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Mathematical optimisation of drainage and economic land use for target water and salt yields*

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Land managers in upper catchments are being asked to make expensive changes in land use, such as by planting trees, to attain environmental service targets, including reduced salt loads in rivers, to meet needs of downstream towns, farms and natural habitats. End-of-valley targets for salt loads have sometimes been set without a quantitative model of cause and effect regarding impacts on water yields, economic efficiency or distribution of costs and benefits among stakeholders. This paper presents a method for calculating a 'menu' of technically feasible options for changes from current to future mean water yields and salt loads from upstream catchments having local groundwater flow systems, and the land-use changes to attain each of these options at minimum cost. It sets the economic stage for upstream landholders to negotiate with downstream parties future water-yield and salt-load targets, on the basis of what it will cost to supply these ecosystem services.

Key words: discounting, landuse, NPV, opportunity-cost, salinity.

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1. Introduction

1.1 Land-use changes for river water yield and salinity targets

In eastern Australia, river salinity has been recognised as an important problem (Beale *et al.* 2000) and it is a focus of a number of federally and state funded institutions dealing with land and water management. A pragmatic approach to salinity management has led to the establishment of end-of-valley targets for salt loads and salt concentrations not to be exceeded in the future. The Murray-Darling Basin Commission (MDBC 2001) anticipates that river salinity can be managed to meet such targets through combinations of engineering, land-use change and flow management. Engineering works and flow management have immediate and measurable impacts and benefits downstream. As in the case of the Colorado River Basin Salinity Control Program, however, many of the cost-effective publicly funded engineering options for dealing with point sources of salt have already been developed in the Murray-Darling Basin. There is rising interest in cost-sharing projects with communities and landowners, such as projects to reduce harmful seepage from irrigation supply systems (Kendall *et al.* 2004; Kendall 2005; USBR 2006).

Typically, the effects of land-use change on river salinity are delayed and the benefits less certain than with engineering or flow management options (MDBC 2001). The present paper focuses on illuminating the economics of land-use change options for areas with local groundwater flow systems, where the effects on river salinity are the most certain and rapid, within 10 to 30 years. We do not deal here with areas having intermediate or regional groundwater flow systems where salinity responses may be delayed by multiple decades or centuries.

1.2 Integrated economic–hydrological models

Previous work has examined the biophysical consequences of siting tree plantations and other land-use changes in the landscape, and calculated benefits to downstream water users from salinity abatement (Bennett and Thomas 1982; Bell and Beare 2000; Heaney *et al.* 2000, 2001a; Bell and Heaney 2001; Herron *et al.* 2003; Hean *et al.* 2004). Issues of appropriate public policies arise where landholders who are in positions to carry out salinity-abatement activities are not those who would benefit, and where spatial and temporal externalities hinder the formation of markets to solve these imbalances (Whitten *et al.* 2004).

To date, land-use change has been the subject of detailed biophysical models that predict river salinity consequences (e.g. Beverly 2004; Tuteja *et al.* 2004; Beverly *et al.* 2005). The extent, location and nature of land-use change can be examined in scenario analyses using these models, where scenarios are posed and/or systematically explored by the user. *Ex post* linking of gross margin calculators to such models would allow views of the economic impacts

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on landholders and provide a basis for comparing the costs of different scenarios for land-use change. However, economic optimisation of land-use changes linked to such detailed process models remains a challenge.

Two models, Salinity and Landuse Simulation Analysis (SALSA) (Bell and Heaney 2001) and 'Namoi' (Letcher *et al*. 2004), have tackled the complex externality problems among farmers' actions, including those arising from conjunctive use of surface water and groundwater for irrigation. Both are integrated economic–hydrological models of land use and water allocation, tracing the dynamic effects of policy change and privately optimal land- and water-use changes over multidecade timespans.

SALSA simulates water yields, salinity processes and water use of the Murray-Darling Basin (1 million km^2). Important insights and generalisations have come from SALSA modelling. For example (i) targeted reforestation is likely to be a more cost-effective strategy to manage salinity than broad-scale land-use change; (ii) the hydrological characteristics of a region affect the costs and benefits of salinity management strategies; (iii) reforestation targeted to landscapes with faster responding aquifers and porous soils are more likely to generate net salinity benefits; (iv) the distribution of favourable hydrological characteristics in the landscape will determine whether revegetation is a cost-effective salinity management tool; and (v) increased irrigation efficiency can generate external benefits to downstream users through reduced discharge of saline groundwater (Heaney *et al*. 2000, 2001b). However, because of its broad spatial scale, SALSA output cannot identify land-use changes that must be implemented at the paddock scale by individual farmers.

The 'Namoi' model of Letcher *et al*. (2004) deals with 42 000 km^2 of one of the Murray-Darling Basin's 14 catchments modelled by SALSA. The Namoi model simulates the behaviour of a complex hydrological network under the influence of water-use decisions made by irrigators who in turn are influenced by water allocation policies. Focused solely on water quantity issues, the Namoi model does not consider water quality measures such as salinity (Ivkovic *et al*. 2005).

In this paper we develop a model that aims to provide timely information for policy choices. Through its simplification of biophysical cause and effect, our model is more akin to the 'minimum-data approach' of Antle and Valdivia (2006) than to detailed hydrology models. However, the irreducible linkages between land use and river salinity dictate a more complex representation of physical processes than is possible with a minimum-data approach. The economic component of our model considers start-up costs, recurring costs and opportunity costs of changing land use. Because of its biophysical simplicity, our model is capable of defining the range of water yield and salt loads possible through changing land use. It selects the mix of land uses to meet specific water and salt targets with minimum cost, but, unlike the minimum-data approach, our model identifies where and how land use should change to reach each target. Thus, at the catchment scale, our model calculates a sample-set 'menu' of specific water and salt combinations (targets) to choose among, and determines how to reach each target at minimum cost with

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specific, geographically located, land-use changes. We document the model and illustrate its use with the cases of three contrasting subcatchments, covering less than 50 km^2 of the 2000 km^2 Little River catchment, a tributary of the Macquarie River of New South Wales.

