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ECONOMIC MODELLING OF DRYLAND SALINITY IN WESTERN AUSTRALIA*

J. Gomboso

Agricultural Economics
Discussion Paper: 4/90

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ECONOMIC MODELLING OF DRYLAND SALINITY IN WESTERN AUSTRALIA*

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*This work is supported by a postgraduate scholarship from the Australian Special Rural Research Council.

ABSTRACT

The clearing of land for agricultural purposes in the low rainfall areas of south-west Western Australia has resulted in soluble salts being transported from upslope recharge areas, through groundwater flows, to downslope discharge areas. Dryland salinity is not confined to individual properties. It may disperse among properties and catchments, and is thus a common property problem. In an attempt to model the effect of natural resource utilisation and the divergence between private and socially optimal rates of land degradation resulting from the exploitation of common resources, a dynamic optimisation model of soil salinity has been developed. The objective of soil conservation models may not necessarily be to stop future degradation in its entirety, but to ensure that all resources are applied to their highest value combination of end uses, both currently and in the future (Morris et al, 1988). The model is also used to examine the steady-state solution to optimal control. In the case of dryland salinity, a steady-state equilibrium occurs when the hydrological balance is in equilibrium.

Salinisation of dryland areas has been caused predominantly by the removal of high water-using, deep-rooted native forest, and its replacement with shallow-rooted annual crops and pastures. Agricultural expansion in the low rainfall areas of south-west Western Australia has modified the natural water balance, thereby affecting the volume and flow of surface and ground water. The resultant change in the hydrological balance of the soil brings rising water tables and stored salts to the surface, and evaporation causes these salts to be left behind.

1: INTRODUCTION

Recent surveys carried out by the Western Australian Department of Agriculture in conjunction with the Australian Bureau of Statistics have indicated that approximately 1.6 percent of cleared agricultural land in Western Australia is now affected by dryland salinity *(Department of Agriculture, 1988).*

The growing concern for conserving environmental quality has led to an increase in interest in renewable resource management issues. The immediate source of this concern is a perception that some of the natural resources associated with agriculture are becoming degraded *(Wills, 1987).* Associated with the problem of dryland salinity are the conflicting economic and ecological objectives which, on one hand, aim to maximise the net benefits received from the production of agricultural goods and services, and from a society viewpoint, aim to conserve the ecological standards of the natural environment *(Braat & van Lierop, 1987).* In addition, the competitive exploitation of common property resources results in a divergence between the private and social costs of land degradation. Consequently, the rate of natural resource utilisation may tend to be economically inefficient and anti-conservationist.

Salinisation of dryland areas has been caused predominantly by the removal of high water-using deep-rooted native forest, and its replacement with shallow-rooted annual crops and pastures *(Wood 1924; Teakle 1937; Burvill 1947; Teakle & Burvill 1945; Smith 1962; Bettenay et al 1964; Peck & Hurle 1973; Mulcahy 1978; Nulsen 1982; Malcolm 1983).* Clearing has modified the natural water balance., reducing the utilisation of stored soil moisture, permitting increased accession of rain to the groundwater, and thereby increasing the volume and flow of ground and surface water. The resultant change in the water balance brings rising watertables and stored salts to the surface. The water percolates upwards through channels created by decayed roots, and then evaporates at the soil surface, leaving the salt behind.

The present study addresses the divergence between private and social costs of degradation, and develops a theoretical optimal control model for dryland salinity, taking into account these two points of view. The model described here discusses the importance of compatibility between agricultural productivity and environmental carrying capacity over an unlimited time period, and thus focuses on the steady-state solution to optimal control. In the case of dryland salinity, a steady-state equilibrium has been reached when the inflows to the groundwater system from precipitation and outflows, through surface runoff, evapo-transpiration and natural drainage, are in equilibrium.

Dynamic optimisation models of land degradation have been developed by Knapp (1984), Burt (1981), Hertzler et al (1985), Salerian (1989), McConnell (1983), Miranowski (1984), and others, and these are discussed throughout the paper.

The objective of this paper is to describe the agricultural and economic aspects of dryland salinisation. Initially, an outline of the nature and causes of salinity is discussed, including: the extent of salinity throughout Western Australia; the definition and types of soil salinity; and the factors affecting the accumulation of salts within the soil.

2: CAUSE AND NATURE OF SOIL SALINITY IN WESTERN AUSTRALIA

(i) Extent Of Dryland Salinity In Western Australia

Throughout Western Australia, approximately 500,000 hectares of saltland exists in agricultural areas, predominantly within the low rainfall areas up to the 600 mm rainfall isohyet. Much of this is primary salinity, occurring naturally in soils as a result of geological and geomorphic process of ancient river systems before agricultural development. However, also present in the soil is secondary salinity, caused by the clearing of native forest for agriculture *(Burvill, 1956).*

In an attempt to monitor the extent of secondary soil salinity throughout Western Australia, a survey was carried out for the 1930-36 period, under the direction of Teakle (1937), covering approximately 500,000 hectares. The area surveyed included Lake Brown, Cleary, Lakes District and Salmon Gums. These were followed by surveys carried out by the Australian Bureau of Statistics in co-operation with the Department of Agriculture in 1955, 1962, 1974, 1979 and 1984 *(Burvill 1956; Henschke 1980; Lightfoot et al 1964; Malcolm et al 1976; Western Australian Select Committee on Salinity 1988).* Recent results of the survey showed that the areas of cleared land now affected by dryland salinity has increased from 0.5 percent in 1955, to 1.6 percent (or 255,000 hectares) in the 1984-85 period.

Results of the most recent survey (the 1984-85 period) is presented in Table 1. The statistical divisions upon which the survey results are categorised are shown in Map 1. From the Table, it is evident that the Southern, Central and Northern Agricultural statistical divisions have the highest proportion of cleared land affected by salt.

<u>The Study Area: North Stirling Ranges, Western Australia</u>

The objective of this research is to develop an optimal control model of dryland soil salinity for the North Stirling Ranges Catchment of Western Australia. The North Stirling Land Conservation District comprises an area of 100,000 hectares. Fifty percent is flat, poorly drained and consists of salt lakes. The area is subjected to severe salinity problems, waterlogging, flooding, wind erosion and non-wetting soils.

The lakes area is underlain with 50 metres of Eocene sediments of gravel, clay, silt, limestone and coal, deposited over 43 million years ago. Clearing occurred between the late 1950's and early 1970's, resulting in groundwater pressure. Because of low topography and low rainfall, there has been dramatic saltland encroachment, resulting in the development of secondary salinity over a short period of time *(Department of Agriculture, 1988b).*

Groundwater studies within the Catchment have recorded the following levels of total soluble salts:

Deep piezometer readings: 100,000 - 200,000 mg/L TSS;
Shallow piezometer readings: 50,000 - 100,000 mg/L TSS;
Salt in sea water (for comparison): 35,000 mg/L TSS.

