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Derivation of supply curves for catchment water effluents meeting specific salinity concentration targets in 2050: linking farm and catchment level models
or
"Footprints on future salt / water planes"

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Summary

The salt burden in a stream reflects the blend of salty and fresh flows from different soil areas in its catchment. Depending not only on long-run rainfall, water yields from a soil are also determined by land cover: lowest if the area is forested and greatest if cleared. Water yields under agro-forestry, lucerne pasture, perennial grass pasture, and annual pasture or cropping options span the range of water yields between the extremes of forested and cleared lands. This study explores quantitative approaches for connecting the hydrologic and economic consequences of farm-level decisions on land cover (productive land uses) to the costs of attaining different catchment level targets of water volumes and salt reaching downstream users; environmental, agricultural, domestic, commercial and industrial. This connection is critical for the resolution of the externality dilemma of meeting downstream demands for water volume and quality. New technology, new products and new markets will expand options for salinity abatement measures in the dryland farming areas of watershed catchments. The development of appropriate policy solutions to address demands for water volumes and quality depends on the possibility of inducing targeted land use change in those catchments or parts of catchments where decreased saline flows or increased fresh water flows can return the best value for money. This study provides such a link.

Key words: salinity, targets, opportunity cost, concentration, dilution, effluent, externality, supply, demand, policy, water quality, new technology, new markets

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INTRODUCTION

Trees, woody shrubs and herbaceous pasture plants, which are able to use more water than annual crops or pastures, may be the means for preventing the excessive groundwater recharge on cleared lands that leads to localised dryland salinity as well as salinisation of streams. One reason often cited for the need to deal with dryland salinity in eastern Australia is the affect on downstream water quality (Beare *et al*, 2002; Bell *et al*., 2000; Heaney *et al*., 2000; Hodge, 1982; Quiggin, 1986; Stoneham *et al*., 2001).

Here we propose a methodological framework for linking hydrologic and biological information already at hand, and arising from new experiments, to the economic and salt/water-effluent consequences of land use decisions at the farm level. These are linked to consequences over time at the catchment level in terms of effluent water volume and quality. Methods of estimating the range of technically feasible future salt/water flow targets for a catchment are combined with calculations of minimum costs of achieving each target in terms of aggregate opportunity costs faced by farmers in the catchment. This provides a framework for defining supply curves for future water volumes of different salt concentrations from the catchment; a link to demands by downstream water users.

The methods we propose are presented in the same natural order as water running down hill, through a cascade of causes and consequences. In each part of the paper we present illustrations of the main points.

Part 1 focuses on hydrology, land characteristics and responses to changes in land use in terms of salt and water outputs from farm-level land units.

Part 2 focuses on development of a farm-level model that can be constrained to represent different farm types and trace the economic and hydrologic consequences of different future salt/water outputs. We introduce a method for quantifying opportunity costs of reaching these future targets.

Part 3 focuses on methods for linking the results of farm-level models for studies of the technical limits and aggregate opportunity costs of achieving catchment-level targets.

Part 4 focuses on the translation of opportunity costs at the catchment level into supply curves to be faced by demands of downstream users. The lump-sum net present value of opportunity costs to farmers in the catchment for reaching a future salt/water flow target may be translated to equivalent annuity prices faced by downstream users.

Part 5 reflects an over-arching perspective on the role of new technologies and markets with respect to salinity abatement.

Part 1. HYDROLOGY AND LAND CHARACTERISTICS: Climate, land-cover, soil, recharge, runoff, salt and water

The consequences of current and changed land use, in terms of **'excess water'** and salt outputs to streams over time, comprise the focus of this section. Our aim is to quantify in the simplest form the likely hydrologic outcomes of land use decisions at the farm level in a dryland production area. Here we will be dealing with areas with local and intermediate groundwater systems (i.e., systems with short to medium term response times to changed land use at the farm and/or sub-catchment level with respect to effluent quantity and quality).

Land use may range from native vegetation, forestry, woodland/lucerne, opportunity or improved cropping, perennial pasture/grazing, to annual pastures or cropping. Excess water is defined as the amount of rainfall that goes from surface runoff and groundwater recharge to become stream-flow, after subtracting the larger amounts that go to evapo-transpiration ($\boldsymbol{E_T}$).

Excess water, then is a function of annual rainfall and land cover. Excess water is minimised with native vegetation and forestry, and greatest with cleared land, annual pastures or crops (Stirzaker *et al*., 2002; Dawes *et al*., 2000; Zhang *et al*. 1999).

In a review by Zhang *et al.* (1999) of some 300 catchments around the world, a third of which are in Australia, a two-parameter model was developed to show the differences in $\boldsymbol{E_T}$ between fully cleared and fully forested catchments (Dawes *et al.* 2000); restrictions on the derived curves 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:

$$E_T = P\left(\frac{1+(wE_0/P)}{1+(wE_0/P)+(P/E_0)}\right) \qquad (1)$$

Where $\boldsymbol{E_T}$ is annual evapo-transpiration in mm, $\boldsymbol{P}$ is annual rainfall in mm, $\boldsymbol{E_0}$ is a rainfall scaling parameter, and $\boldsymbol{w}$ is a plant available water parameter. Parameter values for forested catchments were $\boldsymbol{E_o}$=1410 mm and $\boldsymbol{w}$=2.0, and $\boldsymbol{E_o}$=1100 mm and $\boldsymbol{w}$=0.5 for cleared catchments. Dawes *et al.* (2000) describe the good statistical fits achieved by Zhang *et al.* (1999) (r^2=0.93 in forested and r^2=0.90 in cleared catchments) with this model using estimates of $\boldsymbol{E_T}$ based on measured rainfall minus streamflow. One would assume stable land use and long-run rainfall and streamflow values were used in the case of each catchment.

Following Dawes *et al.* (2000) and Stirzaker *et al.* (2002), we take annual rainfall minus the $\boldsymbol{E_T}$ values (Eq. (1)) for cleared and forested areas to derive "excess water" curves (Eq. (2), Fig 1) over a range of rainfall levels from 300 to 900 mm.

$$\text{Excess water} = \boldsymbol{P}(1-((1+(\boldsymbol{wE_0/P}))/(1+(\boldsymbol{wE_0/P})+(\boldsymbol{P/E_0})))) \qquad (2)$$

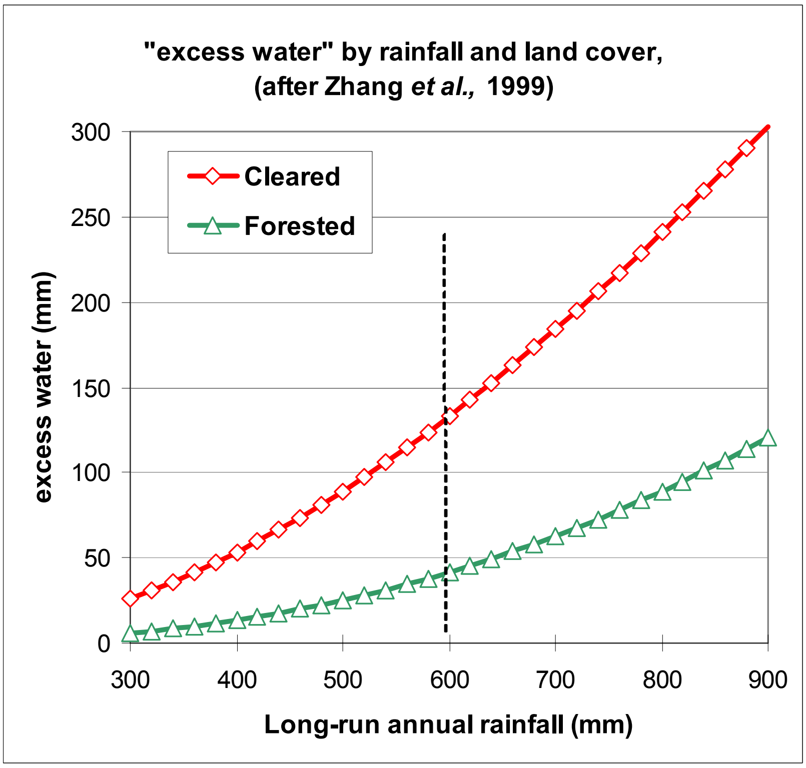


Fig. 1. Estimated ranges of "excess water" going to surface runoff and recharge after accounting for evapo-transpiration in cleared and forested catchments (from Zhang *et al*. 1999).