2. Methods

This section describes a method for defining a 'menu' of least-cost options for future mean water yields and salt loads attainable from a catchment through land-use change. Section 2.1 defines the geographic area from which three example subcatchments are drawn. Section 2.2 develops a simple model of the effects of land-use change on future water and salt yields. In Section 2.3, a farm-level model is defined to maximise the net present value (NPV) of wealth in a subcatchment constrained to meet a future water- and salt-yield target (W, S). The model is re-solved for each of a sample of water- and salt-yield targets in each of three contrasting subcatchments. Each technically feasible sample target will have a minimum-cost set of land-use changes to deliver it. In Section 2.4, the results of the subcatchment models, in terms of triplets of *water*, *salt* and NPV values, are combined in a 'catchment-level' model to predict the land-use configurations that deliver specified aggregate future W, S combinations at least cost.

2.1 Study area

Our study area is the upper 2000 km^2 of the Little River catchment, a sub-catchment of the Macquarie River in central New South Wales, which supplies water to towns, important horticultural and field crop irrigation areas, and wetland environments. Current mean annual flow at nearby Arthurville of 96 250 megalitres (ML) with an associated salt load of 36 580 tons (T) (Geoff Beale, pers. comm. 2006) was assumed to apply to this reach of the Little River. Eighty subcatchments were identified in the study area and the long-term mean rainfall, soil types, current land use, groundwater salinity and hydrological response times were estimated for each subcatchment (Evans *et al*. 2004). Three subcatchments, totalling less than 50 km^2 of the Little River catchment, with contrasting soils, groundwater salinities and current land uses (Tables 1, 3), were selected as examples for the current paper. These subcatchments were selected according to their contributions to stream salinity and designated 'freshest', 'median' and 'saltiest'.

2.2 A biophysical cause-and-effect model

Following Zhang *et al*. (2001), Bell and Heaney (2001), and Stirzaker *et al*. (2002), we assume that long-term equilibrium stream flow equals rainfall minus evapo-transpiration (ET); that is, all rainfall is accounted for by local ET and local stream flow. Our methods, therefore, apply to areas with local

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Table 1 Definitions of hydrological parameters and land-use categories, Little River catchment

Term	Description		Subcatchment		
			Saltiest	Median	Freshest
R	Long-term mean annual rainfall, calibrated values† (mm)		522	555	537
	Land use	F‡	Excess water (ML/ha per year)§		
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, existing plantations (FP is new plantation)	1	0.1	0.12	0.11
GWS	Groundwater salinity¶	(ppm)††	1636	1222	476
RWS	Rainwater salinity, based on‡‡	(ppm)	5.25	5.25	5.25
SWS	Stream water salinity calculated at current land use	(ppm)	763	345	91

†Calibrated for calculated Little River catchment water yields. ‡'Proportion Forest' equivalence in water use, a weighting factor for calculating excess water. §Weighted sum of tuned 'Zhang curve' values for (F) forested and (1 – F) cleared land given mean annual rainfall. ¶From Evans *et al.* (2004). ††Weight ratios of salt to water (mg/L = parts per million, ppm) divided by 0.625 equals electrical conductivity. ‡‡Jolly *et al.* (1997).

groundwater flow systems (Coram *et al.* 2000; Beverly *et al.* 2005) where deep drainage appears as stream flow. Also consistent with local flow systems, our model assumes that water yield and salt load from each subcatchment are independent of those of other subcatchments and the outputs of all are simply additive.

We assume surface run-off water reaches the stream fresh, at the salt concentration of rainwater (5.25 parts per million (ppm)), while deep drainage, after a delay, reaches the stream as groundwater discharge at the salt concentration of groundwater from the particular subcatchment.

2.2.1 Changes in water use, affect stream volumes and salt loads

Zhang *et al.* (2001) estimated the *ET* of forested and cleared land as a function of rainfall. The functions of Zhang *et al.* (2001) were modified to better fit Australian data at the dryer end (300–750 mm per year) of the annual rainfall range considered by Zhang *et al.* (Nordblom *et al.* 2005). These functions were used to estimate *ET* in this study. We consider three land uses that have annual *ET* values between those of forest and cleared land (Table 2). The *ET* of these land uses was assigned a linear scalar (F) between that of forested ($F = 1$) and cleared ($F = 0$) land (Table 2) after Dawes *et al.* (2000).