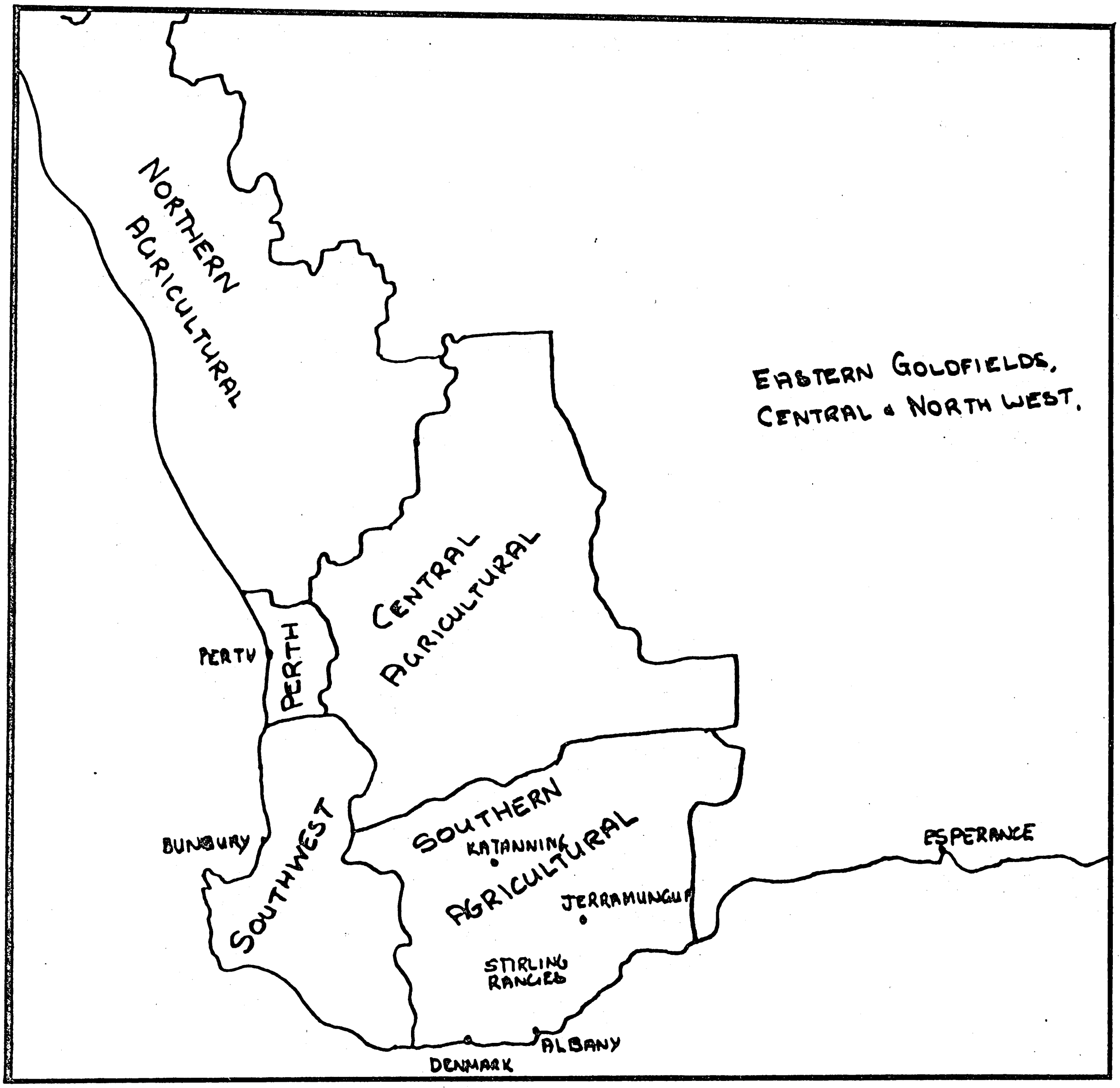
Records show that in deep groundwater aquifers, the total soluble salt concentration may be up to six times saltier than sea water.

TABLE 1
TOTAL HOLDINGS, CLEARING AND SALTLAND IN STATISTICAL DIVISIONS FOR THE 1984-85 SALTLAND SURVEY

	Number of active holdings	Total area of active holdings km^2	Area of cleared land km^2	Number of holdings reported saltland	Total area of saltland km^2	Saltland /cleared land %	Cleared Land /area of holdings %
Perth	1,822	1.037	824	26	0.74	0.06	77
Southwest	3,463	9,908	8,190	230	37.36	0.50	83
Southern Agricultural	3,664	42,939	37,428	1,103	578.81	1.55	87
Central Agricultural	3,645	63,081	54,425	1,472	1,008.16	1.85	86
Northern Agricultural	2,626	64,437	43,104	811	864.24	2.00	67
Eastern Goldfields	972	59,371	18,710	164	57.61	0.31	27
Central & North West	205	68,693	19	-	-	-	<1
Total: Reported by Salt-affected farms	1,397	309,502	162,536	3,806	2,546.92	1.6	56
Total: Western Australia	16,890	1,139,697	162,679	3,807	2,546.90	1.6	14

(Source: Department of Agriculture (1988)., "Salinity in Western Australia - A Situation Statement:., Technical Report No. 81., Division of Resource Management, Western Australia.

MAP 1:
Statistical Divisions



Source: Malcolm, C.V., and Stoneman, T.C., (1976)., "Salt Encroachment - The 1974 Saltland Survey"., Journal of Agriculture, Western Australia., Vol. 17, No. 2., 4th Series., p 43.

(ii) Definition and Types of Soil Salinity

Soil salinity is commonly referred to as the presence of harmful quantities of salt within soils, on the surface of soils, and within water bodies*(Salinity Committee, Parliament of Victoria, 1984)*. Salinisation of dryland areas has been caused predominantly by the removal of high water-using deep-rooted native forest, and its replacement with shallow-rooted annual crops and pastures*(Wood 1924; Teakle 1937; Burvill 1947; Teakle & Burvill 1945; Smith 1962; Bettenay et al 1964; Peck & Hurle 1973; Mulcahy 1978; Nulsen 1982; Malcolm 1983)*. The major sources of soluble salts in Western Australia are weathered rock, wind borne oceanic salts (cyclic salts) and salts that have remained in the landscape after the transgression of marine waters during past geological periods *(Salinity Committee, Parliament of Victoria, 1984)*.

Dryland salinity may be divided into 3 main forms: seepage salinity, watertable saltland and salt scalds. In many cases, land affected by salt may be brought about by a combination of these factors.

Seepage Salinity (or hillside seepage) occurs where shallow watertables are sufficiently close to the surface to cause saline water to seep to the surface where there are changes in topography. There are four main topographical structures which are responsible for seepage salinity. These are bedrock high seeps, dolerite dykes (or texture change) seeps, seeps at the base of sands, and seeps at the change of slope *(Nulsen 1985,; Malcolm 1977; Malcolm & Stoneman 1976; Queensland Department of Primary Industries 1985, 1987)*.

The most common type of salinity is watertable salinity (or valley waterlogging). Watertable salinity occurs in depressions and flat valleys that have an underlying saline watertable. Movement of salts to the surface is dependent on soil type in the valley soils. Watertable salinity is caused by the existence of shallow (or seasonally shallow) groundwater sufficiently close to the soil surface to cause an upward movement of water and concentration of salts in the root zone and soil surface *(Queensland Department of Primary Industries 1985; Malcolm 1977)*. Capillary action transfers water and dissolved salts from the watertable to the soil surface. Evaporation of water and the deposition of salts results in large accumulations of surface salts. Factors which promote surface salt concentrations include a bare soil surface, high groundwater salinity, and a high rate of capillary rise *(Queensland Department of Primary Industries 1987)*.

The third form of dryland salinity is salt scalding. Salt scalds occur in some fine-textured soils with naturally saline subsoils. They are neither the result of salty watertables or seepage. Scalded areas result when wind or water erosion removes the topsoil from texture-contrast soils that have clay subsoils, exposing a naturally saline subsoil. 'Morrell soils', for example, which are poorly leached due to inadequate rainfall and impermeable subsoils, are areas prone to scalding in Western Australia *(Peck 1979; Malcolm 1977; Burvill 1988).*

(iii) Factors Affecting Salt Accumulation

There are 5 main factors affecting the accumulation and movement of salt in soils. These are: rainfall, soil type, topography, hydrology and landuse.

Rainfall

It is universally recognised that salt accumulation in soil is greater where rainfall is light, that is, where it is in insufficient amounts to cause a movement of water through the soil and into natural drainage systems *(Teakle & Burvill, 1945).* In general, the severity of dryland salinity is related to seasonal rainfall distribution. In the lower rainfall areas of Western Australia (up to the 600 mm isohyet) clearing of deep-rooted native vegetation and its replacement with annual crops and pastures result in the development of soil salinity in low lying areas *(Dimmock et al 1974).*

Soils

In Western Australia, a general relationship exists between soil type and salinity. Heavy soil types, in which percolation is restricted and which usually carry a heavy growth of timber, are more susceptible to damage from salt, once cleared, than light porous soils, where soluble salts are rapidly leached *(Teakle 1937, 1938, 1939; Teakle et al 1940).* Soil salinity is practically unknown in the sandy and gravelly soils of the sand plains, due to periodic flushing. It is the woodland and mallee areas that are saline *(Teakle & Burvill, 1938).*

Topography

Topographical features such as slope, dissection and micro-topography all affect the accumulation and movement of salts within soils. In general, valleys with steeper grades do not suffer from salinity problems because the groundwater, if at all present, is usually at sufficient depths not to cause surface salting. Saline areas in the Western Australian wheatbelt tend to be associated not only with the floors of broad flat, low grade valleys, but also with changes in slope that occur along both the course of the valley or at the junction between valley sides and floors *(Malcolm 1983; Bettenay et al 1964).* Micro-topography also plays an important part in influencing salt movement. The existence of dolerite dykes have been found to form subsurface and surface crests and ridges where they would intersect the groundwater flows, causing saline seeps *(Bettenay et al 1964; Engel et al 1987).*

Hydrology

The transportation and redistribution of naturally occurring soluble salts throughout the landscape has been achieved by water movement within the hydrological cycle *(Western Australian Select Committee on Salinity, 1988)*. The hydrological cycle is a process within which precipitation is transferred (both vertically and horizontally) to the land into temporary and permanent water storages. The hydrological cycle may be divided into three areas. These are:

a. the recharge (or intake) area. The two factors affecting groundwater recharge are the source of supply and intake facilities. Precipitation is the main source of supply. Factors determining whether precipitation will become part of the groundwater are: soil permeability, vegetation cover, soil texture and topography *(Bettenay et al 1964; and Green 1977)*.
b. the transmission (of flow path) area. Transmission zones are those areas where the dominant recharge flow is laterally to the groundwater system. They are areas of intermediate or decreasing slope, with deeper, less permeable soils over weathered rock *(Queensland Department of Primary Industries, 1987; Bettenay et al 1964)*.
c. the discharge area. This is the site of water removal from the hydrological cycle. Water may be discharged by evaporation, transpiration, surface runoff, and downslope seepage.