For our purpose, the long-run equilibrium stream-flow or 'excess water' expected with land uses between the extremes of cleared and forested areas are of interest. Catchments or individual farms within catchments may have mixed vegetation and, therefore, expectations for "excess water" falling between the extremes of cleared land and forest shown in Fig. 1. Dawes *et al*. (2000), following the proposal of Zhang *et al*. (1999) that proportions of forest cover and cleared areas could be multiplied by their respective contributions to excess water to derive a combined total, provided a table "as a first estimate of how different land cover types respond relative to native vegetation." We have borrowed these authors' indications for our Table 1 as a basis for our Fig. 2 relating excess water to long-run rainfall and land cover.

Table 1. Excess water response to different land cover (after Dawes *et al.*, 2000) for plotting excess water according to long-run rainfall and land use.

Ranges of weighting values given by Dawes *et al.* (2000)		Weighting values for our plot of excess water by rainfall and land use (Fig. 2)	
Vegetation Cover Type	**Proportion "Forest"**	**Proportion "Forest"**	**Proportion "cleared"**
Native vegetation	1.0	1.00	0.00
Forestry	0.5 – 1.0	0.75	0.25
Woodland or Lucerne	0.5	0.50	0.50
Opportunity or Improved Cropping	0.25 – 0.50	0.37	0.63
Perennial Pastures or Grazing	0.00 – 0.25	0.13	0.87
Annual Pastures or Cropping	0.0	0.00	1.00

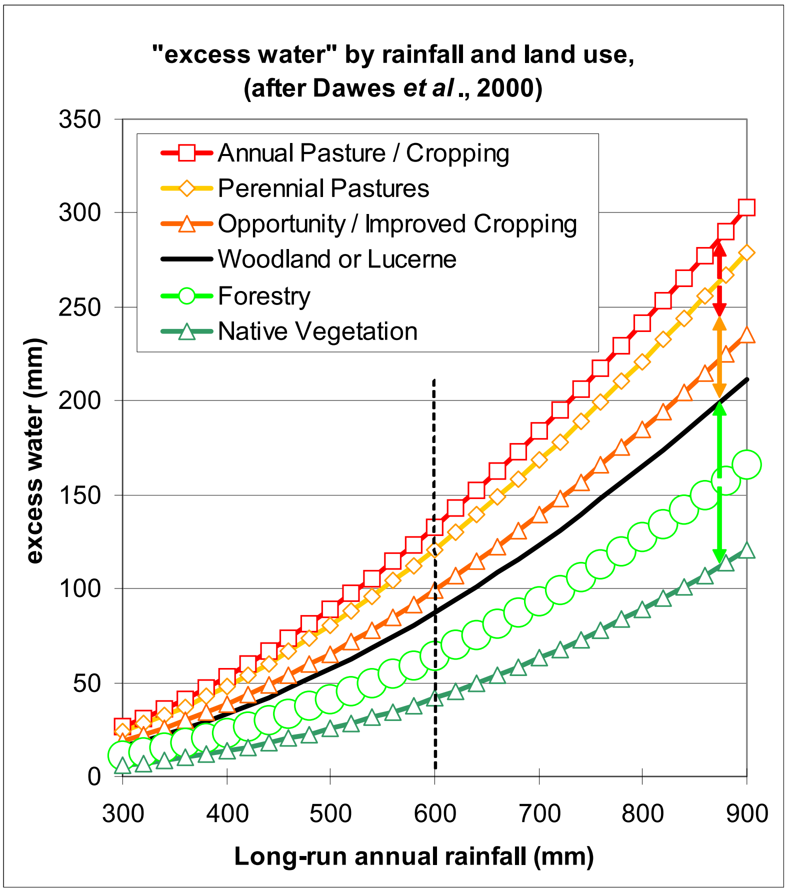


Fig. 2. Ranges of "excess water" expected with different land uses by rainfall (after Dawes *et al.*, 2000)

Following Dawes *et al*. (2000) we may partition excess water (stream-flow) according to soil type into proportions coming from surface runoff and from groundwater recharge. With sandy soils, the largest proportion goes to recharge and the least to runoff. With heavy clay soils the reverse is expected. Dawes *et al*. (2000) report that data presented by Petheram *et al*. (1999) "are consistent with the excess water curves of Zhang *et al*." (1999) … and that "this provides confidence in the use of Zhang Curves at the catchment scale, and as a starting point for runoff-recharge partitioning." "Based on broad soil types only," Dawes *et al*. (2000) provided estimates "of the fraction of excess water… which becomes recharge." Their Table 2 is reproduced here:

Table 2. Recharge fraction of excess water for generic soil type descriptors.

Soil Type / Texture	**Recharge Fraction**
Sand	0.90
Sandy-Loam	0.75
Loam	0.50
Clay-Loam	0.25
Heavy Clay or Duplex Soil	0.10
Source: Dawes *et al*. (2000)	

One should be able to place any land use within the limits of the range for "excess water" (Fig. 2.) given a particular long-run rainfall level. The resulting amount of "excess water" for each land use may then be partitioned between "recharge" and "runoff" fractions based on soil type (Table 2).

The Little River Catchment

An example of the approach suggested by Dawes *et al*. (2000) is developed here for the Little River catchment, a 258,000 ha area in the triangle defined by the cities of Orange, Parkes and Dubbo in NSW. Little River is a tributary to the Macquarie River, which flows through Dubbo, supports some irrigation and feeds the Macquarie Marshes Nature Reserve, where there are significant evaporative losses, before joining the Castlereagh River, which contributes in succession to the Barwon, Darling and Murray Rivers. Long-run annual rainfall in the Little River catchment is about 600 mm, which implies a maximum of 133 mm "excess water" from cleared areas and a minimum of 42 mm from native vegetation areas (Eq. (2) and Fig. 1).

Tables 3 and 4 represent an attempt to "place" the various cropping and pasture land uses found in the Little River catchment in an array of "excess water" expectations between 42 and 133 mm. The activities representing longer pasture phases (in particular lucerne) with shorter cropping phases are assumed to have less excess water than those with short annual pasture phases and long cropping phases. Among the crop and pasture activities, the highest excess water level (133 mm) is expected with annual cropping rotations such as canola-wheat-canola-wheat, while the lowest level (87 mm) is expected with lucerne pasture or similar deep-rooted perennial.

Eight land management units (LMU's) or land classes, characterised by particular soils, are defined in the Little River catchment. These may be "placed" in the array of generic soil types given by Dawes *et al*. (2002), Table 2, for our purpose of partitioning "excess water" of the various land uses into runoff and recharge fractions. This is done in Table 3, below.

In Table 4 the "excess water" values associated with representative categories of cropping and pasture activities are posited for the Little River Catchment, alone and with tree alleys spaced at 100, 50 and 25 m, as well as a forestry plantation option. The "excess water" is then partitioned into recharge and runoff fractions for each land use on each soil type, based on the factors in Table 3. These recharge and runoff amounts are considered in the Farm-Level model as the asymptotic values toward which each particular land use would trend over time if starting from some other current values.

Table 3. Partitioning of "excess water" into "recharge" and "runoff" fractions according to soil characteristics described in the Little River catchment (preliminary assessment)

Recharge[a]	Runoff	Soil Type / Texture[a]	LMUs [b] in Little River catchment [c]	
0.9	0.1	Sand	Siliceous sands	**LMU 8**
0.85	0.15			
0.8	0.2			
0.75	0.25	Sandy-Loam	Shallow Soils	**LMU 7**
0.7	0.3			
0.65	0.35			
0.6	0.4		Alluvial Soils	**LMU 1**
0.55	0.45		Euchrozems	**LMU 2**
0.5	0.5	Loam		
0.45	0.55			
0.4	0.6		Red Podzolic Soils	**LMU 4**
0.35	0.65		Non-calcic Brown Soils	**LMU 3**
0.3	0.7			
0.25	0.75	Clay-Loam	Red-Brown Earths	**LMU 6**
0.2	0.8			
0.15	0.85		Red Solodic Soils	**LMU 5**
0.1	0.9	Heavy Clay or Duplex		

[a] **source:** Table 2, after Dawes *et al*. (2000)

[b] Land Management Units

[c] Factors important for recharge/run off consideration include rainfall intensity, soil texture, soil depth and topography. Because we only have one of these bits of information, caution is justified (Jason Condon and Mark Conyers, personal communication 18 Nov 02).