Following Dawes *et al.* (2000), we call the difference between rainfall and evapo-transpiration excess water (*EW*), which is partitioned between surface run-off (*SR*) and deep drainage (*DD*) according to soil type. We grouped soil

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Table 2 Definitions of land management units, Little River catchment

Land management unit	*Df*†	Soil type descriptors‡	
LMU 1	0.15	L1, L2	lithosol soils, other and over granite
LMU 2	0.25	R1, R4	red chromosols (better) and shallow red chromosol (< 70 cm) on granite
LMU 3	0.50	R2	red chromosols (poorer)
LMU 4	0.50	R3	red sodosols
LMU 5	0.20	R5	shallow red chromosol (< 70 cm) poorer
LMU 6	0.90	S1, S2, S3	siliceous sands, shallow over granite (< 70 cm), over granite or sandstone
LMU 7	0.05	Y1	yellow sodosols, granitic
LMU 8	0.10	Y2, Y3	yellow sodosols, other, and yellow chromosols

†Drainage fractions for partitioning excess water between deep drainage (*Df*) and surface run-off reaching the stream (1 – *Df*). ‡Soil type descriptors drawn from Murphy and Lawrie (1998).

types into eight land management units (LMU), each having particular hydrological and productivity characteristics. The proportion of excess water that drains below the root zone is termed the drainage fraction (*Df*) of each LMU (Table 2). We assume *Df* is constant for an LMU regardless of the land use or level of excess water in a given year. That is,

$$SR = EW(1 - Df) \qquad \text{ML/ha per year} \tag{1}$$

$$DD = EW(Df) \qquad \text{ML/ha per year} \tag{2}$$

While surface run-off reaches the stream in the same year, deep drainage reaches the stream only after a time lag that is specific to each subcatchment, according to topography and geology. We assume a new equilibrium in groundwater discharge to stream (*GDS*) is attained within 30 years of a land-use change, such that in the long term,

$$DD = GDS \qquad \text{ML/ha per year} \tag{3}$$

Total annual stream flow (*W*), from a particular area in a particular year following a land-use change, will be the sum of the surface run-off water in that year (1) and the total groundwater discharge to the stream (3) as follows:

$$W = SR + GDS \qquad \text{ML/ha per year} \tag{4}$$

With this information and knowledge of rainwater salinity (*RWS*) and groundwater salinity (*GWS*) from Table 1, the total salt load entering the stream (*S*), from a particular area in long-term equilibrium is estimated as follows:

$$S = [RWS(SR) + GWS(GDS)]/1000 \quad \text{T/ha per year} \tag{5}$$

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Table 3 Current land uses in three example subcatchments, by areas (ha) in land management units (LMU), with productivity indices assigned to each

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

†See Tables 1 and 2 for descriptions of current land uses and LMU, respectively,

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2.2.2 Samples of feasible long-term equilibrium catchment water-yield and salt-load levels

A 'factorial vector analysis' that uses long-term rainfall, groundwater salinity, 'Zhang curve' values for extremes in land use, and soil distributions was used to model the envelope of biophysically feasible equilibrium combinations of water and salt reaching the stream from a given subcatchment (Nordblom *et al.* 2004). The analysis first considers the long-run water and salt consequences of a subcatchment 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 of the subcatchment; hence the term 'factorial'. The result is a unique elliptical envelope marking the boundaries of possible future equilibrium water–salt combinations from a subcatchment. Within each envelope (Figure 1), a rectangular grid sample of the ranges of possible future water and salt target combinations was defined for economic analysis. We used the excess water estimates (Table 1) and our LMU (*Df*) distributions (Table 2) with the current land-use matrix (Table 3) to estimate current equilibrium water and salt flows per unit area from each of the subcatchments (Figure 1).

2.3 A farm-level model for maximising subcatchment wealth

Land-use activities in the farm-level model are defined by both current and future land uses and the LMU in which they occur. We assume current land uses may be continued in all cases. In the case of cropped land, there is maximum

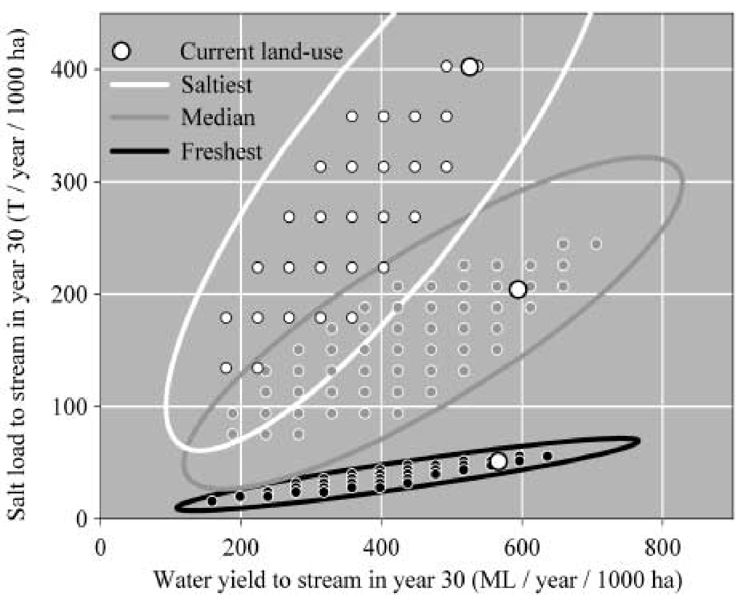

Figure 1 Contrasting envelopes of feasible sample *W*, *S* targets for three subcatchments.

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Table 4 Future land-use activity constraints within LMU_L

	Future land use				
	CR	NP	NB	SP	FN/FP
Current land use					
CR_L	X_{L1}	X_{L6}	X_{L7}	X_{L8}	X_{L9}
NP_L		X_{L2}	X_{L10}		X_{L11}
NB_L		X_{L12}	X_{L3}	X_{L13}	X_{L14}
SP_L		X_{L15}	X_{L16}	X_{L4}	X_{L17}
FN_L		X_{L18}			X_{L5}

Notes: See Table 1 for descriptions of current land use. X_{LU} on the diagonal are continuing activities; others represent transitioning activities. FP represents a forestry plantation, which is assumed to use as much water as a native forest (FN) within 10 years and have the same effect on stream flows by year 30.

flexibility for shifting to any of the other four land uses: the three pasture options or to a forest plantation option (Table 4). We assume the only options for land currently growing poorer pasture are shifts to better pasture or to a forest plantation. In contrast, land currently used for better pasture may be allowed to slip into the status of poor pasture, renovated to the status of sown improved perennial pasture or turned into a forest plantation. Land currently classed as sown improved pasture may be shifted to any land use except cropping. Finally, we assume land that is currently forested can remain so, or be used as poor pasture. Obviously these five categories are unable to represent the full richness of diversity in land use, but are used for simplicity in the present illustration.

