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Farm and catchment scale effects of managing dryland salinity with pastoral and woody perennials.

John Finlayson[1,2], Andrew Bathgate[3], Ziaul Hoque[1], Tom Nordblom[4], Tivi Theiveyanathan[5], Russell Crosbie[6], David Mitchell[7].

[1] New South Wales Department of Primary Industry, 161 Kite St, Orange, NSW 2800. john.finlayson@dpi.nsw.gov.au, ziaul.hoque@dpi.nsw.gov.au
[2] Corresponding author.
[3] 41 Trebor Rd, Cuthbert, WA 6330. abathgate@optusnet.com.au
[4] New South Wales Department of Primary Industry, Wagga Wagga Agricultural Institute, Pine Gully Rd, Wagga Wagga, NSW 2650. tom.nordblom@dpi.nsw.gov.au.
[5] Building 1, Wilf Crane Crescent, Yarralumla, ACT 2604. tivi.theiveyanathan@ensisjv.com
[6] CSIRO Adelaide. russell.crosbie@csiro.au
[7] New South Wales Department of Primary Industries. Orange Agricultural Institute, Forest Road, Orange, NSW 2800. david.mitchell@dpi.nsw.gov.au

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Abstract:
Dry land salinisation is a significant cause of land and water degradation in Australia. Changing land use from annual to perennial crops has been widely proposed as a means to reduce land degradation and increase the productivity of saline land. However, in many areas annual crops are financially more attractive than perennial crops. Increases in perennial crops might also reduce local stream flows with adverse effects on in-stream values. As such salinity control is likely to involve significant tradeoffs between public and private costs and benefits. This paper considers the impact of planting differing areas of pastoral and woody perennials on farm profitability (P), and water (W) and salt (S) exports from the Little River catchment in New South Wales (NSW), Australia. The analysis uses two linear programming (LP) models. The first model represents a mixed crop and sheep system and the outputs of this model are integrated to provide inputs to a second catchment level model. The structure of the LP models is described and an analysis of the potential for perennials to assist in salinity management is presented. The implications of the analysis for farm systems and catchment scale changes in land use are considered.

The study highlighted the importance of targeting management decisions to individual sub-catchments and of using relatively detailed farm level models as part of a catchment level study. The potential for perennials to contribute to profitable and robust farm systems and to reduce degradation to land from salt scalds and to streams arising with elevated discharge and wash-off of salt is demonstrated.

Keywords: Bio-economic modelling, linear programming, farm systems, catchments, dryland salinity.

1. Introduction.

The clearance of native vegetation has played a key role in establishing much of the grazing and cropping land in Australia. However, the replacement of deep rooted native species with shallower rooting crop and pasture species significantly affects the cycling of water in atmosphere, plant and soil, groundwater, and stream systems. Because evapo-transpiration (ET) tends to be lower for agricultural land than for native vegetation, conventional farming practices have contributed to increased runoff to streams and increases in discharges of salt and water to the soil surface and streams (Williamson). In NSW the amount of land affected by salinisation, 1,800 km^2, (NLWRA, 2001) is relatively small compared with other Australian states but issues relating to stream quality and flows are of particular concern (Beale et al., 2000). Elevated discharges of salt and water from groundwater have also been associated with increased areas of water logging and salinisation, reductions in the productivity and sustainability of agricultural land, and damage to infrastructure and the environment (Farrington and Salama, 1996; Greiner, 1997; Holmes and Sinclair, 1986; Madden et al., 2000; Oliver et al., 1996; Stolte et al., 1997)

Changes in vegetative cover often result in relatively rapid changes in runoff, however, it can take many years before changes in recharge reach equilibrium with consequent discharges of salt and water from groundwater (Farley et al., 2005). The time required for a groundwater flow system (GFS) to reach equilibrium with long term changes in recharge depends on various hydro-geological factors and in particular the size of the system (Coram et al., 2000). Coram *et al.* define local flow systems as contained in a topographical catchment and being less than 5 km in length. The time needed for equilibration in local GFS's is generally in the order of 10-30 years. This compares with a slower equilibration (50-100 years) in intermediate GFS's which are 10-50 km in length. Coram *et al.* suggest regional GFS's, which are > 50 km across and comprise more than one topographical catchment can take hundreds of years for equilibration to occur.

The dynamics of these effects imply land clearance can produce short term increases in relatively fresh runoff to streams with proportionately smaller increases in salt discharges to streams. This suggests an initial increase in stream flows with higher salt loads, but lower salt concentrations in stream water. However, as recharge and discharge equilibrate, stream flows are likely to continue to increase with discharges of ground water, and this may be accompanied by proportionally larger increases in salt exports and increases in salt concentrations in stream water. At equilibrium stream flows are likely to involve higher water and salt exports than the pre-clearance situation. However, whether salt concentrations in streams are higher or lower at equilibrium relative to a pre land clearance situation depends on the relative proportion of runoff versus recharge before versus after land clearance and the magnitude and location of salt stores in the landscape (Herron et al., 2003).

Alternately, if cleared land is planted to perennials there is a tendency for the above sequence of changes in relative and absolute flows of water and salt to be reversed. That is, an initial decline in fresh runoff is accompanied by a relatively smaller reduction in water and salt discharges and as a consequence salt concentrations in streams increase. Other things being equal this is likely to be followed by a gradual decline in discharges from groundwater which reduces salt loads and salt concentrations in streams.

An additional point is that equilibrium is likely take longer in situations of reafforestation than for deforestation. In part this is due to the time required for perennial crops to mature. More significantly agricultural practices frequently disrupt the physical, biological, and geochemical attributes of catchments and vegetative cover is only one of these attributes (Walker et al., 2001). Changes such as soil loss, increased leakiness in areas of recharge, and increased clogging of soils in areas of discharge may take significantly longer to reverse than the establishment of alternate vegetation on a site (Fitzpatrick et al., 2000). Changes in catchment function also have implications for the amount of water that follows different pathways through the environment and hence the relative concentration of salt in waterways before versus after changes in land use.

In NSW efforts to control salinity have tended to focus on recharge management[8]. This reflects local concerns about stream and river systems, the high expense of engineering solutions, and the relatively small proportion of salt affected land compared with other Australian states. However, in NSW as in other parts of Australia, efforts to manage dry-land salinity have met with variable success. In part this is because the long time frames for adjustment as stream salinities and saline land can continue to increase for decades after a land use change. Quiggin (1987) has suggested a lack of site specific understanding, a property rights situation where ground water systems are open access resources, and short term decisions associated with high discount rates have contributed to salinity being a difficult issue to manage.

Another difficulty has been the identification of profitable crops which are suitable for recharge management (Pannell, 2001). This is partly because low and medium rainfall areas are significant for agriculture, and for land and water salinisation, but in these regions the growth rates of high ET crops (such as woody perennials) tend to be low. As such woody perennials can be effective at reducing recharge on a per hectare basis, but if they involve high opportunity costs, efforts to control salinity are likely to be expensive and have limited uptake. The absence of skills and infrastructure to plant, manage and harvest tree crops has also been an impediment to adoption. As such questions have been asked whether increased areas of intermediate ET crops (for example perennial pastures such as Phalaris or Lucerne) might be better for salinity management than woody perennials.

Contributing to the complexity of salinity management - recharge is not a spatially uniform process (Williams et al., 2001). Within a groundwater flow system there are variations in soil permeability, slope and land cover. There are also variations in the salinity of different groundwater systems and in the location of sub-surface salt stores. This implies a particular salt and water export target can be achieved with a range of different land use configurations. Given there are differences in yields and profitability's of crops grown on different soils the farm profitability associated with these different land use configurations is also likely to vary. Another complicating factor is that conventional arable crops tend to be more sensitive to salinity than perennial crops and in extreme cases salinity can cause land to become unsuitable for arable crop production (Farrington and Salama, 1996; Stolte et al., 1997).

The bio-economic interactions between farm enterprises and the hydrological implications of alternate patterns of land use are particularly complex in mixed crop and sheep systems as there are close interactions between enterprises. Such interactions become even more difficult to interpret and understand when considered at catchment scale. That is the potential range of farm systems (and their underlying resources) and hydrological characteristics to be considered (e.g. ground water salinities, response times to changes in land use etc) increases. Further, these issues involve assets (land and streams) which are of considerable value, whose management

[8] Approaches to salinity management are often classed as corresponding to either recharge or discharge management. Typically recharge management is associated with mitigating or avoiding salinity by reducing net recharge of groundwater. The planting of trees with high evapo-transpiration demands is a commonly cited example. In contrast discharge management tends to involve adaptive strategies. Planting crops which are tolerant to saline soils or implementing engineering solutions to reduce salt entering streams are examples of this approach. Another, albeit less common approach to salinity management involves the remediation of saline soils.

is complex and the potential to make decisions with adverse affects on their productivity and condition is significant.

