Exploring the optimal degree of internalising external costs:
The case of controlling soil salinisation in an Australian catchment.

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ABSTRACT

Externalities are commonly associated with farming activities. As small portions of landscapes, catchments and regions, farms are embedded in large-scale biophysical and ecological processes. Farm activities in upstream parts of catchments may have hydrological effects that affect the well being of people downstream. Human-induced soil salinisation is an externality problem based on catchment hydrology. This paper investigates the case of intra-sectoral externalities associated with soil salinisation in a dryland catchment in Eastern Australia.

Soil salinity develops in discharge areas of a catchment, caused by a rise of saline groundwater tables. It is commonly induced by land-use change in uphill areas which leads to increased recharge to the groundwater system of a catchment. Hydrological processes transcend artificial boundaries established by individuals property rights. From the perspective of affected landholders, the costs associated with soil salinity are external and should be internalised at their source. Taking a catchment viewpoint, the problem is not so simple. A number of questions arise. From a bio-physical perspective, can salinity be controlled? If so, from an economic efficiency perspective, should it be controlled? If so, to which extent should the externalities associated with uphill recharge be internalised and how could that be achieved?

A dynamic catchment optimisation model called SMAC is developed and applied to the case study catchment to answer the above questions. SMAC combines hydrological process description at the catchment scale with farm-scale economic analysis of agricultural land use.

This paper presents a conceptual understanding of the soil salinisation issue within a partial spatial equilibrium framework. It goes on to show and interpret the results of a series of SMAC scenario runs in the context of the internalisation question.
INTRODUCTION

Definition of the problem

Externalities arise when the activities of at least one economic agent lead to uncompensated physical and/or real economic impacts on other agents. They are, to a large extent, the result of interactions between human activities and the integrated physical and biological processes of the environment. They also tend to appear outside the sphere of defined property rights (Vatn and Bromley 1997).

Externalities are commonly associated with farming activities, the reason being that most farms cover only small areas of landscapes and regions. These areas are embedded in biophysical and ecological processes at the regional scale. Farm activities, in particular land use activities, have hydrological properties which may result in downstream effects. These effects may influence the well-being of people downstream, thus causing externalities.

Human-induced soil salinisation is an externality problem based on catchment hydrology. There are two forms of soil salinisation. Irrigation salinity is caused by irrigation water import and application in a catchment in excess of crop demand, resulting in rising and high groundwater tables. In the case of dryland salinisation the cause of increased accession to the groundwater system lies in the removal of deep-rooted native vegetation. This paper deals only with the issue of dryland salinisation which is emerging as a major resource degradation problem in dryland catchments around the world.

With changing agricultural practices globally, salinisation of land and water resources have become a major form of natural resource degradation in various regions of the earth (Ghassemi et al. 1995, Szabolc 1989). In Australia, human-induced salinity has increased dramatically over the past two decades. The estimated area of land affected by dryland salinity has risen from 0.4 million hectares in 1982 to 1.2 million hectares in 1993 (Robertson 1995). Up to five million hectares may eventually become saline in New South Wales alone (Bradd and Gates 1995).

Dryland salinisation is a land degradation process associated with high and rising saline groundwater tables in the low lying areas (discharge areas) of a catchment. In catchments with a hydrogeological predisposition, such as constrictions to groundwater flow, increased recharge to the groundwater system results in rising groundwater tables which
may mobilise rock salt and concentrate it in the root zone and on the soil surface. Increased recharge is caused by land-use change from deep-rooted and perennial vegetation to shallow rooted pastures and seasonal crops. Traditionally, much of this land-use change has occurred in uphill catchment areas which are the recharge areas of a catchment. Through lateral water movement, this additional recharge causes groundwater table rise in the discharge areas. In the process, salts are being mobilised and redistributed into the soil root zone and surface water, causing soil and stream salinity.

When the natural translocation of water from the recharge to the discharge area in a catchment causes soil salinisation, it results in costs to landholders in the discharge area. Soil salinity causes soil productivity, farm incomes and land values to decline. To the farmers in the discharge area, these costs are external costs.

Dryland salinisation can occur at a small scale, particularly related to a break of slope in a landscape. In comparison, the rise of saline groundwater tables under floodplains is a large-scale problem. The analysis presented here is concerned with the second type of dryland salinisation.

The methodology applied for the analysis represents an unbiased holistic approach to an economic assessment of dryland salinisation in the Liverpool Plains catchment, based on the best available understanding and data.

