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On-farm Costs of Soil Salinisation: a Case Study for the Liverpool Plains in New South Wales

Romy Greiner*

Land affected by a high water table displays waterlogging and salinity effects. This causes costs to farmers through additional land management problems, loss of soil productivity and results in a decline of the farm's capital value. A multi-period mathematical model is developed to investigate best land and financial management strategies for such farms. Water tables rise mainly due to ground water import caused by high recharge in the surrounding parts of the catchment. The hydrological connection between model farm and catchment is established through the variable "condition of the upper aquifer". This paper analyses the effects of different levels of ground water import in terms of progress of soil salinisation, associated farm management responses and farm income development. The condition of the upper aquifer is shown to be decisive for the advance of salinisation and for the financial viability of the model farm. If the upper aquifer is draining or if it causes only minor rise of the water table, then the farming enterprise remains viable and long-term sustainable. If the aquifer condition causes high rates of upward leakage, then salinisation erodes farm productivity to an extent where no financially viable land management strategy is available.

1. Introduction

Soil salinity is a natural component of Australian landscapes. However, there is growing concern over the rapid increase of land affected by secondary salinisation. While first reports on secondary soil salinisation date back to the 1920s, salinity was not publicly recognised as a serious problem in the early 1980s. The estimated area of land affected by dryland salinity in Australia has risen from 426,000 hectares in 1982 to 1.2 million hectares in 1993 (Robertson). For the Murray Darling Basin, there are 180,000 hectares in the early stages of salinity and more than one million hectares at risk (Dryland Salinity Working Group).

Soil salinity can emerge locally where ground water flow is constricted (Anderson *et al.*). Broad scale soil salinisation is induced by saline water tables which have risen above a critical water level. Irrigation salinity relates to the application of irrigation water in excess of crop demand. Dryland salinity is associated with changes in land use since European settlement. In particular, the large-scale replacement of deep-rooted native vegetation with grazing and cropping systems is held responsible for increased recharge to the groundwater system. This shift in the hydrological balance of catchments can lead to rising water tables which relocate historic salts towards the soil surface.

A quantitative analysis of economic aspects of evolving dryland salinity must account for the catchment-scale character of the phenomenon. Land use, soils and climate determine how much water is recharged to the groundwater system. The hydrogeological conditions in a region determine where soil salinity can emerge. Here, salinisation impacts on the profitability of existing farms and influences the way in which land can be managed.

A multi-period mathematical programming model is developed to investigate the farm-level implications of dryland salinity. By capturing the hydrogeological idiosyncrasies of salinisation, agronomic and financial considerations as well as the economic and policy environment of farming, it determines optimal farm management strategies. Answers are sought to the questions as to whether farming can be long-term financial viable and environmentally sustainable.

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The model is applied to the Liverpool Plains in the north west slopes of New South Wales, where dryland salinity is threatening the productivity of black soils over vast areas of the catchment floor. A model farm represents the majority of farms on the black soils that are already affected or at risk from salinisation. The scenarios presented in this article capture the variability of hydrogeological circumstances that has been observed in the catchment (Broughton). The model runs seek to quantify salinity related costs incurred by farms in the salinisation zone. In doing so it focuses on the external cost component from water import from the surrounding catchment.

2. Bio-physical Background

The Liverpool Plains lie in the north western slopes of New South Wales. The catchment covers an area of approximately 12,000 square kilometres and is part of the Namoi catchment within the Murray Darling Basin. There are distinct land use patterns within the catchment. The sandstone and basalt ridges are grazing country. Mixed farming dominates on the red-brown earths on the slopes. Intensive cropping systems characterise land use on the floodways and floodplains with their highly productive black earths. Estimates suggest that if the current annual encroachment rate of 15 per cent persists, then 50,000 hectares of the 750,000 hectare basin will go out of production in this decade due to secondary soil salting (Dryland Salinity Working Group). Broughton supposes that all land with water tables less than five metres from the soil surface is threatened by salinisation. This is an estimated area of 195,000 hectares.

European settlement took place shortly after the region was explored by Oxley in 1818. With the European settlement came extensive clearing of native bush for grazing purposes. The native grasslands on the alluvial black earths in the flood plains were initially grazed but with the availability of increasingly powerful machinery in the 1960s the majority was surrendered to cropping.

In comparison to the native vegetation, the new land management systems have a significantly higher infiltration rate of rainfall. This is particularly true for soils with a low moisture storage capacity where extremely high recharge rates occur during extensive rain. This increased recharge to the groundwater system is pressurising the catchment's aquifers, causing water tables to rise and inducing soil salinisation in parts of the black soils floodplains (Broughton).

The view is generally accepted that there is no single, practical, universally applicable method of managing the water balance of catchments prone to salinisation (Nulsen). Affected catchments require individual approaches which suit their specific hydrogeological and farming conditions. Generally, the problem can be addressed by reducing recharge and increasing discharge, to reduce the quantity of water stored in the saturated zone of a catchment. There is widespread literature on agronomic measure which may be adopted to reduce recharge, including opportunity cropping and establishing perennial pasture. Trees can be seen as a particularly valuable biological means for water table control. Groundwater pumping provides an engineering option that is dealing with the symptoms of the problem rather than its causes, providing immediate relief but creating new problems such as disposal of the saline effluent.

3. Analytical Approach

3.1 General Considerations and Quantitative Approaches

Economic aspects of farm management are of major importance for the farmers in the face of emerging salinisation. The relative negligence of economic variables in promoting remedial action may be one explanation for the reluctance of a large percentage of farmers to adopt suggested "salt action", which comprises all land management decisions directed at reducing recharge to groundwater. This is particularly true in those cases where there is little financial scope for investment and risky action. The majority of farms is located in the recharge zone of the catchment. Here farmers face no incentive to change land use practices for water table control somewhere else because of likely associated income loss.

In the absence of time series data on similar salinisation processes, there are two kinds of quantitative approaches particularly suited when different futures are to be examined. They are simulation and programming models (Heady and Vocke). Both methods can be of an inventory and descriptive character or they can be designed to have predictive value.

The main quantitative analysis work done in Australia on the economics of salinity management is based on a simulation approach developed by Oram *et al.* (1989). The model on soil conservation economics (SOILEC) quantifies the linkages between land management, soil erosion, salinity, and farm incomes. It operates on a per hectare-basis for defined land management units within catchments. Land management units are defined as areas of similar land use. Soil erosion is quantified using the Universal Soil Loss Equation (USLE), the development of salinisation is judged on the basis of recharge per hectare. The economic dimension is represented in per-hectare gross margin figures.