Given the significance of low and medium rainfall agriculture, and the sensitivity of downstream systems to salinisation, the identification of profitable on-farm salinity management options is an important task with relevance for downstream agricultural, urban, industrial and environmental use of water. This study provides an assessment of the relative ability of pastoral and woody perennials to contribute to the profitability of farm systems and to salinity management. The sensitivity of factors which affect the ability of perennial crops to achieve farm and catchment level goals is assessed.

2. Previous studies.

A number of biophysical modelling studies have considered the influence of land use change on catchment scale water balances. Such studies vary considerably in their temporal and spatial scope (Beverly, 2004; Tuteja et al., 2004; Vertessy et al., 1996; Walker et al., 2002). The approaches vary from detailed spatially explicit models (Abbott et al., 1986; Dawes and Hatton, 1993; Ruprecht and Sivapalan, 1991); single dimension models embedded in geographic information systems (Littleboy et al., 1992; McCown et al., 1996); and relatively simple, albeit, less data demanding approaches (Grayson and Blöschl, 2000). Even in relatively intensively studied catchments the utility of simple approaches is sometimes justified by a lack of data to parameterise more complex models.

It is possible to link economic information to biophysical models such as those mentioned above. This allows costs and benefits of a range of alternate scenarios to be compared. An example of such an approach is presented by Bell and Heany (2001) who developed an integrated economic-hydrological model of water and salt flows in the Murray-Darling basin. This model represented large scale changes in land use and water extraction for an area of approximately 1 million km^2. In another economic study Letcher et al. (2004) considered the Namoi, one of the 14 major catchments in the Murray-Darling basin. The Namoi model focused on variations in water quantity with changes in allocation rules but did not consider water quality or in-stream salt loads.

Although the linking of economic and biophysical models can have significant utility a shortcoming of the above approaches is they can be difficult to optimise (Nordblom et al., 2006). The application of optimisation techniques can be particularly useful as these provide a powerful method to draw inferences and quantify tradeoffs in farm and environmental systems. Nordblom et al. present a linked economic–hydrologic optimisation model which predicts changes in water and salt exports with changes in land use. In this model the yields of a range of crops are estimated for different soils and soils are defined in terms of their permeability and the salinity of groundwater they overlay. The model has value, therefore, for estimating least cost strategies to achieve alternate water and salt exports to streams.

A desired outcome of this study was to better understand the relationships which determine the condition of land and streams and hence improve the ability to manage these resources effectively. The current study is similar in scope to Nordblom et al. in that water and salt exports and variations in crops yields are modelled for a range of soils on a mixed crop and sheep farm in the Central West of New South Wales, Australia. As in Nordblom et al. the current study uses optimisation techniques. However, the current study considers an entire catchment and consequently the hydrological characteristics to be considered (e.g. ground water salinities, response times to changes in land use) are greater than those represented by Nordblom et al. The farm systems in this paper are also modelled in greater detail.

3. Methods.

The study area is the Little River catchment in the Central West of NSW (32.75°S 148.65°E). The catchment has an area of approximately 2,000 km^2 and an annual mean rainfall of approximately 620 millimetres (mm). Little River contributes an annual mean of 96,200 mega litres (ML) of water and a salt load of 36,580 tonnes (T) to the MacQuarie River (Geoff Beale, NSW DNR, pers comm). The catchment is comprised of 80 sub-catchments (or local scale GFS's) each of which exhibits variations in soils and groundwater salt concentrations. Various data were collected for each sub-catchment including mean rainfall, soil types, current land use, groundwater salinity (GWS) and hydrological response rate. The predominant land use involves sheep grazing unimproved pasture with smaller areas devoted to arable cropping and native forests and woodland (see Table 1 and Figure 1). Detailed descriptions of the catchment can be found in Evans et al. (2004) and Nordblom et al. (2006).

Table 1. Brief description of the Little River Catchment

Area	≈ 2,000 km^2
Rainfall	≈ 620 mm (560-720 mm)
Stream flow	≈ 96,200 ML / year ≈ 50 mm/ha
Variable soils	(see Table 2)

Predominant farm systems are mixed cropping and sheep

Crop yields:

- Wheat (1.2 – 4.0 T/ha)
- Lucerne (winter 1.3 - 2.7, summer 2.4 - 5.4 T/ha)
- Phalaris (3.0 – 8.2 T/ha)

Sheep systems:

- Meat and wool sales
- Replacements bought in
- Stocking rates ≈ 8.5 dry stock equivalents/ha

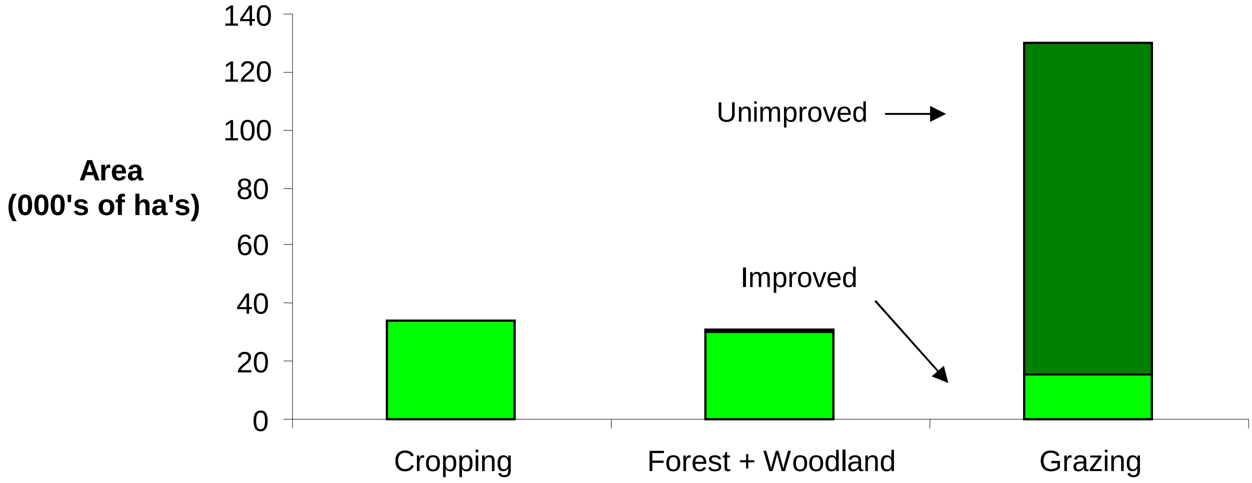

Figure 1. Current land use.

As part of this study cluster analysis techniques were used to reduce the 80 sub-catchments to a more manageable number which could be explicitly modelled. The statistical package SPSS (Version 12 for Windows) was used to perform a two stage clustering. The areas associated with the various soil types and GWS were normalised to a value of 1 and equal weights given to soil composition and ground water salinity. Ten clusters were identified and the characteristics of these are summarised in Table 2.

Table 2. Areas of different soil types (ha) and ground water salinities (ppm[9]) associated with sub catchment clusters.

Cluster	Soil 1	Soil 2	Soil 3	Soil 4	Soil 5	Soil 6	Soil 7	Soil 8	GWS
1	2,637	156	3,884	4,338	5,301	0	0	2,550	768
2	1,019	919	3,018	4,591	2,018	1,210	908	2,055	1,106
3	909	2,431	5,937	1,160	711	258	13	6,061	1,191
4	970	3,570	6,397	825	133	863	185	2,455	1,588
5	711	15,716	2,396	0	1,085	4,868	757	13,120	1,182
6	32	2,787	0	0	0	561	49	3,790	672
7	1,835	3,116	2,008	416	259	16,611	6,061	2,247	755
8	102	12,212	2,307	0	2,519	1,134	519	2,496	1,262
9	67	6,797	445	0	660	227	11	1,853	1,686
10	2,446	485	0	9	121	10,760	3,704	215	705
Total	10,729	48,189	26,392	11,339	12,809	36,492	12,208	36,841	n.a.

