Author: J. Finlayson, A. Bathgate, T. Nordblom, T. Theiveyanathan, B. Farquharson, R. Crosbie, D. Mitchell and Z. Hoque
Title: Balancing land use to manage river volume and salinity: economic and hydrological consequences for the Little River catchment in Central West, New South Wales, Australia.
Journal: Agricultural Systems **ISSN**: 0308-521X
Year: 2010
Volume: 103
Issue: 3
Pages: 161-170

Abstract: It has been widely suggested that changing land use from annual to perennial crops reduces land and stream degradation due to salinisation. However, annual crops are financially attractive and increases in perennials can reduce stream flows with adverse effects on stream values. As such, salinity control is likely to involve tradeoffs between public and private costs and benefits. This study quantifies the expected on-farm economic and catchment-level water yield and salinity effects of altering land use among trees, perennial pastures and cereals. The structure of a two stage linear-programming (LP) process is described. The first stage is the MIDAS farm-level model of mixed cropping and sheep enterprises which provides inputs to a second stage catchment-level LP. It was concluded that perennial pastures can be used in conjunction with trees as a stream salinity-management tool in low to intermediate rainfall areas in New South Wales. The results indicate that land-use decisions should be informed by site-specific information if adverse effects on streams are to be avoided.

URL: http://dx.doi.org/10.1016/j.agsy.2009.12.003
http://researchoutput.csu.edu.au/R/-?func=dbin-jump-full&object_id=19406&local_base=GEN01-CSU01
Author Address: tom.nordblom@industry.nsw.gov.au
CRO Number: 19406

Balancing land use to manage river volume and salinity: economic and hydrological consequences for the Little River catchment in Central West, New South Wales, Australia.

John Finlayson[1], Andrew Bathgate[2], Tom Nordblom[3], Tivi Theiveyanathan[4], Bob Farquharson[5], Russell Crosbie[6], David Mitchell[7] and Ziaul Hoque[8]

1. Corresponding author: School of Agricultural and Resource Economics, University of Western Australia and Future Farm Industries CRC. Phone: +61 8 6488 5507; email: john.finlayson@uwa.edu.au. Formerly: Economic Policy and Analysis Unit, Industry and Investment NSW (I&I NSW), 161 Kite St, Orange, NSW 2800, Australia.
2. Farming Systems Analysis Service, 41 Trebor Rd, Cuthbert, WA 6330, Australia.
3. EH Graham Centre for Agricultural Innovation (Charles Sturt University and I&I NSW), Pine Gully Rd, Wagga Wagga, NSW 2650, Australia.
4. ENSIS, Building 1, Wilf Crane Crescent, Yarralumla, ACT 2604, Australia.
5. Department of Agriculture and Food Systems, The University of Melbourne, Building 142, Parkville Campus, VIC 3010, Australia.
6. CSIRO Land and Water, PMB 2, Glen Osmond, SA 5064, Australia.
7. Orange Agricultural Institute, I&I NSW, Forest Road, Orange, NSW 2800, Australia.
8. ABARE, GPO Box 1563, Canberra 2601, Australia.

Abstract:

It has been widely suggested that changing land use from annual to perennial crops reduces land and stream degradation due to salinisation. However, annual crops are financially attractive and increases in perennials can reduce stream flows with adverse effects on stream values. As such, salinity control is likely to involve tradeoffs between public and private costs and benefits. This study quantifies the expected on-farm economic and catchment-level water yield and salinity effects of altering land use among trees, perennial pastures and cereals. The structure of a two stage linear-programming (LP) process is described. The first stage is the MIDAS farm-level model of mixed cropping and sheep enterprises which provides inputs to a second stage catchment-level LP. It was concluded that perennial pastures can be used in conjunction with trees as a stream salinity-management tool in low to intermediate rainfall areas in New South Wales. The results indicate that land-use decisions should be informed by site-specific information if adverse effects on streams are to be avoided.

Keywords: Bio-economic models, linear programming, MIDAS, model of an integrated dryland agricultural system, dryland salinity, salt and water exports, catchment management.

1. Introduction

The removal of native vegetation has played a key role in developing much of the grazing and cropping land in Australia. This has affected the cycling of water in the atmosphere, plants and soils, groundwater and stream systems. Evapotranspiration (*ET*) tends to be higher for native woodland and shrub vegetation than for agricultural crops and consequently conventional farming practices have contributed to increased runoff to streams, increased rates of recharge to groundwater, and increased discharges of salt and water to the soil surface and streams (Peck & Hatton, 2003; Williamson *et al*., 1997).

Other consequences of land clearing include increased areas of water logging and salinisation, reductions in the productivity and profitability of agricultural land, and damage to infrastructure and the environment (Farrington & Salama, 1996; Graham, 2008; Greiner, 1997; Holmes & Sinclair, 1986; Madden *et al*., 2000; Oliver *et al*., 1996; Stolte *et al*., 1997).

Approaches to salinity management are often described as involving either recharge or discharge management. Recharge management is typically associated with avoiding or minimizing salinity by reducing net recharge to groundwater - planting trees with high *ET* demands is a commonly cited example. In contrast, discharge management tends to involve adaptive strategies, such as planting crops that are tolerant to saline soils, engineering solutions to reduce salt entering streams, and remediation of saline soils.

In New South Wales (NSW) efforts to control salinity have tended to focus on reducing groundwater recharge by using extension and providing subsidies to plant trees (Pannell & Roberts, 2009). This reflects local concerns about maintaining or enhancing stream quality and flow volumes, the perceived cost of engineering solutions, and the relatively small proportion of salt-affected land (Beale *et al*., 2000) compared with other Australian states (see Table 1). In NSW approximately 180,000 hectares or less than 0.3% of the agricultural land are affected by salinisation (National land and water resources audit, 2001).

Table 1 ABOUT HERE

Issues relating to salinity management involve land and stream assets of considerable value and complexity but it has been suggested in recent years that salinity has been exaggerated as a land degradation issue (Keogh, 2005; Pannell & Roberts, 2009). Balanced against this questions of sustainability continue to be important and stream salinisation is a significant component of this wider issue.

The National Action Plan for Salinity and Water Quality (NAP) was the largest salinity management initiative in Australia to date. Between 2000 and 2008 the NAP allocated AUD 1.4 billion of public funds (Pannell & Roberts, 2009). In spite of high levels of public expenditure, efforts to manage dryland salinity have met with limited success. In part this is because of the long timeframes for adjustment as stream salinities and salt-affected land can increase for decades after a land-use change (Beale *et al*., 2000).

Other reasons that salinity is difficult to manage are: site specific hydrological information is often lacking, the existence of a property rights situation where groundwater systems are open-access resources, and the use of high discount rates which favour short term decisions (Quiggin, 1988). Quiggan's concern about a property rights situation that fails to internalise the salinity consequences of land use decisions has not been addressed by policy makers and is still relevant today. The NAP has also been criticised for failing to use technical and socio-economic information to prioritise investment; and consequently for producing few worthwhile and lasting salinity mitigation benefits (Pannell & Roberts, 2009).

Pannell & Roberts (2009) note a large amount of technical information is required to manage salinity effectively. The relative performance of crops on different soils, the effect of individual soils on recharge and runoff, and the salinity of groundwater discharges vary spatially and are not always known or easily observed. However, such factors can determine whether a given land-use change has a beneficial or adverse effect on salinity. For example the inappropriate positioning of crops, such as planting large areas of trees in catchments that produce relatively fresh water, can adversely affect the quantity and quality of river flows (Nordblom *et al.*, 2006).

Low and medium-rainfall agriculture is economically important in NSW (CWIRP, 2007) and the identification of profitable crops suitable for recharge management is an important task (Pannell, 2001; Pannell & Roberts, 2009). This is partly because of the low growth rates of high *ET* crops such as perennial trees and shrubs in low and medium rainfall areas. This means perennials can still be effective at reducing recharge and drying up sources of salt flow, particularly if they are located appropriately, but if the direct and/or opportunity costs are high, efforts to control river salinity are likely to be expensive and poorly adopted (Nordblom *et al.*, 2009).

The absence of skills and infrastructure to plant, manage and harvest trees in regions that have not previously produced commercial tree crops can also be an impediment to adoption. This has led to questions of whether increased areas of intermediate *ET* crops such as phalaris (*Phalaris aquatica*) and lucerne (*Medicago sativa*) are better suited for salinity management.

The objective of this study is to provide information about the possible tradeoffs among farm profitability and water yields and salt exports from a catchment following changes in land use. The study integrates a range of technical information to quantify the effects of alternate land uses on expected farm profitability and water and salt flows from the Little River catchment in NSW. It is intended the approach will assist policy decisions that affect land use change and consequently downstream flows of water and salt. The ability to perform relatively detailed assessments of perennials such as trees, phalaris, and lucerne, which have very different farm system and water use characteristics than annual crops and pastures is important to achieving this objective.

The paper is structured as follows. Section 2 provides some background to the causes of dryland and river salinity and a brief overview of previous modelling studies. The development of the farm-level MIDAS model and the use, verification and sensitivity analysis of a catchment-level LP model of the Little River catchment in Central West NSW is described in sections 3-5. The implications of land-use change for salinity-management purposes are considered in section 6 and the conclusions of the study are discussed in section 7.

2. Background

Changes in vegetative land cover cause relatively rapid changes in *ET*, runoff and recharge. However, it can take many years before groundwater recharge achieves equilibrium with consequent discharges of salt and water to land and streams (Cook *et al*., 2002; Farley *et al*., 2005). The time required for a groundwater flow system to reach equilibrium ranges from 10 to over 100 years depending on various hydro-geological factors, and in particular, the size of the system (Coram *et al.,* 2000). Coram *et al*. define local ground flow systems as contained in a single topographical catchment of less than 5 km in length.