**Case study area**

The Liverpool Plains catchment covers an area of 1.2 million hectares in New South Wales in Australia. It is a sub-catchment of the Murray Darling Basin (Figure 1). More than 1000 farms operate in the catchment.

FIGURE 1 here

In the following description of the catchment, three hydrologically distinct areas become apparent. The catchment is semi-surrounded by mountain ranges called the Liverpool Ranges. The catchment is famous for and named after the vast black soil floodplains which are interspersed with sedimentary hills. Across the floodplains, which account for forty per cent of catchment area, a trend of decreasing depth of water table in bores is indicative for rising groundwater tables (Broughton 1994a,b). The groundwater is generally saline.
Since European settlement, the mountain ranges have been largely cleared for grazing. The sedimentary hills have also been largely cleared for grazing but also for cropping. More recently, the black soil plains have largely been converted from natural pasture to dryland farming. In some areas groundwater is pumped for irrigation of crops. These areas show declining water tables.

Broughton (1995) estimates that 30,000 hectares of the plains have groundwater tables less than two metres from the soil surface and show symptoms of varying degrees of salinisation. An additional 165,000 hectares of land have a groundwater table between two and five metres from the soil surface. The combined area of 195,000 hectares is classified as being at risk of becoming saline. If the observed rate of groundwater table rise, ranges between 5 and 50 centimetres per year across the plains, were to continue, the entire area at risk could become salt-affected within three decades.

Greiner (1996a) showed that, while current dryland cropping systems on the floodplains also contribute recharge to the groundwater system, the majority of costs of dryland salinisation are external to the affected farms. A model analysis of salinity-affected farms shows the level of costs associated with various scenarios of rate of groundwater table rise. In comparison to a hypothetical situation where salinity did not occur, an externally imposed rate of groundwater table rise of 10 and 30 centimetres per year causes the loss of 17 and 48 per cent of cumulative net income, respectively, over a period of 10 years after emergence of salinity. The income loss results from the combination of productivity decline caused by salinity and management activities that seek to control the advance of salinisation. If salinity were caused by farm-internal recharge only, as expressed in an externally imposed groundwater table rise of zero, the comparative income reduction would be less than five per cent.

In isolation, these findings seem to indicate that groundwater table rise should be managed at its very source, by reducing recharge in uphill areas to a level that does not cause groundwater table rise and consequently dryland salinisation. However, from a catchment perspective, the issue is not so clear because trade-off decisions arise at various levels. Firstly, should salinity be controlled or would it be more economical to allow (some degree of) salinisation? Secondly, who should engage in the salinity control activities and bear the associated costs, would it be landholders in the discharge areas or in the uphill (recharge) areas of the catchment? Thirdly, which management activities,
from a range of potential activities, should be implemented, where, to which extent and when?

Managing salinity: an externality problem

In a management sense, there are two general approaches to salinity control. First, the causes of salinisation can be addressed biologically through land use practices that reduce groundwater recharge rates. They include adopting opportunity cropping and reduced-fallow rotations, introducing perennial and saltbush pastures and establishing trees or allowing their regeneration. These options can be applied in the recharge area in an effort to reduce recharge rates. They can also be applied in the discharge area of the catchment in an effort to enhance the discharge of groundwater through plant transpiration. Second, engineering options may be applied to remove water from rising aquifers, thus addressing the symptoms of the problem.

From an economic perspective, there are also two principal approaches to dealing with externalities, the Pigovian and Coasean approaches. The standard Pigovian approach to an externality problem is to make the emitters, the source of the physical dimension, liable for the economic damage that the receiver incurs (Pigou 1946). The underlying logic is that physical causation determines efficiency. In the case of dryland salinisation, the emitters are the uphill farmers whose land-use activities generate salinity-provoking recharge to the groundwater system.

However, taking into consideration the benefits to society from the economic activities of emitters and receivers, it may not be Pareto-optimal to cut emissions to zero. Scheele (1996) demonstrates for the conflict between agricultural production and groundwater quality, the avoidance of external costs leads to a socially sub-optimal resource allocation. He concludes that there are externalities involved not only in production but also in damage control.