An implicit assumption here is that land is already put to its most profitable use. Consistent with this assumption, we find cropping in the catchment where it is economically feasible, grazing on shallower soils and forests mainly limited to rocky landscapes. Constraining our profit-maximising model to satisfy future water and salt flows includes ‘forest’, or other land uses that transpire larger amounts of water, in the land-use mix.

The land-use constraints are summarised as,

$$\left.\begin{array}{l} X_{L1} + X_{L6} + X_{L7} + X_{L8} + X_{L9} = b_{L1} \\ X_{L2} + X_{L10} + X_{L11} = b_{L2} \\ X_{L3} + X_{L12} + X_{L13} + X_{L14} = b_{L3} \\ X_{L4} + X_{L15} + X_{L16} + X_{L17} = b_{L4} \\ X_{L5} + X_{L18} = b_{L5} \end{array}\right\} \tag{6}$$

Where b_{LU} is the land area in LMU L currently in land use U.

The activities for transitions in land use (X_{L6} through X_{L18}) represent shifts in land use in the first year, incurring a start-up cost ($\$AZ_U$ per ha) in that year only, and a recurrent cost ($\$AV_U$ per ha) of the new land use in that year and all subsequent years.

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Table 5 Economic parameter values assumed for land-use activities (X_{LU}), continuing and transitioning

Activity type†	Land-use activity in LMU_L X_{LU}	Start-up cost \$A/ha (Z)	Recurrent cost \$A/ha per year (V)	Mean sales \$A/ha per year (M)	Grazing offtake‡ DSE/ha per year (D)
Continuing					
CR cont'd	X_{L1}	0	200	650	5
NP cont'd	X_{L2}	0	20	0	2
NB cont'd	X_{L3}	0	50	0	5
SP cont'd	X_{L4}	0	100	0	10
FN cont'd	X_{L5}	0	10	0	1
Transitioning					
CR to NP	X_{L6}	0	20	0	2
CR to NB	X_{L7}	40	50	0	5
CR to SP	X_{L8}	150	100	0	10
CR to FP	X_{L9}	200	10	0	1
NP to NB	X_{L10}	40	50	0	5
NP to FP	X_{L11}	200	10	0	1
NB to NP	X_{L12}	0	20	0	2
NB to SP	X_{L13}	150	100	0	10
NB to FP	X_{L14}	200	10	0	1
SP to NP	X_{L15}	0	20	0	2
SP to NB	X_{L16}	40	50	0	5
SP to FP	X_{L17}	200	10	0	1
FN to NP	X_{L18}	0	20	0	2

Notes: †See Table 1 for descriptions of land uses. ‡Grazing valued at \$A15/DSE. Discount rate = 7 per cent.

Mean harvest sales (\$AM_U/ha per year) from dryland cropping rotations (X_{L1}) are supplemented by grazing off-take (D_U) in dry sheep equivalents (DSE/ha per year), valued at \$G/DSE (Table 5). Different levels of grazing off-take are assumed from the other pasture and forest activities. M_U and D_U are adjusted by an LMU-specific productivity index (P_{iL}) ranging from 1.0 to 0.1 (Table 3), assigned using expert knowledge of the soils and conditions of the study area. Start-up costs do not affect continuing land-use activities (X_{L1} *to* X_{L5}), but only those with a transition in land use (X_{L6} *to* X_{L18}).

The net present value of one unit (ha) of a land-use activity in LMU_L in the first year of the future is

$$NPV_{Lu1} = \begin{cases} \{[(M_U + D_U G)P_{iL}] - V_U\}/(1+r) & \text{for } X_{L1} \text{ to } X_{L5} \quad \$/\text{ha} \\ \{[(M_U + D_U G)P_{iL}] - V_U - Z_U\}/(1+r) & \text{for } X_{L6} \text{ to } X_{L18} \quad \$/\text{ha} \end{cases} \quad (7)$$

where r = discount rate. We may now calculate an NPV for a 30-year sequence of costs and benefits for each land-use activity (X_{LU} for U = 1 to 18) in each LMU_L (for L = 1 to 8), where y = year in the future:

$$NPV_{LU} = NPV_{LU1} + \sum_{y=2}^{30} \{[(M_U + D_U G)P_{iL}] - V_U\}/1 + r^y \quad \$\text{A/ha} \quad (8)$$

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This allows us to pose the economic question: 'What combination of changes in land use will deliver a particular future water-yield and salt-load target (W_S, S_S) from subcatchment (s) at least cost?' It is expressed as the mathematical programming problem:

$$\sum_{L=1}^{8}\sum_{U=1}^{18} X_{LU} NPV_{LU} = \text{Max } NPV_S \quad \text{\$/subcatchment} \tag{9}$$

subject to:

$$\sum_{L=1}^{8}\sum_{U=1}^{18} X_{LU} W_{LU} = W_S \quad \text{Target ML water/subcatchment per year,} \tag{10}$$

$$\sum_{L=1}^{8}\sum_{U=1}^{18} X_{LU} S_{LU} = S_S \quad \text{Target T salt/subcatchment per year,} \tag{11}$$

and $X_{LU} \geq 0$, $b_{LU} \geq 0$, in addition to all land-use constraints in (6).

