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Towards a market: geophysical-bioeconomic targeting of plant-based land use change for management of stream water yield and salinity

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Abstract

Land managers in upper catchments are asked to make changes in land use, such as by planting trees, to reduce salt loads in rivers to meet needs of downstream towns, farms and natural environments. End-of-valley targets for salt loads have sometimes been set without a quantitative model of cause and effect, without regard for impacts on stream flow water volumes and without consideration of economic efficiency or the distribution of costs and benefits among stakeholders. In this paper we show how these questions may be treated simultaneously in an integrated framework accounting for the biophysical resource base and the opportunity costs of changing land use.

Introduction

This paper is about quantifying the range of possibilities for change and the trade-offs among river yields, water qualities and the distribution of costs of implementation. We proceed in several steps: (a) defining the biophysical base, including a revision of Zhang *et al.*'s (1999) evapo-transpiration (***ET***) curves for dryer Australian conditions; (b) defining the theoretical range of feasible future equilibrium water and salt (**W**,**S**) targets for a catchment; (c) defining a farm-level economic model that maximises net present value (**NPV**) over a multi-decade period given targets for future **W,S** flows from a sub-catchment; and (d) using results for contrasting sub-catchments to define an aggregate catchment-level economic meta-model to solve the problem of finding least-cost combinations of land use change across the range of possible aggregate **W**,**S** targets. For each of these steps we document our methods and illustrate results with quantitative examples.

We conclude with the implications for landowners in watershed catchments, downstream water users, Catchment Management Authorities and agencies for state and federal NRM policy. We propose a line of research using Experimental Economics techniques with our geophysical-bioceonomic models to explore combinations of market types, institutions and conditions which best lend themselves to linking changes in upstream land use with downstream demand for water yield and quality.

Methods

Our study area is the upper 200,000 ha of the Little River catchment around the settlement of Yeoval, NSW (32.75°S 148.65°E). Mean annual 'end of valley' stream flow at nearby Arthurville was measured as 96,250 ML (or 96.2 GL) with a salt load of 36,580 T. For each of the 80 sub-catchments comprising this area we obtained estimates of long-term mean rainfall, soil types, current land use, groundwater salinity and hydrological response times (Evans *et al*. 2003, Bathgate *et al*. 2005).

Our emphasis is on minimizing opportunity costs in the catchment by optimal selection of changes in land use when constrained to meet a water and salt target. This takes into account local long-term rainfall, ground water salinity, the hydrologic characteristics and productive capacities of soils, and the ***ET*** levels associated with various land uses in the context of whole-farm economic analysis.

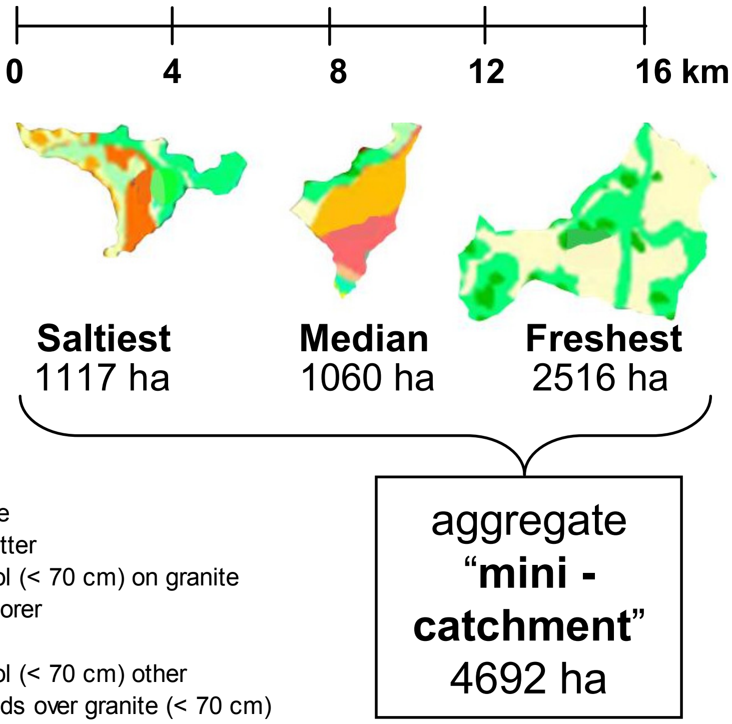
A bio-physical cause-and-effect model

Following Zhang *et al*. (1999) we assume long-term equilibrium stream flow equals rainfall minus evapo-transpiration (***ET***), i.e. all rainfall is accounted for by local ***ET*** and local stream flows (Appendix 1). Our methods, therefore, only apply to local groundwater flow systems, and not to slower-responding intermediate or regional groundwater flow systems. We identify independent sub-catchments on the basis of surface water flows, and groundwater response time and salinity (Bathgate *et al.* 2005; Evans *et al.* 2003). We define eight land management units (**LMU**s) as land with a soil or group of soils with common agronomic and hydrologic properties. That is, each LMU has a unique drainage fraction (**Df**) and productivity potential.

In equilibrium, constant land use and long-term rainfall, "excess water", the remainder of rainfall which is not transpired or evaporated, equals stream flow. **Df** is the proportion of excess water reaching the stream via deep drainage and groundwater discharge; **1-Df** is the proportion reaching the stream by surface runoff. LMUs have a wide range of **Df**; those dominated by sandy soil may have a **Df** of 0.9 while those with impermeable clays may have a **Df** of 0.1. We assume runoff water reaches the stream fresh, at the salt concentration of rainwater (5.25 ppm), while drainage (groundwater discharge) reaches the stream at the salt concentration of the groundwater from the particular sub-catchment. In some cases salt is delivered to the land's surface by seeping groundwater. Though it may subsequently be washed into the stream by surface runoff, we count this salt as having been sourced from groundwater.

Three of the 80 sub-catchments defined in the upper Little River Catchment provide illustrative examples for the present paper (Figure 1 and Table 1).

approximate scales and soil distributions of three sub-catchments:



LMU	Df		Soil type descriptors	
1	0.15	🟨	L1	Lithosol soils -other
		🟧	L2	Lithosol soils _ granite
2	0.25	🟩	R1	Red Chromosols _ better
		🟩	R4	Shallow red chromosol (< 70 cm) on granite
3	0.50	🟧	R2	Red Chromosols _ poorer
4	0.50	🟥	R3	Red Sodosols
5	0.20	🟦	R5	Shallow red chromosol (< 70 cm) other
6	0.90	🟨	S1	Shallow siliceous sands over granite (< 70 cm)
		🟩	S2	Siliceous sands over granite
		🟥	S3	Siliceous sands over sandstone
7	0.05	🟧	Y1	Yellow Sodosols _ granitic
8	0.10	🟧	Y2	Yellow sodosols _ other
		🟨	Y3	Yellow chromosols

Source: Bathgate, A., Nordblom, T., Murphy, B., Evans, W.R. & Hume, I. (in preparation) *Little River Model Documentation: A model to assess the economics of salinity management at the farm and catchment level.* NSW DPI

Fig 1. Soil type descriptors, land management units (LMUs) and drainage fractions (Df) in three contrasting sub-catchments provide a geophysical basis for quantitative analysis of farm and catchment level economics of land use change to manage river salinity and water yields.

The long-term rainfall of each sub-catchment was used in the functions of Zhang *et al*. to estimate ***ET*** under forested and cleared land cover. As mentioned above, we took stream flow to be rainfall-***ET*** (***R-ET***). ***ET*** under current land use was estimated by defining five land uses (LU) and taking a linear combination of the extreme values for forested and cleared lands using the following "proportion forest" equivalents (**F**)**:** forest (FN), 1; sown improved perennial pasture (SP), 0.6; improved volunteer pasture (NB), 0.5; poor volunteer pasture (NP), 0.25; and annual cropping rotations (CR), 0 (Table 1).

As exemplified for the three sub-catchments, we used our excess water estimates (Table 1), our LMU (Df) distributions (Fig.1) and our land use matrix (Table 2) to estimate equilibrium **W** and **S** flows from each of the 80 sub-catchments. The results were much higher than the measured amounts mentioned above. We addressed this by first adjusting the Zhang curve parameters for Australian conditions, then calibrating to bring our calculated whole-catchment yields into line with the measured values (see Appendix 2).

Table 1. Hydrological parameters assumed for three contrasting sub-catchments among 80 sub-catchments defined in the Little River Catchment, NSW.

Term	Description			Sub-catchment		
				Saltiest	**Median**	**Freshest**
R	Long-term mean annual rainfall, calibrated values[A]	(mm)		522	555	537
	Land use		**F**[B]	Excess water (ML/ha/year)[C]		
CR	Cropping, continuous and in rotations with pasture		**0**	0.72	0.83	0.77
NP	Volunteer, naturalised, native or improved pastures, **poor**		**0.25**	0.56	0.65	0.6
NB	Volunteer, naturalised, native or improved pastures, **better**		**0.5**	0.41	0.47	0.44
SP	Sown improved perennial pastures		**0.6**	0.35	0.4	0.37
FN	Forest, native and existing plantation		**1**	0.1	0.12	0.11
Y_H	Hydrologic responsiveness[D]	Half-time (years)		3.1	1.4	13.3
S_H	" "	Slope (dD/dy)		0.8	0.4	3.3
GWS	Groundwater salinity, calibrated values[D,E]	(mg/L or ppm)		1636	1222	476
RWS	Rainwater salinity[F]	(mg/L or ppm)		5.25	5.25	5.25
SWS	Stream water salinity calculated with current land use[G]	(ppm)		**763**	**345**	**91**

[A] We adjusted original estimates of rainfall down by 10% in calibration process for calculated Little River Catchment water yields to match measured values

[B] "Proportion Forest" equivalence in water use assumed for these land uses; a weighting factor for calculating excess water

[C] weighted sum of tuned 'Zhang curve' values for (**F**) forested and (1-**F**) cleared land given long-term mean annual rainfall

[D] from Evans, Gilfedder & Austin (2003). We adjusted estimated GWS values up by 10% in calibration process for calculated Little River Catchment salt loads to match measured values.

[E] weight ratios of salt to water (mg/L and ppm) convert to electrical conductivity (EC) when divided by 0.625

[F] rainwater salinity based on Jolly *et al.* (1997)

[G] our **SWS** calculations used values in this table weighted by areas of different land management units (LMUs, groups of soil types) in the three sub-catchments and the drainage fractions associated with each; see Fig. 1 and Table 2. These **SWS** values are the basis for naming the three contrasting sub-catchments: "Saltiest", "Median" and "Freshest".

Table 2. Current land uses, distributions of Land Management Units (LMUs) with their assumed productivity indices in three contrasting sub-catchments of Little River

	LMU:	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	
	Productivity index (**Pi**):	**0.1**	**1.0**	**0.7**	**0.6**	**0.4**	**0.5**	**0.2**	**0.5**	
	Current land use[A]	area (ha)	area (ha)	area (ha)	area (ha)	area (ha)	area (ha)	area (ha)	area (ha)	Totals (ha)
Saltiest Sub-catchment	**CR**		156			15	9	41	16	237
	NP	115	3				261	42		421
	NB		107			52	53	84	38	335
	SP		36			4		55	27	122
	FN		1							1
	Saltiest total (ha)	**115**	**305**	**0**	**0**	**71**	**324**	**221**	**81**	**1117**
Median Sub-catchment	**CR**		143	4	36	1	16		249	448
	NP			7		5				12
	NB		2	21	118	8	59		171	379
	SP		3		107	7	3		48	167
	FN	17	3	1	4	20	1		6	52
	Median total (ha)	**17**	**151**	**34**	**265**	**40**	**79**	**0**	**473**	**1060**
Freshest Sub-catchment	**CR**		575				4		522	1101
	NP		3						9	12
	NB		431				4		387	822
	SP		273				9		298	580
	FN									
	Freshest total (ha)	**0**	**1283**	**0**	**0**	**0**	**16**	**0**	**1217**	**2516**

[A] Where: **CR** = Cropping, continuous or rotation; **NP** = Volunteer, naturalised, native or improved pastures, **poor**; **NB** = as **NP** but **better**;
SP = Sown improved perennial pastures; **FN** = Forest, native and existing plantations

We developed a “Factorial Vector Analysis” that uses long-term rainfall, groundwater salinity, Australian “Zhang curve” values for extremes in land use, and soil distributions to model the envelope of bio-physically feasible equilibrium blends of water (**W**) and salt (**S**) reaching the stream from a given sub-catchment (Nordblom *et al*. 2004a). The analysis first considers the long run **W**,**S** consequences of a sub-catchment being completely forested (least stream flow), then those of being cleared (greatest stream flow). Then it considers every combination of forested and cleared lands among the LMU’s of the sub-catchment; hence the word “Factorial” in the name. The result is a unique elliptical envelope marking the boundaries of feasible future equilibrium **W**,**S** flows from each sub-catchment. Within each envelope (Figure 2) a sample of feasible future **W**,**S** targets was defined for economic analysis.