As the mechanism for internalising external costs to the Pareto-optimal level Pigou suggests the introduction of a tax on the emission. In the case of dryland salinisation, this would be a recharge tax. Making the emitter liable and imposing an emissions tax would create the necessary and sufficient conditions for restoring optimality. It would be Pareto optimal to tax the emitter at the level where the marginal damage of one unit of emission equals its marginal abatement cost.
However, Vatn and Bromley (1997:141) argue that a Pigovian tax may not be an efficient and least cost measure for correcting externalities. They argue that while it may be morally right to make the emitter liable, it is not always ‘efficient’ to put a tax on this side of the conflict. They conclude that while the endorsement of externalities as a moral issue implicit in Pigou’s policy rule is appropriate, the explicit claim of advancing a value free and objective efficiency rule is contradictory.

The Coasean approach is not concerned with physical causation or morals. Rather, it argues that an efficient dealing with externalities requires determining which party could change behaviour most cheaply (Coase 1960). This could be achieved most efficiently through bargaining and the establishment of a market. Applied to dryland salinisation, the Coasean approach could translate into a market for recharge entitlements. These entitlements would be issued to uphill and plains farmers. Through trade within the catchment, a price for recharge entitlements would evolve that reflects the optimal level of recharge. It would be equivalent to the marginal benefit from recharge-generating land-use practices uphill and the marginal costs of associated groundwater table rise to farmers in the discharge zone.

Basically, the Pigovian and Coasean approaches derive at the same solution (Pareto-optimum) where the marginal social damage equals the marginal social abatement cost. However, the income distribution effects are quite different. With the Pigovian approach, the emitter pays a tax while with tradeable permits the distributional effects depend largely on the initial distribution of permits.

Vatn and Bromley (1997:142) interpret the Coasean position as one where, given an initial allocation of entitlements, the only relevant element in considering judgments about responsibility for action is the level and incidence of transaction costs. Transaction costs are either so high that no change in outcomes is deemed ‘efficient’, or transaction costs are low enough, at least for one side, to permit a bargained transaction. However, there are also costs attached to the Pigovian tax system.

Summing up the above thoughts, the physical process of emission does not immediately equate to an externality. Rather, there are conditions attached which cause the externality to come into being. Externalities do not necessarily represent market failure and it may not be efficient to internalise external costs. If an existing level of externalities is not
Pareto-optimal, choice of approach and policy specification should consider all policy-related costs.

Applied to the case of dryland salinity, there might not be a case that salinity should be controlled at a zero level or controlled at all. The presence of externalities can be interpreted as a rational outcome. Randall (1983:137) explains that ‘the non-existence of certain markets is a rational market response to transaction costs in excess of potential grains from trade’.

Following these considerations, this paper explores to which extent the physical external effects associated with dryland salinisation in the Liverpool Plains catchment represent real externalities and should therefore be internalised. If the catchment’s ability to absorb recharge to the groundwater system is regarded as a resource, the question arises how this resource can be used more efficiently, given the present day situation.

**METHODOLOGY**

**Abstraction of the problem**

For the purpose of this study, the catchment is disaggregated into four areas. They are characterised by maximum internal homogeneity in hydrological, topographical and productivity characteristics with maximum heterogeneity between them. The four areas are called Dryland Plains, Irrigated Plains, Liverpool Range and Sedimentary Hills.

Two of these areas represent the uphill or recharge areas or the catchment. The Liverpool Range and the Sedimentary Hills are the major source areas of recharge to the regional groundwater system. They represent 20 and 40 per cent of the catchment, respectively.

The remaining 40 per cent of the catchment area are plains with a slope of no more than one per cent. The plains are the area affected by rising saline groundwater tables and emerging secondary salinisation. The model differentiates between the Dryland Plains and the Irrigated Plains. The Irrigated Plains is defined as a subset of the plains where the main aquifer yields sufficient quantities of low-salinity water to allow irrigation from groundwater pumping. It covers one fourth of the total plains area or one tenth of the catchment, not all of which is in fact irrigated. The Dryland Plains is the plains area with dryland farming only. It accounts for 30 per cent of the catchment area. Most of the area
classified as being ‘at risk’ from soil salinisation is located within the *Dryland Plains*. Where the paper refers to both areas, this is indicated through the general term *Plains*.

The four areas are connected spatially through surface and groundwater flows. Figure 2 illustrates these flows. The present understanding of hydrological processes assumes that most recharge in the *Liverpool Range* and *Sedimentary Hills* flows laterally, as shallow groundwater, and joins the groundwater system under the *Plains*. This groundwater pool receives additional water from surface runoff from the *Liverpool Range* and, to a lesser degree, the *Sedimentary Hills* through incompetent creeks. These creeks carry water across the plains only after heavy rain but otherwise disappear at the edge of the plains, directly recharging the groundwater aquifers.

