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Modelling the impact of dryland salinity programs in the Liverpool Plains at a catchment level

Nigel Hall¹, Bill Watson¹, Romy Greiner¹ and Ray Evans²
(1) Australian Bureau of Agricultural and Resource Economics
(2) Australian Geological Survey Organisation

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The Liverpool Plains in the north western slopes of New South Wales are a highly fertile cropping area. Groundwater levels are rising in the catchment and the emerging soil salinisation is increasingly affecting agricultural productivity. This trend is expected to continue unless land use methods that reduce accessions to the groundwater are adopted. A catchment model to determine the economic costs and benefits of the management of dryland salinity is proposed in this paper. This research is part of an interdisciplinary project that will incorporate data and other modelling work currently being undertaken by a number of different agencies including ABARE, AGSO, CSIRO and CaLM.

The analysis will use a farm level mathematical programming model which will be embedded in a catchment model that incorporates groundwater movement. Management differences across the catchment will be represented by different farm submatrixes. The catchment-scale dimension of dryland salinity will be modelled by establishing spatial and temporal hydrological linkages between model farms. This will allow for a quantitative analysis of policies that are designed to rectify the externalities associated with managing the water balance of catchments. This work is undertaken as part of the National Dryland Salinity Management Program.

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Introduction

The Liverpool Plains encompass 11 728 square kilometres of mainly fertile land. They are located in the north western slopes of New South Wales in the Mooki and Coxes Creek catchments (figure A). The plains form a shallow basin with deep black soils surrounded by steeper red soils. The Liverpool Plains are an extremely productive cropping and stock rearing area, with an estimated value of output exceeding \$150 million (ABS 1994). The area was partly timbered and partly open grassland at the time of European settlement and extensive clearance of land for farming has taken place since then to provide land for cropping.

In recent years there has been evidence of rising watertables in the Liverpool Plains. The consequences are waterlogging of crop land, most spectacularly in the Gorrán Lake area where a substantial lake has reappeared and an increasing area is affected by dryland salinity (Dryland Salinity Management Working Group 1993).

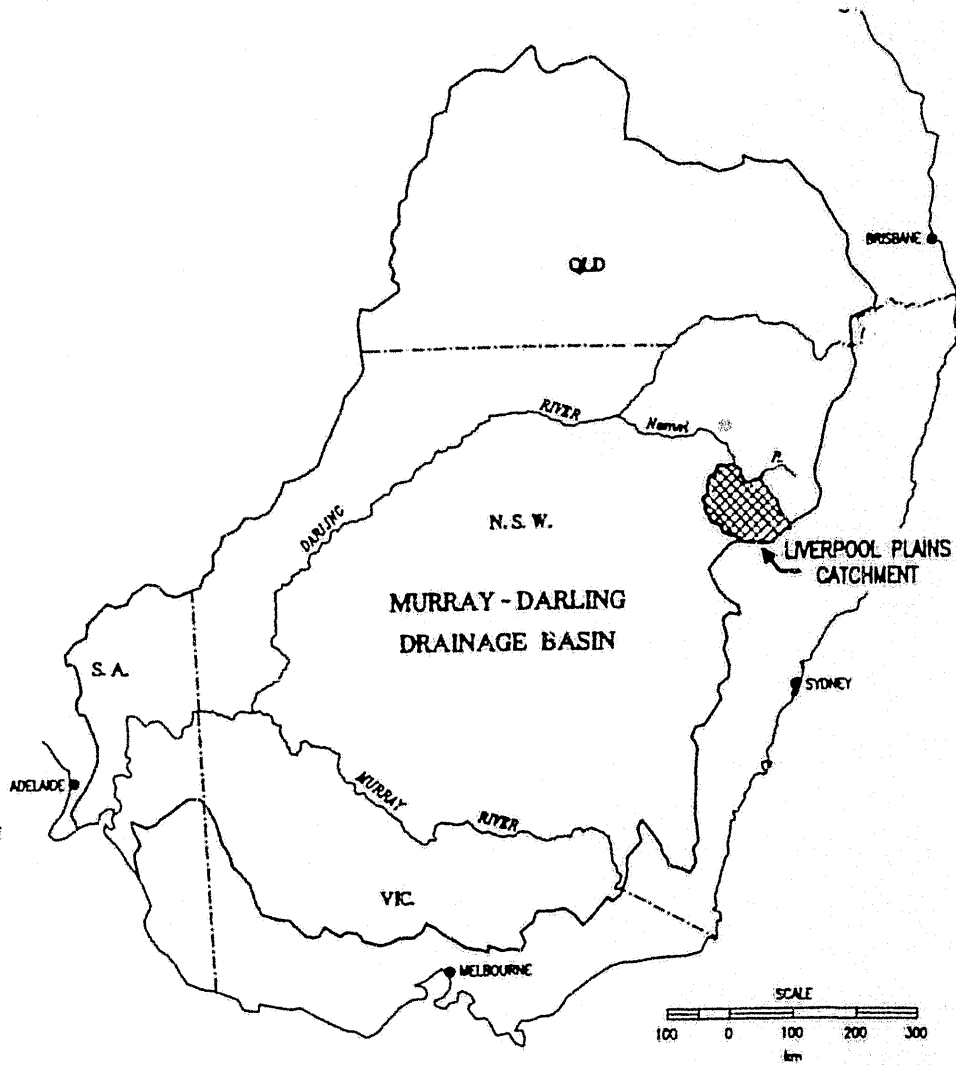
In rising watertables, salt is remobilised and deposited in the surface layer by evaporation of saline groundwater. This occurs through capillary action when the groundwater is within 2 metres of the surface. Increased salt levels in the soil will reduce crop yields. Beyond a certain level of salinity there will be a complete loss of existing crop.