SOILEC has been applied in a number of case studies. For the Avon-Richardson catchment, Oram *et al.*, (1992) calculated that its dryland salinity problem can be "controlled" by introducing one additional crop into the currently prevalent rotations at least every four years. This strategy reduces fallowing times and also improves farm gross margins. SOILEC calculations show for the Goran Basin, a sub-catchment of the Liverpool Plains, that increased cropping rates would reduce recharge in combination with a beneficial income effect, while lucerne would be more effective in recharge control but would come at a higher cost to landholders (Dryland Salinity Working Group).

Greiner and Parton identify a lack of consideration of the general framework of farm decision making in these results. Their major criticism relates to the fact that a gross margin analysis is of limited economic value when large-scale investment decisions are involved in changing present land management practices. Hence a full farm budget analysis is needed for assessing the economic dimension of the salinity problem. Another point of criticism is that the amount of recharge from different land uses can only be a vague indicator of the complex salinisation process. Not all recharge created in the catchment contributes to salinisation. A functional relationship between recharge, soil salinisation and land productivity is required to estimate the true cost of salinisation and to quantify the relative contributions.

3.2 Rationale for a Poly-period Mathematical Programming Approach

For this analysis a normative approach is chosen for a number of reasons. While the simulation approach requires a definition of the management strategy, a programming model will chose the decision variables in the way that best achieves the model objective while fulfilling all constraints (Taha). The objective function represents the behavioural framework of farming together with decision constraints. Resource availabilities constitute boundaries to the solution space. Hence, programming models provide a means of investigating what "ought" to be - given the particular decision framework, whereas simulation model work on a "what happens if" paradigm. How close the programming analysis comes to reality is *inter alia* a question of choosing and formulating the adequate objective function and including reasonable constraints to characterise the decision framework. In agriculture, mathematical programming has been extensively applied to farm management problems for optimising the allocation of limited resources into competing enterprises. In the case of emerging soil salinisation, the capacity of the groundwater system to accept recharge without causing soil salinity has to be treated as a resource, additional to land, labour and capital. This resource requires management in a spatial and temporal sense. Optimisation in a catchment context, by disregarding single-farm objectives in favour of the collective benefit for the farming community, can create a "vision" for the catchment. This can provide an understanding of the optimal spatial and temporal pattern of land use across the catchment, hence aiding the development of a catchment management strategy. However, land management decisions are taken on a farm basis. There are some 1300 farms in the Liverpool Plains, each of them managing their resources to satisfy their own objectives and each of them taking the condition of the groundwater system at their farm location as a *de facto* condition within their decision framework. The spatial and temporal characteristics of hydrological processes thus lead to the situation where farms in the low lying part of the catchment encounter the condition of the groundwater system under their land as a major limiting resource. Due to land management in the surrounding catchment the condition of the upper part of the aquifer under their land is such that it causes water table rise and subsequent soil salinisation. Farmers hence face the task of managing the water table by applying land use options as the only decision variables available to them, while trying to generate sufficient profit to remain financially viable.

3.3 Model Concept

This situation is captured in the model concept. The LP model forms a simultaneous equation system of restraint equations and an objective function to be maximised. The model equation framework is outlined in the box below. The objective function (Equation 1) maximises the cumulative net value of available income after tax *(I)* generated by the model farm over a period *(t)* of *T* years. It sums up the farm's annual revenue from the sale of plant and livestock produce

(Q) at a price *P* less the variable costs of production *(C)*, capital costs *(CA)*, and tax paid and financial obligation *(E)*. A discount rate *(r)* applies to future incomes.

$$(1)\ \text{Max I} = \sum_{t=1}^{T} ((P-C)\,Q - CA - E)\,(1+r)^{-t} \quad t=0..T$$

subject to

$$(2)\ A(t) \geq \sum_{s=1}^{k} \sum_{m=1}^{n} A_{sm} \qquad t=0..T$$

$$(3)\ A_s(t) = f(GWT_{t-1}) \qquad t=0..T$$

$$(4)\ GWT(t) = GWT_{t-1} + R_t + L_t \qquad t=1..T$$

$$(5)\ R(t) = \sum_{m=1}^{n} RC_{mt} \qquad t=0..T$$

$$(6)\ Q(t) = \sum_{s=1}^{k} \sum_{m=1}^{n} A_{sm} * Y_{sm} \qquad t=0..T$$

The major constraint (Equation 2) in every farm management model applies to the farm size *(A)*. Soil productivity and the choice of land use options depend on the advance of salinisation. Consequently the model differentiates *k* soil salinity classes *(s)* that may be dedicated to *n* different land management options *(m)*. The model distinguishes three salinity classes for black soil. Class 1 is unaffected by salinity and hence fully productive. Class 2 represents "reversible" salinity implications mainly from water logging which result in a reduced choice of potential crops and reduced yields. Class 3 applies to "irreversibly" salt-affected land which is suitable for saltland agronomy only.

The area in each salinity class in year *t* is a function of the depth of water table at the end of the previous year (GWT_{t-1}) (Equation 3). The depth of water table (Equation 4) depends upon the groundwater level at the end of the previous year, the on-farm recharge *(R)* and the condition of the upper aquifer applicable to the location *(L)*. *L* takes a positive value when the lateral flow balance of the aquifer is positive and causes the water table to rise independently of on-farm activities. It takes a negative value if the aquifer can discharge of on-farm recharge. On-farm recharge *(R)* is a function of the land use mix in any one year (Equation 5). Different crops have different recharge rates *(RC)*. Crop recharge rates in each year vary according to randomly determined rainfall conditions.

The feedback from increasing salinisation on production and productivity is formulated in Equations (2) and (6). The advance of salinisation determines the area of land in each salinity class. Consequently it controls the land use options available on the each soil category. Crop yields are soil class dependant and hence increasing salinisation reduces farm production.

While for a single model application the upper aquifer condition *(L)* is externally determined, it becomes the link between land management of a range of model farms when applied in a catchment context (Equation 5). The condition of the upper aquifer for model farm in the salinisation zone is then endogenously calculated.

For the model runs presented in this paper, the optimisation period *T* is ten years. This is considered a reasonable decision time frame when soil degradation problems are involved. It can be expected that farmers are willing to forego some short-term profit from taking salt action if it can be shown that this investment yields economic and ecological benefits in the decision period.