Land clearing (removal of native trees and shrubs) is likely to result in relatively quick increases in fresh water runoff and slower increases in salty discharges from groundwater. This implies stream flows and salt loads are likely to increase, but at least initially, salt concentrations in stream water will be lower than the pre-clearing situation.

However, as recharge and discharge move towards a new equilibrium, stream volumes and salt concentrations are likely to continue to increase. Whether salt concentrations are higher or lower at the new equilibrium will depend on the relative contribution of runoff and recharge before and after land clearing, and the magnitude and location of salt stores in the landscape (Bari, 1999; Crosbie *et al*., 2007; Gilfedder *et al*., 2009; Herron *et al*., 2003; Jolly *et al*., 1997, 2001).

Reaching a new equilibrium is likely to take longer in situations of reafforestation than deforestation. In part this is because trees need time to mature to the point where they use water at the maximum rate. However, vegetative cover is only one of a range of physical, biological, and geo-chemical attributes of catchments to be affected by agricultural practices (Walker *et al*., 2001). Site changes such as soil loss, increased leakiness in recharge areas, and increased clogging of soils in discharge areas, may take longer to reverse than the establishment of alternate vegetation (Fitzpatrick *et al*., 2000).

The implications of land-use change for water balances are considered in a variety of bio-physical modelling studies. The studies vary considerably in their temporal and spatial scope. For example, detailed spatially-explicit models (Abbott *et al*., 1986; Dawes & Hatton, 1993; Ruprecht & Sivapalan, 1991); single dimension (vertical profile) models embedded in geographic information systems (Littleboy *et al*., 1992; McCown *et al*., 1996); and simpler less data demanding approaches (Grayson & Blöschl, 2000) have been developed. The range of approaches reflects the challenges inherent in describing the functions of catchments (Beverly, 2004; Gilfedder *et al*., 2009; Tuteja *et al*., 2004; Vertessy *et al*., 1996; Walker *et al*., 2002; Zhang *et al*., 2007)

Graham (2008) provides a detailed review of a range of theoretical and empirical economic studies of dryland salinity in Australia. The studies are discussed with respect to a range of characteristics including: scale (farm or catchment), location, whether the studies are static or dynamic, and the approach they take to model hydrology, agronomic and economic factors. The majority of empirical studies that Graham reviews consider salinity in Western Australia (for example Gomboso *et al*., 1996; Kingwell *et al*., 2003; Kubicki *et al*., 1993; van Bueren *et al*., 2001) which reflects the relatively high level of salt affected land in Western Australia.

Other studies reviewed by Graham include Hajkowicz & Young (2002) and Pavelic *et al*. (1997) in South Australia and Bathgate *et al*., (2004), Greiner (1996), and Nordblom *et al*., (2004) in NSW. In a recent study Nordblom *et al*. (2006) use a bio-economic optimisation model to calculate least cost changes in land use to achieve particular levels of water and salt exports to streams from a catchment. Nordblom *et al*. (2006) estimate crop yields for a range of soils that are defined in terms of permeability and the salinity of the groundwater system they overlay.

3. Methods

3.1 Study Area

The study area is the Little River catchment around Yeovil in the Central West region of NSW (32.75°S 148.65°E) (see Figure 1**).** Little River is a relatively intensively studied catchment (Evans *et al*., 2004; Hall *et al*., 2003; Hoque & Bathgate, 2008; Nordblom *et al*. 2005, 2006, 2009; Watson *et al*., 2003) which is representative of dryland farming systems in the region. Little River has an area of approximately 200,000 hectares or 5% of the agricultural land in the Central West. The Central West is an agriculturally important region and it accounts for 6% of agricultural holdings, 14% of the value of livestock production, and 10% of the total value of agricultural production in NSW (CWIRP, 2007).

FIGURE 1 ABOUT HERE

Average annual rainfall is approximately 560 mm in the west and 700 mm in the south, and the catchment mean is 620 mm. An annual mean of 96,200 mega-litres (ML) of water (≈ 50 mm) and 36,580 tonnes of salt (≈ 180 kg per hectare) are contributed to the Macquarie River (Beale *pers comm*.). The soils in the catchment are highly diverse and reflect the major limitation to changes in land use.

The predominant farming systems involve sheep grazing on unimproved pasture (about 50% of the catchment, Nicholson *pers comm.*) with smaller areas of improved pastures, arable cropping, and native forests and woodland. In this context unimproved pastures include mixes of native and naturalised species and occupy steep or rocky ground or ground with shallow soils that aren't fertilised. Conversely, improved pasture includes introduced species, is typically found in phases with cropping rotations, and normally receives fertiliser.

Average yields for wheat, phalaris, lucerne in winter and lucerne in summer are 3.0, 6.5, 2.2 and 4.4 tonnes per hectare, respectively. Replacement animals are typically purchased and stocking rates are approximately 8.5 dry sheep equivalents (DSE) per hectare (Nicholson *pers comm.*). Farmers rely on meat and wool sales, and to a lesser extent, on crop sales for income.

3.2 Farm model

The farm model is based on the whole-farm Model of an Integrated Dryland Agricultural System (MIDAS) (Kingwell & Pannell, 1987; Morrison *et al.*, 1986). MIDAS was originally developed to represent farms in the eastern wheat belt of Western Australia but it has since been calibrated for other regions in Western Australia, Victoria, South Australia and NSW (Kingwell *pers comm.*). The MIDAS model provides a steady-state representation of the farming system and it is suitable for comparing long-run outcomes which arise with changes in farming practices.

MIDAS represents farm-level bio-physical and economic activities in a relatively detailed manner and it has been used in a wide range of studies. These include analyses of farm-management practices (Schmidt & Pannell, 1996), agricultural policy (Morrison & Young, 1991), research and extension (Pannell 1999), and climate change policies

(Finlayson *et al*., 2008; Petersen *et al*., 2003). Detailed descriptions of MIDAS can be found in Kingwell & Pannell (1987), Morrison & Young (1991) and Young (1995).

The MIDAS model used in this study represents a 900 hectare farm with soils, crop rotations, prices, and productivities corresponding to the Little River catchment. Seventy cropping rotations, each of which is modelled on 8 soil types, are explicitly represented. Activities such as sheep grazing and husbandry, machinery operations, chemical and pesticide use and finance are included in the model. Altogether, the farm LP includes approximately 2,000 activities and 860 constraints.

A variety of data was collected for Little River and 80 sub-catchments or local-scale groundwater flow systems (Coram *et al.,* 2000) with differing soils and groundwater salinities (GWS, mg per litre) were identified (Evans *et al*., 2004). These sub-catchments were aggregated into ten clusters, a manageable number for modelling, which still reflects the diversity among the sub-catchments. This involved a two-stage clustering analysis using the statistical package SPSS (Version 12 for Windows). The farm models discussed in the remainder of this paper refer to the clusters or aggregate sub-catchments identified in this process. Additional information relating to the cluster analysis can be viewed at ?? supplementary material ??

3.2.1 Water and salt transport.

With the exception of trees, the hydrological implications of different land uses are represented using a salt and water mass-balance model adapted from Zhang *et al*. (2001). Variations of this model can be found in Bell & Heaney (2001), Nordblom *et al*. (2005, 2006, 2009) and Stirzaker *et al*. (2002). In the case of trees, runoff and recharge are estimated using the 3PG/Flush model (Landsberg & Waring, 1997).

An important simplifying assumption is a crop's contribution to long-term annual stream flow equals annual rainfall (P, mm) minus ET and the evaporative and seepage losses (L, proportion) associated with runoff (R^o , mm). As such, the model is consistent with Coram *et al.*'s (2000) definition of a local groundwater flow system. Some other assumptions are: runoff enters streams in the same year as incident rainfall; and recharge (R^e , mm) is discharged to streams (D, mm) as a lagged function of changes in recharge.

A farm's contribution to annual stream flows is estimated as the sum of R^o and D in year t and scaled to reflect land area (A, hectares) such that:

$$W_t = \left(R_t^o + D_t\right) \times A/100 \qquad (1)$$

The quantity of salt reaching local streams assumes that: groundwater discharges have the same salt concentration as groundwater (GWS); and the concentration of salt in runoff is equal to that of rainwater (RWS) or 5 mg per litre (Blackburn & McLeod, 1983).

$$S_t = \left(D_t \times GWS + R_t^o \times RWS\right) \times A/100 \qquad (2)$$

The drainage fraction (D^f) or proportion of excess water (E, mm per year) going to recharge is modelled as a function of soil type and varies between 0.1 on heavy impermeable soils and 0.75 on light sandy soils (see Table 2); and L is taken to be 0.1 (Beale *pers comm.*). These assumptions are expressed as follows:

$$E = P - ET \tag{3}$$

$$R^o = \left(1 - D^f\right) \times \left(1 - L\right) \times E \tag{4}$$

$$R^e = D^f \times E \tag{5}$$

A logistic function (Evans *et al*., 2004) is used to account for time lags between recharge and discharge:

$$D_t = \sum_{j=0}^{t} D_{t-j} + \left(R_t^e - R_{t-j}^e\right) \times G_{t-j} \tag{6}$$

$$G_j = \frac{1}{1 + \exp\left(\left(a1 - j\right)/a2\right)} \tag{7}$$

Where $a1$ and $a2$ define the form of the lag function *G*; and *t* and *j* reflect the year.

Table 2 ABOUT HERE

An implication of the model structure is the long-term volume of stream water is largely a function of *ET*, and hence crop type. That is, the proportion of excess water going to runoff versus recharge, affects the timing of water entering a stream, but the amount is largely determined by the relative area of the different crop types. It should be noted that the path taken by water has some effect on stream volume, as evaporative and seepage losses from runoff are modelled (see *L* in equation 4); but this effect is small compared to inter-crop differences in *ET*.