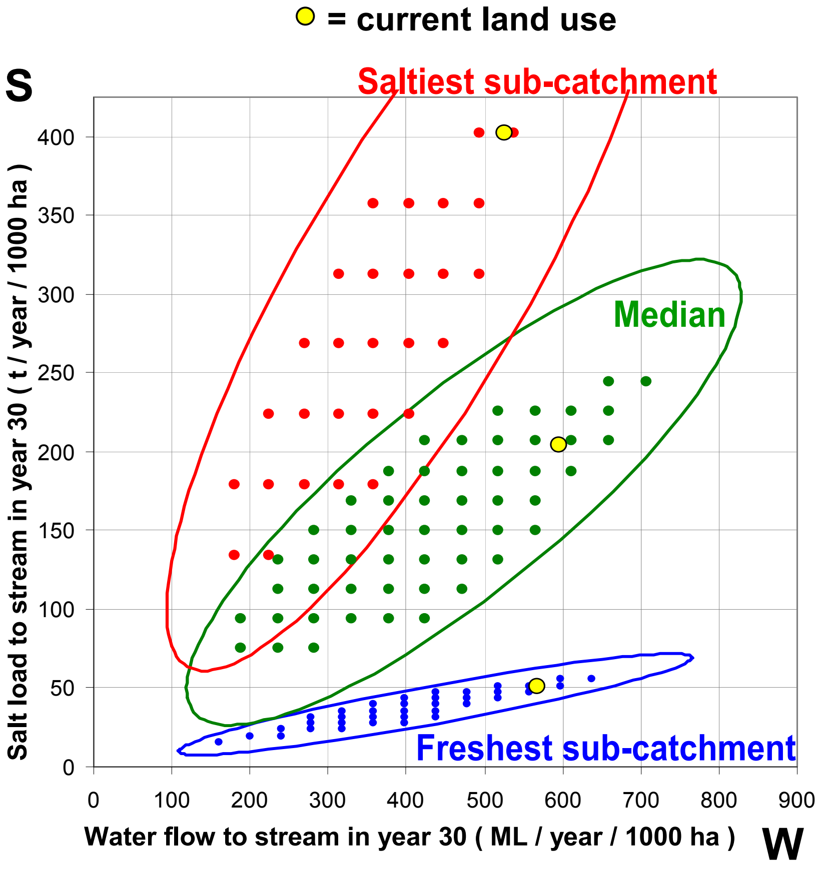


Fig. 2. **Contrasting envelopes of feasible equilibrium W,S targets, expressed on a ‘per 1000 ha’ basis**

Changes in water use, due to changes in land use, affect stream volumes and salt loads

For a catchment with a local groundwater flow system in dynamic equilibrium, stream flow equals long-term rainfall minus evapotranspiration, ‘***ET***’ (Zhang *et al.,* 1999). ***ET*** is greatest from a forested area, least from a cleared (cropped) area and at intermediate levels with permanent pasture options: highest with sown, lower with improved permanent pastures and less again with poor permanent pastures.

Given a change in land use, the amount of water used will change over time. For example, water use will drop quickly if a forest is cleared for use as unimproved grazing land. But in the reverse case, establishing a tree plantation in an unimproved pasture, the change in water use will be drawn out over many years as the trees mature.

To model the effects of changes in water use on sources of stream flow we assume the annual contributions of excess water (rainfall minus ET)**:**

- change over time as a function of land use (mentioned above) and,
- are partitioned by soils into surface runoff and deep drainage (leakage) fractions. Delays for changes in deep drainage to affect changes in stream flow may require many years, depending on hydrologic characteristics.

Changes in annual contributions to excess water over time with a change in land use are assumed to be expressed as smooth shifts from the initial (**I**) equilibrium state to the ultimate (U) equilibrium state. For example, changing one hectare of cropping (CR) in the saltiest sub-catchment (Table 1) to forest (FP) would cause the contribution of excess water to decline from 0.72 to 0.10 ML/ha over a number of years. Even with an abrupt change in water use by plants, as when a forest is cleared for grazing, there will be a time lag in effects as the soil profile fills up with water over a number of years. Excess water in a given year ($\mathbf{EW_y}$), after a transition in land use, is modelled as a logistic function with asymptotes, **I** and U, and parameters for inflection year (Y_x) and abruptness or slope (S_x), after Nordblom *et al.* (2004b) as follows, where Y is the number of years following the change:

$$\mathbf{EW_y} = \mathbf{I}+(U-\mathbf{I})*(1/(1+((Y/Y_x)\text{^}-S_x))) \qquad \text{ML/ha/year} \qquad (1)$$

We assume Y_x and S_x values of 5 and 5 for most transitions in quantities of excess water with changes in land use; the exceptions are for the slower transitions in the cases of shifts to forest plantations where values of 10 and 3 are assumed.

Following Dawes *et al.* (2000) we assume excess water is partitioned between surface runoff (**SR**) and deep drainage (**DD**) differently according to soil type. We have grouped the soil types found in Little River Catchment into eight LMUs and assumed drainage fractions (**Df**) for each (Fig. 1). **Df** is the assumed proportion of excess water in a year that goes to deep drainage, while (1-Df) is the share that goes directly to the stream as surface runoff that year. We assume Df is constant for an LMU regardless of the land use or level of excess water in a given year. That is:

$$\mathbf{SR_y} = EW_y*(1-Df) \qquad \text{ML/ha/year} \qquad (2)$$

$$\mathbf{DD_y} = EW_y*(Df) \qquad \text{ML/ha/year} \qquad (3)$$

While surface runoff reaches the stream in the same year, deep drainage reaches the stream only after a time-lag peculiar to each sub-catchment, according to topography and geology. Evans *et al.* (2003) express this with two hyrologic response parameters: half-time ($Y_\mathbf{H}$) and slope ($S_\mathbf{H}$), as shown in Table 1.

We calculate the lagged **change in groundwater discharge to the stream** (CGD_y), in a particular year following a land use change, as follows:

$$\mathbf{CGD_y} = (DD_y-DD_{y-1})*(1/(1+EXP((Y_H-Y)/S_H))) \qquad \text{ML/ha/year} \qquad (4)$$

And aggregate these changes to calculate the **total groundwater discharge to the stream (GDS_y)**, in a particular year following a land use change, as follows:

$$\mathbf{GDS_y} = (B*Df)+SUM(CGD_1: CGD_y) \qquad \text{ML/ha/year} \qquad (5)$$

Total annual stream flow ($\mathbf{W_y}$), from a particular area in a particular year following a land use change, will be the sum of the surface runoff water in that year (Eq. 2) and the total groundwater discharge to the stream (Eq. 5), as follows:

$$\mathbf{W_y} = SR_y + GDS_y \qquad \text{ML/ha/year} \qquad (6)$$

With this information and knowledge of rainwater salinity (RWS) and groundwater salinity (GWS) from Table 1 (both in units of ppm or mg/L), the total salt load entering the stream ($\mathbf{S_y}$), from a particular area in a particular year following a land use change, may be estimated as follows:

$$S_y = ((RWS*SR_y) + (GWS*GDS_y))/1000 \qquad \text{T/ha/year} \qquad (7)$$

This assumes constant mean annual rainfall levels over each sub-catchment. Of course, the real world with all its day-to-day and year-to-year variations, will present much noisier tracks over time than the simple cause and effect picture we paint here. Simulated trajectories are illustrated in Fig. 3 showing model estimates for $\mathbf{W_y}$ (stream flow in ML/ha/year) over a 30-year run for each of the land use activities assumed possible on one LMU in one sub-catchment.

The greatest time lags are obvious in the cases of shifting to tree plantation activities, due to the time assumed to be required for trees to reach mature capacity for water use. For the purpose of the present mini-model, we deal with water and salt flow (**W,S**) targets at year 30 following land use changes in year 1. After 30 years, most changes in water flow will have settled down at new equilibrium levels. And over the 30-year run of economic results for the same activities, discounted back to the perspective of net present values in year 0, wide contrasts will be exhibited. It is obvious that targets may be set for earlier dates, say, 20, 10 or even 5 years. However, due to the time lags assumed for plant water use responses, in addition to hydrologic response times, very early well-stabilised responses in stream flows cannot be expected.

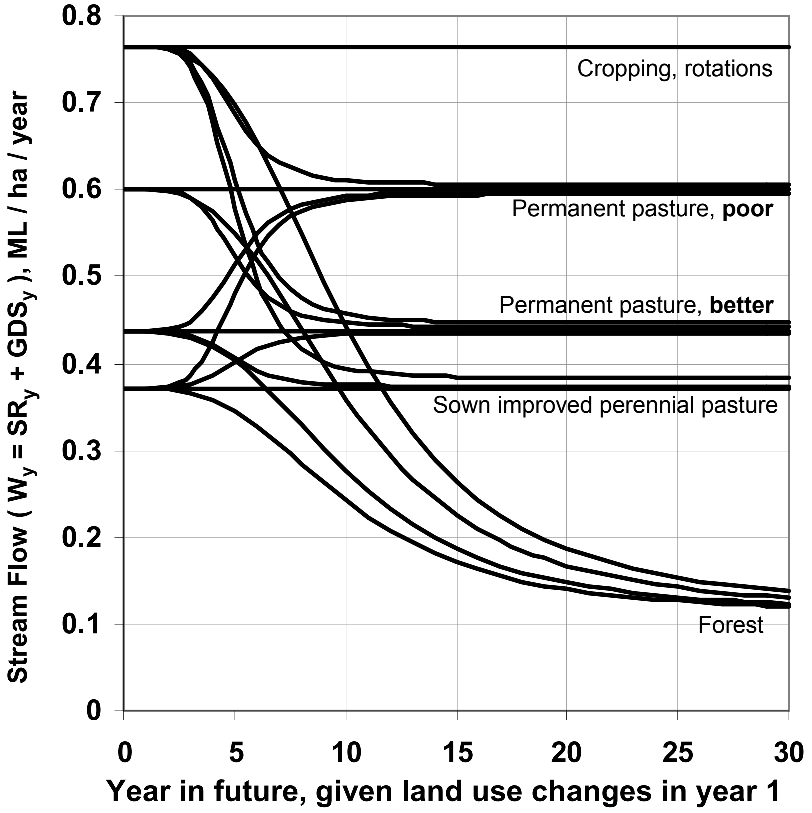


Fig. 3. Changes in stream flow over time, calculated for cases of land use change in LMU 2 of the Freshest sub-catchment (see box in Table 2). These take account of the hydrological characteristics of the sub-catchment (Table 1) and the soils of LMU 2 (Fig. 1)

A farm-level model to maximise Net Present Value (NPV) of wealth in a sub-catchment, subject to **W**,**S** *targets*

A 'whole-farm' linear programming model was developed to find the land use configurations that maximize NPV subject to any feasible **W**,**S** target. The physical properties of different sub-catchments were represented by constraining the land areas to those of its constituent LMUs (Table 2). Each LMU may be used in different ways depending on land capability (i.e., cropping not allowed on shallow soils), commodity prices, and chances for complementary use of other LMUs, such as cropping and pasture areas for livestock feeding at different times of the year. These complementarities highlight the importance of whole-farm analysis, and the inadequacy of gross margin analyses of isolated activities, in studying such natural resource management questions. In the present analysis we consider only five possible land uses (Table1) and we assume potential future land uses are conditional on current land use (Table 2) according to the constraints indicated in Table 3.

