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Downstream benefits vs upstream costs of land use change for water-yield and salt-load targets in the Macquarie Catchment, NSW

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Abstract: The net present value (NPV) of downstream economic benefits of changes in water-yield (W) and salt-load (S) of mean annual river flow received by a lower catchment from an upper catchment are described as a 3-dimensional (NPV,W, S) surface, where $d\text{NPV}/d\text{W} > 0$ and $d\text{NPV}/d(\text{S/W}) < 0$. Upstream changes in land use (i.e. forest clearing or forest establishment, which result in higher or lower water-yields, respectively) are driven by economic consequences for land owners. This paper defines conditions under which costs of strategic upstream land use changes could be exceeded by compensations afforded by downstream benefits from altered water-yields and/or lower salt loads. The paper presents methods, and preliminary calculations for an example river, quantifying the scope for such combinations, and raising the question of institutional designs to achieve mutually beneficial upstream and downstream outcomes. Examples refer to the Macquarie River downstream of Dubbo, NSW, and Little River, an upstream tributary.

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1. Introduction

The question of whether prospects for downstream benefits (or losses) can drive upstream river management has been answered in the affirmative in justifying numerous engineering projects for water regulation. This paper turns to the more specific question of whether downstream water users, who would benefit from certain changes in water-yields and salt-loads, could afford to compensate upstream land owners for land use changes to bring the desired results. Bennett and Thomas (1982), using different model specifications, examined a similar set of questions in Western Australia and determined that a range of water-yield and salinity concentration targets could be achieved, specific to each catchment's characteristics. The costs of achieving such targets are defined here as in Nordblom *et al.* (2006) and matched against downstream demand to illuminate the scope for negotiation of mutually beneficial changes in land use for water yield and quality. If there is large scope for win-win solutions, there may be a case for market formation (Whitten *et al*., 2004)

2. Methods

2.1 Net present value (NPV) of downstream economic benefits of changes in water-yield and salt-load.

Downstream towns, industries, horticultural and field-crop irrigators and wetland environmental assets are often rival users of limited river flows. Subject to 'cap and trade' regulations on water use, including provisions for environmental flows, water will tend to be allocated to its highest-value uses. Given that water is limited in supply relative to its potential beneficial uses, the market will reflect this scarcity in the price of water entitlements in temporary and permanent trades. Damages to infrastructure, equipment, household appliances and irrigated crops due to salt concentrations in water have been estimated in various cases (Wilson & Laurie, 2002; Thomas & Cruickshanks-Boyd, 2001). We assume the downstream benefits of changes in water-yield and salt-loads are a direct positive function of water-yield, diminishing slightly on a per unit basis beyond current water-yield levels. We assume a small negative term as a direct function of salt concentration levels in the river.

2.2 Minimising costs of upstream land use changes to meet catchment targets of river water-yield (W) and salt-load (S).

The present analysis employs and expands on methods documented in Nordblom *et al.* (2006). Prospects for attainment of particular future water-yield / salt-load targets for a catchment depend on current land use and water use information on key land use options, soil hydrologic characteristics, annual rainfall and groundwater salinity. Our analysis assumes responsive local groundwater flow systems. These methods will not be applicable to areas with less responsive intermediate or regional groundwater flow systems. Given this information, optimising land use change for least-cost attainment of targets requires cost, productivity and profitability data on all key land use options that could be carried out.

Each land use option will have an equilibrium level of water use and Net Present Value (NPV); the latter depending on transition costs from current land use and mean profitability, which in turn depends on production costs, productivity, and product prices. A planning horizon of 30 years and a discount rate of 7% are used. Productivity and the hydrologic "drainage fraction" characteristic, which partitions fractions of excess water (rainfall minus evapo-transpiration) to deep drainage or surface runoff, are functions of soil type. Surface runoff is assumed to reach the stream fresh, while deep drainage ultimately transports salt to the stream at the same concentration as the groundwater. Thus, in addition to a characteristic NPV for each land use option on each soil type and groundwater salinity concentration, there will be a characteristic equilibrium annual water-yield (W = fresh surface runoff + salty base flow) and a characteristic annual salt-load (S) delivered to the stream. That is, each option will yield a characteristic triplet of values: NPV, W and S.