[9] Parts per million

The results of the cluster analysis were used to scale the area of soil types in proportion to their presence in the identified clusters. The level of groundwater salinity, average rainfall, the hydrological parameters (a3 and a4, see equation 7), and the initial land cover of the modelled sub-catchments were estimated in relation to the respective clusters.

The choice of discriminating variables to include in the clustering analysis was somewhat subjective as any of the variables that were scaled in terms of the clusters could have been chosen. However, the selected variables were considered appropriate as the explanatory power of additional variables can be compromised if there is correlation between the discriminating variables. For example soil type and land use are likely to be correlated so these variables are unlikely to be equally useful in identifying clusters. The sensitivity of the clusters was informally tested by running the sub-catchment models with differing clustering variables. The model results appeared relatively insensitive to the inclusion of these other variables.

The farm model used in this study is based on MIDAS which is a well known whole farm model of sheep and cropping systems (Abadi and Pannell, 1998; Kingwell and Pannell, 1987). The MIDAS model has previously been calibrated to reflect the soil classification used in this study as well as crop rotations, and prices and productivities appropriate to the Little River catchment (Bathgate, pers comm). Seventy crop rotations, each of which is modelled on 8 soil types, are explicitly represented in the model. Activities such as sheep grazing and husbandry, machinery operations, chemical and pesticide use and finance are accounted for. Altogether the farm LP matrix includes approximately 2,000 activities and 860 constraints. As such the model provides a detailed representation of farm systems common to the study area and is well suited to the current study.

As part of this study various modules were added to the MIDAS farm model. This was necessary to represent processes, not explicitly modelled in MIDAS, but of interest to this study. These include: a simple water and salt transport model (see section 3.1); inter-temporal transitional activities to allow for changes in land use capability (see section 3.2); and activities to represent the presence and management of woody and herbaceous perennials.

3.1. ***A simple model of water and salt transport.***

As part of this study a salt and water mass balance model was adapted from Zhang et al. (2001), Bell and Heaney (2001), Stirzaker et al. (2002) and Nordblom et al. (2005b). An important simplifying assumption of the resulting model is that long term stream flow equals rainfall (P, mm/ha) minus evapo-transpiration (ET, mm/ha). As such the model is consistent with Coram et al's. (2000) definition of local groundwater flow systems. Other assumptions are: excess water (E, mm/ha), that is rainfall minus ET, is distributed between runoff which enters streams in the same year as incident rainfall (Ro, mm/ha), and recharge or deep drainage (Re, mm/ha). It is assumed all recharge is eventually discharged to the surface and the rate of discharge conforms to a lagged function of recharge. This implies discharge may not occur until many years after the associated recharge event. The drainage fraction (Df) or proportion of water going to recharge versus runoff is modelled as a function of soil type and in this study Df varies between 0.1 on heavy impermeable soils and 0.5 on light sandy soils (see Table 3).

Table 3. Soil types.

Soil	General description[10]	Df[11]
1	Lithosols	0.15
2	Red chromosols - better soils	0.25
3	Red chromosols – poorer soils	0.20
4	Red sodosols	0.20
5	Red chromosols – shallow	0.10
6	Siliceous sands, shallow siliceous sands (over granite and sandstone)	0.75
7	Yellow sodosols – granitic	0.10
8	Yellow sodosols, Yellow chromosols	0.10

The above assumptions are made explicit as follows:

$$E = P - ET \quad (1)$$

$$Ro = (1-Df) * E \quad (2)$$

$$Re = Df * E \quad (3)$$

For most crops in the model ET is modelled as a function of precipitation, and crop type (c) where crop type is specified in terms of low or high ET (Zhang *et al.* 2001):

$$ET_c = P * (1+a1_c*a2_c/P) / (1+a1_c*a2_c/P+P/a2_c) \quad (4)$$

The parameters a1 and a2 were estimated to form upper and lower bounds that enclosed a sub-set of Zhang et al's data. The selection criterion applied to Zhang *et al.'s* data was it referred to dry land systems in low and intermediate rainfall areas in temperate Australia (Iain Hume, NSW DPI, pers comm). Typically ET from annual arable crops equals the lower ET boundary while ET from perennials are higher but must be less than or equal to the upper boundary. This assignment reflects a crops similarity (FS) with respect to the ET of a mature native forest. In this study, wheat has a similarity or FS of 0 and consequently an ET equal to the lower ET bound. This compares with established Lucerne which has a FS of 0.6 or an ET which is slightly higher than the midpoint between the upper and lower bounds (see Figure 2). The ET of a given crop is calculated as:

[10] Descriptions are taken from Soil Landscapes of Dubbo (Murphy and Lawrie, 1998) and the soil sequence broadly corresponds to the transition of soils from crest top to valley bottom.
[11] Source: Dr Iain Hume personal communication.

$$ET = ET_{low} + FS * (ET_{high} - ET_{low}) \quad (5)$$

As previously mentioned long term average rainfall at Little River is approximately 620mm per year. This suggests a low ET crop will produce approximately 75mm of excess water versus 6mm for a mature forest. This relative difference is large and consequently land use has significant implications for stream flows and the amount of rainfall which is returned to the atmosphere.

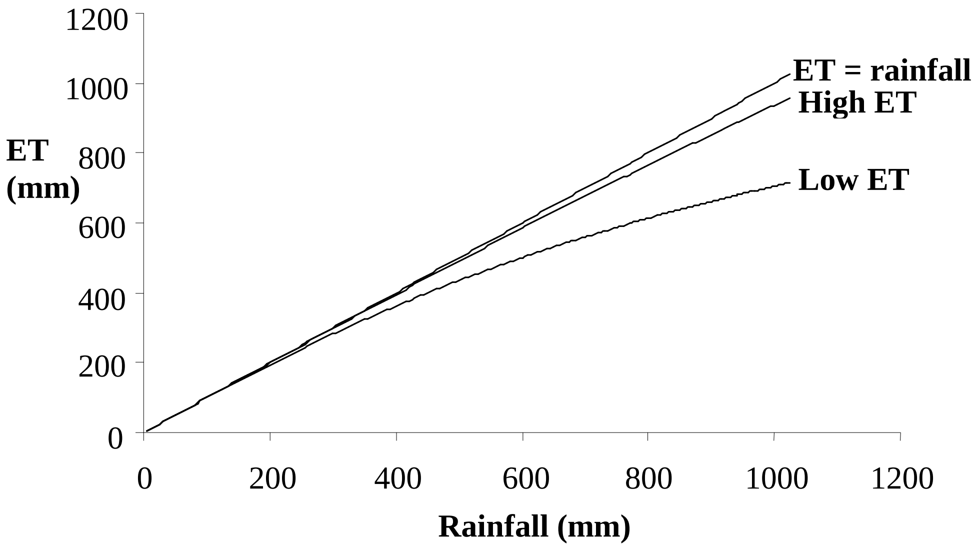

Figure 2. Evapo-transpiration versus rainfall (mm)

Table 3: ET parameters[12]

Parameter	Low	High
a1	1	4
a2	1400	2820

The approach taken to model water cycling in new plantings of exotic forest differs somewhat from that outlined for other crops. Sugar Gum (*Eucalyptus cladocalyx*) was selected as a suitable species for commercial plantings in low to intermediate rainfall areas such as the study area (Nico Marcar, CSIRO Ensis, pers comm). Sugar Gum is a relatively slow growing but hardy tree which can be grown either in conventional blocks or in alley plantings. The growth and water use of sugar gum

[12] Source: Zhang et al (2001).

was estimated using the 3PG model (Landsberg and Waring, 1997) for each of the 8 modelled soil types and each year of a fifty year rotation. The specification of equations 4 and 5, and the use of the 3PG model, provided a straightforward method to estimate excess water for the crops represented in this study.