We assume current land uses may be continued in all cases. In the case of cropped land (CR) there is maximum flexibility for shifting to any of the other four land uses, the three pasture options NP, NB or SP, or to a forest plantation option FP (Table 3). In the case of land currently classed as poorer pasture (NP) we assume the only other options are shifts to better pasture (NB) or to a forest plantation (FP); we assume shifts to cropping (CR) or sown improved pastures (SP) will not be possible. Likewise, land currently classed as better pasture (NB) may be allowed to slip into the status of poor pasture (NP), renovated to the status of sown improved perennial pasture (SP) or turned into a forest plantation (FP); a shift to cropping (CR) is assumed to be impossible (sown pasture phases are assumed already captured in the CR category). Finally, land currently classed as sown improved pasture (SP) may be shifted to any land use except cropping (CR). Obviously these five categories are unable to represent the full richness of diversity in land use, but simplicity is an advantage for the present illustration. Bathgate *et al.* (2005) define over 60 land uses for each LMU.

Table 3. The 18 land use activities (X_j ha) assumed to be feasible in a land management unit of a sub-catchment in the future include continued current land uses and transitions to new uses, conditioned on current use

	CR current	**NP current**	**NB current**	**SP current**	**FN current**
CR continued	X_1=**CR** cont				
NP continued		X_2=**NP** cont			
NB continued			X_3=**NB** cont		
SP continued				X_4=**SP** cont	
FN continued					X_5=**FN** cont
NP new	X_6=**CR** to **NP**		X_{12}=**NB** to **NP**	X_{15}=**SP** to **NP**	X_{18}=**FN** to **NP**
NB new	X_7=**CR** to **NB**	X_{10}=**NP** to **NB**		X_{16}=**SP** to **NB**	
SP new	X_8=**CR** to **SP**		X_{13}=**NB** to **SP**		
FP new	X_9=**CR** to **FP**	X_{11}=**NP** to **FP**	X_{14}=**NB** to **FP**	X_{17}=**SP** to **FP**	

Where:
CR = Cropping, continuous and in rotations with pasture
NP = Volunteer, naturalised, native or improved pastures, **poor**
NB = Volunteer, naturalised, native or improved pastures, **better**
SP = sown improved perennial pastures
FN = Forest, native and existing plantation **FP** = New forest plantation

Our implicit assumption here is that 'if land could have been put to more profitable use this would have been done long ago'. The corollary to this is the expectation that land use patterns observed currently are approximately the most profitable mix from the private point of view. Without such constraints on land use options, an optimizing economic analysis would incorrectly call for shifting all land to whichever use is most profitable (cropping in this case) though, due to practical constraints such as steep terrain or shallow soils, this could never be implemented. On the other hand, if technical advances and prices should favour forestry over other uses in the future, the present model would allow all land to be shifted to plantations. Also, because forests are assumed to transpire greater amounts of water than any of the other land uses, the model allows forest plantations to be drawn into the profit-maximizing mix of land uses in order to satisfy a constraint on future water and salt flows to the stream. The land use constraints explained above may be expressed as a set of linear equations laid out in standard matrix format (Table 4).

In addition to land use constraints, we need to specify several economic values for the present analysis. These are expressed in a generic format (Table 5) with the same land-use options for column headings as in Table 4. With the aim of creating a simple example, we have specified five possible continuing land uses, with no start-up costs and only recurrent annual costs. We assume cropping is the only option that provides directly sellable products as well as five DSEs (dry sheep equivalents) in grazing per hectare each year. The other four land uses are assumed to yield only grazing capacity, though the amounts vary markedly among them.

Table 4. Generic land use constraint matrix for a land management unit (LMU) in a sub-catchment

	Future options for land use in an LMU of a sub-catchment																			
	continued **W**,**S** yields and economic performance over future periods					Changed land uses and economic performance accompanied by curved **W**,**S** yield trajectories to future equilibria														
Current land use	CR cont	NP cont	NB cont	SP cont	FN cont	CR to NP	CR to NB	CR to SP	CR to FP	NP to NB	NP to FP	NB to NP	NB to SP	NB to FP	SP to NP	SP to NB	SP to FP	FN to NP		**Land area const-raints (ha)**
	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	X_{12}	X_{13}	X_{14}	X_{15}	X_{16}	X_{17}	X_{18}		
CR current	**1**					**1**	**1**	**1**	**1**										=	**b CR**
NP current		**1**								**1**	**1**								=	**b NP**
NB current			**1**									**1**	**1**	**1**					=	**b NB**
SP current				**1**											**1**	**1**	**1**		=	**b SP**
FN current					**1**													**1**	=	**b FN**
LUC_i	**A**																		**=**	**B**

where:

LUC_i = land use constraint (ha) = SUM(X_{ij}) = $\mathbf{b_i}$ In particular:

$1X_1 + 1X_6 + 1X_7 + 1X_8 + 1X_9$ = **b CR** current area of cropping, continuous and in rotations with pasture

$1X_2 + 1X_{10} + 1X_{11}$ = **b NP** " " Volunteer, naturalised, native or improved pastures, **poor**

$1X_3 + 1X_{12} + 1X_{13} + 1X_{14}$ = **b NB** " " Volunteer, naturalised, native or improved pastures, **better**

$1X_4 + 1X_{15} + 1X_{16} + 1X_{17}$ = **b SP** " " Sown improved perennial pastures

$1X_5 + 1X_{18}$ = **b FN** " " Forest, native and plantation

Subject to the non-negativity constraint that all variables $X_j \geq 0$

We simplify further by assuming all grazing capacity is valued at $15/DSE, avoiding on one hand considerable complication of the model; on the other hand this misses an element of reality, which is that grazing livestock can offer enormous complementarities among land use options, particularly when considering the timing of feed availability during the year. Here we make the heroic assumption that all the apparent grazing value is able to be captured, either through agistment or through livestock enterprises not explicitly in the model but earning only $15/DSE.

Except for transitions from other land uses to poor pasture (NP), start-up costs are expected. These vary according to the intended new land use (Table 5). We assume land use transitions can happen only in year 1 in the future, incurring start-up costs in that year only and recurring costs in that and every subsequent year out to a horizon of 30 years. While these generic cost assumptions hold across all LMUs, productivities of crop and grazing lands vary according to LMU (Table 2). This reflects our assumption that profitability across LMUs varies greatly.

Table 5. Generic economic parameters assumed for land use activities (X_j), continuing and new, for each of eight LMUs in the mini-model

	Continued costs and yields over future periods					**Transitions in land use with changed costs, sales and DSE oftakes**												
	CR cont X_1	**NP cont** X_2	**NB cont** X_3	**SP cont** X_4	**FN cont** X_5	**CR to NP** X_6	**CR to NB** X_7	**CR to SP** X_8	**CR to FP** X_9	**NP to NB** X_{10}	**NP to FP** X_{11}	**NB to NP** X_{12}	**NB to SP** X_{13}	**NB to FP** X_{14}	**SP to NP** X_{15}	**SP to NB** X_{16}	**SP to FP** X_{17}	**FN to NP** X_{18}
Start-up cost $/ha (**T**)	0	0	0	0	0	**0**	**40**	**150**	**200**	**40**	**200**	**0**	**150**	**200**	**0**	**40**	**200**	**0**
Recurrent cost $/ha (**N**)	200	20	50	100	10	20	50	100	10	50	10	20	100	10	20	50	10	20
Mean sales $/ha (**M**)	650	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DSE offtake/ha (**D**)	5	2	5	10	1	2	5	10	1	5	1	2	10	1	2	5	1	2
Present Values of	**5 continuing current land uses**					**13 options for transition to new land uses in year 1**												
PV year 1 (future)	**= (((M+D*G)*Pi)-N)/(1+r)**					**= (((M+D*G)*Pi)-T-N)/(1+r)**												
PV years 2 to 30 (in future)	**= (((M+D*G)*Pi)-N)/(1+r)^y**					**= (((M+D*G)*Pi)-N)/(1+r)^y**												
NPV (years 1 to 30)	**= SUM (PV year 1 to PV year 30)**					**= SUM (PV year 1 to PV year 30)**												

Where: Land use activities are as defined in Tables 2, 3 and 4; y = year in the future; G = grazing value, $15/DSE; r = discount rate, 7%

Note: Mean sales and DSE offtakes are applied only after adjustment by the LMU-specific productivity index (Pi) in Table 2

We take each sub-catchment as a unit for whole-farm economic optimization, subject to LMU by LMU land use constraints, constraints on **W** and **S** yields in year 30, given the discounted 30-year NPV of each land use option. The generic sub-catchment model is presented in schematic form in Table 6. While sub-catchments and farms in the area vary in size and actual farms may overlap sub-catchments, the present analysis assumes sub-catchments are a reasonable proxy for Farm Types.

Table 6. Schematic single sub-catchment level LP model matrix, allowing maximisation of whole-farm NPV across eight LMUs over 30 years, subject to land use constraints and constrained to meet a target combination of **W** (water yield) and **S** (salt load) in the stream in year 30

	units	**LU1** [A]	**LU2**	**LU3**	**LU4**	**LU5**	**LU6**	**LU7**	**LU8**		**RHS**[B]
LUC-LMU**1**[A]	**(ha)**	**A1** [A]								**=**	**B1** [A]
LUC-LMU**2**	**(ha)**		**A2**							**=**	**B2**
LUC-LMU**3**	**(ha)**			**A3**						**=**	**B3**
LUC-LMU**4**	**(ha)**				**A4**					**=**	**B4**
LUC-LMU**5**	**(ha)**					**A5**				**=**	**B5**
LUC-LMU**6**	**(ha)**						**A6**			**=**	**B6**
LUC-LMU**7**	**(ha)**							**A7**		**=**	**B7**
LUC-LMU**8**	**(ha)**								**A8**	**=**	**B8**
Water yield, yr 30	**(ML/yr)**	W1[C]	W2	W3	W4	W5	W6	W7	W8	**=**	**W target**
Salt Load, yr 30	**(t/yr)**	S1[D]	S2	S3	S4	S5	S6	S7	S8	**=**	**S target**
Sum: NPV years 1-30		NPV1[E]	NPV2	NPV3	NPV4	NPV5	NPV6	NPV7	NPV8	Maximise **NPV**	

[A] see Table 4 for expanded definitions of LUC$_i$ (land use constraints for an LMU), $\mathbf{A}_i$ and $\mathbf{B}_i$.
Note: $\mathbf{A}_i$ is a 5x18 matrix and $\mathbf{B}_i$ is a 5x1 array of land area constraints representing current use in LMU$_i$

[B] **RHS** = the Right Hand Side of this set of linear equations represents the constraint levels for a solution

[C] see Eq.6 for derivation of W1 (a 1x18 array). Other W in row are analogous but apply to other LMUs

[D] see Eq.7 for derivation of S1 (a 1x18 array). “ S “ “ “ “ “ “ “ “ “

[E] see Table 5 for derivation of NPV1 (a 1x18 array). “ NPV “ “ “ “ “ “ “ “ “

A given sub-catchment will offer a range of land use configurations to meet each of its sample of **W**,**S** targets with the best NPV possible. The best NPV for some of the extreme targets, however, may be quite poor compared to the best NPV in the neighborhood of current land use (Figure 4). Establishing a **W**,**S** target with a poor NPV implies an opportunity cost, or loss of wealth, compared to current land use. Each of the values plotted in Figure 4 represents an optimal solution of the generic model (Table 6) constrained to the land areas of a particular sub-catchment, and constrained to a particular **W**,**S** target.