Change in Recharge and Runoff over time

If we take each recharge or runoff value in Table 4 as an ultimate asymptote (U) for a land use option and the starting value (base level, B) corresponding to current land use, a four-parameter logistic function may be used to describe a trajectory of change over time. To illustrate this most dramatically, we take the example of a parcel of land in LMU 2, with Euchrozem (loam) soil (Table 3), which has long been used for annual cropping and, therefore, has the highest level of excess water (stream flow), from base values of 73 mm recharge and 60 mm runoff (Table 4).

Let us consider the trajectories of these components of excess water, where land use is switched to 'forestry'; recharge ultimately falls to 23 mm and runoff to 19 mm (Table 4). The change in runoff is expected to be more rapid while the change in recharge reaching the stream will be lagged by some years. The trajectory function (Eq. (3)) expresses excess water in terms of ML/year (note: 1 ML/ha/year = 100 mm/ha/year).

$$R = B+(U-B)*(1/(1+((Y/Y_x)\hat{}(-S)))) \quad (3)$$

Where:

		Recharge	Runoff
B =	base level of annual recharge (ML/year)	0.73	0.60
U =	ultimate asymptote (ML/year)	0.23	0.19
Y_x =	year of inflection	10	5
S =	abruptness exponent (>0)	3	5
Y =	year (variable)	(0 to 50)	

Table 4. Partition of "excess water" to recharge (Rec) and runoff (Run) asymptotes by soil type (LMU) and land use in the Little River Catchment (mm/year)

			Land Management Units (LMUs) [a]															
		Excess	1		2		3		4		5		6		7		8	
Code		Water	Rec	Run	Rec	Run	Rec	Run	Rec	Run	Rec	Run	Rec	Run	Rec	Run	Rec	Run
Name	Land Use Activity	(mm)[b]	0.6	0.4	0.55	0.45	0.35	0.65	0.4	0.6	0.15	0.85	0.25	0.75	0.75	0.25	0.9	0.1
AC	Annual Cropping	**133**	80	53	73	60	47	86	53	80	20	113	33	100	100	33	120	13
AC+PGP	AC+Perennial Grass Pasture	**110**	66	44	61	50	39	72	44	66	17	94	28	83	83	28	99	11
AC+LP	AC+Lucerne Pasture	**100**	60	40	55	45	35	65	40	60	15	85	25	75	75	25	90	10
LP	Lucerne Pasture	**87**	52	35	48	39	30	57	35	52	13	74	22	65	65	22	78	9
AC+T100	(AC)+Tree Alleys@100m	**126**	76	51	69	57	44	82	51	76	19	107	32	95	95	32	114	13
AC+PGP+T100	(AC+PGP)+Tree Alleys@100m	**105**	63	42	57	47	37	68	42	63	16	89	26	78	78	26	94	10
AC+LP+T100	(AC+LP)+Tree Alleys@100m	**95**	57	38	52	43	33	62	38	57	14	81	24	71	71	24	86	10
LP+T100	(LP)+Tree Alleys@100m	**83**	50	33	45	37	29	54	33	50	12	70	21	62	62	21	74	8
AC+T50	(AC)+Tree Alleys@50m	**106**	64	43	59	48	37	69	43	64	16	90	27	80	80	27	96	11
AC+PGP+T50	(AC+PGP)+Tree Alleys@50m	**88**	53	35	48	40	31	57	35	53	13	75	22	66	66	22	79	9
AC+LP+T50	(AC+LP)+Tree Alleys@50m	**80**	48	32	44	36	28	52	32	48	12	68	20	60	60	20	72	8
LP+T50	(LP)+Tree Alleys@50m	**70**	42	28	38	31	24	45	28	42	10	59	17	52	52	17	63	7
AC+T25	(AC)+Tree Alleys@25m	**80**	48	32	44	36	28	52	32	48	12	68	20	60	60	20	72	8
AC+PGP+T25	(AC+PGP)+Tree Alleys@25m	**66**	40	26	36	30	23	43	26	40	10	56	17	50	50	17	59	7
AC+LP+T25	(AC+LP)+Tree Alleys@25m	**60**	36	24	33	27	21	39	24	36	9	51	15	45	45	15	54	6
LP+T25	(LP)+Tree Alleys@25m	**52**	31	21	29	23	18	34	21	31	8	44	13	39	39	13	47	5
Forest	Forest plantation	**42**	25	17	23	19	15	27	17	25	6	36	11	32	32	11	38	4

[a] See Table 3 for description of LMUs and for factors used to partition "excess water" into Recharge and Runoff

[b] "excess water" given land use and 600 mm annual rainfall, from Fig.3.

Tree alleys	Fraction of 'no-tree' excess water
@ 100 m spacing	0.95
@ 50 m spacing	0.80
@ 25 m spacing	0.60

The trajectory for **runoff** is expected to be more abrupt than that for **recharge** because runoff reaches the stream immediately while recharge moves laterally through the soil and underlying geologic structures before contributing to stream flow. In this example, delays are assumed also due to the pace of tree growth. In a reverse example, where a mature forest is cleared from the land to make way for annual pastures or cropping, more abrupt changes in excess water are expected. However, some lags in response are still expected as the relatively dry soil and ground water fill with water under the annual management regime.

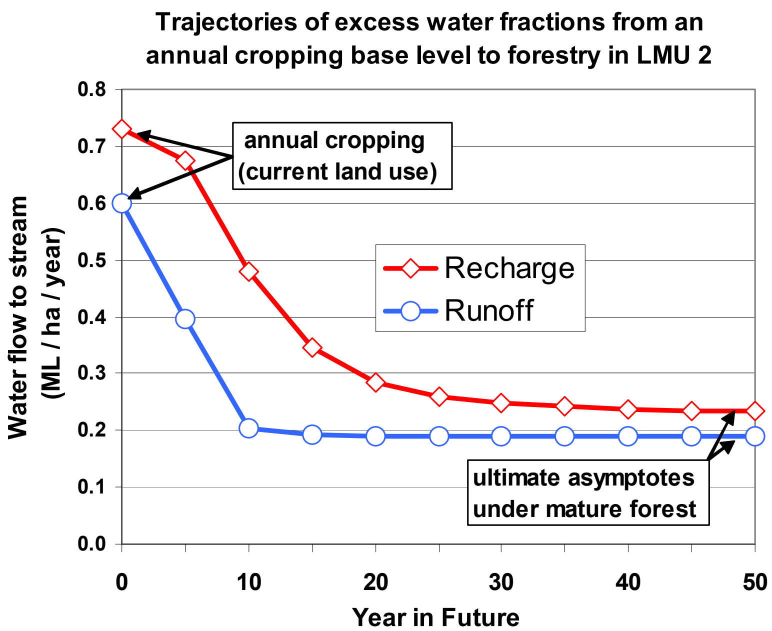


Fig. 3. Simulated consequences for stream-flow following a major change in land use: annual cropping to forestry.

In addition to soil texture characteristics of a particular LMU with respect to runoff and recharge proportions, we require salinity parameters which relate the salt burden of the LMU soil to the level of salt in the recharge water. We assume salt release from the landscape to streams is a direct function of LMU-specific (lagged) recharge reaching streams.

Part 2. FARM LEVEL MODEL: Farm Types (FT_) are defined by characteristic mixes and sizes of land management units (LMUs)

A linear programming framework is defined with the objective of maximizing net present value (NPV) of private wealth generated by the farm over the course of a 50-year run. As Salerian (1991), we aim to optimize wealth over time from land use options across soils with different salinity constraints. Operational constraints, productivities, incomes, costs and salt/water outputs are modeled at 5-year intervals for each of several land use (land-cover) activities with coefficients specific to LMUs. The year-specific water coefficients (water out) in the model are derived using the hydrology information (Table 4) with respect to each land use option on each LMU and knowledge of current land use on each LMU to project the trajectories of runoff and recharge for each land use (as in Fig. 3). “Water out” is the sum of runoff and (lagged) recharge reaching the stream. “Salt out” is a function of the salt burden of an LMU and the volume of recharge. Our model was implemented with a WB! (1999) spreadsheet solver.