To account for time lags between changes in recharge and equilibrium with resulting changes in discharges of salt and water from groundwater, a logistic function (Evans *et al*. 2004) is used to model water discharge (D, mm/ha):

$$D_t = D_{t-1} + (Re_t - Re_{t-1}) * G_{t-1} \qquad (6)$$

$$G_t = 1 / (1 + e^{((a3 - t) / a4)}) \qquad (7)$$

where: t is the year; G is a lag function; and the parameters a3 and a4 determine the shape and speed of the lag function. To calculate stream flows (W, ML/year) the sum of runoff and discharge is scaled to reflect land area (A, ha), such that:

$$W_t = (Ro_t + D_t) * A / 100 \qquad (8)$$

The amount of salt reaching local streams (S, tonnes) is estimated as follows: water discharges to the surface are assumed to have the same salt concentration as groundwater (GWS, ppm); all salt discharged to the surface enters streams directly or is washed into streams with rainwater; and all salt in runoff enters waterways. The concentration of salt in rainwater (RWS, ppm) is assumed to be 5ppm (Iain Hume, pers comm).

$$S_t = (D_t * GWS + Ro_t * RWS) * A / 100 \qquad (9)$$

The model structure suggests the long term volume of stream water is a function of ET and hence crop type. That is the proportion of excess water which goes to runoff versus recharge, may affect the timing of water entering a stream, but the amount of water that ultimately enters the stream is primarily affected by the relative area of different crop types.

This contrasts with salt exports which are likely to vary depending on the path of water entering the stream. This occurs as the amount of salt in streams depends on the relative amount of runoff (salt in rainfall) versus recharge (salt in groundwater). This implies salt concentrations in streams can be altered by varying the crops which are planted on different soils. Further, targeted land use change, or the careful matching of crops to soils and sub-catchments, has the potential to modify salt flows to streams.

This is illustrated as follows: we assume a farmer has equal areas of two soil types, one that is relatively permeable (Df = 0.5) and one that is impermeable (Df = 0.1) (see equations 2 and 3). Some other assumptions are: two crops are available, a low ET crop (e.g. wheat, see equation 2) and a high ET crop (e.g. trees); and for cash flow or other reasons an equal area of each crop is planted. We also assume rainfall is 620 mm and excess water from trees and wheat, are 6 and 75 mm, respectively.

Because the relative area and water use of crops in this example are constant, the model implies regardless which soils these crops are planted on, the amount of excess water which eventually enters streams won't vary (see Figure 3). However, the amount of salt exported to streams may vary significantly depending on the soils the crops are planted on.

In our example if the permeable soil is planted to trees and the impermeable soil to wheat (scenario 1) the model suggests recharge will be less than 15% of excess water. This contrasts with scenario 2 where the permeable soil is planted entirely to wheat and the impermeable soil to trees in which case recharge amounts to approximately 45% of excess water. Because salt concentrations in rainwater (≈ 5 ppm), tend to be much less than in groundwater (≈ 670 – 1,690 ppm in the Little River catchment, see Table 2), discharge has a greater potential to deliver salt to streams than runoff. As such salt exports to streams are likely to be greater for scenario 2 than for scenario 1. This is particularly the case if low ET crops and permeable soils overlay groundwater with high levels of salinity. The presence of such variations has implications for the value of targeting land use change to particular soils and ground water salinities.

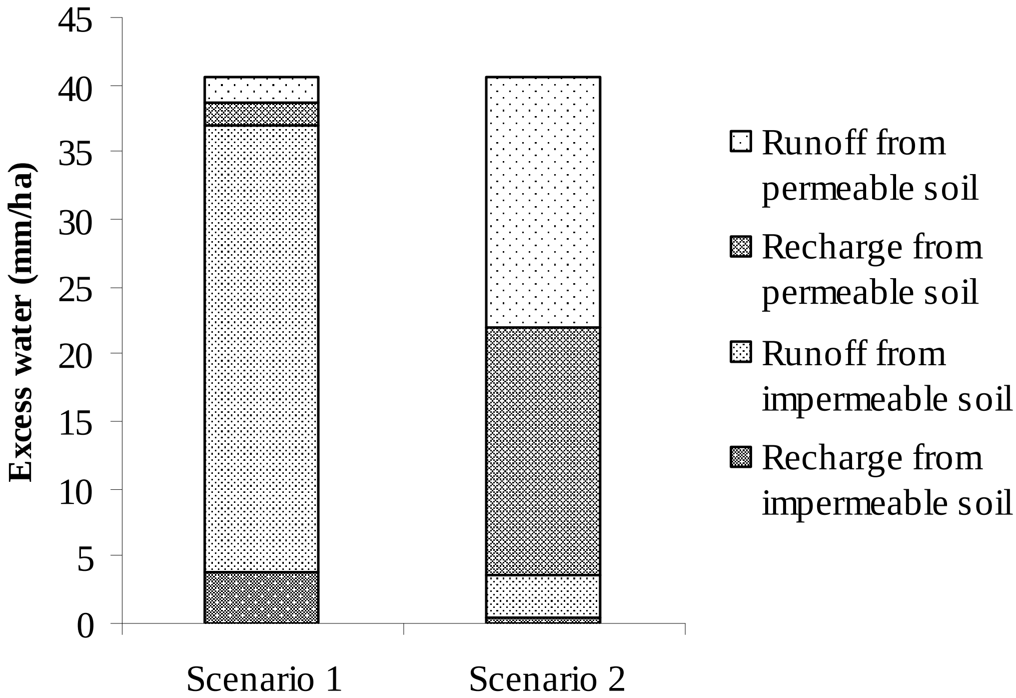

Figure 3. Excess water (mm/ha) from low and high ET crops on permeable and impermeable soils.

In this study crop water use is assumed to be constant between soil types. An implication of this assumption is that ET is primarily limited by rainfall. However, the location of crops in the landscape can have a significant influence both on ET and crop yield. This is relevant where water enters the root zone either by lateral or upward flow. In these situations plant available water and hence ET may be greater than that implied by the model. Discrepancies between actual and estimated ET are also likely to be greater for crops with a high potential ET and this may have implications for the “best” location to plant crops. Another complicating factor is that water which is near the soil surface is frequently highly saline. The ability of crops to tolerate saline water in their root zone is likely, therefore, to affect whether crop yields are positively or negatively affected in such areas.

As discussed above crop yields are assumed to vary with soils. However, with the exception of sugar gums variations in water use with changes in soils are not explicitly accounted for. It would be relatively straightforward to model variations in water use with changes in soils and consequently yields, however, it may be difficult to model yield changes that are due to variations in the depth of sub-surface water as these are likely to exhibit high levels of spatial and temporal variability.

It should also be mentioned there is considerable variability surrounding how much salt is delivered by runoff versus recharge. This is because runoff or lateral flow, which doesn’t interact with groundwater, still has the potential to mobilise large amounts of salt from at or near the soil surface and from salt scalds (Ray Evans, Salient Solutions, pers comm). The amount of salt transported by water flows at or near the surface will depend on the location of salt in the landscape and consequently the model may not accurately reflect variations in salt exports that are due to changes in runoff versus recharge.

The model has been calibrated against historical data from the Little River catchment and provides reasonable estimates of long term flows of salt and water (Iain Hume, pers comm). In spite of this it is unclear how well the model predicts changes in salt exports with changes in land use. An extremely large amount of time series data would need to be collected if the resolution with which variations in salt and water exports are modelled is to be improved. This is a problem shared by many economic and hydrological studies. However, by making assumptions explicit and performing sensitivity analyses to highlight if the model structure or shortcomings in data availability are important in terms of the conclusions being presented – a modelling study can still have significant value. That is, models can yield insights into the relative importance of obtaining different forms of data.

3.2 *Transition activities.*

The farm or sub-catchment model provides estimates of patterns of land use that maximise farm profitability subject to achieving specified hydrologic or crop area targets. The financial implications to farms of land use change are likely to have a significant time component particularly if large areas of perennials are considered. To account for these types of changes the catchment model was structured as a multi-period model with a time horizon of 50 years. This time horizon was assumed sufficient to achieve a steady state in hydrology, and in the farm system, following a change in land use.

In contrast the sub-catchment model is a single period model with time included as an exogenous variable. To populate the catchment model the sub-catchment model is run multiple times with time incremented between individual runs. The structure of the model experiments are described in more detail in section 3.3. To ensure inter-temporal consistency between these runs - transitional variables are defined to account for irregular or occasional events which have implications for the target variables (including farm profit, and in stream water and salt). Transitional variables are also used to link changes in one period and the starting conditions for a following period.

A key feature of the transitional variables, as defined in this study, relates to land capability. Land capability is defined here in terms of the ability of land to support arable crop production (AC), improved permanent pasture (PP), better native pasture (NB), poor native pasture (NP), or woody and herbaceous perennials (PW). The initial land capabilities are specified in terms of existing land use (see Figure 1) and feasible transitions in land use are included in Table 4.

Typically, transitions in land use are accompanied by investment (e.g. expenditure on capital fertiliser or planting), or disinvestment (e.g. allowing land to revert to poor native pasture). The positive values in Table 4 refer to the amount of investment or cost of achieving a land capability change and negative values refer to disinvestment or returns from a transition to a less intensive use.

