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ABSTRACT

A multiperiod mathematical programming model of dryland farming in the wheatbelt of Western Australia is presented. The model integrates a water balance model with a farm management model to account for the long run implications of ground water recharge and dryland salinisation. The model is used to examine the value of various management strategies for dealing with secondary salinisation. These strategies are evaluated for catchment where groundwater recharge and groundwater discharge (secondary salinisation) occur on adjacent properties. Costs are quantified under different property right scenarios.

INTRODUCTION

Dryland salinity is caused by salt accumulation in surface soil leading to lost production and mitigation costs. It occurs in the natural state as primary salinity. Salt comes from rainfall and is retained in the surface soil or is translocated by ground water movement to accumulate at natural ground water discharge sites. Secondary salinity occurs when the clearing of native vegetation for agricultural land use causes increases in dryland salinity. This may be brought about either by soil erosion exposing naturally saline soil or by a decrease in water use in the root zone leading to greater ground water recharge (water percolating beneath the root zone to the water-table) and thus ground water discharge (water-table meeting the ground surface, causing evaporation and deposition of salts). The latter process is predominant in WA and is the focus of this paper.

In a 1989 survey (ABS,1989) 443,000 ha or 2.8 % of 15.7 million ha of cleared farm land in southwest Western Australia was salt affected. This was an increase of 180,000 ha when compared to results of a similar survey in 1979 and indicates a rapid increase in severity of the problem. Some estimates put the future potential loss as high as 15% of arable farm land (Anon,1988) if suitable land management is not adopted over large areas.

If the benefits of controlling salinity are greater than the costs, but inadequate control measures are taken then economic inefficiencies exist. In this case allowing salinisation to occur causes a loss to individuals and to society. Due to the difficulty in measuring both the benefits and costs, decisions about dryland salinity management are difficult. Thus lack of information is one of the causes of the dryland salinity problem. The other cause is externalities. Those contributing to ground water recharge do not bear the costs of their actions when the water discharges on their neighbour's property. The difficulty of collecting information and the presence of externalities are the strongest reasons for government intervention. The management problem presented by dryland salinity is thus one for individuals as well as policy makers.

The aim of this paper is to examine the socially optimal approach to dryland salinity management in the Western Australian wheatbelt and to compare this with the best solution obtained by individual action, thus quantifying, for representative examples, the extent of the externality problem. This is achieved with a two-farm multi-period optimisation model, representing a catchment in profile with one upslope and one downslope farm. The model is solved under a series of assumptions regarding property rights and physical parameters.

DRYLAND SALINITY

THE PHYSICAL ENVIRONMENT

The wheatbelt of W.A. receives 250 to 450 mm of average annual rainfall. The landscape is divided into wide gently sloping valleys separated by broad gravelly sandplains. The process of dryland salinity in this environment has been outlined by many authors (eg Peck,78, Malcolm,1983, Anon,1988 and McFarlane,1991) and is summarised below:

Large amounts of salt have been deposited in rainfall onto the landscape over many thousands of years. Coastal regions receive 300 kg of salt per ha per year. Moving inland into the lower rainfall regions the salt deposited decreases to 40 kg/ha/yr in the central wheatbelt (Anon,1988) but the salt concentrations in the soil increase as the low rainfall is unable to leach and drain this salt.

Removal of native vegetation has led to large increases in drainage of water into the ground water table. Increases in ground water recharge of between 20mm and 50mm per year are common (Anon,1988). This has led to mobilisation of stored salt and rising water tables. Typical increases in water table height range from 0.2 m/yr to 0.6 m/yr (Anon,1988). When rising water tables come within a critical depth of the ground surface plant growth is inhibited. This is caused by high soil salt concentrations and in many cases an interaction with the associated waterlogged conditions (Barrett-Lennard,1984).

The aquifer that causes valley floor salinity underlies most of the landscape and is often semi-confined. It is recharged from rainfall through permeable upland soils and via preferred pathways beneath permanent and ephemeral perched water tables. Thus much of the water contributing to valley floor salinity emanates from the upland area.