This problem is solved for an individual subcatchment for a number of targets identified as the intersections of a grid regularly spaced across the ranges of W_S and S_S in convenient increments in the water and salt planes. The highest calculated NPV attainable when constrained to current water yield and salt load is required for comparison with the highest NPV_S of other W_S, S_S targets. The change in NPV_S for shifting land use to meet each of a range of targets is necessary in deciding which, if any, targets would be pursued.

2.3.1 Current subcatchment W_S, S_S yields and NPV

Removing the constraints to meet any W_S or S_S target and adding a new constraint (12) to exclude all transitional land-use activities,

$$\sum_{L=1}^{8}\sum_{U=6}^{18} X_{LU} = 0 \tag{12}$$

such that solving the model now, allowing only the continuation of current land uses, reveals the current water and salt yields as the left-hand sides of Equations (10) and (11), which we refer to as W_{SO} and S_{SO}.

2.3.2 Maximum subcatchment NPV of current water-yield and salt-load

Setting the calculated current water and salt yields as new constraining target levels in Equations (10) and (11) and removing the constraint on land-use transitions (12), the model may be solved to find the land-use mix that delivers the same amount of water and salt as the current land use but maximises NPV. In a subcatchment the cost or benefit of attaining a different

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target water yield and salt load is the difference between this NVP_{SO} value and the maximum NPV_S of that sample target:

$$Max\ NPV_{SO} - Max\ NPV_S = \text{Opportunity Cost for } W_S, S_S \quad \text{\$/subcatchment} \tag{13}$$

2.4 Catchment-level model

At the subcatchment level triplets of NPV_S, W_S and S_S, from (9), (10) and (11) represent unique feasible configurations of land use and profitability of a complete subcatchment unit. These results are used as coefficients in the catchment-level model activities (C_{SN}) that represent the Nth (W_S, S_S) target in the Sth subcatchment. The economic question of maximising catchment-level NPV while satisfying the supply of a particular future water and salt target is posed as the mathematical programming problem:

$$\sum_{S=1}^{J}\sum_{N=1}^{K} NPV_{SN}C_{SN} = Max\ NPV_C \quad \text{\$NPV/catchment} \tag{14}$$

subject to:

$$\sum_{S=1}^{J}\sum_{N=1}^{K} W_{SN}C_{SN} = W_C\ target \quad \text{mean catchment water yield in year 30,} \tag{15}$$

$$\sum_{S=1}^{J}\sum_{N=1}^{K} S_{SN}C_{SN} = S_C\ target \quad \text{mean catchment salt load in year 30,} \tag{16}$$

$$W_{SN}, S_{SN}, C_{SN} \geq 0, \text{ and} \tag{17}$$

$$\sum_{N=1}^{K} C_{SN} = 1, \quad \text{for each subcatchment} \tag{18}$$

such that the sum of any subcatchment's land-use activities exactly equals that subcatchment's area.

Analogous to sampling a grid of subcatchment water and salt target W_S, S_S levels, a grid of aggregated catchment-level targets (W_C, S_C) may be sampled. Solving the catchment-level model for each of these W_C, S_C targets will result in a set of catchment NPV_C, W_C, S_C values.

This will allow us to answer the economic question, 'What will be the minimum cost of achieving a particular future mean water yield and salt load from this catchment?' Comparing the aggregate NPV of attaining W_{CO} and S_{CO} with the maximum NPV of the arrangement of land uses that deliver W_C and S_C will indicate the minimum cost of that change at the catchment scale:

$$\left(\sum_{S=1}^{J} Max\ NPV_{SO}\right) - Max\ NPV_C \text{ (for target } W_C, S_C) \tag{19}$$

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Where $Max\ NPV_{SO}$ is the maximum NPV of the current water yield and salt load of the Sth subcatchment, as defined in Section 2.3.2.

3. Results

The potential W_S and S_S targets of each subcatchment occupy a distinct envelope in W_S, S_S space (Figure 1). The ability of land-use change on a hectare of land to manage water yield is quite similar in all three subcatchments. However, the three subcatchments differ markedly in their ability to change salt yield. As expected the range in salt-load management of the freshest subcatchment is much lower than that of the saltiest with the median subcatchment lying in-between. In each subcatchment the water and salt yields of current land-use are high, approaching the 'completely cleared' catchment condition.

Each solution of the subcatchment model, Equations (9–11), represents an optimal configuration of land use, constrained to the land areas and to a water-yield and salt-load target of the particular subcatchment. The economically optimal land-use mix that yields the same volume of water and weight of salt as the current land use have been shown to have an NPV between 4 and 12 per cent greater that the NPV of current land use (Nordblom *et al.* 2005, Appendix 4). Plotting the NPV_S, W_S, S_S triplets (Figure 2) shows that the lowest NPV_S are associated with the lower water-yield and salt-load targets. The maximum NPV_S in all three subcatchments occurred at water and salt yields close to those of the current land-use. Also, the NPV surface in the neighbourhood of the current water-yield and salt-load is relatively flat and stable. However, the best NPV_S for some of the 'extreme' targets, far from the current subcatchment water and salt yield, may be much lower than the best NPV_{SO} in the neighbourhood of current land-use, implying a large opportunity cost, or loss of wealth, compared to current land use. Shifts towards the origin of water–salt space are associated with increases in the proportion of land under forest, which is costly to establish and has low returns in our low-rainfall study area (Table 5).

