop water requirements, seasonal water availability, water table levels and river salinity concentration, and market prices.

3. A selection process for each type of agent that results from competition between different natural system and various human actors in the river system Irrigators try to divert water and apply it profitably to crops, wetland vegetation communities try to extract fresh water to grow, and river management authorities try to set water allocation and salinity mitigation rules to balance consumptive and ecosystem health goals.

4. Selection among agents that is partially determined by exogenous factors. For example seasonal variations in rainfall and evapotranspiration, interest rates and commodity prices are all exogenous conditions that influence commercial viability of irrigators. Floodplain tree communities survive or die depending on climatic variation, actions of irrigators contributing to floodplain salinisation and actions of river managers to mitigate or reduce salinity impacts of irrigation.

5. "Agents are capable of 'learning' from experience – by altering their behavioural rules – either directly or because less successful agents 'die out'" (Wills, 2005).

The model will when fully developed simulate key hydrogeology, irrigator and river manager responses and follow-on consequences including:

- irrigation development level and location choices of irrigators,
- irrigation technology and management choices of irrigators,
- irrigation economic activity levels and profits from irrigation.
- irrigation application rates and drainage level consequences of irrigator choices by location
- salt and water processes that will result in time lagged salinity impacts of irrigator choices on irrigators, urban water infrastructure users, and floodplain ecological health.
- The cost to governments (or irrigators, depending on assumed policy) of investment in mitigation to reduce salinity damages of irrigation

The overall project goal is build a modelling capacity for scenario analysis with stakeholders including irrigators, local, state and Commonwealth officers involved in salinity policy explore response to changes in:

- economic conditions (e.g. commodity prices, production costs)
- policy (e.g. irrigation land use zoning, or salinity charges)
- biophysical system state (e.g. salinity of irrigation water, climate influence on crop ET and water availability).

A modelling challenge arises in integrated economic response and salinity process models because changes in irrigation practice and consequent economic impacts occur in much shorter time frames than salinity impacts.

The time required for water to travel through the unsaturated zone and groundwater, mean that changes in irrigation in the Lower Murray lead to changed saline groundwater base flow to the river many years later. Delays between irrigation changes and onset of salinity impacts are estimated to vary from less than one decade to more than a century depending on depth to water table, distance to the river and aquifer transmissivity at the location of irrigation (Miles et al). The hydrogeology model that will be used to assess salinity impact of irrigation (Miles et al) assumes a constant repeated annual pattern of irrigation drainage across the corridor for several decades in predicting changes in 20, 50 and 100 years to groundwater base flow, and river salt load. In contrast significant irrigation practice changes typically take place in a few years to a decade and consequent economic impact result follow-on within a matter of months to perhaps a few years.

For modelling tractability, in integration of irrigation practice change and salinity impact that take place on very different time scales, scenarios are modelled as consisting of two distinct time periods. The first is a period of change (typically a decade or more) in which economic, policy or biophysical system state changes result in changes in irrigation. The second period is the salinity impact assessment period, where salinity impacts that would follow-on from changes in the period of change in 20, 50 and 100 years are assessed. In salinity impact assessment it is assumed that changes in irrigation assumed in change period persist for the entire 100 year salinity impact assessment period.

Analysis using the model

Results reported for the conference paper and presentation will focus on modelling irrigator temporary water market and water use response to changes in weather and river salinity and evaluation of:

- Cost of a policy of offsetting all impacts of irrigation with engineering to pump salt water away from the river to evaporation basins (salt interception and drainage disposal);
- And cost of a policy of offsetting all impacts of irrigation with salt interception and drainage disposal as well as strategic purchases of water for dilution of peak salinities;

Modelling system specification

The overall structure is an annual time step simulation model with irrigator agents choosing irrigation responses which will eventually be based on mutli-attribute utility function (but in present reporting consider only economic criteria in decision making. Other examples of the proposed modelling approach include Jansen *et al*, 2001. An advantage of this methodology is that it can provide meaningful estimates outcomes that are possible when diverse water user pursue responses in their best interest subject to limitations and incentive created by policy. In contrast the global optimisation approach used in similar studies (e.g. Rosengrant *et al*, 200? Howitt *et al*,

2000) have an objective of finding the greatest social net benefit including a range of economic and external cost. While such approaches can identify responses from water users that would lead to global welfare maximisation they give little insight into potential for welfare improvements that are also incentive compatible for agents effecting the system.