To calculate a crop's *ET*, the minimum and maximum *ET* for all crops is first estimated (Zhang *et al*., 2001). The individual crop's *ET* is then interpolated between these lower ($ET^{\min}$) and upper ($ET^{\max}$) bounds depending on its *ET* relative to a mature forest (*FE*). Typically, the *ET* of an annual arable crop equals $ET^{\min}$, while the *ET* of a perennial crop is greater than an annual crop, but less than or equal to $ET^{\max}$. The *ET* of crop c is calculated as:

$$ET_c = ET^{\min} + FE_c \times \left(ET^{\max} - ET^{\min}\right) \tag{8}$$

$$ET^{\min} = P \times \frac{1 + a3 \times a4 / P}{1 + a3 \times a4 / P + P / a4} \tag{9}$$

$$ET^{\max} = P \times \frac{1 + a5 \times a6 / P}{1 + a5 \times a6 / P + P / a6} \tag{10}$$

In this study, arable crops such as wheat have an *FE* of 0 and consequently an *ET* equal to $ET^{\min}$. This compares with an *FE* of 0.1 for poor native pasture, 0.15 for better native pasture, and 0.4 for established lucerne and phalaris (Hume *pers comm*.). The parameters *a*3 … *a*6 were estimated using selected data from Zhang *et al*. (2001) at 1, 1400, 4, and 2820, respectively. The selection criteria was that Zhang *et al*.'s data had to refer to dryland crops in low and intermediate rainfall areas in temperate Australia (Nordblom *et al*., 2006).

The mean annual rainfall at Little River is 620 mm. This is consistent with a low *ET* land use such as arable cropping producing a mean of 74 mm of excess water and compares with 7 mm for a maximum *ET* land use such as forestry (see equations 9 and 10). The large relative difference between $ET^{\min}$ and $ET^{\max}$ explains why land use can have a large effect on stream flows and evaporative flows to the atmosphere (see Figure 2).

FIGURE 2 ABOUT HERE

The water cycle for new plantings of commercial forest and mature native trees is modelled differently than other crops. In this study commercial forests are assumed to be comprised of Sugar Gum (*Eucalyptus cladocalyx*) which is a relatively slow growing but hardy species producing high-value sawlog timber. Sugar Gum is suitable for commercial plantings in low to intermediate rainfall areas such as the study area, and it can be grown either in conventional blocks or in alley plantings (Marcar *pers comm.*).

The growth, recharge and runoff of sugar gums is estimated using the 3PG/Flush model for alley and block plantings, on each of the 8 modelled soil types, as part of a fifty year rotation. To ensure consistency, runoff and recharge from native trees is assumed to conform to a mature commercial forest. This allowed estimates of runoff and recharge from trees to be consistent with the growth of trees at differing ages and on different soils.

3.2.2 Transition activities

Perennials have important temporal implications for cash flow and hydrology. To account for this the catchment model was structured as a multi-period model with a time horizon of 50 years which was assumed to be sufficient for the hydrology and the farm system to achieve a steady state. However, the time horizon in the catchment model is different from the MIDAS farm model which is a single period steady-state model.

To resolve these different time scales, transitional activities and constraints are included in the farm model. Their purpose is to ensure inter-temporal consistency between farm-model runs and to account for irregular events or variables whose time frame could not otherwise be adequately represented. These include changes in land use, farm profit, the area, location and maturities of tree crops, and stream water yields and salt loads. Details relating to the transition activities and constraints can be found at ?? supplementary material ??

3.2.3 Farm model runs.

This study considers the implications of perennials versus annual crops for salt and water exports to streams and for farm function and profitability. The objective function of the farm model is to maximise farm profit subject to various constraints. These include normal or typical constraints on production as well as runoff, recharge, and crop area targets. The runoff and recharge values from the individual farm-model runs are combined with runs involving the same strategy but different time periods. The linking of these runs allowed changes in variables such as discharge of water and salt to streams, which are subject to lags and not explicitly represented in the farm model, to be included in the catchment model.

The farm model runs involved 10 farms or clusters, five periods (each representing a 10-year period), and various strategies. Altogether 54 forestry strategies or combinations of runoff targets (low, medium and high), recharge targets (low, medium and high), and six areas of forestry are considered. In addition target areas for annual pasture, cereal, phalaris and lucerne are combined with low, medium and high runoff and low, medium and high recharge targets that are specific to the crop area being considered.

The forestry strategies include cutting down versus retaining existing forest and planting various areas of additional conventional and alley forest. Commercial forestry involves a large change from current farming systems and the upper limit of additional forestry (33%) corresponds to a likely medium term (10-15 years) maximum (Marcar *pers comm.*). For strategies that involve additional forestry the optimal location of the new trees are identified. Altogether, the farm model was run 13,540 times to populate the catchment model.

3.3 Catchment model

The main differences between the farm and catchment models relate to the detail with which spatial and temporal activities are represented. The catchment model explicitly includes a subset of the farm model outputs. However, detailed outputs from the farm model runs which populated the catchment model were recorded, and these provide the opportunity to perform detailed analyses of farm-level responses to catchment-level changes. For example, changes in the pattern of soils that crops are planted on are represented in the farm model and can be investigated in relation to solutions generated by the catchment model.

The objective function of the catchment model is to maximise catchment level farm profit subject to a hydrologic target or crop area being achieved. In this paper profit is defined as gross farm revenue minus operating expenses and accounts for: the value change in livestock numbers, unpaid labour and management, depreciation, and value changes in supplementary feed inventory (Ferris & Malcom, 1999).

A simplified version of the catchment-level matrix is presented in Table 3. For illustrative purposes, the matrix includes two farms or sub-catchments, two periods, two strategies and three variables: Profit, in-stream water yield and salt load. The subscripts associated with Profit, W and S refers to sub-catchment, strategy and period, respectively. This compares with the actual model which represents 10 farms, 126 strategies or combinations of crop, runoff and recharge targets, 5 periods, and 8 variables: Profit, W, S, and areas of cereals, annual pasture, phalaris, lucerne, and forestry.

TABLE 3 ABOUT HERE

4. Verification and validation

To assess the models ability to reflect farm systems at Little River the catchment model was initially solved with normal production constraints. The model solution was then compared with actual data from Little River. Current land use is associated with a profit of approximately $280 per hectare; water exports of 50 mm; and salt exports of 180 kg per hectare. This compares with a modelled profit of $310 per hectare; water exports of 40 mm; and salt exports of 120 kg per hectare. A similar area of cereals and trees, but more annual pasture and less perennial pasture is planted in the catchment than the model suggests is optimal. The differences between actual and predicted water and salt exports and farm profit are largely explained by the differences between actual and predicted annual and perennial pasture (see Figure 4).

There are a number of possible reasons for the differences between the actual and predicted pattern of land use. In particular the model only approximates the decision problem faced by farmers. The model is deterministic and it assumes that farmers have perfect knowledge of future productivity and price relationships. These assumptions make model construction and analysis more tractable but they also reduce the model's realism.

The results suggest the net financial gain of changing from the current land use pattern to the modelled optimum is relatively small. Further the financial optimum involves an increase in farm intensity and factors such as labour requirements, debt, stocking rates and the incidence of financial risk are likely to be higher. This may explain why current land use is less intensive than the modelled optimum. Nevertheless, for the purpose of this study the land-uses selected as financially optimal by the model provide a reasonable match with real-world management.

5. Sensitivity analysis

The sensitivity analysis involved assessing the effect of altering ground water salinity, forestry equivalence of pasture, and soil drainage parameters on water and salt exports from the catchment. *GWS*, *FE* and D^f are included at their medium or default levels (M, see section 3.2.1), and various combinations of low (L = 0.75 * default) and high (H = 1.25 * default) values. In the case of *FE* the values for cereal and tree crops are not changed in the L and H scenarios. This relates to uncertainty over the level of *ET* of perennial pasture and lucerne, relative to cereals and trees, and consequently the ability of perennial pasture and lucerne to act as salinity management tools.

In the sensitivity analysis the objective function is profit maximisation subject to water yield being varied between its minimum and maximum feasible level and the level of *GWS*, *FE* and D^f. The resulting salt and water estimates are presented in Figure 3.

Figure 3 about here

Changes in *GWS* and D^f have a similar effect on salt exports. A high *GWS* and high D^f are associated with an increase in salt exports relative to the medium situation; a high (low) *GWS* and a low (high) D^f tend to offset each other and are similar to the medium situation; and a low *GWS* and D^f are associated with decreases in salt exports. The similarity of *GWS* and D^f in terms of salt yields is most apparent when water exports are greater than 40 mm.

At water yields of less than 40 mm, a low *FE* is associated with an increase in salt exports relative to a high *FE*. Of the different variables *FE* has the largest effect on the range of water exports. High *FE* is associated with a wider range of water exports, albeit at a lower average, than low *FE*. Similarly the range of salt exports is wider, but with a lower average, when the *FE* of pasture plants is high than when it is low. This is consistent with perennial pastures ability to make greater reductions in salt and water exports if their *FE*, and consequently *ET*, is high.

The model estimates of salt exports vary between individual soils from 5 kg per hectare and 700 kg per hectare depending on the crop and the sub-catchment. The minimum salt exports from an individual sub-catchment varies from 8 kg per hectare to 26 kg per hectare and the maximum salt exports from individual sub-catchments vary from 90 kg per hectare to 280 kg per hectare. This compares with salt exports from the experimental runs described in section 6 below, for the catchment as a whole, which range from 85 to 210 kg per hectare.