Table 4. Investment and disinvestment ($/ha) associated with transitions in land use capability.

		To AC	To PP	To NB	To NP
From	AC	-	100	40	-20
	PP	50	-	0	-20
	NB	100		-	-20
	NP			40	-

The transition matrix only allows transitions between some land capabilities. However, it is assumed any land capability can be transformed to any other by a series of transitions. For example, if permanent pasture is planted after native pasture there is a high risk of failure due to weeds (Ian Fillery, CSIRO, pers comm). To account for this permanent pasture is only allowed to follow a phase of arable cropping. Alternately if poor native pasture is to be developed into a permanent pasture the following transitions need to occur: NP $\rightarrow$ NB $\rightarrow$ AC $\rightarrow$ PP (Michael Reynolds, NSW DPI, pers comm).

The transition from better native pasture to poor native pasture occurs when maintenance expenditure, primarily on fertiliser and weed control, is reduced. Following such reductions there is typically a period before pasture yield equilibrates with the new level of maintenance. In this case the value of disinvestment is estimated as the value of additional production, over that of a poor native pasture, during the period of equilibration.

The transition values in Table 4 reflect the capital costs and returns of changing from one land capability to another. As previously noted the sub-catchment model is a single period model and financial values are included as steady state values. To ensure the "one-off" transition values in the sub-catchment model are consistent with the steady state financial values in the rest of the model – the transition values are translated to an equivalent annuity value[13]. However, in the catchment model, the timing of land use change is of interest. The economic farm surpluses[14] (EFS) from the sub-catchment model are adjusted, therefore, to reflect the capital values of transitions in the year they occur. The net present values of these "adjusted" farm surpluses are included in the catchment model.

3.3 *Sub catchment model*

The structure of the salt and water balance model has implications for how targets are set in the model. This study is primarily interested in the implications of perennials for salt and water exports to streams and for farm function and profitability. However, salt and water exports are modelled as lagged functions of previous land use as well as the characteristics of individual sub-catchments. To simplify target setting the sub-catchment model was structured so runoff and recharge (both of which are modelled with zero lags) became the target variables. By varying these between their respective minimums and maximums the model provides estimates of the feasible range over which water and salt exports to streams can be varied.

As previously discussed the catchment model is populated with outputs from the sub-catchment model runs. The objective function of the sub catchment model was to maximise economic farm surplus subject to various constraints. These constraints include normal or typical constraints on production but in addition farm plans were required to achieve various runoff, recharge, and crop area targets. The runoff and recharge values from the sub-catchment model runs were subsequently processed to reflect salt and water exports to streams (see equation 8). These were then combined in the catchment model with the associated areas of perennial pasture (Phalaris and Lucerne), trees, arable crops, annual pasture, and selected animal production variables.

Specifically model runs were performed for 10 sub catchments, 5 periods (each representing a 10 year period), and various strategies. These included 54 forestry strategies which correspond to different combinations of recharge targets (low, medium and high), runoff targets (low, medium and high), and areas of forestry ((1) cut down existing native forest, (2) retain existing forest, (3) plant 16% of pastoral and cropping land to conventional forest, (4) plant 33% of pastoral and cropping land to conventional forest, (5) plant 8% of pastoral and cropping land to alley forest, and (6) plant 16% of pastoral and cropping land to alley forest). Other strategies evaluated with the sub-catchment model included differing combinations of recharge

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[13] The discount rate = 7.5%.

[14] Economic farm surplus is used as to compare whole farm profitability. As such it includes cash and non cash items but excludes debt servicing. More formally it reflects: gross farm revenue – operating expenses adjusted for (1) the value change in livestock numbers, (2) unpaid labour and management, (3) ownership of run-offs, (4) depreciation, and (5) the value change in supplementary feed inventory.

and runoff targets and varying areas of other modelled crops: that is annual pasture, cereals, Phalaris and Lucerne.

As a precursor to the above runs, the minimum and maximum levels of recharge and runoff and the optimal location of additional forestry were estimated. The first in this set of runs involved determining the minimum and maximum bounds for recharge. This was achieved by specifying recharge as the objective function and running the model as a minimisation and then a maximisation problem for each sub catchment and forestry strategy. In these initial runs runoff, the location of new forest, and financial returns were unconstrained.

It was also assumed that any new forest was in a steady state. The economic farm surplus from the forestry rotation was included, therefore, as an equivalent annuity value and the amount of excess water (see equation 1) was estimated as the mean of a forest in a steady state rotation. The actual recharge targets were estimated in relation to the minimum and maximum bounds identified in the previous step.

A similar sequence of calculations was used to determine the runoff targets. The objective function of the model was set as runoff, and the model solved as a minimisation and then as a maximisation problem for each sub-catchment, forestry strategy, and the recharge targets determined in the previous step. Similarly the low, medium and high runoff targets were interpolated between the runoff bounds in the same way as the recharge targets were established. This resulted in 9 combinations of recharge and runoff targets for each sub catchment and forestry strategy.

To estimate the optimal location of additional trees the economic farm surplus was specified as the objective function and model was solved as a maximisation problem. The solution vector from these runs included information about the area of each soil type which is occupied by additional trees. This information was used to constrain subsequent model runs so that any additional trees were required to occupy the soil types identified in these initial runs.

A similar sequence of calculations was then followed to determine low, medium and high runoff and recharge targets for the various sub catchments and forest strategies, with trees at differing ages. However, in this sequence of runs the location of any additional trees was not allowed to vary. The outputs of these runs were used to generate estimates of salt and water exports in different time periods, sub catchments, recharge and runoff targets and forestry strategies.

The preliminary runs to determine the runoff and recharge targets for other crop strategies were simpler than those described for additional trees. It was assumed other perennial crops achieve maturity within a single modelled period. The other crop strategies involved planting zero and a large amount of a crop (that is annual pasture, cereals, Phalaris and Lucerne). In these runs, other crops were allowed to enter the solution, at any level, subject to the recharge and runoff targets being achieved. The first step involved determining the minimum and maximum bounds for recharge, subject to the target area of crop being planted. Low, medium and high levels of recharge were then estimated in relation to these bounds and used to determine the minimum and maximum runoff. The final step involved maximising economic farm surplus subject to the area of crop and required runoff and recharge targets being achieved. Altogether, this process involved 7240 preliminary and 6300 final runs with the sub-catchment model.

3.4 *Catchment Model*

The catchment model fulfils a variety of purposes. As with the sub-catchment model it can be used to optimise economic farm surplus subject to achieving hydrologic targets or to plant a particular area of a crop. The main difference between the models relates to the sub-catchment model including a larger amount of detail and complexity, albeit, with a smaller spatial and temporal scope than the catchment model. Although not explicitly included in the catchment model the detailed results of the sub-catchment model runs, which populated the catchment model, were retained. The pattern of land use associated with different strategies and sub catchments (for example the soils different crops are planted on) can be determined and evaluated against solutions produced by the catchment model. This provides the potential to perform very detailed analyses of farm level changes within the catchment model.

The structure of the catchment matrix is illustrated in Figure 4. For presentation purposes the matrix includes two sub catchments, two periods, two strategies and three variables (NPV, W and S) which were derived from the sub-catchment model runs described in the previous section. This compares with the actual catchment model which includes 10 sub-catchments, 126 crop strategies, 5 periods, and 9 variables: NPV, W, S, and the associated area of: cereals, annual pasture, Phalaris, Lucerne, forestry and sheep numbers.

The subscripts associated with NPV, W and S corresponds to sub-catchment, strategy and period, respectively. NPV refers to the net present value of economic farm surpluses and W and S are discounted amounts of in-stream water and salt. The method used to discount water and salt is identical to that used to determine the net present value of financial values. Typically discounting is used to express preferences for a sum of money in one period versus another. It is less common to use discounting with physical quantities, however, discounting can provide a consistent measure of preferences for water and salt in different periods.

The NPV activities allow the economic farm surpluses from the various sub-catchments, strategies and periods to be summed, and in Figure 4, are included in the objective function. Alternately, NPV can be included as an “equals” constraint or be unconstrained. In Figure 4, W and S are summed and constrained to equal the targets W* and S*, respectively. However, W and S can also be specified as the objective function or be unconstrained. Similarly, other variables in the matrix (that is area of different crops and animal numbers) are summed and may be required to equal a specific target, be unconstrained, or be included as the objective function. The model structure is very flexible, therefore, and is able to perform a wide range of different experiments.