TYPES OF DRYLAND SALINITY

The recognised types of hydrologically induced dryland salinity are: (A) valley floor salinity (this occurs in the lowest part of the landscape where groundwater discharges from the deep regional aquifer system which may be semi-confined by less permeable surface soil); (B) sandplain seeps at the base of sandy rises (water tables form in sandy soil above less permeable soil and drain out at the edge of these soil types); (C) seeps caused by intrusive dykes (soil formed from dykes are of lower permeability and bring ground water to the surface); (D) bedrock highs (a rise in the underlying bedrock has a similar effect to an intrusive dyke); and (E) seeps at changes in slope (the lower hydraulic gradient down slope doesnt allow water draining from above to disperse, causing a rise in water table at this point).

The model to be developed focusses on (B) sandplain seeps which is the most prominent current problem and (A) valley floor salinity which is a potentially greater long term problem, often involving externalities.

CONTROL MEASURES

Abatement strategies involve reducing recharge, enhancing discharge and utilising saltland.

Strategic clearing and re-planting can reduce recharge if permeable soils like deep sands are left uncleared or replanted with high water use vegetation.

High rates of recharge occur beneath waterlogged soils. Diverting excess water reduces waterlogging and reduces recharge. This may take the form of drainage or absorption banks to prevent runoff and waterlogging on soils lower in the landscape.

Annual agricultural species transpire water only during the growing season. If perennial pastures are able to be grown then water use can be increased.

Tillage and fertiliser practices affect water holding capacity of soil and plant water use. These can be modified to affect recharge rates.

Drainage can reduce water tables in some saline areas. This can involve surface or sub-surface drains and may also involve pumping.

High water use trees can be used to lower water tables. Trees are selected for different locations in the landscape according to their tolerance of water logging and salt levels.

A wide range of halophytes are available with salt and water logging tollerance suitable for different climatic regions. These species are able to grow on saline discharge areas unsuitable for crops and pastures and can provide a valuable source of feed during autumn and winter (Malcolm,1983).

THE AGRICULTURAL SYSTEM

The southwest of Western Australia has a mediterranean climate featuring hot dry summers and cool wet winters. The soils have developed from very old, leached parent material and are relatively infertile, requiring fertiliser and trace elements for most introduced plant growth. The agricultural system is rainfed and is predominantly cereal and pasture based. The growing season is from April to October (winter and spring). Sheep graze the annual pasture during this time and survive on cereal stubble, dry pasture and supplements during summer, autumn and early winter when new pasture growth is poor. Sheep are grown for wool production and provide a diversification against seasonal cropping risks. They also play an integral part in the farming enterprise due to the high degree of complementarity between cropping and sheep enterprises (Morrison et al,1986).

WATER BALANCE

Management of ground water in conjunction with the agricultural use of the land involves the integration of hydrological, biological and economic information into a suitable model for answering management questions.

The standard ground water model solves simultaneous equations calculating water head at and flow between a number of points in a two or three dimensional space. Results are generated for a steady state or transient flow. This approach can give detailed site specific results but has a high information requirement.

A simplification of the groundwater model is the water balance model. Schofield(1990) presents a water balance model for determining reforestation areas in the higher rainfall areas of Western Australia:

$$Ef = As*Es + Ac*Ec + Aa*Ea - Z*theta$$

where E is evaporation, A is area, f is native forest, s is groundwater seep, c is crop, a is afforestation, Z is the reduction in water table level and theta is storativity. The A's sum to one, thus the sum of evapotranspiration from the various land 'uses' (including seeps) must be equal to the evapotranspiration of the original vegetation plus, if desired, the amount of water that must be removed to lower the water table by a given amount. Thus steady state and transient flow results are approximated.

Schofield advocates determining reforestation area with a water balance model and then planning the layout of reafforestation with site specific ground water flow models.

Determining the viability of a salinity abatement programme requires examining many options for ground water control. This can lead to repetitive solutions to simulation based models and dimensionality problems for dynamic programming models. For these reasons a mathematical programming approach was adopted.