For the purpose of the current analysis, characterisation of land is by groundwater salinity class, using the area-weighted mean groundwater salinity level of all sub-catchments in the class, and by soil type, with aggregated areas of each type. Current land uses were likewise cross-tabulated with soil types. Mathematical programming for "farm-level" constrained optimisation was carried out for each groundwater salinity class, aimed at maximising NPV given target-level constraints on future water-yield and salt-load and subject to resource constraints in the form of initial areas of land-use on each soil type. Land uses could be changed but with an associated transition cost… most dramatically in the case of establishing a forest plantation. A rectangular sample grid of mean future water-yields and salt-loads was used to provide target-level constraints in multiple-solution sequences for each groundwater salinity class. The sample grid for each class is extended to water and salt combinations for which there were no feasible solutions on all sides of the water and salt targets found to be feasible. A unique NPV is to be defined for each feasible sample water and salt target.

3. Data

3.1 Downstream demand for water and water quality.

In the case of the Macquarie River, at Dubbo, NSW, we assume the mean annual reference point is 1,100 GL of water flow, carrying 200,000 tons of salt. We assume greater or lower mean water-yield would raise or lower downstream NPV by + or **-** \$1.2m/GL, respectively, being the approximate price of permanent trades of water rights. We assume lower or higher mean salt concentrations in river water at Dubbo are valued at + or **-** \$0.3m/ppm, respectively. These values are placed in the downstream benefits equation in Table 1, which is evaluated over a wide range of water-yields and salt-loads in Figure 1 at the appropriate scale: assuming mean annual water-yields and salt loads are as above. The expression of this downstream benefits surface at the scale of influence appropriate to Little River has been evaluated in Figure 2; representing a small patch of the larger Macquarie River benefit surface (Figure 1).

Table 1. Current mean annual water-yield and salt-load of Macquarie River at Dubbo, NSW, with assumed economic parameters for change in downstream benefits (\$m / year) from changed mean water-yield and salt-loads.

$$\textbf{Downstream Benefits} = a*dGL + b*(dGL)^2 + c*dC$$

where:

dGL = change in Water yield, in GL = (W - Wc)
dC = change in Salt concentration, in ppm or mg/L = 1000*((S/W)-(Sc/Wc))

given

Wc = current mean Water yield, **1100** GL / year at Dubbo
Sc = current mean Salt load = **200** *1000 t / year at Dubbo

and

W = new mean Water yield, GL / year
S = new mean Salt load, 1000 t / year

where ecomonic parameters are:

a =	1.2	\$m/dGL = approx current price for permanent sale of water right
b =	-0.002	\$m/dGL^2
c =	-0.3	\$m/dC

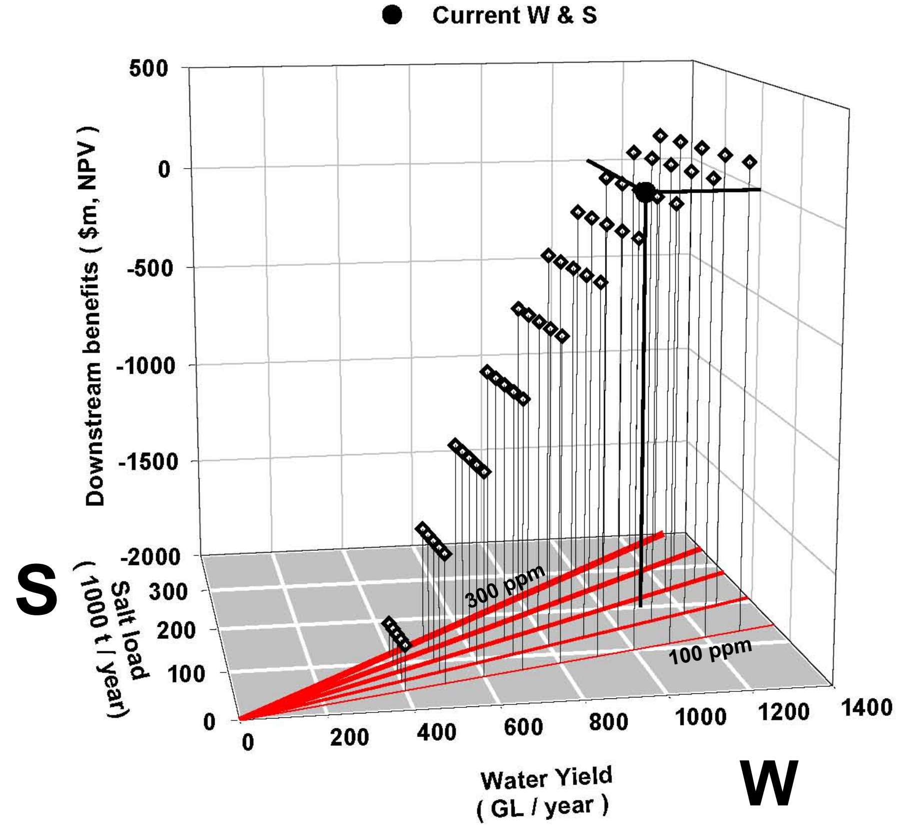

Figure 1. Downstream benefits of a permanent change in mean water-yield and/or salt-load in Macquarie River at Dubbo, NSW