Collectively these three zones make up the water balance. Over many years, under a stable climate, the natural landscape system reaches a hydrological equilibrium, where outflows from the cycle are in equilibrium with inflows from precipitation *(Queensland Department of Primary Industries, 1985)*. The result is a simplified water balance equation:

Rainfall = Evapotranspiration + Surface Run-off + Interception Loss + Drainage Below the Root Zone + Change in Stored Soil Water in the Root Zone. *(Henschke (undated))*.

<u>Landuse</u>

The clearing of native forests for agriculture has long been regarded as the major cause of dryland salinity *(Nulsen 1984; Mulcahy 1973; Smith 1966; George 1979; Peck et al 1984; Peck 1978; Teakle 1928, 1929; Dimmock et al 1974; Malcolm 1983; Bettenay et al 1964)*. Clearing has modified the natural water balance, thereby affecting the volume and flow of ground and surface water. The removal of high water-using, deep-rooted perennials, and their replacement with shallow-rooted crops and pastures, reduces the utilisation of stored soil moisture, thereby permitting increased accession of rain to the groundwater *(Western Australian Select Committee on Salinity, 1988)*. The resultant change in the water balance brings rising watertables and stored salts to the surface. The water percolates upwards through channels created by decayed roots, and then evaporates at the soil surface, leaving the salt behind *(Nulsen, 1984)*.

3: ECONOMICS OF SOIL SALINITY

The growing concern for conserving environmental quality and the increasing demand for productive agricultural land, has led to an increase in interest in renewable resource management *(Kennedy 1986; Lewis & Neher 1982; Mirman & Spulber 1982; Luptacik & Schubert 1982; Braat & van Lierop 1987)*.

Associated with the problem of dryland salinity are the conflicting economic and ecological objectives which, on one hand, aim to maximise the net benefits received from the production of agricultural goods and services, and from a society viewpoint, aim to conserve the ecological standards of the natural environment. The aim of this study is to address these conflicting issues and develops a theoretical optimal control model for dryland salinity, taking into account these two points of view.

The clearing of native forest in the agricultural areas throughout Western Australia and their replacement with shallow rooted crops and pastures has caused water tables to rise, bringing stored salts to the surface. The effect of these saline soils on agricultural productivity has been to decrease agricultural output and limit plant species diversity on farm land. Because the effect that clearing has on groundwater is not confined to individual farms, a <u>common property problem</u> arises. The clearing of land for agriculture may result in saline groundwater being transported from upslope recharge areas through groundwater flows to downslope discharge areas.

The traditional understanding of a common property resource is that of free access for its utilisation *(Anderson & Thampapillai, 1989)*. Miller (1982), for example, describes common property resources as those resources which are owned by everyone, and therefore owned by no one. Quiggin (1986, 1988) and Ciriacy Wantrup & Bishop (1975) criticize the externality approach of Pigou and the Coasian approach of private property rights, and argue that the term 'common property' implies the existence of ownership and collective property rights - or common ownership. According to Quiggin (1986), common property structures involve well defined rights of exclusion and use.

Quiggin (1986) applies his common property approach (socially managed optimum) to the case of dryland salinisation, by developing a dynamic model and examining the changes in cropping practices as the external effects of salinity are internalised. With respect to dryland salinity, the utilisation of common resources results in the generation of three types of externalities: costs borne by downstream water users; losses in agricultural productivity associated with dryland salt; and loss of unique flora and fauna species and species diversity *(Quiggin 1986, Hardin 1968)*. As a result of these externalities, the exploitation of a common resource often results in a divergence between social and private values.

Results of his study show that under an open-access approach, increased stream salinity results in the absence of stone fruits and its replacement with more salt tolerant grapes and irrigated pastures. In the socially managed optimum dynamic model, by contrast, the cropping pattern has altered, moved towards stone fruit resources and away from pastures. A comparison of the two hypothetical results show that estimated total profits has increased by $19 million under the socially managed system.

External costs and benefits of soil salinity include the effect that degradation and reclamation have on downslope land and water users, and future users of agricultural land. The yield reductions that arise from salinity develop over time and accordingly, several authors including McConnell (1983), Miranowski (1984), Van Kooten et al (1989), Walker (1982), and Walker and Young (1986), have introduced time explicitly into the model *(Anderson & Thampapillai, 1989)*. The degradation of productive agricultural land brought about by increased salinity levels reduces total availability of productive land area for future production. This reduction in consumption net benefits on future generations is defined as <u>user cost</u>.

Noting the importance of user cost in determining the social costs and benefits of salinity degradation, land use and management decisions should be evaluated within an intertemporal framework. The basic framework of the theory of intertemporal resource economics is well defined by optimal control theory *(Anderson & Thampapillai 1989; Salerian 1989)*.

McConnell (1983, 1986), for example, uses optimal control theory to analyse the economics of soil conservation at a theoretical level. The paper develops an economic model for the optimal soil loss at both the private and social level. The focus is on the intertemporal path of soil use which determines when the private path of erosion differs from the social optima. The two model solutions suggest that, under most institutional arrangements, the social and private rates of erosion would generally converge *(McConnell 1983; Anderson & Thampapillai 1989)*. Kiker and Lynne (1986), however, argue that the certainty assumptions in McConnell's framework are too restrictive because only soil depletion is considered and environmental disruptions caused by soil erosion are excluded from the analogy. McConnell assumes that product prices, input costs, the length of the planning horizon and the discount rate are all known with certainty *(Anderson & Thampapillai 1989)*. In addition, the model ignores two important components - the contribution of erosion to water pollution, and soil quality over time *(McConnell, 1983)*.

However, McConnell's model is able to present a dynamic model of soil erosion that provides an insight into the economic factors influencing a farmer's use and conservation of soil *(Kiker & Lynne, 1986).*

Empirical applications involving intertemporal resource economics are limited. Dynamic models which have been applied to the problems of land degradation include those by Burt (1981) and Miranowski (1984) for soil erosion, and Salerian (1989) , Quiggin (1988) and Knapp (1984) for soil salinity. The popularity of dynamic models arises from the flexibility of the methods used to describe systems operation, including non-linear responses of components to controlling variables, and both positive and negative feedback, which are characteristic of the ecological system *(Braat & van Lierop, 1987; Jeffers, 1987).*

Econometric and linear programming steady-state models have also been developed by Dinar and Knapp (1988) and Greig and Devonshire (1981), respectively, for stream salinity and irrigation salinity problems.

Burt (1981) has approximated optimal control theory to evaluate soil conservation strategies in the Palouse area of the United States, using a continuous-choice dynamic programming model. Burt (1981) uses depth of topsoil and percentage of organic matter as the state variables, and percentage of land planted to wheat as the control variable.

The results of his intertemporal study demonstrate that relatively high grain prices exacerbate soil erosion problems. One of the conclusions by Burt (1981) is that the reduction in net returns, brought about by soil loss and organic matter loss, does not become a significant threat to the soil due to the assumption that good cropping practices (including the use of fertiliser) can substitute these losses. Taylor et al (1986) has criticised various conceptual and data limitations of Burt's optimal control model, including the above mentioned conclusion.

The most important conceptual limitation of Burt's model (according to Taylor et al, 1986) is the use of the percentage of land planted to wheat as the only control variable, explaining that Burt's optimal solutions depart from what farmers in the region were (and are) doing. Spring crops of barley, lentils and peas have been dominant rotations, with wheat being planted to 47 percent of cropland. Additional limitation of Burt's analysis was the omission of technical progress in projecting future yields, and the use of 25 year old data to represent current agricultural conditions *(Taylor et al ,1986).*

Miranowski (1984) uses a discrete-choice multiperiod linear programming model to find the optimal choice of tillage method and crop rotation for a catchment in Iowa affected by soil erosion. The intertemporal model evaluates the impact of productivity losses on crop production and management decisions over a fifty year period. The objective function of the model is to maximise the net present value of crop production, and test the sensitivity of the results to assumed relationships between soil loss and crop yields. According to Hertzler et al (1985), the results of the model indicate that a more erosive alternative will usually incur greater total user cost, but these costs may be more than offset by lower total operating costs or returns from higher yields. Thus, there is no simple correspondence between user costs and the rate of erosion from the optimal alternative.