This paper develops a mathematical programming model which incorporates farm management decision making into a water balance model. The model is based on a landscape profile in the lower rainfall wheatbelt region of W.A. It incorporates two management units: one an upland farm on which the principal recharge occurs and a valley floor farm on which ground water discharge occurs. This approach, based on Salerian's model (1990) gives information on private and social optima. The analysis is ex-ante in that it deals with control of salinity rather than reduction of salinity. This is valid for the eastern wheatbelt where valley floor salinity is yet to become a large problem (Anon.,1988).

MODEL

The mathematical programming model is a synthesis of a multi-period water balance and farm-management optimistation model.

The farm-management component was developed along the lines of the MIDAS model (Kingwell and Pannell,1987) .The hydrological component is an extension of Schoffield's model with parameters from Loh and Stokes(1981), Henschke(1989), George(1990) and George and Frantom(1990). Ground water recharge upslope depends on agronomic practice, drainage and trees. Ground water discharges downslope depends on saline land and enhanced evapotranspiration from trees. The onset of salinity is determined by the initial water table depth, the lag time for recharge to increase the valley floor aquifer, recharge rate and storativity. The area of salinity increases at a diminishing rate to a steady state determined by recharge and storativity. The steady state area of saline land is proportional to the rate of recharge. Control measures regulate recharge and discharge to prevent salinisation.

The model is formulated as follows:

$$\text{MAX} \sum_{t=0}^{T} ((P - Cu)Qu - Ccu + (P - Cv)Qv - Ccv)(1+r)^{-t} \qquad (1)$$

S.T.

$$A(t) \geq Ac + Ap + Atr + As \qquad t = 0..T \qquad (2)$$

$$R(t) = RF - ET(y) \qquad t = 0..T \qquad (3)$$

$$D(t) = f(As,Atr) \qquad t = 1..T \qquad (4)$$

$$D(t) \leq R \qquad t = 1..T \qquad (5)$$

$$GWV(t) = GWV(t-1) + R - D \qquad t = 1..T \qquad (6)$$

$$WTD(t) = f(GWV) \qquad t = 1..T \qquad (7)$$

$$As(t) = f(WTD) \qquad t = 1..T \qquad (8)$$

$$\dot{A}s(t) = f(As,Atr,R) \qquad t = 1..T \qquad (9)$$

Where u is the upland farm and v is the valley floor farm. P is the price of agricultural goods produced, Cu is the production costs on the upland farm and Ccu is the salinity control costs on the upland farm. A is area of crop, pasture, trees and salinity respectively. R is recharge, RF is rainfall, ET is evapotranspiration, y is yield, D is discharge, GWV is ground water volume and WTD is water-table depth.

Two adjoining farms (upland and valley floor) each are represented by a set of the above equations except for equations (5) and (6) which link the two farms through the common ground water table and equations (4),(7) and (8) which are unique to the low land farm.

SOIL TYPES

Management units are divided on the basis of soil types which correspond with positions in the landscape. Each soil type has an expected yield.

The landscape profile comprises three land types, working from the higest to the lowest point in the landscape these are: sandplain (L1), slopes (L2) and valley floor (L3). The upland farm comprises the L1 soil type and the valley floor farm comprises the L2 and L3 soil types. Salinity can occur on L3 (valley floor salinity due to ground water emanating from L1) and L1 (sand plain seep from ground water emanating from L1). Some areas will have valley floor soils that were subject to primary salinity. For the purpose of this analysis only soils subject to secondary salinity and contributing to ground water recharge are considered. Salinity on soil types L1 and L3 may be controlled.

A distinguishing characteristic of regions in WA is the productivity of the more recently cleared upland soils. These soils, previously considered infertile, were cleared in the 1950's when the introduction of superphosphate and trace elements allowed crops to be grown. Since then many of these sandy soils, especially in the north-eastern wheatbelt have developed severe subsoil acidity problems and yields have declined. It is these poor yielding acid sands which also contribute most to ground water recharge from the low crop water use.

Yields on the valley floor soils also vary due to water logging and other factors relating to soil structure and topography that cannot be directly overcome.