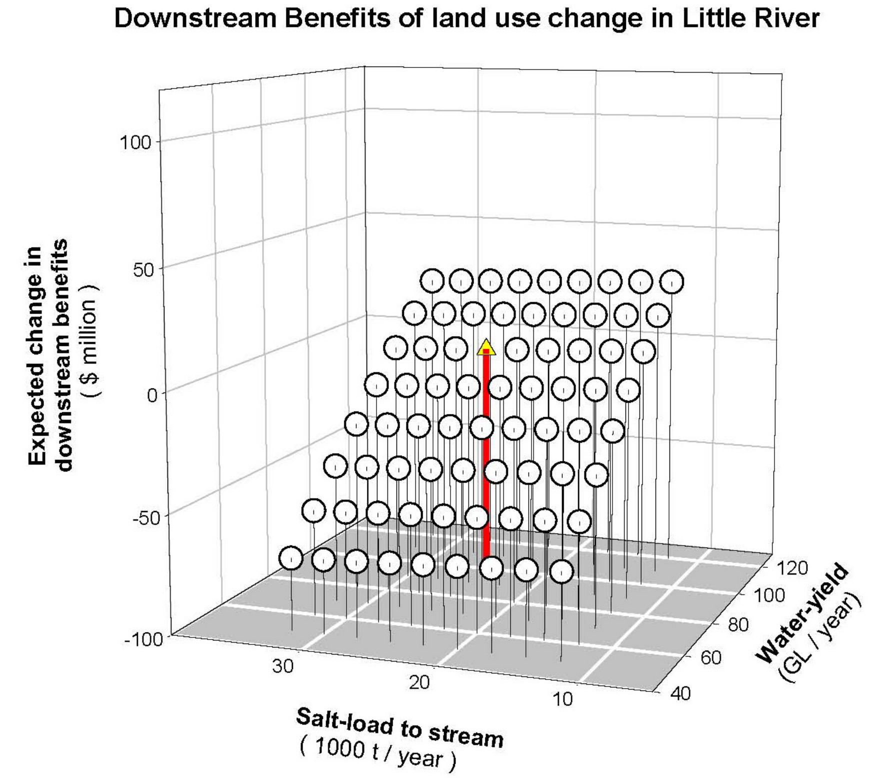

Figure 2. Downstream benefits based on changes in water-yield and salt-load from Little River, with current levels at 100 GL and 25,000 t. Assumes permanent water entitlements are valued at **$1.2 million / GL**.

3.2 Data for computing minimum-cost upstream land use changes to meet catchment targets of river water-yield (W) and salt-load (S).

Five classes of groundwater salinity are identified by Evans *et al.* (2004) in the Little River catchment, ranging from low (512 - 999 EC) to high (2500 – 2999 EC), along with membership of each of the 80 subcatchments in these classes. For each of the five classes of sub-catchments aggregate areas of each of the five current land uses are given for each of eight general soil types, or land management units (Table 2). These values are used as resource constraints in the 'farm-level' stages of the analysis in place of the single-subcatchment constraints in Nordblom *et al.* (2006).

Across Little River catchment, mean annual rainfall differs from place to place with the lowest being 580 mm and the highest 688 mm, due to differences in relief and location with respect to isohyet gradients. While year-to-year variations are wide, this is ignored in the present analysis; we focus only on differences in long-term equilibrium values.

The theoretical envelope for feasible water and salt yields was calculated according to methods described in Nordblom *et al.* (2004).