3.4 Verification of Model of Farm Economics of Dryland Salinity (MoFEDS)

The value of a model is determined by the reliability of its results. Validation is the comparison of model results resulting from experimentally chosen variable settings with statistically valid experimental observation data. Once a model is validated, the confidence in its predictive power is high. A mathematical programming model investigating a catchment-scale land degradation problem of unprecedented occurrence can, for obvious reasons, not be validated. Comprehensive data sets regarding land use and the development of salinisation do not exist. 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 the model results.

Also, given the increasing insecurities inherent in multi-period analyses with respect to the values of technical and objective function coefficients, the predictive information from such a model have to be interpreted in terms of the assumptions. Consequently, MoFEDS has been verified. The consistency of the mathematical framework was tested for all model components. The results of all modules were searched for inconsistencies, for values which could not be explained or did not make sense. This involved discussing results and all critical input parameters with experts in the particular fields. The results were scrutinised with respect to the temporal linkages in the multi-period model. During its development, the model and preliminary results were presented to expert audiences at conferences and published and the feedback received on these occasions contributed to the sophistication of MoFEDS. The methodology represents an unbiased holistic approach to an economic assessment of dryland salinity in the Liverpool Plains which is based on the best available data.

4. The Model Farm Approach

4.1 The Theoretical Concept

The concept of generating model farms that reflect the major land management zones in the catchment is of central importance to the analytical concept. The concept of a model farm approach is chosen to merge the two management levels relevant to salinity. At catchment scale, land use patterns and hydrogeological properties rule the biophysical aspect of the process. In the areas where salinity emerges it imposes a management challenge at the farm level.

Within the whole-catchment model framework, farm models represent the farm-scale dimension of land use decision making. The structure of the farm model integrates all relevant aspects of the agronomy, hydrogeology, farm operation, prices and costs, and farm financing within its module structure (Greiner 1994a). Agronomy and price data as displayed in the NSW Agriculture budget handbooks (1993) apply. For future years prices are inflated and incomes are discounted. Current taxation conditions apply. Prevailing interest rates on business loans and savings apply.

The model farms are distinguished by specific factor endowments such as area constraints, present land use system and livestock. Because they are allocated to different sections of the catchment which are characterised by different soil types and soil productivity, the model farms are furthermore characterised by production parameters including crop yields and recharge which reflect the bio-physical conditions of the catchment sections in which they operate.

4.2 Generating Model Farms

In order to obtain model farms which serve the analytical purpose, a hierarchical cluster analysis is performed on the farms in the catchment. Land use data recorded in the 1991/92 Australian Bureau of Statistics (ABS) Agriculture Census serve as cluster variables (Greiner 1994a). The cluster analysis results in six farm clusters which are characterised by maximum internal homogeneity and maximum external heterogeneity for the variables used in the clustering procedure (Hair *et al.*). His method significantly reduces the bias of ad-hoc methods of obtaining representative farms (Kennedy). The theoretical attractiveness of aggregating farms into clusters is based on the mathematical theory underlying the decomposition of programming problems and the elimination of aggregation errors (Onal and McCarl; Raine *et al.*).

The significance of these model farms has to be seen as being representatives of the land-use systems in the distinct segments of the catchments which have specific impacts on the hydrological balance in the catchment. As such they are likely to have distinct needs for land management changes to achieve hydrological sustainability of farming in the catchment.

4.3 The Model Farm that Represents the Cropping Operations on the Black Soils

The analysis presented in this paper investigates the externalities imposed by the model farm which represents the majority of the farms located in the black soil areas of the Liverpool Plains which are already salt affected or in danger of experiencing dryland salinity in the near future. Table 1 shows the characteristics of this model farm, which are the mean values of agriculture census variables obtained for the cluster. The standard deviations indicate that the farms that are represented by this model farm vary greatly in area of holding and enterprise mix, despite relatively homogenous geographical conditions. Specific estimates of parameters characterising the financial, economic and policy environment of the model farm are listed in Table 2.

Table 1: Characteristics of the Model Farm "Cropping the Black Soils in the Liverpool Plains"

Model Farm Characteristics	Mean	Standard Deviation
Total area of holding (ha)	932	558
Land Use Perennials		
Pure lucerne for grazing (ha)	79	119
Other pasture legumes (ha)	2	10
Sown grasses (ha)	10	60
Grasses and legumes (ha)	20	57
Native pasture (ha)	50	129
Area Sown to Winter Crops		
Wheat for grain (ha)	132	151
Wheat for hay (ha)	1	10
Oats for grain (ha)	5	14
Oats for hay (ha)	1	8
Barley for grain (ha)	40	62
Canary seed (ha)	0	0
Triticale for grain (ha)	0	3
Livestock		
Sheep and Lambs (head)	253	534
Cattle (head)	210	229

5. Hydrogeological Data

5.1 Catchment-scale Data

Generally, the degree of confidence in estimates of the rate of change of salt-affected areas is low. For the Liverpool Plains the rate of change is estimated at 15 per cent (Dryland Salinity Working Group). This rate of change is reflected in the salinity encroachment function in MoFEDS which is described by a linear plateau function (Greiner 1994a). As outlined in Section 3, the model structure accommodates for a feedback from recharge to soil productivity via a salinisation function in which arable land is related to water table depth. First, the total water volume resulting from on-farm recharge in combination with the upper aquifer condition is converted into water level movement at the end of each year. Second, the new water table depth translates into waterlogged and severely salt-affected areas.

The critical water level for the occurrence of capillary action is 1.5 metres below the surface. At shallower depths, capillary rise brings water and salt to the surface causing water logging and salt accumulation. For this analysis it is assumed that the model farm area is at a gentle slope, the degree of which determines the critical average depth of water table ie. the threshold for the appearance of salinity.

The model incorporates two-stage salinity encroachment. Once a first water table threshold is exceeded, slight, "reversible" salinisation effects lower the productivity of the low lying parts of the farm. This "reversibly" affected area may still be used for cropping but crop rotations are restricted and crop yields decline. Once the average water level rises above a second threshold, then "severe" salting takes effect and the resulting salted area can only be used for growing salt-tolerant plants.

For the following model runs it is assumed that the model farm is at the verge of emerging salinity. The average depth of water table is equal to the first critical water level which determines the emergence of "reversible" salinisation. The second critical water level which marks the emergence of "irreversible" salinity is 0.3 metres higher. These conditions and other relevant assumptions relating to hydrogeological factors are outlined in Table 2.

5.2 On-farm Accessions to the Groundwater System

For the farms in the salinisation zone of the catchment, the condition of the upper aquifer suggests that there is substantial water import and a significant farm-external component to soil salinisation. This is indicated by a positive lateral flow balance. In addition, there is also the on-farm recharge to consider.