Econometric models of soil salinity have been developed by Greig and Devonshire (1981), Dinar and Knapp (1988), Quiggin (1988), Salerian (1989) and Knapp (1984).

Greig and Devonshire (1981), used a logarithmic time-series econometric model to establish a quantitative relationship between tree clearing and stream salinity in Victoria. The study does not enter the debate into whether reforestation will decrease salinity. Instead, it uses the relationship to evaluate the benefits of retaining forests to prevent future salinisation.

Greig and Devonshire (1981) have taken into account the exponential relationship between salinity increases and forest clearing in their model. Results of Western Australian studies undertaken by Peck and Hurle (1973), and Loh and Stokes (1981), like Greig and Devonshire, show an exponential relationship between the two variables, only at much higher salinity levels.

Although the model provides a useful contribution to both hydrologic research and to the evaluation of forest externalities, its applicability to Western Australia's dryland salinity problem is limited. The exclusion of reforestation may have a significant impact on modelling results, especially in areas such as the North Stirling Ranges, Denmark and Wellington, where tree planting plays a major role. Re-establishment of deep-rooted trees plays a major role in helping to reduce groundwater levels that have risen as a result of their removal. It is important that reforestation be included in the model, especially when long periods of time are involved, as this is the direction in which the Western Australian farming system is heading.

The lagged effect of clearing on stream salinity was omitted from the econometric model of Greig and Devonshire (1981). Studies by scientists on soil salinity suggest a lagged response of salinity after clearing. Refer Holmes and Wronski (1981); Western Australian Select Committee on Salinity (1988); Williamson et al (1987); Peck and Hurle (1973). The timing of salt encroachment after clearing plays an important part in economic modelling, especially in the case on an infinite planning horizon model, when steady-state levels are being estimated.

The omission of soil type and variations in evapo-transpiration and groundwater recharge under different catchment vegetation types are additional limitation to this time series model. These factors, along with the differences in rock-type and salt levels between the Victorian catchment and south-west Western Australia prevent the extrapolation of Greig and Devonshire's results beyond south-eastern Australia.

Dinar and Knapp (1988), developed a long-run, steady-state model of on-farm solutions to drainage problems in irrigated agriculture, affected by salinity. On-farm drainage management strategies for reducing and disposing of drainage water included: reducing applied water quantities per unit area; changing cropping patterns; re-using drainage water from sensitive crops to more salt-tolerant crops; constructing evaporation ponds; and improving water application efficiency through changes in irrigation systems and management practices.

Soil salinities are calculated in the model using steady-state relations. This means that sufficient leaching water is applied every year so that the annual quantity of salt entering the root zone, equals the quantity leaving, and soil salinity remains unchanged on average. This differs from the saline areas of south-west Western Australia where the lagged effects of clearing on groundwater recharge has resulted in the environment currently being in a state of disequilibrium. The model also differs in its specification of the profit function. Annual returns to land and management are assumed to be non-linearly related to salinity. In addition, due to the disequilibrium steady-state that currently exists, and the lagged effect of clearing on the hydrological balance and future profits, a dynamic approach is required.

Quiggin (1988), Salerian (1989) and Knapp (1984) use dynamic optimisation models to evaluate the economic relationship between salinity and farm profit.

Although time is a common element in models of dynamic optimisation, not all programming models are applied within an intertemporal framework. Quiggin (1988), for example, uses a socially managed optimum approach to address irrigation-related salinity in Australia's Murray River system, and identifies the combination of agricultural inputs that should be used to maximise farm profits in this area. His static model differs from the dynamic models above, in his replacement of time with land area. In Quiggin's model, the external costs and benefits of land management decisions have been examined not by incorporating time into the analogy, but by modelling six different degrees of salinity, beginning with upstream non-saline water, to downstream salt-affected irrigation water. Quiggin models salinity as increasing in magnitude as one moves further downstream, for a given time period. Hence in Quiggin's model used land area is used as a proxy for time.

Salerian (1989) developed a non-linear programming model of soil salinity which is empirically estimated using a series of linear programming and non-linear regression models. The model is applied to a subcatchment in Western Australia, and examined over a period of fifty years. The results of the study indicate that, in the Wallatin Creek subcatchment, externalities and imperfect information are not causing excessive levels of dryland soil salinity. This is because the recharge zone and salt-affected land represents only a small part of the total farm area, and, as a result, the marginal cost of salinity in terms of total farm profits is low. The applicability of this model to the North Stirlings District would yield considerably different results, as a greater proportion of the Stirlings Catchment (approximately 50 percent) is flat, poorly drained, and extensively salt-affected. The regional groundwater system in this District now severely affects 50,000 hectares of the North Stirling Basin.

Salerian's model differs from that of Knapp (1984) in that it estimates optimal soil salinities and cropping practices when the environment is not at a steady-state optimum. Knapp (1984), alternatively, uses an algorithm to determine the steady-state solution to a dynamic optimisation problem relating to soil salinity. Optimal water quantities and soil salinity levels in the steady-state were calculated for naval oranges in two areas of California. His study described various solutions that could be used to reach optimal steady-state salinity levels, and how the underlying biological and physical processes in economic analyses of agriculture and natural resources can affect these solutions *(Knapp, 1984).*

4: AN OPTIMAL CONTROL MODEL FOR DRYLAND SALINITY

(i) Objectives of the Study

The study develops a dynamic optimisation model for dryland salinity. The point of view taken in optimal control modelling of soil salinity is to maximise social welfare. This is achieved by maximising the net present value of agricultural production by considering the costs and benefits of soil salinity on future land users.

Using discrete-time optimal control modelling, the objective function is:

$$J\,(Wo) = \underset{Z_1 Z_2 Z_3}{\mathrm{Max}} \sum_{t=0}^{T-1} \left(\frac{1}{1+r}\right)^t \left[\, pf(W_t, Z_{1t}, Z_{2t}, Z_{3t}) - c(Z_{1t}, Z_{2t}, Z_{3t})\,\right] + \left(\frac{1}{1+r}\right)^T F(W_T) \quad \text{...(1)}$$

where J is the optimal value as a function of the initial level of the state variable, (W_0). Based on Bellman's principles of optimality, "State variables in a dynamic optimisation problem must encompass sufficient information on the decision process so that when the variables are at given levels at a point in time, the history of the decision process is almost completely subsumed for purposes of optimal decisions in the future". *(Burt, 1981, p84)*. The state variable in this model is the groundwater level (W_t). Once this variable is identified, the size of the recharge and discharge areas can be determined. The different pasture and crop types, and tree species that will grow on these areas can also be determined. Hence W_t determines the potential and actual agricultural capacity of the land.

The control variable represents the vector of inputs which encompass all possible farming practices that jointly affect the rate of recharge, water-table depth, salt accession and net cash flow from the landscape. The decision or (control) variables are specified as a vector of three inputs:

Z1. the use of agronomic techniques - such as the planting of trees and crops on recharge areas, and the use of salt-tolerant plants on marginally discharge areas;
Z2. the implementation of engineering techniques such as grade banks, interceptor drains and banks, and levees; and
Z3. the application of fertiliser to crops and pastures on recharge and discharge areas.

The control variables, Z_1 and Z_2, determine the rate of water infiltration to the groundwater system. Controlling the amount of water entering the groundwater system depends, in the long-run, on the various crops and pastures grown on that system, and the types of engineering techniques used. The introduction of high water-using pastures and trees on recharge land, for example, will reduce water infiltration, thereby reducing upslope run-off and infiltration accumulation in the discharge area. The control variable Z_3, is another input into the production process, but differs from the controls Z_1 and Z_2 in that the quantity and rate of fertiliser application has no affect on the state variable, W_t.

The social rate of discount is r. This estimates how we value the welfare of future generations. Farm output (q) is a function of watertable (or groundwater) level (W_t), the rate of water infiltration to the groundwater system (Z_1 and Z_2), and the rate of fertiliser application (Z_3), such that:
$q = f(W_t, Z_{1t}, Z_{2t}, Z_{3t})$. The price, p, is the inverse demand system for all possible cropping, pastoral and tree-planting activities *(Hassan & Hertzler, 1988; McConnell, 1983)*. The cost of the agronomic, engineering techniques and the variable input, fertiliser, is represented by the cost function c. The function $F(X_T)$ represents the final resale value of the land at terminal time T. In infinite time models, the terminal function is omitted. In empirical models of discrete-time optimal control, a planning horizon is specified. In the case of dryland salinity, if a steady-state optimum is to be achieved, trees planted on the recharge zones must be allowed time to mature so their

complete evapo-transpiration properties can be accounted for in the model. This may take several hundred years.