Our catchment-level results for future water-yield and salt-load targets also produce a smooth NPV surface (Figure 3). The opportunity costs for achieving the various feasible catchment water-yield and salt-load targets can be calculated by subtracting the NPV_C for a catchment-level water-yield and salt-load target from NPV_{CO}, the best NPV calculated for the aggregate current W_C, S_C levels. This is the aggregate cost to the land managers for departing from their best private NPV land-use configurations.

Current flows from our example catchment (based on three subcatchments) deliver a stream salt concentration of 300 ppm. From Figure 3 it is clear that future stream salinity can be shifted between 200 and 500 ppm through manipulating land use.

Three example targets (A, B and C, in Figures 3, 4) illustrate trade-offs among aggregate farm opportunity costs and downstream water volumes

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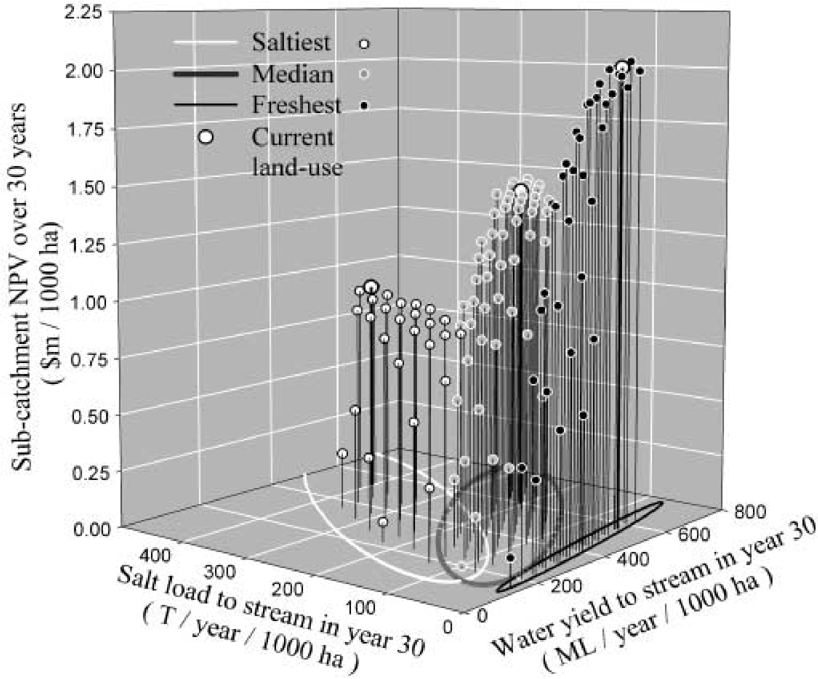

Figure 2 Best *NPV* ($Am) for samples of *W*, *S* targets in the three contrasting subcatchments (white dots, saltiest; grey dots, median; black dots, freshest). These are the same target *W*, *S* points indicated in Figure 1. *W*, *S* yields given current land use, and the associated best *NPV*s (large open dots), become the reference points for calculating opportunity costs of attaining other targets.

and salt loads. Target A incurs over $A6 m in costs (lower *NPV* across the catchment), 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 $A0.4 m and yields 500 ML less stream flow than current, but improves stream salinity to 200 ppm. Target C offers the same improvement in water quality as B but costs only $A0.1 m with little loss in stream flow compared to the current level. These three examples demonstrate the scale of trade-offs that could be faced in terms of costs and ranges of choice among future water-yield and salt-load targets at the level of a catchment with less than 5000 ha surface area. The different water-yield and salt-load targets, and changes in land use required in the three subcatchments to achieve the aggregate targets A, B and C at least cost are shown in Figure 5 and Table 6, respectively.

The changes in land use (Table 6) to meet targets A, B and C can be summarised as:

- In all three cases (A, B and C) there was a move away from improved volunteer pasture, which was assumed to yield relatively low grazing values given its water use.

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Table 6 Summaries of current land use in the three subcatchments and changes calculated to achieve aggregate catchment *W*, *S* targets A, B, or C† at least cost by year 30

Land use	Summary of current land use in the three subcatchments comprising the example mini-catchment				Summary of new land uses to achieve target A by year 30				Summary of new land uses to achieve target B by year 30				Summary of new land uses to achieve target C by year 30			
	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

Notes: †*W*, *S* targets A, B and C are identified in Figures 3 and 4. For details on current land use by LMU, see Table 3.