This process of rising groundwater has different consequences for different parties. Some farms are sources of recharge but are unaffected by rising groundwater because of, for example, location on higher and steeper ground. Other farms in discharge areas have external costs imposed on them by inflows of saline groundwater. In addition, there can be costs to farmers outside the catchments from surface or subsurface flows of saline water and to non-farm industries through damage to roads and water supplies and the environment. The indirect nature of the damage and the long time lags in its impact make this situation one that is unlikely to be resolved by the actions of individual producers in the existing market framework.

The National Dryland Salinity Management Research Plan is set up to coordinate research into this problem. Besides the Liverpool Plains, four other 'focus' catchments are being studied. They are the Loddon Campaspe region of Victoria, South East South Australia, the Kent River catchment in Western Australia and Upper Burdekin catchment in Queensland. In each of these catchments, coordinated research is underway to explore

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Figure A: The location of the Liverpool Plains catchment within the Murray–Darling Basin



particular aspects of the management of dryland salinity in Australian agriculture (Focus 1994).

In the Liverpool Plains the focus of one line of research is on identifying the extent of and reasons why agronomically feasible salinity management practices are not being adopted. That is, why farmers do not adopt new or additional practices that will reduce infiltration and hence prevent or at least slow the rising of watertables. This is being tackled in a coordinated approach through a National Dryland Salinity Program project involving ABARE, the New South Wales Department of Conservation and Land Management (CaLM), the Department of Water Resources of New South Wales and the Australian Geological Survey Organisation. ABARE's work is being funded by the Land and Water Resources Research and Development Corporation (LWRRDC).

This research will be done in three phases. The first phase involves collection of producer profile data through an ABARE economic survey and through a survey of social and management practices carried out by CaLM. A system of land management units will be defined to identify representative regions and the survey data will be combined with existing data sets to form a catchment information system. Farm and catchment models will also be adapted from existing models for use in later stages of the analysis.

In the second phase in 1995-96, the data collected in phase 1 will be analysed to identify costs and benefits of current policies and programs in the Liverpool Plains catchment. This will use the catchment level model described in this paper as well as farm level modelling of farmers' options for salinity management using FARMULA, a simulation model (Kubicki, Denby, Haagensen and Stevens 1991).

In the third phase, an attempt will be made to rank options for managing dryland salinity by their costs and benefits and to assess the applicability of the approach to other catchments. The results of the whole project will be presented to and discussed with other researchers, landholders and other stakeholders at a workshop to be held in the Liverpool Plains during 1996 and later published as ABARE reports.