If the condition of the upper aquifer is such that on-farm recharge to the groundwater can drain away, water table management is not an issue for the model farm because this situation does not imply a limiting constraint. If this condition is not fulfilled, however, recharge management becomes part of farm management because the capacity of the hydrological system to accept recharge without causing salinity effects has to be regarded as an additional limited resource.

Recharge data for the full range of land uses on the black soils are required. In the absence of sufficient site-specific experimental recharge data, PERFECT, a simulation model of "Productivity, Erosion, Runoff Functions to Evaluate Conservation Techniques" is applied to the specific soil and climatic conditions on the Liverpool Plains (Freebairn *et al.*). The model contains six main modules which are data input, water

Table 2: Relevant Model Parameters and their "Standard" Setting

Initial average depth of water table	4m
Critical water level for the emergence of reversible salinisation	4m
Critical water level for the emergence of irreversible salinity	3.7m
Upward leakage of upper quifer	0.05m per year
Salinity encroachment rate	0.15ha per mm of exceeding the critical water levels
Weather conditions	Average seasonal rainfall
Property size	932ha (50ha native pasture, 132ha improved pasture)
Initial owings	$0 (equity 100 per cent)
Initial savings	$20,000
Maximum available loan	$300,000
Household consumption expenditure	$26,000
Personal discount rate	5 per cent
Commercial interest rate	12 per cent
Incentives for salinity management	tree planting is tax deductible
Lucerne establishment for hay production	Optional, failure rate 35 per cent, $100,000 initial investment required

balance, crop growth, crop residue, erosion and model output (Thomas *et al.*). It simulates the interactions between soil, climate and land management practices in a 100 year time frame, using actual daily rainfall figures (Littleboy *et al.*).

The crop yields and recharge rates displayed in Table 3 show significant differences in recharge for the same soil depending on whether it is under crop or fallowed. However, soil type has an even bigger influence, as the water storage capacity is associated with the clay content of the soil.

Most importantly, accessions to the groundwater system are strongly influenced by sporadic rainfall events. Rainfall variability is a major external variable. Most recharge occurs after prolonged and heavy rain. Consequently, the aspect of climatic variability cannot be ignored in a quantitative analysis. Kingwell *et al.*, introduce climatic variability into a farm programming model using a discrete stochastic programming approach. Using an adaptation of this approach, recharge and crop yields are categorised for three climatic conditions "average", "dry" and "wet" for summer and winter seasons (Greiner and Parton). They are defined at the long-term rainfall mean and one standard deviation above and below the mean. Allocating frequencies to these season types allows random selection of weather conditions for both seasons in each year. It also enables the construction of scenarios which simulate the effect of climatic extremes on water table movement, salinisation, and profitability of farming.

Table 3: Average Crop Yields and Recharge for Different Land Management Practices and Soil Types

	Yields (t/ha)		Recharge (mm)	
	black soil	red earth	black soil	red earth
Winter wheat	2.703	1.611	5	20
Winter fallow	n.a.	n.a.	7	53
Sorghum	2.523	1.975	3	18
Sunflower	0.943	0.632	2	31
Summer fallow	n.a.	n.a.	7	58

The model results presented in this paper assume "average" rainfall conditions. Greiner (1994b) showed the accelerating effect of above-average rainfall on water table rise and soil salinisation.

6. The Model Farm in a Catchment Context

6.1 External Costs Associated with Dryland Salinity

External costs arise from the fact that a large proportion of the accessions to the groundwater system that result in dryland salinisation on some farms result from land management decisions of farmers in upland parts of the catchment that are hydrologically connected. External costs which dryland salinity inflicts on affected landholders include costs from lost production, damage to on-farm infrastructure, and complication of land management. The Dryland Salinity Working Group explains these and other aspects in detail.

There is evidence that the soil conservation status of a property is reflected in the transaction price when the farm is sold. King and Sinden show a significant correlation between the conservation status of properties with respect to soil erosion and the prices paid for farms. Indications are that properties in salinisation zones may be impossible to sell (D. Schroder, Department of Conservation and Land Management, Gunnedah, *pers. comm.*). However, there has been no specific analysis on the transaction values of salt-affected properties in the Liverpool Plains that would justify an introduction of this substantial aspect into the analysis. The following results will therefore focus on the cost aspect related to soil productivity which, in turn, is reflected in the income generated from farming.

6.2 External Effects in MoFEDS

Every section of the catchment adds recharge to the groundwater system. This applies to the model farm in the salinisation zone as well. Increased accessions to the groundwater system in the surrounding catchment do not necessarily lead to external costs for this model farm. If groundwater discharge out of the catchment is restricted due to hydrogeological reasons, increased recharge in the upland parts of the catchment first leads to aquifer pressurisation. This reduces the capacity of the groundwater system to drain away recharge in areas where the pressurised aquifers are close to the soil surface, which is the case in low-lying parts of the catchment. The aquifers may even leak upward, causing the water table to rise. This is a necessary but not a sufficient condition for inflicting salinity-related external costs to farms in these locations. Only if this off-farm inflicted water table rise results in on-farm soil salinisation, then the model farm incurs external costs.

Upward leakage of water from pressurised aquifers is the suspected major driving force of salinisation in the Liverpool Plains (Broughton). The volume of this vertical component of aquifer discharge is found to vary significantly within the catchment floor. Its magnitude is of major importance for land management decisions and the future productivity of farms operating on the catchment's flood plains.

6.3 The Scenario Variable

The MoFEDS variable "condition of the upper aquifer" represents the model farm's hydrological connection with the uphill parts of the catchment given its hydrogeological disposition. The variable captures the off-farm effect that land management has on the aquifer condition under the black soil plains. In the presented single-farm situation, it is externally determined and will be referred to as scenario variable A.

The implications resulting from the condition of the upper aquifer and costs associated with it are subsequently analysed. The values which the scenario variables takes cover the range of observed hydrogeological conditions in the Liverpool Plains (Broughton). Ideally, the aquifer is capable of draining on-farm recharge away (A1). Under this condition, salinity is not expected to emerge. The worst case scenario investigated in the following runs is an independent rise of water table of 30cm per year caused by high upward aquifer leakage (A6). The six scenarios are,

A1	aquifer drains at a rate of 10cm per year
A2	aquifer is pressurised but no upward leakage
A3	upward leakage is 5cm per year
A4	upward leakage is 10cm per year
A5	upward leakage is 20cm per year
A6	upward leakage is 30cm per year.