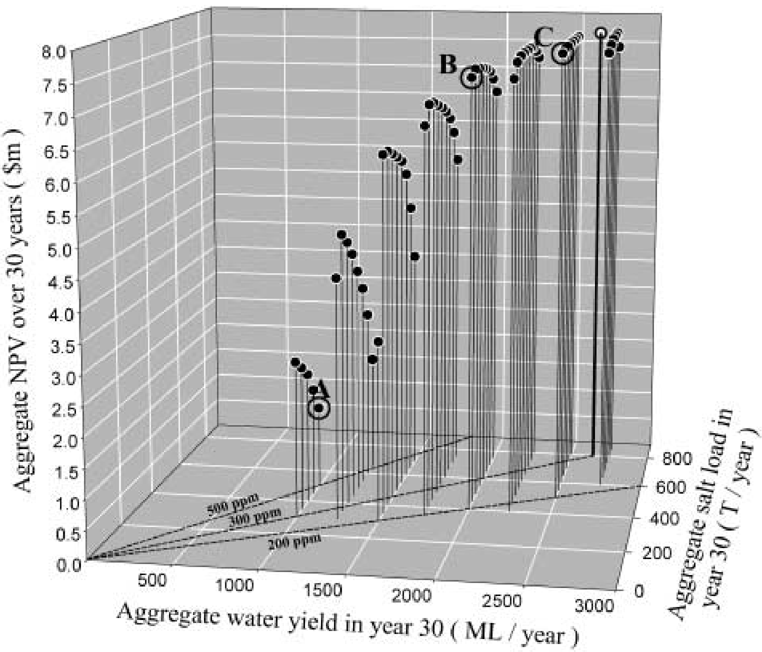

Figure 3 Best *NPV* ($Am) for sampled end of valley target *W*, *S* flows in year 30 from the aggregate (three-subcatchment) catchment. In addition to the best *NPV* calculated for the *W*, *S* yields of current land use (light dot), delivering water with a salt concentration of 300 parts per million (ppm), three other feasible *W*, *S* targets (circled dots A, B and C) illustrate future river flows with 500, 200 and 200 ppm salt.

- Target A is met by increasing the proportion of forest in all subcatchments. The greatest change to forest is in the freshest subcatchment at the expense of cropping. A similar but smaller shift was called for in the median subcatchment. These shifts incurred the high costs reflected in Figures 3 and 4.
- Target B was met at the catchment level by little change in the area cropped but a shift into forest at the expense of improved volunteer pasture. This was called for in all three subcatchments. There was a shift from sown perennial pasture to forest in the saltiest and median subcatchments, accompanied by a small increase in the area of sown perennial pasture in the freshest subcatchment.
- Target C was met with a general shift from volunteer improved pasture into volunteer poor pasture to yield more water from the median and freshest subcatchments. A small shift from cropping and larger shifts from volunteer pastures into forest were called for in the saltiest subcatchment.

4. Discussion

Envelopes developed in *W*, *S* space using ‘factorial vector analysis’ allow us to visualise the potentials possessed by different subcatchments to manipulate the water flow and salt load. In our example (Figure 1) the long narrow

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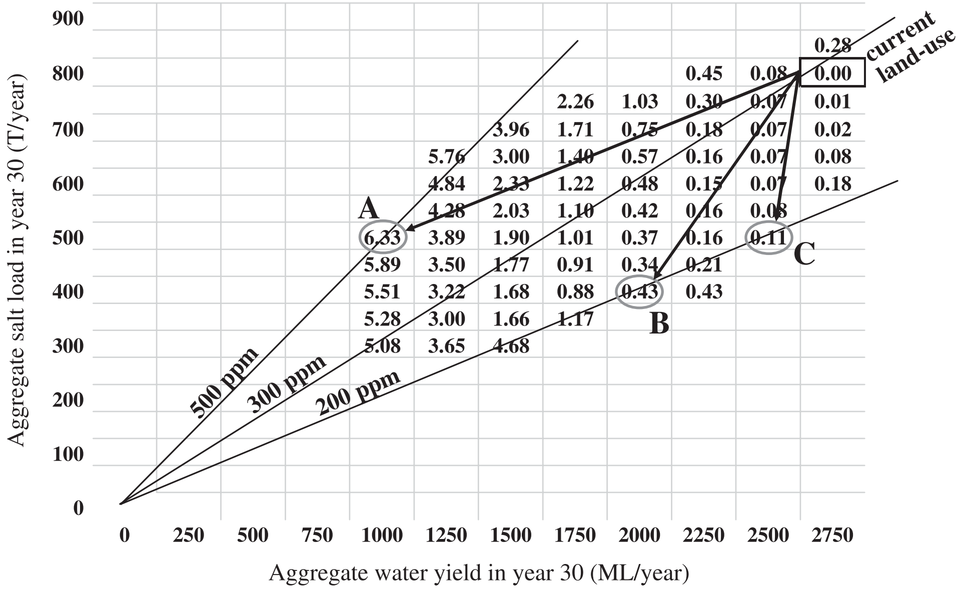

Figure 4 Costs of meeting aggregate catchment *W*, *S* targets by year 30.
Note: Calculated as best *NPV* for current water yield and salt loads minus the best *NPV* for the particular target, as in Figure 3.

envelope in the fresh subcatchment allows manipulation of water yields more than salt loads. In contrast, the salty subcatchment allows the manipulation of both water yield and salt load.

The effect of a profitable forestry land use, say with establishment of local processing of new and valuable forest products, or the negotiation of carbon sequestration credits for a plantation, would be to lift the lower ends of the *NPV* surfaces. In a higher rainfall zone, with shallow soils and/or steep slopes unsuited for cropping or improved pasture, but well suited for forestry, the *NPV* surfaces would have their peak in the lowest ranges of water yields and salt loads.

The 'best *NPV*' for land uses that deliver the current water-yield and salt-load levels appear close to the best attainable with any mix of land uses (see Figures 3, 4) among all future water-yield and salt-load targets. Thus, without new, more profitable technologies or altered economic conditions, any change in water yield and salt load will be at a cost to farmers.