The modelling approach

The focus in this paper is on catchment level modelling of farmers' responses to salinity and rising watertables. There are several quantitative economic tools available for investigating resource issues. They range from simple enterprise level gross margin

analysis to benefit-cost analysis and from static simulation modelling to dynamic programming modelling. The choice of method depends predominantly on the characteristics of the system under investigation, the data availability, the level of aggregation, and the questions that need to be answered.

A mathematical programming approach was chosen to integrate farm level decision making and catchment-scale soil salinisation. As used here, mathematical programming follows a normative paradigm, 'What action ought to be taken to achieve a specific goal?' It therefore provides the classic method for investigating best possible strategies for achieving a goal under resource limitations. Simulation is an alternative approach that is highly suitable for analysing complex systems through formulating well defined logical relationships in the form of IF/THEN decision rules. However, simulation is not very well suited for integrating behaviour and resource constraints for land use decision making. In a simulation model, the value of the decision variables is determined a priori and the analysis seeks to answer the question, 'what happens when a certain decision is taken' (Taha 1992).

The mathematical programming model approach to analysis of regional changes in farm management and groundwater allows exploration of new scenarios in land management. It also allows projections to the future based on known or estimated changes in land use, technology or groundwater.

One approach is to use representative farms to represent the key social and physical areas of the region to be modelled. This approach was first used by Mighell and Black (1951) in the United States and has been widely used since. Recent Australian examples based on this approach and relevant to natural resource management issues include Morfe and Parton (1994), Tulpulé and Dann (1994), Marshall, Jones and McGrath (1994), Gyles, Prendergast and Young (1994), Jones, Wall, Marshall and Darvall (1994) and Greiner (1994a). In this type of model, a separate mathematical programming model is specified for each area of interest based on physical, social or economic characteristics.

In recent ABARE work, representative farms were defined for four farm types in the Berriquin Irrigation District of New South Wales based on soil, groundwater and activity differences (Poulter, Hall and Greer 1993; Hall, Scoccimarro, Wilson and Poulter 1993). The farm models were solved separately, then the results were combined to obtain a district perspective. The disadvantage of this approach is that the farms are solved separately and so direct links between farms, such as those in the goods markets or flows of groundwater,

cannot be made in the optimisation process. This means that a direct solution of a regional model integrating farm management and groundwater flows cannot be carried out.

There are methods that will allow a representative farm approach to approximate the cooperative regional optimal solution produced by a model with both spatial and temporal dimensions but at the cost of some complexity. The first best solution to the problem is to use an integrated model to take account of both between farm (groundwater) and within farm constraints. This can be done with a spatial equilibrium model integrating the entire region of interest into a single matrix for optimisation. An example of this approach is the Irrigated Murray–Murrumbidgee System (IMMS) model developed by ABARE for the southern Murray–Darling basin (Hall, Poulter and Curtotti 1994). This model brings together individual farm regions linked by markets for water allocations as well as the river system. A possible problem with this approach, is that the size of the matrix may become very large.

In this study, MoFEDS (Model of Farm Economics of Dryland Salinisation) (Greiner 1994d) will be used as the basis of a spatial and temporal model for analysing the farming of the Liverpool Plains. MoFEDS is a multiperiod farm level model incorporating accessions of water to the groundwater and consequent future yield effects from higher groundwater and salinity. In this study, the original model will be reimplemented in GAMS (Brooke, Kendrick and Meeraus 1988). The farm level model will then be extended to a catchment level by creating a set of representative farms to cover each of the main land management units in the Liverpool Plains. Financial information will be derived from a special ABARE farm survey of the Liverpool Plains carried out as part of this study during 1994 and from the CaLM survey to be carried out in early 1995. The model will be required to bring together farm models for each land management unit and the flow of groundwater between land management units over an extended time.

Modelling the groundwater flows between land management units will involve a model of the hydrology of the catchment for which it is intended to use a transfer function approach. The hydrology model will be incorporated into the matrix of the catchment model.