The post-clearing ground-water systems may be summarised as follows:

L1: perched water table draining half through sandplain seeps, half to the deep groundwater system.

L2: perched water table draining into L3 water table and subject to waterlogging.

L3: seasonally waterlogged soil subject to salinity when deep groundwater table reaches the critical depth.

The deep groundwater system underlies all soil types but reaches the surface only on L3.

Other hydrological assumptions include:

a)The only types of salinisation that can occur are sandplain seeps and valley floor salinity. Other types of salinity are site specific and not accounted for in this model.

b)If land is 'salt affected' it exhibits all the characteristics of saline land including high soil salt concentrations and water logging. There is no marginally salt affected land.

c)Equation (7) relates the area of arable land to the average water table depth. The area of arable land is unaffected if the groundwater table is beneath the critical depth but decreases to zero as the average ground water table depth approaches ground level. 'Ground level' in this context is that water table depth at which all potential saline land is saline and the 'critical water table depth' is that average depth at which the first land becomes saline. This function simulates a diminishing rate of spread of salinity as the steady state is approached. Initial rates of spread of salinity are taken from McFarlane et al(1988).

d)Recharge in one part of the landscape causes a lagged rise in the watertable in lower parts of the landscape. This is a critical assumption in establishing cause and effect between recharge and salinisation. The time taken for water to travel from recharge area to valley floor can be many years due to the low gradients and low hydraulic conductivity (Nulsen pers. com). Lags were extrapolated from Loh and Stokes(1981), supported by calculations from various hydrological surveys, (Henschke,1985 George and Frantom,1990) including work by the Water Authority in the higher rainfall region which suggests that post clearing equilibrium may be reached in as little as 7 years (Sivapalin pers.com.). This suggests that lag times are in the order of several years. It is likely that the time required to achieve equilibrium in lower rainfall regions is significantly longer.

e)The size of the upland area in relation to the size of the valley floor area is proportional to that found in many valleys in the wheatbelt.

f)Recharge is confined to the upland areas although in some catchments significant recharge occurs beneath valley floor soils (McFarlane,1991).

g)Establishment costs and transpiration rates of trees are fixed.

h)Strategic tree planting is necessary to fully control recharge and to enhance discharge.

AGRICULTURAL SYSTEMS

Agricultural rotation options available include pasture, cereal crops and legume crops as land capability allows. Combinations may be selected and specific interactions between land uses are accounted for.

SOLUTION PROCEDURE

The model is solved to provide a socially optimal solution whereby the combined income of the two farms is maximised. In this case marginal costs are equated and none, some or all recharge from the upland farm is abated.

The model is also solved for the case where the upland farm operates independently of the lowland farm, bearing no cost of salinisation or control. This will be referred to as the 'common property' solution whereby neither farm has any rights over the deep aquifer.

If initial water table depth is less than the critical depth then no control measures are taken until salinity is imminent. For this reason initial water table depth is set equal to the critical depth.

The model has many parameters, such as land productivity and prices, that are measurable and can be expected to vary across different regions. Other parameters, for example relating to hydrogeology, are difficult to measure and some such as future productivity and prices must be assumed. For this reason sensitivity analysis is very important and principal results are expressed as relationships between sensitive parameters.

A number of representative catchments are examined. A representative catchment in this analysis is just a landscape cross-section of unit size with different characteristic soil types. For each, net present values are determined for allowing salinity to develop, for the common property solution and for the socially optimal solution.

The model simulates a fifty year period, long enough for a secondary salinity equilibrium to be established.

Table 1 summarises the principal assumptions. Of note is the higher cost of tree establishment on the valley floor. It is asumed that water logging and higher salinity levels in the ground-water result in a 50% establishment success rate, doubling the establishment cost.

		upland farm	valley floor farm
relative areas		50	15
cost of trees	($/tree)	1.00	2.00
transpiration	(L/day/tree)	30	30

Price of cereal	120	$/tonne
time for recharge to reach valley floor	10	years
storativity	0.1	
discount rate	5	%

table 1. Principal assumptions

In summary, for each catchment the management options available for valley floor salinity are recharge control on the upland farm, discharge enhancement on the valley floor farm or allowing salinity to develop. The model is run to determine under what circumstances each strategy should be adopted.