Water exports vary between individual soils and sub-catchments by approximately 6 to 70 mm and for the catchment from 28 to 60 mm. This reflects the area of different soils and ground water salinities, crop *ET*'s and soil permeability's in the model. As a general statement salt exports are correlated with water exports and large changes in water exports are unlikely without salt exports being affected. However, the differences in salt and water exports imply there is potential to target specific land uses to particular soils and sub-catchments.

The above discussion suggests salt exports are sensitive to the model assumptions and this is likely to be the most uncertain aspect of the model. It is likely more confidence can be placed on the water component as it is based on the relatively widely used Zhang *et al*. (2001) model. The model should provide reasonable estimates of long-term changes in water exports and acceptable rankings of strategies that involve large scale changes in land use. The results of experiments with the catchment model are discussed in the following section.

6. Results and discussion

The first experiment considers changes in land use, profitability, and salt exports with changes in water exports from the catchment. In these runs the objective function of the model is profit and water exports are incremented between 30 and 60 mm (see Figure 4). At low water yields, perennial pasture and trees are the dominant land-use. Conversely, at high water yields cereals and annual pasture are the dominant land use while perennial pasture and trees have a small presence.

Figure 4 about here

Salt yield tends to be proportional to water yield and produces an average concentration of 300 mg of salt per litre of water. In spite of the large changes in land use profitability is relatively insensitive to changes in water yield. The global optimum or maximum profit of $310 per hectare is associated with water exports of 40 mm or 0.4 ML per hectare; salt exports of 120 kg per hectare; and land use of 65%, 5%, 10%, 20% for perennial pasture, annual pasture, cereals, and trees, respectively.

If the catchment was planted entirely to trees or entirely to cereals the feasible range of water yields would be approximately 6 to 68 mm or 0.06 to 0.68 ML per hectare. The results are consistent with trees and, to a lesser extent, perennial pasture being effective salinity management tools that can be varied from a relatively small to large area.

The second experiment involved altering water yield and salt concentrations in water (see Figure 5). The highest salt concentration that is considered is 300 mg per litre which is consistent with the global optimum in the preceding experiment. The minimum and maximum water yields achievable at this concentration are 32 and 58 mm respectively. Successively lower salt concentrations of 250, 230 and 225 mg of salt per litre of water were evaluated with 225 being the lowest feasible concentration. Compared to the global optimum, minor increases in water yield and water quality can be achieved at relatively low cost, but larger changes in water yield and quality become increasingly expensive. Increases in water quality are also associated with a smaller feasible range of water yields.

Figure 5 about here

The remaining experiments assess changes in land uses, profit and water yield. In these experiments salt loads tended to be consistent with salt concentrations in water of approximately 300 mg per litre. The third experiment constrains the percentage of the catchment planted in trees to between 0 and 40%. Aggregate farm profit is maximised, and other crops and water and salt exports can enter the model solution at any level subject to normal constraints on production (see Table A.2 in ?? supplementary information ??).

The land use, profitability, and water yields associated with maximum profit are consistent with the results presented in Figure 4. The range between the least and most profitable area of trees is relatively small: $280 per hectare for the catchment when 40% of the farm area is allocated to trees, up to $310 per hectare at 20% trees. The results suggest that the existing area of trees (about 20% of the catchment) is approximately optimal from a financial perspective.

Increases in tree areas are associated with declines in perennial pasture and to a smaller extent declines in annual pasture and cereal crops. There is relatively little variation in water yield (30-47 mm or 0.3-0.47 ML per hectare) for the range of tree areas that is considered. This result was contrary to expectations as large areas of trees are likely to produce low water yields. However, the increase in tree area was accompanied by declines in perennial pasture and this partly offsets the effects of trees on water yield.

Variations in the area of perennial pasture are considered in Figure 6. In this experiment other land uses (including trees) are allowed to freely adjust to the level that maximises profit, subject to the constraint on perennial pasture area. Profit tends to increase with the area of perennial pasture to a global maximum of $310 per hectare when perennial pasture occupies approximately 65% of total land. Thereafter, profit declines with further increases in perennial pasture. Profit is not particularly sensitive to the area of perennial pasture, with areas of perennial pasture between 35% and 85% of the catchment, exceeding 95% of the maximum profit. This is largely due to substitution between perennial and annual pastures; annual pastures have lower yields and are less profitable, but they also have lower establishment and maintenance costs and the resulting differences in profitability are small.

The yield of water tends to decline as perennial pastures increase to the global optimum. This is consistent with the substitution between annual pasture and cereals (low *ET* crops) and perennial pasture (an intermediate *ET* crop). For increases in perennial pasture above the financial optimum, the area of annual pasture and cereals stabilise and instead trees (a high *ET* crop) are displaced. This results in an increase in water yield relative to the point of maximum financial return.

FIGURE 6 ABOUT HERE

The next land use to be considered is cereals. The results suggest cereals are profitable, but only on a narrow range of farm areas due to their suitability to particular soils (see Table A.3 in ?? supplementary information ??). The profit curve is more sensitive to changes in the area of cereals than to changes in other crops in the analysis. If cereals aren't planted on land they are well suited too a large opportunity cost is incurred. Conversely, if cereals are grown on unsuitable soils, yield and consequently profit tends to be low.

The analysis suggests perennial and annual pastures offer the most flexibility in terms of manipulating water and salt exports to streams. However, as perennial pasture is an intermediate *ET* crop, increased adoption will only achieve moderate reductions in salt exports. However, these crops can be substituted with relatively little impact on farm profit.

If there are concerns about low stream flows a large area of annual pasture might be grown but if excessive salt discharges 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 groundwater salinity, and increased plantings of perennial pastures in areas with salty groundwater and permeable soils, should produce stream flows that are acceptable in terms of quantity and quality whilst retaining profitable farming systems.

Trees and cereal crops also offer high and low water use, respectively. However, these are likely to have less value as salinity-management tools at Little River. In particular, cereals are unlikely to be profitable if they are grown on soils where they are not well suited. Conversely, trees can be grown widely and the analysis suggests small increases in trees are unlikely to be expensive. If large decreases in water (< 20 mm) and salt exports to streams are required increased planting of trees (>40% of the catchment) are likely to be needed.

7. Conclusions

The integration of salinity into considerations of environmental, social, and economic bottom-lines is likely to continue to present challenges for data collection and analysis and be an important issue for policy, decision makers and communities. Changes in land-use patterns can have significant implications for the profitability of farming systems and salt and water yields from catchments.

The objective of this study was to demonstrate the tradeoffs among farm profitability, water yields and salt exports from a catchment following shifts in land use and to provide this information in a form that will be useful for informing policy decisions. The ability to combine detailed assessments of farm-level changes with catchment level estimates of hydrological changes provides a powerful approach to collate information and analyse a range of resource management options.

The potential for trees and perennial pastures to contribute to profitable and robust farming systems and to reduce degradation of streams from elevated discharges of salt was demonstrated. The level of salt and water exports from individual soils and sub-catchments is likely to depend on a range of factors and the ability to target land use change to soils and sub-catchments is important if efforts to manage salinity are to achieve their intended outcomes.

Acknowledgements.

The project was funded by the National Action Plan for Salinity and Water Quality. This paper would not have been possible without this funding or discussions and collaboration with other colleagues from I&I NSW, CRC for Plant-Based Management of Dryland Salinity, NSW Department of Natural Resources and CSIRO Ensis. The authors particularly wish to thank Dr Iain Hume, Dr Nico Marcar, Michael Reynolds, Geoff Beale, Ray Evans, Alan Nicholson, Peter Regan, Dr Garry Griffith, Dr Randall Jones, Dr Robyn Hean, Professor David Pannell, Professor Ross Kingwell, Dr Jason Crean and Dr Ian Fillery for their assistance in the preparation of this paper.

References:

Abbott, M.B., Bathurst, J., Cunge, J.A., O’Connell, P.E., and Rasmussen, J., 1986. An introduction to the European hydrological system – systeme hydrologique Europeen SHE, 1. History and philosophy of a physically-based distributed modelling system. Journal of Hydrology (Amsterdam), 87, 45-59.

Bari, M., 1999. Reforestation reduces ground water level and stream salt load. In: Marcar, N. & Hossain, A. (Eds.), Managing Saltland into the 21st Century: Dollars and Sense from Salt: Productive Use and Rehabilitation of Saline Land National Conference. National Committee for the Productive Use and Rehabilitation of Saline Land (PURSL), Tamworth NSW, 38-46.

Bathgate, A., Wooley, J., Evans, R., McGowen, I., 2004. Farm and catchment benefits of reducing recharge to ameliorate dryland salinity: an economic study of the Boorowa River catchment in NSW, SEA Working Paper 1704.

Beale, G., Beecham, R., Harris, K., O'Neill, D., Schroo, H., Tuteja, N.K., Williams, R.M., 2000. Salinity Predictions for NSW Rivers within the Murray- Darling Basin., New South Wales Department of Land and Water Conservation, Parramatta, New South Wales.

Bell, R., Heaney, A., 2001. A basin scale model for assessing salinity management options: Model documentation. ABARE technical working paper, Canberrra.

Beverly, C., 2004. A review of hydrologic models for salinity management. In: Graham, T., Pannell, D., White, B., (Eds.), Dryland salinity: Economic issues at farm, catchment and policy levels. Cooperative Research Centre for Plant Based

Management of Dryland Salinity. University of Western Australia, Perth, Western Australia, 31-53.

Blackburn, G., McLeod, S., 1983. Salinity of Atmospheric Precipitation in the Murray-Darling Drainage Division, Australia. Australian Journal of Soil Research, 21, 411-434.

Cook, P.G., Jolly, I.D., Walker, G.R., Robinson, N.I., 2002. From Drainage to Recharge to Discharge: Some Time lags in Subsurface Hydrology, Dubai International Conference on Water Resources and Integrated Management in the Third Millenium, Dubai, UAE.