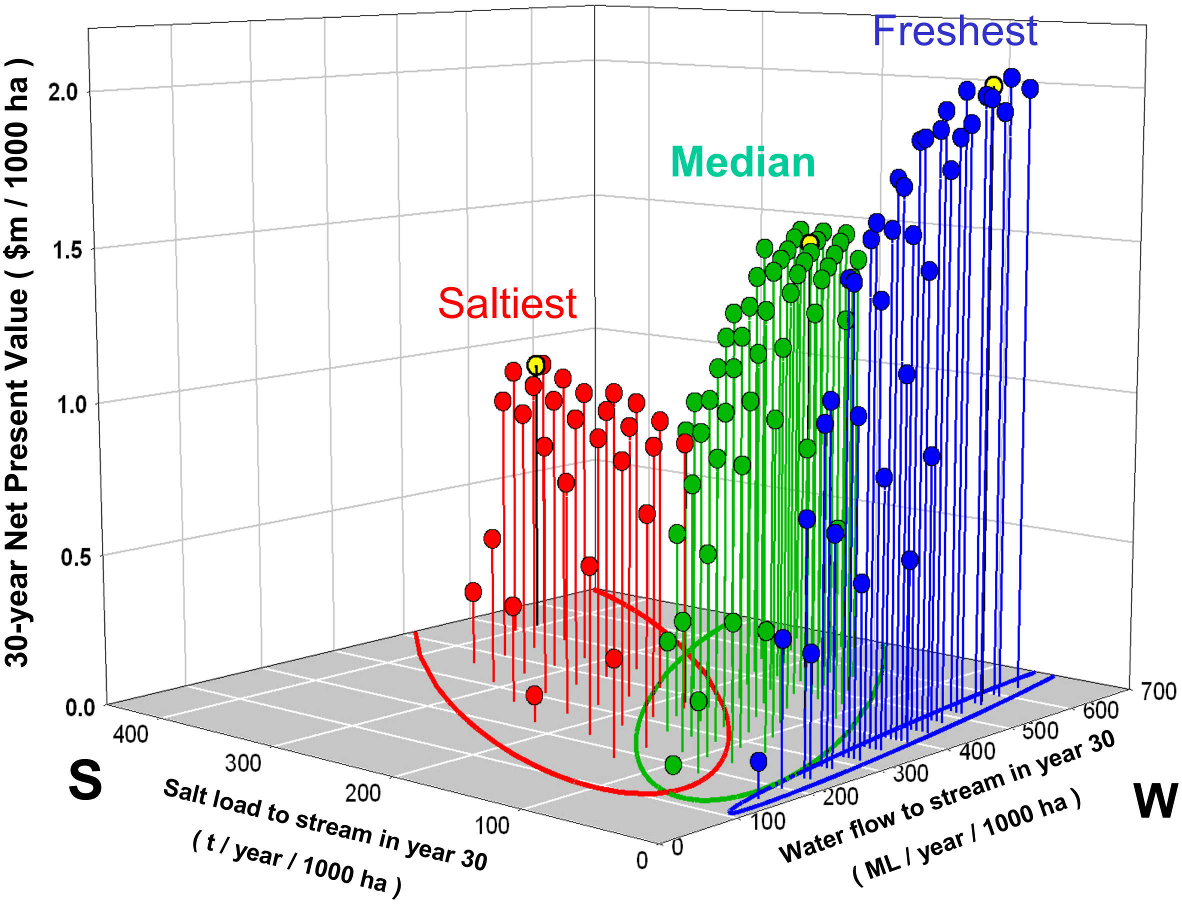


Fig. 4. Best NPVs ($m) for samples of W,S targets in the three contrasting sub-catchments. These are the same target W,S points indicated in Figure 2. W,S flow levels given current land use, and the associated best NPVs (yellow dots) determined for these, become the reference points for calculating opportunity costs of attaining other targets.

In the case of each sub-catchment's NPV surface (Figure 4), the lowest values are associated with the lower ranges of **W**,**S** targets… attained by shifts toward greater use of forest plantations. This is a consequence of our assumptions regarding the high costs and low grazing benefits of plantations, and the assumption that no commercial harvest will be forthcoming (Table 5), so we may not be generalize from this result. The effect of a real prospect for profitable forestry, say with establishment of local processing of new and valuable forest products, or the negotiation of carbon sequestration credits for a plantation, could be to lift the lower ends of the NPV surfaces significantly. As will be shown below, forestry and improved pastures can have important strategic roles in manipulating water use in the landscape and, thereby, altering future river volumes and salt loads at least cost for the benefit of downstream uses.

A catchment-level economic meta-model aggregates and integrates results of sub-catchment (whole-farm) models to face downstream demands

Each feasible future **W**,**S** target at the sub-catchment level (Figure 2) will have an associated best NPV (Figure 4) generated by the sub-catchment (or whole-farm) model (Table 6). We take each of the resulting triplets of data (**W**, **S**, NPV) as the basis for an ‘activity’ in a ‘mini-catchment model’ with constraints on aggregate end-of-valley water yield (**W**) and salt load (**S**), and the ‘objective’ of maximizing overall NPV. Here, we aggregate results of the above three sub-catchments to build a ‘mini-catchment’ economic model (Table 7, Fig. 5). Our full Little River catchment model similarly integrates the economic results from all 80 sub-catchments for full long-term end-of valley results (Bathgate *et al.* 2005).

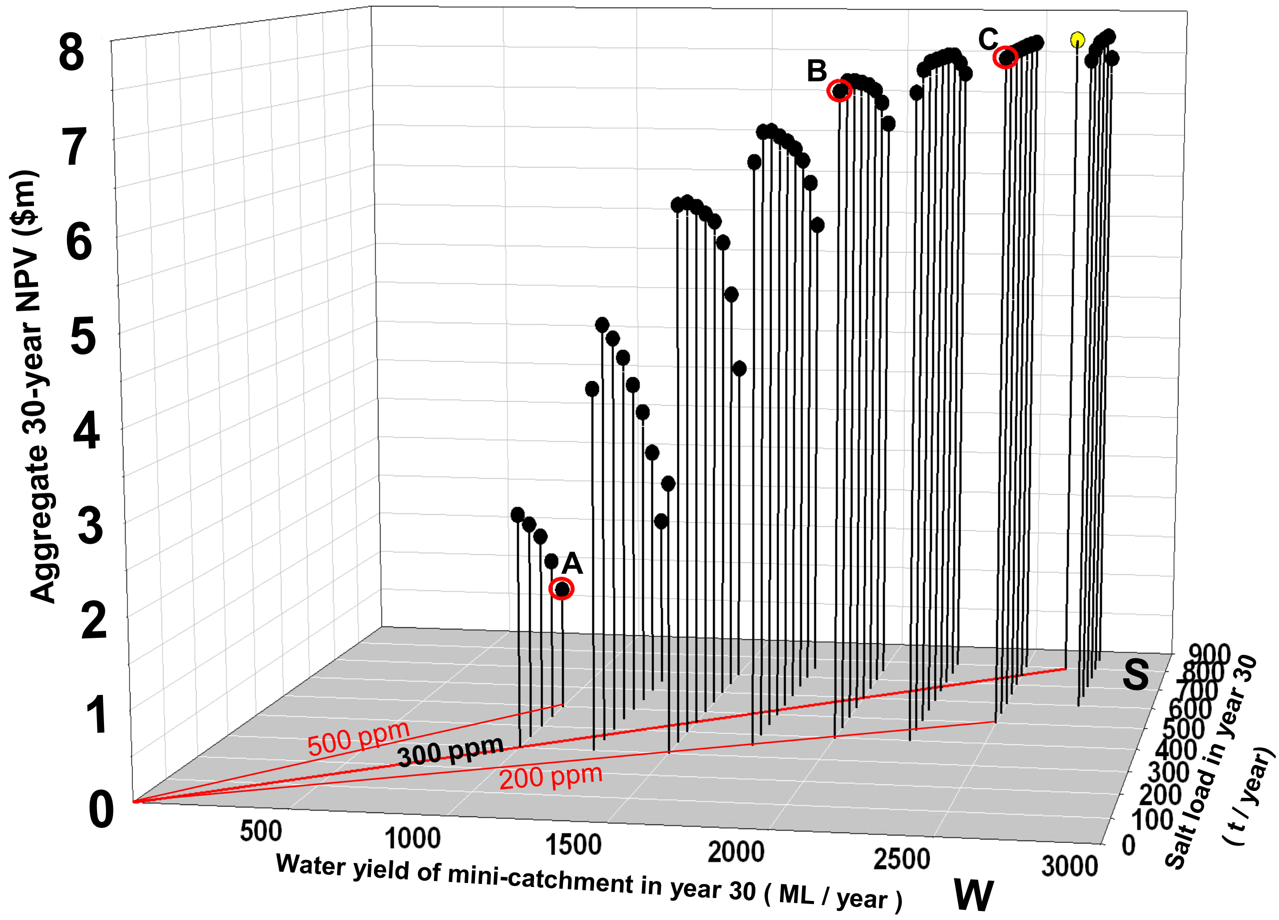


Fig. 5. Best NPVs ($m) for sampled end of valley target W,S flows in year 30 from the aggregate (3-sub-catchment) mini-catchment. In addition to the best NPV calculated for the W,S levels of current land use, delivering water with a salt concentration of 300 ppm, three other feasible W,S targets (labelled A, B and C) illustrate different future river flows with 500, 200 and 200 ppm salt.

Table 7. Schematic mini-catchment LP model, using the results (W,S,NPV)[A] for feasible **W,S** targets in each of three contrasting sub-catchments, to maximise aggregate NPV subject to mini-catchment **W,S** targets

	"**S**altiest" Sub-catchment					"**M**edian" Sub-catchment					"**F**reshest" Sub-catchment					**Sign**	**RHS**
Variables	X_{ST1}	X_{ST2}	· · ·	X_{ST27}	X_{ST28}	X_{MT1}	X_{MT2}	· · ·	X_{MT52}	X_{MT53}	X_{FT1}	X_{FT2}	· · ·	X_{FT35}	X_{FT36}		
W,S Target Name:	**ST1**	**ST2**	. . .	**ST27**	**ST28**	**MT1**	**MT2**	. . .	**MT52**	**MT53**	**FT1**	**FT2**	. . .	**FT35**	**FT36**		
SSC constraint	**1**	**1**	· · ·	**1**	**1**	·	·	· · ·	·	·	·	·	· · ·	·	·	**=**	**1**
MSC constraint	·	·	· · ·	·	·	**1**	**1**	· · ·	**1**	**1**	.	.	· · ·	·	·	**=**	**1**
FSC constraint	·	·	· · ·	·	·	·	·	· · ·	·	·	**1**	**1**	· · ·	**1**	**1**	**=**	**1**
W constraint (ML/y)	**200**	**200**	· · ·	**550**	**600**	**200**	**200**	· · ·	**700**	**750**	**400**	**500**	· · ·	**1500**	**1600**	**=**	**W target**
S constraint (T/y)	**200**	**150**	· · ·	**350**	**450**	**100**	**80**	· · ·	**220**	**260**	**40**	**50**	· · ·	**130**	**140**	**=**	**S target**
NPV/$1m	**-0.16**	**0.35**	· · ·	**1.02**	**1.06**	**0.01**	**0.24**	· · ·	**1.55**	**1.56**	**0.29**	**1.15**	· · ·	**5.13**	**5.02**	**Maximise NPV**	

[A] For a given **W,S** target for year 30 at the sub-catchment level, as indicated in the RHS of Table 6, there will be one mix of land uses that maximises the 30-year NPV subject to all the land use constraints of that sub-catchment. Each **NPV** value in the present table is the result of the sub-catchment level model solved subject to the associated **W,S** target values. In this example, multiple runs of the sub-catchment model over a sample of W,S targets yielded 28 (**W,S,NPV**) triplets of feasible results for the "saltiest" sub-catchment, 53 triplets for the "median" and 36 for the "freshest" sub-catchment. These results provided the data for the present mini-catchment LP model in which the range of feasible **W,S** targets was sampled and best NPVs determined for each (Figure 5).