Table 2. Current land use areas, by land management unit (LMU) with productivity and drainage factors, in five groundwater salinity classes of sub-catchments, Little River, NSW. Source: compiled by authors

	Soil types of LMUs:	**Litho-sols**	**Red Chromo-sols**	**Poorer Red Chromo-sols**	**Red Sodo-sols**	**Shallow Red Chromo-sols**	**Siliceous Sands over rock**	**Yellow Sodosols (granitic)**	**Yellow Sodosols (other) & Yellow Chromo-sols**	
	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**	
	Drainage fraction (**Df**):	**0.15**	**0.25**	**0.5**	**0.5**	**0.2**	**0.3**	**0.5**	**0.1**	
Groundwater salinity class	**Current land use**[A]	area (ha)	area (ha)	area (ha)	area (ha)	area (ha)	area (ha)	area (ha)	area (ha)	Totals (ha)
Class 1 Sub-catchments 512 - 999 EC	**CR**	0	1135	119	472	21	530	577	1655	4509
	NP	1235	27	253	20	14	3945	782	33	6311
	NB	317	2334	1409	1554	410	13536	5879	3504	28942
	SP	0	439	4	62	6	218	212	1042	1984
	FN	1985	46	2535	990	3314	1080	133	175	10258
	Class 1 total (ha)	**3537**	**3982**	**4319**	**3098**	**3765**	**19308**	**7584**	**6410**	**52003**
Class 2 Sub-catchments 1000-1499 EC	**CR**	1	4888	725	213	356	94	75	3958	10311
	NP	1766	85	41	0	48	4075	404	83	6503
	NB	771	8582	5459	689	1961	7008	2642	5149	32262
	SP	0	2116	778	234	176	81	51	2244	5681
	FN	555	11	303	232	619	584	40	25	2368
	Class 2 total (ha)	**3094**	**15681**	**7306**	**1369**	**3161**	**11844**	**3212**	**11459**	**57126**
Class 3 Sub-catchments 1500-1999 EC	**CR**	11	5516	964	1053	304	272	69	3457	11645
	NP	0	92	79	7	59	0	0	53	292
	NB	335	6607	2899	2108	1397	1643	348	4847	20183
	SP	1	2428	289	440	197	34	18	1344	4751
	FN	1640	214	1761	1059	1660	383	30	898	7644
	Class 3 total (ha)	**1986**	**14856**	**5992**	**4667**	**3618**	**2332**	**464**	**10600**	**44515**
Class 4 Sub-catchments 2000-2499 EC	**CR**	0	3634	775	334	237	179	94	1395	6649
	NP	119	89	79	3	60	332	115	68	864
	NB	255	5495	3701	1072	798	2392	636	3334	17683
	SP	0	1423	428	112	91	18	66	799	2937
	FN	1736	1006	3600	662	878	9	5	2144	10040
	Class 4 total (ha)	**2110**	**11647**	**8583**	**2182**	**2065**	**2929**	**916**	**7740**	**38172**
Class 5 Sub-catchments 2500-2999 EC	**CR**	0	634	0	0	92	0	0	127	853
	NP	0	33	0	0	0	0	0	0	33
	NB	0	964	152	0	84	52	0	274	1526
	SP	0	247	0	0	7	0	0	58	312
	FN	0	3	1	0	0	0	0	2	6
	Class 5 total (ha)	**0**	**1880**	**153**	**0**	**183**	**52**	**0**	**462**	**2730**
Little River Totals (ha)		**10727**	**48046**	**26355**	**11316**	**12791**	**36465**	**12176**	**36671**	**194547**

[A] Where: **CR** = Cropping, continuous or rotation; **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 plantations

Table 3. Land use budgets assumed for LMU 2 in Little River. Transitioning from one land use to another involves a 'start-up cost' in year 1. Sales and DSE offtakes are adjusted downward for other LMUs according to productivity indexes given in Table 2

Continued Current* Activity:	Start-up cost $/ha	Recurrent cost $/ha/year	Mean sales $/ha/year	DSE** offtake/ha
CR	0	200	450	3
NP	0	20	0	2
NB	0	50	0	5
SP	0	80	0	10
FN	0	10	0	1
FP	0	10	0	1
Land Use Transitions				
CR-NP	20	20	0	2
CR-NB	40	50	0	5
CR-SP	150	80	0	10
CR-FP	1200	10	0	1
NP-NB	40	50	0	5
NP-FP	1200	10	0	1
NB-NP	20	20	0	2
NB-SP	150	80	0	10
NB-FP	1200	10	0	1
SP-NP	20	20	0	2
SP-NB	40	50	0	5
SP-FP	1200	10	0	1
FN-NP	20	20	0	2

* see Table 2 for definition of land use codes. FP = new forest plantation

** Dry Sheep Equivalent (grazing value) assumed: $25

Source: compiled by authors

4. Results

The widest ranges of water-yield and salt-load targets, within each of the groundwater salinity land classes, were sampled as constraints for the farm-level model. The NPVs of all feasible solutions given these targets provide the basis for an aggregate catchment-level analysis (Figure 3), again maximising aggregate NPV for each of a wide range of target future water-yield and salt-load levels. Results of this catchment-level model are given in Table 4 and plotted in Figure 4. The latter helps understand the shape of the cost surface, Figure 5, which is obtained by finding the difference between the NPV of the most profitable land use configuration yielding the current mean annual water and salt flows and the NPV of each of the other technically feasible targets.