7. Results

The MoFEDS results can be characterised in three categories. First, the land management variables display the "optimal" development path for the cropping regime, pastoral enterprise, and saltland agronomy over the optimisation period. These are the agronomic outcomes. They are analysed in detail in Greiner (1994a) and are not subject of discussion in this paper. Second, given the deterministic framework of MoFEDS, the implications for hydrological and salinity-related entities are quantified. These are the biophysical results. They include the development of depth of water table and the extent of soil salinisation. Third, the farm financial module provides the corresponding farm financial outcomes and developments, looking at farm profit, farm income, taxation, investment, cash flow, and farm equity.

7.1 Salinisation

Figure 1 displays the implications of the aquifer condition for the speed and extent of soil salinisation over the optimisation period. There is a direct relationship between the variable (aquifer condition) and the outcome (salinisation), given the linear relationships employed. It is interesting to note, though, that the salinisation function levels off in all scenarios except for A6, which has to be interpreted as a sign that various degrees of groundwater management can be achieved.

In the case of a draining aquifer (A1) no salinisation effects occur, as was expected. In scenario A2, where the aquifer is pressurised, the model farm manages to reduce on-farm recharge to zero within 5 years and to a contain salinity at a low level.

Salinisation feeds back to soil productivity. The question arises as to how the various salinity developments feed back onto calculated farm incomes and consequently on to the financial viability of the model farm.

7.2 Costs of Salinisation

Figure 2 shows the impact of salinisation on the objective value, ie. the accumulated discounted net value of available household income over the optimisation period. The relationship between salt-affected area and income is clearly negative. Worst case scenario A6 yields less than 40 per cent of the cumulative income

Figure 1: Development of Soil Salinisation Depending on the Condition of the Upper Aquifer

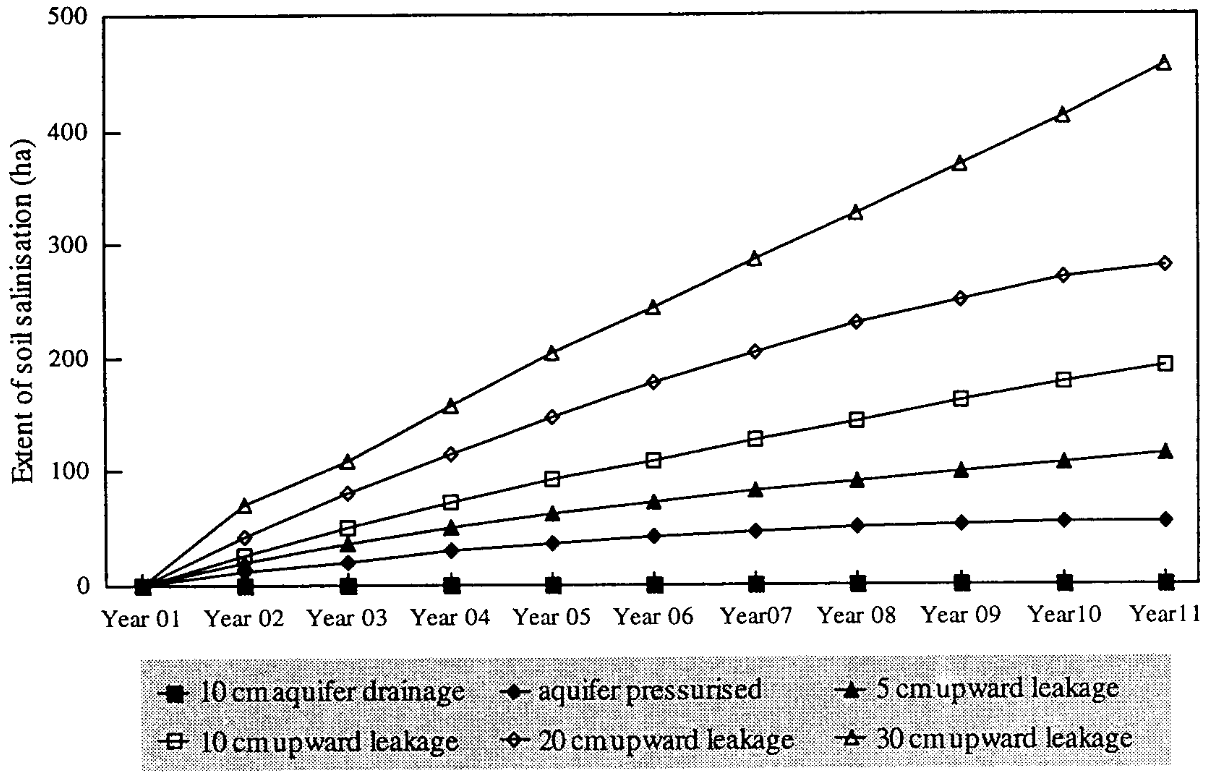
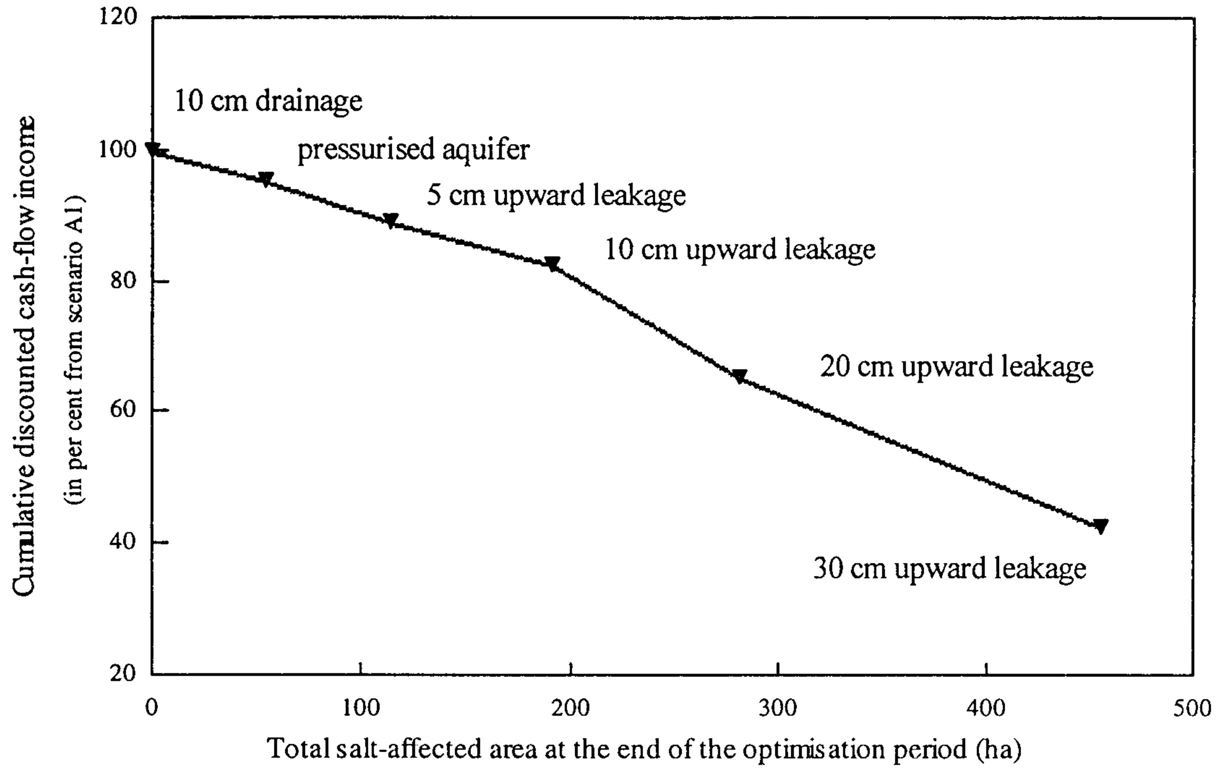