Sub catchment 1		Sub catchment 2		NPV		Water		Salt					
Strategy 1	Strategy 2	Strategy 1	Strategy 2	Period 1	Period 2	Period 1	Period 2	Period 1	Period 2				
1	1									=	1	Sub catchment 1	Land
		1	1							=	1	Sub catchment 2	
$-NPV_{1,1,1}$	$-NPV_{1,2,1}$	$-NPV_{2,1,1}$	$-NPV_{2,2,1}$	1						<	0	Period 1	NPV
$-NPV_{1,1,2}$	$-NPV_{1,2,2}$	$-NPV_{2,1,2}$	$-NPV_{2,2,2}$		1					<	0	Period 2	
$-W_{1,1,1}$	$-W_{1,2,1}$	$-W_{2,1,1}$	$-W_{2,2,1}$			1				<	0	Period 1	
$-W_{1,1,2}$	$-W_{1,2,2}$	$-W_{2,1,2}$	$-W_{2,2,2}$				1			<	0	Period 2	Water
						1	1			=	W*	Total	
$-S_{1,1,1}$	$-S_{1,2,1}$	$-S_{2,1,1}$	$-S_{2,2,1}$					1		<	0	Period 1	
$-S_{1,1,2}$	$-S_{1,2,2}$	$-S_{2,1,2}$	$-S_{2,2,2}$						1	<	0	Period 2	Salt
								1	1	=	S*	Total	
				1	1							Objective function	

Figure 4. Structure of Catchment Model.

4. Results.

A number of experiments were performed as part of the analysis. These included an assessment of feasible combinations of salt and water exports from individual sub-catchments. The results of this analysis were subsequently combined to estimate the range of water and salt targets that might be achieved from the catchment as a whole. The second part of the analysis considers a range of stream flow targets and how the attainment of these might affect the quality of stream water and the profitability and structure of farm systems. The implications of the analysis for policy design and implementation is discussed and conclusions relating to future work are presented.

The first part of the analysis considers the feasible range of salt and water exports from each of the sub-catchments. As with the runs that populated the catchment model a number of steps needed to be performed. The first step was to solve the model, for each sub-catchment, as a minimisation and then as a maximisation problem. In these initial runs W was the objective function and S was unconstrained. The next step was to solve the model, for each sub-catchment, as a minimisation and then as maximisation problem but with S as the objective function. In these runs W was included as an equality constraint which was parametrically altered between the lower and upper bounds identified in the preceding step.

These runs allowed the feasible range of W and S exports from each sub catchment to be determined (see Figure 5). In the current example there is relatively little difference between the rainfalls recorded in the different sub-catchments and hence larger water exports are associated with larger sub-catchments: for example, sub-catchment 6 has an area of 72.2 km^2 c.f. sub-catchment 5 with 386.5 km^2. Another observation is the steeper the slope of the water-salt envelope the greater the salinity of water exports. For example salt concentrations in sub-catchment 6 (the freshest sub-catchment) range from 50 to 100 ppm. This compares with sub catchment 4 where salt concentrations range from 480 to 720 ppm.

In absolute terms, high salt concentrations tend to be associated with higher ground water salinities, and with more permeable overlying soils. This compares with the relative range of variations in salt concentrations that can arise as these tend to be positively related to greater ground water salinities and also the range of soil permeability's that are present. That is if only a single soil type is present in a given sub catchment the model implies the water-salt envelope will form a line segment that lies on a vector from the origin. Clearly this has implications for the value of targeting land use change to achieve hydrological targets. That is altering the area of perennials is likely to change the amount of water exported from a sub catchment, but unless land use changes are associated with variations between soils, it is unlikely these will have an effect on salt concentrations of in stream water.

However, there are differences between sub catchments in rainfall, ground water salinity, and soil composition such that changes in land use might be targeted to different sub catchments. The relative variability in these factors influences the value of targeting land use changes within or between sub catchments (Nordblom et al., 2005a). Another point is the water-salt envelopes are approximately symmetrical in their major and orthogonal axes. This implies the range of feasible salt concentrations in water tends to be higher at low rather than high water yields. That is the potential to contribute water that is either fresher or saltier than average is greater at low water yields than at high water yields. As such, the value or importance of identifying where land use change should occur is also likely to be greater at low water yields than at high water yields as the potential to make decisions with either beneficial or adverse effects on stream quality is greater. This is illustrated in Figure 6 which shows the feasible range of water and salt combinations and salt concentrations for the whole of the Little River catchment.

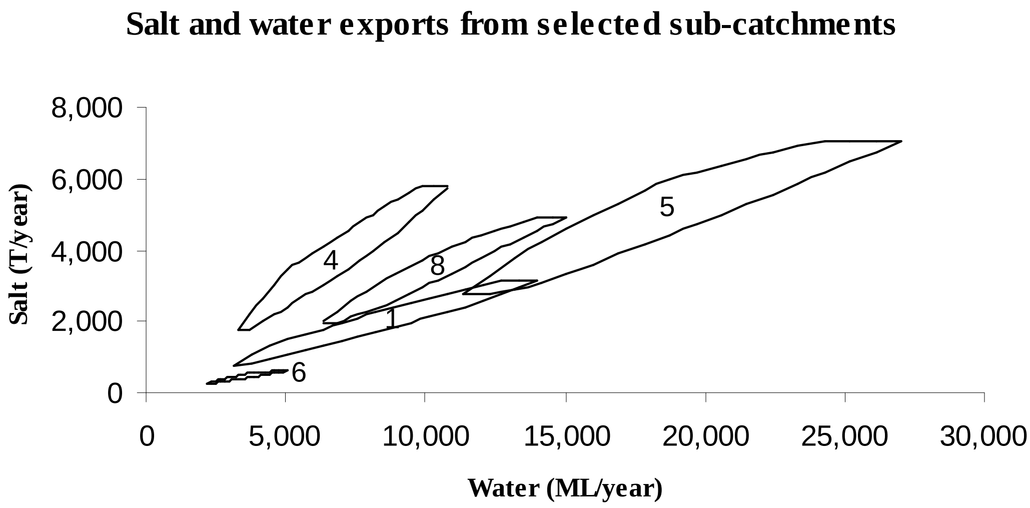

Figure 5. Salt and water exports from selected sub-catchments.

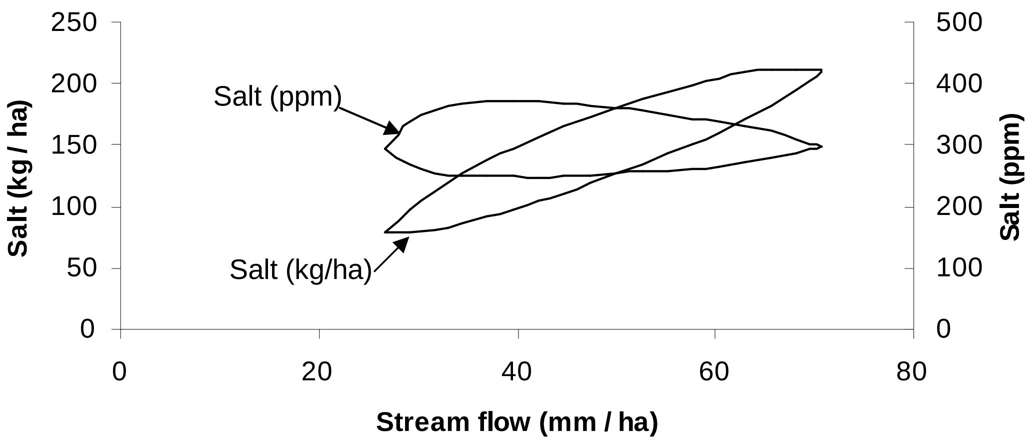

Figure 6. Feasible range of salt and water exports and salt concentrations in water from the Little River Catchment.

The second experiment involved evaluating different land use patterns that are consistent with maximising economic farm surplus and achieving a range of differing stream flows. Very low stream flows were associated with the maximum permitted area of trees and large areas of perennial pasture in conjunction with small areas of annual pasture, and cereals are planted. As stream flow increases, land use changes reflect declines in perennial pasture and trees and increases in cereals and annual pasture.