Coram, J.E., Dyson, P.R., Houlder, P.A., Evans, W.R., 2000. Australian Groundwater Flow Systems contributing to dryland salinity. A Bureau of Rural Sciences Project for the National Land and Water Resources Audit's Dryland Salinity Theme. 74 p.

Crosbie, R.S., Hughes, J.D., Friend, J., Baldwin, B.J., 2007. Monitoring the hydrological impact of land use change in a small agricultural catchment affected by dryland salinity in central NSW, Australia. Agricultural Water Management, 88, 43-53.

CWIRP, 2007. Central West Rural Lands Inquiry: Review of Land Use Planning in the Central West. In: Central West Independent Review Panel, Report to the Minister for Planning, NSW. (http://www.planning.nsw.gov.au/planningsystem/pdf/panelreport_centralwest_aug07.pdf, seen 10-Oct-2009).

Dawes, W.R., Hatton, T.J., 1993. TOPOG_IRM 1. Model description, Technical memorandum 93/5, CSIRO Division of Water Resources, Australia.

Evans, W., Gilfedder, M., Austin, J., 2004. Application of the biophysical capacity to change (BC2C) model to the Little River (NSW). CSIRO Land and Water Technical Report No 16/04. (http://www.clw.csiro.au/publications/technical2004/tr16-04.pdf, seen 10-Oct-2009)

Farley, K.A., Jobbagy, E.G., Jackson, R.B., 2005. Effects of afforestation on water yield: a global synthesis with implications for policy: Global Change Biology, 11, 1565-1576.

Farrington, P., Salama, R.B., 1996. Controlling dryland salinity by planting trees in the best hydrogeological setting. Land Degradation & Development, 7, 183-204.

Ferris, A., Malcolm, B., 1999. Sense and nonsense in dairy farm management economic analysis. Agribusiness Perspectives Paper 31.

Finlayson, J.D., Crean, J., Bathgate, A., 2008. The Impact of Greenhouse Reduction Policies on Agriculture: A Case Study of a Mixed Cropping Farm in the Central West, New South Wales. In: Hatcher, S., Richards, J S. (Eds.), Coping with a changing environment: environmental, technological, social and economic. Proceedings of the NSW DPI Sheep and Beef Conference 2008.

Fitzpatrick, R.W., Merry, R.H. Cox, J.W., 2000. What are saline soils? What happens when they are drained? Natural Resource Management, Special Issue, June 26-30.

Gilfedder, M., Walker, G.R., Dawes, W.R., Stenson, M.P., 2009. Prioritisation approach for estimating the biophysical impacts of land-use change on stream flow and salt export at a catchment scale. Environmental Modelling & Software. 24, 262–269

Gomboso, J., Ghassemi, F., Hertzler, G., Jakeman, A., 1996. Dryland salinity management in south west Western Australia – a hydrological and economic assessment of land use options. Hydrology and Water Resources Symposium, 23rd Hobart, Tasmania, Proceedings of the Australian Institute of Engineers, 349-356.

Graham, T.W., 2008. Economics of protecting road infrastructure from dryland salinity in Western Australia. PhD Thesis, Department of Agricultural and Resource Economics, University of Western Australia

Grayson, R.B., Blöschl, G., 2000. Spatial Patterns in Catchment Hydrology: Observations and Modelling. Cambridge University Press. 404 p.

Greiner, R., 1996. On-farm costs of soil salinisation: a case study for the Liverpool Plains in New South Wales. Review of Marketing and Agricultural Economics. 64, 60-74.

Greiner, R., 1997. Optimal farm management responses to emerging soil salinisation in a dryland catchment in eastern Australia: Land Degradation & Development. 8, 281-303.

Hajkowicz, S., Young, M., 2002. An economic analysis of revegetation for dryland salinity control on the Lower Eyre Peninsula in South Australia, Land Degradation and Development. 13, 417-428.

Hall, N., Watson, W., Oliver, M., 2003. Farm Economic Analysis: Little River Catchment. Integrated Catchment Assessment and Management Centre (iCAM), The Australian National University, Canberra , iCAM Report 2003/6 , 41 p.

(http://www.dnr.nsw.gov.au/salinity/science/pdf/fea_final_report-little_river.pdf, seen 10-Oct-2009)

Herron, N., Davis, R., Dawes, W., Evans, R., 2003. Modelling the impacts of strategic tree plantings on salt loads and flows in the Macquarie River Catchment, NSW, Australia. Journal of Environmental Management. 68, 37-50.

Holmes, J.W., Sinclair, J.A., 1986. Water yield from some afforested catchments in Victoria. In: Hydrology and Water Resources Symposium, 1986: River Basin Management.

Hoque, Z., Bathgate, A., 2008. Lucerne, profits and salinity in the Central West Slopes of NSW. 2nd International Salinity Forum: Salinity, Water and Society–Global issues, local action. Adelaide, South Australia, 31 March – 3 April 2008

Jolly, I.D., Dowling, T.I., Zhang, L., Williamson, D.R., Walker, G.R., 1997. Water and salt balances of the catchments of the Murray–Darling Basin. Technical Report 37/97, CSIRO Land and Water, Canberra.

Jolly, I.D., Williamson, D.R., Gilfedder, M., Walker, G.R., Morton, R., Robinson, G., Jones, H., Zhang, L., Dowling, T.I., Dyce, P., Nathan, R.J., Nandakumar, N., Clarke, R., McNeill, V., 2001. Historical stream salinity trends and catchment salt balances in the Murray-Darling Basin, Australia. Marine and Freshwater Research. 52, 53-63.

Keogh, M., 2005, The National Dryland Salinity Audit 5 years on: Is the 17 Million Hectare estimate still valid or useful? *Farm Policy Journal*. 24, 19-27.

Kingwell, R., Pannell, D., 1987. MIDAS, A Bioeconomic Model of a Dryland Farm System, Pudoc, Wageningen, 207 p.

Kingwell, R., Hajkowicz, S., Young, J., Patton, D., Trapnell, L., Edward, A., Krause, M., Bathgate, A., 2003. Economic evaluation of salinity management options in cropping regions of Australia. Grains Research and Development Corporation.

Kubicki, A., Denby, C., Stevens, M., Haagensen, A., Chatfield, J., 1993. Determining the long term costs and benefits of alternative plans. In: Hobbs, R., Saunders, D., (Eds.). Reintegrating fragmented landscapes. Springer Verlag, New York, 245-278.

Landsberg, J., Waring, R.H., 1997. A generalised model of forest productivity using simplified concepts of radiation-use efficiency, carbon balance and partitioning: Forest Ecology and Management. 95, 209-228.

Littleboy, M., Silburn, D.M., Freebairn, D.M., Woodruff, D.R., Hammer, G.L., Leslie, J.K. 1992. Impact of erosion on production in cropping systems. I. Development and validation of a simulation model. Australian Journal of Soil Research. 30, 757-774.

Madden, B., Hayes, G., Duggan, K., 2000. Repairing the Country-A National Scenario for Strategic Investment. (http://www.nff.org.au/). Australian Conservation Foundation and National Farmers' Federation.

McCown, R.L., Hammer, G.L., Hargraves, J.N.G., Holzworth, D.L., Freebairn, D.M., 1996. APSIM - A novel software system for model development, model testing, and simulation in agricultural systems research. Agricultural Systems, 50, 255-271.

Morrison, D. A., Kingwell, R. S., Pannell, D. J., Ewing, M. A. (1986). A mathematical programming model of a crop-livestock farm system. Agricultural Systems. 20(4): 243-268.

Morrison, D.A., Young, J., 1991. Profitability of increasing lambing percentage in the Western Australian wheatbelt. Australian Journal of Agricultural Research, 42, 227–241.

Murphy, B.W., Lawrie, J.W., 1998. Soil Landscapes of the Dubbo 1:250 000 Sheet Report Department of Land and Water Conservation. 357 p.

National land and water resources audit, 2001, Australian Dryland Salinity Asssesment Canberra.

Nordblom, T., Bathgate, A. Young, R., 2004. Derivation of supply curves for catchment water effluents meeting specific salinity concentration targets in 2050: Linking farm and catchment level models. In: Graham, T., White, B., Pannell, D., (Eds.). Proceedings of the Australian Agricultural & Resource Economics Society Preconference Workshop – Dryland Salinity: Economic Issues at Farm, Catchment and Policy Levels. Fremantle, WA. ISBN 1-74052-104-8. 81-100.

Nordblom, T., Hume, I.D., Bathgate, A., Hean, R., Reynolds, M., 2005. Towards a market: Geophysical bio-economic targeting of plant-based land use change for management of stream water yield and salinity. Invited paper, 2nd Economics and Environmental Network (EEN) National Workshop, The Australian National University, Canberra, ACT, May 5-6, 2005. (http://een.anu.edu.au/e05prpap/nordblom.pdf, seen 10-Sep-2009)

Nordblom, T., Hume, I.D., Bathgate, A., Reynolds, M., 2006, Mathematical optimisation of drainage and economic land use for target water and salt yields. Australian Journal of Agricultural and Resource Economics. 50, 381-402.

Nordblom, T.L., Finlayson, J.D., Hume, I.H., and Kelly, J.A., 2009. Supply and demand for water use by new forest plantations: a market to balance increasing upstream water use with downstream community, industry and environmental use? Economic Research Report No 43, NSW Department of Primary Industries. (http://www.agric.nsw.gov.au/reader/10550, seen 10-Sep-2009).

Oliver, M., Wilson, S., Gomboso, J., Muller, T., 1996. The costs of salinity to government agencies and public utilities in the Murray-Darling Basin. ABARE Research Report 96.2, Canberra, Australian Bureau of Agricultural and Resource Economics.