The proposed catchment model

The catchment model will solve for all farms simultaneously under a specified scenario and store the solutions for analysis. The solution data can be aggregated as needed for analysis and presentation. This will allow assessment of the cost of management strategies

to different farmers and their effect on changing accessions to the groundwater in each land management unit.

The optimal solution of the model with endogenous groundwater flows maximises the total income in the catchment. This solution can be compared with one in which farms disregard the external effects of their actions on others. The difference will be an estimate of the overall catchment benefit to be obtained by taking a catchment perspective rather than an individual farm perspective in managing dryland salinity. A significant output of the analysis will be the degree to which each farm's income would be affected by taking a catchment perspective. If all the income effects are small then it is possible that cooperation and neighbourliness expressed through, for example, the Liverpool Plains Land Management Committee will be enough to manage the salinity problem. If, however, the income impacts on some farms are very large, more direct approaches may be needed involving income transfers by subsidy or tax or perhaps purchase of recharge areas by those in potential or actual discharge areas.

Particular management practices will be tested with the model by applying special constraints forcing the expected adoption of the desired policy for each representative farm. This would use data from the farm profiles including the sociological survey. One constraint to be tested will be a requirement of long term sustainability by constraining a productive and stable solution in the long term.

MoFEDS (Model of the Farm Economics of Dryland Salinisation)

The existing MoFEDS model of a single representative farm is described in this section. In the catchment model, several farms as well as the hydrological links between them will be represented. MoFEDS includes the traditional resources for agricultural production models, land, labour and capital and, in addition, the capacity of the groundwater system to accept recharge without displaying adverse effects (salinity).

MoFEDS was developed as a linear programming model. The objective function (equation 1) maximises the cumulative net present value of the available income after tax (I) generated by the model farm in periods (t) over T years. It sums the net present value of the farm's annual revenue from the sale of crop and livestock produce (Q) at a price P less the variable costs of production (C), capital costs (CA), and tax paid and financial obligation (E). A discount rate (r) is applied to future incomes.

$$\begin{aligned}
 (1) \quad & \text{Max } I = \sum_{t \in T} [(P - C)Q - CA - E](1 + r)^{-t} & t = 1, \dots, T \\
 (2) \quad & A(t) \geq \sum_{s \in S} \sum_{m \in M} A_{sm} & t = 1, \dots, T \\
 (3) \quad & Q(t) = \sum_{s \in S} \sum_{m \in M} A_{sm} * Y_{sm} & t = 1, \dots, T \\
 (4) \quad & A_s(t) = f(GWT_{t-1} - GWT_c) & t = 1, \dots, T \\
 (5) \quad & GWT(t) = GWT_{t-1} + R_{t-1} + L_{t-1} & t = 1, \dots, T \\
 (6) \quad & R(t) = RF - \sum_{m \in M} (ET_m + RN_m + \Delta SM_m) & t = 1, \dots, T
 \end{aligned}$$

Soil salinisation directly affects the availability and productivity of land. Hence, a central constraint (equation 2) in every farm management model applies to the farm size (A). The total farm area is divided into soil classes of different management and yield potential according to the farm salinity status. For soil productivity, S salinisation stages (s) can be used through M different land management options (m). Yields (Y) are depressed on salt affected land, which reduces the total production of the farm (equation 3). The salinisation stages in year t are determined by the difference between the groundwater level at the end of the previous year (GWT_{t-1}) and the critical depth of watertable (GWT_c) (equation 4).

Equations 5 and 6 are the functional framework for calculating the depth of watertable. The depth of the groundwater level (equation 5) depends on the previous year's groundwater level as well as the recharge caused by on-farm land management (R) and lateral water movement (L). This functional relationship links the model farm to its catchment environment. Through L , the condition of the aquifer under a specific area can be characterised. A positive value of L indicates that the aquifer underneath the farmland is rising independently of the on-farm recharge. The on-farm water balance is calculated in equation 6 as recharge occurring under every form of agricultural land use. Recharge is a function of the annual rainfall (RF), the evapotranspiration (ET) and surface runoff (RN) under various land use options, and the change in soil moisture storage (SM).