The current land use involves water exports of approximately 50 mm/ha. The optimal pattern of land use, consistent with this level of water exports, is likely to involve an economic farm surplus of $250/ha or close to the maximum EFS of $275/ha at water exports of 38 mm/ha. The results suggest current land use involves a similar area of cereals and trees, but more annual pasture and less perennial pasture, than is optimal in terms of current water exports. Transitions to optimal land use[15] are likely to involve transfers from annual to perennial pasture and an associated reduction in water exports compared with the current situation.

Perhaps the main reason current land use differs from that suggested by the model is that any increases in EFS are only likely to be moderate. These are also associated with relatively significant increases in farm intensity. Consequently factors such as labour requirements, debt, and stocking rates are likely to be higher for the modelled optimum than for existing systems of land use. Issues such as risk aversion might explain, therefore, why land use systems are less intensive than might otherwise be considered optimal.

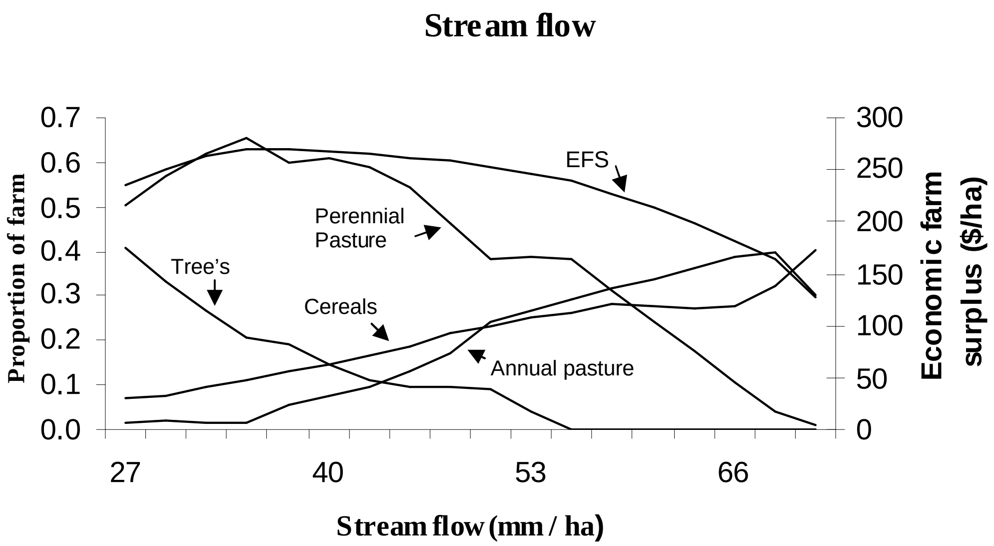

Figure 7. Profitability and pattern of land use associated with different stream flow targets

Other experiments with the catchment model involved maximising economic farm surplus subject to varying the area of selected crops. The purpose of these runs was to evaluate the sensitivity of the farm system to variations in the area of crops being

[15] Assumes zero value for water and salt.

planted. That is increases in trees and perennial pasture are likely to reduce recharge and areas of salt affected land, however, altering the areas of these crops might have significant implications for farm structure and profitability. Consequently, it is useful to have a clear understanding of the economic significance of different crops in terms of achieving alternate hydrological outcomes. The magnitude of such effects is also likely to have implications for incentive structures that might be necessary to achieve socially desired outcomes in terms of water and salt flows in streams.

The first of these experiments involved altering the area of trees in the catchment. Assuming patterns of land use consistent with profit maximisation the main effect of increasing trees is likely to involve declines in perennial pastures. Also likely are smaller declines in cereals and annual pasture. The changes in EFS with changes in tree areas suggest the existing area of trees (approximately 20% of total area) is approximately optimal. The reason for this is it is relatively expensive to cut down existing trees and the quality of agricultural land that is released tends to be relatively low. Similarly, planting additional trees is likely to displace other land uses which are more profitable.

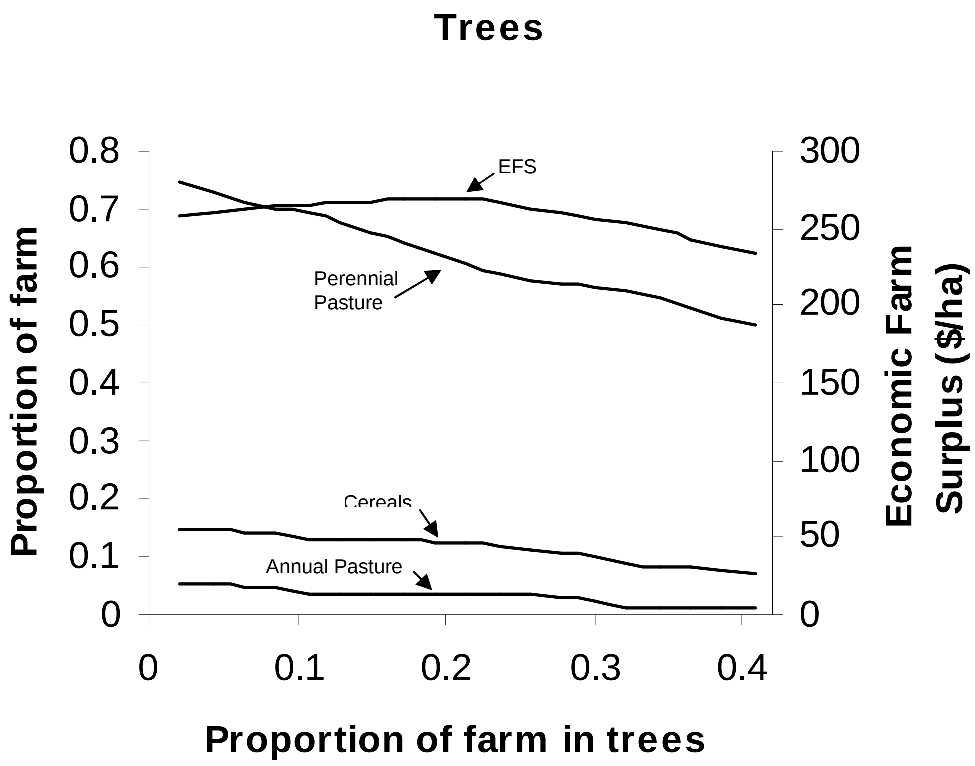

Figure 8. Profitability and pattern of land use associated with differing areas of trees.

The range of perennial pasture areas considered in this analysis vary from 3-80% of the total catchment with EFS tending to increase with the area of perennial pasture to a maximum of $275/ha at approximately 60% land coverage. Thereafter small declines in EFS occur with further increases in perennial pasture. The EFS doesn't appear particularly sensitive to the area of perennial pasture with quite small areas achieving EFS's in excess of 80% of the global optimum. The low sensitivity of EFS appears to be due to substitution between perennial and annual pastures. That is annual pastures are less profitable as they have lower yields but they also have lower establishment and maintenance costs.

Increases in perennial pasture are mainly associated with decreases in annual pasture, and also with smaller declines in the area of cereals. This compares with trees whose area remains unchanged across a wide range of areas of perennial pasture and it is only when very high levels of perennial pasture occur are trees are displaced. This is consistent with earlier conclusions that economic performance is likely to be adversely affected if the area of trees increases or decreases from current levels.

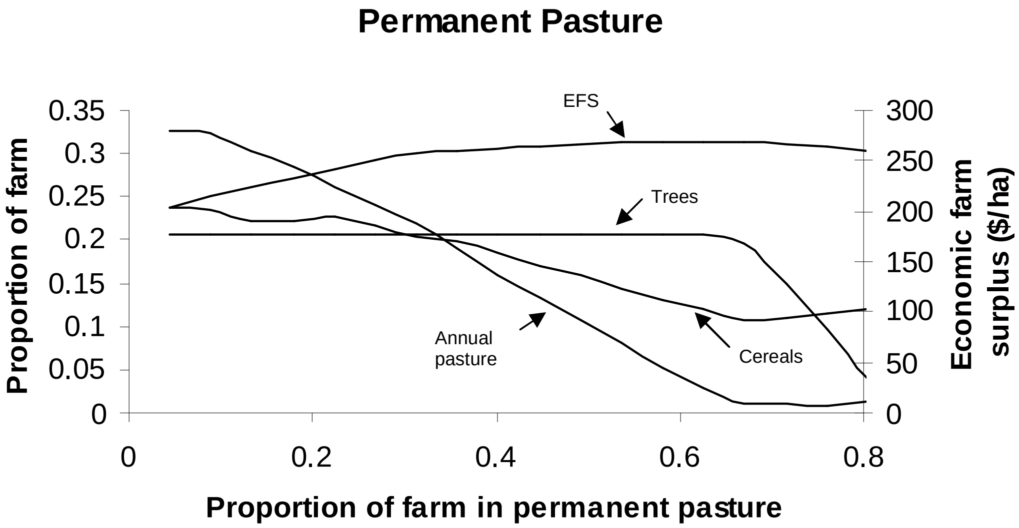

Figure 9. Profitability and pattern of land use associated with differing areas of permanent pasture.