**FIGURE 2** here

Taking an economic approach, this situation can be conceptualised in a framework whereby land use practices associated with maximum profit from agriculture in the uphill areas (\(P^u\)) generate a level of recharge \(R_p\), as shown in Figure 3a. This can be interpreted as the present level of uphill recharge, assuming profit maximising behaviour on behalf of the uphill farmers in the given institutional framework.

Recharge in the uphill areas causes salinisation in the discharge zone of the catchment and consequently reduced profit from agriculture in that area. Consequently, avoidance of uphill recharge can be interpreted as a profit to the catchment through salinity prevention (\(P^d\)). Accordingly, the difference between the maximum profit for the catchment from uphill recharge control and its actual level can be interpreted as opportunity costs associated with uphill land use (\(O^u\)). These opportunity costs equate to the external costs that plains farmers incur from soil salinisation. The present level of uphill recharge \(R_p\) is associated with opportunity costs of the magnitude \(O^u_p\). The total profit to the catchment from present uphill land use is \(P^c_p\).

**FIGURE 3** here

Figure 3a indicates that from a catchment perspective the present situation is sub-optimal. There is scope for welfare gains to the catchment through increasing the level of recharge control by uphill farmers, thereby reducing recharge to level \(R_c\). Figure 3b illustrates that a further reduction of recharge below the level \(R_c\) would result in marginal costs of the
catchment because the associated loss of profit from uphill production would outweigh the gain from downstream salinity control.

It is also obvious from Figure 3a that at the catchment optimum, the opportunity costs of uphill land use are not reduced to zero but to the magnitude $O^{o_u}$, which is equivalent to a level of externalities $E_0$. This means that the level of externality $E_0$ is Pareto-irrelevant. Only the level of present externalities $E^*$ is Pareto-relevant. Pareto-relevant externalities describe the proportion of externalities which, if avoided, increase social/catchment well-being (Buchanan and Stubblebine 1962).

A model is developed to quantitatively describe the above relationships for the case of dryland salinity management in the Liverpool Plains catchment.

Spatial optimisation model for analysing catchment management issues

Systems analysis is proposed as an adequate approach for exploring a complex dynamic system such as dryland salinity management in a catchment. The systems framework has to capture the idiosyncrasies of dryland salinisation and link farm-level decision making and catchment-scale hydrological process description (Greiner and Parton 1995).

The systems analysis is embedded in a partial spatial equilibrium framework (Lambert 1985; Baumol 1977). For the purpose of quantifying externalities, the model must be able to price recharge. The spatial boundary of the dryland salinisation problem is the watershed which requires the model to be a catchment optimisation model. If the area of productive land which is at risk of becoming saline is considered a finite resource, then salinisation is a process of depleting it and the salinity encroachment rate equals the rate of resource depletion.

The model built for the purpose of investigating salinity management at the catchment scale is called SMAC (Spatial optimisation Model for Analysing Catchment management). It captures the relationships between agricultural land use, groundwater flows and tables, and salinity at a catchment level (Greiner 1996b).

The normative approach constitutes a dynamic computable partial equilibrium model. While spatial equilibrium models usually determining commodity prices, SMAC prices recharge to the groundwater system endogenously to determine the optimal level of
recharge and salinisation. Of particular interest are trade-offs between the costs of preventing salinisation and the costs resulting from salinisation (Salerian 1991). Other trade-offs are between the different options for water table control and between activities in the plains and activities in the recharge areas.

Optimisation creates a vision for the catchment. This vision provides an understanding of the optimal spatial and temporal pattern of land use across the catchment, hence facilitating the development of a catchment management strategy. It reveals which changes to the current land use pattern ought to be made. It also explores whether there is an optimal level of salinisation under the assumed economic conditions and what this level is.

The four areas within the Liverpool Plains catchment described above are distinct with respect to land productivity and hydrogeological characteristics. Each area is also represented by a model farm with specified land, labour and capital resources. The description of the prevailing farm organisation and land-use systems is based on data collected in a farm survey (ABARE 1996). Fifty-eight survey farms were located in the catchment and grouped into four model farms, given their recorded location in the catchment with respect to the four land areas identified. Appendix 1 gives a description of the model farms. The land use options of each farm are associated with yields, recharge and runoff which are defined through their area association. This area association also means that the farms are linked spatially and temporally through and flows of ground and surface water.

The objective function (Equation 1) of SMAC maximises the welfare of the catchment as represented by the total discounted income \( TNPV \) from farming in the catchment over the optimisation period \( T=\{t|1,\ldots,T\} \). The optimisation period is 30 years.