RESULTS

Sandplain Seeps

Sandplain seeps have been shown to be easily and quickly treated with localised tree planting or drainage (George,1988). In the context of this model this is an internalised problem for the upland farmer and is worthwhile treating.

Valley Floor Salinity

Valley Floor Salinity as discussed above is more threatening in the long run and introduces the problem of externalities. Controlling salinity is viable if the net present value of agricultural production from potentially saline land plus the cost of trees is greater than the net present value of allowing salinity to develop. The cost of trees is incurred either on upland areas to prevent recharge or on valley floor soils to enhance discharge and maintain the water table beneath the critical depth.

The problem is managed differently according to the assumptions made. For example table 2a to 2c show returns, assumptions and management adopted for three soil type combinations, catchment A, B and C, managed in a socially optimal way. By Bettenay's vegetation landform types (Bettenay and Hingston,1961), catchment A has grevillea and tamma soil on the upland farm and salmon gum soils in the valley floor, catchment B has wodjil soil on the upland farm and salmon gum soil in the valley floor and catchment C has wodjil soil and morrel soil respectively.

		upland farm	valley floor farm	total
NPV	($/ha)	1549	823	1382
cereal yield	(t/ha)	1.2	1.1	
recharge rate	(mm)	35		
saline area, yr 50	(ha)		0	
management		-	67 trees/ha planted in yr 10	

table 2a returns and salinity management, catchment A.

		upland farm	valley floor farm	total
NPV	($/ha)	393	1033	541
cereal yield	(t/ha)	1.0	1.1	
recharge rate	(mm)	50		
saline area, yr 50	(ha)		0	
management		48 trees/ha planted in yr 0	-	

table 2b returns and salinity management, catchment B.

		upland farm	valley floor farm	total
NPV	($/ha)	512	77	453
cereal yield	(t/ha)	1.0	1.0	
recharge rate	(mm)	50		
saline area, yr 50	(ha)		15	
management		-	-	

table 2c returns and salinity management, catchment C.

In catchment A trees are grown on the valley floor to enhance discharge. They do not need to be planted before year 10 as the water-table does not exceed the critical depth before this time. In catchment B the yield on the valley floor farm is as for catchment A but the yield on the upland farm is lower . Trees are grown on the upland farm to prevent ground-water recharge. The lower yield on the upland farm allows greater recharge, requiring more trees in total than catchment A but the opportunity cost of the upland farm is lower. Trees are planted in year 0 to prevent the water-table rising beneath the valley floor in year 10. In catchment C the yield and recharge rate on the upland farm is as for catchment B. The yield on the valley floor soil is low enough such that it is not economic either to plant trees to reduce recharge nor to plant trees to enhance discharge. Saline land increases to a secondary equilibrium after 50 years (fig.1).

Sensitivity of yield parameters can be expressed in a two-dimensional surface with lines delineating the yields at which management practices change, Fig 2. For all catchments with yield combinations falling within the area containing catchment A, the best management option is to plant trees to enhance discharge, when necessary. The remaining area enclose sets of catchments to be managed as for catchment B and C.

From fig 2 it is seen that absolute and relative yields on upland and valley floor soils are principal determinants of the salinity management adopted. Other important variables effecting the decision include:

1)Response time between recharge and the water reaching the discharge water table.
2)Discounting.
3)Cost of tree establishment.

The effect of these variables are described qualitatively below and in fig 3.

1)Response time between recharge and the water reaching the discharge water table.

Longer lag times have the effect of increasing the cost of controlling recharge through discounting.

2)Discounting

Higher discount rates have the same effect as longer lag periods i.e. the cost of recharge control increases.

3)Cost of tree establishment.