Modeling short and long run decisions

The ultimate goal is to model significant irrigated agricultural sector change in response to policy, economic and biophysical system state changes. This involves modeling irrigation agent decisions on investments in land, permanent water rights, vine and horticultural stock and irrigation equipment, all assets with expected economic lives of 15 years or more. Following Dantzig (1955) such investment can be thought of as involving a two stage process. The first stage is upfront investments such as planting of vines or horticultural stock. Costs of such investments are borne upfront when the investments are made regardless of uncertain outcomes of the investments.

The second stage is the annual management decisions like irrigation water application rate (this is the only relevant stage in the existing irrigator model). These decisions depend on levels of variables determining profit that vary stochastically from year to year such as weather conditions, commodity and temporary market water prices. The first stage decision must be made based on some expectation of the probability of factors such as future weather and prices that are determined stochastically in the second stage of the investment. Second stage decision must be made given that capital assets chosen in the first stage can not be varied from year to year.

To model this two stage investment decision we intend to use the Dantzig (1955) two stage investment optimization process that has been successfully applied by McCarl (1999) to a related US problem but not yet in Australia to our knowledge.

The overall model is structured so that in each year over the 20 year irrigation development simulation period an exogenously set amount of existing irrigation and perennial stock capital become fully depreciated. Agents with fully depreciated capital stocks face the long-run decisions of what types of perennial plantings (if any to establish and what types of irrigation system investments to make (if any). All remaining agents face the short run decision choosing level of irrigation and amount of water to buy or sell on temporary markets given established perennial crops and irrigation technology and permanent water allocations.

Long-run decision model

<u>Model variables</u>

The choice variable in the long run model is $HN_{l,z,h,j,t}$ – areas chosen for new development in hectares by management district (l), zone (z), agricultural activity (j), irrigation management (h) and year (t). In modelling reported on here each agent (i) has an objective to maximise profit from their decision PR_t^{LR} in each year (t) that they face long-run decisions related to irrigation equipment, permanent water rights and perennial crop stock investment. Functionally this is expressed as

1. Maximise $PR_t^{LR} = \Sigma_l \Sigma_z \Sigma_h \Sigma_j$ [$- fc_j - fic_{l,z,j,h} - pwc*(wp_{l,z,t}+wa_{l,z,s,t})$
$- \Sigma_s Prob(s)*\{ y_{j,s}*p_{j,s} + vc_{j,h,s}) + twc_s*(awr_{l,j,h,s} - wp_{l,z,s,t} - wa_{l,z,s,t})\}] *HN_{l,z,j,h,t}$

Subject to
2. $\Sigma_{j,h} HN_{l,z,j,h} \leq \alpha_l^{Ha} * \Sigma Hs_{l,z}$ new irrigation land developed less than or equal to available land for new development and redevelopment.
3. $awr_{l,j,h,s} = (et_{l,j,s} - rain_{l,j,s})/ ie_{j,h}$ annual water requirement by crop equal to et requirement less effective rainfall divided by irrigation efficiency by crop, irrigation practice, and state of nature

Short run model

Each year in the short-run each irrigators face fixed permanent water allocation $wa_{i,l,z,s,t}$ that vary by agent (i) lwmp (l), irrigation impact zone (i) and state of nature (s), and areas of existing irrigation development (hectares) by management district (l), zone (z), agricultural activity (j) and irrigation management (h), $he_{l,z,h,j,i}$. Their decision is modelled as the choice of irrigation level $w_{l,z,h,j,i}$ by area and level of water to purchase $WP_{l,z}$ given the temporary water market price they face that varies over climatic and reservoir storage determined state of nature twc_s

<u>Model variables</u>
PR_t^{ED} – expected profit from existing development by year.
$LF_{l,z,h,j,t}$ – fraction of irrigation leached by management district (l), zone (z), agricultural activity (j) and irrigation management (h) by year (t)

<u>Short run model governing equation and constraints</u>
4. Maximise $PR_{l,z,t}^{ED} = \Sigma_h \Sigma_j \Sigma_s Prob(s)*\{ y_{j,s}*p_{j,s} + vc_{j,h,s}) + twc_s*(WP_{l,z} - w_{l,z,h,j,i} + awr_{j,h,s,y})\}] *he_{l,z,j,h,t}$

Subject to
5. $awr_{j,h,s,y} = (et_{j,s} - rain_{j,s})/(ie_{j,h})$ annual water requirement by crop (j) equal to attain fraction of maximum potential yield (z = 1.0, 0.95,…,0.05, 0) equal to et requirement less effective rainfall divided by irrigation efficiency by crop (j) , irrigation practice (h), and state of nature (s).