Figure 2: Relationship Between Salinisation and Cumulative Discounted Farm Income



of the no-salinisation scenario. Given equal starting conditions, the income disparity between scenarios A1 (draining aquifer) and A6 increases with time. However, the difference in farm income between scenario A1 and A6 cannot be completely attributed to external effects because part of the salinity is caused by on-farm recharge. This becomes obvious in a comparison of scenarios A1 and A2.

The cumulative available income is reduced in scenario A2 (pressurised aquifer) in comparison to A1 (draining aquifer). In scenario A2 there is no water import into the farm from its surrounds. Rather, the aquifer's capacity to accept on-farm recharge without causing salinity has become a limiting resource that requires management. Optimally, the results show the development of a small area of salt-affected land which is contained from year 6 onwards (Figure 1).

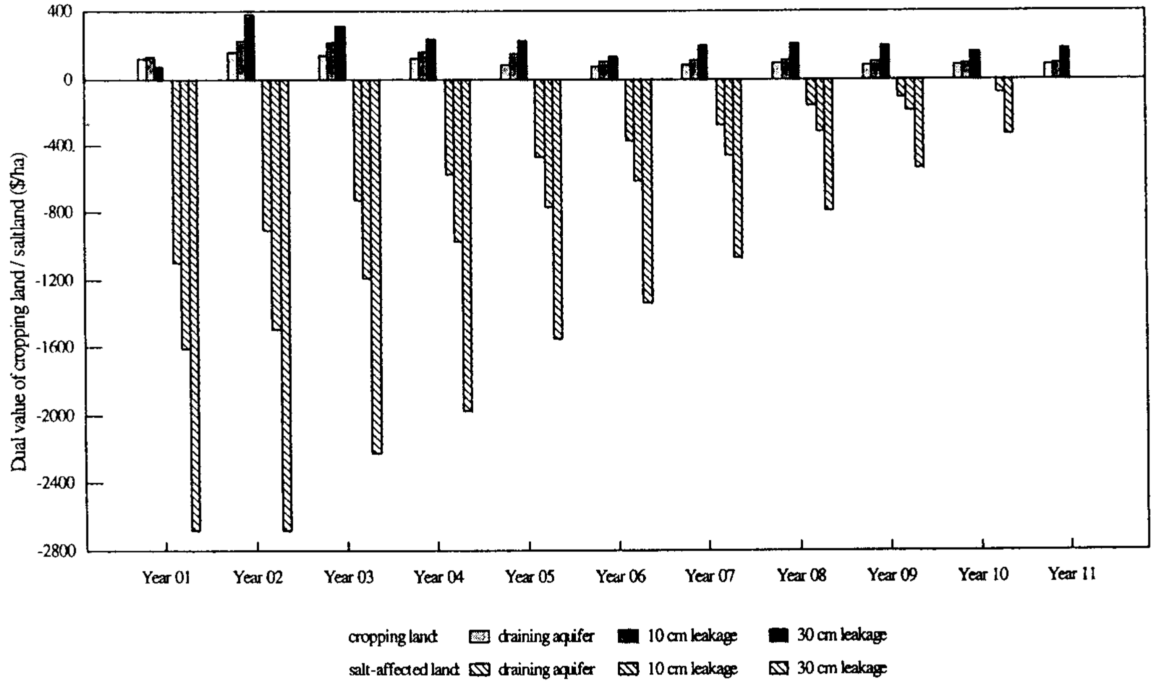
All scenarios with upward leakage of the upper aquifer (A3 to A6) incur external costs. The costs in terms of the objective function are the difference in objective value between these scenarios and the A2 scenario. For the worst-case scenario it can be concluded that the external costs imposed on the model farm in terms of foregone cash-flow income alone amount to approximately 55 percent of the farm's total potential cash-flow income over 10 years after emergence of salinity.

7.3 Shadow Price of Salinisation

The dual solution of the scenario runs provides further evidence of the costliness of soil salinisation. It contains information on the status of the resources, on the unit worth of each resource, on the cost of constraints, and on the sensitivity of the optimal solution to changes in availability of resources, technical coefficients (which define the usage of resource by the decision variables) and objective-function coefficients.

The unit worth of a resource is defined as its "shadow price" or "dual value". This value gives the rate of improvement in the objective value for a one unit increase of its availability. Consequently resources which are in surplus supply have a dual value of zero, its constraint being redundant. The more the scarcity of a resource limits the objective value of a linear programming model, the higher is its shadow price.

Figure 3: The Cost of Salinisation Expressed as Dual Cost of Salt-affected Land and the Dual Value of Cropping Land



The cost aspect of dryland salinisation is explored in Figure 3, where the dual value of the marginal hectare of salt-affected land is compared to the dual value of the marginal hectare of cropping land. For clarity reasons, the Figure focuses on the results for scenarios A1 (draining aquifer), A4 (10cm rise of water table) and A6 (30cm rise of water table). The dual values for cropping land are shown above the x-axis, indicating the increase in the objective value with the availability of an additional hectare of arable land. The dual value shows the contribution of this increase in resource to the cumulative discounted available farm income. The dual values for fully productive arable land decline over the optimisation period because of the discount rate applicable and because income at the beginning of the optimisation period is available for investment in the remaining time period.