Our mini-catchment results for future **W,S** targets produce an NPV surface (Figure 5). Our aim for the moment is the determination of minimum opportunity costs for achieving the various feasible mini-catchment **W,S** targets. Subtracting the NPV for a mini-catchment-level **W**,**S** target from the best NPV in the envelope of targets gives the desired result. This is the aggregate cost to the land managers, in terms of lost opportunities, for departing from their best NPV land-use configurations.

Minimum-cost attainment of whole-catchment targets is possible by simultaneous analysis of all sub-catchment W, S and NPV results (Figure 4). Current flows from our example (three-sub-catchment) mini-catchment deliver a stream salt concentration of 300 ppm; changes in land use offer a range of 200 to 500 ppm (320 to 800 EC).

Three example targets (**A**, **B** and **C**) illustrate trade-offs among aggregate farm opportunity costs and downstream water volumes and salt loads (Figures 5 & 6). Target **A** is attainable but incurs over $6m in opportunity cost, lowers annual stream flow by 1500 ML and increases stream salinity to 500 ppm: a poor option compared to others. Target **B** halves current salt load, costs $0.4m and 500 ML stream flow, but improves stream salinity to 200 ppm. Target **C** offers the same improvement in water quality as **B** but costs only $0.1m with little loss in stream flow compared to the current level. These three examples demonstrate the scale of tradeoffs that could be faced in terms of costs and ranges of choice among future **W,S** targets at the level of a mini-catchment with less than 5000 ha surface area and comprised of three contrasting sub-catchments.

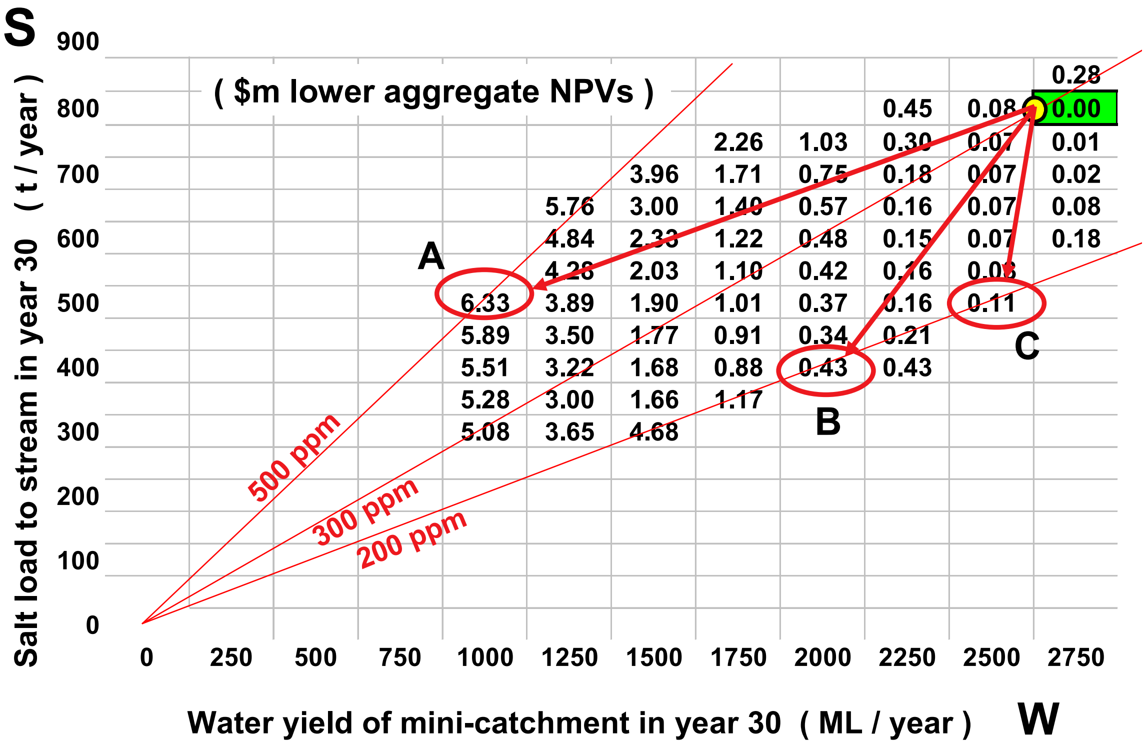


Fig 6. Opportunity costs of meeting mini-catchment W,S targets by year 30

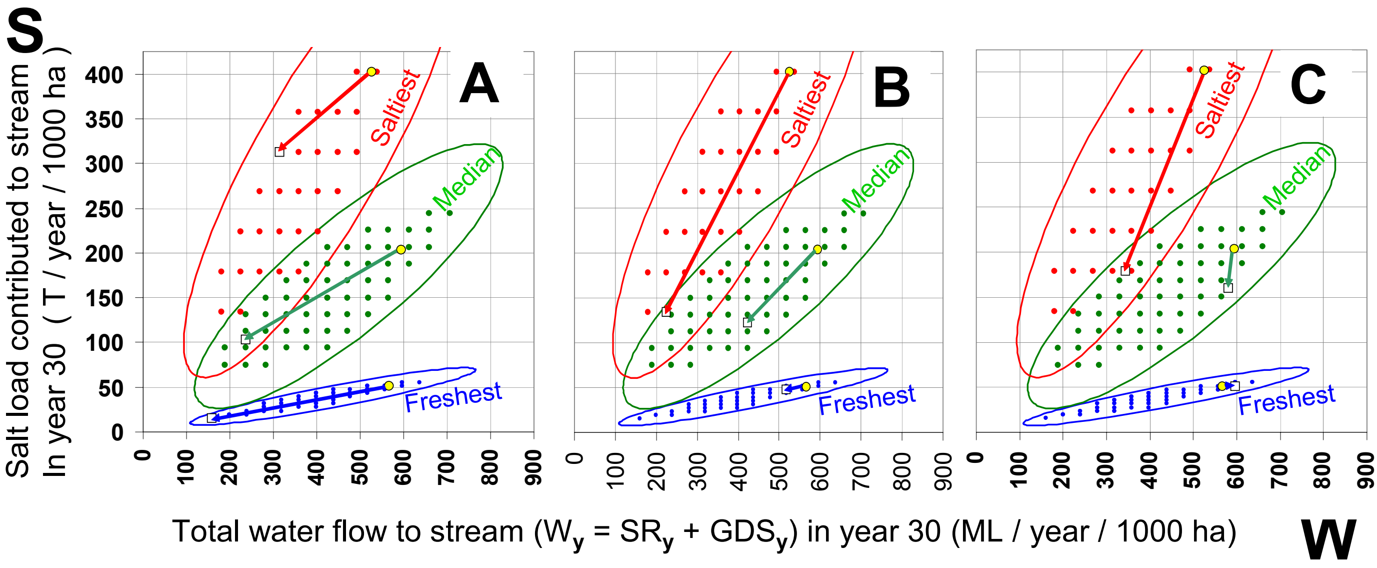


Fig. 7. Least-cost W,S target-shifts in three sub-catchments to achieve aggregate mini-catchment W,S targets A, B and C (of Figures 5 & 6) by year 30. See Table 8 for the land use changes calculated to deliver these targets (for LMU-by-LMU details see Appendix 3)

The benefits resulting from such shifts, in terms of altered future **W,S** flows, could accrue to downstream uses (environmental, agricultural, industrial, domestic). We have not attempted to place a dollar value on these here, though something like this is clearly needed for efficient compensation of up-stream land-holders' opportunity costs for dramatic change. This is the subject of Appendix 5 (also see Nordblom *et al.* 2005a,c).

Discussion

One of the premises of the present analysis is that current land use distributions are the result of many years of private decisions motivated by wealth maximization, which is consistent with (and often dependent upon) sustained productivity. This implies that, under prevailing prices, all land suitable for cropping is being cropped, land best suited for use as sown improved perennial pasture is used in that way, and that clearing of forests to open up pastures for grazing has already progressed to the limit of what is worth clearing. Other motivations, such as maintenance of nature reserves are also apparent but these hold mainly on rough country where opportunity costs are minimal. Reforesting good pasture land would entail opportunity costs, more so in the case of good crop land. Exceptions are where forest belts can be placed strategically to prevent rising water tables from spoiling good farm land. Therefore, it should not be surprising that our calculated NPV's for current land use are close to (overall only 4% below) the 'best' calculated NPV's when constrained to current **W,S** levels (see Appendix 4).

The 'best' NPV's for current **W,S** levels appear very close to the best attainable with any mix of land uses (see Fig. 6 and Fig. 7) for other future **W,S** targets. This does not confirm our premise that farmers are doing their best, but it is consistent with the idea. A consequence of this is that without new technologies or altered economic

Table 8. Summaries of current land use in the three sub-catchments and changes calculated to achieve aggregate mini-catchment W,S targets A, B or C* at least-cost by year 30

	Summary of current land use in three sub-catchments of the example mini-catchment				**Summary of land use in three sub-catchments of the example mini-catchment**											
					- to achieve Target A by year 30				**- to achieve Target B by year 30**				**- to achieve Target C by year 30**			
Land use	**Saltiest** (ha)	**Median** (ha)	**Freshest** (ha)	**Total (ha)**	**Saltiest** (ha)	**Median** (ha)	**Freshest** (ha)	**Total (ha)**	**Saltiest** (ha)	**Median** (ha)	**Freshest** (ha)	**Total (ha)**	**Saltiest** (ha)	**Median** (ha)	**Freshest** (ha)	**Total (ha)**
Cropping (**CR**)	237	448	1101	**1786**	117	125	125	**368**	170	426	1101	**1697**	195	448	1101	**1744**
Volunteer pasture, Poor (**NP**)	421	12	12	**446**	335	33	0	**369**	30	22	227	**278**	232	292	644	**1169**
Volunteer pasture, Improved (**NB**)	335	379	822	**1536**	0	0	0	**0**	0	0	3	**3**	1	37	3	**41**
Sown perennial pasture (**SP**)	122	167	580	**869**	0	0	0	**0**	0	4	705	**708**	119	5	705	**829**
Forest (**FN/FP**)	1	52	0	**54**	665	901	2390	**3956**	917	608	480	**2005**	568	277	63	**909**
Total area	**1117**	**1060**	**2516**	**4692**	**1117**	**1060**	**2516**	**4692**	**1117**	**1060**	**2516**	**4692**	**1117**	**1060**	**2516**	**4692**

•**W,S** targets **A**,**B** & **C** are identified in Figures 5 and 6

For details on current land use by LMU see Table 2. For land use changes by LMU to reach Targets **A**, **B** and **C** see Appendix 3 conditions there will be few if any 'win-win' solutions available for changing **W,S** output levels at no cost to farmers. Given that there will be costs, we can estimate them as a basis for negotiating changes in land use… and for aiming land use change where it is able to do the most good for the least cost. At the same time, research work on the new technologies that will make salinity management more economical is on track through the CRC Salinity and needs continuing support.

Conclusions

Contributions to stream water flow (**W**) and salt load (**S**) differ widely among sub-catchments depending on groundwater salinity, soils and land use. Some sub-catchments deliver relatively high salt concentration flows and some relatively fresh. From the 80 sub-catchments of Little River (in NSW) we selected three (with the saltiest, median and freshest flows) to comprise a mini-catchment for illustration. Current land use is a mix of annual cropping and pastures, permanent pastures and some forested areas. We showed a range of **W,S targets** can be met in the future by changing land use now. Cleared land yields the upper end of the ranges of **W,S** possibilities and forest the lower end.

Using a linear programming model and a discount rate of 7%, our economic analysis found the land use mix with the best whole-farm Net Present Value (**NPV**) for each of a sample of **W,S** targets in each sub-catchment.

The difference between the **NPV** of current land use and that of another **W,S** target is the opportunity cost of that target. Current land use, which shifts slowly with changes in prices, markets and technology, tends toward the most profitable private use of local resource bases. Depending on its profitability and location in a whole-farm context, increasing perennial land cover may reduce **W** and/or **S** with little or no sacrifice in economic performance. Profitable or unprofitable perennials can increase or reduce farm profits. But poorly sited on a large scale, either can reduce stream flow as well as water quality.