The benefits resulting from altered future water yield and salt load could accrue to downstream users (environmental, agricultural, industrial and domestic). We have shown that the opportunity costs of meeting downstream demand can be estimated, and could be used as the basis for negotiating compensation from downstream beneficiaries. Finding the 'best' target is a question of balancing the upstream costs against downstream demands for water and water quality. Our framework provides a means for resource managers to avoid selecting land uses that may make river salinity worse while causing major loss of profit and water flow. Thus, we have presented an approach to

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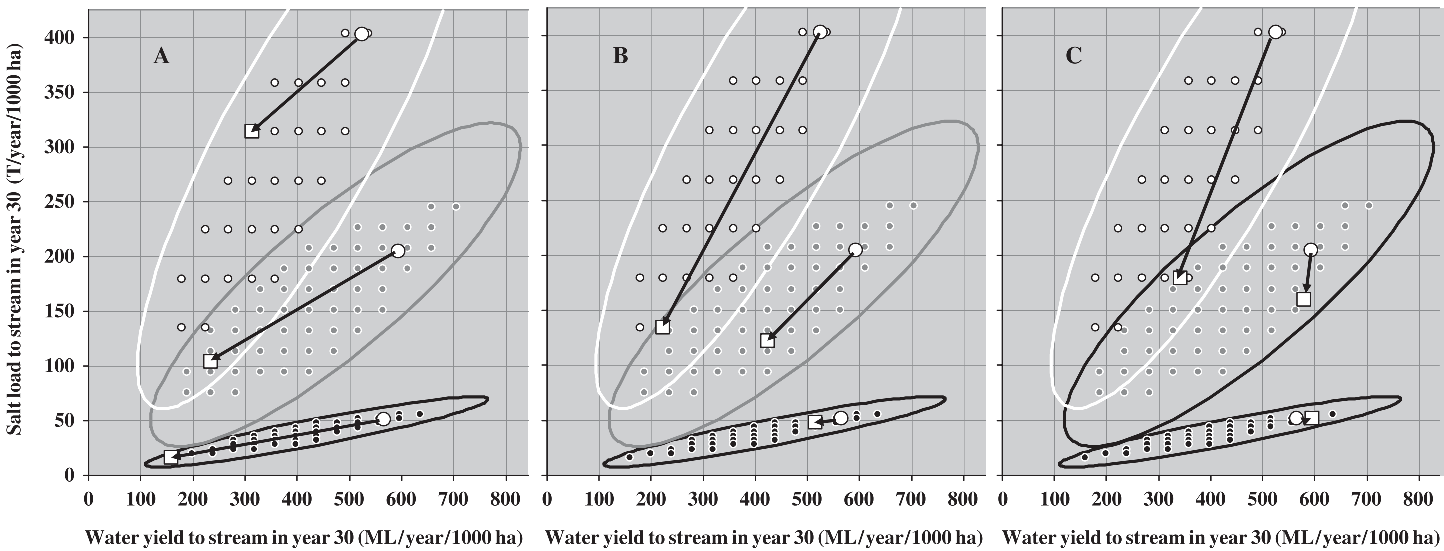

Figure 5 *W*, *S* target-shifts in three subcatchments to achieve aggregate catchment *W*, *S* targets A, B and C (see Figures 3,4) at least aggregate cost by year 30.

Note: See Table 6 for the land-use changes calculated to deliver these targets.

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the supply side of the problem through land-use change. Downstream demands for water and water quality comprise the other side of the issue. Both sides may now deal quantitatively in an economic context with the dimensions of future quantity and quality of river water.

One policy message is clear: blanket solutions will not work. 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 uses of river water and water quality downstream. 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 (Whitten *et al.* 2004). Our analysis may provide part of the basis for exploring market-based instruments to find such matches.

Our land-use constraints limit the range of changes from the current mix of land uses based on the assumption that any forested land that could be profitably cleared to open up cropping or pasture lands has already been cleared; land that could be profitably cropped in this area is already being cropped, etc. Of course, such assumptions would not have held true in the earlier history of the region, such as the years following both World Wars I and II, when land clearing was very active (see Herron *et al.* 2003). The maturity of the region's land-use development is therefore an important consideration in applying this method to other catchments.

5. Conclusions

The framework presented here will hold for upstream catchments with local, responsive groundwater flow systems, but not for slower-responding intermediate or regional groundwater flow systems. It presents decision-makers with a full set of trade-offs on the supply side with respect to land-use change options.

Contributions to stream water flow and salt load differ widely among subcatchments depending on groundwater salinity, soils and land use. Some subcatchments deliver relatively high-salt-concentration flows and some relatively fresh flows. We showed that a range of water-yield and salt-load targets can be met in the future by strategic changes in land use now. Our method uses this variability to determine the locations and levels of land-use change required to achieve particular future water-yield and salt-load targets at the subcatchment and catchment levels at least cost. This is a means to inform policy-makers, landholders in upstream catchments, and downstream interests of the likely scope for, and costs of, altering water and salt flows.

Depending on its profitability and location in a whole-farm context, increasing perennial land cover may reduce salt loads with little or no sacrifice in economic performance at the catchment scale. But, poorly sited on a large scale, perennials can reduce stream flow, water quality and profitability from an upper catchment. Thus, our method quantifies the obvious: that the

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question of what is the 'best' land use is geophysically and bioeconomically context sensitive.

Significant reductions in stream salinity will require strategic land-use change on a scale that will only occur if the changes are profitable to farmers. While markets may lead to efficient resource allocation, they are likely to impinge unevenly on different resource owners (i.e. landowners of our three example subcatchments). Our model, because it is spatially explicit, quantifies the social equity effects (who is able to change land uses when compensated for their opportunity costs) for most efficiently attaining specific sets of environmental services (in this case, future water volumes and salt loads in streams). Where parties cannot or will not participate, this information may be set as new constraints and the framework used to calculate 'second-best' target options and their costs.

Our framework links biology, which drives profitability at the whole farm level, with hydrology at subcatchment and catchment scales. This sort of analysis can help land managers, catchment managers and policy-makers quantify trade-offs and negotiate targets with downstream demands for water volume and water quality. It also provides a tool for valuing emerging technologies in plant-based management of dryland salinity where stream water yield and salinity are issues.

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