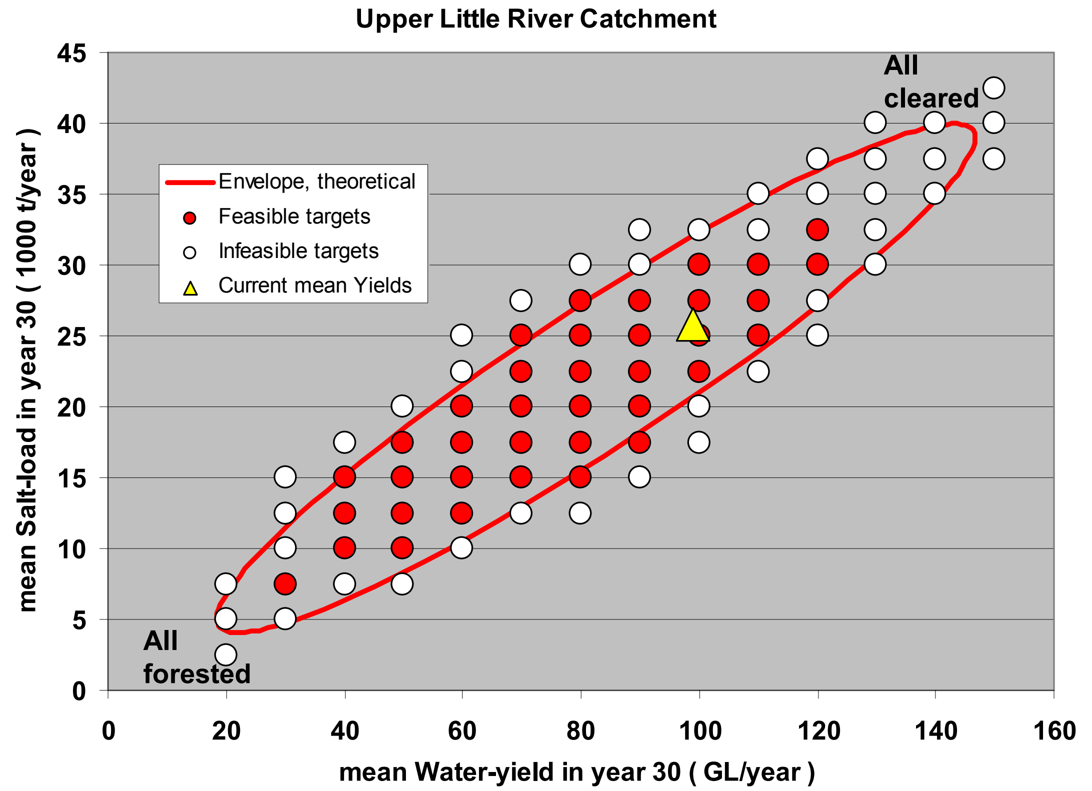

Figure 3. Identification of technically feasible future Water-yield and Salt-load targets in the upper Little River catchment. All sample dot points were analysed with the catchment-level model. The dark dots represent combinations found to have feasible solutions in the form of NPV-maximising land use change

Table 4. Maximum aggregate 30-year Net Present Value of farming and grazing in Little River, constrained to future water-yield and salt-load targets (**bold type**). (Table values are $ millions)

			Water-yield (GL / year)									
	Macquarie River	→	1030	1040	1050	1060	1070	1080	1090	1100	1110	1120
	↓	**Little River**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**	**110**	**120**
Salt-load (1000 t / year)	207.5	**32.5**										109.7
	205.0	**30.0**								110.1	124.8	107.5
	202.5	**27.5**						30.5	113.8	130.6	126.5	
	200.0	**25.0**					27.4	105.3	131.5	**131.2**	106.6	
	197.5	**22.5**					88.6	125.4	131.5	117.2		
	195.0	**20.0**				58	109.1	124.7	112.5			
	192.5	**17.5**			14.5	80.4	106.8	101.6	42.6			
	190.0	**15.0**		-72.1	38.9	78.9	80.5	29.6				
	187.5	**12.5**		-18.4	35.6	47						
	185.0	**10.0**		-19.7	-7.3							
	182.5	**7.5**	-93.5									