Zoning policy is simulated as a restriction not allowing development in highest impact areas.

Salt and water process models

The salt and water process model builds on hydrogeology modelling discussed in detail in Miles et al 2001 and Doble 2005 to model delayed salt load impacts of each 20 year irrigation development scenario t=20,50 and 100 years after development for each irrigation area l. The basic representation of the salt and water processes for a given modelling area, l can be written as
7. $\mathbf{D_{l,t}} = (1-ie_{l,t})w_{l,t}$ Irrigation drainage, $\mathbf{D_{l,t}}$ = water allocated times drainage % modelled as a result of irrigator short- and long-run responses
8. $\mathbf{FI_{l,t}} = f_{l,t} \mathbf{D_{l,t}}$ Total discharge from irrigation, $\mathbf{FI_{l,t}}$ is function of drainage amount, location
9. $\mathbf{F_{l,t}} = \mathbf{FI_{l,t}} + fn_{l,t} + fd_{l,t}$ Total discharge $\mathbf{F_{l,t}}$ = sum of irrigation + natural + dryland discharge
10. $\mathbf{S_{l,t}} = gw_l \mathbf{F_{l,t}}$ Salt load to River edge, $\mathbf{S_{l,t}}$ = discharges (ML) * groundwater salinity (mg/ML)
11. $\mathbf{SR_{l,t}} = \mathbf{S_{l,t}} (1- fp_l)$ Salt load to River, $\mathbf{SR_{l,t}}$ = salt to River edge * % not attenuated by floodplain

12. $\mathbf{EC_{l,t}} = TEC_l\ \mathbf{SR_{l,t}}$ River EC contribution, $\mathbf{EC_{l,t}}$ = salt Rivers times tonne to EC conversion factor

Where

$f_{l,t}$ ML/ha of irrigation drainage reaching river in year t
$fn_{l,t}$, $fd_{l,t}$ expected ML from natural sources and dryland clearing
gw_l, TEC_l groundwater salinity, tonne of salt to EC conversion
fp_l % of groundwater discharge attenuated by floodplain

Mitigation cost

In all scenarios the River manager is assumed to work to choose among a range of salt interception investment designs and locations to minimise the cost of meeting the goal of the Murray Darling Basin agreement on salinity (MDBMC, 2001), no increase in average river salinity level $EC_t - EC_{t=0}$ in each future time period (t). In addition in some scenarios restrictions on saline inflow level to floodplains $\mathbf{FI_{l,t}}$ are imposed to represent policy to protect the floodplain from rising water table Functionally the optimisation model used to predict mitigation costs can be represented as:

13. Minimise **Cost** $= \Sigma_{l,t}\ siscost_l\ \mathbf{ML_{l,t}} + \mathbf{DF_t} * pw_t *$ Choose location and timing of SIS capacity ($\mathbf{ML_{l,t}}$)and timing of dilution flow purchases, $\mathbf{DF_t}$ to minimise **cost**, the sum of cost/ML times ML pumped times discount factor $1/(1\text{-}i)^t$ for investment that can be delayed > 20 years
Subject to:
14. $\Sigma_l\ (EC_t - EC_{t=0}) >=0$ EC reduction >= EC reduction required for no salinity increase in each period
15. $EC_t - EC_{t=0} = \mathbf{ML_{l,i,t}}\ (1\text{-}\ fp_l)\ gw_{l,i}\ TEC_l + \Delta EC_{l,t} * \mathbf{DF_t}$ EC salinity impact reduction = ML pumped with salt interception * % not attenuated by floodplain * groundwater salinity * tonne to EC conversion factor plus dilution flow volume multipled by dilution flow salinity impact factor by
16. $\mathbf{ML_{l,i,t}} => \mathbf{FI_{l,i,t}} - fp_{l,i,t}$ salt interception capacity => amount required for floodplain

Preliminary results discussion

While analysis with the model is just getting underway, there are already several interesting preliminary results. One finding is that there are considerable opportunities to reduce irrigation drainage the source of salinity at much less costly to society than efforts to mitigate the salinity impacts of drainage once it has occurred. As shown in figure 3, the cost of mitigation in scenario 2 with buyout of water from low profit high salinity impact regions and a continued trend of profitable and drainage reducing irrigation technology renewal would be expected to reduce cost of meeting salinity goals by 2050 by over $250 million (Australian).