Minimum-cost attainment plans for whole-catchment targets were found by simultaneous LP analysis of all sub-catchment **W, S** and **NPV** results. Current flows from our example mini-catchment deliver a stream salt concentration of 300 ppm, while selected changes in land use offer a range of 200 to 500 ppm (320 to 800 EC).

Our study demonstrates new methods for determining the locations and levels of land use change required to achieve particular future **W,S** flow targets at the sub-catchment and catchment levels at least cost. This is a means to inform policy makers, land-holders in catchments and downstream interests of the likely scope for, and costs of, altering water and salt flows from particular catchments. It demonstrates that a limited envelope of **W,S** targets will be feasible in a particular catchment and each target presents different costs of attainment. This work provides a new context for valuing emerging technologies in plant-based management of dryland salinity where stream water yield and salinity are at issue. It shows the obvious: that 'best land use' is a geo-physically and bio-economically context-sensitive question.

One policy message is clear**:** there are no good blanket solutions. This is due to the geophysical diversity in distributions of groundwater flow systems, groundwater salinity, soils and long-term rainfall levels, combined with complexity in current and potential land uses in upper catchments and diversity in current and potential uses of river water and water quality downstream. This paper has focused on the ranges of costs associated with the ranges of possibilities for changing future stream volumes and salt loads by strategically altering plant-based land covers in upstream catchments. The next logical question is how to match the possibilities and costs for changing the water supply and water quality flowing from catchments with the downstream demands for water volume and quality. This is the subject of Appendix 5, which summarizes a new research proposal.

Significant reductions in stream salinity will require strategic land use change on a scale that will only occur if profitable to farmers. Our framework links the complex biology, which drives profitability at the whole farm level, with hydrology at sub-catchment and catchment scales. Such a framework can help land managers, CMAs and policy makers quantify trade-offs and negotiate targets with downstream demands for water volume and water quality.

Acknowledgements

This study follows from, and documents more completely, models presented first in a 'poster paper' (Nordblom *et al*. 2004c) at the Bendigo (Vic) conference *"Salinity Solutions, Working with Science and Society"* organised by the CRC for Plant-based Management of Dryland Salinity. The body of this paper and Appendices 1 - 4 are drawn from Nordblom *et al.* 2005b. Appendix 5 is based on a proposal made to RIRDC and the CRC Salinity (Nordblom *et al*. 2005a,c). The paper depends heavily on Nordblom *et al*. (2004a) and Bathgate *et al.* (2005) in which Brian Murphy (DIPNR-Cowra), Geoff Beale (DIPNR-Wagga Wagga), Nick Sharp (DIPNR-Parramatta) and Ian McGowen (NSW DPI - Orange) are gratefully acknowledged for timely help and guidance with data on soils and land use in the Little River Catchment. We also thank Ray Evans (Salient Solutions Australia, Pty Ltd, Jerrabomberra, NSW) and Matt Gilfedder (CSIRO Land & Water, Canberra) for help in defining local sub-catchment boundaries and the groundwater salinity levels associated with these in the catchment. The authors wish to acknowledge the contributions of ideas for the present paper by Dave Pannell (UWA), Peter J. Regan and Rob Young (NSW DPI), Gary Stoneham and Charlotte Duke (Vic DPI) and Kevin Parton (Charles Sturt University, CSU - Orange). Valuable criticism and questions were received from Mark Conyers (NSW DPI - Wagga), Jim Virgona (CSU - Wagga Wagga), Tim Ferraro, Richard Chewings and Alan Nicholson (Central West Catchment Management Authority, Wellington), and Jessica Brown and Tom McKeon (Macquarie River Food & Fibre, Dubbo). Of course, any errors in the paper are due to the authors alone. Opinions expressed are those of the authors and do not necessarily represent the policy of NSW DPI or any other institution.

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APPENDIX 1. ET and Excess Water

Zhang *et al*. (1999) developed a model of catchment scale evapo-transpiration (***ET***) based on long term equilibrium catchment land use, stream-flow and rainfall. Using data from some 300 catchments around the world, a minority of which are in Australia, a two-parameter model was developed to predict catchment scale equilibrium ***ET***. Restrictions on the model include: (a) precipitation is mainly rainfall, (b) slopes are generally low throughout the catchment, and (c) soils are deep (> 2 m). Dawes *et al.* (2000) describe the model of Zhang *et al*. (1999) as:

$$ET = R\left(\frac{1+(wE_0/R)}{1+(wE_0/R)+(R/E_0)}\right) \quad \text{(mm)} \qquad \text{(A1.1)}$$

Where ***ET*** is annual evapo-transpiration in *mm*, ***R*** is long term annual rainfall in mm, $\boldsymbol{E}_O$ is a rainfall scaling parameter, and ***w*** is a plant available water parameter. Zhang *et al.* (1999) estimated parameter values at $\boldsymbol{E}_O$ =1410 mm and ***w*** =2.0 for forested catchments, and ***E***o =1100 mm and ***w***=0.5 for cleared catchments. Dawes *et al.* (2000) noted these parameters resulted in good fits (r^2=0.93 in forested and r^2=0.90 in cleared catchments). ***ET*** was estimated as measured rainfall minus measured stream flow.

Given that a megalitre (ML) of water is the equivalent of 100 mm of water over an area of one hectare (ha), we use equation (A1.1) following Dawes *et al.* (2000) and Stirzaker *et al.* (2002), in calculating "excess water" as long term annual rainfall minus ***ET***:

$$ExcessWater(ML/ha) = R\left(1-\left(\frac{1+(wE_0/R)}{1+(wE_0/R)+(R/E_0)}\right)\right)\Big/100 \qquad \text{(A1.2)}$$

We adopted the original parameter values of Zhang *et al*. (1999) for forested and cleared catchments for an earlier paper focusing on methods for estimating the ranges of water yields and salt loads possible from a catchment with different land use configurations (Nordblom *et al*. 2004a). We found the derived estimates of salt load and excess water under the current land use were greater than indicated by recent measures in the Little River catchment. This prompted us to review our rainfall data and to question whether the parameter values of Zhang *et al*. (1999) are suitable for the dry regions of Australia (see Appendix 2).

APPENDIX 2. Tuning the 'Zhang curves' for Australian catchments

Zhang *et al*. (1999) estimated their parameters using a global data set that included catchments with rainfalls ranging up to 3000 mm / year. The resulting curves under-predict ***ET*** where annual rainfall is low, as in many Australian settings. We fitted new curves to Zhang *et al.*'s function, using only their Australian data and adjusting the parameters to capture as many of the data points as possible while minimising the "gaps" between the curves and the data cloud. Our parameter adjustments to Eq.A1.1 (E_O =1800 mm and ***w*** =4.0 for forested catchments, and ***E***o =1400 mm and ***w***=0.5 for cleared catchments) depict a general increase in ***ET*** for Australian conditions in both the forested and cleared cases (Figure A2.1). The new curves reduced our catchment **W**,**S** estimates to ones closer to the measured level (from A to B in Figure A2.2). Further minor adjustments, 10% reduction in rainfall to account for retention by widespread farm dams (B to C) and a 10% increase in groundwater salinity (C to D), brought our estimates of catchment water yield and salt load suitably close to the measured values (X in Figure A2.2).

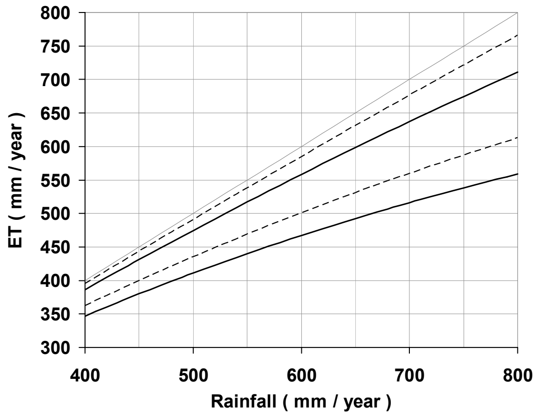


Fig. A2.1. Zhang curves for Australia's low rainfall (---) and original based on a world data set (—). The upper curves are for forested land, the lower for cleared land. A straight reference line for *ET* = rainfall (—) is also shown.

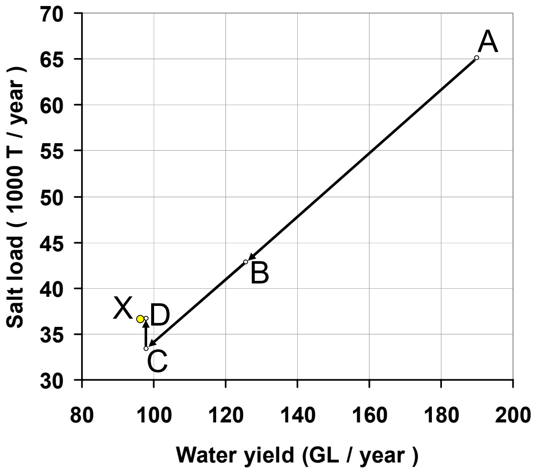


Fig. A2.2. Upper Little River catchment water yield and salt load calculations at steps in parameter calibration. Arrows from points A to D show steps toward the 'measured' value X

APPENDIX 3. Details of calculated changes in land use mixes, hectares by LMU, in three contrasting sub-catchments to achieve W,S targets A,B and C by year 30 at lowest cost at the aggregate mini-catchment level

	Land Use[A]	Change in land use mixes to yield aggregate mini-catchment Target **A**			Change in land use mixes to yield aggregate mini-catchment Target **B**			Change in land use mixes to yield aggregate mini-catchment Target **C**		
		Saltiest (ha)[B]	**Median** (ha)	**Freshest** (ha)	**Saltiest** (ha)	**Median** (ha)	**Freshest** (ha)	**Saltiest** (ha)	**Median** (ha)	**Freshest** (ha)
LMU 1	**1CR**	0	0	0	0	0	0	0	0	0
	1NP	-115	0	0	-115	0	0	-38	**4**	0
	1NB	0	0	0	0	0	0	0	0	0
	1SP	0	0	0	0	0	0	0	0	0
	1FN/FP	**115**	0	0	**115**	0	0	**38**	-4	0
LMU 2	**2CR**	-49	-34	-475	-2	0	0	0	0	0
	2NP	-3	0	-3	-3	0	-3	**24**	**3**	-3
	2NB	-107	-2	-431	-107	-2	-428	-106	-2	-428
	2SP	-36	-3	-273	-36	**1**	**431**	**83**	**2**	**431**
	2FN/FP	**196**	**39**	**1182**	**149**	**1**	0	-1	-3	0
LMU 3	**3CR**	0	-4	0	0	0	0	0	0	0
	3NP	0	-7	0	0	-7	0	0	-7	0
	3NB	0	-21	0	0	-21	0	0	**1**	0
	3SP	0	0	0	0	0	0	0	0	0
	3FN/FP	0	**33**	0	0	**28**	0	0	**6**	0
LMU 4	**4CR**	0	-36	0	0	-9	0	0	0	0
	4NP	0	0	0	0	0	0	0	**23**	0
	4NB	0	-118	0	0	-118	0	0	-103	0
	4SP	0	-107	0	0	-107	0	0	-107	0
	4FN/FP	0	**261**	0	0	**234**	0	0	**188**	0
LMU 5	**5CR**	-15	-1	0	-15	0	0	0	0	0
	5NP	0	-5	0	0	-5	0	**55**	**32**	0
	5NB	-52	-8	0	-52	-8	0	-52	-8	0
	5SP	-4	-7	0	-4	-7	0	-4	-7	0
	5FN/FP	**71**	**20**	0	**71**	**20**	0	**1**	-18	0
LMU 6	**6CR**	0	0	-4	-9	-8	0	-1	0	0
	6NP	**53**	**33**	0	-261	**4**	**2**	-253	0	**3**
	6NB	-53	-59	-4	-53	-59	-4	-53	-59	-4
	6SP	0	-3	-9	0	-3	-9	0	-3	-9
	6FN/FP	0	**29**	**16**	**324**	**66**	10	**308**	**62**	**9**
LMU 7	**7CR**	-41	0	0	-41	0	0	-41	0	0
	7NP	-21	0	0	-42	0	0	-42	0	0
	7NB	-84	0	0	-84	0	0	-84	0	0
	7SP	-55	0	0	-55	0	0	-55	0	0
	7FN/FP	**200**	0	0	**221**	0	0	**221**	0	0
LMU 8	**8CR**	-16	-249	-497	0	-5	0	0	0	0
	8NP	0	0	-9	**30**	**18**	**215**	**65**	**225**	**632**
	8NB	-38	-171	-387	-38	-171	-387	-38	-171	-387
	8SP	-27	-48	-298	-27	-48	-298	-27	-48	-298
	8FN/FP	**81**	**468**	**1192**	**35**	**206**	**470**	0	-6	**53**
Total Area (ha)		**1117**	**1060**	**2516**	**1117**	**1060**	**2516**	**1117**	**1060**	**2516**

[A] For LMU descriptors, see Fig. 1, for land use options see Tables 1 & 3, for current land use areas by sub-catchment & LMU, see Table 2.