The environmental model must be incorporated into the problem. Changes in the distance of the groundwater from the soil surface over time is subject to the following constraints:

$$W_{t+1} - W_t = - g(W_t) + h(Z_{1t}) + j(Z_{2t}) \quad \text{... (2a)}$$

$$W_0 = a \quad \text{... (2b)}$$

where g is the rate of water removal from the environmental system through natural drainage and waterways, and h and j are the rates of water infiltration to the watertable from agronomic and engineering techniques, respectively. There is an inverse relationship between the amount of recharge entering the environmental system from natural drainage and changes in the level of the groundwater aquifer. As the natural drainage rate is increased, the groundwater level drops and salinity is reduced. The rate of water infiltration from agronomic and engineering techniques is positively related to the changes in groundwater level. As the amount of water infiltrating through the system rises, so too does the depth of the watertable. The coefficient a, in Equation 2(b), represents the initial depth of the groundwater level at time 0.

(ii) Maximum Principle Solutions

The first step in the optimisation problem is the construction of the current-value Hamiltonian. The right hand side of the environmental constraint are multiplied by the costate variable, ψ, and added to the benefits for a single time period extracted from the objective function:

$$\tilde{H}_t = [\ pf\,(W_t, Z_{1t}, Z_{2t}, Z_{3t}) - c\,(Z_{1t}, Z_{2t}, Z_{3t})\ ] + \psi_{t+1}\, [-g_t + h_t + j_t] \quad \text{... (3)}$$

The Hamiltonian in period t, is the total profits of the decision-makers in period t, which comprises the direct and indirect profits effects of (W_t, Z_{1t}, Z_{2t}) *(Benavie, 1970)*. The costate variable (ψ_t) is the implicit price of salt affected land brought about by changes in the groundwater level. For example, if agricultural land is being used to produce different crops, pastures and trees, the net effect of agriculture on the watertable level and salinity at time t is -g+h+j; the dynamic cost of the saltland is ψ_{t+1}, and the total cost of changing the groundwater level is $\psi_{t+1}(-g_t+h_t+j_t)$. These dynamic costs are the costs to future generations of degrading land, and should be subtracted from other benefits to calculate the dynamic benefits *(Hassan & Hertzler, 1988)*.

There are seven first-order conditions:

$$\frac{\partial \tilde{H}_t}{\partial Z_{1t}} = 0 = p\frac{\partial f}{\partial Z_{1t}} - \frac{\partial c}{\partial Z_{1t}} + \psi_{t+1}\frac{\partial h_t}{\partial Z_{1t}} \qquad \text{...(4)}$$

The first two terms in equation (4) reflects the influence that the control variable, agronomic recharge (Z_{1t}) has on marginal revenue and marginal cost (or marginal value product, MVP). The third term represents the marginal costs of water infiltration caused by clearing and revegetating land through agronomic manipulation at time t, rather than conserving the land for future generations.

$$\frac{\partial \tilde{H}_t}{\partial Z_{2t}} = 0 = p\frac{\partial f}{\partial Z_{2t}} - \frac{\partial c}{\partial Z_{2t}} + \psi_{t+1}\frac{\partial j_t}{\partial Z_{2t}} \qquad \text{...(5)}$$

Similarly, the first two terms in equation (5) reflects the influence that manipulating groundwater recharge through engineering techniques (Z_{2t}) has on marginal revenue and costs. The third term represents the marginal cost of allowing shallow groundwater aquifers and surface run-off to infiltrate into the groundwater system at time t, rather than controlling with drains, banks and levees for future users.

$$\frac{\partial \tilde{H}_t}{\partial Z_{3t}} = 0 = p\frac{\partial f}{\partial Z_{3t}} - \frac{\partial c}{\partial Z_{3t}} \qquad \text{...(6)}$$

Equation (6) shows the effect of changes in variable cost, fertiliser, on current profits. It differs from equations (5) and (6) above, in that it equates the current MVP to MC.

$$-\frac{\partial \tilde{H}_t}{\partial W_t} = \Psi_{t+1} - (1+r)\Psi_t = -p\frac{\partial f}{\partial W_t} + \psi_{t+1}\frac{\partial g_t}{\partial W_t} \qquad \text{...(7)}$$

The first term on the right-hand side of equation (7) denotes the external effects of increasing groundwater levels in determining agricultural output and costs. The latter term includes the effect of natural drainage on groundwater levels. In dynamic terms, equation (7) equates the MVP to the MC of high groundwater flow areas.

$$\frac{\partial \tilde{H}_t}{\partial W_T} = -\psi_T + \frac{\partial F}{\partial W_T} = 0; \qquad \frac{\partial F}{\partial W_T} = \psi_T \qquad \text{...(8)}$$

This condition equates the implicit price of salt affected discharge land caused by high groundwater levels at terminal time T, to the marginal sale price of land at T. It represents the boundary condition defining the terminal value of the multiplier sequence ψ_T *(Conrad & Clark, 1987).*

$$\frac{\partial \tilde{H}_t}{\partial \psi_{t+1}} = W_{t+1} - W_t = -g_t + h_t + j_t \qquad ...(9)$$

Equation (9) is the partial derivative of the Hamiltonian with respect to the costate variable (ψ_{t+1}). It is equal to the change in the state variable (groundwater level) over time, and therefore is equal to the difference equation for the state variable described in equation (2) *(Conrad & Clark, 1987).*

$$W_0 = a \qquad (10)$$

Equation (10) is another boundary condition defining the initial condition of the state variable.

(iii) Policy Implications

Concerns over the use and management of agricultural land and associated natural resources such as soil, water, flora and fauna have arisen essentially as a result of increasing scarcity of land relative to user demands *(Morris et al, 1988).* The immediate source of this concern is a perception that some of the natural resources associated with agriculture are becoming degraded.

"Environmental and resource problems result from the use of ecological systems for socioeconomic production and consumption activities. These problems can be seen as discrepancies between the demand for goods and services and their supply by ecological systems". *(Braat & van Lierop, 1987, p7).* Generally, environmental and resource problems have an economic and ecological side. Economic activity is characterised by social and psychological factors, by law, institutions, politics and technology. The main objective of economic policy is the 'maximisation of production of goods and services at minimum cost'. Ecological activity, alternatively, is governed by the laws of physics, chemistry, biology and geology. The main objective of ecological policy-making, is 'minimum exploitation and damage to the natural system'. *(Braat & van Lierop, 1987).* Collectively, the aim of renewable resource management and conservation is to maximise sustainable use of resources and the environment over time.

In the case of soil salinity, the imposition of costs on those not directly associated with the resource use, suggest that current market arrangements are not achieving social objectives. The objective of economic analysis in natural resource use decisions is to maximise the net benefits to society over time, from a given combination of resources. This objective may not necessarily be to stop future degradation and promote the reclamation of existing degraded land it its entirety, but to ensure that "all resources are applied to their highest value combination of end uses, both currently and in the future" *(Morris et al, 1988, p2)*. Thus soil salinity may only be regarded as a problem if there would be net social benefits to society in changing to some other level of salinity.

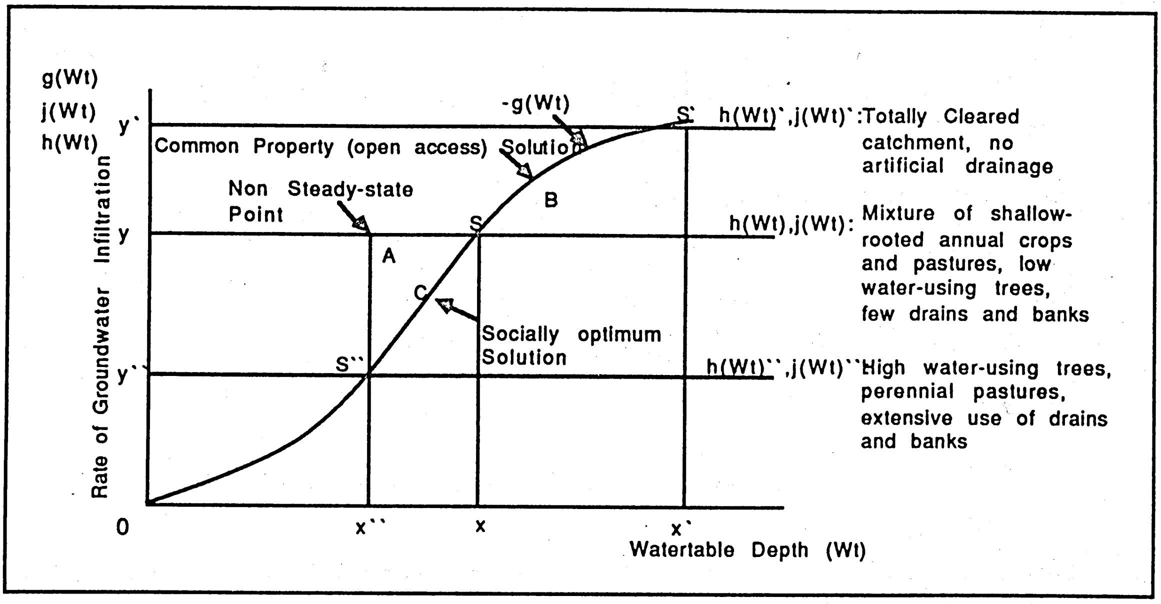
To establish whether an economic problem exists, knowledge of the costs and benefits of reducing soil salinity and the costs and benefits of reclaiming saltland are required. Two types of costs must be taken into account when determining the level of degradation control. These are private costs (which include the agronomic and engineering costs associated with land degradation and reclamation borne by the individual land user) and external costs (which represent the cost of land degradation borne by others beyond the source of production *(Blyth & McCallum, 1987)*.