The costs and benefits of dilution flows were estimated across a range of scenarios representing alternative rules for choosing when to release dilution flows. As shown in Figure 4, for the scenario modelled involving releasing water for dilution based on river condition (release when river salinity reaches threshold level), on average the cost of providing salinity damage reduction with dilution flow is estimated to be more expensive than providing salinity damage reduction with the most cost effective potential future salt interception schemes. However, if release is contingent on both river salinity state and opportunity cost of water (that varies temporarily in the model with reserviour storage and weather state) there are some opportunities as illustrated on the to provide dilution as a less costly way of reducing salinity exceeding than all any salt interception scheme options.

Figure 3: cost of salinity mitigation with and without salinity source control policy

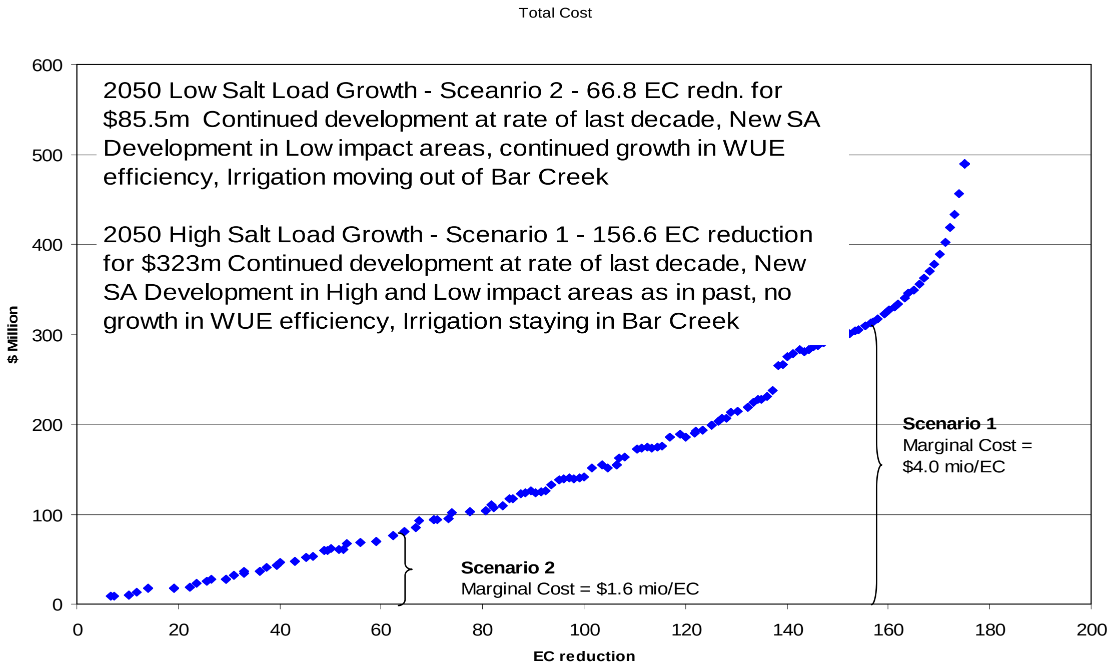
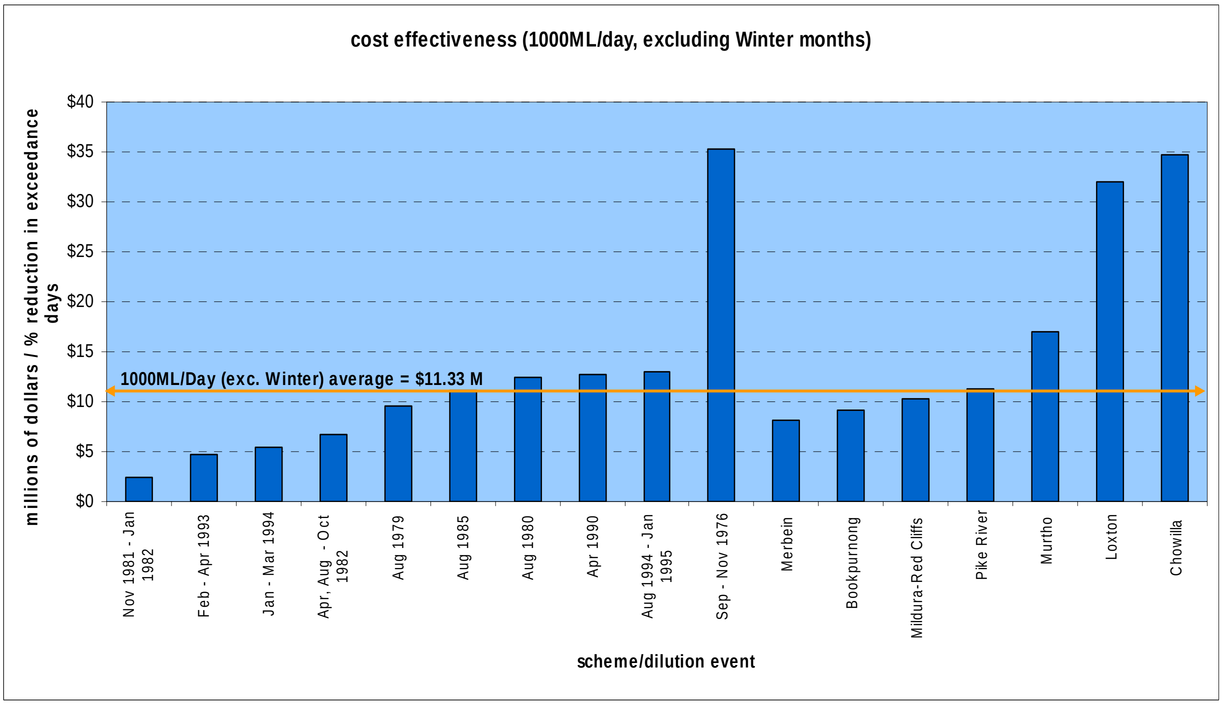