In the case of annual pastures, there is a decline in EFS as the area of annual pasture increases. This decrease in EFS is relatively gradual but becomes increasingly significant as annual pasture increases above approximately 45% of the catchment. Of the different crops permanent pasture is the most sensitive to changes in annual pasture. When the area of annual pasture is small, changes in annual pasture have little effect on the area of trees. However, large areas of annual pasture are associated with declining areas of trees. Conversely, except when there are very high levels of annual pasture (> 60% cover), cereals are relatively unaffected by changes in the area of annual pasture. The reason for the relative lack of sensitivity exhibited by cereals may be due to cereals only being suited to a relatively small proportion of soils, but on these soils cereals are very profitable.

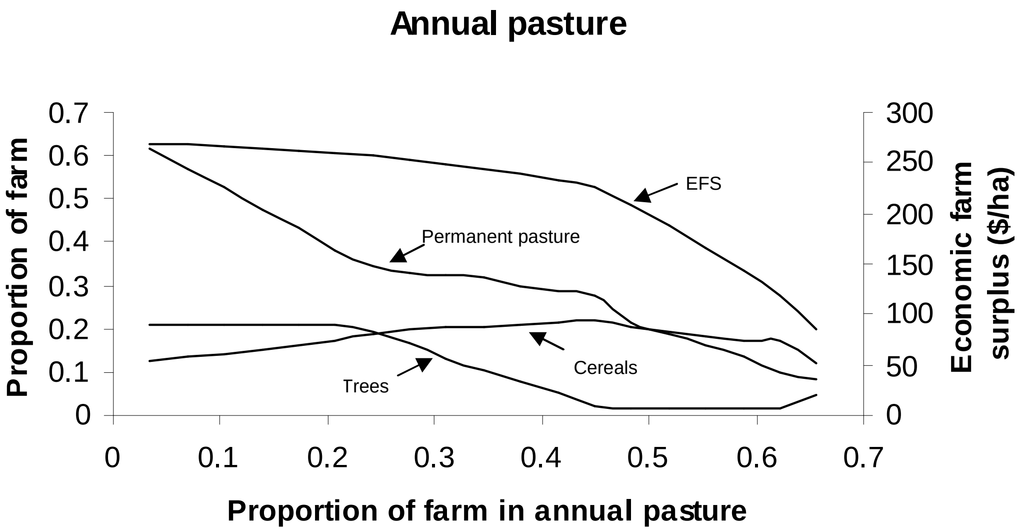

Figure 10. Profitability and pattern of land use associated with differing areas of annual pasture.

The point that cereals can be profitable on a narrow range of soils becomes particularly clear in Figure 11. The curve which describes changes in EFS with changes in crop area is more peaked for cereals than for other crops in this analysis. Further, if cereals are not included in the farm plan this is likely to involve significant opportunity costs. However, if cereals are grown on soils which they are not suited to, this has a large adverse effect on farm profitability. The crop most likely to be displaced with increasing areas of cereals is permanent pasture and to a lesser extent trees. In contrast there is an increase in the area of annual pasture with increases in cereals. It is likely this reflects the role of annual pastures as a break crop in cereal rotations.

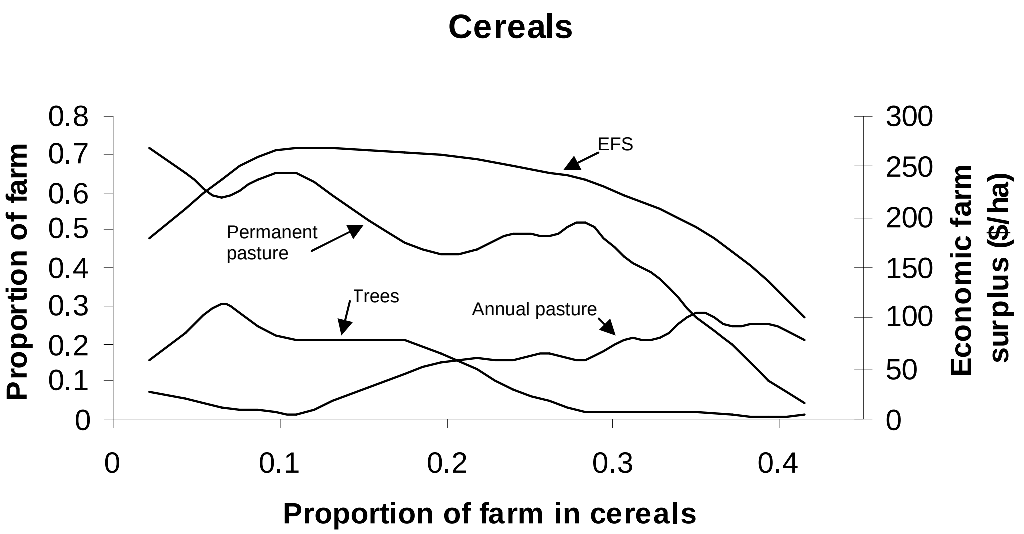

Figure 11. Profitability and pattern of land use associated with differing areas of cereals.

The above discussion reflects the attributes of alternate land uses and their role in farm systems. The analysis suggests perennial and annual pastures offer the most flexibility in terms of manipulating runoff, recharge and salt exports to streams. That is there are large differences in the water use of perennial versus annual pastures. Further, these crops can be substituted with relatively little impact on farm profit. As such, if stream flows are of concern a relatively large area of annual pasture might be grown. However, if salt discharges to the soil surface and to streams are important the increased use of perennial pasture may be desirable.

Similarly, a combination of targeting annual pastures to areas of low soil permeability and low ground water salinity and increased plantings of perennial pasture in areas with salty ground water and permeable soils may produce stream flows that are acceptable in terms of volume and quality and result in profitable farm systems. Trees and cereal crops also reflect high and low water use, respectively. However, these are likely to have less value as salinity management tools in low to intermediate rainfall areas such as Little River. In particular, cereals are profitable, but are unlikely to be robust if grown on soils they are not well suited to. Conversely trees can be grown widely. However, the analysis suggests large areas of trees are likely to be an expensive option for reducing runoff and recharge.

5. Conclusions.

Issues relating to salinity management involve assets (land and streams) of considerable value, whose management is complex and the potential for decisions to have adverse affects on their productivity and condition is significant. A desired outcome of this study was to better understand the relationships that determine the condition of land and streams and improve the ability to effectively manage such resources.

Changes in land use patterns have implications for the profitability and robustness of farm systems, land degradation, and the export of water and salt to streams. The bio-economic interactions between farm enterprises and the hydrological implications of alternate patterns of land use are complex. The application of optimising techniques provides a powerful method to make sense of the complexity inherent in such systems.

The study highlighted the importance of targeting management decisions to individual sub-catchments and of using relatively detailed farm level models as part of a catchment level study. The ability to combine quite detailed assessments of farm level changes and combining these with estimates of hydrological changes is extremely powerful in terms of providing information for resource managers. The potential for perennials to contribute to profitable and robust farm systems and to reduce degradation to land from salt scalds and to streams arising with elevated discharge and wash-off was demonstrated. However, increased adoption of perennials is likely to be associated with reduced stream flows. The ability to assess the relative costs and benefits of such effects will depend on the value of in-stream water and salt.

Perennials are also likely to have significant implications for bio-diversity and carbon sequestration. These issues have not been explicitly considered in this study but such issues are likely to become increasingly important in the future. This is particularly the case in relation to the recent New South Wales Greenhouse Gas Abatement Scheme. Dryland salinity involves important questions of water and land sustainability. However, it has been suggested that salinity has been oversold as a land degradation issue in Eastern Australia. Balanced against this questions of sustainability will continue to be important and salinisation is a significant component of this wider issue. The integration of salinity into considerations of environmental, social, and economic bottom-lines will continue to be an important issue for policy and decision makers.

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