Pannell, D., 1999. On the estimation of on-farm benefits of agricultural research. Agricultural Systems 62, 123–134.

Pannell, D., 2001. Salinity policy: a tale of fallacies, misconceptions and hidden assumptions: Agricultural Science. 14(1): 35-37.

Pannell, D., Roberts, A., 2009. (in press). The Australian National Action Plan for Salinity and Water Quality: A retrospective assessment, Australian Journal of Agricultural Economics.

Pavelic, P., Dillon, P., Narayan, K., Herrmann, T., Barnett, S., 1997. Integrated groundwater flow and agronomic modelling for management of dryland salinity of a coastal plain in Southern Australia. Agricultural Water Management. 35, 75-93.

Peck, A.J., Hatton, T., 2003. Salinity and the discharge of salts from catchments in Australian Journal of Hydrology. 272, 191-202.

Petersen, E., Schilizzi, S., Bennett, D., 2003. The impacts of greenhouse gas abatement policies on the predominantly grazing systems of south-western Australia. Agricultural Systems, 78, 369-386.

Quiggin, J., 1988. Murray River salinity – an illustrative model. American Journal of Agricultural Economics. 70, 634-645.

Ruprecht, J., Sivapalan, M., 1991, Salinity modelling of experimental catchments: Proceedings of International Hydrology and Water Resources Symposium. Institute of Engineers Australia, Perth, W.A. 126-131.

Schmidt, C., Pannell, D.J., 1996, The role and value of herbicide-resistant lupins in Western Australian agriculture. Crop Protection 15: 539-548.

Stirzaker, R.J., Vertessy, R., Sarre, A., 2002. Trees, Water and Salt: An Australian Guide to Using Trees for Healthy Catchments and Productive Farms. RIRDC Report 01/0186. 159 p.

Stolte, W.J., McFarlane, D.J., George, R.J. 1997. Flow systems, tree plantations, and salinisation in a Western Australian catchment. Australian Journal of Soil Research. 35, 1213-1229.

Tuteja, N.K., Vaze, J., Murphy, B., Beale, G., 2004. CLASS - Catchment scale multiple land use atmosphere soil water and solute transport model. Cooperative Research Centre Technical Report. Cooperative Research Centre for Catchment Hydrology.

van Bueren, M., Panell, D., Hodgson, G., 2001. Spatio economic assessment of salinity scenarios and control treatments. CSIRO CLW Technical Memorandum.

Vertessy, R.A., Hatton, T.J. Benyon, R.G., Dawes, W., 1996. Long term growth and water balance for a mountain ash (Eucalyptus Regnans) forest catchment subject to clear felling and regeneration. Tree Physiology. 16, 221-232.

Walker, J., Thompson, C.H., Reddell, P., Rapport, D.J., 2001. The importance of landscape age in influencing landscape health. Ecosystem Health. 7, 7-14.

Walker, G., Zhang, L., Ellis, T.W., Hatton, T., Petheram, C., 2002. Estimating impacts of changed land use on recharge: review of modelling and other approaches appropriate for management of dryland salinity: Hydrogeology Journal. 10, 68-90.

Watson, W., Evans, R., Powell, J., Oliver, M., Hall, N., 2003. Sustainability profile for the Little River Catchment. Integrated Catchment, Assessment and Management Centre (iCAM), The Australian National University, Canberra, iCAM Target Report 2003/2, 56 p.

Williamson, D.R., Gates, G.W.B., Robinson, G., Linke, G.K., Seker, M.P., Evans, W.R., 1997. Salt trends: historic trends in salt concentration and salt load of stream flow in the Murray Darling Drainage Division. Murray Darling Basin Commission. Dryland Technical Report No. 1, 64 p.

Young, J., 1995. MIDAS: Model of an Integrated Dryland Agricultural System: Manual and Documentation for the Great Southern Model Version GS92-3. Centre for Legumes in Mediterranean Agriculture, Nedlands.

Zhang, L., Dawes, W.R., Walker, G.R., 2001. Response of mean annual evapotranspiration to vegetation changes at catchment scale. Water Resources Research. 37, 701-708.

Zhang, L., Vertessy, R., Walker, G., Gilfedder, M., Hairsine, P., 2007 Afforestation in a catchment context: understanding the impacts on water yield and salinity. Industry report 1/07, eWater CRC, Melbourne, Australia. (http://www.ewatercrc.com.au/documents/Afforestation%20in%20catchments.pdf, seen 10-Oct-2009)

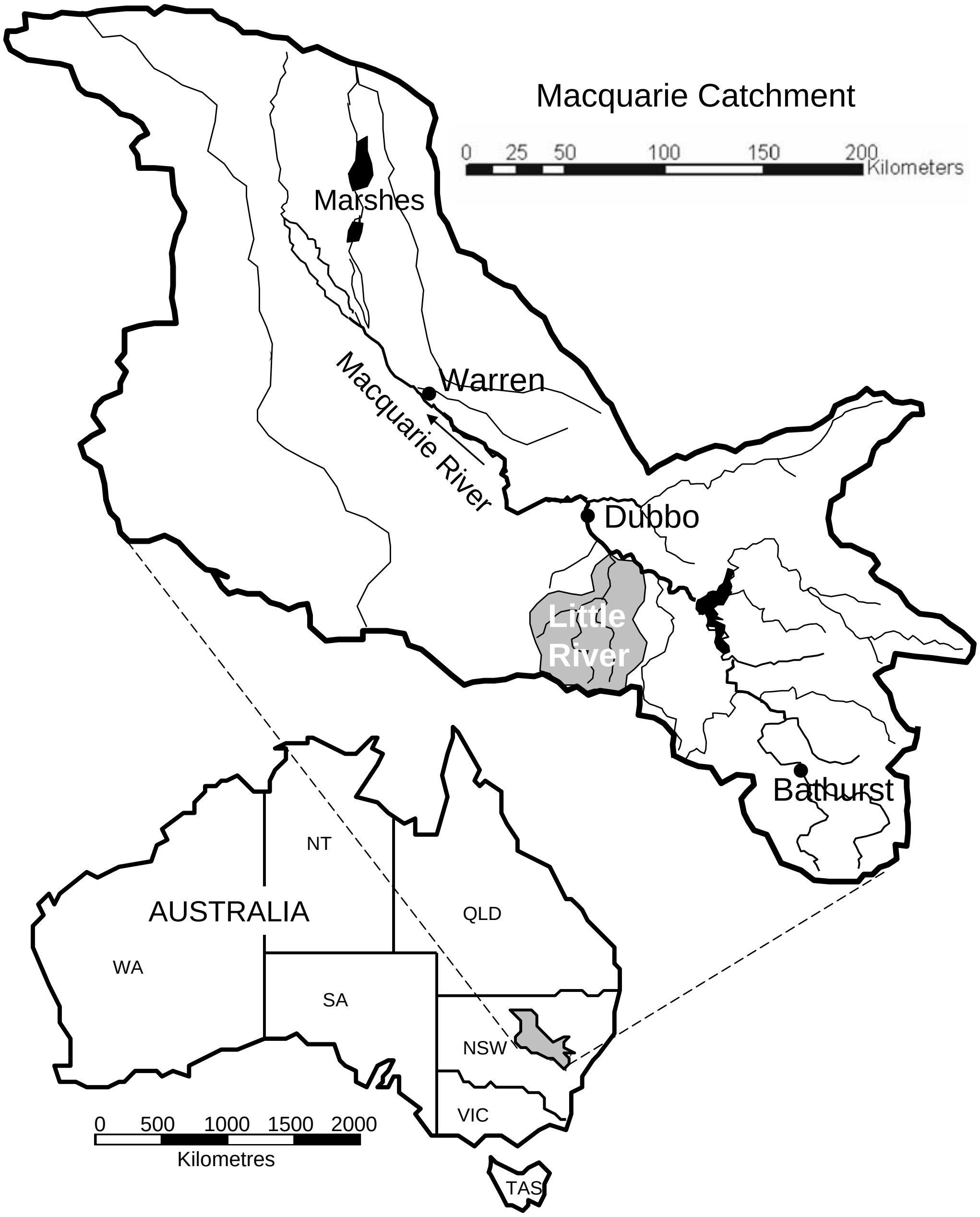

Figure 1. Little River catchment in the Macquarie River Valley of New South Wales, Australia