Note: Calculated mean current annual Little River water-yield is 99 GL with a salt-load of 25.9 t. This is represented most closely by the cell with 100 GL water and 25 t salt, corresponding to the 1100 GL water and 200 t salt levels of the Macquarie River at Dubbo.
Source: compiled by authors

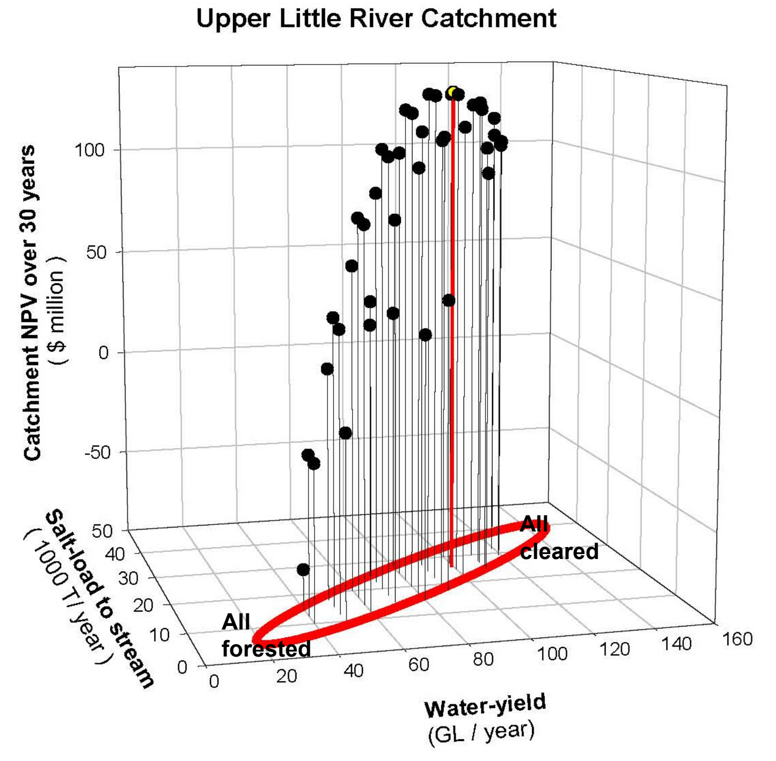

Figure 4. NPVs of land use configurations delivering different mean water-yield / salt-lc targets from Little River cachment, NSW. Light dot indicates the highest-NPV land use yielding the current mean water-yield (100 GL) and salt-load (25,000 tons)

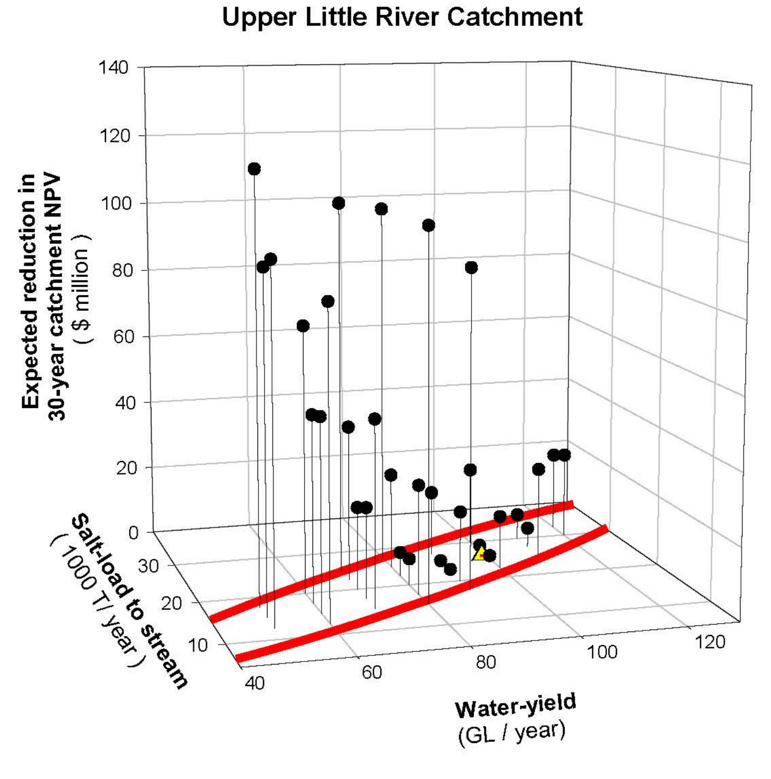

Figure 5. Costs of land use changes to obtain target water-yield and salt loads. Calculated as the difference between the NPV of the most profitable land use configuration yielding the current mean annual water and salt flows and the NPV of each of the other technically feasible targets