Farm Level CONCEPT MODEL May be run with constraints on water and salt effluents from farm		Land Class W		Land Class X		Land Class Y		Land Class Z		Livestock grazing & sales	Cereal grain Sales	Eucalyptus Timber	NPV Calculations		Total WATER in farm effluent		Total SALT in farm effluent			
		WWWC	TRET	WWWC	TRET	PPP	TRET	PPP	TRET	Lvstk, year 0	Cereal Sale, 0	E timber sale 0	NPV of year 0	NPV of year 50	Water Out 0	Water Out 50	Salt Out 0	Salt Out 50	Relation	RHS
	Units	ha	ha	ha	ha	ha	ha	ha	ha	DSE	t	t	$	$	ML	ML	t	t		
NPV of years 0-50													1	1					Obj.	MAX
Expected +$, year **0**	$	-250	-100	-250	-350	-100	-350	-100	-350	25	200	30	-1						=	0
Expected +$, year **50**	$	-250	-800	-250	-800	-100	-800	-100	-800	25	200	30		-11					=	0
Land Class **W**	ha	1	1																=	263
Land Class **X**	ha			1	1														=	105
Land Class **Y**	ha					1	1												=	0
Land Class **Z**	ha							1	1										=	158
Cereal Prodn. In year **0**	t	-3.0		-2.9							1								=	0
grazing **DM** in year **0**	t					1.0		1.0		0.4									≤	0
grazing **ME** in year **0**	GJ					2.5		2.4		1									≥	0
TRET products 0	t		0.1		0.1		0.1		0.1			1							=	0
Water out 0	ML	0.6	0.6	0.7	0.7	0.8	0.8	0.8	0.8						-1				=	0
in year **50**	ML	0.8	0.2	0.8	0.5	0.9	0.6	1.0	0.7							-1			=	0
Salt out 0	t	0.2	0.2	0.1	0.1	0.2	0.2	0.2	0.2								-1		=	0
in year 50	t	0.3	0.1	0.2	0.0	0.2	0.0	0.3	0.0									-1	=	0
Water constraint, year 50	ML															1			=	W
Salt constraint, year 50	t																	1	=	S

Change these values to sample the W & S space around the unconstrained solution

Fig. 4. Schematic farm level model illustrating modes for solutions not constrained by salt/water targets (i.e., without bottom two rows), and with binding targets (bottom two rows).

An NPV-maximizing run for a particular Farm Type with its characteristic size and composition of LMUs is first made without constraints on salt/water effluents to the stream. The resulting ‘unconstrained, best private’ solution for each Farm Type, however, will trace salt/water effluent levels over the 50-year sequence.

The salt/water effluent levels at a future point in time (say, in 50 years) under the unconstrained "best private" solution provides the starting point for sampling a range of salt/water combinations to find the entire technically feasible set of 'targets' expected for each Farm Type in that future period (Figure 5). Increments between the sample targets at the whole-farm level may be on the order of 10 t salt and 10 ML of water per year, but finer or coarser increments may be used if necessary.

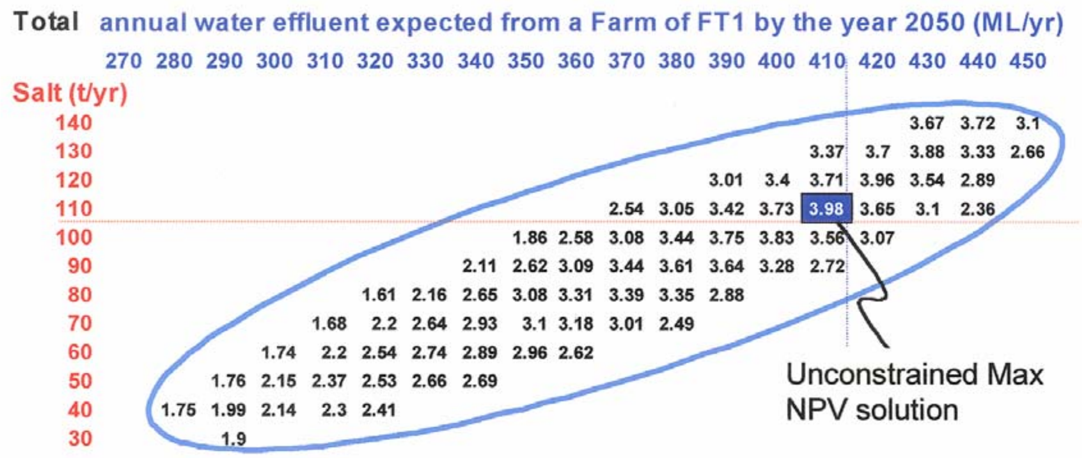


Fig. 5. Footprint (or range) of technically feasible farm-level salt/water targets in year 50 with NPV levels ($ m) calculated for each for hypothetical Farm Type 1.

It is expected that all other feasible salt/water targets for a Farm Type will exhibit lower NPVs than that with unconstrained salt/water effluents. The NPV values associated with these targets may be plotted above the salt/water plane (the highest is given a 'halo' in Fig. 6).

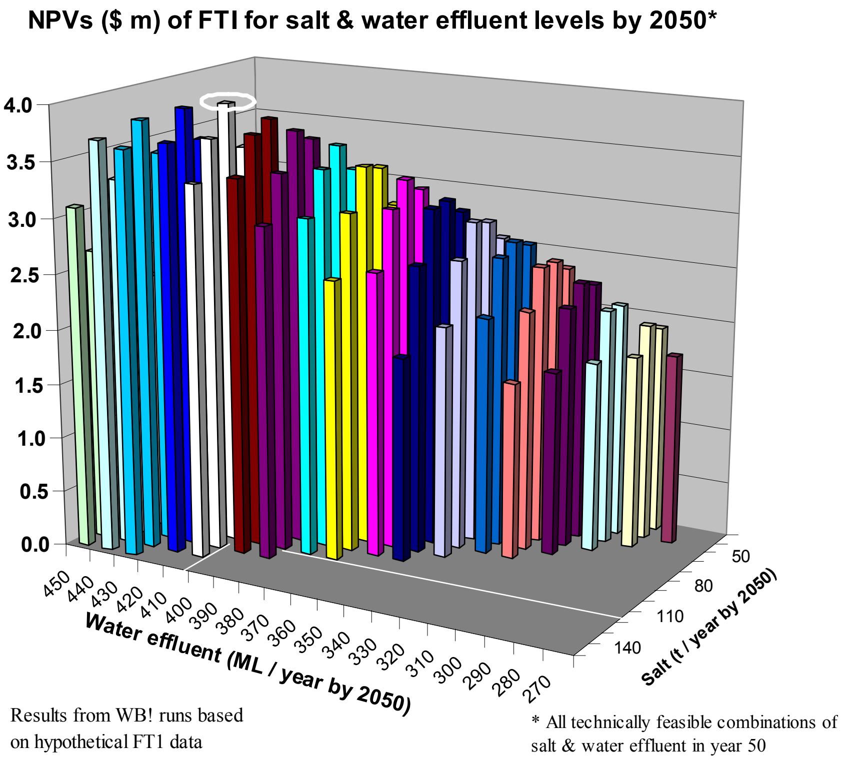


Fig. 6. NPVs of technically feasible salt/water output levels from Farm Type 1 in year 50.

Because each **Farm Type** is defined as having a different size and composition of LMUs, it is expected that each **Farm Type** in a catchment will have a unique and differently oriented "footprint" of technically feasible targets in the salt/water plane. It is expected that these "footprints" will be oriented chiefly along rays of constant salt concentration (more salt and more water, or less salt and less water) in the salt/water plane (Fig. 7).