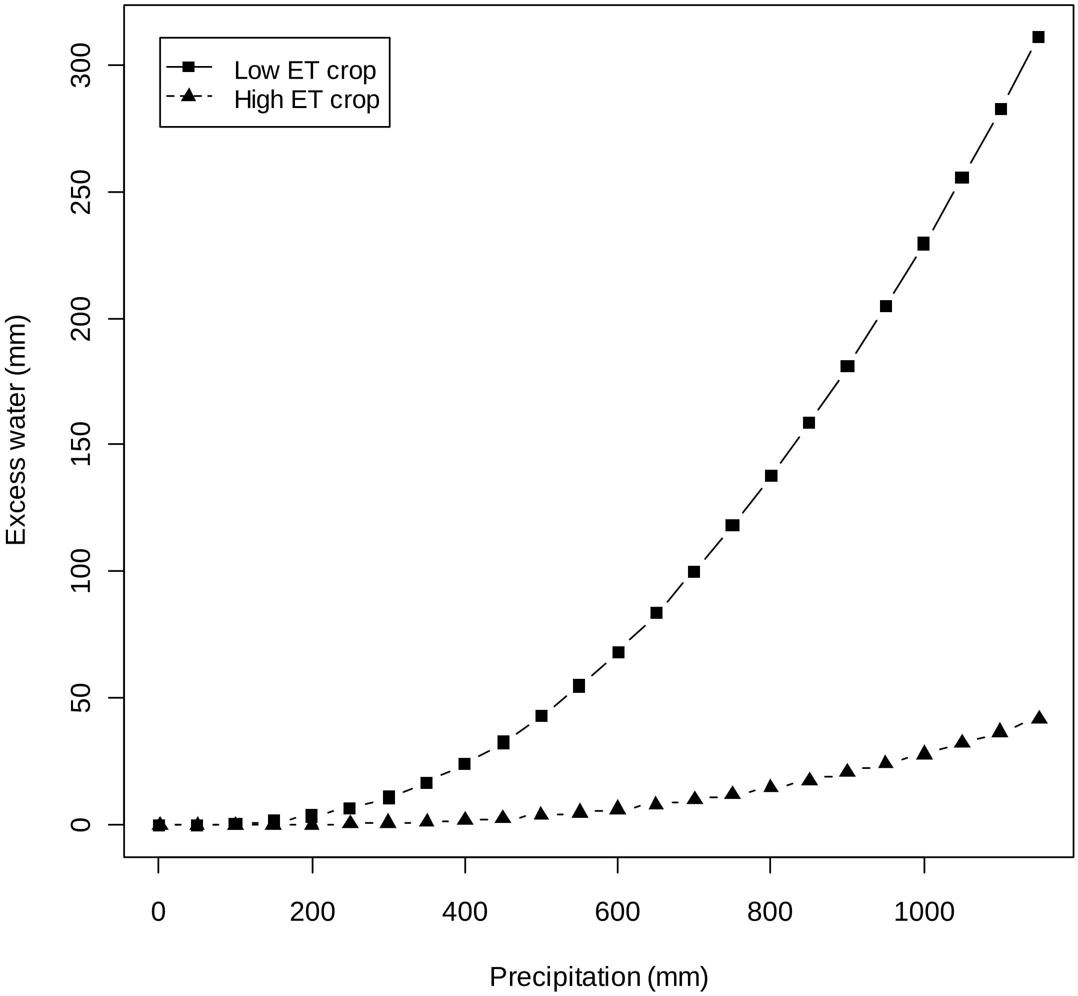

Figure 2. Excess water (mm).

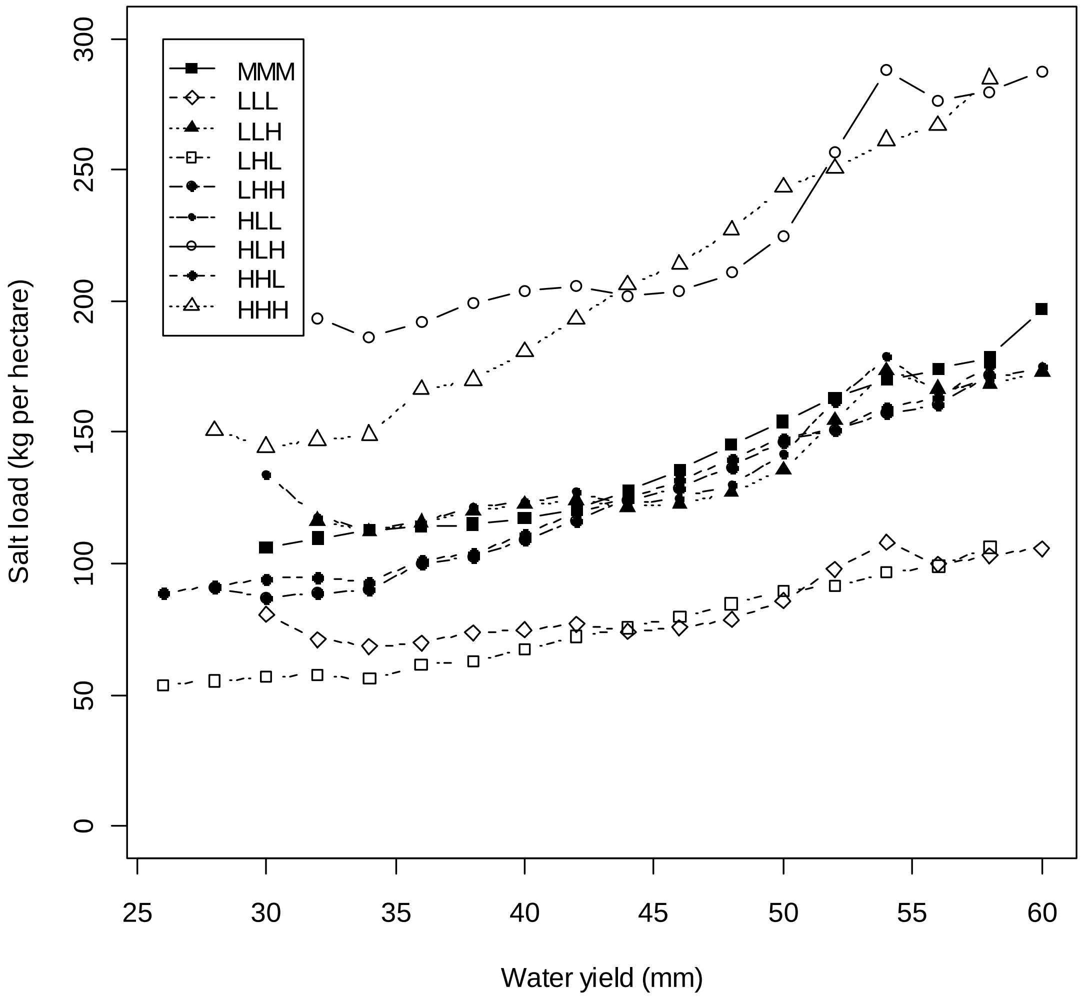

Figure 3. Sensitivity analysis: changes in salt exports at differing water yields, ground water salinities (*GWS*), forestry equivalences (*FE*), and drainage fractions (*Df*). The code MMM refers to medium or current *GWS*, *FE* and *Df*. LLH refers to low, low, and high - *GWS*, *FE* and *Df*, respectively.

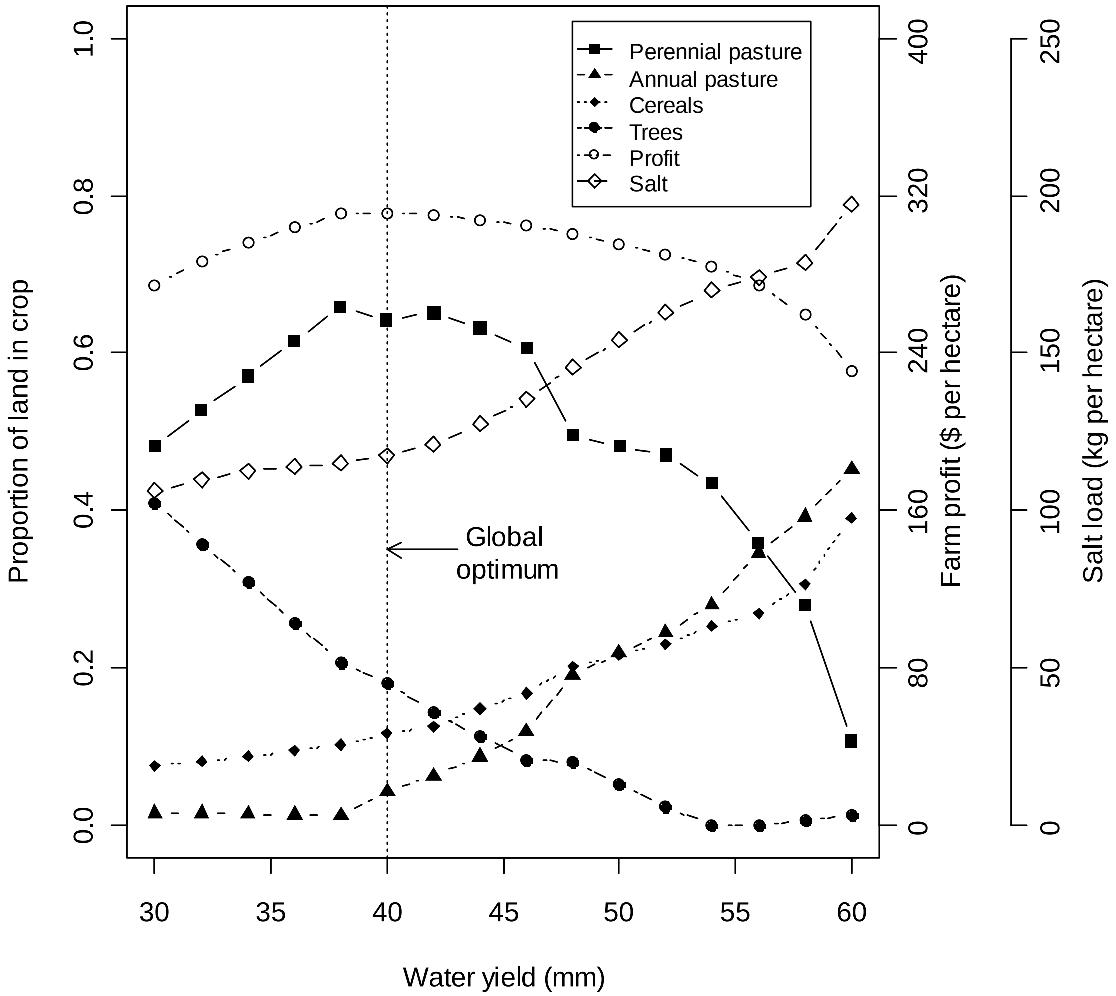

Figure 4. Changes in land use, profitability and salt exports to streams with changes in water yield.