All farms \( I=\{i|1,\ldots,I\} \) located in the catchment have income functions which are defined in terms of the productivity of their resource base. Only a subset of farms \( J=\{j,1,\ldots,J\} \) with \( J \subseteq I \) lie within the discharge area. Catchment income is a function \( R \) of the potential productivity of the farms’ land resources \( L \). The \( C \) function captures land productivity loss and therefore income decline through salinisation \( S \). At the end of the planning period, salt-affected land incurs a 'penalty' because of its reduced land value. This reduction of asset value through resource degradation is expressed in \( V \). A discount rate \( r \) applies.
Max \( TNPV \)

\[
= \sum_{i,T} \left( R_i(L_{i,t}) - C_i(S_{i,t}) \right) (1 + r)^{-t} - V_i(S_{i,T+1}) (1 + r)^{-(T+1)}
\]

\( t = 1,...,T \)  \hspace{1cm} (1)

The spatial effects associated with the hydrological connections between areas are considered the major specifying condition in this optimisation framework. An initial salinity status \( S_{j1} \) is given for each farm in the discharge area (Equation 2).

Salinity encroachment on a farm is specified as a function of the land use on farm \( j \) and the land use of the surrounding farms \( i \) (Equation 3). A time lag factor \((t-1)\) applies to account for the dynamic component in the biophysical process.

\[
S_{jt} = \bar{S}_{j1} \hspace{1cm} t = 1 \hspace{1cm} (2)
\]

\[
S_{jt} = S_{jt-1} + f_j \left( L_{jt-1}, L_{i,t-1}, j \neq i \right) \hspace{1cm} t = 2,...,T \hspace{1cm} (3)
\]

To derive the optimal solution of the optimisation problem, the model is converted into its modified Lagrangian Form \( (L^*) \) where \( \lambda \) is the discounted Lagrangian variable denoting the shadow price of soil salinity (Equation 4) (Lambert 1985, Baumol 1977).

Max \( L^* \)

\[
= \sum_{i,T} \left( R_i(L_{i,t}) - C_i(S_{i,t}) \right) (1 + r)^{-t} - V_i(S_{i,T+1}) (1 + r)^{-(T+1)}
+ \lambda_{t-1} \left( S_{jt} - \bar{S}_{j1} \right)
+ \sum_{t=2}^{T} \lambda_{jt} \left( S_{jt-1} + f_j \left( L_{jt-1}, L_{i,t-1}, j \neq i \right) \right) \hspace{1cm} t = 1,...,T \hspace{1cm} (4)
\]

Applying the Kuhn-Tucker conditions by forming first order derivatives of the Lagrangian to all positive variables, the optimal solution and therefore the optimal level of salinisation is given, where the marginal cost of salinisation is equal to or greater than the net present value of income from the land use that causes the marginal hectare to salinise, in or outside the salinisation zone. The optimal level of salinity at the end of the
optimisation period is given where the marginal cost of salinisation equals the associated reduction in capital value of the land resource.

**Key data and assumptions**

Figure 2 schematically outlines the hydrological connections between the four areas within the catchment. The quantitative expression of these connections is the single most critical biophysical assumption in SMAC. The quantification of those connections is based on best available information and expert opinion. The assumptions are outlined in Table 1.

<table>
<thead>
<tr>
<th>Table 1: Hydrological connections between the catchment areas</th>
</tr>
</thead>
<tbody>
<tr>
<td>(proportion of recharge and runoff in recharge areas contributing to groundwater pool in discharge areas)</td>
</tr>
<tr>
<td><strong>Recharge areas:</strong></td>
</tr>
<tr>
<td><strong>Type of water connection:</strong></td>
</tr>
<tr>
<td>Recharge and lateral shallow groundwater flow (%)</td>
</tr>
<tr>
<td>Runoff infiltration depending on in-season rainfall (%)</td>
</tr>
<tr>
<td>Very dry season</td>
</tr>
<tr>
<td>Average season</td>
</tr>
<tr>
<td>Very wet season</td>
</tr>
</tbody>
</table>