Given the information on downstream benefits (Figure 2) and upstream costs of land use changes for attaining water-yield and salt load targets in Little River (Figure 5) it is now possible to define the range of targets for which there are mutual benefits. That is, where downstream benefits exceed upstream costs (Table 5).

Because downstream benefits exceeded upstream costs in so few cases, only where annual mean water yields were increased by 10 or 20 GL (Table 5.a), two other water price scenarios were examined: one with water value increased from $1.2 to $1.5 million per GL (Table 5.b) and one increased to $2 million per GL (Table 5.c). Of course these made water-yield-increasing land use changes (toward annual pastures or cropping) more attractive and water-using changes (forest options) far less attractive.

Table 5.a Downstream benefits of altered mean future water-yields and salt-loads in the Macquarie River minus the minimum costs of land use changes to bring these about from the tributary catchment of Little River. Assumes permanent water entitlements are valued at **$1.2 million / GL**. (Table values are $ millions)

			Water-yield (GL / year)							
	Macquarie River	→	1050	1060	1070	1080	1090	1100	1110	1120
Salt-load (1000 t / year)	↓	**Little River**	**50**	**60**	**70**	**80**	**90**	**100**	**110**	**120**
	207.5	**32.5**								**0.7**
	205.0	**30.0**						-22.4	**4.6**	-0.8
	202.5	**27.5**				-127.1	-30.8	-1.2	**7.0**	
	200.0	**25.0**			-143.1	-51.6	-12.4	**0.0**	-12.3	
	197.5	**22.5**			-81.2	-30.9	-11.7	-13.3		
	195.0	**20.0**		-60.0	-60.0	-30.9	-30.0			
	192.5	**17.5**	-182.1	-61.6	-61.6	-53.3	-99.2			
	190.0	**15.0**	-157.0	-87.2	-87.2	-124.6				
	187.5	**12.5**	-159.6	-125.0						

Table 5.b As Table 5.a, but with permanent water entitlements valued at **$1.5 million / GL**. (Table values are $ millions)

			Water-yield (GL / year)							
	Macquarie River	→	1050	1060	1070	1080	1090	1100	1110	1120
Salt-load (1000 t / year)	↓	**Little River**	**50**	**60**	**70**	**80**	**90**	**100**	**110**	**120**
	207.5	**32.5**								**6.7**
	205.0	**30.0**						-22.4	**7.6**	**5.2**
	202.5	**27.5**				-133.1	-33.8	-1.2	**10.0**	
	200.0	**25.0**			-152.1	-57.6	-15.4	**0.0**	-9.3	
	197.5	**22.5**			-90.2	-36.9	-14.7	-13.3		
	195.0	**20.0**		-69.0	-69.0	-36.9	-33.0			
	192.5	**17.5**	-197.1	-70.6	-70.6	-59.3	-102.2			
	190.0	**15.0**	-172.0	-96.2	-96.2	-130.6				
	187.5	**12.5**	-174.6	-137.0						

Table 5.c As Table 5.a, but with permanent water entitlements valued at **$2.0 million / GL**. (Table values are $ millions)

		Water-yield (GL / year)								
	Macquarie River	→	1050	1060	1070	1080	1090	1100	1110	1120
	↓	**Little River**	**50**	**60**	**70**	**80**	**90**	**100**	**110**	**120**
Salt-load (1000 t / year)	207.5	**32.5**								**16.7**
	205.0	**30.0**						-22.4	**12.6**	**15.2**
	202.5	**27.5**				-143.1	-38.8	-1.2	**15.0**	
	200.0	**25.0**			-167.1	-67.6	-20.4	**0.0**	-4.3	
	197.5	**22.5**			-105.2	-46.9	-19.7	-13.3		
	195.0	**20.0**		-84.0	-84.0	-46.9	-38.0			
	192.5	**17.5**	-222.1	-85.6	-85.6	-69.3	-107.2			
	190.0	**15.0**	-197.0	-111.2	-111.2	-140.6				
	187.5	**12.5**	-199.6	-157.0						