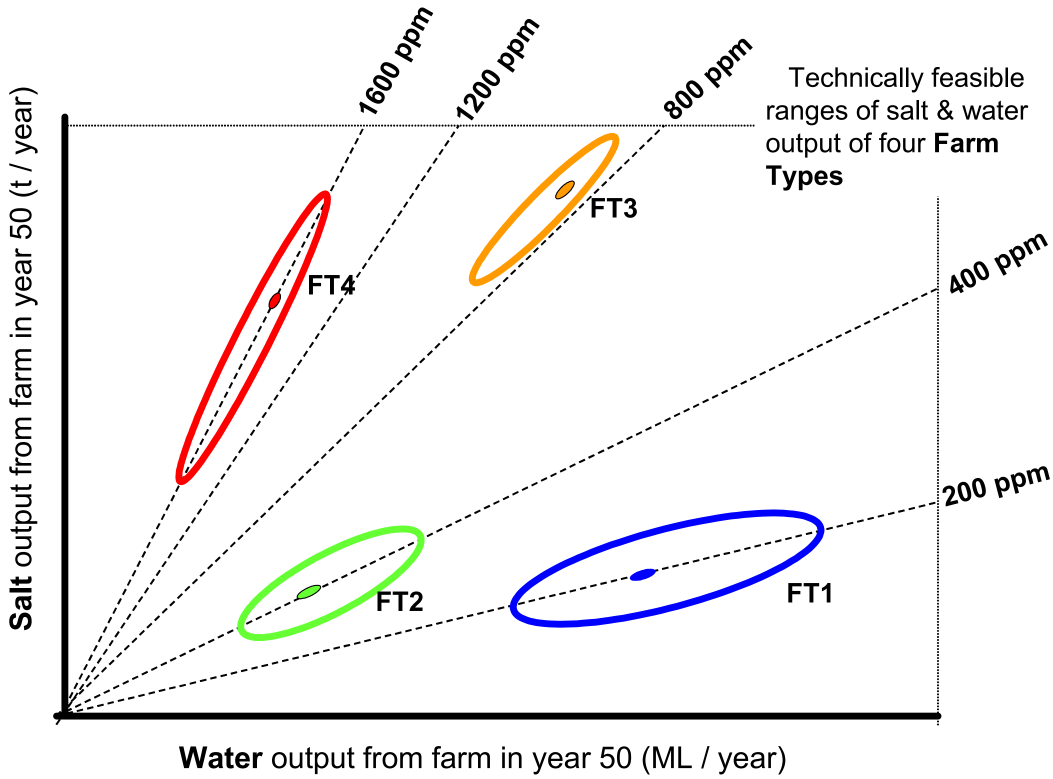


Fig. 7. Schematic chart of "footprints" of technically feasible salt/water combinations in the salt/water plane attainable by four Farm Types.

Further, "footprints" for the various Farm types will not only be positioned differently in the salt/water plane, according to differences in the saltiness of their constituent LMUs, but they are expected to exhibit different shapes in the dimension of NPVs (Fig 8). From this perspective, it becomes clear that some Farm Types may offer cost effective opportunities to reduce the saltiest salt/water effluents by shifting to herbaceous perennial pasture or agro-forestry options that decrease excess water. Other Farm Types may offer cost effective opportunities for increasing their dilution flows of fresh water by shifting to land use options leading to increased excess water, such as annual pastures or cropping, or perennial grass pastures. The cost-effectiveness of such adjustments is an economic question (when the hydrologic and biological responses are known). Of course the latter are often not known with confidence under all conditions that will be of interest. Weaving these questions into the larger context of unknowns and concerns for the environment gives rise to a need for continuing natural resource management research.

The perspective afforded by the 3-dimensional (NPV, salt, water) nature of the cost-effectiveness of achieving future salt/water targets at the individual farm level (Fig. 8) raises the opportunity to examine the economics of target blends at the catchment level.

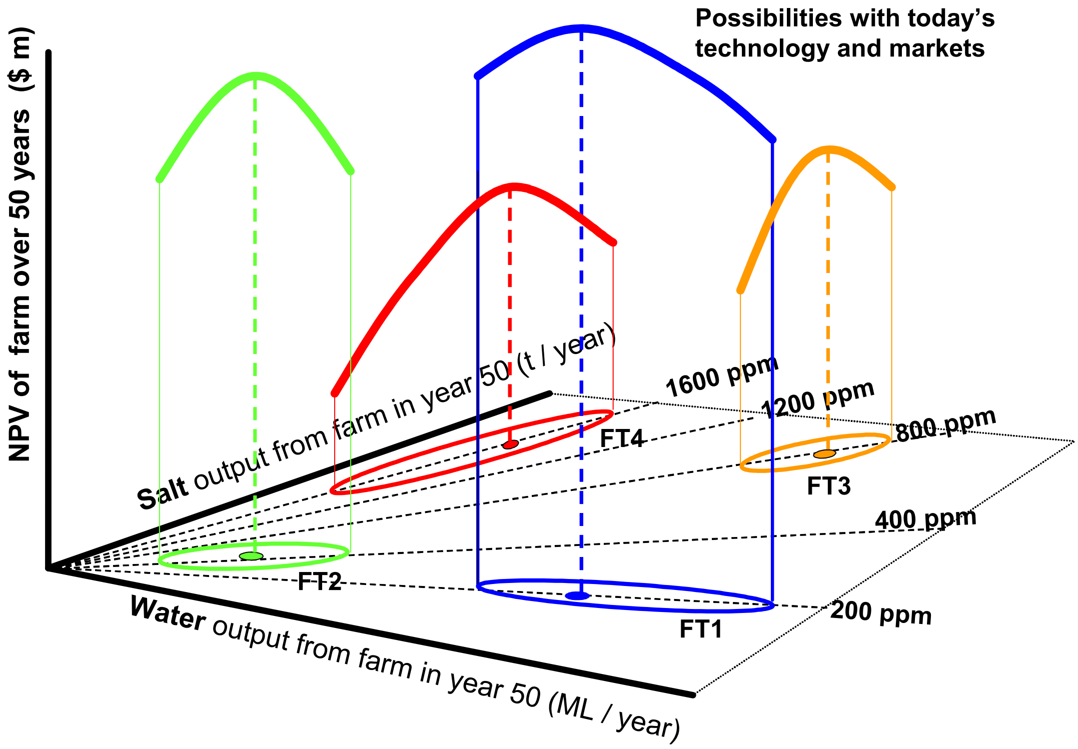


Fig. 8. Schematic chart of "footprints" of technically feasible salt/water combinations attainable by four farm types in the salt/water plane with the added dimension of NPV.

Part 3. A CATCHMENT-LEVEL MODEL

Each of the several **Farm Types** is represented in the catchment LP model, each with a unique technically-feasible "footprint" of targets in the salt/water plane. Associated with each feasible salt/water target for each **Farm Type** is an NPV value (Fig. 8). The resulting triplets of data (NPV, salt, water), each representing a configuration of a Farm Type to meet a particular future target, are used as the input data for a catchment-level model.

As with the farm-level models, the objective of the catchment model, is to find the maximum collective NPV, but across **Farm Types**, given each of a range of catchment salt/water targets (Fig. 9).

The blended sum of salt/water effluents of the various **Farm Types**, each with its highest NPV without salt/water constraints, provides a starting point for sampling to find the technical limits of the catchment. Also contributing to the aggregate blend of salt/water effluent will be that arising from state or national forest lands in the catchment. Departures from the "best" economic target from the point of view of farmers in the catchment will be associated with opportunity costs to them.

The NPVs of these opportunity costs may be estimated as the differences between the "best" catchment NPV and those of the various other targets in the feasible range. The result is a set of minimum-cost ways of achieving various salt/water targets when departing from the unconstrained outcome. The model is constrained to maximize NPV at each target future effluent quality target level (salt ppm ratios) in multiple runs sampling a range of water quantities (Fig. 10). As in the case of the farm level model, no feasible solution may be found for some salt/water targets. The targets sampled should cover a range wide enough to find the upper and lower limits of the catchment.