The connections are quantified in terms of the proportions of total recharge and runoff (from the uphill areas) which join the groundwater pool under the plains. It is assumed that the Liverpool Range is of more significance as a recharge area than the Sedimentary Hills due to hydrogeological characteristics and geographical location. Similarly, runoff infiltration is greater from the Liverpool Range due to the higher rainfall. Runoff infiltration is also season-dependant. So called ‘incompetent creeks’ coming from the Liverpool Range will flood only in wet seasons, taking runoff water across the plains. In average and dry years the creeks do not flow. Instead, the water which they carry infiltrate on the footslopes where the uphill areas meet the plains, adding to the groundwater pool under the plains. SMAC deals with climatic variability through a discrete stochastic programming approach which is detailed in Greiner (1997).
Model validation and critique

Limitations of SMAC currently include its coarse resolution, the application to salinity as the only natural resource management issue, and the preliminary character of the hydrological assumptions. The spatial resolution of the model can be increased significantly given its GIS-like design (Greiner 1996b) if data are available to support additional detail. Limited quantitative understanding of the hydrological connections within the catchment has been the major limiting factor to spatial disaggregation and forced a re-aggregation of initially eleven areas within the catchment to the four area units portrayed earlier. Confidentiality of farm survey information and sampling density are factors limiting the spatial resolution of farm economic data.

The modular structure of the model enables a widening of scope through the inclusion of other natural resource management issues that concern the catchment such as soil erosion and surface water management.

The model has been calibrated to replicate the expectations of hydrologists that the maximum area at risk from salinisation will become salt-affected over three decades if land-use practices do not change (Broughton 1994a,b).

A major caveat is that SMAC has not been fully validated due to lack of empirical data. Given its high level of abstraction which results from the attempt to contrive highly complex and interactive relationships in an open system environment, it is impossible to design statistically based experiments to confirm model results. However, all model aspects and data were verified and the consistency of the mathematical framework was tested. Also, recent hydrological modelling experiments seem to convey the same messages. The methodology represents an unbiased holistic approach to an economic assessment of dryland salinity in the Liverpool Plains catchment, based on the best available understanding and data.

RESULTS

This paper presents one set of SMAC model runs. As a basis for comparison, a ‘business as usual’ scenario is simulated to establish the development of salinisation in a situation where present land use patterns are maintained into the future irrespective of high water tables and soil salinisation.
This result is compared to three optimisation runs that assume average rainfall conditions. Proposed land-use changes and corresponding development of salinisation are shown. These simulations represent a sensitivity test of the economically optimal level of salinity in the catchment depending on the costs assumed. The results are interpreted in the context of marginal cost analysis.

Under the “business-as-usual” scenario the model simulates a linear development of salinisation and estimates that 191,000 hectares will be salt-affected at the end of the planning period (Figure 4). This simulation replicates the concern of hydrologists that, if landholders were to ignore the salinity hazard, the entire area at-risk could be salt-affected within just over three decades. This development can be interpreted as continuous mining of a finite soil resource, which is the area at risk of soil salinisation, until exhaustion of the resource.

The other three trajectories shown in Figure 4 are the result of optimisation runs. They vary in that they incrementally increase the cost of soil salinisation, adding other cost components. Scenario C1 accounts only for the costs of salinity caused by the loss of soil productivity. Scenario C2 also takes into consideration costs associated with a loss of capital value of salt-affected land. Scenario C3 also takes into account further costs of salinisation.

An important observation in Figure 4 is that all optimisation trajectories are well below the “business-as-usual” line. This indicates that the rate of ‘mining’ of the land resource in the “business-as-usual” scenarios is far above the economically optimal rate of exploitation. Even if it is assumed that costs from salinity arise only from lost agricultural production (scenario C1), the rate of ‘mining’ of the soil resource through salinisation is halved in comparison to the “business-as-usual” scenario.

The higher the costs associated with soil salinisation, the lower is the area of salt-affected land that is accepted in the optimal solution at the end of the planning period. For a capital value of $3800 per hectare at the end of the planning period in scenario C2 (equivalent to a net present value of $500 at an assumed discount rate of 7 per cent), salinity reaches a steady state situation halfway through the planning period when the
salt-affected area stabilises at 38,000 hectares. This is little more than the area estimated to show some signs of salinisation already.

When additional costs from salinisation are taken into consideration in scenario C3, associated with downstream effects and infrastructure damage, the model indicates that a total control of salinisation would be economical. The initial development of some level of (reversible) salinisation is due to the time lags associated with hydrological responses to land management changes.