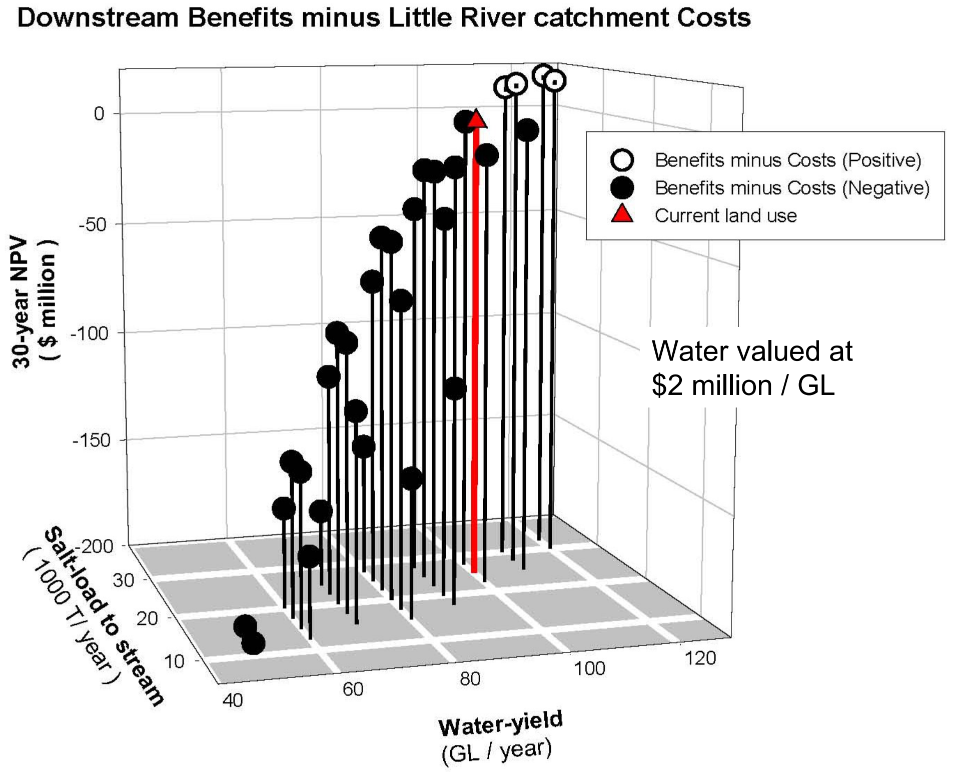

Figure 6. Downstream benefits minus upstream costs

5. Discussion and Conclusions

The Little River catchment hosts dryland farming and grazing enterprises over the majority of its area on land cleared of trees in the process of European settlement (Herron *et al.*, 2003). This, unintentionally lead to increases in water-yield, contributing to the downstream water supply upon which a considerable irrigation industry has developed. Water supplied by the Macquarie river, to which Little River is a tributary, has grown in value… now being in the range of $1.2 to $1.5 million per GL in permanent trades. This value reflects scarcity due to drought. Other northern NSW rivers have water values above $3 million per GL.

While Little River is a water source, it remains a dryland area… long-term annual rainfall differs from place to place with the lowest being 580 mm and the highest 688 mm. This is at the low end of the rainfall scale for forestry activities. Our model assumes any new forest planted would produce no income (i.e., neither agro-forestry nor carbon sequestration benefits), but use lots of water. Such new forest may replace any of the other current land uses (volunteer or native pastures, improved sown pastures or crop/pasture rotations). On the other hand clearing any remaining areas of forest would allow use only as poor pasture, which would serve also as a watershed. This set of constrictive assumptions make forestry particularly unattractive.

This is exemplified in Table 4 and Figures 4 and 5. Land use options that produce the least water yield involve new forest areas and lower NPV's (highest costs among the land use options). When we consider the costs imposed on downstream interests by reducing river volumes (Table 1 and Figures 1 and 2), the affects of introducing new forests in Little River are dramatically negative. The combined results of within catchment costs of land use change to forest and downstream losses accompanying the reductions in water yield are seen in Figure 6 and Tables 5.a, 5.b, and 5.c.

Reductions in salt-load from Little River appear to give only minor benefits, which are vastly overwhelmed first by the accompanying reductions in valuable water yields and, second, the large upstream costs of attainment.

Where the introduction of forest areas is motivated by habitat provision, agro-forestry and/or carbon sequestration benefits, we need to be aware of possible, even very likely, consequences for reductions in downstream water supplies.

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