The land user will control salinity to the point at which private benefits from additional salinity prevention and additional profits generated from increased production, are equal to private costs of salinity. Socially optimum salinity control, alternatively, must take into account the private and external costs and benefits of saltland degradation and reclamation. The results of private decision-making may thus diverge from those which would occur if full social costs and benefits were accounted for *(Blyth & McCallum, 1987)*.

In natural resource economics steady-state refers to "the characteristics of a natural resource system when production/extraction rates are limited to the flow components of the system and natural resource stocks remain unchanged through time". *(Burt & Cummings, 1977, p1)*. In the case of dryland salinity, a steady-state equilibrium has been reached when the inflows to the groundwater system from precipitation, and outflows, through surface runoff, evapotranspiration and natural drainage, are in equilibrium.

The relationship between steady-state conditions and dryland salinity is shown in the following diagram.

Figure 1
Steady-State Infiltration Levels



The curve -g(W_t) graphs the relationship between watertable depth and the rate of natural drainage. When the watertable depth is low, the amount of water that the environment can naturally remove is also low. As the watertable rises, natural drainage and waterways begin to fill and move groundwater at a faster rate. For very high levels of the watertable, however, there will be a point at which watercourses and drainage outlets will have reached their maximum waterflow and storage capacities. At this point, there will be no change in the rate of natural drainage as the watertable is increased.

The functions h(W_t) and j(W_t) denote the relationship between groundwater infiltration and watertable depth arising from agronomic and engineering techniques, respectively. The curves h(W_t) and j(W_t) represent a specified combination of agronomic and engineering techniques that result in varying levels of groundwater infiltration. For example h(W_t)`, represents a totally cleared catchment and j($W_t$)`, represent agricultural practices free of artificial drainage which, when combined, result in a high rates of groundwater infiltration and watertable levels of y` and x`, respectively. By contrast, the use of high water-using trees and perennial pastures, and extensive drainage techniques (denoted as h(W_t)``, j($W_t$)``), results in a low rate of water infiltration (y``), and watertable depth (x``).

At any point along the curve -g(W_t), a steady-state condition exists for different h(W_t) and j(W_t), in which the amount of recharge entering the watertable from various agronomic and engineering techniques, and the amount of water being removed from the environment through natural drainage, are in equilibrium. At point S, for example, the rate of water infiltrating to the watertable from the use of shallow-rooted crops and pastures, low water-using tree species and the use of only a low number of man-made drainage techniques, is represented by y (with x being the depth of the watertable). Note also that point S, natural drainage is also occurring at the rate y. The rate of infiltration and drainage are equal, the watertable depth remains constant and a steady-state equilibrium exists. The hydrological balance is in equilibrium.

Changes in agricultural practices modifies the hydrological balance. As a result of the recent clearing of native vegetation for agriculture, and the delay of some decades before all the hydrological changes become evident *(Williamson et al 1987; Holmes and Wronski 1981; Western Australian Select Committee on Salinity 1988; Peck & Hurle 1973; and George 1978)*, south-west Western Australia's hydrological balance is currently in a state of disequilibrium. This is shown in Figure 1 as point 'A' (for example). As a result of over-clearing and the use of low water-using crops and pastures, the amount of water infiltrating into the groundwater system is greater than the level of natural drainage, and the environment is at a non steady-state condition. Over many years, under stable climatic conditions, the watertable would rise, the production mix would alter, the natural landscape would reach a hydrological equilibrium, and the level of salinity converges to a steady-state equilibrium *(Knapp, 1984)*.

The complex phenomena of soil salinity and the multitude of external effects and lagged onsite effects, may result in current rates of land degradation that are higher than socially desirable. "These external effects represent a failure of market decision-making processes insofar as land users do not take into account the incidental damages their activities impose on other parties" *(Chisholm, 1987, p225)*. These externalities must be added to the onsite costs of agriculture if a measure of the full social costs of land degradation are to be obtained *(Upstill & Yapp, 1987)*. Social costs, if they were taken into account would result in different and socially preferable land management decisions *(Chisholm, 1987)*. The failure of the market to determine the socially optimum level of soil salinity may result in Western Australia's current hydrological disequilibrium converging to an <u>non-optimum</u> steady-state condition.

The private costs of salt-degraded land ignores the implicit price of degradation over time. By setting the costate variable equal to zero wherever it occurs in the first-order conditions, the current situation of land degradation of the <u>common property</u> land can be described *(Hassan & Hertzler, 1988; Heal 1981; Kamien & Schwartz, 1981)*. For example, if the costate variable in equation (4) is set to zero, the cost of clearing land and increasing groundwater and salinity levels to future generations is not considered. Because the implicit (current-value) cost is too low in all time periods, agricultural land will be depleted at a rate that is greater than socially optimal, resulting in land degradation. The common property (or open-access) outcome is represented in Figure 1 as point B, for example. The implicit cost of saltland degradation is zero, and, as a result, a high level of clearing occurs combined with the use of low-water-using crops and pastures that generate high profits in the current period.

For a socially managed optimum use of agricultural land in the current period (which Quiggin (1986) defines as the common property outcome) ,the cost of production should be less than the marginal value product of production by the marginal cost to future generations. Initially, the net cost of production should grow at the discount rate to reflect the scarcity value of productive land. Increased degradation, increases the scarcity value of land, making productive land more valuable, and thus causes the costs of inputs of optimally managed production to grow more rapidly. In the long-run, net costs of land degradation would be constant over time.

This scenario, which is shown in Figure 1 as point C, for example, involves land-use patterns that are compatible with the long-run productive and carrying capacity of the natural environment. The implication that this compatibility extends over an unlimited period of time, is consistent with the convergence to a steady-state condition, where the royalty from salinity (represented by the costate variable ψ_t) is constant, but positive.

Thus, it is important to recognise that, in the case of dryland salinity, a steady-state can be achieved at many levels of recharge, but only three specific classes of steady-state are usually considered of economic interest. These are:

i. the current non steady-state condition, brought about by existing land management practices;

ii. the long-run non-optimal steady-state equilibrium recharge resulting from unaltered clearing, agricultural and revegetation practices, to which the environment is currently converging; and

ii. the steady-state associated with the socially optimum rate of utilisation of the land resources.

The model should be a useful planning tool for policymakers and researchers and can be used to design optimal policies to control the level of salinity. Once the model has been formulated, the impact on net present value of future profits can be evaluated.

In conclusion, any policy against land degradation should impose a royalty, or fee, on landusers, to reflect the scarcity value of the land and to take into account the costs of soil salinity on future generations, caused by current land-users. Revenues from the fee could then be used to fund land reclamation projects and research. The management of future land resources depends upon the inclusion of the user costs of dryland soil salinity incurred by present generations *(Hassan & Hertzler, 1988)*.

Despite the progress in environmental-ecological modelling, optimal control modelling is not designed to completely replicate the 'real world', but rather abstract from the real world. Modelling limitations exist primarily due to the gaps in knowledge at both the scientific and economic levels. The inability to exactly model human and institutional behaviour, the impact of exceptional or unforeseen events (such as drought), and the difficulties in modelling complex hydrological systems into mathematical approximations, requires that model interpretation and policy recommendations be treated with caution. Despite the gaps that remain in our scientific and economic understanding of the ecological processes associated with dryland salinity, sufficient understanding of the degradation processes exist to remedy more effectively many of the problems associated with the salinisation *(Burch et al, 1987)*.