Managing the groundwater balance for controlling dryland salinisation requires significant changes to the current land-use system. Given the economic and hydrological parameters that characterise the land-use options in the four areas, the SMAC results suggest that land-use change should focus on the **Dryland Plains** where salinity occurs. Some land-use change is recommended in the **Liverpool Range**, being the major recharge area. They involve the replacement of cropping on the foot slopes with permanent pasture. Figure 5 shows the suggested land-use changes in those two areas for scenario C2. The various changes to the present land-use system in the **Dryland Plains** are a combination of response to salinity and groundwater table control measures. The land-use changes are implemented quickly, over a period of less than ten years. In the model runs, land use in the **Irrigated Plains** and the **Sedimentary Hills** remains largely unchanged from the present day situation. This does, however, not suggest that land-use change in those areas may not be advisable on the basis of other considerations.

**FIGURE 5**

Land-use change focuses on the re-introduction of deep rooted, salt-tolerant native species into the landscape. In the **Dryland Plains**, saltbush pasture is adopted on salt-affected cropping land and replaces conventional pasture, lucerne becomes a more important part of crop rotations and a proportion of the current cropping and pasture area is planted to salt-tolerant trees for groundwater table management. The change from cropping to pasture in the **Liverpool Range** contributes more than one fifth to the reduction in recharge on the **Dryland Plains**.

The recharge and runoff reductions associated with the suggested land-use changes are significant (Table 2). In the optimisation runs, the contribution of the **Liverpool Range** to managing the catchment’s water balance is a recharge reduction by 24 per cent of the
initial value, equivalent to 98,000 megalitres or 38 millimetres per square metre and year. Runoff is reduced by 10 per cent, equivalent to 44,000 megalitres or 12 millimetres per square metre and year. The result is a reduction of the effective additions to the groundwater system under the Plains areas from 394,000 megalitres to 314,000 megalitres per year (-20 per cent).

The land-use changes in the Dryland Plains achieve a discharging water balance, represented by negative numbers in the recharge column in Table 2. This is the result of the newly introduced deep-rooted vegetation that transpires more water than the area receives from rain, thereby drawing on groundwater for transpiration. While the discharge balance of 65,000 megalitres in scenario C1 does not stop the encroachment of salinisation, a further increase to 131,000 megalitres sees salinisation controlled at a low level in scenario C2. It takes another, substantial, increase in the transpiration capacity of the vegetation in scenario C3 to increase the discharge balance to a level where groundwater tables in the Dryland Plains decline and the initial symptoms of salinisation are reversed.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Dryland Plains Recharge</th>
<th>Dryland Plains Runoff</th>
<th>Liverpool Range Recharge</th>
<th>Liverpool Range Runoff</th>
</tr>
</thead>
<tbody>
<tr>
<td>Business as usual</td>
<td>75</td>
<td>61</td>
<td>389</td>
<td>310</td>
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<tr>
<td>Scenario C1</td>
<td>-65</td>
<td>45</td>
<td>291</td>
<td>266</td>
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<tr>
<td>Scenario C2</td>
<td>-131</td>
<td>40</td>
<td>291</td>
<td>266</td>
</tr>
<tr>
<td>Scenario C3</td>
<td>-219</td>
<td>31</td>
<td>291</td>
<td>266</td>
</tr>
</tbody>
</table>

These results indicate that a large proportion of the recharge and runoff associated with uphill land use in the Liverpool Plains catchment is Pareto-irrelevant: it remains under optimality conditions. The outcomes suggest that, from a catchment perspective, it is efficient that the majority of costs associated with dryland salinisation and its control should be borne by the Dryland Plains.

The reason for a focus of activity on the Dryland Plains is obvious if the dual solution of the scenario runs is taken into consideration. Figure 6 shows the marginal cost per megalitre of recharge for the Dryland Plains and the Liverpool Range. The marginal or
dual cost is an expression of the impact of an additional megalitre of recharge on the total net present value of agricultural production in the catchment over the planning period.

FIGURE 6 here

The marginal cost of one megalitre of recharge generated in the Dryland Plains, due to its full and immediate impact on the groundwater table and consequently salt-affected area, is significantly larger than the marginal cost for the same volume of recharge generated in the Liverpool Range.

The dual cost or recharge is higher in the first year than in subsequent years. This can be explained by the first-year condition applicable to all scenario runs which forces the model farms to adopt the present land-use systems. From a catchment perspective, these land-use systems are obviously not optimal. Dual costs decline over the optimisation period for two reasons. First, a discount rate applies to agricultural income. Second, recharge at the beginning of the optimisation period has, once the threshold groundwater levels for salinisation are exceeded, a longer lasting effect on the productivity of the catchment’s soil resources than recharge that occurs later in the optimisation period.