The cost of tree establishment influences the location of trees. Establishment costs are more likely to vary in the valley floor (waterlogging and ground water salt concentration affect establishment success rate). Higher valley floor tree costs require a higher threshold valley floor yield to make planting in this area worthwhile. Higher recharge area tree costs mean that the recharge area yield below which trees can be grown is lower.

Table 3 shows the NPV of each management option applied to each catchment and indicates the potential losses from adopting incorrect management practices.

catchment:	A	B	C
do nothing	1380	521	453 *
enhance discharge	1382 *	514	369
control recharge	1376	541 *	421
cost of externality	0	20	0
benefit of enforcing recharge reduction	-6	20	-32

* optimal solution.

table 3 NPV/ha of different management policies for three catchments.

The three columns of table 3 represent the three catchments A, B and C. The three rows are the three alternative management strategies: do nothing, plant trees on the valley floor to enhance discharge and plant trees on the upland farm to reduce recharge. The values are the NPV's averaged over the whole catchment.

The first column indicates that there is little difference in NPV between the three management options for catchment A. The second column shows that controlling recharge is a clearly superior management option for catchment B and the third column shows that allowing salinity to develop is clearly superior to attempting to control it.

In catchment A recharge is low and salinity is slow to develop. The benefits are therefore less than in catchment B where the higher recharge rate means that there are greater returns to controlling salinity.

As recharge control requires altruistic action on the part of the upland farm, fig 3 suggests that common property solutions will be inefficient for society for all catchments with yield combinations in the area containing B. Table 3 quantifies this loss as $20/ha for catchment B.

In catchment C yield are low and recharge rates are high. The greater cost of trees and the lower value of potentially saline land mean that the cost of planting trees is greater than the benefit.

In catchment B where it is best to control recharge on the upland farm, this will not occur unless some means is adopted to bring this about. If property rights are granted to the valley floor farmer and the upland farm is forced to plant trees then an efficient solution is achieved. If however the valley floor farmers in catchment A and C demand the same rights then the benefit is negative in these catchments.

DISCUSSION

The results showed that different management practices are suitable for different catchments, dependent largely on the relative and absolute productivity of the land types and the time for ground-water recharge to influence the valley floor hydrology. Because in some situations it is better to prevent ground-water recharge which often occurs on different properties, some government intervention may be justified. However in many cases on-site treatment or allowing salinity to develop is the best solution. In this case these catchments are already being managed optimally from societies point of view, if not equitably from the individual's point of view. Identification of these areas is difficult and the potential exists for losses if regulation to control groundwater recharge are applied unnecessarily.

The question of timing was alluded to in the solution procedure section. It is worth pointing out that threshold effects exist in a temporal sense. This suggests that clearing land for agriculture is (was) the correct course of action providing measures are taken at a later date to prevent damage occuring.

Efficiency requires analysis and policy prescription for individual soil types, catchments, or zones as discussed by Oram and Dumsday, (1986). The information requirements for this type of scheme are large and expensive but advances in technology are constantly reducing this cost.

In the absence of detailed information decision still have to be made regarding management of catchments. Economic information derived from an extension of the type of approach employed in this analysis can play a part in this decision making process. The minimum information requirements being a standardised assesment of land areas and capabilities, their spatial relationships and a rudimentary assesment of hydrological parameters.

Where regulation is necessary there exists a number of problems:
The non-point source nature of dryland salinity makes attributing cause and thus cost difficult (Clarke,1983), the inter-temporal nature of dryland salinity makes these solutions even more difficult. Any policy introduced to reduce ground water recharge faces timing problems; the cost of the policy is incurred at the present time, but the effect of the policy may or may not be felt at some indeterminate time in the future, according to whether the critical water table depth would be reached with the current recharge.

The problem of currently saline land has not been addressed in this paper but the implications for management are that discharge enhancement is required to restore land productivity, at least in the interim period, doubling up on control costs if recharge reduction is optimal in the long run. Restoration costs (to lower rather than maintain a water table level) of saline land will be greater.

The linearity of the functions in the model produce corner solutions with respect to choice of salinity management. Although the real functions are non-linear this is unlikely to significantly effect the solution.