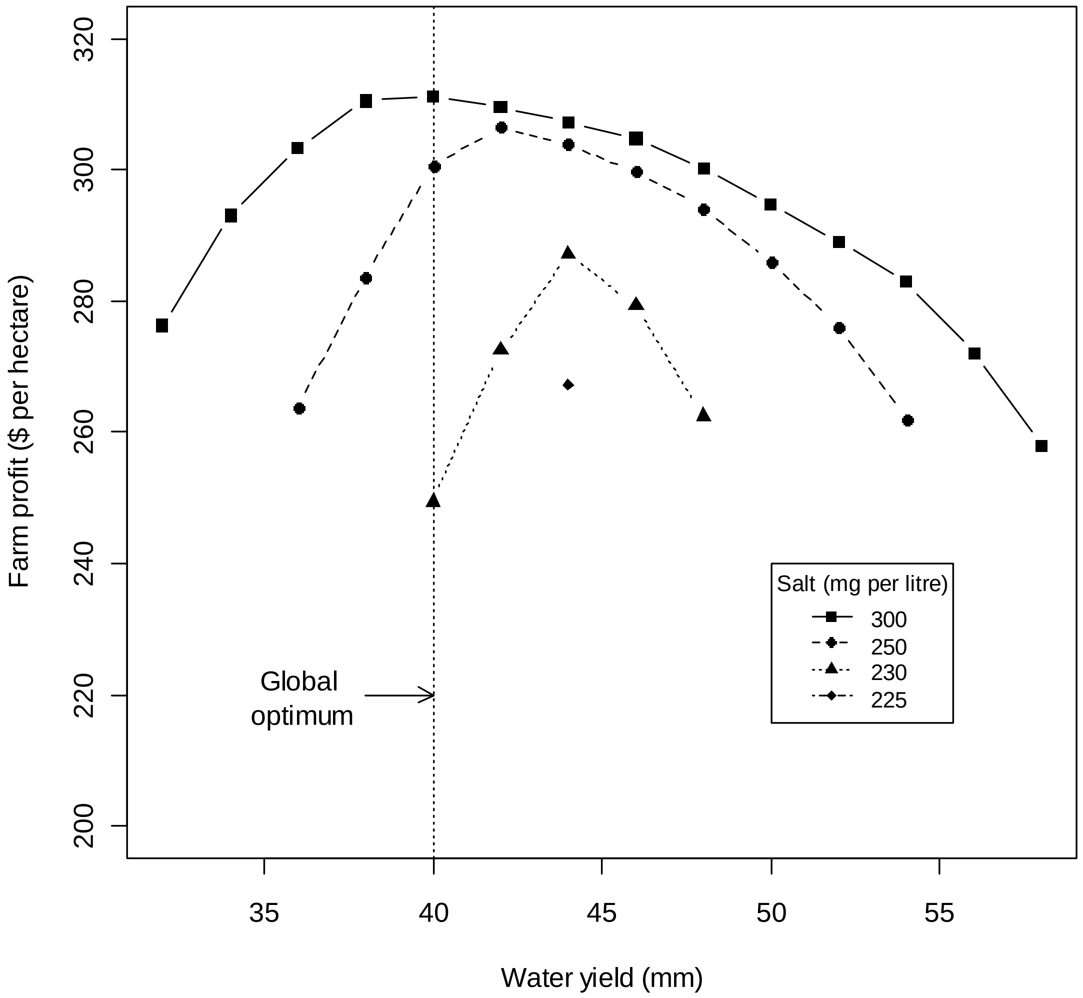

Figure 5. Change in farm profit with changes in salt concentrations and water yield.

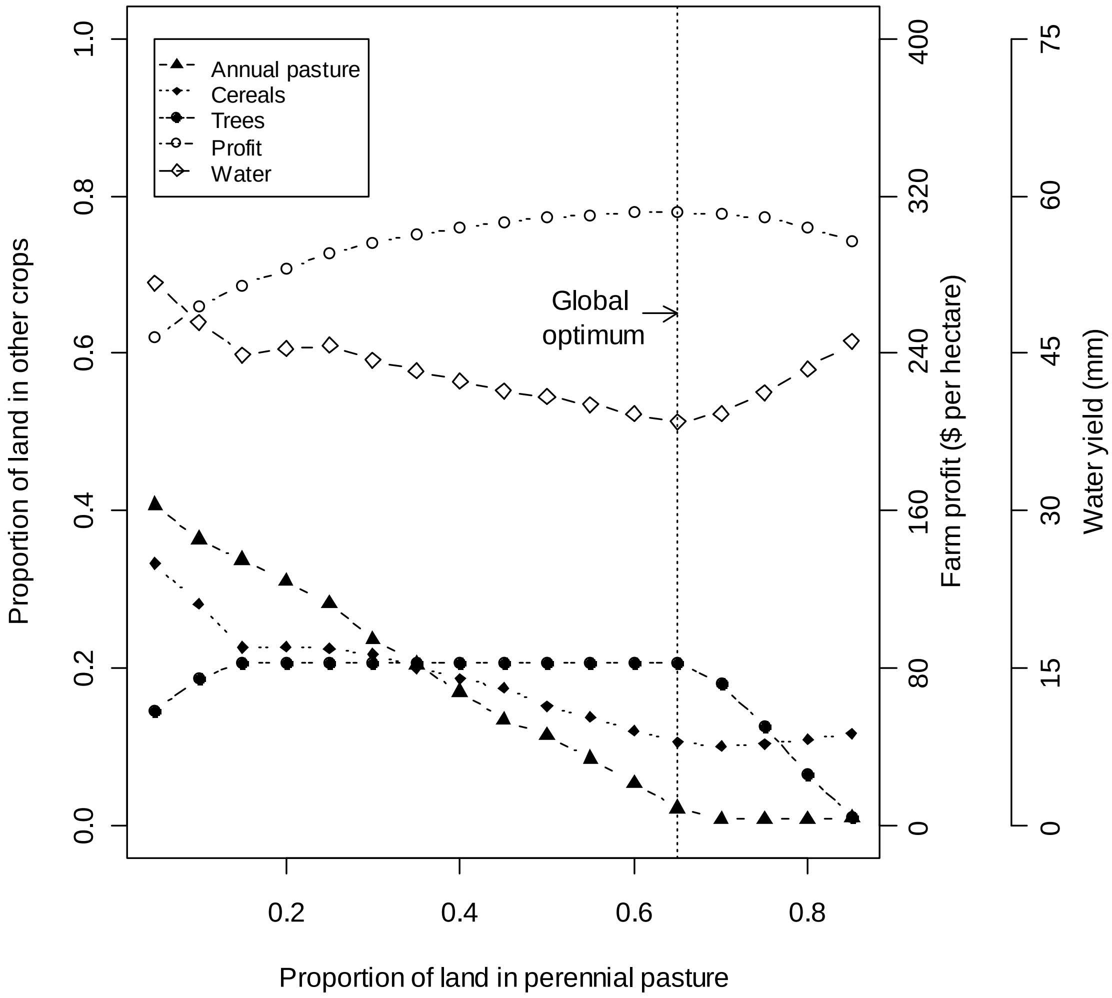

Figure 6. Changes in land use, profitability and water yield with changes in perennial pasture.

Table 1. Area of agriculture and of land affected by, or with a high potential to develop, dryland salinity in 1998-2000 by Australian State[1]

	000's Hectares		Saline land as a percentage of
State	Agricultural land[2]	Saline land[3]	agricultural land
New South Wales	64,802	181	0.3
Victoria	13,865	670	4.8
South Australia	56,110	390	0.7
Western Australia	117,138	4,363	3.7
Tasmania	1,752	54	3.1

---

[1] The area of salt affected and salt threatened land was not assessed in 1998-2000 for Queensland, Northern Territory, and Australian Capital Territory in the National Land and Water Resources Audit (2001).

[2] Estimated as the sum of Livestock grazing, dryland and irrigated agriculture (Australian Natural Resources Atlas, http://www.anra.gov.au/topics/land/landuse/index.html, seen 10-Oct-2009)

[3] National Land and Water Resources Audit (2001)

Table 2. Soil types and drainage fractions.

Soil	General description[4]	Df[5]
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

---

[4] Descriptions are taken from Murphy and Lawrie (1998). The soil sequence broadly corresponds to the transition of soils from crest top to valley bottom.

[5] Source: Dr Iain Hume, personal communication.

Table 3. Structure of catchment model.

		Results from farm model				Profit		Water		Salt			
Farm		1		2									
Strategy		1	2	1	2								
Period						1	2	1	2	1	2		
Land	Farm 1	1	1									=	1
	Farm 2			1	1							=	1
Profit	Period 1	$-\text{Profit}_{1,1,1}$	$-\text{Profit}_{1,2,1}$	$-\text{Profit}_{2,1,1}$	$-\text{Profit}_{2,2,1}$	1						=	0
	Period 2	$-\text{Profit}_{1,1,2}$	$-\text{Profit}_{1,2,2}$	$-\text{Profit}_{2,1,2}$	$-\text{Profit}_{2,2,2}$		1					=	0
Water	Period 1	$-W_{1,1,1}$	$-W_{1,2,1}$	$-W_{2,1,1}$	$-W_{2,2,1}$			1				<	0
	Period 2	$-W_{1,1,2}$	$-W_{1,2,2}$	$-W_{2,1,2}$	$-W_{2,2,2}$				1			<	0
	Total							1	1			=	W*
Salt	Period 1	$-S_{1,1,1}$	$-S_{1,2,1}$	$-S_{2,1,1}$	$-S_{2,2,1}$					1		<	0
	Period 2	$-S_{1,1,2}$	$-S_{1,2,2}$	$-S_{2,1,2}$	$-S_{2,2,2}$						1	<	0
	Total									1	1	=	S*
Objective function						1	1						