Compared to scenario C1, the marginal costs of recharge are higher in scenario C3 where a more comprehensive costing of soil salinisation is adopted. The marginal costs remain on a high plateau towards the end of the optimisation period because the additional costs are costed in the final year.

CONCLUDING REMARKS

The paper reports the results of an economic model analysis for the Liverpool Plains catchment in Australia where soil salinisation in the discharge areas is a major natural resource management issue. To farmers in the Dryland Plains, the area where dryland salinisation occurs, the costs associated with salinity are external because the underlying cause is recharge generated by land use in uphill areas. This causal relationship is taken as an argument for recharge control in the uphill areas, along the lines of the Pigovian morale that emitters are liable for the damage resulting from their emissions.

From a catchment perspective, the issue of salinity management is more complex. Questions have to be asked and answered as to whether salinity control is possible and if
so, to which extent salinity should be controlled given the cost associated with both, salinisation and its control. Subsequently the externality issue must be addressed because externalities are, *per se*, not necessarily Pareto relevant. It may be more efficient to engage in salinity control in discharge areas. The final question is how the Pareto-relevant externalities are best internalised, whether a recharge tax or tradeable recharge entitlements may provide a solution given the costs associated with alternative policies. One potential outcome may be that the transaction costs associated with any of these approaches are too large to justify a (economically based) recommendation for policy initiative.

A dynamic catchment optimisation model, SMAC, was developed to provide answers to these questions. The model forms an abstraction of a complex catchment management system. It integrates catchment-scale hydrological process description, on the basis of best available hydrological information, and farm-scale decision-making considerations. The scenario runs presented in this paper provide answers to the above questions except the last one about how to internalise Pareto-relevant externalities. The results indicate that from a catchment perspective, it is important to control salinisation at a level that is a fraction of the area at risk. The results recommend that changes in land-use in the uphill areas should support catchment-scale groundwater management but the majority of salinity control activities should focus on the areas at risk from salinisation. A large proportion of the externalities associated with uphill recharge are not Pareto relevant. The time lag in a hydrological response to land-use changes is significant and land-use changes should be implemented quickly for maximum effectiveness.

To increase the confidence in the results and the emerging messages, an update of the hydrological parameters and a re-run of the model is planned as soon as better information becomes available. More confidence in the parameters is also important to engage in the second phase of the analysis which is to investigate alternative policies for implementing the recommended land-use changes.

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### Appendix 1: Major characteristics of the typical farms: average per farm

<table>
<thead>
<tr>
<th></th>
<th>Dryland Plains</th>
<th>Irrigated Plains</th>
<th>Liverpool Range</th>
<th>Sedimentary Hills</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mean</td>
<td>rse</td>
<td>mean</td>
<td>rse</td>
</tr>
<tr>
<td>Area of holding (ha)</td>
<td>1000</td>
<td>(17)</td>
<td>960</td>
<td>(12)</td>
</tr>
<tr>
<td>Cropping area (ha)</td>
<td>800</td>
<td>*</td>
<td>800</td>
<td>*</td>
</tr>
<tr>
<td>Irrigated area (ha)</td>
<td>0</td>
<td>(na)</td>
<td>270</td>
<td>(37)</td>
</tr>
<tr>
<td>Number of cattle</td>
<td>130</td>
<td>(23)</td>
<td>100</td>
<td>(25)</td>
</tr>
<tr>
<td>Debt ($’000)</td>
<td>100</td>
<td>(39)</td>
<td>285</td>
<td>(28)</td>
</tr>
<tr>
<td>Land value ($m)</td>
<td>1.0</td>
<td>(18)</td>
<td>2.0</td>
<td>(16)</td>
</tr>
</tbody>
</table>

Relative standard error (rse) is a measure of the variability of sample survey data (ABARE 1996). No relative standard error can be calculated for cropping area (*) as this is not a survey estimate but derived from other data sources.
Figure 1: Locality map of the Liverpool Plains catchment
Figure 2: Conceptual model of water flows in the Liverpool Plains catchment
Figure 3: Optimal level of internalising opportunity costs of uphill recharge (adapted from Scheele 1996)
Figure 4: Salinisation trajectories in the business-as-usual scenario and under optimality conditions with increasing costs of salinisation
Figure 5: Land-use change suggested in the Dryland Plains and Liverpool Ranges for stabilising salinity
Figure 6: Marginal cost of recharge in Dryland Plains and Liverpool Range depending on cost of salinisation