[B] Change values in this table for each LMU in a sub-catchment sum to zero due to the constraint requiring use of exactly all the land.

APPENDIX 4. Discrepancies in NPVs for calculated current land use and for current W,S yields at sub-catchment and aggregate mini-catchment levels

An apparent 4% over all discrepancy (which includes a 12% discrepancy in the saltiest sub-catchment, Appendix Table 2), between the calculated consequences of current land use and the "best" NPV land use for the current **W,S** levels, may be due to the following causes:

- our hydrology, water use and salinity parameters (Table 1) may be in error;
- our data on current land use and productivity (Table 2) may be in error;
- our economic parameters (Table 3) may be in error;
- some combination of the above.

A possibility we regard as less likely is that the farmers have got it wrong and are not managing their land in their own best interest. It is far more likely we have got some or all of our assumptions a little wrong!

Appendix Table 2. Long-term W,S yields and NPVs of three sub-catchments under current land use (Scenario 1) compared with best sub-catchment NPVs when each is constrained to current W,S levels (Scenario 2) and best mini-catchment aggregate NPVs where constrained to current aggregate W,S levels but with W,S yields of the sub-catchments allowed to change (Scenario 3)

		sub-catchment			aggregate mini-catchment
		Saltiest	**Median**	**Freshest**	
Scenario 1	**W** (ML/y)	587	632	1425	2643
	S (T/y)	449	217	129	795
	NPV ($m) **x**	**0.95**	**1.51**	**4.95**	**7.41**
Scenario 2	**W** (ML/y)	587	632	1425	2643
	S (T/y)	449	217	129	795
	NPV ($m) **y**	**1.06**	**1.53**	**5.07**	**7.67**
	NPV **y/x**	1.12	1.01	1.02	1.04
Scenario 3	**W** (ML/y)	527	650	1467	**2643**
	S (T/y)	427	240	128	**795**
	NPV ($m) **z**	1.05	1.54	5.12	**7.71**
	NPV **z/x**	1.11	1.02	1.03	1.04

Where:

Scenario 1 shows **W,S** and NPV values calculated for current land uses indicated in Table 2. These are the **W,S** levels plotted in Figures 2, 4 and 7

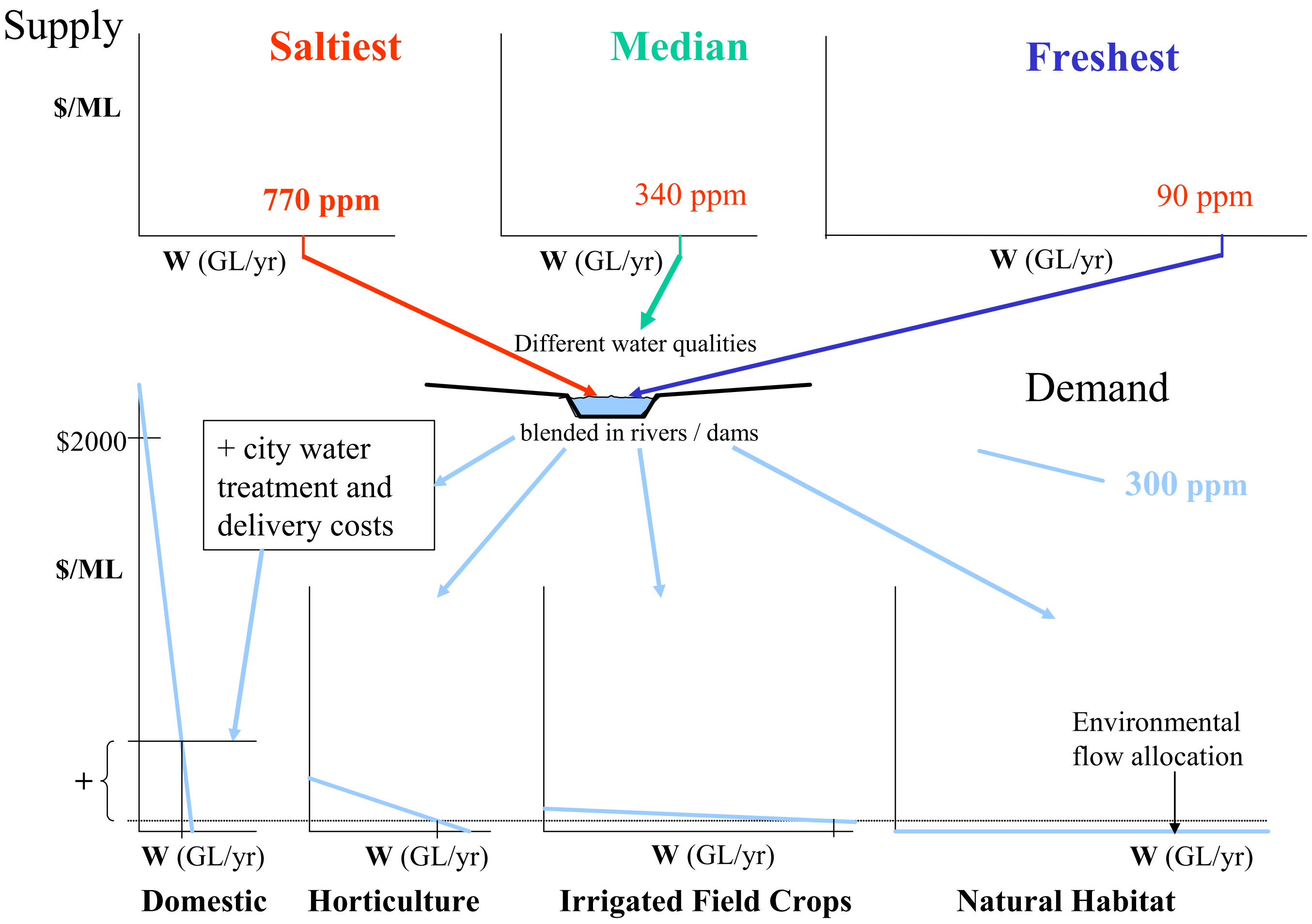
Scenario 2 reports best NPV values attainable by shifting land uses within sub-catchments while constrained to current sub-catchment **W,S** yields. These NPVs are plotted in Fig. 4.

Scenario 3 reports best aggregate NPV values when aggregate mini-catchment NPV is maximised while constraining aggregate **W,S** to the current values. These **W,S** and NPV values are used to plot the "current" land use case for the aggregate mini-catchment in Figs 5 & 6

APPENDIX 5. A proposed study for evolution of markets with Experimental Economics: toward land use change for management of stream water yield and salinity*

Experimental Economics

This appendix describes the modelling base and main features of a feasibility study for development of water and salt markets as means for creating greater private incentives for specific land use changes, such as strategically-sited upstream tree plantations and other land use changes, supported by the downstream water users who will benefit in terms of better water availability and quality (main paper). Downstream water users include domestic, commercial (city water users), agricultural (horticulture and irrigated field crops) and environmental flows. Upstream supply from three sub-catchments with salty, medium and fresh water yields, and downstream demand for water, are depicted in Appendix Figure A.5.1



Appendix Figure A 5.1 Schematic map of water supply and demand. Conventionally, the three sub-catchments (saltiest, median and freshest) supply current long-term total water yield at a salinity concentration of 300 ppm (300 mg/L) with downstream water use allocated by 'cap and trade' rules.

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* This appendix summarises a proposal to RIRDC and CRC Salinity (Nordblom *et al.*, 2005a), and an AARES 2005 conference paper (Nordblom *et al.*, 2005c).

Trees upstream are heavy users of water and must be located with great care so that stream yield and quality will not suffer unduly (Beverly, 2004a,b: Evans *et al*. 2004; Nordblom *et al*. 2004a,b,c; Tuteja *et al*. 2004). This study extends past work that has provided a context for weighing up the factors involved in locating carbon sequestration plantations for best advantage (Hean *et al*. 2004). Solving these issues of land and water use involves complex technical, social, economic and environmental factors (Pannell, 2001a,b; Weersink *et al.* 2002; Cacho *et al.* 2004; Cacho and Hean, 2004).

Due to externalities, where some agents' actions impose costs on others, markets may fail to arise spontaneously to reconcile the interests of all parties. Regulation dealing with broadly defined classes of conditions may also fail to produce efficient solutions to the problem due to an inability to cater to needs of individual businesses. These facts have given new interest to development of Market Based Instruments (MBIs) and, in particular, to the use of Experimental Economics for designing the rules for such new markets (Smith, 2002; Cason *et al*. 2003; Whitten *et al*. 2004; Schillizi and Latacz-Lohmann, 2005).

The proposed project follows up on the MBI pilot programs of the National Action Plan on Salinity and Water Quality (NAP, 2002). One MBI pilot program in the Macquarie Catchment was successful in establishing a plantation of trees to soak up water contributing to stream salinity. Another, the Bush Tender MBI pilot program, is aimed at restoring stream-bank habitats in Victoria. The proposed project, unlike the MBI pilots, will simulate the consequences of a wide variety of ways of siting, financing and regulating such on-the-ground actions on a larger, strategic scale; it will not in itself establish MBIs.

This project will search for market mechanisms that allow downstream water users, who stand to benefit in terms of better water quality, to pay a fair price for those benefits. Optimised upstream siting of new tree plantations (for forestry products and /or carbon sequestration) or perennial pastures will be identified through modelling that traces economic, hydrological and biological consequences of changes in land use, including their affects on water yield and quality.

Where such efficient markets can be organised, adoption is expected to be based on profitability and to be self-sustaining. Other outcomes envisioned for the project include: increased knowledge of the scale and nature of off-site impacts of dryland salinity, increased awareness of policy tools for such issues and, ultimately, better policies regarding land and water use.

River water yield and quality are controlled by rainfall, soils, geology and land use in the catchment. Current land use has evolved through clearing, cultivation and grazing, motivated by private incentives to generate profits. Further land use changes will occur in response to input and commodity prices, new technologies, new markets and policies.

Mean flows of water and salt from some areas are different to others given spatially variable groundwater salinity and land use. Land managers in the watershed are mostly unaffected by the water and salt flow consequences of their privately-motivated land use decisions. However, their actions may decrease stream flows and increase salt loads with negative impacts on downstream water users (towns, irrigators and environmental areas). The existing 'disconnection' of signals between downstream users and upstream suppliers of water is a classic example of 'market failure'

Catchment targets and blueprints developed to date by CMAs do not account fully for the likely upstream costs of attaining downstream benefits. The biophysical links between land use and salt and water delivery can be made most confidently where groundwater flow systems are local and responsive; much less so for regional flow systems with very long time-lags.