In this analysis ground-water recharge does not occur beneath valley floor soils. As this does occur in some areas the implication is that the valley floor farm would have to plant trees to control the water table in the future regardless of any off-site recharge. If this were the case then the marginal damage cost to the valley floor farm may be reduced.

The beneficial effects of growing saltbush on saline land (Salerian et al,1987) has been excluded in this model. Although valuable in supplimenting sheep feed, diminishing returns are experienced as other constraints are met and the land is of little use for alternative crops, reducing the flexibility of management.

Another factor not accounted for is the beneficial effect of integrating trees into the agricultural landscape. Trees can act as wind breaks, livestock shelters and soil stabilisers. There is also potential to develop the small commercial wood market, currently confined to higher rainfall areas for transport cost reasons. Government intervention may be better directed towards developing infrastructure for this industry. Already schemes exist for investing private capital into agroforestry projects, in which case no incentive need be offered to induce trees to be planted on recharge areas.

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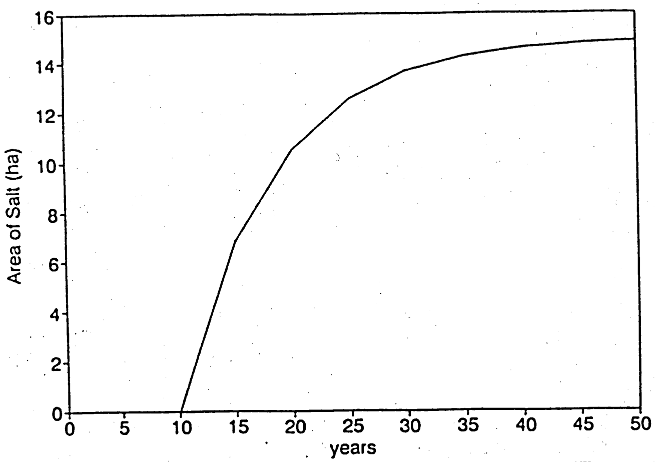

Figure 1: Spread of Salinity with Time

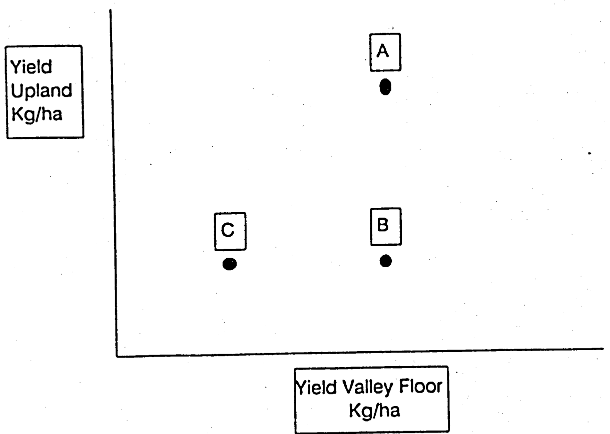

Figure 2: Upland and Valley Floor Crop Yields: Example Catchments

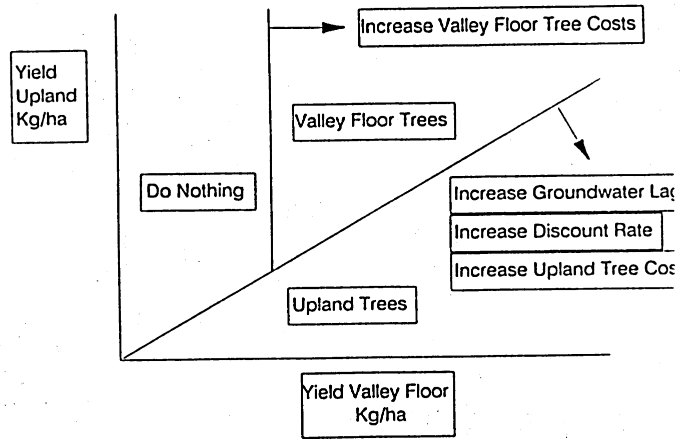

Figure 3: Upland and Valley Floor Crop Yields Sensitivity