Two other aspects warrant mentioning. First, the dual values in the first year are lower than in the subsequent years. This can be explained by the first-year condition applicable to all scenario runs which forces the model farm to initially adopt a cropping system that prevails on the Liverpool Plains that obviously is not optimal. Returns from cropping are increased from year two onwards when this restriction is relaxed. Second, comparing the worth of the marginal hectare of arable land between the scenarios in the same year shows a marked increase in dual value from scenario A1 to A4 to A6. The higher values can be explained by that increasing scarcity of arable land due to increased loss of formerly productive land to salinisation.

Emerging soil salinity incurs costs to the farm by reducing the cash flow income and consequently the objective value. Hence the dual values for saltland in the scenarios are displayed below the x-axis. Figure 3 indicates that the cost of any additional salt-affected hectare of land is much higher than the benefit obtained from an additional hectare of productive cropping land. This can be explained by the long-term consequences of salinisation. Once land becomes severely salt-affected, its productivity is reduced to almost zero for the remainder of the optimisation period. Hence, the dual costs represent cumulative values. On the other hand, the dual value of cropping land is assessed on an annual opportunity cost basis.

Figure 3 also shows that the dual values decrease over the optimisation period. In the case of the cropping area, this is due solely to the discounting of future incomes. In the case of the dual cost for salt-affected land, it is a combined effect from discounting and the length of time remaining in the optimisation period. In the scenario comparison it becomes evident that the shadow price for the marginal hectare of soil salinisation and the dual value of the marginal hectare of cropping land increase as the extent of salinisation increases, as determined by the upper aquifer condition. This indicates that cropping land becomes more valuable with increasing scarcity. Salinity on the other hand becomes more costly on a marginal hectare basis the more rapid the salinisation process is.

7.4 Income and Equity Development

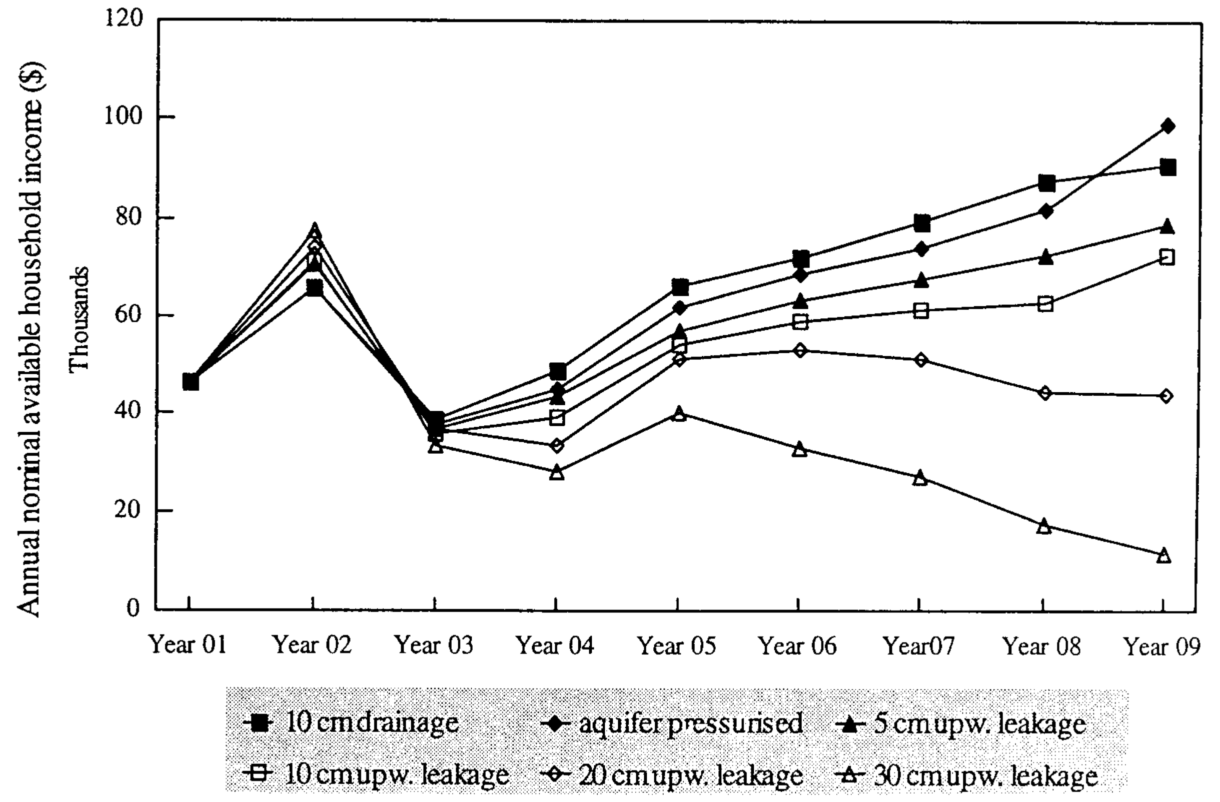
The income aspect of soil salinisation in its dependence on the upper aquifer condition is further explored in Figure 4, where the development of the model farm's annual nominal cash-flow income is depicted. The scenarios have the same starting point. Without wanting to go into the details of optimal land management practises in the scenarios (Greiner 1994a), a few explanatory comments are required. The peak income of the second year results from the abandoning of the initial long-fallowing cropping system which brings a significant area under crops in year two. Also, there is additional income from interest on savings.

In year three a major income reduction is visible. This depression in annual nominal household income is associated with lucerne establishment in year three, which is a feature of the optimal solution in all scenarios. It is caused by the major investments into the necessary infrastructure for lucerne hay production with the resulting financial liabilities imposing a significant drain on available income.

Another observation from Figure 4 is that the income developments in the scenarios fan out considerably after year three. In the scenarios where the aquifer is draining or pressurised (A1 and A2), the available income from farming is recovering in the subsequent years.

Upward leakage of the upper aquifer in the vicinity of five and ten centimetres per year (A3 and A4), which leads to total rises of the water table characteristic of

Figure 4: Impact of Aquifer Condition on the Model Farm's Cash Flow Income



the Liverpool Plains, results in a reduced annual income. However, the results suggest that the income levels are sustainable over the optimisation period. Longer-term calculations would have to determine the degree of sustainability as the rate of salinisation is diminished but still positive after year eleven.

For the two scenarios which assume high independent rises of the upper aquifer (A5 and A6), the model results clearly indicate that even over a period as short as ten years after the first emergence of salinity, these hydrological circumstances incur a situation where neither best land management strategies nor good financial management can sustain a viable income for the model farm.