Catchment targets developed to date lack effective and well considered means to actually achieve those targets. The existing biophysical / economic 'cause and effect' models for local groundwater flow systems, developed by NSW DPI (Bathgate *et al*. 2005; main paper), connect water suppliers with users and can provide the physical basis for water and salt markets when adapted to the greater Macquarie Catchment. These express the biophysical and economic potentials of the combined upstream and downstream river community to find an appropriate self-determined balance of land and water use. But how can a market process be designed to reconcile the potential benefits and costs of the players in a real-world setting characterised by externalities and 'market failure'?

Experimental Economics is one way of finding combinations of market forms and institutions likely to converge on stable, mutually-satisfactory solutions. Market forms could include auctions or tender processes. Institutions could include targeted subsidies, disincentives and various regulations. Experimental outcomes are affected by decisions of participants as their combined simulated consequences are traced through the biophysical / economic model. The project is a bridge between policy design and the catchment modelling work in Program 5 of the CRC Salinity. It integrates and adds value to a number of currently separate research efforts. It extends the existing work being done in the MBI pilot program by simulating the consequences of larger-scaled markets.

Plans

This study will use Experimental Economics methods pioneered by Charles Plott (Cal Tech) and Vernon Smith (2002a,b) to 'laboratory-test' market and institutional designs with panels of human subjects representing different sectors of the market, given different cost / incentive structures, and able to make bids and offers following specific rules. The project will extend the existing biophysical / economic 'cause and effect' model developed by NSW DPI for the Little River Catchment (main paper) to the greater Macquarie Catchment, but at coarser resolution. Clusters of typical market players will be differentiated: upstream water suppliers (e.g., farmers with different resource bases) and downstream users (e.g., towns, irrigators, environmental assets and interests still further downstream). Benefits and losses to the various potential players, with respect to generating or using different water quantities and qualities, will be estimated. These depend on the players' resource bases, production possibilities, cost structures and water-use options. We cannot know these details for every farmer and consumer in a catchment. So, for Experimental Economics experiments, we frame the market as a manageable number of representatives of clusters of players.

Activities proposed under the project in the three-year (2005-2008) period are described in the following eleven steps (Nordblom *et al*., 2005a)**:**

1. Define the geographic extent of the market, the market players and any limits to market entry (to Macquarie Catchment?, to MDB?, to Australia?, open to the World, i.e., with carbon sequestration credits?). (Appendix Figure 5.1 and 5.2). Consultation with Little River Landcare members, Macquarie River Food & Fibre, Macquarie Marshes Management, Central West CMA, the MDBC, NSW DIPNR and others is envisioned at this early stage.

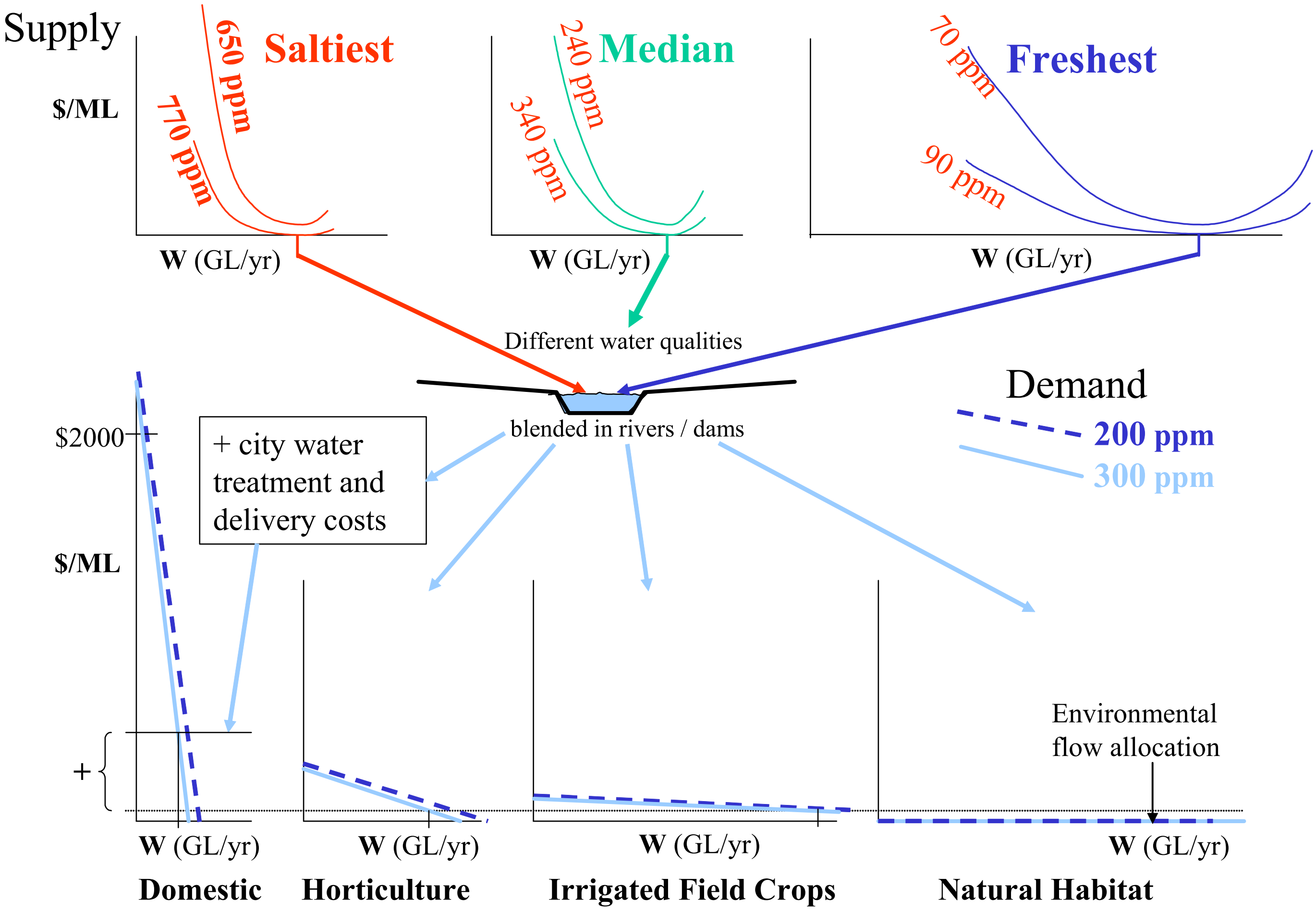
Appendix Figure 5.2. Example, location of the Macquarie Catchment and its major features, including the Little River Catchment

2. Extend the NSW DPI biophysical / economic model of Little River Catchment (main paper) to the greater Macquarie Catchment, but at coarser resolution in the extended sectors, in collaboration with DIPNR. (main paper, Figure 4 and 5).

3. Define representative clusters of suppliers and demanders of water grouped by their biophysical resource characteristics and benefit and loss potentials with respect to yielding or using different water quantities and qualities. (Appendix Figure 5.3).

4. Select market types – auctions (eg, single, double) – closed bid (eg, tender process) for investigation.

5. Define institutional arrangements including existing institutions (e.g., river regulation, water rights incentive/disincentives) and additions such as targeted proscription of activities (i.e., no tree plantations in fresh watersheds) or trade (i.e., some players not to trade with some others, associations of upstream suppliers or downstream demanders of water volumes and qualities).



Appendix Figure 5.3. The project allows the possibility of altering long-term water yields and salinity by strategic changes in land use in the sub-catchments, funded through markets in which downstream users participate.

6. Set the Experimental Design Pre-schedule, based on a sample of the scenarios in points 1-5 above, defining the combinations for replicated testing.

7. Identify and acquire Experimental Economics software (‘off the shelf’ to the extent possible) capable of processing simultaneous offers and bids by multiple players; develop software links to the existing biophysical / economic ‘cause and effect’ model of land use and long term water and salt flows.

8. Conduct experiments to assess convergence of sellers and buyers using software linked to the biophysical / economic model. Pilot testing and refinement: players in workshops represent interested parties (eg, dryland farmers / graziers, town councils, irrigation companies and environmental interests). Landcare groups and CMAs also participate at this model development stage.

9. Participatory trial series with collaborating parties: Little River Landcare members, Macquarie River Food & Fibre, Macquarie Marshes Management, Central West CMA, the MDBC, NSW DIPNR, NSW DPI, CSU and others. This both informs the participants and provides key feedback to the process, which may point to changes needed in Experimental Pre-schedule and/or software/server package.

10. Experiments will aim to determine the best strategies for each of a range of scenarios. That is, in the full trial series it is expected that many combinations of market types and rules will fail to converge or lead to viable markets (where benefits of trade exceed transaction costs). Each experiment is expected to require about 10 replicate sessions of about 2 hours, with about 10-12 participants in each for statistically valid comparisons. In the full experiment series, university students will be engaged for repeated replicate testing under different scenarios.

11. Analysis and evaluation, briefing subject parties, and reporting. A RIRDC publication is proposed as part of this project: *Assessment of market structures and institutions for linking farm-level land use, catchment water and salt flows and downstream water demand.*

Tasks ahead

If we take each of the three example sub-catchments as single farms, the owner of each would face losses if changing to a land use mix that consumes more water than the current mix. Generally the losses attending such changes will be greater as the targeted **W,S** level is further from the current **W,S** level, given the set of assumptions used for this analysis, in particular, that of assigning zero income to forestry plantations in this area where annual rainfall is about 700 mm (see main paper).

Given the cost structures for land use change such as in Figure 4 (main paper), the question is whether it is possible for these farmers to negotiate with downstream water users, who have their own diversity of demands for water and water quality (Appendix Figure 5.3), to bring about land use changes that result in an annual stream flow at a “market equilibrium” price, volume and quality? What would such a “market” look like and under what sort of rules would it operate with efficiency, stability and social equity? How best may environmental aspirations be accommodated or ensured in the context of (or set as constraints on) such a market?

Optimisation modelling to determine minimum aggregate catchment costs for attaining end- of-valley W,S targets has revealed a cost surface in three dimensions (**W,S,NPV**) analogous to those of the three individual sub-catchments (Figure 6). But this result assumes perfect knowledge held by a single optimiser. How different would a market result at the catchment level look when negotiated by three such "sellers" (land managers), each knowing their own but not the other's cost structures… dealing with downstream buyers (irrigators, town councils and environmental interests) each of whom knows only their own demand structure for water volume and quality? These are some of the questions we aim to approach with Experimental Economics. Could it work in the real world? How would it?

The aggregate NPV surface in Figure 5 (main paper), may be taken as a 'constructivist' ideal of 'best' land use configurations, providing the 'least-cost' means of reaching future **W,S** targets. Points **A**, **B** and **C** on this surface all appear attainable, but which of these would be most desirable from the viewpoints of cost and changes in water yield and salt loads?

It is difficult to imagine downstream water users choosing target **A** in Figure 6 (main paper); it would cost $6.33m in lost opportunities in the three catchments as well as the loss of 1.5 GL/year in water yields… and the remaining water yield would have increased salinity from 300 to 500 ppm. Target **B** would be preferred to **A** on all counts; it would cost less in terms of lost opportunities, it would entail a lower sacrifice in water yields and the remaining yield would be of better quality (changing from the current 300 ppm salt to only 200 ppm). Even better would be Target **C**, which offers the fresher (200 ppm) water yields at even lower cost and less sacrifice in water yield.

Whether the land use changes required to bring about such minimum-cost shifts in water quality as indicated by **C,** or any other target, in Figure 6 could be negotiated between land managers in the three sub-catchments and downstream water users is analogous to the key question of our Experimental Economics investigation. Our 'constructivist' model, which appears to calculate exact least-cost results when run in an optimising mode, can be used to simulate long-term outcomes from the aggregation of individual players' decisions in an Experimental Economics setting.

Our ongoing work in Little River catchment on the Macquarie River, with proposed support from NAP/NHT, and a new project funded by GRDC for Simmons Creek in the Billabong catchment on the Murray River (Cresswell and Hume 2004), are aimed at illuminating the 'cause and effect' processes linking changes in land use with future sub-catchment and catchment-level water yields and qualities… as well as the opportunity costs of such changes. The proposed project builds upon and adds value to this other work by linking information on cost structures with downstream demand for water volumes and quality.