Figure 4: comparative cost of salt interception and dilution as salinity mitigation strategies



References

Author, 2003. Reducing the cost to South Australia of achieving agreed salinity targets in the River Murray. Final report to Department of Water, Land and Biodiversity Conservation, South Australia, CSIRO Land and Water.

Danzig, G.B. Linear programming under uncertainty. *Management science*, 1:197-206.

Folke, C.S. *et al*., 2002. *Resilience and sustainable development: building adaptive capacity in a world of transformations*. Scientific Background Paper on Resilience for The World Summit on Sustainable Development on behalf of The Environmental Advisory Council to the Swedish Government. Available from: http://resalliance.org/ev_en.php?ID=1498_201&ID2=DO_TOPIC [Accessed 1 October 2004]

Gunderson, L. (1999) Resilience, Flexibility and Adaptive Management – antidote or spurious certitude. *Conservation Ecology* 3(1):7.

Government of South Australia (2001b) *River Murray Salinity Strategy, 2001-2015*. Department for Water Resources, Adelaide.

Holling, C. S. and L. A. Gunderson (2002). Resilience and Adaptive Cycles. in *Panarchy: Understanding Transformations in Human and Natural Systems*. Ed. L. A. Gunderson and C. S. Holling. Washington, D. C., Island Books.

Janssen, M.A., B. Walker, J. Langridge, N. Abel (2000) An adaptive agent model for analysing con-evolution of management and policies in a complex rangeland system. *Ecological Modelling* 131(2000): 249-260.

McCarl, B, C. Dillion, K. Kepplinger, R. Williams (1999) Limiting pumping from the Edewards Acquifer: An economic investigation of proposals, water markets and spring flow guarantees. *Water resources research* 35(4): 1257-1268.

Miles, M.W., Kirk, J.A. and D.D. Meldrum (2001) Irrigation SIMPACT, a salt load assessment model for new highland irrigation along the River Murray in SA. Environmental and Socio-Economic Databases, Government of South Australia.

Murray-Darling Basin Ministerial Council (2001) *Murray-Darling Basin Salinity Management Strategy*. MDBMC, Canberra.

Overton, Ian; Ian Jolly; Kate Holland; and Glen Walker (2003) *The Floodplain Impact Model (FIP): A Tool for Assisting the Assessment of Impacts of Groundwater Inflows to Floodplains of the Lower River Murray*. Progress Report for the River Murray Water Management Board, May, 2003.

Pahl-Wostl, C. (2004). The Implication of Complexity for Integrated Resources Management. iEMS 2004 International Congress, Osnabrück, Germany

Roe, E. and M. van Eeten (2001) Threshold-based resource management: aframework for comprehensive ecosystem management. *Environmental management*, 27(2): 195-214.

Rosegrant M.W., C. Ringler, D.C. McKinney[b], X. Cai, A. Keller, G. Donoso (2000), Integrated economic-hydrologic water modeling at the basin scale: the Maipo river basin, **Agricultural Economics,** Volume 24 Issue 1 Page 33 - December 2000

Wills, I. (2005) Information, institutions and sustainability: implications of research on complex systems. Proceedings of the 49th Annual Australian Agricultural and Resource Economics Society Meeting, February 2005, Coffs Harbor, NSW