The average depth to the watertable determines the on-farm salinity situation. Three salinisation stages for black soil have been included in the model. Stage 1 represents soil that is unaffected by salinity and hence is fully productive. Stage 2 represents reversible salinisation associated with water logging and results in a reduced choice of potential crops

and reduced yields. Stage 3 applies to irreversibly salted land that is suitable for salt land agronomy only. As mentioned above, the salinity status of the model farm feeds back to its financial viability (equation 3). Land reclamation is possible in some circumstances but is not currently modelled in MoFEDS. MoFEDS estimates the impact of farm management on accessions to the groundwater under the farm and hence on future salinity and yields. MoFEDS also allows for the impact of externally set accessions from other areas.

The planning horizon, T , that applies for the model runs presented in this study is currently twelve years. This will be extended to at least twenty years to provide a reasonable decision time for soil degradation problems. It can be expected that farmers would be willing to forgo some short term profit from taking action to mitigate salinity if this investment yields financial or non-financial benefits over the planning horizon.

MoFEDS is a mathematical programming model. The LOTUS 1-2-3 spreadsheet program is currently used both for storing the data and to formulate the mathematical linkages between variables, objective value, resources and other constraints.

The model structure is organised in a module system, where different aspects of the land management and dryland salinity system are formulated in different spreadsheets. There are 1266 activities and 1842 constraints. The model is solved by a program called eXtended Application (XA) using the simplex algorithm (Sunset Software Technology 1993). Given the high complexity of functional linkages within the model a visually comprehensible spreadsheet format was preferred over an equation-style model when MoFEDS was developed. The model will now be respecified in GAMS because the current solver cannot handle nonlinear functions and the current format is not favourable for a further enhancement of the model.

MoFEDS has been tested during its development by discussion of coefficients and results with experts familiar with the farming and hydrology of the Liverpool Plains and the model and preliminary results have presented at conferences and published (Greiner 1993, 1994a,b,c,d; Greiner and Parton 1993). The comments received on these occasions have contributed to the development and validation of MoFEDS.

Disaggregation within the catchment

The catchment model represents farms and locations within the catchment with submatrixes which correspond to representative farms. The areas represented should be broadly homogeneous and take account of topography, geology and soil types, hydrology,

human impacts such as fencing and farm structures and land ownership. Such areas can be described as land management units. These have been differently defined in different catchments and the system for the Liverpool Plains is still being discussed (Chris Glennon, Liverpool Plains Land Management Committee, personal communication, November 1994).

The land management unit system that is being developed for the Liverpool Plains is to be consistent with those being developed elsewhere under the National Dryland Salinity Program and other programs. It is clear at this stage that there are three main land systems in the plains. These are, black soil plains, black soil slopes and red earths. Black soil plains are the lowest lying parts of the Liverpool Plains, with very deep black soils. It is these areas that are suffering rising groundwater that partly originates under the other soil types. The black soil slopes have a soil structure similar to black soil plains but greater slope. Around these black soil areas are higher and steeper areas of red earths originating from volcanic rocks.

The difference in soil types described leads to the externality problem. Simplistically, the farmers on the red earths around the rim of the Liverpool Plains can maximise their profit by cropping. This leads to increased accessions to the groundwater system. The excess groundwater causes an external cost to the farmers on the black soils who are in the lowest part of the system. The pattern of response and the full costs and benefits of adopting various practices can be explored across the whole catchment when land management units are linked by a hydrologic model. The value of catchment economic modelling is to quantify the costs and benefits from the adoption of different management practices on different land management units.

Hydrogeology model

A catchment contains water in streams and lakes and beneath the ground as soil moisture and groundwater in pores and fractures of the rock. The depth to groundwater depends primarily on the physical nature of the aquifer system and the volume of water flowing through it. When the addition of water to the aquifer through recharge is balanced by outflows or discharge, then the groundwater system is in equilibrium and groundwater levels will experience small scale perturbations.

In some areas such as the Great Artesian Basin there are very large volumes of fresh water below the surface that can be used for human consumption, stock water or for irrigation.