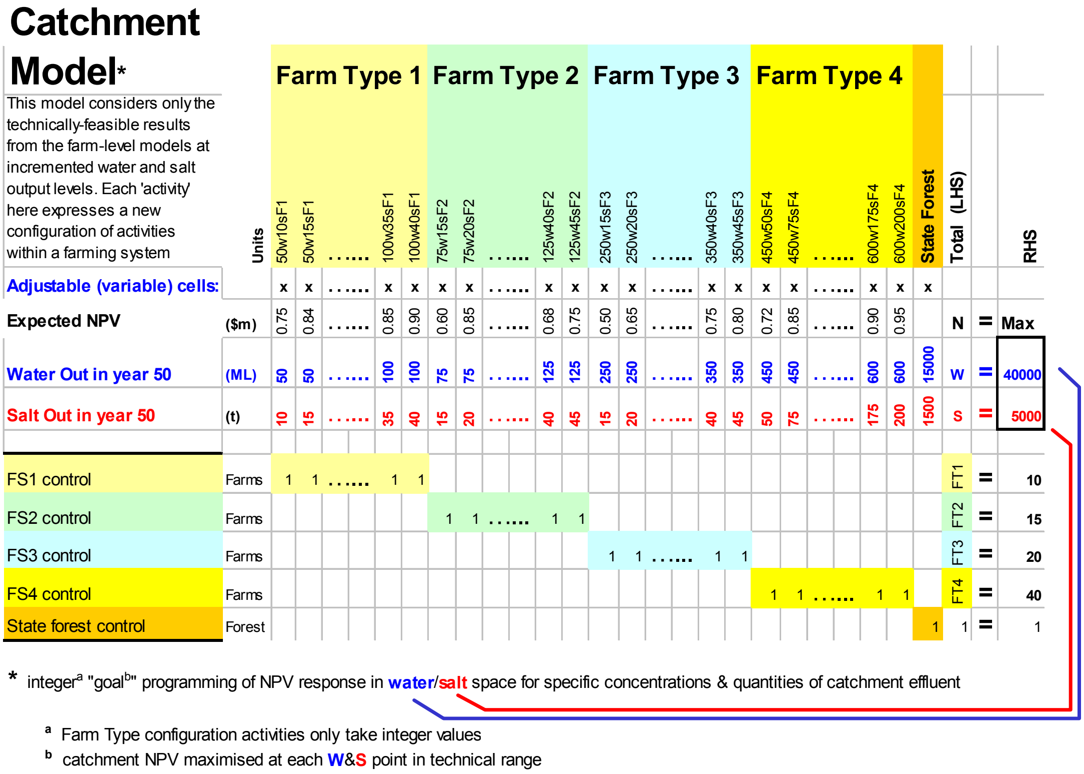


Fig. 9. Schematic chart of the catchment-level model for calculating minimum-cost configurations of farming systems across farm types for meeting catchment targets for salt/water effluents in year 50.

Because these other targets may be selected for the benefit of (and compensation by) downstream users of water, the catchment model is a '**goal programming model**'.

For a given set of technologies, for a given catchment, there will be a "footprint" of technically feasible targets in the salt/water plane. The role of future new technologies in widening or lengthening these "footprints" is discussed later.

Each salt/water target solution for a **Farm Type** in the farm-level models is represented as an activity in the catchment-level model with a minimum of three dimensions (Fig. 9). Feasible targets are represented as triplets of data points: NPV ($), salt (t / year) and water (ML / year), where the 'year' chosen is some standard time in the future (say, at year 50). The model will pick points from the NPV 'surface' over the salt/water plane of each **Farm Type** (Fig. 8) to reach a catchment-level target at least-cost (indicated by arrows in Fig. 10 and Fig. 11)

Because each target's NPV, salt/water triplet represents a unique configuration of farming systems for a **Farm Type** (calculated with the farm-level model), and because interpolation between targets raises difficulties, the catchment model may be solved as an '**integer-programming model**'. This allows the model only to present solutions with integer numbers of farms of a **Type** in particular targets. For each **Farm Type** in the model there is a constraint row to limit the number of farms to the total number of farms of that **Type** in the catchment.

Catchment Water Out (GL year^{-1})	Maximum NPV of farming systems in catchment given salt / water output targets ($ millions)				
	ppm				
	125	150	175	200	225
39	0	0	0	0	0
40	76.3	81.8	87.0	91.8	95.9
41	75.3	80.8	86.2	91.1	95.1
42	73.3	79.1	84.5	89.7	93.6
43	68.6	77.2	82.8	88.2	92.0
44	62.6	75.1	81.1	86.8	90.2
45	54.5	72.1	79.3	85.3	88.2
46	44.7	68.3	77.5	83.7	86.2
47	0	64.6	74.8	81.6	84.1
48	0	60.8	71.7	79.2	81.9
49	0	0	0	0	0

Note: 1 GL of water = 1000 ML = $m^3 \times 10^6$

from WB! runs based on hypothetical catchment data

Fig. 10. Maximum NPVs of technically feasible salt/water targets for year 50 at the catchment level.

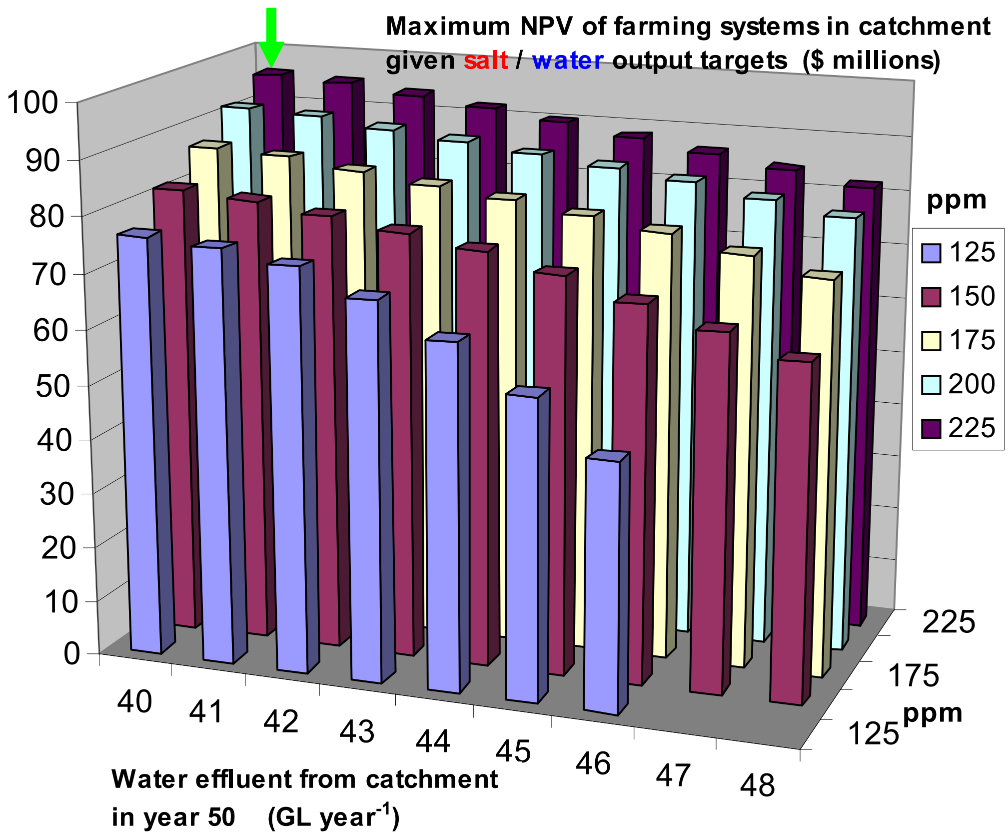


Fig. 11. Chart of maximum catchment-level NPVs given salt/water targets for year 50.

The catchment level opportunity costs calculated as we propose are 'minimum' costs not only in the LP sense of optimality, but in the sense also that they include neither the transaction costs of planning and implementing adjustments at the farm level, nor of any necessary institutional changes. Instead the model (naively) assumes farmers in the catchment can be motivated to promptly undertake the system changes (tree-planting, establishment of lucerne pastures, etc.) on appropriate pieces of land, and at the appropriate scale, to deliver the future benefits.

The key message of our farm and catchment level models is the point that opportunity costs will be faced when salt/water targets are pursued which differ from the 'unconstrained' maximum NPV solutions at the farm. This may assist policy makers in their assessments of options for salinity management, including targeting in the development of market based salinity measures. This may also assist advisers and farmers in thinking of profitability comparisons among land use options, and their relative effectiveness as spin-offs for salinity.