5: BIBLIOGRAPHY

Anderson, J.R., and Thampapillai, D.J., (1990)., "Soil Conservation: Project and Policy Intervention in Developing Countries"., World Bank Staff Paper., PPR Policy Research Series., World Bank, Washington DC (in press).

Benavie, A., (1970)., "The Economics of the Maximum Principle"., Western Economic Journal., Vol. 8., pp 426-30.

Bettenay, E., Blackmore, A. V. and Hingston, F. J. (1964), "Aspects of the Hydrologic Cycle and Related Salinity in the Belka Valley, Western Australia", Australian Journal of Soil Research, Vol. 2, pp 187-210.

Blyth, M., and McCallum, A., (1987)., "Onsite Costs of Land Degradation in Agriculture and Forestry"., in Chisholm, A., and Dumsday, R., ed., "Land Degradation - Problems and Policies"., Cambridge University Press., pp 79-98.

Braat, L.C., and van Lierop, W.F.J., (1987)., "Environment, Policy, and Modeling" in Braat, L.C., and van Lierop, W.F.J., (eds)., "Economic-Ecological Modeling - Studies in Regional Science and Urban Economics"., North-Holland Publishing Company., pp 7-19.

Burch, G., Graetz, D., and Noble, I., (1987)., "Biological and Physical Phenomena in Land Degradation"., in Chisholm, A., and Dumsday, R., ed., "Land Degradation - Problems and Policies"., Cambridge University Press., pp 27-48.

Burt, O.R., (1981)., "Farm-Level Economics of Soil Conservation in the Palouse Area of the Northwest"., American Journal of Agricultural Economics., Vol. 63, No. 1., pp 83-92.

Burt, O.R., and Cummings, R.G., (1977)., "Natural Resource Management, the Steady State, and Approximately Optimal Decision Rules"., Land Economics., Vol. 53, No. 1., pp 1-22.

Burvill, G. H., (1988)., "The Soils of the Salmon Gums District Western Australia"., Western Australia Department of Agriculture., Technical Bulletin No. 77.

Burvill, G.H., (1956)., "Salt Land Survey, 1955"., Journal of Agriculture of Western Australia., (3rd Series)., Vol. 5., pp 113-119.

Burvill, G. H. (1947)., "Soil Salinity in the Agricultural Area of Western Australia"., The Journal of the Australian Institute of Agricultural Science"., Vol. 13, No. 13., pp 9-19.

Chisholm, A., (1987)., "Abatement of Land Degradation: Regulation vs Economic Incentives"., in Chisholm, A., and Dumsday, R., ed (1987)., "Land Degradation - Problems and Policies"., Cambridge University Press., pp 223-247.

Ciriacy-Wantrup, S.V., and Bishop, R., (1975)., "Common Property as a Concept in Natural Resource Policy"., Natural Resource Journal., Vol. 15., pp 713-27.

Conrad, J.M., and Clark, C.W., (1987)., "Natural Resource Economics - Notes and Problems"., Cambridge University Press, New York.

Department of Agriculture., (1988)., "Salinity in Western Australia - A Situation Statement"., Technical Report No. 81., Division of Resource Management, Western Australia.

Department of Agriculture., (1988b)., "North Stirling Land Conservation District Situation Summary"., Katanning Department of Agriculture, Western Australia., unpublished.

Dimmock, G. M., Bettenay, E. and Mulcahy, M. J. (1974), "Salt Content of Lateritic Profiles in the Darling Range, Western Australia", Australian Journal of Soil Research, Vol. 12, pp 63-9.

Dinar, A., and Knapp, K.C., (1988)., "Economic Analysis of On-Farm Solutions to Drainage Problems in Irrigated Agriculture"., Australian Journal of Agricultural Economics., Vol. 32, No. 1., pp 1-14.

Engel, A., McFarlane, D. J. and Street, G. (1987), "The Influence of Dolerite Dykes on Saline Seeps in South-Western Australia", Australian Journal of Soil Research, Vol. 25, pp 125-36.

George, P. R. (1979), "The Causes of Saltland - a Case Study of Esperance", Journal of Agriculture, Vol. 20 (3), 4th Series, pp 74-77.

George, P. R., (1978), "The Hydrogeology of a Dryland Salt Seepage Area in South-Western Australia"., Proceedings - Meeting of Sub-Commission on Salt Affected Soils., 11th International Soil Science Society Congress, Edmonton.

Green, C. C., (1977)., "The Water Cycle - Concepts and Processes"., Cassell Australia Limited.

Greig, P. J., and Devonshire, P. G., (1981)., "Tree Removals and Saline Seepage in Victorian Catchments: Some Hydrologic and Economic Results"., Australian Journal of Agricultural Economics., Vol. 25, No. 2., pp 134-148.

Hardin, G.J., (1968)., "The Tragedy of the Commons"., Science., Vol. 162 (3859)., pp 1243-8.

Hassan, R.M., and Hertzler, G., (1988)., "Deforestation from the overexploitation of Wood Resources as a Cooking Fuel"., Energy Economics., April., pp 163-168.

Heal, G., (1981)., "The Use of Common Property Resources"., in Smith, V.K., and Krutilla, J., (eds)., "Explorations in Natural Resource Economics"., Johns Hopkins University Press, Baltimore, MD.

Henschke, C. J. (1980), "Saltland in Statistics - the 1979 Saltland Survey", Journal of Agriculture, Vol. 21 (4), 4th Series, pp 116-119.

Henschke, C. J., (undated)., "East Perenjori Catchment Hydrological Studies"., in Catchment Approach to Conserving Farm Land., Department of Agriculture, Three Springs.

Hertzler, G., Ibanez-Meier, C.A., and Jolly, R.W., (1985)., "User Costs of Soil Erosion and Their Effects on Agricultural Land Prices: Costate Variables and Capitalized Hamiltonians"., American Journal of Agricultural Economics., Vol. 67, No. 5., pp 948-953.

Holmes, J. W. and Wronski, E. B., (1981)., "The Influence of Plant Communities upon the Hydrology of Catchments"., in Holmes, J. W. and Talsma, T. (eds)., Land and Stream Salinity., Proceedings of an International Seminar and Workshop., Perth, Western Australia., November 1980., Elsevier Scientific Publishing Company, Amsterdam., pp 19-34.

Jeffers, J.N.R., (1987)., "Ecological Modeling: Shortcomings and Perspectives"., in Braat, L.C., and van Lierop, W.F.J., ed., "Economic-Ecological Modeling - Studies in Regional Science and Urban Economics"., North-Holland Publishing Company., pp 36-48.

Kamien, M., and Schwartz, N., (1981)., "The Role of Common Property Resource in Optimal Planning Models"., in Smith, V.K., and Krutilla, J., (eds)., "Explorations in Natural Resource Economics"., Johns Hopkins University Press, Baltimore, MD, 1981.

Kennedy, J.O.S., (1986)., "Dynamic Programming - Applications to Agriculture and Natural Resources"., Elsevier Applied Science Publishers, London.

Kiker, C., and Lynne, G., (1986)., "An Economic Model of Soil Conservation: Comment"., American Journal of Agricultural Economics., Vol. 68, No. 3., pp 739-741.

Knapp, K.C., (1984)., "Steady-State Solutions to Soil Salinity Optimisation Problems"., American Journal of Agricultural Economics., Vol. 66, No. 3., pp 279-285.

Lewis, T.R., and Neher, P., (1982)., "Consistent and Revised Plans for Natural Resource Use"., in Mirman, L.J., and Spulber, D. F., ed., "Essays in the Economics of Renewable Resources - Contributions to Economic Analysis"., North-Holland Publishing Company., pp 55-74.

Lightfoot, L. C., Smith, S. T. and Malcolm, C. V. (1964), "Salt Land Survey, 1962 - Report of a Survey of Soil Salinity in the Agricultural Areas of Western Australia", Journal of Agriculture, Vol. 5, 4th Series, pp 396-410.

Loh, I. C. and Stokes, R. A., (1981)., "Predicting Stream Salinity Changes in South-Western Australia"., in Holmes, J. W. and Talsma, T. (eds)., Land and Stream Salinity., Proceedings of an International Seminar and Workshop., Perth, Western Australia., November 1980., Elsevier Scientific Publishing Company, Amsterdam., pp 227-254.

Luptacik, M., and Schubert, U., (1982)., "Optimal Investment Policy in Productive Capacity and Pollution Abatement Processes in a Growing Economy"., in Feichtinger, G., ed., "Optimal Control Theory and Economic Analysis"., First Viennese Workshop on Economic Applications of Control Theory held in Vienna, October 28-30, 1981., North-Holland Publishing Company., pp 231-244.