In the winter rainfall belt of southern Australia, the common situation is one of saline groundwater and rising groundwater levels as a result of increased recharge. Under native land cover, the groundwater systems may have been in equilibrium, but clearing of native vegetation and planting annual crops and pastures has greatly increased the amount of recharge, leading to rises in groundwater. When groundwater comes within capillary reach of the surface (usually about 2 metres or so) water can be drawn up by evaporation, depositing any contained salt in the surface soil layer. Such discharge zones suffer losses of crop yields and can become bare and salt crusted.

The catchments in this model are assumed to be made up of several land management units, each of which is a homogeneous block with farms or other vegetation on the surface and a homogeneous groundwater system at some depth below the surface. Each farming system selected by the farm model leads to a different level of infiltration of water. This causes a rise in pressure that may or may not be transmitted to other land management units in the catchment depending on the geometry of the groundwater system.

Hydrologic modelling of the Liverpool Plains catchments is part of the overall project and will provide an essential link to analyse the externality effects between land management units. The form of the hydrologic modelling to be used is still under discussion but will probably involve the use of a soil moisture balance model for water calculations internal to the land management unit and a series of transfer functions to deliver water between land management units. Some form of routing routine that accounts for time lags in the system will possibly also be necessary.

Analysis using the catchment model

The full catchment model is still under development. The structure of the farm level model is determined and tested, data have been collected and are being processed on the characteristics of farms in the Liverpool Plains catchments and a system of land management units is being developed. The hydrogeology of the catchment has been extensively studied (Hamilton 1992; Broughton 1994) and scoping style deterministic groundwater modelling is being developed.

The catchment model can be used to assess the cost to farmers of adopting specified dryland salinity management policies by simulating the effect on farm incomes over a twenty year horizon. It will not take into account the costs of dryland salinity such as damage to roads or the costs to farmers outside the Liverpool Plains catchments. Thus the costings estimated

are partial. Within the farm sector in the Liverpool Plains, however, the catchment model will provide disaggregated estimates of costs and responses to dryland salinity management policies.

The types of analysis to be carried out will focus on the application of specific policies throughout the Liverpool Plains targeting areas with a major impact on dryland salinity. Practices that may be examined include the effects of increasing planting of lucerne, dryland cotton, trees and increased numbers of livestock. The aim is to gauge the impact on the rate and cost of soil salinisation. This will be done by constraining representative farms to adopt the practices and observing the resulting changes in farm incomes.

The effects of rainfall variation

An extension of the basic analysis would be to allow for the impact of stochastic rainfall on the analysis. The relationship between management and groundwater accessions depends on the level of rainfall. In a dry year, accessions will be small under any management system. Where the effects of rising watertables may be nonlinear and partially irreversible the possibility exists that the effects of mean rainfall may be different from that of the actual pattern of wet and dry years.

The MoFEDS system allows for this to be tested by using three values for rainfall in a year. The three values correspond to a normal, a dry and a wet year. A daily rainfall model was used to estimate the relationship between these rainfall values and the level of accessions and crop yields under each management system. The probability of one of these levels of rainfall occurring will be estimated from historical data.

For each simulation, the model would be run initially assuming expected rainfall. The solution would be saved and the effects of different rainfall in each year simulated by holding cropping fixed and allowing the model to recalculate farm incomes and watertable accessions. The different rainfall patterns give different watertable levels in later years and hence different yield effects. The model has a twenty year time horizon and for each simulation twenty years of randomly chosen data will be used. The simulation should be repeated at least 100 times with different randomly selected rainfall patterns to obtain the mean and distribution values of farm incomes and watertable accessions.

Discussion and conclusions

The economic and hydrological catchment model described in this paper will form only part of the whole project in the Liverpool Plains. The planned approach to the economic modelling of the catchment is reported in this paper. The approach consists of integrating an existing model into a representative farm system incorporating groundwater flows. The economic catchment model will provide a catchment and land management unit perspective on the costs of the adoption of policies and programs to reduce dryland salinity in the catchment.

The project is intended to run for a further two years. In this time the modelling results will be integrated with the farm profile data including the economic and sociological surveys and the farm level analyses using FARMULA. Descriptions of the final catchment model and results from the analyses will be presented in future papers. It is intended that the completed research will be presented at a workshop to be held in the Liverpool Plains region in late 1996 and published as one or more ABARE research reports.

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