Part 4. SUPPLY CURVES FOR WATER AND WATER QUALITY

Given a discount rate and time horizon, a required annual annuity payment by downstream water users may be equilibrated to the lump-sum minimum NPV of the opportunity costs faced by farmers who must reconfigure their farming systems to meet a particular annual catchment salt/water effluent target in the future. We may calculate the annuity value which is equivalent to a present value of 1 (Eq. (4)), convert this to a dollar annuity amount (Eq. (5)) and confirm that the discounted present value of the stream of such annual payments continuing to the time horizon equals the original NPV value (Eq. (6)) (Beyer, 1984)

Annuity with $PV_d = 1$ $$A_d = \frac{i}{1-(1+i)^n} \quad (4)$$

Annuity amount $$A_\$ = A_d NPV_\$ \quad (5)$$

and

Present value $$PV_\$ = \frac{A_\$ (1-(1+i)^{-n})}{i} \quad (6)$$

where:

$\boldsymbol{A_d}$ = annuity, expressed as a decimal fraction of a PV whose value is 1

$\boldsymbol{A_\$}$ = annuity amount in annual dollar payments to farmers in the catchment by downstream users

$\boldsymbol{PV_d}$ = 1 = the discounted sum of decimal annuity fractions from the present to the end of the time horizon

$\boldsymbol{NPV_\$}$ = the minimum NPV of opportunity costs by farmers in the catchment to meet a salt/water effluent target

$\boldsymbol{PV_\$}$ = the discounted sum of annual annuity payments to farmers in the catchment by downstream users, from the present to the end of the time horizon; set equal to ***NPV$***

$\boldsymbol{i}$ = annual discount rate

$\boldsymbol{n}$ = number of years to the time horizon

The annuity equivalents for lump-sum catchment opportunity costs of meeting salt/water targets may be expressed as total annual payments (Fig. 12) or in terms of annuity surcharges per ML of water (Fig. 13).

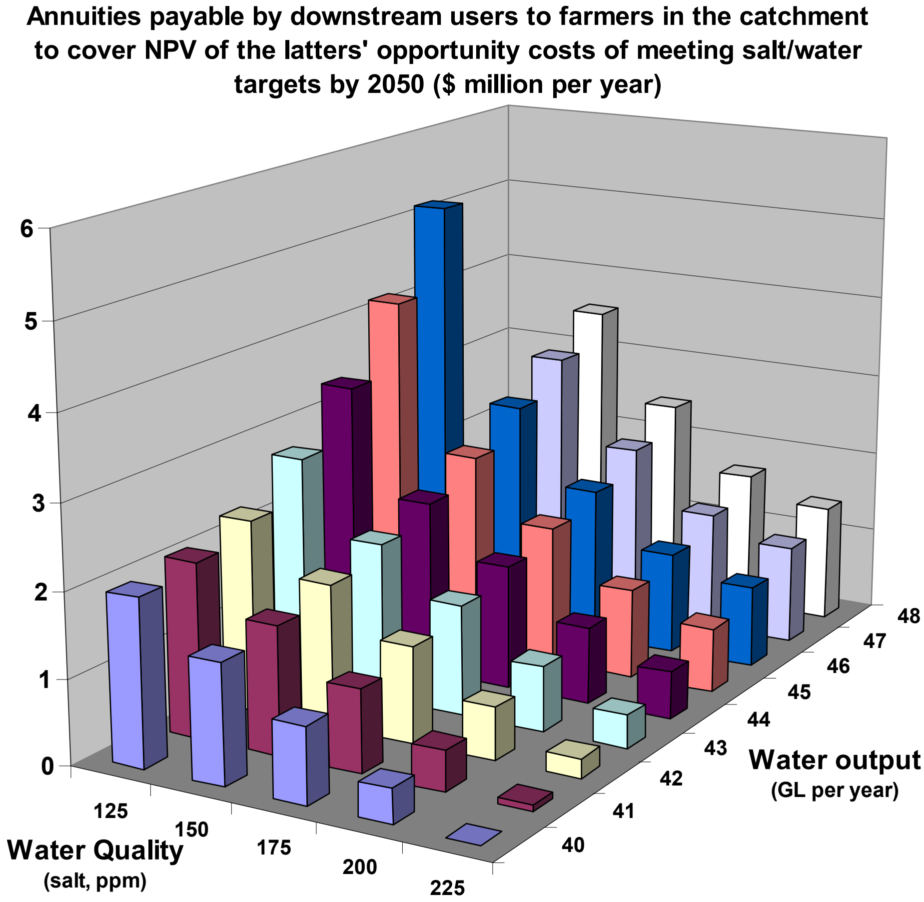


Fig. 12. 50-year annuities (sums payable annually) equivalent to catchment NPVs of opportunity costs associated with targets for salt/water effluent levels

The conversion of an annuity ($A_\$$ expressed in \$m, as in Fig. 12), for **x** GL of water at a particular salt concentration, to an annual surcharge cost C (\$/ML) is given in Eq. (7). The resulting annuity cost equivalent per ML of future water is given in Fig. 13.

$$C(\$/ML) = 1000(A_\$ / xGL) \qquad (7)$$

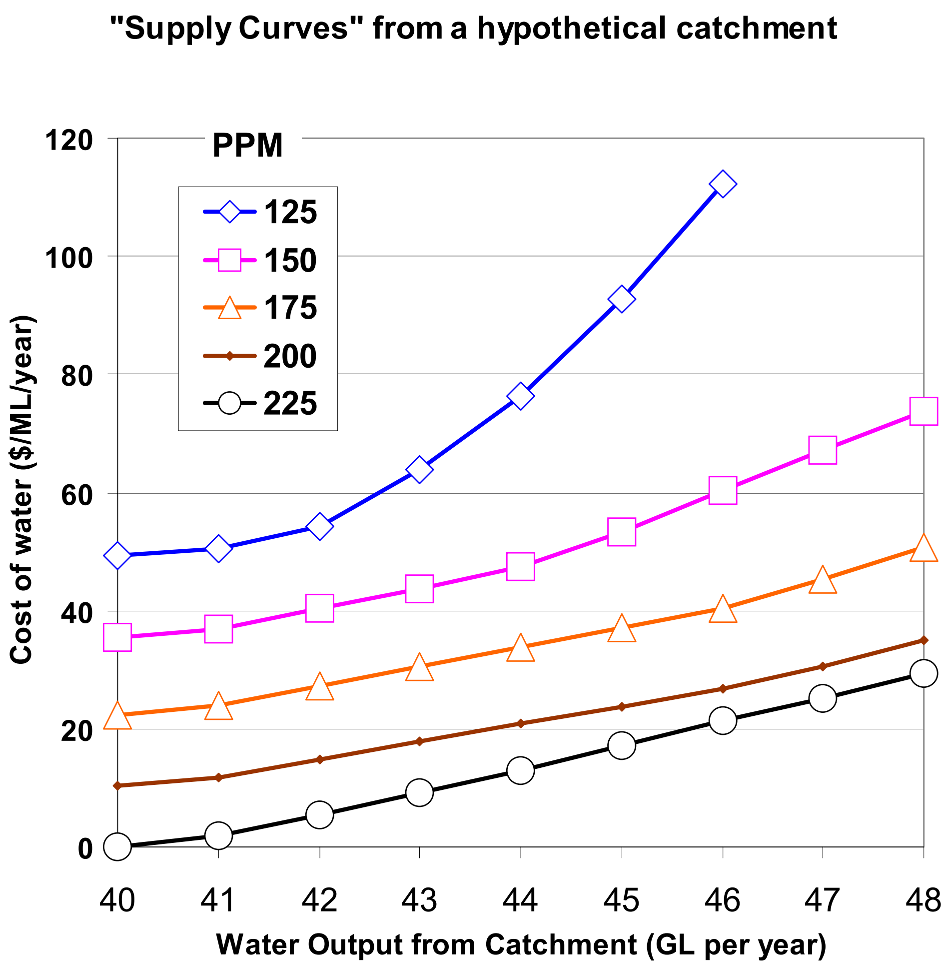
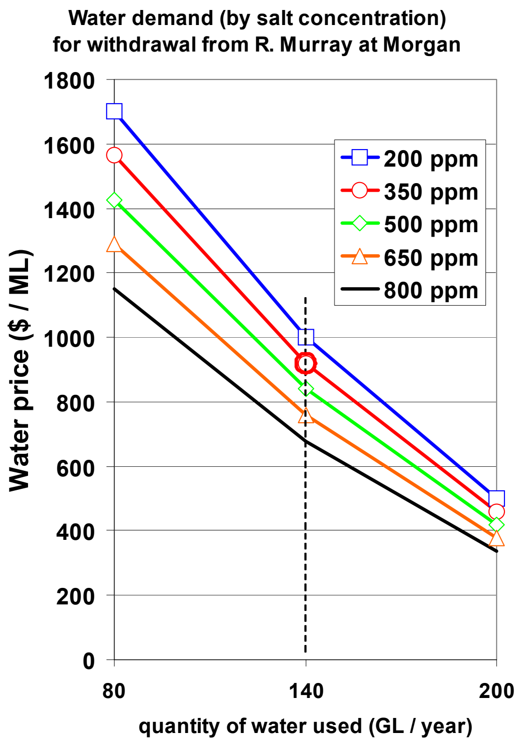


Fig. 13. Costs of supplying water at different quality levels in year 50 in terms of annual annuity surcharges payable to suppliers of catchment water (farmers in the catchment) over the full course of the 50 years.