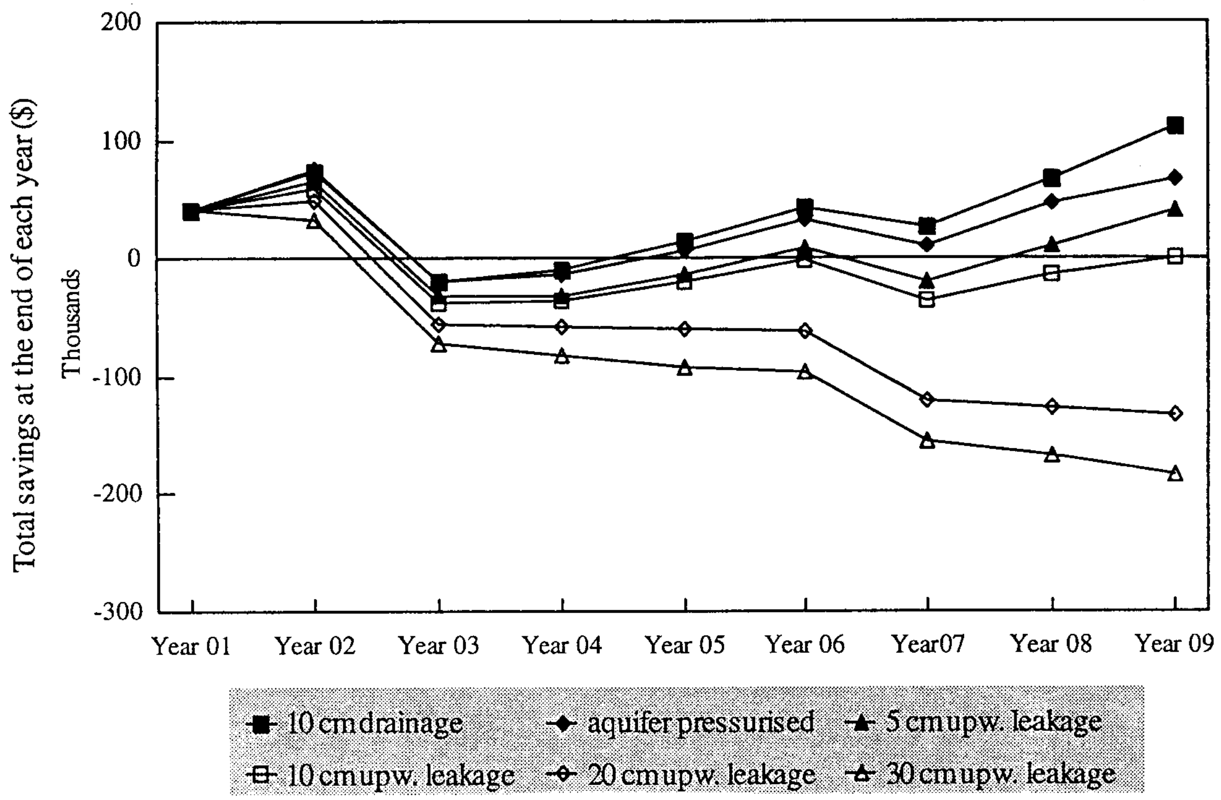
This distinguishing effect of the speed of rise of water table on the financial viability of the model farm is confirmed by the corresponding development of savings and debt (Figure 5). In the situation of a draining upper aquifer (A1), the model farm recovers from the reduction in equity associated with the lucerne-related investment in less than two years as a result of the farm's high productive capacity, and the farm accumulates savings from year five onwards. The scenarios with a pressurised aquifer, a five and a ten centimetre water level rise (A2 to A4) show reduced savings in comparison to the ideal situation. However, the model farm still manages to recover from debt and regain full equity. The two worst-case scenarios (A5 and A6) on the other hand, display a negative spiral of increased salinity, reduced income and increased debt. This tendency is accelerated by a substantial investment into lucerne growing which is part of the optimal solution in all model runs.

8. Conclusions

This paper present a programming approach for assessing the on-farm costs of soil salinisation. Specifically, it quantifies the costs for a model farm representing the farms in the low-lying parts of a dryland catchment that are at risk from salinity. Here, water tables rise due to increased accessions to the groundwater system. While on-farm land use practices contribute to the problem, the major source is land management in the surrounding parts of the catchment.

The model incorporates a recharge-water balance-salinisation simulation procedure into a linear pro-

Figure 5: Development of the Model Farm's Savings/Debt Depending on the Aquifer Condition



gramming model of land and financial management. The model farm is linked to the surrounding catchment through the variable 'condition of the upper aquifer'. The state of this variable determines whether the model farm can drain on-farm recharge away or whether it is confronted with externally imposed water table rise and soil salinisation. In the latter case, the variable causes external costs through productivity loss and imposes an additional resource constraint to the model farm manager.

The model runs investigate a range of conditions of the upper aquifer that are observed in different parts of the black soil floodplains in the Liverpool Plains. The results suggest that water table control through land management is possible to a certain degree. If the model farm cannot drain on-farm recharge away, it can restrict soil salinisation to a small proportion of its land and contain it while incurring minor associated costs which do not affect its financial viability. This degree of water table management is achieved by reducing fallowing of land and introducing perennial crops.

Land management becomes unprofitable in a situation where the aquifer condition causes the water table to rise irrespective of what the model farm does. This represents a situation where the land management decisions of landholders in the uphill parts of the catchment incur high external costs to the farmers in the plains through the hydrological connections within the catchment. The negative income effect of an additional hectare of salt-affected land is a multiple of the income generated from an additional hectare of productive arable land due to the irreversible loss of soil productivity from salinity.

These results have major implications for catchment management. They indicate that landholders across the catchment have a responsibility for managing the catchment's groundwater system. From an economic efficiency perspective, however, a substitution of land use options which cause high recharge in the uphill parts of the catchment with lower-recharge options would only be justified if the associated economic gain in the low-lying parts of the catchment through salinity prevention outweighed the associated costs to uphill farmers. While the soil productivity on the plains is much higher than the productivity of uphill soils it is difficult to estimate whether this condition holds. At the same time it has to be stressed that the costs of soil salinisation identified in this paper account for the farm income component only. Additional quantifiable costs to the farming community accrue from loss of land value and salt damage to farm infrastructure, while the costs associated with reduced regional economic activity and increased infrastructure maintenance are borne by the wider rural community.

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