McConnell, K.E., (1986)., "An Economic Model of Soil Conservation: Reply"., American Journal of Agricultural Economics., Vol. 68, No. 3., pp 743-744.

McConnell, K.E., (1983)., "An Economic Model of Soil Conservation"., American Journal of Agricultural Economics., Vol. 65, No. 1., pp 83-89.

McKelvey, R., (1980)., "Common Property and the Conservation of Natural Resources"., in Levin, S.A., and Hallam, T.G., (eds)., "Applied Mathematical Ecology"., Springer-Verlag, Berlin., pp 58-80.

Malcolm, C. V., (1983)., "Wheatbelt Salinity - A Review of the Salt Land Problem in South-Western Australia"., Technical Bulletin No. 52., Department of Agriculture, Western Australia.

Malcolm, C. V. (1977), "Saltland and what to do about it", Journal of Agriculture, Vol. 18 (4), 4th Series, pp 127-133.

Malcolm, C. V. and Stoneman, T. C. (1976), "Salt Encroachment - the 1974 Saltland Survey", Journal of Agriculture, Vol. 19 (4), 4th Series, pp 42-49.

Miller, R.L., (1982)., "Intermediate Microeconomics - Theory, Issues, Applications"., Second Edition., McGraw-Hill International Book Co.

Miranowski, J.A., (1984)., "Impacts of Productivity Loss on Crop Production and Management in a Dynamic Economic Model"., American Journal of Agricultural Economics., Vol. 66, No. 1., pp 61-71.

Mirman, L.J., and Spulber, D. F., ed (1982)., "Essays in the Economics of Renewable Resources - Contributions to Economic Analysis"., North-Holland Publishing Company.

Morris, P., Wilks, l., and Wonder B., (1988), "Natural Resource Management: Some Economic and Policy Considerations"., Australian Bureau of Agricultural and Resource Economics, Canberra., Paper Presented to the Australian Institute of Valuers and Land Administrators, Country Conference, Bowral, 14-16 October.

Mulcahy, M.J., (1978)., "Salinisation in the Southwest of Western Australia"., Search., Vol. 9, No. 7., pp 269-272.

Mulcahy, M. J., (1973)., "Landforms and Soils of Southwestern Australia"., Journal of the Royal Society of Western Australia., Vol. 56, Parts 1 & 2., pp 16-23.

Nulsen, R. A. (1985), "Hillside Seepages", Journal of Agriculture, Vol. 26 (4), 4th Series, pp 128-129.

Nulsen, R. A., (1984)., "Saltland Management - the Catchment Approach"., Department of Agriculture, Western Australia., Farmnote No. 133/84.

Nulsen, R. A. (1982), "Water Use by Lupins", Journal of Agriculture, Vol. 23 (3), 4th Series, p 91.

Peck, A. J., Thomas, J. R., and Williamson, D. R., (1984)., "Effects of Man on Salinity in Australia"., Division of Groundwater Research, CSIRO, Western Australia., Salinity Issues., Water 2000: Consultant Report No. 8., Canberra, AGPS.

Peck, A. J. (1979), "How Saltland can be Reclaimed", Journal of Agriculture, Vol. 20 (3), 4th Series, pp 72-73.

Peck, A. J. (1978), "Salinisation of Non-Irrigated Soils and Associated Streams: A Review", Australian Journal of Soil Research, Vol. 16, pp 157-68.

Peck, A.J. and Hurle, D.H., (1973)., "Chloride Balance of Some Farmed and Forested Catchments in Southwestern Australia"., Water Resources Research., Vol. 9, No. 3., pp 648-657.

Queensland Department of Primary Industries., (1987)., "Landscape, Soil and Water Salinity"., Proceedings of the Brisbane Regional Salinity Workshop, Brisbane, May 1987., Queensland Department of Primary Industries Conference and Workshop Series QC87003.

Queensland Department of Primary Industries., (1985)., "Landscape, Soil and Water Salinity"., Proceedings of the Brisbane Regional Salinity Workshop, Brisbane, May 1985., Queensland Department of Primary Industries Conference and Workshop Series QC87002.

Quiggin, J., (1988)., "Murray River Salinity - An Illustrative Model"., American Journal of Agricultural Economics., Vol. 70, No. 3., pp 635-645.

Quiggin, J., (1986)., "Common Property, Private Property and Regulation - The Case of Dryland Salinity"., Australian Journal of Agricultural Economics., Vol. 30., No. 2-3., pp 103-117.

Salerian, J., (1989)., "Application of an Economic Model to Dryland Soil Salinity in Western Australia"., Department of Economics, University of Western Australia., Discussion Paper 89.25.

Salinity Committee, Parliament of Victoria., (1984)., "Salt of the Earth: Final Report on the Causes, Effects and Control of Land and River Salinity in Victoria"., Third Report to the Parliament., Victoria., October 1984.

Smith, S. T. (1966), "The Relationship of Flooding and Saline Water Tables", Journal of Agriculture, Vol. 7 (8), 4th Series, pp 334-340.

Smith, S. T., (1962)., "Some Aspects of Soil Salinity in Western Australia"., U.W.A., M.Sc. (Agric) Thesis., (unpublished).

Taylor, D.B., Young, D.L., Walker, D.J., and Michalson, E.L., (1986)., "Farm-Level Economics of Soil Conservation in the Palouse Area of the Northwest: Comment"., American Journal of Agricultural Economics., Vol. 68, No. 2., pp 364-366.

Teakle, L. J. H. and Burvill, G. H., (1945)., "The Management of Salt Lands in Western Australia"., Journal of Agriculture, Western Australia., Vol. 22, (2nd Series)., pp 87-93.

Teakle, L. J. H., Southern, B. L. and Stokes, S. J., (1940)., "A Soil Survey of the Lakes District, Western Australia"., Journal of Agriculture, Western Australia., Vol. 17, (2nd Series)., pp 251-295.

Teakle, L. J. H., (1939)., "A Soil Survey of the Denmark Agricultural Research Station, Denmark, Western Australia"., Journal of Agriculture, Western Australia., Vol. 16, (2nd Series)., pp 243-257.

Teakle, L. J. H., (1938)., "The Movement of Soluble Salts in Soils Under Light Rainfall Conditions"., Journal of Agriculture, Western Australia., Vol. 15, (2nd Series)., pp 218-245.

Teakle, L. J. H., (1937)., "Saline Soils of Western Australia and Their Utilisation"., Journal of Agriculture, Western Australia., Vol. 14, (2nd Series)., pp 313-234.

Teakle, L. J. H., (1929)., "Soil Alkali - (lll) The Problem in Western Australia"., Journal of Agriculture, Western Australia., Vol. 6, (2nd Series)., pp 88-99.

Teakle, L. J. H., (1928)., "Soil Alkali - (II) The Tolerance of Plants for Alkali in Soils"., Journal of Agriculture, Western Australia., Vol. 5, (2nd Series)., pp 402-408.

Teakle, L. J. H., (1928)., "Soil Alkali - (l) Its Nature and Occurrence"., Journal of Agriculture, Western Australia., Vol. 5, (2nd Series)., pp 399-402.

Upstill, G., and Yapp, T., (1987)., "Offsite Costs of Land Degradation"., in Chisholm, A., and Dumsday, R., ed., "Land Degradation - Problems and Policies"., Cambridge University Press., pp 99-107.

Van Kooten, G.C., Weisensel, W.P., and de Jong, E., (1989)., "Estimating the Costs of Soil Erosion In Saskatchewan"., Canadian Journal of Agricultural Economics., Vol. 37., pp 63-75.

Walker, D.J., (1982)., "A Damage Function to Evaluate Erosion Control Economics"., Vol. 64, No. 4., pp 690-698.

Walker, D.J., and Young, D.L., (1986)., "The Effect of Technical Progress on Erosion Damage and Economic Incentives for Soil Conservation"., Land Economics., Vol. 62, No. 1., pp 83-93.

Western Australian Select Committee on Salinity., (1988)., "Report on Salinity in Western Australia - First Report"., Parliament of Western Australia, Legislative Council., June 1988.

Williamson, D. R., Stokes, R. A. and Ruprecht, J. K. (1987), "Response of Input and Output of Water and Chloride to Clearing for Agriculture", Journal of Hydrology, Vol. 94, pp 1-28.

Wills, I., (1987)., "Resource Degradation on Agricultural Land: Information Problems, Market Failures and Government Intervention"., Australian Journal of Agricultural Economics., Vol. 31, No. 1., pp 45-55.

Wood, W. E. (1924)., "Increase of Salt in Soil and Streams following the Destruction of the Native Vegetation"., Journal of Royal Society of Western Australia., Vol. 10, No. 7., pp 35-47.