Though obvious, it must be stated that compensation to farmers in the catchment is not to be distributed evenly, but in accordance with opportunity costs borne by the Farm Types, and specifically to those individual farms contributing effectively to improved effluent water quality (by reduced salty flows or increased fresh flows). Some Farm Types may not be asked to contribute. Others would be asked to make important adjustments to their land uses, otherwise against their direct financial interests, but nevertheless offering cost-effective abatement to a problem emanating from their land. These are the ones who would require compensation.

While the practical obstacles of transaction costs and institutional development will certainly be present (Challen, 2000), we have outlined the essential steps for focusing on those specific lands and land uses which provide the most cost-effective contributions to water quality in particular catchment settings. Others have studied the practical prospects for market-based solutions for pollution abatement (van Bueren & Pannell, 2001; Stoneham *et al.*, 2001). Such prospects may be linked to our hydrologic, biologic and farm-level economic framework to distinguish minimum-cost (farm type-specific) ways of changing salt/water effluent levels and linked to catchment-level opportunity costs for water flow volumes in the future at different salt concentration levels. We have expressed the NPVs of these opportunity costs as annuity-equivalent costs that may be taken on by downstream consumers wanting higher quality water.

Others have made strides in estimating damages incurred by downstream household, commercial, industrial and agricultural consumers due to increased salinity of stream water (Hill, 2002; Quiggin, 1986; Wilson, 2001; Thomas & Cruikshanks-Boyd, 2001). A synthetic example of demand for water quality is offered in Fig. 14.



Assumptions:

- Damages are **$173,000** per unit increase in EC at an overall use rate of 139 GL (say 140 GL / year) total for household, commercial and industrial consumers in Adelaide

- Current price of $920 / ML and current quality of 350 ppm

…Thomas & Cruickshanks-Boyd (2001)

- Calculate damages along 140 GL line at incremented quality levels

- To give shape to 'curves', take demand prices at 80 and 200 GL to be 1.7 and 0.5 times demand price for 140 GL, respectively.

-Ultimate price cap could be cost of desalinating sea water … c. $2000 / ML … Winter *et al.* (2002)

Note: 1 GL = 1000 ML and

1 ppm = 1 mg TDS / L = 0.625 EC

Fig. 14. Demand for water quality in the case of withdrawals from the Murray River at Morgan in 2000; indicative values only to join the discussion of supply costs for water from catchments offering different quality levels at different prices.

Obviously the "demand curves" for water quality here (Fig. 14) do not match up exactly with the "supply curves" for catchment water volumes and quality (Fig. 13). The important point is that water quality improvements and increased volumes of water from source catchments in the future may come with substantial opportunity costs. Demand for future water quality and quantity may possibly be matched with sources positioned to provide it efficiently. Further, market based means of making these future options meet will be helped by fuller understandings of how the hydrologic, biological and economic forces are felt at the farm level.

Part 5. THE ROLE OF NEW TECHNOLOGIES AND MARKETS

New technologies dealing with dryland salinity may have the effect of expanding the technically feasible "footprints" of the different farm types in the directions of greater water use in salty recharge situations where this is most beneficial, and in directions of lower water use where fresh water effluent is most beneficial. New markets may have the effect of changing the shapes of the NPV surfaces over the salt/water planes. The combined result of new technologies and new markets will likely be expanded ranges of choice for farmers and greater ability to institute systems changes that are more effective and profitable in controlling dryland salinity. This situation is depicted in Fig. 15.

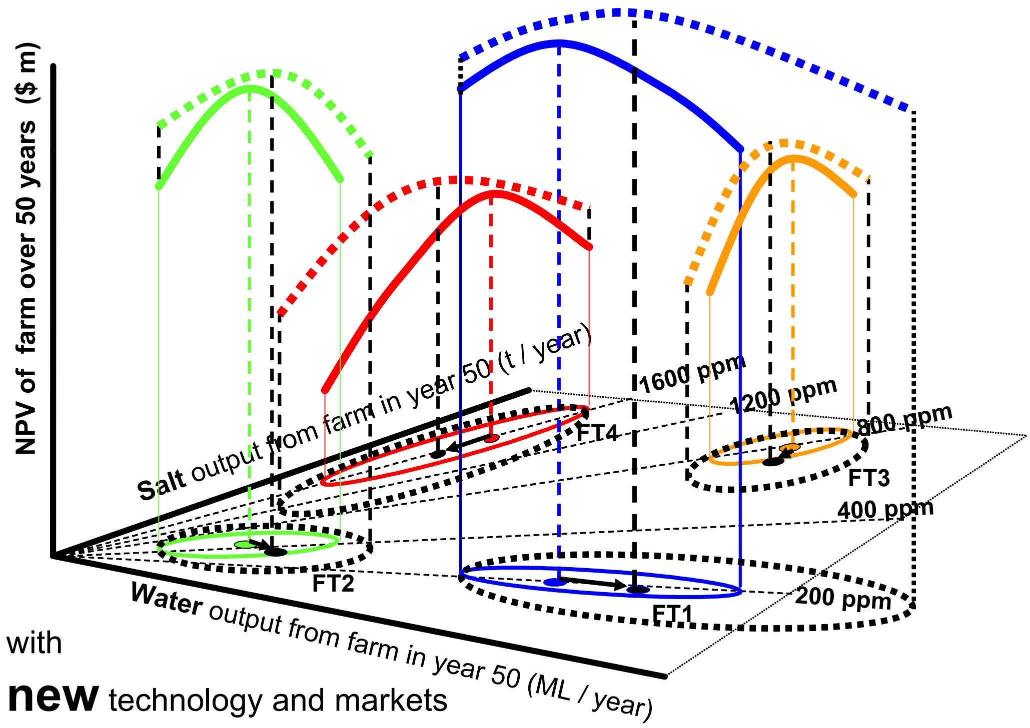


Fig. 15. Expanded ranges of technically feasible "footprints" of options for various Farm Types in a catchment to contribute to catchment targets, with altered profitabilities due to new markets.

Conclusions

- Salinity targets other than the salt/water effluents arising from the long run wealth-maximising configuration of a farm may have high opportunity costs.

- Costs will vary among farms and catchments for achieving different salt/water targets by certain dates.

- Applying the same actions on every farm or catchment, without regard to the hydrologic, biological and economic consequences, will be ineffective and costly.

- Least-cost adjustments across farms and sub-catchments imply supply curves for water quality, which may be matched with downstream demand for water quality.

- New technologies and markets may lower the costs of supplying better quality water by making salinity-abating production more profitable.

- We have outlined the essential steps for focusing on the specific lands and land uses which provide the most cost-effective contributions to water quality in particular catchment settings.

We have attempted in this paper to provide an overarching vision and perspective of the economics of dryland salinity management where externalities related to downstream water quality are concerned. This is based on hydrologic and agronomic principles, and is focussed on the technical possibilities for farms with different resource bases to change their salt/water outputs to streams, and the economic consequences in terms of opportunity costs to these farms for doing so. We use the farm-level results as inputs to a catchment-level model. Based on the farm level differences in ability to respond, we find minimum-cost target blends of future salt/water flows at the catchment level.

It remains a challenge to define market based mechanisms (salinity credits, permits, auctions, etc.) to bridge the needs of future consumers of water and the needs of land owners in the source catchments. The quantitative framework outlined in this paper may help in this bridging process by providing in sufficient detail the hydrologic, biological and economic potentials at the farm and catchment levels for changing salt/water flows.

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